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Research Article

Modeling the Mechanical Properties of Sustainable Mortar Modified with Waste Glass Granular (Particles) Using ANN and Multi-Scale Approaches

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ABSTRACT

Since concrete and mortar production (industry) are the biggest natural resource user, their industry's sustainability are under threat. The environmental and economic concern is the most important challenge that the construction industry is facing. The usage of the waste materials in recent years become interested subject for researchers, one of these waste materials is waste glass usage as sand replacement. This article, dealt with proposing models to predict compressive strength of mortar which modified with waste glass granular, showing its effect on the compressive strength. In this paper, 134 data are collected from previous paper with different parameter and statically analyzed, and represented in four models (Linear Regression Model (LRM) and Non-Linear Regression model (NLR), Multi Logistic Regression model (MLR) and ANN model) for predicted compressive strength. In the process of modeling, these variables are important and affect on the value of compressive strength, such as curing time, w/c, cement content, sand content, waste glass content. Various statistical assessments such as Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Scatter Index (SI), OBJ value, and the coefficient of determination (R^2) were used to evaluate the efficiency and performance of the proposed models. The obtained results showed that the ANN-model showed better efficiency for predicting the compressive strength of NC mixtures containing fine glass compared to other models.

Keywords: ANN; Compressive strength; Waste glass granular; Modeling; Mortar

INTRODUCTION

Main subject which control researcher idea in last few years was management and reuse waste materials, especially these materials which have low rate of recycle process and high amount of production, waste glass is one of these materials [1]. Glass is a transparent material produced by melting a mixture of materials such as silica, soda ash, and $CaCO_3$ at high temperature followed by cooling where solidification occurs without crystallization, it being non-biodegradable, is not suitable for addition to landfill, and as such recycling opportunities need to be investigated [2]. The total annual domestic glass product and usage is growing up more and more. This rise in production and use of glass in recent years is due to the increase in industrialization and the rapid improvement in the life process, because of these processes, collecting of waste glass, including all kinds of waste glasses, is challenging, which requires effective and rational solutions [3]. Since concrete and mortar is approximately major material requirement in the construction process, during preparing large amount of raw materials like cement and aggregate (sand and gravel) are required. Process of bringing these materials from the nature, will be the reason of

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reducing the natural source in the land fill [4]. Therefore, from the economic and environmental points of view, the use of recycled waste glass in the production of new concrete and mortar is acquiring increasing interest in recent years. Many researches have been used different kinds of waste glass as a partial replacement to the sand in the mortar like cathode ray tube glass which obtained from electronic equipment and television, treated cathode ray tube with nitric acid, broken glass used for door and window, cathode ray tube from funnel glass, recycled glass used as food and medical container mostly as bottles, or spent fluorescent waste glass, or colour waste glass to be used in architectural mortar, heavy weight waste glass [5]. Since the compressive strength considered as main mechanical properties for used material in the construction and other properties are related to it, and every mix which designed multiple sample must be prepared from it and must be cured for required time by specification which is mostly not less than 28 days which cause the delay in the process and any change in the mix new samples must be prepared and cured for required time after that tested. Ghafor, et al. used nonlinear model to predict the CS of mortar modified with silica fume by including these parameters which effect on the value of compressive strength including w/c, curing time(t) and various rate of silica fume as replacement of cement from 5% to 55% of dry weight of cement, also Qadir, et al. used nonlinear equation to predict compressive strength of mortar which modified with fly ash, with various w/c, curing time and various replacement ration of fly ash from 5% to 75% of dry weight of cement [6,7]. This article deals with showing the effect of each composition of mortar modified with waste glass granular on the compressive strength for different curing time, for these reasons different models including linear regression, nonlinear regression with ANN model used by including 134 data which collected from literature and by using splitting divided to training data and tested to obtain most accurate and reliable model to predict the compressive strength of mortar modified with waste glass granular as sand replacement [8].

Research significant

This article deals with a numerical model for predicting compressive strength of mortar without containing any cement replacement to find the effect of waste glass granular, w/c and curing time on the compressive strength, express statistical analysis for each independent variable alone and evaluate and find the best reliable model through LR, NLR, MLR and ANN model to estimate the CS of mortar containing FG at different ratio, using statistical parameters.

MATERIALS AND METHODS

From literature 134 data collected as in Table 1, each independent including w/c, cement content (kg/m^3), sand content (kg/m^3), glass granular (kg/m^3) and curing time (days). All of these independent variables have been statically analyzed, and splited to 99 data as training data and 35 data as testing data to show the efficiency for the predicted models. The flow chart further explains all the steps, including all the independent variables collected in the equations for predicting compressive strength as in below Figure 1.

