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Performance Modeling of Open-Graded Friction Course Pavements

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Abstract: An open-graded friction course (OGFC) is a special-purpose surface layer of hot-mix asphalt (HMA) pavement that is increasingly being used around the world. Owing to its numerous benefits, OGFC is being regularly used as a final riding surface on interstate and high-traffic expressways by different highway agencies in the United States. However, some OGFC sections have experienced premature failure due to ravelling only after 6-8 years of service life. The major problems associated with OGFC can be classified into three categories: design, maintenance and premature failures. Permeability is an important performance measure of OGFC mixtures in design phase. Regression models developed in this research paper will be helpful in getting estimate of permeability values during the design phase of OGFC pavement layer. This estimated permeability values will be helpful in improving the design procedure based on laboratory permeability data.

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***Key words**: Design phase; Open-graded friction course; Performance; Regression models.*

Background

Open-graded friction courses (OGFC) are thin and permeable surface layer of hot mix asphalt (HMA) mixtures that incorporate coarse aggregate skeleton with minimum fines. The load is supported through stone to stone contact and the asphalt binder keeps the skeleton intact. This inherent attribute in OGFC enhances resistance to rutting and its porous nature ensures immediate drainage of water from pavement surface. It provides numerous benefits for the road users in terms of safety, environment and economy including improved friction, minimized hydroplaning, reduction of splash and spray, improvement of night visibility and reduction of noise levels [1].

The performances of flexible pavements are generally predicted from laboratory determined parameters. In case of OGFC, permeability is one of the most important performance prediction measures as it is the most influencing factor in long term performance/ functionality of OGFC pavements. Regression is used as a powerful tool to develop model. The model is used to predict a dependent variable from a set of independent variables. For the fitting data, evaluation is done to find how well the model fits the data on which it was developed. An important aspect of regression modeling is whether results of the regression analysis on a particular data set can be extended to the population of the data from which data set has been chosen. This process is called validation of the model. The validation of the model quantifies the closeness of the model's probability estimates to the correct dependent value. For the validation data, evaluation is done to validate the model is as it attempts to predict an independent data set.

Due to large number of interacting influencing factors, it is difficult to develop an analytical equation that reflects the complex relationship between permeability and all the predicting factors. Westerman [2] developed a regression equation that develop relationship among voids in total mix (VTM), lift thickness and in-place permeability. Later, the relationship was used by Haddock and Prather et al. [3] in an investigation project to determine the cause of pavement failure. Mohammad et al. [4] developed a regression equation to predict the permeability of HMA mixtures from the mixture volumetric properties. The permeability regression equation is expressed as follows:

$$\begin{aligned}\text{Perm} = 10 - 4\,(&76.6\,\text{VTM} - 17.2\,P_{0.075} + 163.4\,P_{0.3} \\ &- 197.5\,P_{0.6} + 33.2\,P_{2.36} + 4.5\,P_{12.5} - 1.7H)\end{aligned} \tag{1}$$

where,
Perm = coefficient of permeability (mm/s);
VTM = air voids (%);
$P_{0.075}$ = percent passing 0.075 mm sieve;
$P_{0.3}$ = percent passing 0.3 mm sieve;
$P_{0.6}$ = percent passing 0.6 mm sieve;
$P_{2.36}$ = percent passing 2.36 mm sieve;
$P_{12.5}$ = percent passing 12.5 mm sieve; and
H = height of specimen (mm).

