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Synergistic Correlative Assessment of Compressive Strength of Concrete Based on Cement-Water Ratio and Hydration Period

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Abstract: This paper presents a synergistic correlative assessment of the compressive strength of concrete based on water-cement ratio and hydration period. The assessment was carried out based on process parameter ranges16.91-16.99 (N/mm^2), 3-16 days and 0.4 – 0.49 for compressive strength, hydration period and water-cement ratio respectively. The input concentration of super plasticizer was 2.0%. A derived empirical model; $V = 8.347 (e^{0.036\S} + 1.012\, e^{0.0004\alpha})$ assesses the compressive strength of the concrete as a function of the sum of exponentials of the water-cement ratio and hydration period. Results predicted by the model show that compressive strength of the concrete increases with increase in both water-cement ratio and hydration period in line with previous research. This implied that the negative effect of increasing water-cement ratio was over shadowed by the desirable impact of increased hydration on the concrete. The validity of the model was rooted on the core model expression $0.1198V = e^{0.036\S} + 1.012e^{0.0004\alpha}$ where both sides of the expression are correspondingly almost equal. The standard error incurred in predicting the model-based concrete compressive strength relative to the actual results was 0.004%. Evaluations from generated results reveal that the compressive strength of the concrete per unit hydration period were 0.0062 and 0.0064(N/mm^2)/ days as obtained from actual and model-predicted results respectively. Deviational analysis of model-predicted results (with respect to actual results) indicates a maximum < 0.05%. This translated into over 99% operational confidence levels for the derived model and 0.99 dependency coefficient of concrete compressive strength on water-cement ratio &hydration period. The correlation coefficients between the compressive strength of concrete and water-cement ratio &hydration period were all > 0.99.

Key words: Synergistic - Correlative assessment - Compressive strength - Concrete - Water - Cement ratio - Hydration period

INTRODUCTION

A mix of ground Portland cement clinker and various contents of limestone gives Portland limestone cement (PLC). The limestone is more easily ground than clinker, and becomes concentrated in the finest particles.

Studies [1,2] have evaluated the merits of using PLC cement to include proffering better workability and less bleeding than control concrete. In addition, usage of PLC concrete ensures better ecological advantages, prompted by reduction in the emissions of CO_2 and NO_x during cement manufacturing.

In studying PLC cement, water-to-binder ratio (W/B) implies the mass ratio of water to Portland cement plus limestone, and water-to-cement ratio (W/C) means the mass ratio of water to Portland cement. Research [3] has shown that the water-to-cement (W/C) ratio and the degree of hydration of cement most likely increases with limestone replacement (replacing a portion of the Portland cement with limestone). Another researcher [4] revealed that replacement of limestone-to-binder materials leaves the properties related to the pore structure of the concrete unimpaired up to a maximum of 25% input. Beyond this level, the pores begin to deteriorate.

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It has been reported [5] that the early-stage strength of PLC concrete is higher than that of control concrete. Other studies [6, 7] revealed that increase in the carbonation depth of concrete results from limestone replacements. Results of these works indicate that the carbonation resistance of concrete increases with increase in the curing period.

Several numerical models [3-7] have been derived in the course of studies to predict the properties of PLC concrete. Model for evaluation of the heat evolution rate of PLC was proposed [8, 9]. These models considered the effects of limestone on the reaction-controlling stage and the diffusion-controlling stage in cement hydration.

Researches [10, 11] shows successful simulation of the hydration process and microstructure development of PLC concrete as well as calculation the heat evolution rate and porosity using the degree of hydration. An efficiency function was proposed [12] to consider the effect of limestone on the strength development of concrete. Similar research [13] adopted the efficiency function evaluated in the work [12] in simulating the heterogeneous nucleation effect of fly ash on cement hydration. The hydration of PLC was simulated [14, 15], prompting modeling of the dilution effect, physical effect (nucleation effect), and chemical effect (formation of monocarboaluminate phase). Thermodynamic modeling of PLC were created [16] and the evolution of phase volume fractions of hydration products were calculated. In recent time, hydration models mainly focus on cement-limestone hydration [8-11, 16] as well as strength development [12-15].

