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Simplified Parametric (Phenomenological) Model of Creep of Concrete in Direct Tension

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Abstract An analytical model based on the experimental trend of the creep deformation of concrete in direct tension is developed. The model is calibrated for normal and high strength concretes and the results show close agreement with experimental data. The inclussion of the stress level is a unique feature of the model and presents a prospect for predicting concrete deformation for any regime of loading. The model confirm that the creep strain of concrete in tension are non-linear right frm the begining of loading therby ruling out the applicability of the principle of superposition The model presents a means for incorporating the nonlinearlity of creep into other predictive models of concrete.

Keywords: *concrete, tension, model, creep, microfracture*

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1. Introduction

The complex behaviour of concrete, arising from the composite heterogeneous nature of its internal structure is difficult to model. This calls for the development of appropriate constitutive models for its deformation under load. Consequently, the existing creep models have been developed with increasing levels of complexity in a bid to reflect the complete features of the material. Thus, several theories and hypotheses based on various perceptions about the concrete internal structure have been propounded for the explanation of the mechanism of the creep phenomenon in concrete.

Generally, the study of creep under compression has received significantly greater attention of researchers than of its behaviour under tensile loading. The early functional formulations were derived from two fundamental theories: the hereditary theories and he theory of ageing. The basic mathematical espression from these theories espressed as afunction of stress level,age at loading and duration of loading have the form of integral equations [2,3,4,5,6,7,8,18].

In addition, there are few approximations of laboratory experimental data in use for quick assessment of creep deformations in design [1,2,9,10]. Recently, the contribution of micro cracking in the overall mechanism of resistance and deformation of concrete has been given greater recognition.These studies have resulted in the formulation of various three dimensional models of creep deformation of concrete in tension [2,7,8,13,20]. The interesting features of the recent models are described in the following section

(a) Three-dimessional Rheological Model

The Ephraim-Yaschuk Model [13] is in the form of a regular three dimensional rheological lattice, representing the concrete microvolume. Micro-fracture is represented by the continuous depletion of the bond cross sections, resulting from outage of broken weaker bond fibres, as loading is progressed with time. The resulting equations of longitudinal creep deformations are in the form of a system of ordinary homogeneous differential equations. The model allows the prediction of transverse creep strains and Poisson's effect as a consequence of its spatial configuration.

(b) The Stochastic Three-dimensional Finite Element Models.

These include the numerical concrete models of fracture mechanics with incorporation of microprestress and solidification processes attributable to an ageing medium such as concrete [2,3,4,5,6,7,20]. A recent extension of these models has resulted in the confinement shear lattice model [11]. The creep equations from these models are complex and ammenable only to computer applications.

Thus, in spite of the great contributions of the above theories and models, their practical application in structural design is difficult, for example, in the calculation of deformations and cracks at the serviceability limit state. The authors therefore recognise the need for simpler, perhaps more reliable creep models At the same time, the paucity of models of concrete creep behaviour under tensile stress is recognised,and this paper is dedicated to filling that gap.

2. Creep of Concrete under Direct Tension

As observed earlier, technical literature reveals a dire paucity of experimental work on concrete in uniaxial tension. This is associated with known technological difficulties, including gripping problems, presence of imperfections and difficulty of applying a purely concentric pull among others. It is for these reasons that several researchers have recognised the modeling option as a more perspective approach [2-9,12,13,14,15]. None-the-less, the few authoritative researches on tensile concrete [1,13,21] have produced invaluable data on the magnitude and variational trend of creep strain in concrete under axial tensile loading.

Among these are the extensive experimental studies of Karapetyan reviewed by Ephraim in is work on creep of normal concrete under varying stress levels [13] and duration of loading and on recent experimental studies on creep of high strength concrete under axial tension is reported in the publication of Hans-Wolf Reinhardt, Tassilo Rinder [14]. Further, the various factors influencing the stress strian relation of concrete in uniaxial tension are investigated by Komlos [17]. The accumulated experimental evidence it may be concluded that creep strains in concrete depend principally on the age at loading, the stress level applied and the duration of loading.

