Investigating the Deflection and Strain of Reinforced Green Concrete Beams Made with Partial Replacement of RCA under Sustained Loading

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Abstract-Artificial intelligence (AI) and statistical methods are used in various fields and have played a vital role in investigating the deflection and strain of reinforced green concrete beams made with partial replacement of recycled concrete aggregates under sustained loading. The methods used to assess structural contributors are time-saving and cost-effective compared to experimental evaluation. This study investigated the numerical modeling of reinforced concrete beams produced by replacing 50% of coarse natural aggregates with demolished vintage concrete under sustained loading. Multivariate regression analysis was used to determine the mathematical equations for long-term deflection and stress from experimental data of 6, 9, and 12 months of loading. Three software suites were used for the regression analysis, namely NCSS, Matlab, and Microsoft Excel. Six beams were cast using demolished concrete as 50% of coarse aggregates to test and validate the regression equations, where three of them were examined for two months of sustained loading and the other three for three months. The regression results were in accordance with the experimental observations with a maximum error of 10.34%. Therefore, the provided regression equations for deflection and pressure could be used to estimate the parameters of reinforced concrete beams.

Keywords-Artificial Intelligence (AI); green concrete; long-term loading; numerical modeling; recycled concrete aggregates; sustained loading

I. INTRODUCTION

Many structural engineering challenges remain outstanding although the sector grows its interest in technological solutions [1]. Most of these problems are hard optimization problems [2], making them relatively difficult to resolve, as an increase in the dimensionality of a problem increases its complexity [3]. Conventional optimization strategies cannot tackle complicated issues for numerous reasons, especially in the case of the referred curse of dimensionality. Furthermore, investigating the use of gradient-primarily based strategies for engineering problems with neighborhood solutions is time-consuming, as these methods depend on the region of the initial issue [4]. All these drawbacks made researchers to extend machine learning methods consisting of metaheuristic or hybrid methods [5] to resolve engineering problems. Estimation of concrete properties, particularly green concrete, before and after hardening is a key effort to ensure its quality [6]. Green concrete is preferred as it is environmentally friendly and preserves the natural constituents of conventional concrete, but it requires extensive research to determine its behavior under different conditions. On the other hand, the experimental assessment of required parameters is not only time-consuming, but also requires much care, labor, and cost. Moreover, any inaccuracy in an experimental setup or procedure requires repetition and modification. Therefore, an alternative tool is required to avoid these problems. The best option is numerical analysis, carried out by mathematical modeling of the required parameters based on experimental data. Regression analysis is the most widely used method for this purpose [7].

Many concrete manufacturing methods have been proposed using domestically available substances or waste [8]. The use of demolished concrete as coarse aggregates in new concrete could reduce the environmental impact due to the transport of natural coarse aggregates and the waste dumping in landfills. In

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addition, it could help reduce waste control issues and the overall cost of the structure. Various proportions of recyclable aggregates from demolished concrete [9, 10] or plastics [11] have been investigated in concrete mixtures, examining their compressive and tensile strength. In [12], a relationship between the cylindrical and cubic compressive strength of concrete using recycled concrete as coarse aggregate was presented, using regression analysis of the experimental observations of 400 samples. Regression analysis is a process of predicting the deviation in the dependent variables for the deviation of the independent variables. This process is effectively used in civil engineering to determine mathematical equations for different properties based on experimental observations. In [13], a regression model was presented considering the variable workability of recycled aggregate concrete. In [14], regression analysis was used to model concrete delivery and placement, while in [15] the cost estimation of a project was studied using the same method.

Traditional strategies for modeling and optimizing complicated structures require huge amounts of computing resources. AI-based methods can provide valuable alternatives to efficiently solve issues in civil engineering [16], while many studies examined concrete's strength using numerical modeling. In [17], the age and curing period of concrete were used to predict its strength, finding correlation coefficients equal to 0.995 and 0.994 for 7 and 28 days of curing and demonstrating the validity of the model. In [18], a combination of multivariate regression analysis and neural networks was investigated to study the strength of concrete with mineral admixtures. The concrete samples, using fly ash and a blast furnace, were cast and cured from 3 to 180 days, followed by nondestructive testing. Laboratory results were used as data for numerical modeling, and the neural network showed better performance. However, the combination of both methods was more suitable for non-linear relationships of the parameters. Numerical modeling of the relationships between the properties of demolished concrete, recycled aggregates, and recycled concrete aggregate and the flexural behavior of amorphous concrete are some other examples of regression analysis studies [19-23]. Numerical modeling of several aspects of normal and recycled aggregate concrete under short-term loading has been investigated in several studies. However, very few studies are available on the numerical modeling of concrete behavior when using green concrete produced by demolished concrete as coarse aggregates. This study presents a regression analysis of the deflection and strain of reinforced green concrete beams under sustained long-term loads (6, 9, and 12 months) [24-26]. NCSS [27], Matlab 2016 [28], and Microsoft Excel 2016 were used to perform regression analysis, and their results were compared. To validate the results, 6 RC green concrete beams were cast and tested. A comparison of the test with the predicted results showed very good agreement between the two sets.

