DURABILITY PERFORMANCE PREDICTION USING ANALYTICAL MODELING

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Abstract

Temperature and humidity (hygro-thermal) cycles degrade composite strengthening materials by changing the properties of based material due to plasticization and hydrolysis. Although there is no comprehensive mechanistic modeling of the hygro-thermal effect on durability/life-prediction including temperature, relative humidity, aging of exposure, and cycle periods, fairly precise predictions can be made through the sensible use of an equation based on micro mechanics and semi-empirical approaches that are based on extensive prior experimental testing results. This paper includes equations related to the prediction of hygro-thermal effects, and then describes the predicting results on long-term strength of concrete that exposed to various environmental conditions. William-Landel-Ferry (WLF) equation was employed here to develop the shift factor for regular concrete, which is exposed to different environmental conditions. The shift factors were determined empirically on basis of previous experimental test results.

Keywords: Regular Concrete Beam; William-Landel-Ferry (WLF) Equation (11); Strength of Concrete.

Introduction

Since last decades, regular concrete is considered as the best choice of material for construction activities around the world. Multiple reasons are considered for that. The first is that concrete still the most economical material in the construction industry. Second reason is that itis easy to use, and it can be shaped into any forms. The third reason is that concrete is excellent structurally, and the last reason is that concrete has high resisting strength to different environmental exposures. However, the service life of concrete has been seriously shortened due to durability problems, particularly when serving in non-ideal environments and suffering internal/external attacks. In this regard, the development of a better understanding of the deterioration mechanisms as well as reliable prediction methods for durability properties and/or long-term performance of concrete is necessary.

Modern computational modelling theories and methods are favourable for developing solutions to the above issues. Our objective here is to present William-Landel-Ferry (WLF) equation on concrete durability by using analytical/numerical approaches alone or in conjunction with experimental techniques. The temperature and aging effects are considered empirically for regular concrete by utilizing the WLF equation. The combined effect of temperature and time on the strength of various materials could be represented by time-temperature superposition (TTS) principle. One of the common applications of TTS is to expand time range of the short-term strength test results by taking such data at various temperatures and shifting them along the time axis, and then fitting the curve to find a master curve at the reference temperature, which usually was the standard lab temperature (25C°). The TTS principle was employed to construct the master curves for regular concrete that were utilized in the experimental work of this research. The master curves were determined separately by using linear strength and time data, and by logarithmic scale of these strength and time data.

Methodology

Experimental work

In total, 48 specimens were constructed, cured, and tested under various environmental conditions. Concrete mix was designed for a nominal compressive strength of 35MPa. The control specimens were tested at the age of 28 days. All specimens were taken out from the moulds at the second day of casting and placed into water basin for curing. All the specimens were subjected to Flexure test using MTS-810 testing machine.

Concrete Mix Design

The ACI Standard Practice ACI 211.1-91 was used to determine the mix portion of this study. We needed a mix with a mean 28-day compressive strength (measured on standard cylinders) of 35MPa and a slump of 50mm; ordinary Portland cement was used. The maximum size of well-shaped, angular aggregate is 20mm, its bulk density is 1680 kg/m3, and its specific gravity is 2.7. The available fine aggregate has a fineness modulus of 2.40 and a specific gravity of 2.54. No air entrainment is required. For the sake of clarity, all steps, even when obvious, will be presented.

Step 1: A slump of 50mm was specified.

Step 2: The maximum size of aggregate of 20mm was specified.

Step 3: From Table 6.3.3 (given in ACI 211.1-91) for a slump of 50mm and a maximum size of aggregate of 20mm (or 19mm), the water requirement is approximately 190kg per cubic meter of concrete.

Step 4: From experience, the water/cement ratio was assumed as equal to 0.54 to get concrete with a compressive strength, measured on cylinders, of 35MPa. There are no special durability requirements.

Step 5: The cement content is 190/0.54 = 351kg/m3.

Step 6: From Table A. 1.5.3.6 (given in ACI 211.1-91), when used with a fine aggregate having a fineness modulus of 2.40, the bulk volume of oven-dry rodded coarse aggregate with a maximum size of 20mm is 0.66. Given that the bulk density of the coarse aggregate is 1680 kg/m3, the mass of coarse aggregate is 0.66×1680=1109kg/m3.

Step 7: To calculate the mass of fine aggregate, we needed to calculate the volume of all the other ingredients first. The required values are as follows:

Volume of water is 190/1000=0.190m^3.

Solid volume of cement, assuming usual specific gravity of 3.15, is 351/ (3.15×1000) =0.111m^3.

Solid volume of coarse aggregate is 1109/ (2.7× 1000) =0.41m^3.

Volume of entrapped air, given in table 3.5, is 0.02× 1000=0.020m^3.