Vivar and Haddock [5] developed a regression equation to predict permeability of HMA mixtures based on VTM, Nominal maximum aggregate size (NMAS) and gradation. The gradation used for HMA mixtures was coarse-graded and fine-graded, NMAS of 9.5 and 19.0 mm, and VTM of 4, 6, 8 and 10%. HMA samples were prepared in Superpave gyratory compactor, and Florida method of Permeability tests were performed on all samples. An excellent goodness of fit (R^2 of 0.93) was achieved for this equation. The permeability regression equation is expressed as follows:

$$\text{Perm} = \text{VTM}^{6.8}\, e^{0.11\,\text{NMAS} - 0.89\,\text{gradation} - 10.97} \tag{2}$$

where,
Perm = Permeability (10^{-5} cm/s)

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NMAS = Nominal maximum aggregate size (mm)
VTM = Voids in the total mixture; and
Gradation = 0 for coarse-graded, 1 for fine-graded.

Literature review revealed lack of model development research for OGFC mixtures, in particular. However, model development efforts highlighted above, show that permeability of HMA has been modeled based on explanatory variables i.e. VTM, lift thickness, gradation and NMAS using linear and nonlinear regression techniques.

Scope and Objective

The objective of the study was to develop a regression model to predict permeability of OGFC based on easily quantifiable explanatory variables. The variables were based on laboratory permeability testing data to evaluate performance of OGFC mixtures.

In order to explain the variability in permeability of the OGFC mixtures and develop a regression model to predict permeability, statistical analysis was done on laboratory permeability data. Minitab software was used for statistical analysis and regression modeling. Multiple regression analysis was carried out on laboratory permeability data of a project carried out on improvement of OGFC mixture design at National Center for Asphalt Technology (NCAT), Auburn, Alabama, USA in 2004. The laboratory permeability testing was part of study to evaluate laboratory performance of OGFC mixtures. Permeability tests were performed using the procedure adopted by the Florida Department of Transportation [6] for mix designs with specimens compacted at 50 gyrations with the Superpave gyratory compactor (SGC). Samples compacted with the SGC are 150 mm (6 in) in diameter by 115 mm (4.5 in) high. The mix design gradations used for this permeability study are shown in Table 1. Details on regression models and regression parameters are available in the literature [7, 8].

Table 1. Gradation for OGFC Permeability Test Data.

Sieve Size, mm	Master Gradation	Fine	Medium	Coarse
19.00 (3/4 in.)	100	100	100	100
12.50 (1/2 in.)	80-100	100	90	80
9.50 (3/8 in.)	35-60	60	47	35
4.75 (#4)	10-25	25	17	10
2.36 (#8)	5-10	10	7	5
0.075 (#200)	2-4	3	3	3

Permeability Model Development

Summary of Descriptive Statistics of Permeability Testing Data

The laboratory permeability test data shows mix design gradations (fine, medium or coarse), asphalt content and VTM of OGFC mix based on sandstone and granite aggregate, respectively. The data consisted of 78 and 70 experimental test observations on aforementioned mixes. Descriptive statistics of important permeability test variables of OGFC mixes for sandstone and granite aggregate are tabulated in Table 2.

Selection of Explanatory Variables from the Laboratory permeability Test Data

Based on literature review concerning factors effecting OGFC and hot-mix asphalt (HMA) permeability modeling, following test variables were considered as independent variables to predict permeability (dependent variable) from laboratory permeability test data:

(i) Aggregate Gradation,
(ii) Voids in total mix (VTM),
(iii) Effective asphalt content (AC)

As such, aggregate gradation cannot be used as a variable in regression modeling, because it represents percentages of different sizes of aggregate in the mix. In order to use gradation in regression modeling, different sieves are considered [4]. Sieve sizes of 4.75 and 2.36 mm sieves were considered for differentiating coarse and fine aggregates. The variable used with regards to gradation is given below:

$$\text{Coase aggregate ratio (CA)} = \frac{\text{Percent material retained on 4.7mm (No.4) sieve}}{\text{Percent material passing 4.7mm (No.4) sieve}}$$

$$\text{Aggregate ratio (AR)} = \frac{\text{Percent material retained on 2.36mm (No.8) sieve}}{\text{Percent material passing 2.36mm (No.8) sieve}}$$

The four primary explanatory variables considered for the regression model were AC, VTM, CA and AR. Two separate