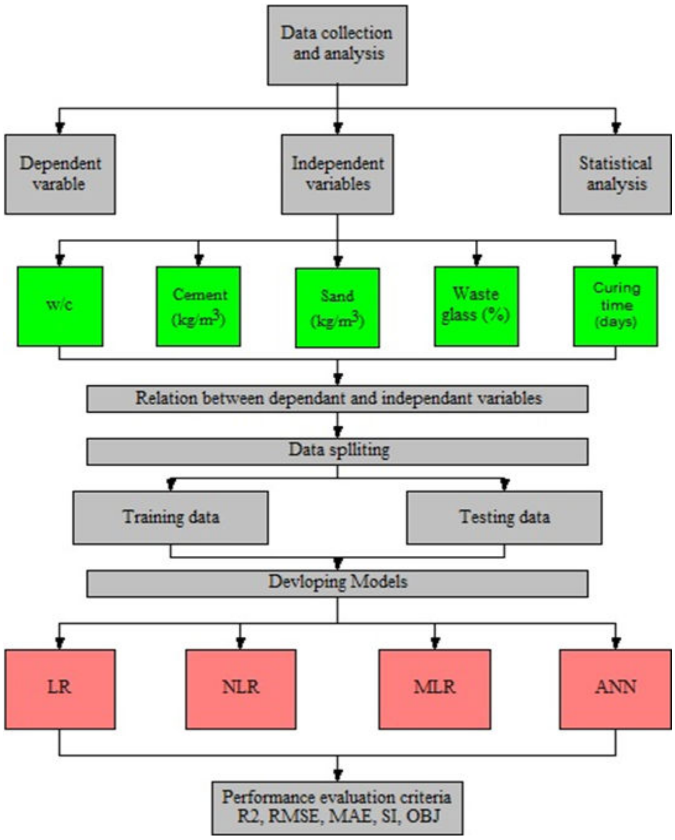

Figure 1: Methodology flow chart.

Table 1: Summary of collected data of mortar modified with glass granular.

w/c	Cement content (kg/m^3)	Sand (kg/m^3)	W.G (kg/m^3)	Curing time (Days)	Compressive strength (MPa)
0.67	292	879	0	28	23.03
0.67	292	439	439	28	18.28
0.67	292	659	219	28	21.03
0.67	292	791	88	28	20.66

1.12	271	0	1083	90	30.64
0.89	339	948	406	60	11.25
0.99	305	488	733	3	9.2
0.84	349	1186	209	7	4.6
0.84	400	1600	0	3	1.93
0.89	339	948	406	90	13.1
0.84	349	1186	209	28	6.5
1.12	271	0	1083	7	20
0.99	305	488	733	90	17.5
0.84	349	1186	209	90	8.5
0.99	305	488	733	7	11
0.84	400	1600	0	7	2.95
0.99	305	488	733	60	17
0.99	305	488	733	28	14.3
0.84	400	1600	0	90	7.2
0.84	400	1600	0	60	5.85
0.84	349	1186	209	3	3.32
0.84	349	1186	209	60	7.45
0.84	400	1600	0	28	4.95
0.89	339	948	406	28	10.2
0.89	339	948	406	3	4.61
0.89	339	948	406	7	6.83
1.12	271	0	1083	3	15.13
0.35	721	598	703	7	41.78
0.35	721	299	1055	91	43.56
0.45	578	646	760	7	36.52
0.35	721	0	1406	91	40
0.35	721	1195	0	28	54.01
0.45	578	968	380	91	44.5
0.35	721	0	1406	28	37.19
0.35	721	299	1055	7	40

0.45	578	323	1139	7	34.21
0.35	721	1195	0	7	46.36
0.45	578	968	380	7	38.32
0.35	721	897	352	7	45.35
0.45	578	323	1139	28	37.29
0.45	578	646	760	91	41.15
0.35	721	897	352	91	53
0.45	578	323	1139	91	39.35
0.45	578	646	760	28	41.15
0.45	578	1291	0	7	42.7
0.35	721	299	1055	28	40.76
0.45	578	0	1519	28	32.41
0.45	578	0	1519	7	29.58
0.35	721	598	703	28	43.56
0.35	721	0	1406	7	35.92
0.35	721	897	352	28	48.15
0.45	578	0	1519	91	36.01
0.35	721	598	703	91	50.2
0.35	721	1195	0	91	58.6
0.6	450	1350	0	180	41.04
0.5	450	0	1350	3	13.13
0.47	450	0	1350	3	9.85
0.5	450	0	1350	28	27.16
0.56	450	675	675	28	26.41
0.45	450	0	1350	3	11.34
0.56	450	675	675	3	14.77
0.56	450	675	675	28	28.2
0.6	450	1350	0	3	15.37
0.56	450	675	675	180	33.28
0.45	450	0	1350	180	26.86
0.5	450	0	1350	180	32.38