The features of a typical creep curve can be devided into three distinct segments as shown in the curve 1 of Figure 1.

- Segment I: an initial period of rapid increase in creep deformation immediately after load application when the creep rate tends to infinity;
- Segment II: an intermediate period of gradual decrease in growth of creep deformation(about 3-7 days after loading), and
- Segment III: a final period of renewed rapid increase just before failure of the material.

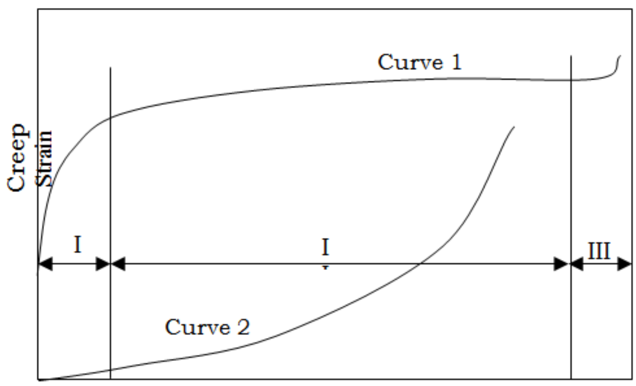

Figure 1. Plot of total Creep strain versus time(Curve 1) and stress level(Curve 2)

Although various non-linear effects are observed to be associated with the creep of concrete, concrete is generally considered as an aging linear viscoelastic material in the range of service stresses [2,3,4,5]. Consequently, the common basis for most of the proposed creep models in the literature is the assumption of creep linearity, i.e. creep strains under constant stresses are assumed to be linearly related to the stress level. Meanwhile, Ostergaard, Altoubat and Stang [19] in their recent experimental study have confirmed that the relationship between early age tensile creep and stress level is nonlinear. This further cofirms the results of Karapetyan and Kotikyan as reviewed by Ephraim [13].

3. The Proposed Model of Tensile Creep

The proposed model is developed in accordance with the requirements of RILEM [21] regarding the identification of physical varibles, theoritical formulation and validation for prediction models fro creep and shrinkage of concrete. The most important of these includes:

(1) After optimizing its coefficients, the model should be capable of providing close fits of the individual test data covering a broad range of times, ages, humidifies, thicknesses, etc.;

(2) The model should have a rational, physically justified theoretical basis, and

(3) Should allow good and easy extrapolation of the short-time tests into long times, high ages, large thicknesses etc.

On the basis of the general trends of creep curves of Figure. 1, the following assumptions are adopted in the formulation of the proposed model.

(i) The functional dependence between creep deformaton (ε_c) and the duration of loading ($t-\tau$) may be approximated by a logarithmic function of the form

$$\varepsilon_c = f\left[\ln\left(\frac{t-\tau}{\lambda}\right)\right] \qquad 1$$

Where, t - age of concrete,

τ - Age of concrete at time of loading,

λ- Time scaling factor =1 day

(ii) In line with the observation of [13,19], the functional relationship between creep strains (ε_c) and the stress level applied η may be approximated by an exponential function as follows

$$\varepsilon_c = f\left[e^{2\eta}\right] \qquad 2$$

Where, η = stress level defined as the ratio of applied stress to 28-day tensile strength of concrete.

(iii) The concrete material is considered unageing for which the effects of technological and environmental factors as well as micro-prestress may safely be neglected

Thus, the significant independent variables for modelling are; the tensile strength of concrete (f_t), the applied stress ltvel (η), the duration of load application ($t - \tau$) and the initial modulus of elasticity of concrete (E_O).

