The diagnostic plots give information about fitting, reliability, adequacy, the correlation between the observed and predicted data, and homogeneous and heterogeneous error variances of the model's performance (Moradi et al., 2016). The normal distribution of data was evaluated using the normal probability plots. For each response, the experimental values plot relatively close to the normal probability line and indicate a satisfactory correlation between values, hence inferring that the set of data approximately follows a normal distribution. Figure 9 presents the predicted compressive strength, flexural strength, and splitting-tensile strength against the actual data from experimentation. The figure shows that for all model equations, the responses predicted by the model are statistically accurate relative to the experimental data.

The mathematical relationship between the independent variable and the response was visualized by contour and three-dimensional surface plots. Figures 10, 11, and 12 display the contour and 3D plots of the three investigated responses drawn in terms of the two independent variables, which gives an idea regarding the strength variation when DLW content and curing age vary. From the contour and 3D plot of compressive strength presented in Figure 10, evident is the interaction between DLW content and curing age characterized by the elliptical contour obtained. In this case, the region of the optimum (maximum) was shown clearly for the two factors, and this pattern was usually obtained when there was perfect interaction between the independent variables.

The contour and 3D plot for flexural strength illustrated in Figure 11 shows that flexural strength was maximized at about the central region of the DLW content at any value of curing age, whereas the latter factor has a positive effect on flexural strength. It is worth noting that the effect of curing age on flexural strength was linear.

The effect of varying the DLW content and curing age on splitting-tensile strength was also explored, as depicted in Figure 12. Observation from the contour and 3D plot implies that as DLW content and curing age increase, the splitting-tensile strength also increases. Notice also that the effect of DLW content on splitting-tensile strength was linear.