0.56	450	675	675	3	15.67
0.56	450	675	675	28	26.71
0.56	450	675	675	180	40.89
0.56	450	675	675	3	16.41
0.47	450	0	1350	28	14.92
0.45	450	0	1350	28	23.13
0.6	450	1350	0	28	29.55
0.54	529	0	1588	3	31.5
0.51	529	1588	0	3	20
0.5	519	1546	0	2	28.1
0.5	519	1159	386	2	25
0.5	519	386	1159	7	34.3
0.5	519	0	1546	2	23
0.5	519	773	773	2	24.3
0.5	519	386	1159	2	22.8
0.26	440	990	0	28	42
0.47	440	742.5	247.5	7	28.15
0.25	440	742.5	247.5	28	43.23
0.47	440	990	0	7	29.38
0.23	440	247.5	742.5	7	33.69
0.47	440	0	990	28	37.53
0.47	440	742.5	247.5	28	39.53
0.23	440	0	990	7	30.61
0.24	440	495	495	28	43.23
0.26	440	990	0	7	36.3
0.24	440	495	495	7	36.46
0.47	440	495	495	28	40.15
0.47	440	247.5	742.5	7	27.53
0.47	440	247.5	742.5	28	38.61
0.25	440	742.5	247.5	7	36.15
0.23	440	247.5	742.5	28	40.3

0.47	440	0	990	7	28.76
0.23	440	0	990	28	36.3
0.47	440	990	0	28	39.07
0.47	440	495	495	7	28
0.67	602.9	1356.6	150.7	3	11.22
0.67	602.9	904.4	602.9	28	20.86
0.67	602.9	753.7	753.7	7	11.89
0.67	602.9	1055.1	452.2	28	19.25
0.67	602.9	979.8	527.6	28	19.29
0.67	602.9	904.4	602.9	7	10.25
0.67	602.9	1431.9	75.4	28	21.01
0.67	602.9	1130.5	376.8	7	15.29
0.67	602.9	979.8	527.6	7	10.92
0.67	602.9	1281.2	226.1	3	9.08
0.67	602.9	829	678.3	28	15.36
0.67	602.9	904.4	602.9	3	8.28
0.67	602.9	1507.3	0	3	9.2
0.67	602.9	1205.9	301.4	28	21.52
0.67	602.9	1356.6	150.7	7	11.94
0.67	602.9	1431.9	75.4	3	10.84
0.67	602.9	1356.6	150.7	28	20.66
0.67	602.9	1431.9	75.4	7	13.36
0.67	602.9	1055.1	452.2	7	10.93
0.67	602.9	829	678.3	7	9.29
0.67	602.9	1507.3	0	7	10.4
0.67	602.9	753.7	753.7	28	18.28
0.67	602.9	1055.1	452.2	3	9.65
0.67	602.9	1507.3	0	28	20.84
0.67	602.9	1281.2	226.1	7	14.77
0.67	602.9	753.7	753.7	3	8.91
0.67	602.9	829	678.3	3	7.88

0.67	602.9	1130.5	376.8	3	10.63
0.67	602.9	1281.2	226.1	28	21.1
0.67	602.9	1130.5	376.8	28	20.57
0.67	602.9	979.8	527.6	3	10.44
0.67	602.9	1205.9	301.4	3	10.5
0.67	602.9	1205.9	301.4	7	13.79

Statistical analysis

As shown in graphs below, distribution of each independent parameters and relation between each independent variables w/c (Figures 2 and 3), sand content (kg/m^3) (Figure 4 and 5), cement content (kg/m^3) (Figures 6 and 7), waste glass content (kg/m^3) (Figure 8 and 9) and curing time (days) (Figures 10 and 11) have drawn with compressive strength alone to find them effect on the compressive strength. Statistical analysis has been done for each independent variables (w/c, sand content, cement content, waste glass content and curing time) including minimum, maximum, mean, standard devuation, skewness and kurtosis as in Table 2 below.

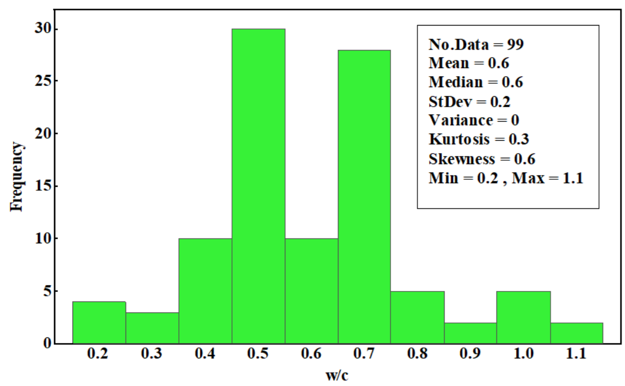

Figure 2: Histogram for water cement ratio.