One of the main causes of corrosion initiation in steel rebar in reinforced-concrete (RC) structures has been attributed to carbonation [9]. This is because the service life of RC structures in an atmospheric environment is closely related to carbonation. Based on the foregoing, analytical models have been proposed to evaluate the carbonation resistance of concrete. A researcher [17] calculated the contents of carbonated materials and concrete porosity. The scientist predicted carbonation depth of concrete by considering concrete material properties and environmental conditions. Other researchers [18, 19] proposed a probabilistic approach in evaluating the carbonation depth of concrete, considering the level of uncertainties involved with carbonation prediction. Report [17] assumed that all of the binders in concrete would hydrate regardless of water-to-binder ratio. Similar research [9] indicates that concrete with a lower W/B has a slower hydration rate and a lower ultimate degree of hydration. Furthermore, observation [20, 21] has shown that carbonation resistance of concrete was enhanced following extension of the curing period.

It has been observed [17, 19] that the effect of curing periods on carbonation has not been given consideration in current carbonation models. The shortcoming in previous studies [3-19] involving model formulation for the study of PLC concrete was overcome through derivation of a numerical model [22] to systematically assess and evaluate the hydration kinetics, compressive strength development, and carbonation depth of PLC concrete. The hydration degree of cement, the amount of reaction products, porosity, gel-space ratio, and compressive strength were predicted, using a PLC hydration model. The degree of cement hydration was calculated by considering concrete mixing proportions, binder properties, and curing conditions. Calculated results from the hydration model are used as input parameters for the carbonation model. In addition, evaluation of CO_2 diffusivity and the carbonation depth of PLC concrete were carried out, considering material properties and environmental conditions. The hydration model evaluates the influence of limestone on the strength and carbonation of concrete. It also analyzes the dilution effect and the nucleation effect of limestone during the hydration of cement in line with previous studies [14, 15].

The aim of this research is to embark on the synergistic correlative assessment of the compressive strength of concrete based on the water-cement ratio and hydration period.

MATERIALS AND METHODS

The concrete cube size measuring 150x150x150mm in dimension was used. The batching of the concrete cubes was by weight. The concrete was produced using different water-cement ratio ranging from 0.4-0.49 and hydration period 3-16 days. The cement used is Ordinary Portland Cement (Eagle) and the super plasticizer (Poly carboxylic ether) produced and marketed by Chinese company in Lagos was also used as an admixture. The coarse aggregate used is granite and clean river sand was used as fine aggregate. Both aggregate conformed to BS877 (1967) and BS3797 (1964) respectively for coarse and fine aggregate while the cement conformed to BS12 (1978). The concrete cubes were lubricated with oil before the mixed concrete was placed inside it in order to reduce friction between the concrete and the cubes. When the concrete was properly mixed, the concrete cubes were filled one-third of their height and compacted 150 times. The cubes were later filled to two-third of their height and finally filled completely. In each of the layer, the concrete cubes were compacted 150 times respectively. The concrete cubes were cast and cured for 7, 14, 21 and 28 days respectively. At the end of each hydration period, the concrete cubes were crushed to determine, their compressive strength [23].

RESULTS AND DISCUSSION

Table 1: Variation of compressive strength of concrete Ʋ with water-cement ratio § and hydration period α respectively [23]

(α)	(§)	(Ʋ)
3	0.36	16.91
7	0.40	16.94
10	0.43	16.96
14	0.47	16.98
16	0.49	16.99

Computational analysis of the actual results shown in Table 1, gave rise to Table 2 which indicate that;

$$K\text{Ʋ} = e^{N\text{§}} + \text{ђ}\, e^{S\alpha} \quad (1)$$

Introducing the value of K, N,ђ and S into equation (1) reduces it to;

$$0.1198\text{Ʋ} = e^{0.036\text{§}} + 1.012e^{0.0004\alpha} \quad (2)$$

Dividing both sides of equation (2) by 0.1198 gives;

$$\text{Ʋ} = 8.347\, (e^{0.036\text{§}} + 1.012\, e^{0.0004\alpha}) \quad (3)$$

The derived model is equation (3).

Where

K = 0.1198, N = 0.036,ђ = 1.012, S = 0.0004; equalizing constants and Ä= 8.347; empirical constant (determined using C-NIKBRAN [24])

(§) = Water-cement ratio
(α) = Hydration period (days)
(Ʋ) = Compressive strength of concrete (N/mm^2)

Boundary and Initial Conditions: A cube sized concrete block 150 x 150 x 150mmproduced from a mixture of water, sand, aggregates and cement was considered and subjected to compressive test using appropriate crushing loads. The concreter is assumed to be unaffected by dissolved gases in the atmosphere.