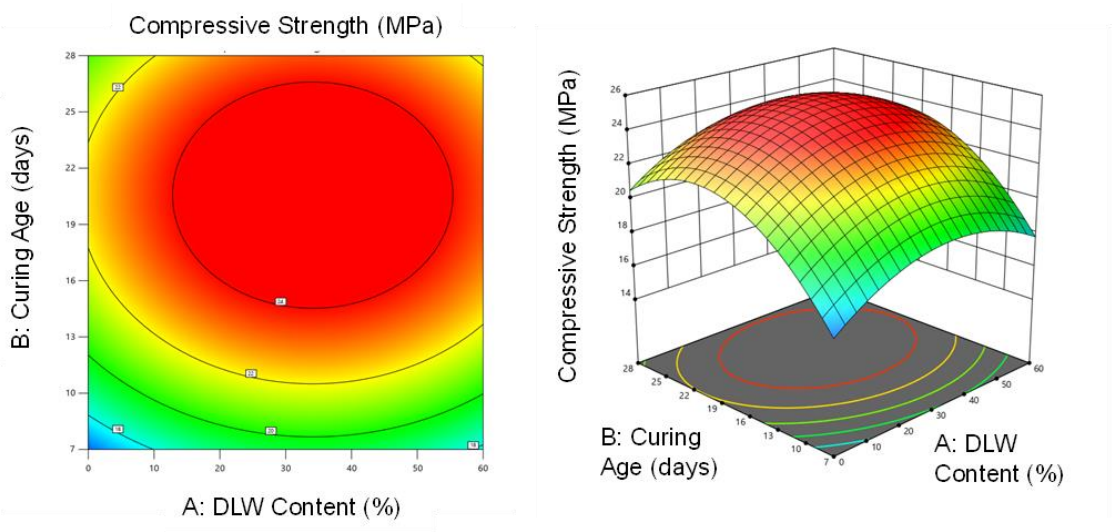

Fig. 10 Contour and 3D plots for compressive strength

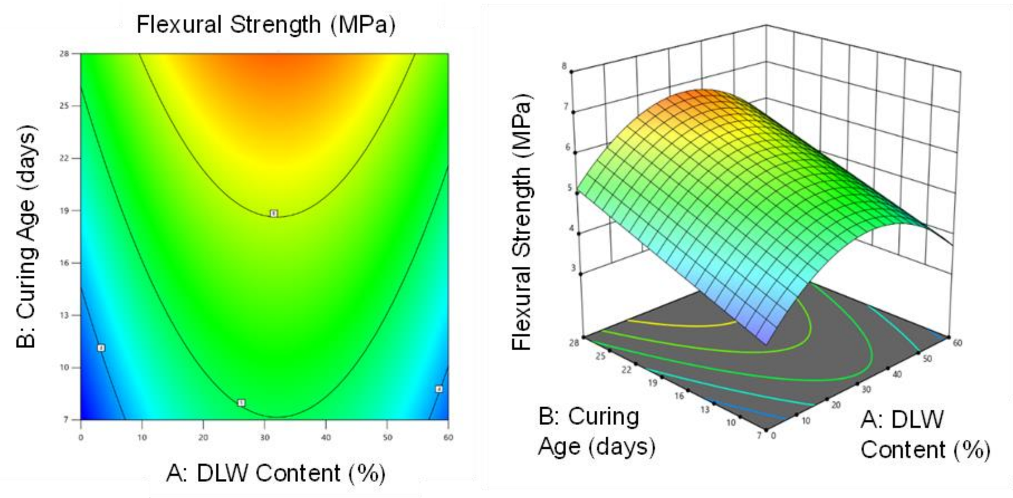

Fig. 11 Contour and 3D plots for flexural strength

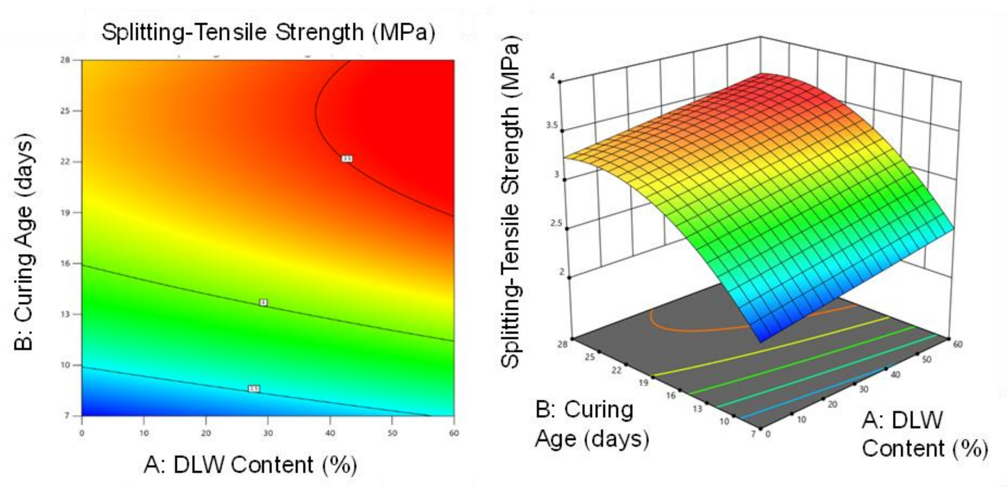

Fig. 12 Contour and 3D plots for flexural strength

In this study, the optimal levels of DLW content and curing age were investigated to maximize compressive strength, flexural strength, and splitting-tensile strength. When multiple responses are considered in the design, it is important to find the compromise optimum that does not optimize only one response (Awolusi et.al, 2019). Therefore, the multi-response optimization process of RSM was carried out, considering all responses simultaneously to determine the optimum values for DLW content and curing age required to achieve values favorable for the three investigated responses. The maximum condition was selected for all strength properties to achieve the highest strength possible. The optimization process that gave the solution with the highest desirability equal to 0.937 was selected and presented in Table 9. As shown in the table, the optimum condition to achieve the highest strength possible was a DLW replacement level of 36 % and a curing age of 26.4 days. The corresponding predicted values obtained were 24.07 MPa, 6.65 MPa, and 3.483 MPa for compressive strength, flexural strength and splitting-tensile strength, respectively.

Table 9. Optimum condition for all variables

Parameters	Unit	Goal	Model Prediction
DLW content	%	in range	36.018
Curing age	Days	in range	26.378
Compressive strength	MPa	maximum	24.070
Flexural strength	MPa	maximum	6.649
Splitting-tensile strength	MPa	maximum	3.483

After the optimization process a validation study was implemented. Additional experiment was carried out to verify the reliability of the response surface quadratic models. The experimental and predicted values for compressive strength, flexural strength and splitting tensile strength were compared using the statistical analysis of paired t-test. The p-values for two-tailed form of t-test conducted were found to be higher than the standard significance level of 0.05 which indicates that there is no significant difference between the experimental and predicted results. Hence, it can be concluded that the developed models could predict the desired responses with good accuracy.

4.0 CONCLUSIONS

The study investigated the effect of using DLW as a replacement for fine aggregates on the mechanical properties of concrete. The mechanical properties were assessed through strength evaluation. Based on the findings of this study, the following conclusions were drawn:

The workability is inversely proportional to the amount of DLW. The reduction in workability increases as the amount DLW added to replace sand increases. The absorption behavior and fineness of DLW are the contributing factors to this reduction. Nonetheless, up to 40% DLW replacement level exhibits slump values that are within the target limit of 50 to 90 mm. The negative effect of DLW on workability of concrete can be eased using concrete admixture like superplasticizers.

The incorporation of DLW as fine aggregates improved the mechanical properties of concrete. Strength first increased until maximum value was attained then decreased with the increase in DLW content. The maximum strength value was reached at DLW content of 40% for compressive and splitting-tensile strength while maximum flexural strength was reached at 20% replacement ratio. The strength improvement is generally attributed to the filler effect of the much smaller and finer particles found in DLW. In addition, fine limestone participates in hydration of cement and as a result the early-age compressive strength gain was improved. Similar to control concrete, DLW concrete experiences a continuous strength development over time. This was particularly evident from the compressive and flexural strength results which implies that long-term strength was also improved.

Through response surface methodology, predictive models for strength properties of DLW concrete were established. The optimum strength obtained by RSM was modeled under 36 % DLW content at curing age of 26.4 days and were equal to 24.07MPa for compressive strength, 6.65MPa for flexural strength and 3.48MPa for splitting-tensile strength. Paired t-test used in model validation shows good accuracy of the predictive models which proves the efficiency and usefulness of RSM techniques in design mix optimization for concrete.

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