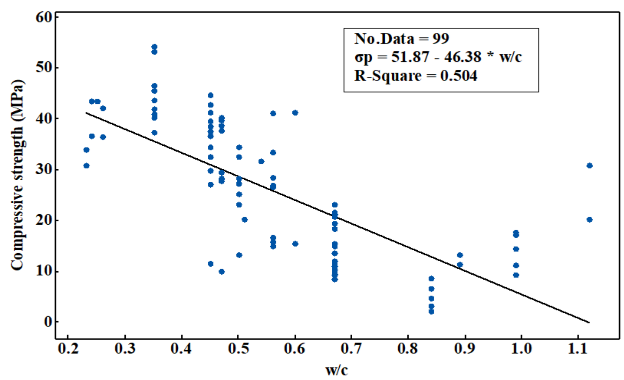

Figure 3: Scatter graph for compressive strength (MPa) to w/c.

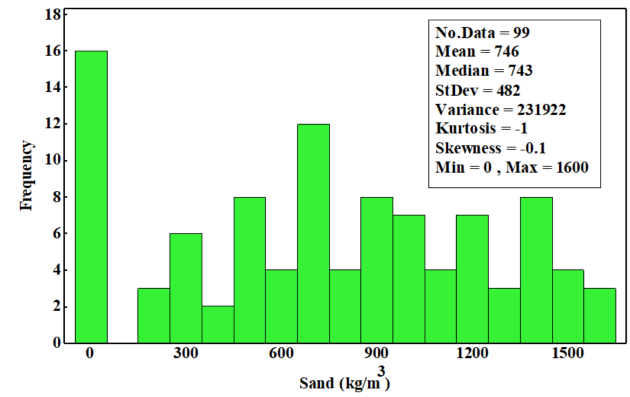

Figure 4: Histogram for sand content (kg/m^3).

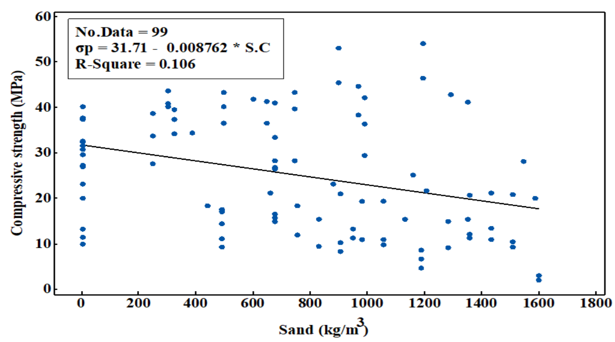

Figure 5: Scatter graph for compressive strength (MPa) to sand content (kg/m^3).

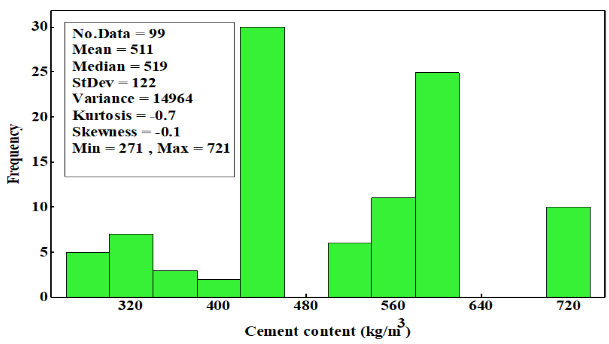

Figure 6: Histogram for cement content (kg/m^3).

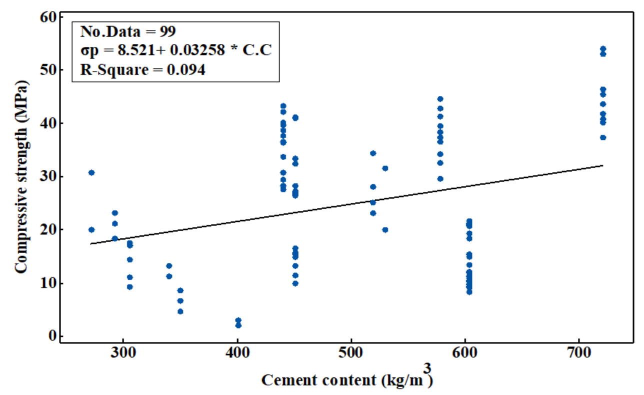

Figure 7: Scatter graph for compressive strength (MPa) to cement content (kg/m^3).

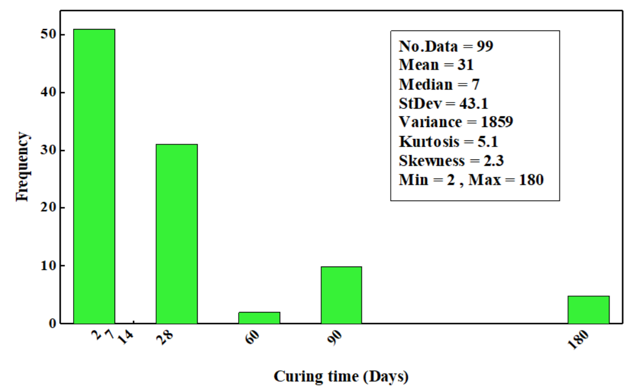

Figure 10: Histogram for curing time.