The range of considered parameters: compressive strength of concrete, water-cement ratio and hydration period are16.91 – 16.99 (N/mm^2), 0.36- 0.49 and 3-16 (days) respectively. The input concentration of super plasticizer is 2.0%.

Table 2: Variation of 0.1198Ʋ with $e^{0.036\text{§}}$+ $1.012e^{0.0004\alpha}$

0.1198Ʋ	$e^{0.036\text{§}} + 1.012\, e^{0.0004\alpha}$
2.0258	2.0263
2.0294	2.0293
2.0318	2.0317
2.0342	2.0347
2.0354	2.0363

Model Validity: Equation (3) is the derived model. The validity of the model is rooted on the core model equation (2) where both sides of the equation are correspondingly almost equal. Table 2 also agrees with equation (2) considering values of 0.1198Ʋ and $e^{0.036\text{§}}+1.012e^{0.0004\alpha}$evaluated from the actual results in Table 1. Furthermore, the derived model was validated by comparing the compressive strength of concrete predicted by the model and that obtained from the experiment. This was done using various analytical techniques which includes computational, statistical, graphical and deviational analyses.

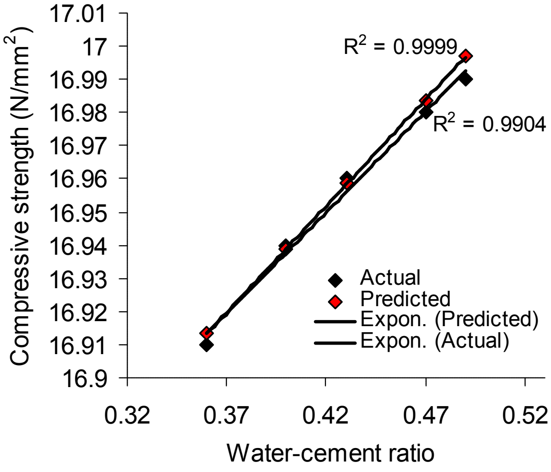

Fig.1: Coefficient of determination between compressive strength of concrete and water-cement ratio as obtained from actual and model-predicted results

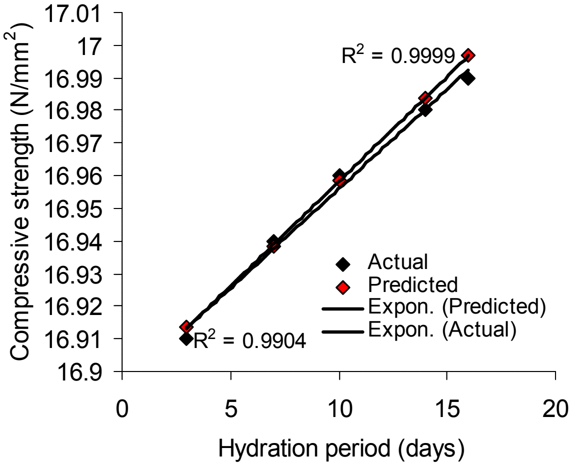

Fig. 2: Coefficient of determination between compressive strength of concrete and hydration period as obtained from actual and model-predicted results

Computational Analysis: Compressive strength of concrete per unit hydration period.

The compressive strength of concrete per unit hydration period $V\alpha$ (N/mm^2)/days was calculated from the equation;

$$V\alpha = V/\alpha \quad (4)$$

Re-written as

$$V\alpha = \Delta V/\Delta\alpha \quad (5)$$

Equation (5) is detailed as

$$V\alpha = V_2 - V_1/\alpha_2 - \alpha_1 \quad (6)$$

where

$V\alpha$= Change in the compressive strengths V_2, V_1 at hydration periods α_2, α_1.

Considering the points (3,16.91) &(16,16.99) and(3,16.9135) &(16,16.997) as shown in Fig. 3, designating them as (V_1,α_1) &(V_2,α_2) for actual and model-predicted results, and then substituting them into equation (6), gives the slopes: - 0.0062 and-0.0064N/mm^2/days respectively as compressive strength per unit hydration period. The negative sign preceding the values is an indication that the compressive strength-hydration period slopes of (as shown in Fig. 3) are all negative. Therefore, the real values of the compressive strength per unit hydration period are 0.0062 and 0.0064 N/mm^2/days for the actual and model-predicted results respectively.