Hence, total volume of the ingredients, except fine aggregate, is 0.731m^3.

Therefore, the required volume of fine aggregate is 1- 0.731= 0.269m^3.

Hence, the mass of fine aggregate is 0.269× 2.54× 1000= 685kg/m^3.

From the various steps, we could list the estimated mass of each of the ingredients of concrete in kg/m3 as listed in Table (1).

Table (1): Mix Compositions of Regular Concrete.

Concrete Material	Quantity (Kg/m^3)
Cement	351
Coarse Aggregate	1109
Fine Aggregate	685
Water	190

Concrete Mixing Procedures

A 0.170 cubic meter heavy-duty concrete mixer was used to produce concrete; all concrete compositions were measured by weight by using a digital balance. The dry constituents were mixed for one minute before water was added and mixed for three more minutes to provide a homogeneous concrete mix. The composition ratio of the overall concrete mix was 1:3.2:1.95:0.54 of cement, coarse aggregate, fine aggregate, and water respectively. All the specimens were casted from the same batch, and cured for 28-days in a water tank (see Figure (1)).

Figure (1): The Specimens in the Water Tank.

Concrete Slump Test

The slump test is an empirical test that is used for the measurement of the fresh property of regular concrete such as its consistency and workability. The test was done per ASTM C143-08 “Standard Test Method for Slump of Hydraulic-Cement Concrete”. The characteristics used to find the slump value were as follows: a standard concrete slump test cone with 305mm high, the base 203mm diameter, and 102mm diameter at the top. The cone was placed on a smooth surface plate, the small diameter at the top, and the cone was filled with three layers of fresh concrete. Each layer was tamped 25 times with a standard 16mm diameter steel rod before add the next layer. The final top surface of regular concrete was struck off by a screeding and rolling motion of the tamping rod. The cone was firmly held by footrests against its base during the operation. After the filling, the cone was slowly lifted and put upside down and then the slump value was measured. The slump value for regular concrete is as seen in Figures (2a), (2b).

Figure (2a): Slump Test Cone Filled out by Concrete.

Figure (2b): Measure the Slump Value.

Description of Test Specimens

406mm, 109mm, and 04mm are length, width, and height respectively. Rectangular beam moulds, (see Figure (3)), were used for beam specimens. The dimensions of the beam moulds were selected according to the ASTM standard C293-8 for flexural strength concrete using simple beam with centre-point loading, whereas the effective span length was three times of the beam depth, and the distance from the centre of the support to the beam edge was 50mm each side.

Figure (3): Rectangular Beam Moulds.

Environmental Conditioning

Temperature and humidity play an important role in the mechanical properties of regular concrete. In order to investigate the effects of the hot weather environment and hygro-thermal aging on the mechanical properties of regular concrete, the following procedures were carried out. After curing, specimens of the samples, and to accelerate aging conditions, the specimens were exposed to temperature and humidity sources for a certain period before being tested.

Temperature

The influence of temperature on regular concrete was the most important part of this research. In addition to room temperature, specimens were exposed to four different temperatures (25C°, 100C°) with 100% humidity. One environmental chamber, with a maximum temperature of 200C°as shown in Figure (4), was used for this purpose.

Relative Humidity

Relative humidity is another factor that was investigated in this research. Two levels of relative humidity were used for this experimental work. These relative levels were 0.0% and 100%. The two furnaces were used for all samples conditioned at 0% humidity, whereas the environmental chamber was used for the 100% humidity tests.

Figure (4): Temperature/Humidity Environmental Chamber.

Age Accelerating

To evaluate the durability performance of regular concrete, the environment factors considered in this test program are number of thermal cycles, cycle length, exposure time, and media type including various degrees of humidity and dry air.

In this study, flexural strength test was carried out to evaluate the deterioration after 0, 40, 100, 250, 625, and 1250 cycles. The cycle period was 2hrs.The temperature and humidity regime cycles for 2hrs for 100C° of temperatures are shown in Figure (5). This was for 100% humidity condition.

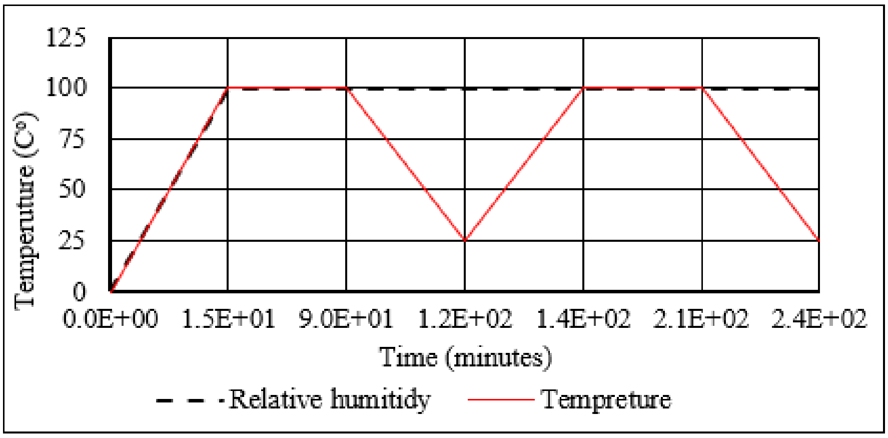

Figure (5): Temperature and Humidity Regime Cycles (2hrs-Cycles).