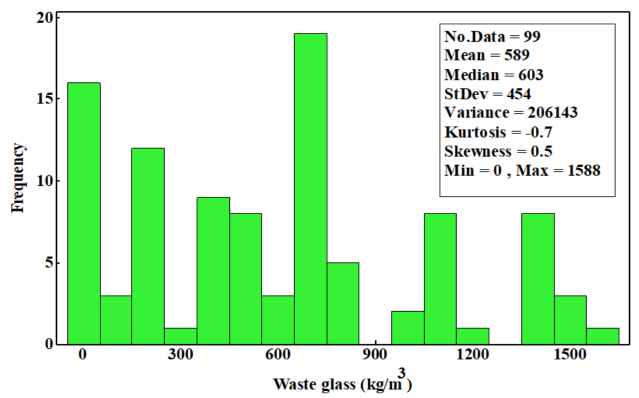

Figure 8: Histogram for waste glass (kg/m^3).

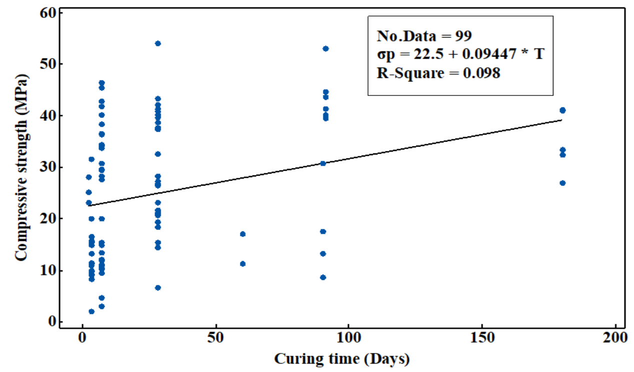

Figure 11: Scatter graph for compressive strength (MPa) to curing time.

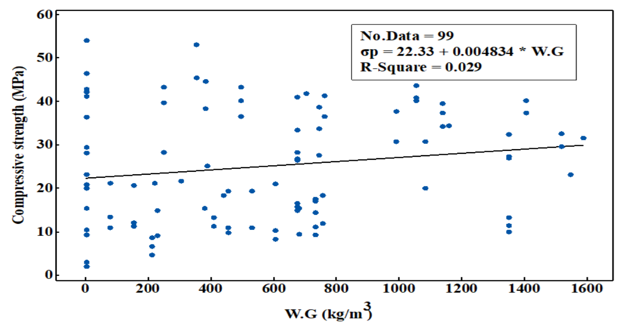

Figure 9: Scatter graph for compressive strength (MPa) to waste glass (kg/m^3).

Table 2: Statistical analysis for independent parameters.

Functions	w/c	Cement content (kg/m^3)	Sand (kg/m^3)	W.G (kg/m^3)	Curing time (Days)
Mean	0.6	511	746	589	31
Standard error	0	12.3	48.4	45.6	4.3
Median	0.6	519	743	603	7

Mode	0.7	603	0	0	28
Standard deviation	0.2	122	482	454	43.1
Sample variance	0	14964	231922	206143	1859
Kurtosis	0.3	-0.7	-1	-0.7	5.1
Skewness	0.6	-0.1	-0.1	0.5	2.3
Range	0.9	450	1600	1588	178
Minimum	0.2	271	0	0	2
Maximum	1.1	721	1600	1588	180
Sum	57	50603	73878	58314	3068
Count	99	99	99	99	99

Modelling

According to the statistical analysis, there are no direct relation between inputs parameter with compressive strength lonely, to find them affect, independent variables taken inside one equation (model), for this reason four different models (Linear Regression (LR), Nonlinear Regression (NLR), Multi Logistic Regression model (MLR) and ANN model) have chosen to collect all independent variables together and them results compared together using some statistical parameters as explained below:

LR model: Linear regression model form was as in the equation 1 [17], as in below:

$$\sigma_c=a+b(w/c) \qquad (1)$$

But since these factors which effect on the compressive strength more than w/c, the general form of the equation changed to the form as expressed in equation 2 to include all independent parameters (w/c, Cement Content (C.C), Sand Content (S.C), Waste Glass (W.G) and Curing Time days (t):

$$\sigma_c=a+b(w/c)+c(C.C)+d(S.C)+e(W.G)+f(T) \qquad (2)$$

MLR model: Sine independent variables effect on the compressive strength not linear another form of model has been predicted as in below [18]:

$$\sigma_c=a(w/c)^{C}\,(C.C)^{d}\,(S.C)^{e}\,(t)^{f}+b(w/c)^{g}\,(C.C)^{h}\,(S.C)^{i}\,(T)^{j}\,(W.G)^{k} \qquad (3)$$

In the above equation in first part effect of all independent parameter together can be finding on the compressive strength without modification while in the second part all parameter inputted with the modification effect.