Table 2. Descriptive Statistics of Permeability Test Data for Sandstone and Granite Based OGFC Mixtures

Variable	Type	Mean	Std Dev	Minimum	Median	Maximum
Sandstone Based OGFC Mixtures						
Asphalt Content	Discrete	6.50	0.41	6.00	6.50	7.00
Voids in Total Mix	Continuous	17.75	1.51	15.10	17.65	21.40
Permeability	Continuous	94.61	38.49	27.69	89.62	195.89
Granite Based OGFC Mixtures						
Asphalt Content	Discrete	6.00	0.41	5.50	6.00	6.50
Voids in Total Mix	Continuous	17.30	1.57	14.00	17.35	21.00
Permeability	Continuous	82.16	38.65	21.60	70.50	167.00

* Std Dev = Standard Deviation

regression models were made from laboratory permeability test data for sandstone and granite aggregate, as, type of aggregate is a significant factor in permeability evaluation of OGFC mixtures.

Choice of Modeling Technique and Model Mathematical Form

Regression analysis was used as a statistical tool to develop model in this research paper. The purpose of regression analysis in this research was to develop a model representing a relationship between permeability (response variable) and a set of candidate explanatory variables i.e. AC, VTM, CA, and AR. Response or dependent variable for this research was permeability, which is a continuous variable. Therefore, ordinary least square (OLS) regression analysis technique was selected for development of permeability prediction model in this research.

Multiple regression analysis is used to develop a model that predicts response variable based on explanatory variables. The general form of multivariable regression model is as under;

$$Y = a + bX_1 + cX_2 + dX_3 \tag{3}$$

where,
Y = Response/Dependent variable,
X_1, X_2 and X_3 = Explanatory variables,
a, b, c, and d = Variable coefficients.

In Eq. (3), Y is the dependent variable and; X_1, X_2 and X_3 are independent variables; and a, b, c, and d are the variable coefficients. The use of regression technique assumes that the errors are normally distributed, uncorrelated and rather independent. The variance of error is assumed to be constant across observations (i.e. termed as homoscedasticity). One of the assumptions of multiple linear regression analysis using OLS technique is that the predictor variables are linearly independent.

Preliminary Analysis

The preliminary analysis of all the considered variables was carried out to find out the suitable and significant predictor variables for the regression model. Scatter Plot helps in indicating some important issues including trend of data i.e. linear or curvilinear. Correlation matrix helps in indicating correlation of predictor or response variables with response variable and correlation of predictor variables between each other i.e. multicollinearity.

Scatter Plot

Scatter Plot of permeability (response variable) with all the four explanatory variables of permeability test data for sandstone and granite aggregate based OGFC mixtures is shown in Figs. 1 and 2, respectively. The relationship between permeability (response variable) and explanatory variables (VTM, CA, AC and AR) seems to be linear for both the aggregate types. Scatter plots of permeability for both aggregate types show a positive correlation between permeability and VTM, CA and AR whereas a negative correlation between permeability and AC. Scatter plot of permeability for both aggregate types show that VTM data, in case of granite aggregate, is more widely spread as compared to sandstone aggregate.

Correlation Matrix

Multicollinearity among explanatory variables is a problem often encountered with observational/experimental data. Correlation matrix of four explanatory variables of permeability test data for