Results predicted by the derived empirical model show that the compressive strength of the concrete increases with increase in both water-cement ratio and hydration period in line with previous work [23]. This implies that the negative effect of increasing water-cement ratio was overtaking by the desirable impact of the increased hydration on the concrete.

Statistical Analysis

Correlation: The correlation coefficient between compressive strength of concrete and water-cement ratio & hydration period were evaluated (using Microsoft Excel Version 2003) from results of the actual and derived model. These results are 0.9999 and 0.9952 for both input parameters respectively. The evaluations were based on the coefficients of determination $R^2$from Figs. 1and 2using equation (7).

$$R = \sqrt{R^2} \quad (7)$$

Standard Error (STEYX): The standard error incurred in predicting the model-based compressive strength relative to values of the actual results is 0.004%. The standard error was evaluated using Microsoft Excel version 2003.

Graphical Analysis: The derived empirical model was validated much further by plotting values of the actual, besides the model-predicted results using Microsoft Excel (version 2003) to evaluate the trend of both results. Very close alignment of curves and shapes were shown in Figs. 3 and 4 indicating significantly similar trend of data point's distribution for the actual and model-predicted compressive strength. This shows proximate agreement between both results.

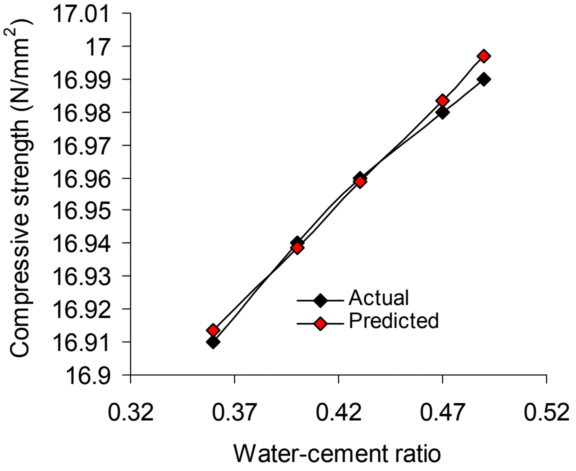

Fig. 3: Variation of concrete compressive strengths with water-cement ratio as obtained from actual and model-predicted results

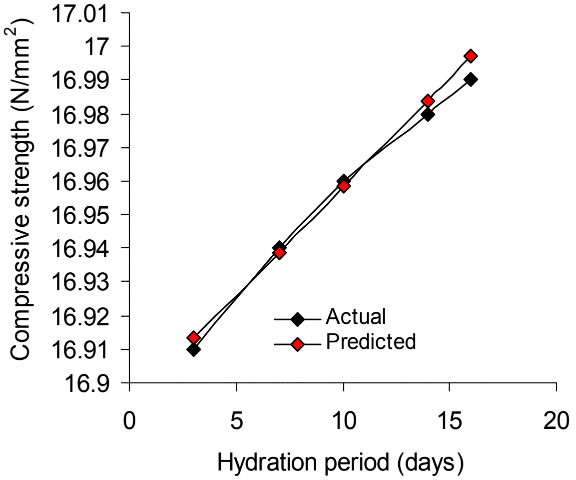

Fig. 4: Variation of concrete compressive strengths with hydration period as obtained from actual and model-predicted results

Deviational Analysis: Comparative analysis of the compressive strength of concrete obtained from the actual and model-predicted results shows very insignificant level of deviation of predicted results from the actual. This was attributed to the fact that the effects of the surface properties of the cement which played vital roles during the hydration were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted concrete compressive strength to those of the corresponding experimental values.

The deviation Dv, of model-predicted compressive strength from the corresponding actual result was given by

$$Dv = \left(\frac{V_P - V_E}{V_E} \right) \times 100 \qquad (8)$$

Where,
V_E and V_P are compressive strengths evaluated from experiment and derived model respectively.

Fig. 5 shows that maximum deviation of model-predicted compressive strength from the actual results was less than 0.05%.This translates into over 99% model operational confidence. The figure also shows that the least and highest deviations of model-predicted results (from actual results) are -0.01 and -0.04 %.