NLR model: Since the independent parameter in this modification may contain zero value, the below form of nonlinear value has also considered as in equation below:

$$\sigma_c=a\,(w/c)^{b}+c\,(C.C)^{d}+e\,(S\,\%)^{f}+g\,(W.G)^{h}+i\,(T)^{j} \qquad (4)$$

ANN model: It is one of the most reliable models analyser which behave like human brain, it consists of input parts (independent parameters) and hidden parts (the analysis process) with output parts (the required target). ANN does not have general structure and the process of analysis depend on the inputted parameters and the form of the proposed problems as provided in the Figure 12 below. As a result of the analysis multiple results will be obtained and the best performable models will be chosen based on the value of the R^2, MAE and RMSE.

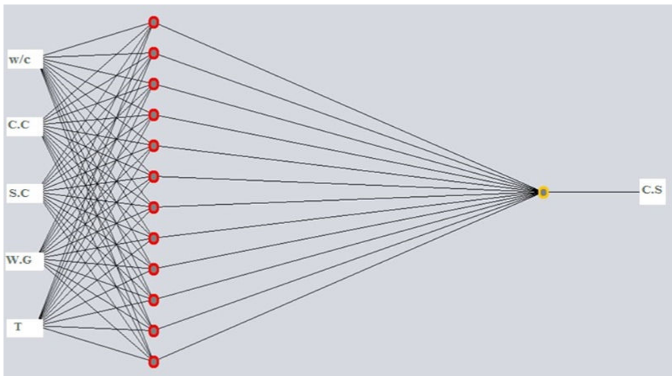

Figure 12: Analysis of input parameters in hidden part.

Assessment criteria for models: For selecting the best model for accuracy and most efficiency, following parameters are considered:

$$Mean = \frac{\sum x}{n} \quad (5)$$

$$R - square = 1 - \frac{\sum(Yi-Yp)^2}{\sum(Yi-Mean)^2} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum(Yi-Yp)^2}{N}} \quad (7)$$

$$SI = \frac{RMSE}{Mean} * 100 \quad (8)$$

$$MAE = \frac{\sum(Yi-Yp)}{n} \quad (9)$$

$$SD = \sqrt{\frac{\sum(Yi-Mean)^2}{N}} \quad (10)$$

$$U95 = 1.96 * \sqrt{SD^2 + RMSE^2} \quad (11)$$

$$OBJ = \left(\frac{N.Traial}{N.Total}\right) * \left(\frac{RMSE_{Traial}+MAE_{Traial}}{R^2_{Traial}+1}\right) + \left(\frac{N.Testing}{N.Total}\right) * \left(\frac{RMSE_{Testing}+MAE_{Testing}}{R^2_{Testing}+1}\right) \quad (12)$$

Based on the used statistical parameters, the higher R^2 value will be more desirable, and the model with SI>0.3 will consider as bad performance, while 0.2<SI<0.3 consider as acceptable performance and 0.1<SI<0.2 consider as excellent performance but if 0<SI<0.1 will measure as great performance [19,20].

RESULTS AND DISCUSSION

Relationship between independent parameters and compressive strength

LR model: Based on the statistical analysis using training and testing data below equation has been predicted with using 99 data as training data and 35 data as testing, with R^2 equal to 0.73 for training data and 0.86 for testing data. RMSE value equal to 6.71 MPa for training data and 5.57 MPa for testing data, while MAE value is 5.55 MPa for training data and 4.63 MPa for testing data. OBJ value is equal to 7.44, and SI value in the range 0.2 to 0.3 which is showing good efficiency (Figure 13)/

σ_p=57.04-25.96w/c+0.043C.C-0.032 S.C-0.03W.G+0.1*T (13)

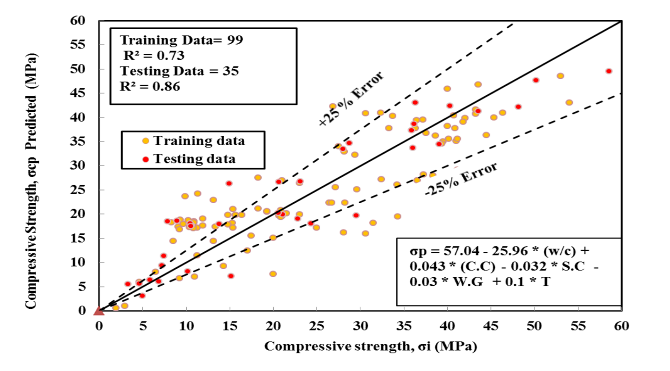

Figure 13: Linear regression model for training and testing data.

NLR model: With using 98 data as training data and 34 data as testing, the below equation has been predicted with R^2 equal to 0.79 for training data and 0.89 for testing data. RMSE value equal to 5.92 MPa for training data and 4.76 MPa for testing data, while MAE value is 4.77 MPa for training data and 4.76 MPa for testing data. OBJ value is equal to 6.08, and SI value in the range 0.2 to 0.3 which is showing good efficiency (Figure 14).