(iv) The basic creep is assumed proportional to the product of the two functions.The creep strain may be represented in the form.

$$\varepsilon_c = \frac{ke^{2\eta} f_t}{E_0} F\left[\ln\left(\frac{t-\tau}{\lambda}\right)+C\right] \qquad 3$$

where, k is model parameter depending on the strength of concrete and

determined by calibration;

C - calibration constant

f_t - the 28-day tensile strength of concrete

E_o - the age-independent elastic modulus of concrete.

Equation 3 shows the proposed model for thereep strain of concrete,As mentioned earlier, experimental data on direct tensilecreep are scarse.However,the author have relied on the experimental resulsts published by Karapetyan and Kotikyan as reviewed by Ephraim [13] for creep of normal concrete and Hans-Wolf Reinhardt, Tassilo Rinder [14] for high strength concretefor calibration and validation of the proposed model inline with RILEM guidelines [21].

4. Model Calibration

The principle of least squares enables the fitting of a polynomial of any degree to achieve a close functional relationship between variables. The constants k and C were determined using the least square method for curve-fitting.

The general polynomial equation is given as:

$$Y = a_o + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 + \dots\dots + a_n X^n \qquad 4$$

A typical creep curve for a given concrete and stress level represents asymptotic logarithmic functions (Figure 1) and can be linearized in the form of first degree polynomial with two constants

$$Y_c = a \ln X + b \qquad 5$$

Rearranging equation 3, we have:

$$\frac{\varepsilon_c E_o}{e^{2\eta} f_t} = \left[k \ln\frac{(t-\tau)}{\lambda} + kC\right] \qquad 6$$

If D = kC then, equation 6 becomes:

$$\frac{\varepsilon_c E_o}{e^{2\eta} f_t} = \left[k \ln\frac{(t-\tau)}{\lambda} + D\right] \qquad 7$$

Adopting the first degree polynomial, equation 4 can be reduced to:

$$Y = a_O + a_1 X \qquad 8$$

The constant are determined by solving the resultant simultaneous equations presented in the following matrix form:

$$\begin{bmatrix} N & \sum X \\ \sum X & \sum X^2 \end{bmatrix} \begin{bmatrix} a_o \\ a_1 \end{bmatrix} = \begin{bmatrix} \sum Y \\ \sum XY \end{bmatrix} \qquad 9$$

Where, $Y = \frac{\varepsilon_c E_o}{e^{2\eta} f_t}$, $a_O = D$, x = $\left[\ln\frac{(t-\tau)}{\lambda}\right]$ and $k = a_1$.

5. Model Validation

The accuracy of the model was evaluated in terms of an error coefficient M suggested by Neville and Meyers et al [18]:

$$M = \left(\sqrt{\frac{C_p - C_e}{n}}\right) / C_e \qquad 10$$

Where

C_p = predicted creep from measured creep after t days under load

C_e = actual creep after t days under load;

n = number of specimens or experimental sets for which creep was observed at time t.

The error coefficient for the predicted creep strains are shown in Appendices 2 and 3. As modeled from the analysis the coefficients are less than 10%.

6. Analysis and Discussion of Results

As mentioned earlier, experimental data on direct tensilecreep are scarse. However, the author have relied on the experimental resulsts published by Karapetyan and Kotikyan as reviewed by Ephraim [13] for creep of normal concrete and Hans-Wolf Reinhardt, Tassilo Rinder [14] for high strength concrete for calibration and validation of the proposed model inline with RILEM guidelines [21].

The results of creep strains, calculated based on the proposed model are plotted in Figure 2 and Figure 3 for normal and high strength concretes. The errors calculated from equation 10 are tabulated in Appendices 2 and 3..

6.1. Model Calibration

The computations for normal and high strength concretes of [13,17] are shown in Appendices 1 and 2. These computations show that k varies from 0.01 for high strength concrete to 0.40 for normal concrete. The constant has a numerical value of 1 and is independent of the strength of concrete.