II. METHOD AND ANALYSIS

Regression analysis is a statistical method to estimate a relationship between two or more variables and can be used to predict future values from available datasets. The method mainly depends on a dependent or target variable and independent or predictor variables. This process requires the declaration of dependent and independent variables, and then it fits the data for regression and gives the coefficients of a mathematical equation along with the statistical analysis of the data. This study used a dataset from experimental investigations of long-term deflection and strain under sustained load for 6, 9, and 12 months [24-26]. These studies used reinforced concrete beams cast using 50% replacement of natural coarse aggregates with demolished concrete. The beams were tested in frames with a constant central point load maintained with the help of screw jacks and load cells. The central point deflection was monitored and recorded on daily basis. The strain was measured at 11 locations along the central line (depth) of the beam, and then all these values were averaged. Six beams were used for each loading duration, three made from all-natural coarse aggregates (NAB) and three with an equal dosage of natural and recyclable aggregates (RAB). Figure 1 shows the plot of deflection in mm of all beams versus time in days and the proportion of recyclable aggregates (%). Similarly, Figure 2 shows the average recorded strain in all beams. Both figures show the results of beams cast with all-natural and recyclable aggregates on the same axis.

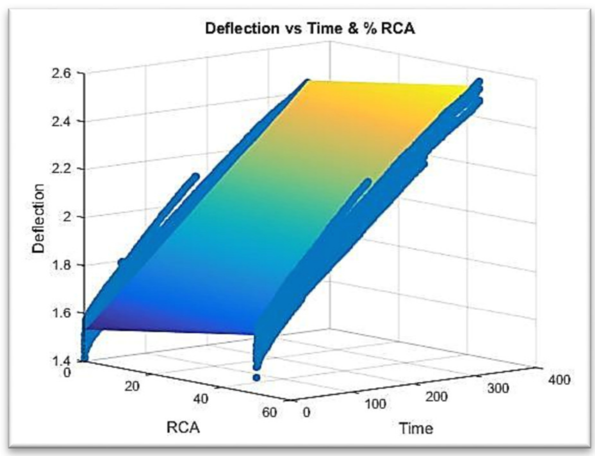

Fig. 1. Deflection in all beams.

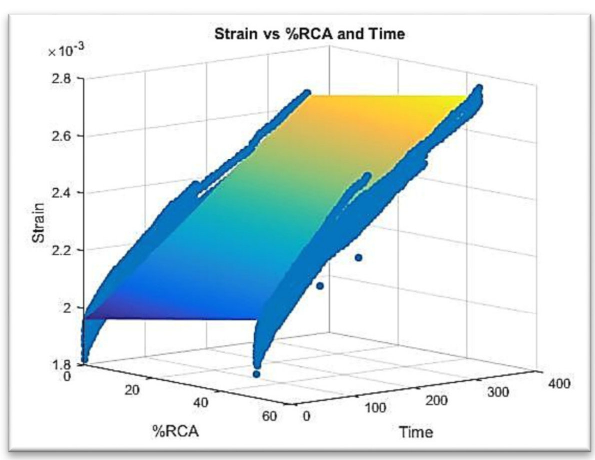

Fig. 2. Strain in all beams.

At first, a regression equation was produced for deflection, considering the proportion of recyclable aggregates (0 or 50) and time as independent variables. Initially, the load was also considered as an independent variable, but as it was the same throughout the sustained load duration, it had no impact and was removed from the list of variables. Similarly, a regression equation was investigated for strain, In this process, the strain was considered as the dependent variable while all the other parameters were kept constant. Although several software suites are available for regression analysis, this study used NCSS, Matlab, and Microsoft Excel. NCSS and Matlab have been widely used for statistical analysis. The coefficients of the regression equation for the deflection and the strain, generated by NCSS, along with standard error are given in Tables I and II.