σ_p=83.83-66.27w/b$^{0.3}$+0.0034C.C$^{1.66}$-0.00054S.C$^{1.5}$-0.545W.G$^{0.546}$ +7.3T$^{0.246}$ (15)

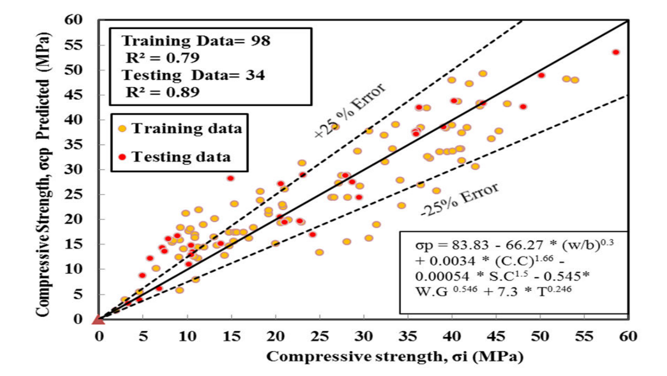

Figure 14: Nonlinear regression model (plus form) for training and testing data.

MLR model: By using 98 data as training data and 35 data as testing, the below equation has been predicted with R^2 equal to 0.73 for training data and 0.81 for testing data. RMSE value equal to 6.7 MPa for training data and 6.45 MPa for testing data, while MAE value is 5.642 MPa for training data and 5.488 MPa for testing data. OBJ value is equal to 7.8, and SI value in the range 0.2 to 0.3 which is showing good efficiency (Figure 15)

σ_p=1.79*(w/c$^{-1.03}$) * (C.C$^{0.258}$) * (T$^{0.135}$)-(0.00017)*(w/c$^{-5.38}$) * (C.C$^{0.0286}$) * (W.G$^{0.537}$) * (T$^{0.0.001}$) (16)

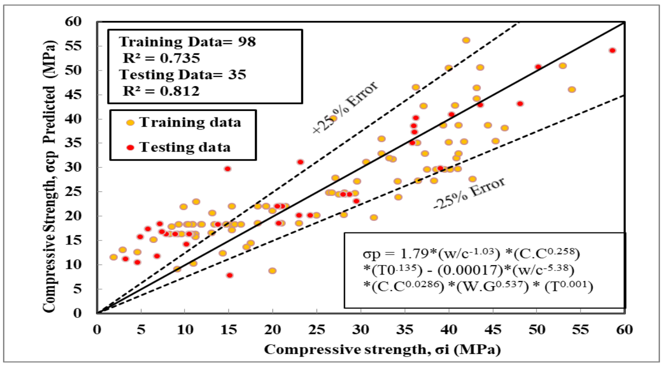

Figure 15: MLR model for training and testing data.

ANN model: Based on the obtained analysis from ANN the following analysis have been obtained, and based on the value of

RMSE, MAE and R^2 the best reliable result has been chosen and the below graph obtained (Figure 16 and Table 3).

Table 3: Obtained results from trial and error by using ANN.

No. of hidden layers	No. of neurons in left side	No. of neurons in right side	R^2	MAE (MPa)	RMSE (MPa)
1	5	0	0.9819	1.8562	2.5517
1	6	0	0.9904	1.6862	2.2158
1	7	0	0.9911	1.5379	1.9477
1	8	0	0.9892	1.6136	2.0808
1	9	0	0.9865	1.6	2.1268
1	10	0	0.9913	1.3635	1.7758
1	11	0	0.9924	1.331	1.7552
1	12	0	0.9922	1.3055	1.723
2	4	4	0.9636	2.7497	3.6843
2	5	5	0.9842	1.9769	2.5085
2	6	6	0.9823	2.0118	2.4559
2	7	7	0.9807	2.2999	2.9697
2	8	8	0.9902	1.4929	1.9905

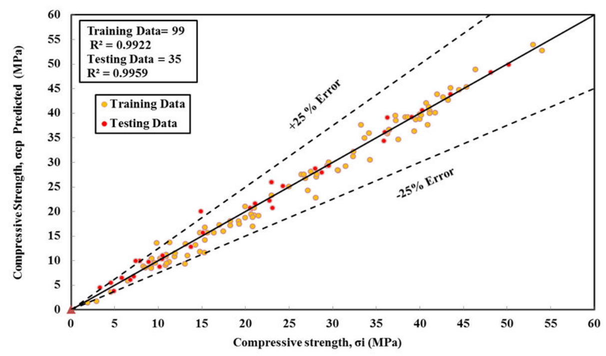

Figure 16: ANN model for training and testing data.

Models compression

Based on the obtained value of R^2, MAE and RSME as in the figures below the ANN is most reliable compare to other proposed model when the value of R^2 in ANN 26% higher than regression and 20% higher the NLR and 26% higher than MLR, value of RMSE in ANN 289% smaller than regression and 243% smaller the NLR and 288% smaller than MLR, value of MAE in ANN 327% higher than regression and 267% higher the NLR and 334% higher than MLR. OBJ value of ANN, lower than OBJ of LR by 418%, 323% of NLR and 443 % of MLR. SI value of ANN between 0 to 0.1, which performed excellency (Figures 17-21).