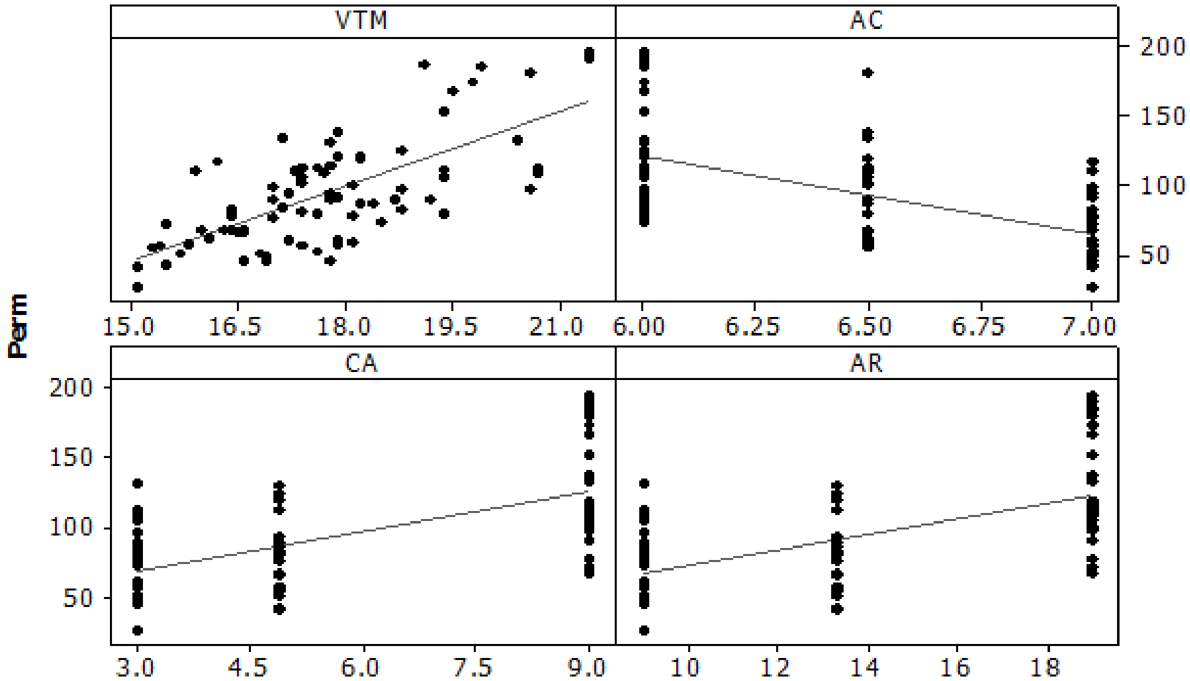

Fig. 1. Scatter Plot of Permeability Versus Explanatory Variables for Sandstone Aggregate.