6.2. Model Validation

For the validation of the model, use was made of the experimental results of tensile creep test of Karapetyan and Kotikyan as reviewed by Ephraim [13] for normal concrete and Hans-Wolf Reinhardt, Tassilo Rinder [14] for high strength concrete the with tensile strength and elastic modulus of 1.375N/mm^2 and 25.30MN/mm^2 for the former and, 5.20N/mm^2 and 45.50MN/mm^2 for the latter. The results are plotted in Figure 2 and Figure 3 upon which the model creep curves are superimposed for comparative analysis.

6.3. Tensile Creep of Normal Concrete

The creep curves borrowed from the works of Karapetyan and Kotikyan as reviewed by Ephraim [13] are plotted in Figure 2.

Comparison of the model curves with the experimental for the same concrete shows that the model is capable of reproducing the vibrational trend of the creep deformation of normal concrete and yeild the intermediate and long term values as a function of the stress level and duration of constant tensile stress. In relation to model accuracy, it can be observed from Appendix 3 that the model predicted strains are sufficiently accurate to about 5-8 percent error.

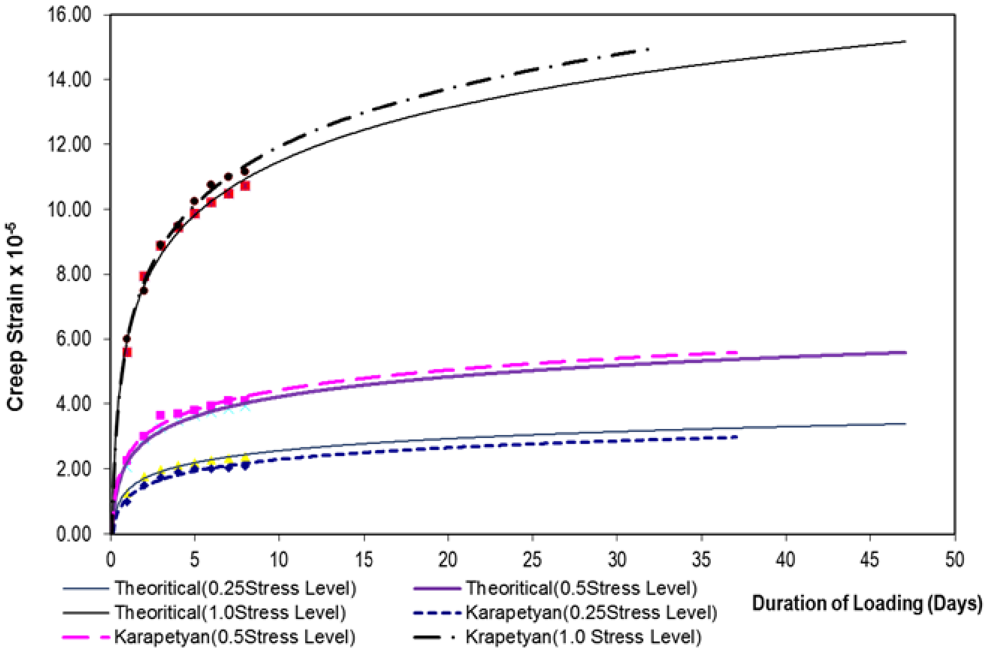

Figure 2. Plot of creep strain versus Time data obtianed from [13]

6.4. Tensile Creep of High Strength Concrete

Figure 3 shows the creep curve for high strength concrete based on the experiments of Hans-Wolf Reinhart et al. [14]. The theoretical curve obtained from the model is superimposed.

From these graphs it can be observed that the model strain showed a significant deviation from the experimental values for the high strength concrete within a few days of application of load. This error could be attributed to the rather rapid development of strain at early period of loading which may be difficult to follow in a normal experimental setting.

From Appendix 4, it can be seen that the model accuracy for HSC fall within 80%. With this in-view, it may be concluded that the model results are quite reliable for practical application.