Mechanical Test Procedures

One mechanical tests was carried out in this experimental program namely flexural strength test. All plain concrete beams were subjected to flexural strength testing.

Flexural Strength Test Procedures

The 406mm, 109mm, 104mm concrete beams were simply supported over a 305 mm span and loaded at the middle of the span according to ASTM C293. The load was applied monotonically under displacement control at a constant rate of 0.003mm/sec. The load and displacement data were recorded every 0.8 sec up to the test specimen failure. Figure (6) shows the MTS-810 testing machine which was used for all flexural strength tests. All tests were done at laboratory temperature and humidity (23C° and 25%) respectively.

Figure (6): MTS-810 Material Test System.

Experimental Results and Discussions for Regular Concrete Beams

Experimental Results for Regular Concrete Beams (100% Relative Humidity)

Three plain concrete beams B1, B10, B15 were used as the control beam. These beams were tested for flexural strength using three-point loading according to ASTM C293-08 after 28 days in water. As shown in Table (2), the average maximum flexural load of these three specimens was 13572N. The type of failure of these three beams was flexural failure. The relationship curves between flexural load and deflection of these specimens are shown in Figure (7).

Table (2): Flexural Strength Test Results of Control Beam Specimens.

Beam #.	Max deflection (mm)	Max. load (N)	Mean (N)	Max. flexural Strength (MPa)	Stiffness (N/mm)	Failure mode
B1	0.66294	13329.1	13572	5.82	17579.58	FLEXTURE
B10	0.69088	13568.9		5.92	17895.86	FLEXTURE
B15	0.70104	13818		5.03	17699.02	FLEXTURE

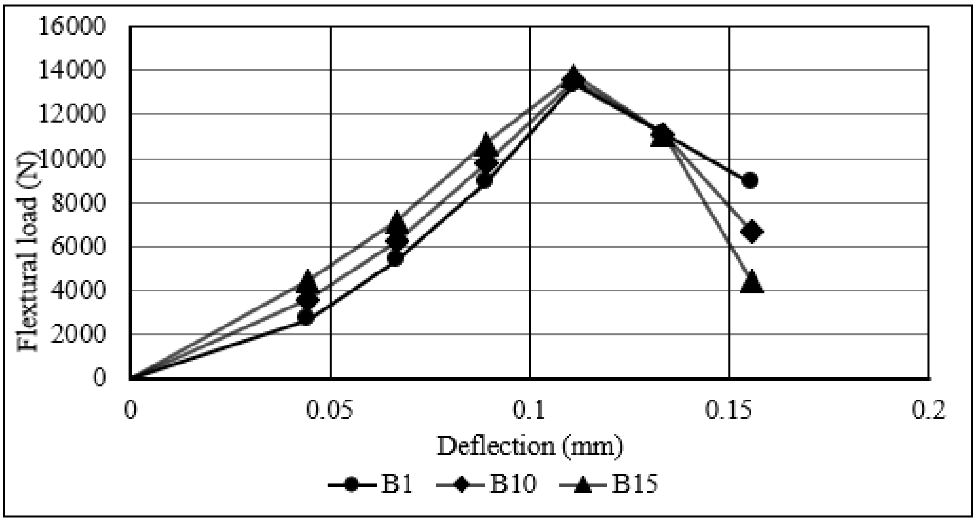

Figure (7): Control-Concrete Beams, Flexural Load- Deflection Results.

To study the effect of hygro-thermal condition on concrete flexural strength, 15 plain concrete beams were exposed to 100% relative humidity, number of cycles, and cycle periods. Table (3) shows the average results of the specimens. Figure (8) shows Concrete beam specimen.

Table (3): Flexural Strength Test Results of Concrete Beam Specimens at 100% Relative Humidity.