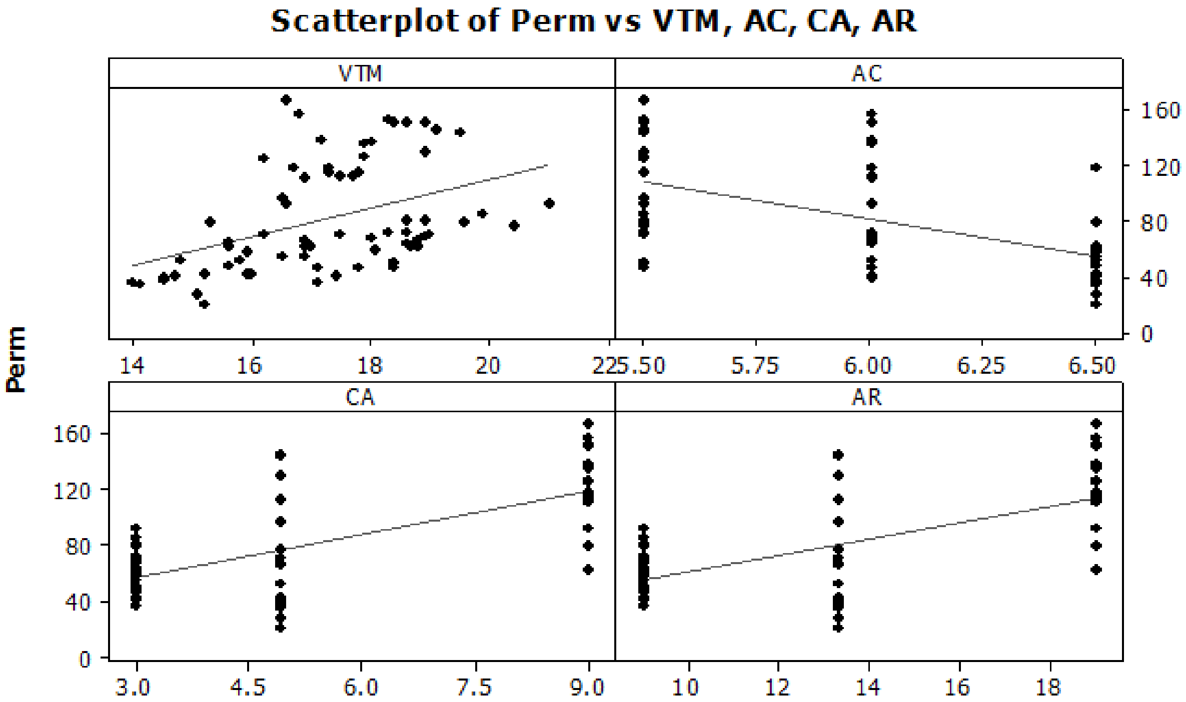

Fig. 2. Scatter Plot of Permeability Versus Explanatory Variables for Granite Aggregate.

sandstone and granite aggregate based OGFC mixtures is tabulated in Table 3. All values are shown in terms of values of R (Pearson correlation). As observed in correlation matrix for sandstone aggregates that correlation coefficient for CA and AR is 0.992, representing strong multicollinearity between these variables. Correlation coefficient for VTM and AC is 0.598, which shows medium multicollinearity. For other correlation coefficients of the pair of variables, no significant multicollinearity has been observed, in case of sandstone aggregate. As observed in correlation matrix for granite aggregate that correlation coefficient for CA and AR is 0.992, representing strong multicollinearity between these variables. Correlation coefficient for VTM and AC is 0.633, which shows medium multicollinearity. For other correlation coefficients of the pair of variables, no significant multicollinearity has been observed, in case of granite aggregate.

Model Selection

Preliminary analyses revealed that strong multicollinearity exist between variables CA and AR making unsuitable to include both variables in the model. Based on American Association of State Highway and Transportation Officials (AASHTO) standard (No. 4 sieve being used for separating coarse and fine aggregate), CA was selected to be a candidate explanatory variable for the permeability model [9]. Stepwise Regression Procedure was adopted for selection of significant explanatory variables for the permeability model. This procedure starts with a complete model with all independent variables entered and eliminates one variable at a time until a suitable regression model was found. The three primary variables AC, CA, VTM were used for stepwise regression procedure in Minitab software at a significance level of 0.05. The results of stepwise regression procedure revealed that model based on all the three candidate explanatory variables is statistically significant.

Table 3. Correlation Matrix of Explanatory Variables of Permeability Test Data for Sandstone and Granite Based OGFC Mixtures.

Sandstone Based OGFC Mixtures				
Variable	AC	CA	AR	VTM
AC	1	-0.043	-0.041	-0.616
CA	-0.043	1	0.992	0.068
AR	-0.041	0.992	1	0.015
VTM	-0.616	0.068	0.015	1
Granite Based OGFC Mixtures				
AC	1	-0.086	-0.072	-0.640
CA	-0.086	1	0.992	-0.156
AR	-0.072	0.992	1	-0.207
VTM	-0.640	-0.156	-0.207	1

Statistical significance parameters of stepwise regression procedure have been tabulated in Table 4 for permeability test data for sandstone and granite based OGFC mixtures.