Overall, the close correspondence of the model creep prediction to the experimental provide concrete evidence of the eficacy of the proposed model as on analytical and design tool.

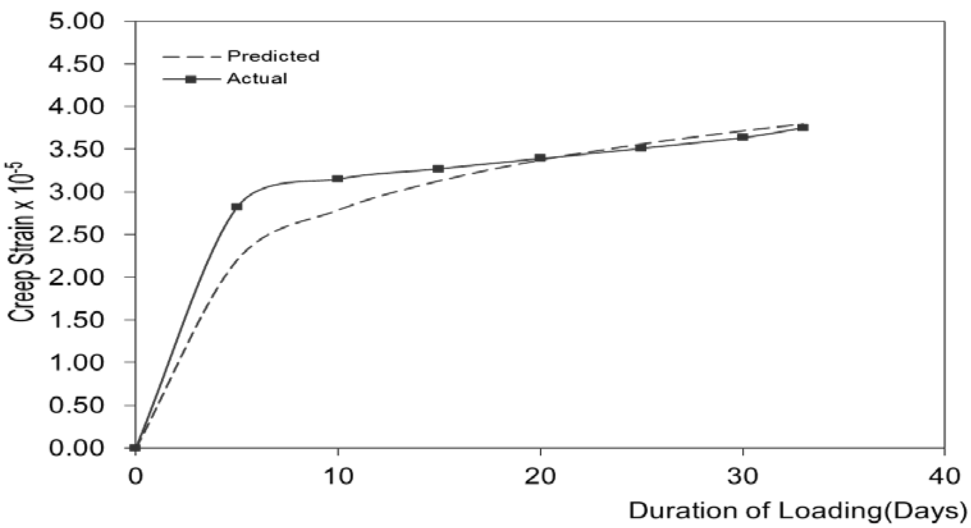

Figure 3. Plot of creep strain versus time for HSC data obtianed from [14]

7. Conclusions and Recommendations

The study considered the modelling of long-term creep strain of aged concrete under constant tensile stress in absence of shrinkage effects and the following conclusions were arrived at.

1. The proposed model themajor factors influencing concrete creep strains in direct tension are the tensile strength of concrete, the level of tensile stress and its duration of action.

2. The reliability of the model is eveidenced by the close agreement of predicted strains with experimental values. The error average about 6% for both normal and high strength concrete.
3. The proposed model was formulated on the basis of RILEM guidelines for prediction of creep and shrinkage for concrete both in its rationality and physically justified theoretical basis.
4. The new simplified model can be optimised to produce close fits of individual experimental observations and thus reliably predict the creep of tensile concrete based on its 28-day tensile strength as a function of applied stress and duration of loading.
5. The new model provides scope for further developments on the areas of tensile creep of reinforced concrete, stress relaxation and elastic recovery among others.

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APPENDIX 1 MODEL CALIBRATION

A Calibration of Normal Concrete

As mentioned earlier, the proposed model is calibrated using the experimental results of tensile creep tests by Karapetyan and Kotikyan as reviewed by Ephraim [13] for normal concrete. The optimization operations is presented in Table A1

Tensile strength f_t = 1.375N/mm^2

Elastic modulus E_O = 25.30MN/mm^2

Table A1 Calibration of model for normal concrete using equation 9

S/N	Stress Level η	Time (days)	x = $\left[\ln\frac{(t-\tau)}{\lambda}\right]$	ε_c x 10^{-5}	$Y=\frac{\varepsilon_c E_o}{e^{2\eta} f_t}$	X^2	XY
1		40	2.485	1.15000	0.14184	6.175	0.3525
2		80	3.951	1.32000	0.16281	15.612	0.6433
3		120	4.522	1.60000	0.19734	20.447	0.8923
4	0.20	160	4.883	1.75000	0.21584	23.842	1.0539
5		200	5.147	1.85000	0.22818	26.497	1.1745
6		240	5.357	1.91000	0.23558	28.693	1.2619
7		280	5.529	2.05000	0.25284	30.575	1.3981
			31.874		**1.43443**	**151.840**	**6.7765**