Temp. C°	Cy	CP (Hr)	Max deflection (mm)	Mean (N)	Max. flexural strength (MPa)	Strength Comparing with control beam	Deflection comparing with control beam	Stiffness (N/mm)
25-100	40	2	0.69342	13616	5.95	FLEXTURE	0.32% increase	1.1% increase
	100		0.88138	17881	7.81	FLEXTURE	31.75% increase	28.5% increase
	250		0.86614	19349	8.45	FLEXTURE	42.57% increase	26.3% increase
	625		1.016	16947	7.4	FLEXTURE	24.87% increase	48.1% increase
	1250		0.68834	8629	3.77	FLEXTURE	36.4% decrease	0.37% increase

Figure (8): Concrete Beam Specimen.

All the above 15 specimens failed due to flexural crack at the centre of the beam, Figure (9) shows the mode of failure for one of these beams.

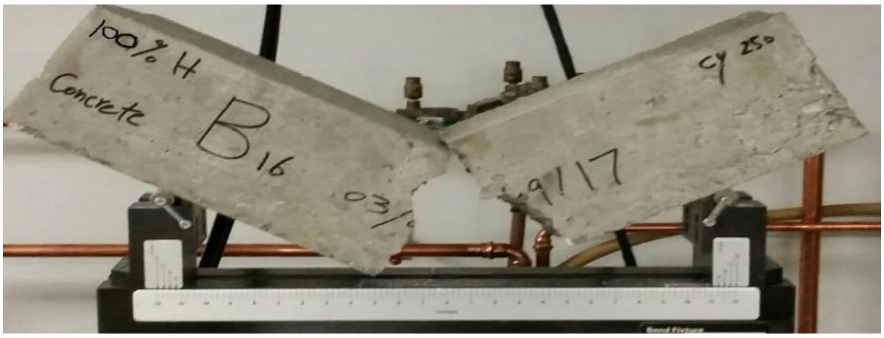

Figure (9): Flexural Failure of Concrete Beam-100% Relative Humidity.

The relationship curve between flexural load and deflection of the average of regular concrete beam specimens are shown in Figure (10).

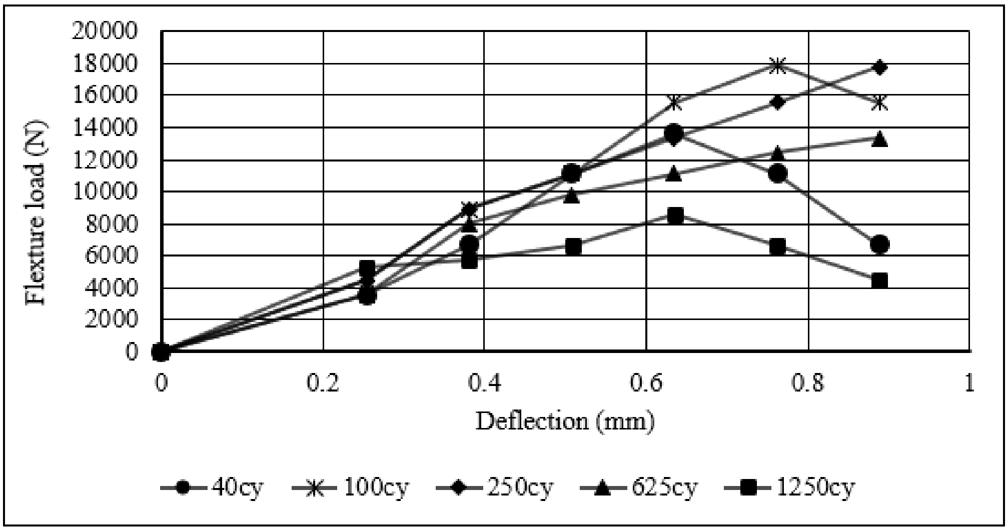

Figure (10): Concrete Beams, Flexural Load - Deflection Results.

The above results showed that the flexural load of concrete beams increased due to subjecting them to 100% relative humidity and temperatures changing from 25C° to 100C°; the magnitudes of flexural load increase varied with the number of cycles. The load was the highest after 250 cycles, compared to 100 cycles and 40 cycles, and then the load was reduced after 625 cycles.

This can be due to the change of the chemical and the physical properties of the plain concrete (Naus 2005). The increase of temperature increased the hydration process of the Portland cement and the chemical reaction speeded up at a certain point. The modules of elasticity (stiffness) increased by increasing the temperature cycle, and because of the humidity, concrete members kept some moisture and the strength kept increasing at a certain point (from 40cy into 250cy). Then because of temperature exposure duration, the properties of plain concrete started losing some of their advantages. The modules of elasticity decreased and the load as well (625cy into 1250cy).

Figures (11a) and (11b) shows the relationship between the flexure load and the number of cycle temperature, and the relationship between the deflection sand number of cycle temperature respectively. Figure (12) shows the relationship between stiffness and number of temperature cycle compared with control specimens.