Permeability Prediction Models and their Analysis

Permeability Prediction Models

The final permeability prediction models developed through multiple linear regression analysis of permeability test data for sandstone and granite based OGFC mixtures are given in Eqs. (4) and (5) below, respectively and discussed in subsequent paragraphs.

$$\text{Perm Sand stone} = -170 + 13.4\,(\text{VTM}) - 10.8\,(\text{AC}) + 8.62\,(\text{CA}) \quad (4)$$

$$\text{Perm Granite} = -120 + 9.18\,(\text{VTM}) - 7.02\,(\text{AC}) + 10.2\,(\text{CA}) \quad (5)$$

Table 4. Statistical Significance Parameters of Stepwise Regression Procedure for Permeability Test Data of Sandstone and Granite Based OGFC Mixtures.

Regression Statistics	Stepwise Inclusion of Variables		
	VTM	CA	AC
Sandstone Based OGFC Mixtures			
SE	27.5	16.7	15.3
R-Sq, (%)	49.74	81.72	84.89
R-Sq(adj), (%)	49.08	81.23	84.28
P-value	<0.005	<0.005	<0.005
Granite Based OGFC Mixtures			
SE	18.9	27.3	18.3
R-Sq, (%)	73.35	43.42	75.26
R-Sq(adj) , (%)	72.51	42.55	74.08
P-value	0.03	<0.005	<0.005

***** SE = Standard Error of Regression

Table 5. Statistical Significance Parameters of Permeability Regression Model for Sandstone and Granite Based OGFC Mixtures.

Regression Statistics	Model		
	VTM	AC	CA
Sandstone Based OGFC Mixtures			
t-statistic	9.07	-3.94	12.39
P-value	<0.005	<0.005	<0.005
VIF	1.62	1.61	1.01
SE		15.26	
R-Sq, (%)		84.9	
R-Sq (adj), (%)		84.30	
Durbin-Watson Statistic		1.67	
Granite Based OGFC Mixtures			
t-statistic	5.07	-2.21	10.94
P-value	<0.005	0.03	<0.005
VIF	1.83	1.80	1.09
SE		18.31	
R-Sq, (%)		75.30	
R-Sq (adj), (%)		74.10	
Durbin-Watson Statistic		1.59	

Analysis

Statistical significance parameters of the regression analysis of permeability test data for sandstone based OGFC mixtures are tabulated in Table 5. The number of observed response values was 78 in case of permeability test data for sandstone aggregate. Asphalt content (AC) was used as discrete variable in the model. Eq. (4) shows that permeability is directly proportional to VTM and CA whereas it is inversely proportional to AC, which is quite intuitive. Appropriateness of the model and confirmation of regression assumptions were analyzed through statistical significance parameters tabulated in Table 5 and diagnostic/residual plots shown in Fig. 3. Normal probability plot and histogram of residuals (Fig. 3) clearly shows that residuals are distributed normally. Residual versus fits plot (Fig. 3) depicts that residuals have reasonably constant variance. Residual versus order plot (Fig. 3) depicts that residuals are fairly independent. The permeability prediction model for sandstone based OGFC mixtures showed reasonable statistical efficiency at 95% confidence level, which includes satisfactory R^2 values, significant t-statistics and p values and low multicolinearity between explanatory variables. The important regression statistics of model for sandstone aggregate are R^2(adj) = 84.28 and standard error of regression (SE=15.3), seems quite reasonable. The regression model seems quite reasonable when SE of regression model is compared to Std Dev of permeability data, which is 38.49.