TABLE I. COEFFICIENTS AND STANDARD ERROR FOR DEFLECTION USING NCSS

Independent variable	Regression coefficient	Standard error	Lower 95% conf. limit	Upper 95% conf. limit
Intercept	1.519958	0.0067	1.5067	1.5331
Time	0.017779	0.0002	0.0173	0.0182
RCA%	0.002341	0.0001	0.0021	0.0025

TABLE II. COEFFICIENTS AND STANDARD ERROR FOR STRAIN USING NCSS

Independent Variable	Regression Coefficient	Standard Error	Lower 95% Conf. Limit	Upper 95% Conf. Limit
Intercept	0.001953044	3.42×10^{-6}	0.00195	0.00195
Time	1.336448×10^{-5}	1.20×10^{-7}	1.31×10^{-7}	1.35×10^{-5}
RCA%	2.200535×10^{-6}	6.56×10^{-8}	6.56×10^{-8}	2.33×10^{-6}

Regression analysis on experimental observations for deflection and strain in Matlab produced the coefficients of regression equations given in Table III. Finally, regression analysis was conducted in Microsoft Excel, and the coefficients obtained for deflection and strain are shown in Tables IV and V.

TABLE III. COEFFICIENTS FOR DEFLECTION AND STRAIN USING MATLAB

Independent variable	Regression coefficient	
	Deflection	Strain
Intercept	1.5309459	0.0019583
Time	0.0025159	1.8728203×10^{-6}
RCA%	0.0022354	2.1973138×10^{-6}

TABLE IV. MS EXCEL REGRESSION RESULTS FOR DEFLECTION

Description	Regression coefficient	Standard error	P-value	Lower 95%	Upper 95%
Intercept	1.531000785	0.001403289	0	1.528249712	1.533751858
Time	0.002515843	7.07153×10^{-6}	0	0.00250198	0.002529707
RCA %	0.002234576	2.66382×10^{-5}	0	0.002182353	0.002286799

TABLE V. MS EXCEL REGRESSION RESULTS FOR STRAIN

Description	Regression coefficient	Standard error	P-value	Lower 95%	Upper 95%
Intercept	0.001958191	1.23844×10^{-6}	0	0.001955763	0.001960619
Time	1.87426×10^{-6}	6.24082×10^{-9}	0	1.86202×10^{-6}	1.88649×10^{-6}
RCA %	2.19487×10^{-6}	2.3509×10^{-8}	0	2.14878×10^{-6}	2.24096×10^{-6}

The regression coefficients obtained from NCSS were used to write the regression equations for deflection and strain in (1) and (2), respectively:

$$\delta = 1.530946 + 0.0022354 \times RCA + 0.0025159 \times T \quad (1)$$

$$\varepsilon = 0.0019583 + 2.19731379 \times 10^{-6} \times RCA + 1.8728203 \times 10^{-6} \times T \quad (2)$$

where δ represents deflection, ε denotes strain, *RCA* is used for proportions of recyclable aggregates (0 for 0%, 50 for 50%, etc), and *T* is time in days. Similarly, the coefficients given in Table III, obtained from regression analysis in Matlab, were used in (3) and (4):

$$\delta = 1.5309459 + 0.0022354 \times RCA + 0.0025159 \times T \quad (3)$$

$$\varepsilon = 0.0019583 + 2.1973138 \times 10^{-6} \times RCA + 1.8728203 \times 10^{-6} \times T \quad (4)$$

Similarly, the regression coefficients given in Tables IV and VI obtained using Microsoft Excel can be used for the respective regression equations for strain and deflection. These equations were used to predict the deflection and strain values. To further validate the performance of the equations, six beams were cast and cured for 28 days. The proportion of recycled aggregates in the beams was 50%. Three beams were tested for 2 months of sustained load, and the other three were tested for 3 months. The load and loading mechanism was maintained the same with the test results used to develop the regression equations. Figure 3 shows the loading system.

Fig. 3. Loading system.

III. RESULTS AND DISCUSSION

Several statistical parameters were computed and compared in regression analysis to check the authenticity of the process. The R-square value is one among them and is presented along with the standard error in Table VI. The R-square values obtained from the regression analysis by NCSS are equal to 0.953 and 0.9496 for deflection and strain. This shows that about 95% of deflection and 96% of strain predicted values are around the mean value. The normal probability plots of deflection and strain are shown in Figures 4 and 5. Both figures also verify that the vast majority of data points fall in a close band, indicating a good agreement of predicted and test values.

A similar observation was made for the R-square value obtained from the Matlab regression analysis. Similarly to the above, Microsoft Excel R-square values were equal to 0.9645 and 0.9525 for deflection and strain. These values also show that about 96% of the data points are close to the mean.

Additionally, the *p*-value for all variables computed by the software was nearly zero. Both R-square and *p* values show the validity of the developed regression equations.