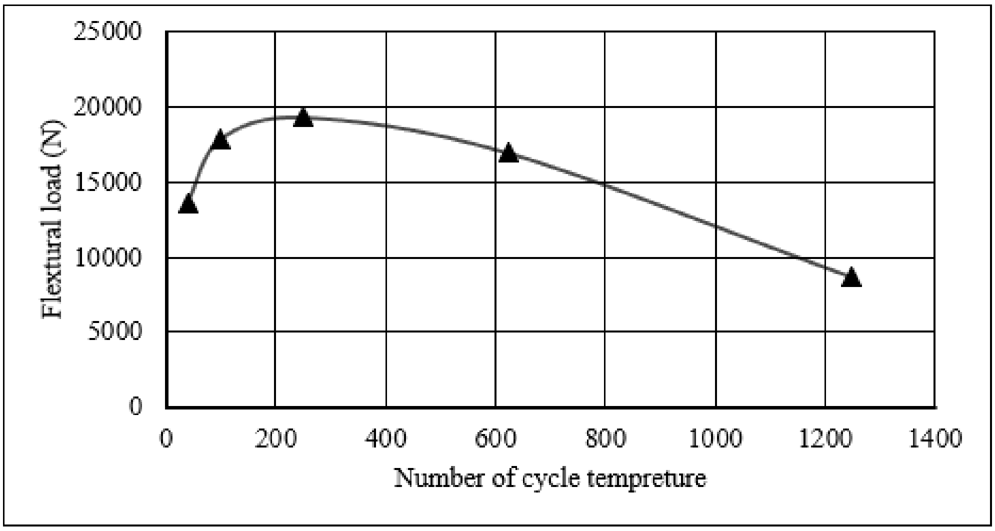

Figure (11a): Concrete Beams, Max Flexural Load Results vs Number of Cycles.

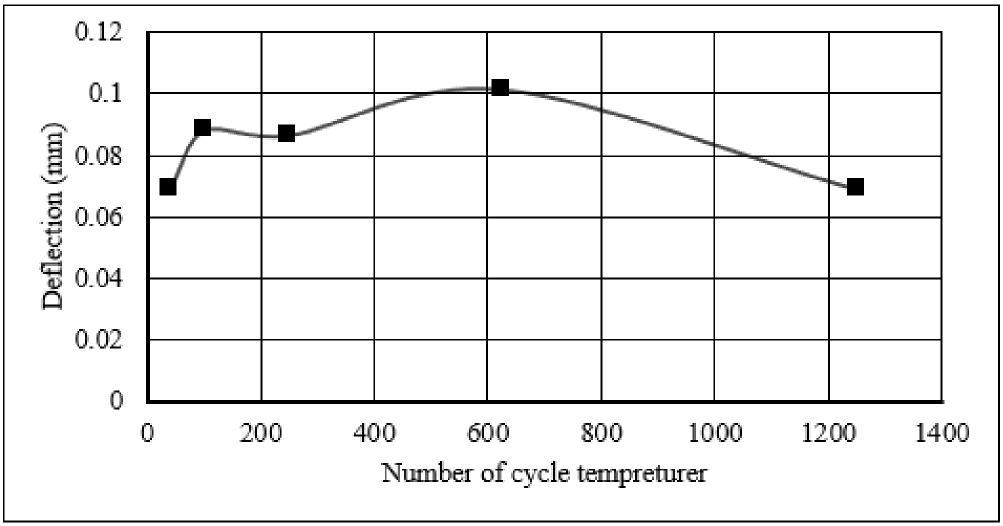

Figure (11b): Concrete Beams, Max Deflection Results vs Number of Cycles.

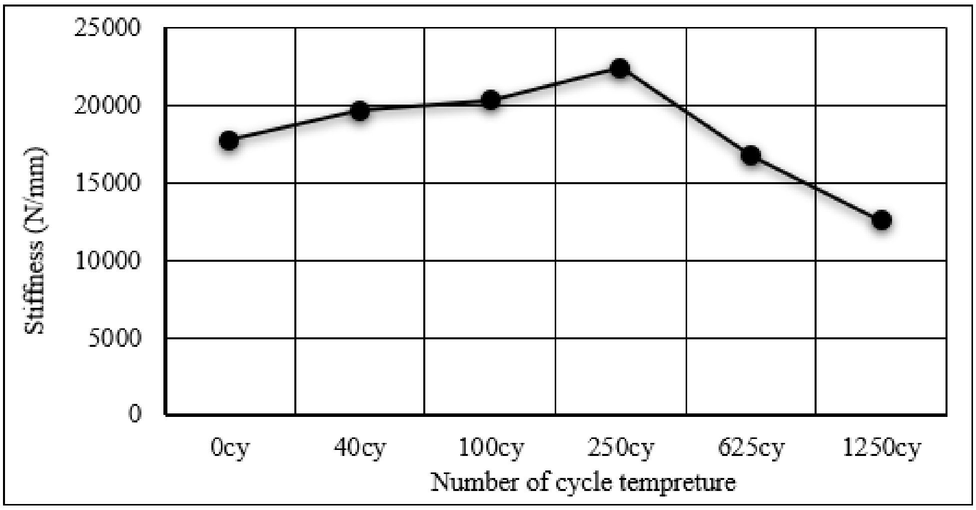

Figure (12): Relationship Between the Stiffness and Number of Cycle Temperature Comparing with Control Specimens.