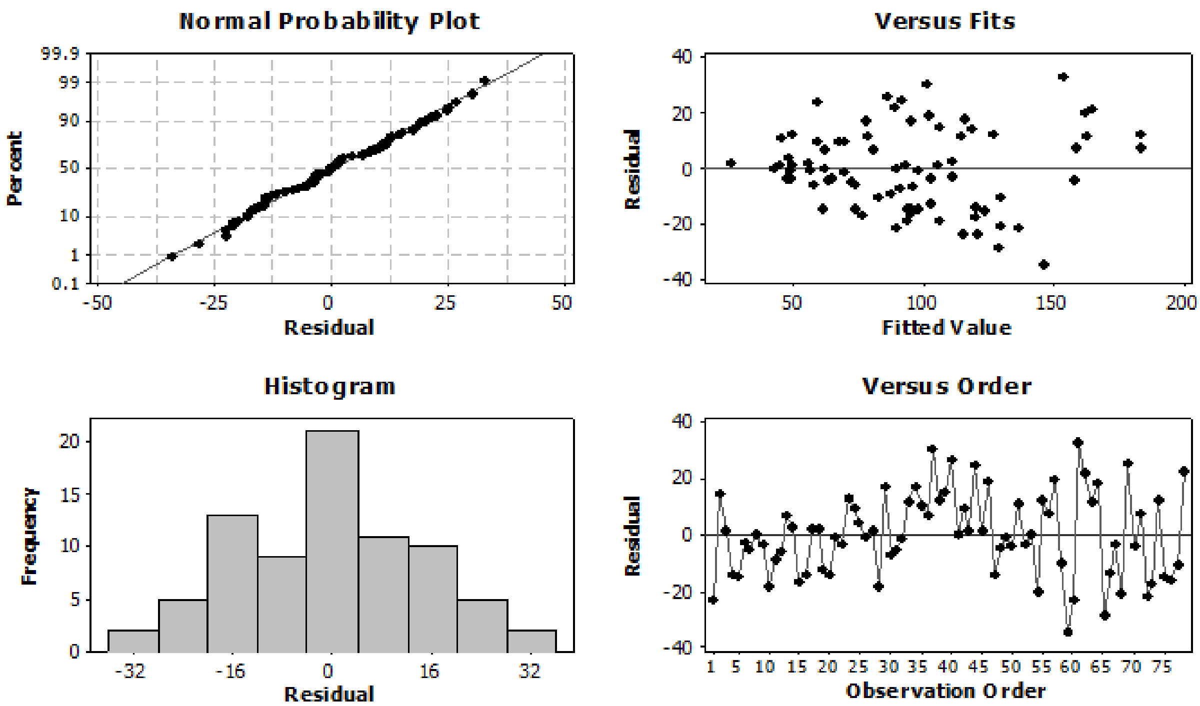

Fig. 3. Residual Plots of Permeability Regression Model for Sandstone Based OGFC Mixtures.