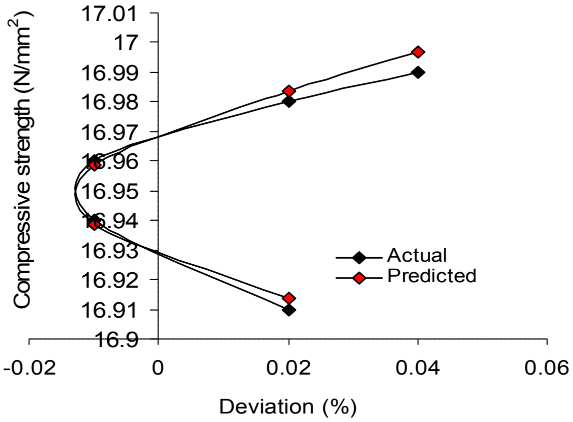

Fig. 5: Deviation of model–predicted results from actual values relative to compressive strength

These deviations correspond to model-predicted compressive strengths: 16.9386 or 16.9586 and 16.997 (N/mm^2); hydration periods: 7 or 10 and 16daysandwater-cement ratios: 0.4 or 0.43 and 0.49respectively. The word “or” is an indication that the deviation value of 0.01% is double and so corresponds to two parameter values.

Correction factor, Cf to the model-predicted results was given by,

$$Cf = -\left(\frac{V_P - V_E}{V_E} \right) \times 100 \qquad (9)$$

Analysis of Figs. 5 and 6 show that the evaluated correction factors are negative of the deviation as shown in equations (8) and (9).

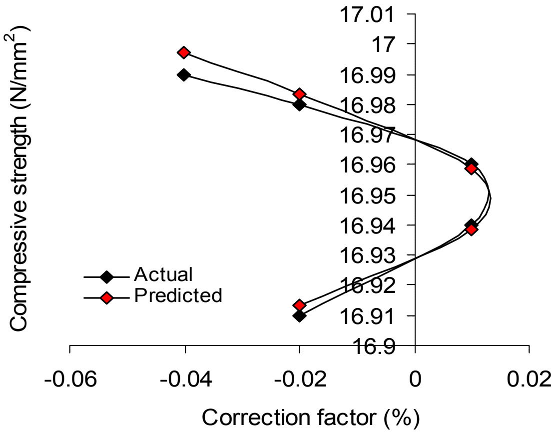

Fig. 6: Correction factor to model–predicted results relative to compressive strength

The correction factor took care of the negligence of operational contributions of the effects of surface properties of the cement which actually affected the concrete hydration process. Substituting the corresponding values of Cf from equation (9) into the model gives exactly the corresponding actual compressive strength. Fig. 6 indicates that the maximum correction factor to the model-predicted results was less than 0.05%. Fig. 6 shows that the least and highest correction factors to the model-predicted results are -0.01 and 0.04%. These correction factors also correspond to model-predicted compressive strengths: 16.9386 or 16.9586 and 16.997 (N/mm^2); hydration periods: 7 or 10 and 16 days and water-cement ratios: 0.4 or 0.43 and 0.49 respectively.

The deviation of model predicted results from that of the actual is just the magnitude of the value. The associated sign preceding the value signifies deviation deficit (negative sign) or surplus (positive sign).

CONCLUSION

Synergistic correlative assessment of compressive strength of concrete was carried out based on water-cement ratio and hydration period. A derived empirical model; $V = 8.347\ (e^{0.036ß} + 1.012\ e^{0.0004\alpha})$ assessed the compressive strength of the concrete as a function of the sum of exponentials of the water-cement ratio and hydration period. The empirical model predicts increase in compressive strength of the concrete as both water-cement ratio and hydration period increases. This implied that the negative effect of increasing water-cement ratio was over shadowed by the desirable impact of the hydration period on the concrete. The validity of the model was rooted on the core model expression $0.1198V' = e^{0.036\S} + 1.012e^{0.0004\alpha}$ where both sides of the expression are correspondingly almost equal. The standard error incurred in predicting the model-based concrete compressive strength relative to the actual results was 0.004%. Evaluations from generated results reveal that the compressive strength of the concrete per unit hydration period were 0.0062 and 0.0064 (N/mm^2)/ days as obtained from actual and model-predicted results respectively. Deviational analysis of model-predicted results (with respect to actual results) indicates a maximum < 0.05%. This translated into over 99% operational confidence levels for the derived model and 0.99 dependency coefficient of concrete compressive strength on water-cement ratio & hydration period. The correlation coefficients between the compressive strength of concrete and water-cement ratio & hydration period were all > 0.99.