Temperature and Aging Effects

The temperature and aging effects are considered empirically for regular concrete by utilizing the WLF equation. The combined effect of temperature and time on the strength of various materials could be represented by the time-temperature superposition (TTS) principle. One of the common applications of TTS is to expand the time range of short-term strength test results by taking such data at various temperatures and shifting them along the time axis, and then fitting the curve to find a master curve at the reference temperature, which usually is the standard lab temperature (25C°). The TTS principle was employed to construct the master curves for regular concrete that were utilized in experimental work. The master curves were determined separately by using linear strength and time data, and by logarithmic scale of these strength and time data.

Temperature and Aging Effects on Regular Concrete Material

The experimental data of regular concrete beams was applied to obtain the master curve of concrete material. The William-Landel-Ferry (WLF) equation is:

$$\log aT = -\frac{C_1(T-T_r)}{C_2+(T-T_r)} \qquad (1)$$

Where:

aT= temperature-dependent shift factor

T= temperature

T_r = reference temperature,

C_1 and C_2 are material constants.

By using the flexural strength data under various aging conditions for regular concrete beam specimens that were determined from the experimental tests, the original data on flexural strength- time are plotted in Figure (13) using linear scales. Figure (14) shows the logarithmic curves of these original data.

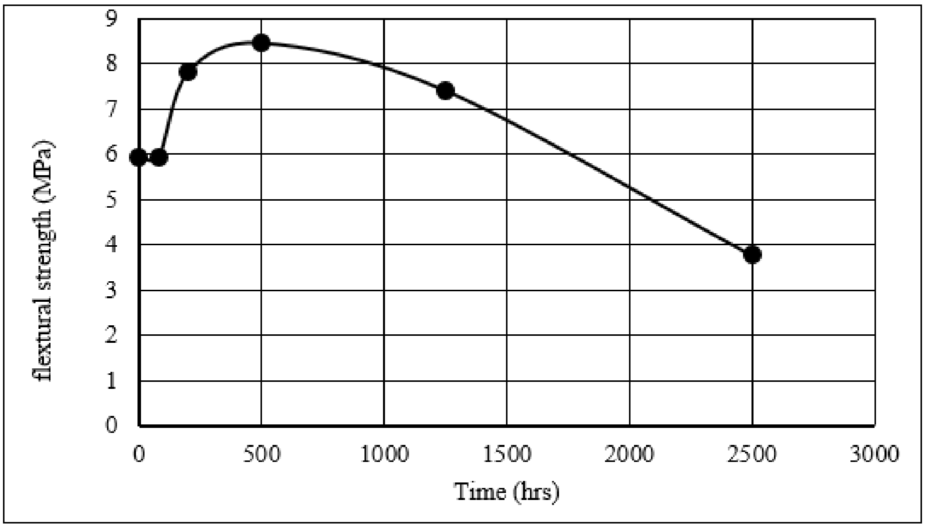

Figure (13): Flexural Strength vs. Time Curves for Concrete Beams.

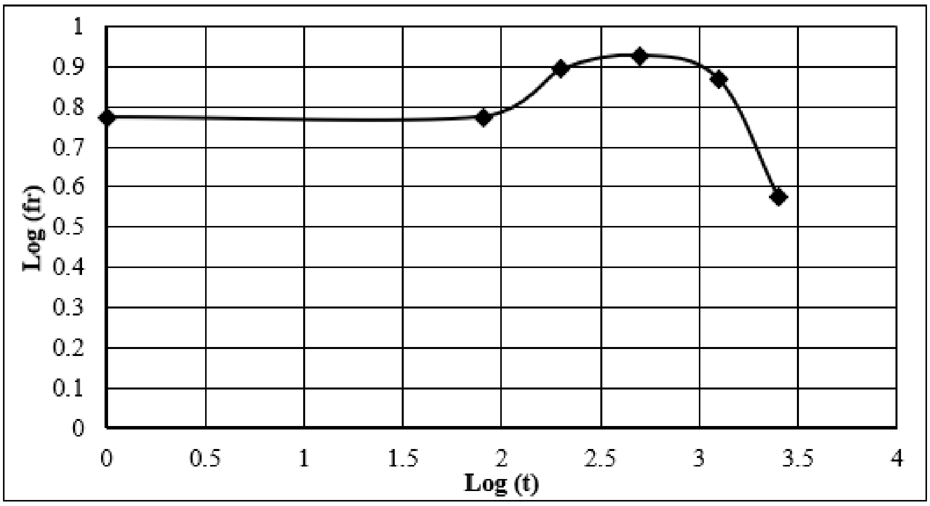

Figure (14): Flexural Strength vs. Time Curves for Concrete Beams (Logarithmic Scale).