1 2 3 4 5 6 7	0.50	40 80 120 160 200 240 280	2.485 3.951 4.522 4.883 5.147 5.357 5.529 **31.874**	2.25000 3.00000 3.65000 3.70000 3.80000 3.93000 4.10000	0.15230 0.20307 0.24707 0.25045 0.25722 0.26602 0.27753 **1.65366**	6.175 15.612 20.447 23.842 26.497 28.693 30.575 **151.840**	0.3785 0.8024 1.1172 1,2229 1.3240 1.4250 1.5346 **7.8045**
1 2 3 4 5 6 7	1.00	40 80 120 160 200 240 280	2.485 3.951 4.522 4.883 5.147 5.357 5.529 **Σ31.874**	6.0000 7.5000 8.9000 9.5000 10.2500 10.7500 11.0000	0.14941 0.18676 0.22163 0.23657 0.25524 0.26769 0.27392 **Σ1.59122**	6.175 15.612 20.447 23.842 26.497 28.693 30.575 **Σ151.840**	0.3713 0.7379 1.0021 1.1551 1.3139 1.4339 1.5146 **Σ7.5289**

Substituting in equation 9, we have

$$\begin{bmatrix} 7 & 31.874 \\ 31.874 & 151.840 \end{bmatrix} \begin{bmatrix} a_o \\ a_1 \end{bmatrix} = \begin{bmatrix} 1.434 \\ 6.779 \end{bmatrix}$$

Recalling the process for stress values of 0.50 and 1.00, the values of k and C are found as follows:

η	K	C
0.20	0.041	0.878
0.50	0.054	0.741
1.00	0.039	1.061

$$k=(k1+k3)/2=(0.041+0.039)/2=0.040$$
$$C=(C1+C3)/2=(0.878+1.061)/2=0.970$$

From the above values of constants, C can be approximated to unity
Thus, for normal concrete equation 3 becomes:

$$\varepsilon_c = \frac{0.04e^{2\eta} f_t}{E_o}\left[\ln\frac{(t-\tau)}{\lambda}+1\right] \qquad \text{I}$$

B Calibration of High Strength Concrete

For high strength concrete, the experimental results of tensile creep tests by K. Hans-Wolf Reinhardt, Tassilo Rinder [14] were used for calibrating the model. The optimization operations is presented in Table B1

Tensile strength f_t = 5.20N/mm^2

Elastic modulus E_O = 45.50MN/mm^2

Stress Level = 1.00

Table B1 Calibration of model for high strength concrete, using equation 9

S/N	Time (days)	$x = \left[\ln\frac{(t-\tau)}{\lambda}\right]$	ε_c x 10^{-5}	$Y = \frac{\varepsilon_c E_o}{e^{2\eta} f_t}$	X^2	XY
1	29	0.0000	5.35000	0.00634	0.0000	0.0000
2	33	1.6094	3.00000	0.03553	2.5903	0.0572
3	53	3.2189	3.51000	0.04156	10.3612	0.1338
4	58	3.4012	3.63600	0.04306	11.5681	0.1464
5	63	3.4965	3.75000	0.04441	122256	0.1553
		11.7260		**0.17089**	**36.7452**	**0.4927**

Using equation 9

$$\begin{bmatrix} 5 & 11.726 \\ 11.726 & 36.745 \end{bmatrix} \begin{bmatrix} a_o \\ a_1 \end{bmatrix} = \begin{bmatrix} 0.171 \\ 0.493 \end{bmatrix}$$

From the above values of constants, k and C can be approximated to 0.01 and 1.00 respectively
Thus, for high strength concrete equation 3 becomes:

$$\varepsilon_c = \frac{0.01e^{2\eta} f_t}{E_o}\left[\ln\frac{(t-\tau)}{\lambda}+1\right] \qquad \text{II}$$