TABLE VI. SUMMARY REPORT

Software	**NCSS**		**MATLAB**		**EXCEL**	
Dependent variable	Deflection	Strain	Deflection	Strain	Deflection	Strain
R^2	0.9530	0.9496	0.951	0.9642	0.9645	0.9526
Adj R^2	0.9527	0.9496	0.951	0.9642	0.9645	0.9526
Standard error	0.0022	8.66×10^{-7}	-	-	0.0467	4.12×10^{-5}

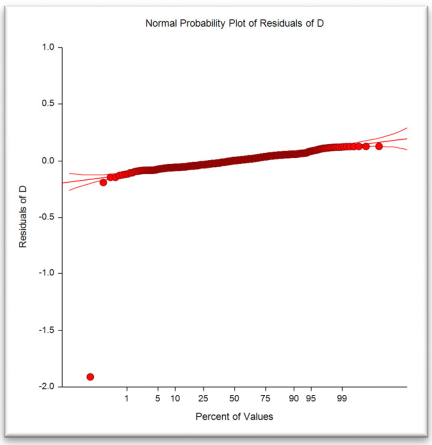

Fig. 4. Normal probability plot of deflection (NCSS).

The three sets of regression coefficients have very minor or ignorable differences, showing the similarity of the capabilities of these suites for the purpose. The regression equations were then used to predict the deflection and stress of the concrete beams and compare them to the experimental results. Table VII shows the error in the computed values. It can be observed that the maximum error in deflection computations is about 12%, whereas in stress is about 10%, proving the validity of the regression equations. The regression analysis cannot only save from the experimental procedures but additionally provides results in little time. To further verify the validity of the equations, six reinforced concrete beams were prepared and tested with the same conditions. Table VIII shows the variables, numerical results, and experimental observations.

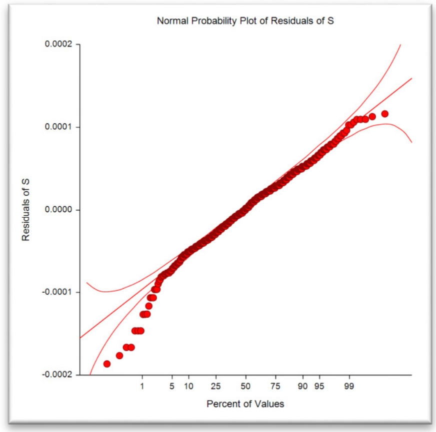

Fig. 5. Normal probability plot of strain (NCSS).

TABLE VII. ERROR % IN PREDICTED VALUES OF DEFLECTION AND STRAIN

Description	**Deflection**		**Strain**	
	Maximum (%)	Minimum (%)	Maximum (%)	Minimum (%)
NCSS	12.30248	-6.03898	10.107397	-4.82636
MATLAB	12.348812	-6.09497	10.0916	-4.84347
Excel	12.30491	-6.0357	10.29922	-4.85232

It may be noted that almost the same deflection results were produced by all three equation sets. The same strain value was calculated using the regression equations of NCSS and Matlab, whereas a slightly higher strain value was calculated using the strain equation developed by Excel. The percentage difference with the other two regression models was about 2%, which is negligible. In comparison to the findings with the average values of test results of the beams loaded for 2 months, it was observed that the regression value of deflection was about 11.8% higher than the average test results. The difference in strain for the beams was recorded as equal to 2%. The difference between regression and average test observations of deflection and strain for reinforced concrete beams loaded for 3 months was recorded equal to 1% for both parameters. Therefore, it can be concluded that the regression equations predicted very well the long-term deflection and strain of the reinforced green concrete beams under sustained load, even beyond the data set.

TABLE VIII. DATA AND RESULTS FOR TEST BEAMS

#	**Variables**		**Deflection**				**Strain**			
	T	**RCA**	**Lab**	**NCSS**	**MATLAB**	**EXCEL**	**Lab**	**NCSS**	**MATLAB**	**EXCEL**
B1	60	40	1.58				0.00211			
B2	60	40	1.59	1.7713	1.7713	1.7713	0.00212	0.002159	0.002159	0.002164
B3	60	40	1.59				0.00211			
B4	90	40	1.83				0.0022			
B5	90	40	1.85	1.8468	1.8468	1.8468	0.0023	0.002215	0.002215	0.002219
B6	90	40	1.85				0.0023			

IV. CONCLUSION

This study used regression analysis to investigate the numerical modeling of deflection and strain under sustained long-term loads of reinforced green concrete beams, using three software suites, namely NCSS, Matlab, and Microsoft Excel. The experimental results of 6, 9, and 12 months of loading were used as input variables to develop regression equations for deflection and strain. It was observed that all software suites used developed almost similar regression equations. The use of regression equations to predict the parameters showed good agreement between the two sets with a maximum error of 12.34%. Further validation of the regression equations was performed by casting and testing six additional reinforced green concrete beams. The numerical results of these beams were observed to be 12% higher than the experimental results. Therefore, the regression equations may be confidently used to predict the deflection and strain of proposed beams under long-term loading.

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