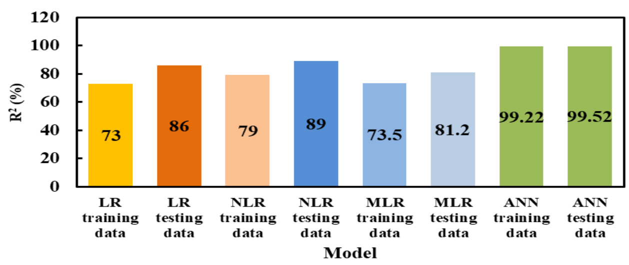

Figure 17: R^2 value for three proposed models.

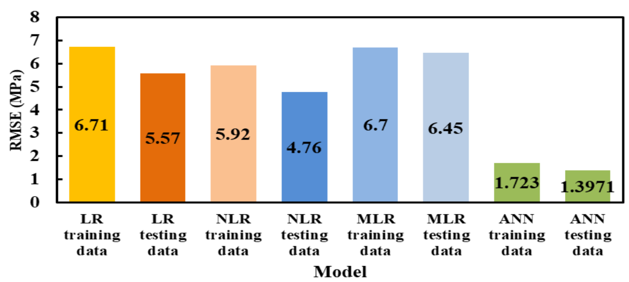

Figure 18: RMSE value for proposed models.

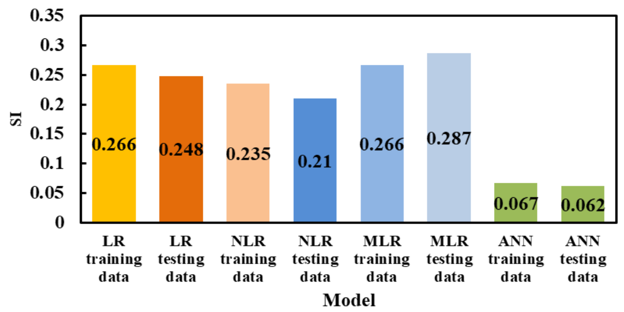

Figure 19: MAE value for proposed models.

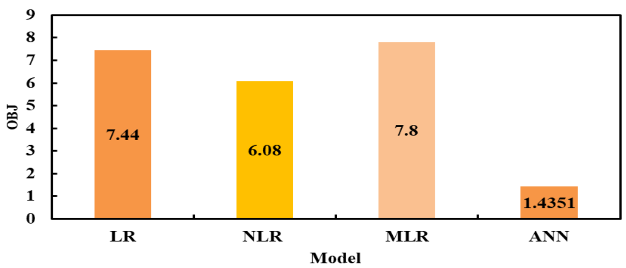

Figure 20: OBJ value for proposed models.

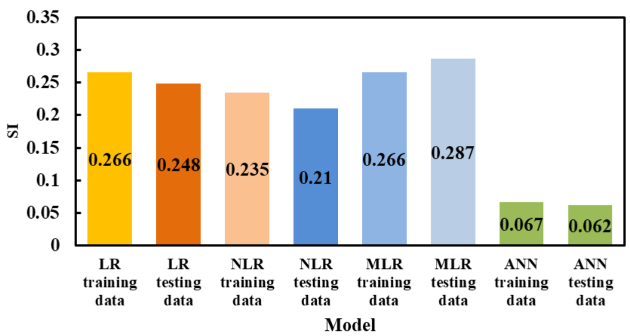

Figure 21: SI value for proposed models.

CONCLUSION

Predicting an accurate and efficient statistical model to predict the compressive strength of the mortar, modified with waste material will be helpful, based on this process the following points have been obtained:

- Used range of waste glass as replacement of sand vary between 0 to 100%.
- With using different statistical parameters, R, RMSE, MAE, OBJ and SI showing that ANN is most accurate and efficient compare to other models since it provide higher value of R and lower value of other parameters.
- OBJ value of ANN lower than MAE of LR by 418%, 323% of NLR1 and 443 % of NLR.
- SI value of ANN between 0 to 0.1, which performed excellency.
- R value of ANN higher than R of LR by 26%, 20% of NLR1 and 26% of NLR.
- MAE value of ANN lower than MAE of LR by 327%, 267% of NLR1 and 334 % of NLR.
- RMSE value of ANN lower than RMSE of LR by 289%, 243% of NLR1 and 288% of NLR.

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Not applicable.

AVAILABILITY OF THE DATA AND MATERIALS

All data generated or analysed during this study are included in this published article.

CONFLICT OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant support for this work that could have influenced its outcome.

RESEARCH INVOLVING HUMAN/ ANIMAL PARTICIPANTS

This article does not contain ant studies involving animal's human participants performed by any of the authors.

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