APPENDIX 2 COMPUTATION OF ERROR COEFFICIENT M FORNORMAL CONCRETE

Time	(a).Error coefficient for 0.20 Stress Level [13]				
(days)	Predicted(C_p)	Experimental(C_e)	$(C_p-C_e)^2$		
40	1.130E-05	1.150E-05	3.93E-14	$\sum(C_p-C_e)^2/n$	2.45E-12
80	1.606E-05	1.320E-05	8.17E-12		
120	1.791E-05	1.600E-05	3.64E-12	$[\sum(C_p-C_e)^2/n]^{0.5}$	1.56E-06
160	1.908E-05	1.750E-05	2.49E-12		
200	1.994E-05	1.850E-05	2.07E-12	$\sum C_e/n$	1.72E-05
240	2.062E-05	1.910E-05	2.30E-12		
280	2.118E-05	2.050E-05	4.56E-13	M	9.12
320	2.165E-05	2.100E-05	4.27E-13		
		1.373E-04	1.96E-11		

Time	(b).Error coefficient for 0.50 Stress Level [13]				
(days)	Predicted(C_p)	Experimental(C_e)	$(C_p-C_e)^2$		
40	2.059E-05	2.250E-05	3.64E-12		
80	2.926E-05	3.000E-05	5.50E-13	$\sum(C_p-C_e)^2/n$	4.78E-12
120	3.263E-05	3.650E-05	1.50E-11		
160	3.476E-05	3.700E-05	5.00E-12	$[\sum(C_p-C_e)^2/n]^{0.5}$	2.19E-06
200	3.633E-05	3.800E-05	2.80E-12		
240	3.756E-05	3.930E-05	3.02E-12	$\sum C_e/n$	3.57E-05
280	3.858E-05	4.100E-05	5.84E-12		
320	3.946E-05	4.100E-05	2.39E-12	M	6.13
		2.853E-04	3.820E-11		

Time	(c).Error coefficient for 1.00 Stress Level [13]				
(days)	Predicted(C_p)	Experimental(C_e)	$(C_p-C_e)^2$		
40	5.598E-05	6.000E-05	1.62E-11		
80	7.953E-05	7.500E-05	2.05E-11	$\sum(C_p-C_e)^2/n$	1.56E-11
120	8.870E-05	8.900E-05	9.16E-14		
160	9.450E-05	9.500E-05	2.54E-13	$[\sum(C_p-C_e)^2/n]^{0.5}$	3.94E-06
200	9.875E-05	1.025E-04	1.41E-11		
240	1.021E-04	1.075E-04	2.91E-11	$\sum C_e/n$	9.38E-05
280	1.049E-04	1.100E-04	2.62E-11		
320	1.073E-04	1.115E-04	1.81E-11	M	4.20
		7.505E-04	1.25E-10		

APPENDIX 3 COMPUTATION OF ERROR COEFFICIENT M FOR HIGH STRENGTH CONCRETE

Time	Error coefficient for 1.00 Stress Level [14]				
(days)	Predicted(C_p)	Experimental(C_e)	$(C_p-C_e)^2$		
5	2.204E-05	2.920E-05	5.13E-11		
10	2.789E-05	3.150E-05	1.30E-11	$\sum(C_p-C_e)^2/n$	2.69E-12
15	3.131E-05	3.270E-05	1.92E-12		
20	3.374E-05	3.390E-05	2.48E-14	$[\sum(C_p-C_e)^2/n]^{0.5}$	1.64E-06
25	3.563E-05	3.510E-05	2.77E-13		
30	3.717E-05	3.636E-05	6.51E-13	$\sum C_e/n$	3.45E-05
33	3.797E-05	3.750E-05	2.22E-13		
		2.071E-04	1.61E-11	M	4.75