Results and Discussion

WLF equation was used; and the following were used T=100C° ,T_r=25C° , C_1= -8260.30 and C_2= 146.26 (note: these values of $C_1$and C_2were obtained by using linear data from other experimental study (Elarbi, 2011)). When the logarithmic data were used, the constants of C_1 and C_2 equalled-38.40 and 2325.0 respectively. Because of applying time-temperature superposition (TTS) using the available experimental data and shifting 100C° curve, the new curve was combined to generate the master curve (see Figures (15) and (16)).

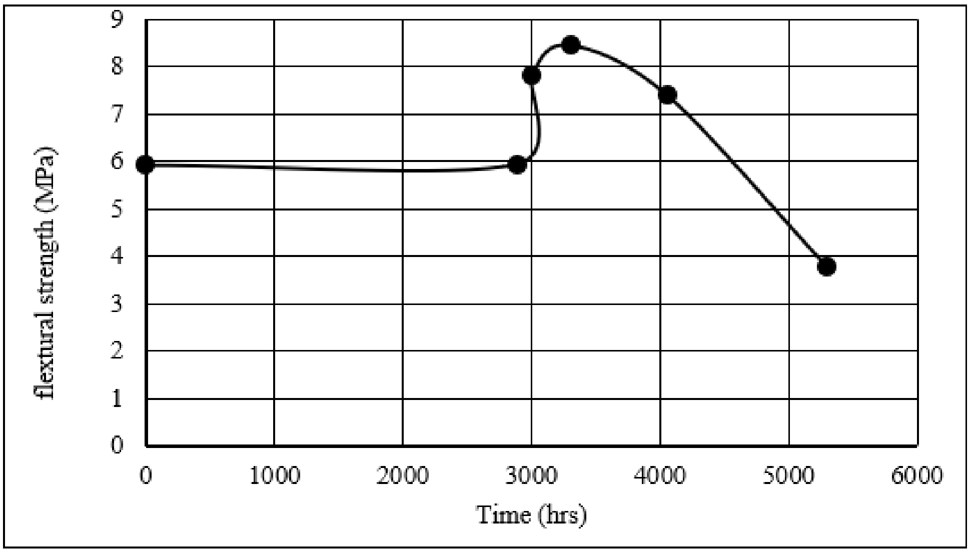

Figure (15): Shifting of Flexural Strength vs. Time Curves for Concrete Beams.

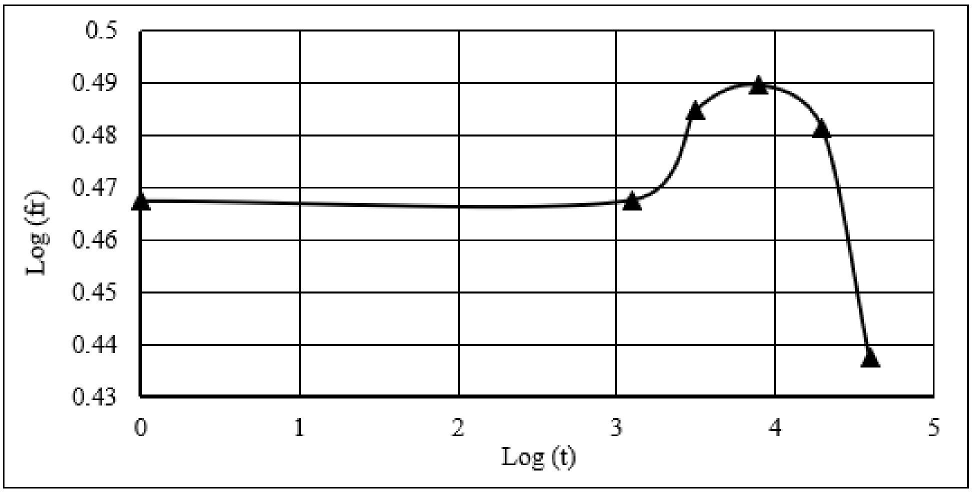

Figure (16): Shifting of Flexural Strength vs. Time Curves for Concrete Beams (Logarithmic Scale).