REFERENCES

1. Tennis, P.D., M.D.A. Thomas and W.J. Weiss, 2011. State-of-the-Art Report on Use of Limestone in Cements at Levels of Up to 15%; Portland Cement Association: Skokie, IL, USA.
2. Hooton, R.D., M. Nokken and M.D.A. Thomas, 2007. Portland-Limestone Cement: State-of-the-Art Report and Gap Analysis for CSA A 3000; University of Toronto: Toronto, ON, Canada.
3. Bonavetti, V., H. Donza, G. Menendez, O. Cabrera and E.F. Irassar, 2003. Limestone filler cement in low w/cconcrete: A rational use of energy. Cem. Concr. Res., 33: 865-871.
4. Elgalhud, A.A., R.K. Dhir and G. Ghataora, 2016. Limestone addition effects on concrete porosity. Cem. Concr. Compos., 72: 222-234.
5. Bentz, D.P., E.F. Irassar, B.E. Bucher and W.J. Wesis, 2009. Limestone fillers conserve cement, Part 1: An analysis based on Powers' model. Concr. Int., 31: 41-46.
6. Parrott, L.J., 1996. Some effects of cement and curing upon carbonation and rein for cement corrosion in concrete. Mater. Struct., 29:164-173.
7. Balayssac, J.P.,C.H. Detriche and J. Grandet, 1995. Effects of curing upon carbonation of concrete. Constr. Build. Mater., 9:91-95.
8. Toshiharu, K. and D. Saruul, 1999. Hydration heat modeling for cement with limestone powder. Iabse Colloq. Phuket, 81: 133-138.
9. Maekawa, K., T. Ishida and T. Kishi, 2009. Multi-Scale Modeling of Structural Concrete; Taylor & Francis: New York, NY, USA.
10. Poppe, A. and G. De Schutter, 2005. Cement hydration in the presence of high filler contents. Cem. Concr. Res., 35: 2290-2299.
11. Ye, G., X. Liu, A.M. Poppe, G. De Schutter and K. Van Breugel, 2007. Numerical simulation of the hydration process and the development of microstructure of self-compacting cement paste containing limeston eas filler. Mater. Struct., 40: 865-875.
12. Cyr, M., P. Lawrence and E. Ringot, 2005. Mineral admixtures in mortars Quantification of the physical effects of inert materials on short-term hydration. Cem. Concr. Res., 35: 719-730.
13. Zeng, Q., K. Li, T. Fen-chong and P. Dangla, 2012. Determination of cement hydration and pozzolanic reaction extents for fly-ash cement pastes. Constr. Build. Mater., 27: 560-569.
14. Bentz, D.P., 2006. Influence of water-to-cement ratio on hydration kinetics: Simple models based on spatial considerations. Cem. Concr. Res., 36: 238-244.
15. Bentz, D.P., 2006. Modeling the influence of limestone filler on cement hydration using CEMHYD3D. Cem. Concr. Compos., 28:124-129.
16. Lothenbach, B., G. Le Saout, E. Gallucci and K. Scrivener, 2008. Influence of limestone on the hydration of Portlandcements. Cem. Concr. Res., 38: 848-860.
17. Demis, S., M.P. Efstathiou and V.G. Papadakis, 2014. Computer-aided modeling of concrete service life. Cem. Concr. Compos., 47: 9-18.
18. Kwon, S. and U. Na, 2011. Prediction of durability for RC columns with crack and joint under carbonation based on probabilistic approach. Int. J. Concr. Struct. Mater., 5: 11-18.
19. Ann, K.Y., S.W. Pack, J.P. Hwang, H.W. Song and S.H. Kim, 2010. Service life prediction of a concrete bridge structure subjected to carbonation. Constr. Build. Mater., 24: 1494-1501.
20. Marques, P.F., C. Chastre and A. Nunes, 2013. Carbonation service life modelling of RC structures for concrete with Portland and blended cements. Cem. Concr. Compos., 37: 171-184.
21. Marques, P.F. and A. Costa, 2010.Service life of RC structures: Carbonation induced corrosion. Perspectivevs. performance-based methodologies. Constr. Build. Mater., 24: 258-265.
22. Xiao-Yong, W., 2017. Modeling of Hydration, Compressive Strength, and Carbonation of Portland-Limestone Cement (PLC) Concrete. Materials, 10(115): 1-16.
23. Mbadike, E.M., 2011.Effect of super plasticizer on the compressive strength of concrete. International Journal of Natural and Applies Sci., 7(1): 37-40.
24. Nwoye, C.I., 2008. Data Analytical Memory; C-NIKBRAN.