The master curves at the reference temperature (25C°) were obtained by fitting all the data points in Figures (15) and (16), and are shown in Figures (17) and (18). The normalized strength equations as a function of time are equal:

$$f_r(t) = -6\times10^{-5}(t^2)+0.2622(t)+839.41 \qquad \textbf{(linear scale)} \qquad (2)$$

$$f_r \log(t) = -0.0356\log(t^2)+0.1522\log(t)+2.9263 \qquad \textbf{(logarithmic scale)} \qquad (3)$$

Where $f_r(t)$: The strength of concrete (MPa), and t: The time (hrs).

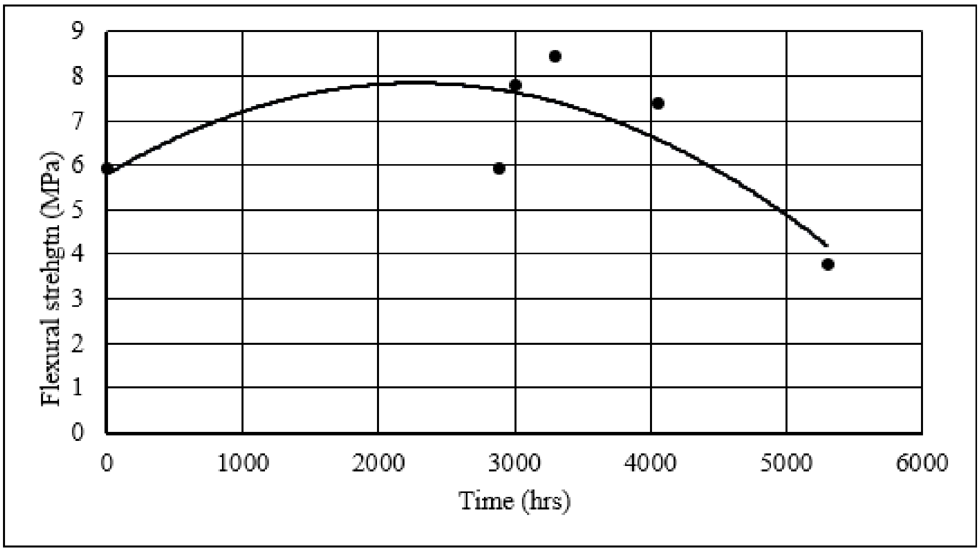

Figure (17): Master Curve for Concrete at Reference Temperature (Linear Scale).

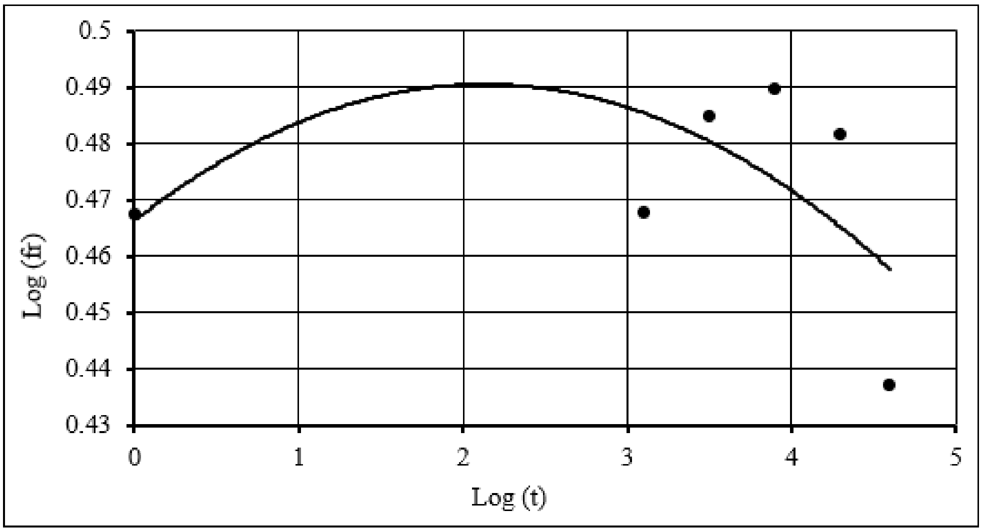

Figure (18): Master Curve for Concrete at Reference Temperature (Logarithmic Scale).

Conclusions

Based on the work described in this paper, the following conclusions are drawn:

- The increase of temperature will increase the hydration process of the Portland cement and the chemical reaction will fast at a certain point.
- The modulus of elasticity will increase by increasing the temperature cycle.
- Because of the humidity, the concrete members will preserve some moisture and the load will continue its increasing at a certain point (from 40cy into 250cy).
- Due to temperature exposure duration, the properties of plain concrete will lose some of its advantages.
- As a result of applying time-temperature superposition (TTS), using the available experimental data, and shifting 100C° curve, the new curve was combined to generate the master curve

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