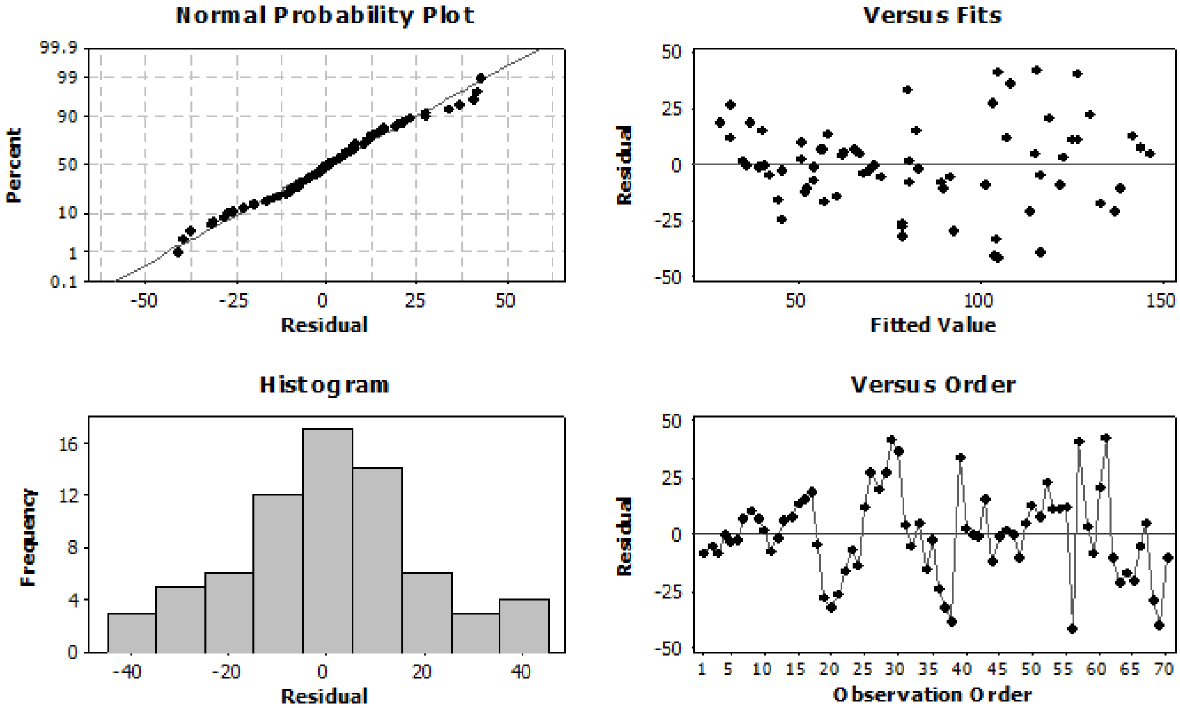

Fig. 4. Residual Plots of Permeability Regression Model for Granite Based OGFC Mixtures.

Also, P and T values of all the independent variables show that all variables are statistically significant in regression equation. In statistics, variance inflation factor (VIF) quantifies the severity of multicollinearity in an ordinary least squares regression analysis. VIF value in between 1 and 2 of all the independent variables show that multicollinearity is within reasonable limits in this regression model. The autocorrelation in the residuals in the regression model are detected by Durbin-Watson statistic, which in this case Durbin-Watson statistic value of 1.67 is showing insignificant autocorrelation.

Statistical significance parameters of the regression analysis of permeability test data for granite based OGFC mixtures are tabulated in Table 5. The number of observed response values was 67 in case of permeability test data for sandstone aggregate. Eq. (5) shows that permeability is directly proportional to VTM and CA whereas it is inversely proportional to AC. Suitability of the model and verification of regression assumptions were analyzed through statistical significance parameters tabulated in Table 5 and diagnostic/residual plots shown in Fig. 4. Normal probability plot and histogram of residuals (Fig. 4) clearly shows that residuals are distributed normally. Residual versus fits plot (Fig. 4) depicts that residuals have reasonably constant variance. Residual versus order plot (Fig. 4) depicts that residuals are fairly independent. The permeability prediction model for granite based OGFC mixtures showed reasonable statistical efficiency at 95% confidence level, which includes satisfactory R^2 values, significant t-statistics and p values and low multicolinearity between explanatory variables. The important regression statistics of model for sandstone aggregate are R^2 (adj) = 74.08 and standard error of regression (SE=18.3), seems quite reasonable. The regression model seems quite reasonable when SE of regression model is compared to Std Dev of permeability data, which is 38.65. Also, P and T values of all the independent variables show that all variables are statistically significant in regression equation. VIF value in between 1 and 2 of all the independent variables show that multicollinearity is within reasonable limits in this regression model. The Durbin-Watson statistic value of 1.26 shows insignificant autocorrelation.

Mean Absolute Percentage Error (MAPE)

Mean absolute prediction error (MAPE) of permeability regression model for sandstone and granite based OGFC mixtures as given in Eqs. (4) and (5), respectively, was calculated and found to be 2.24% for sandstone based OGFC mixtures and -6.03% for granite based OGFC mixtures. MAPE is an important measure of trend estimation in statistics and modeling. MAPE value of 2.24% for sandstone based OGFC mixtures and -6.03% for granite based OGFC mixtures shows that model fits perfectly. Figs. 5 and 6 show comparison between true and predictive permeability values.

Significance

From the p value and t-statistics, it is clear that CA and VTM are two most significant factors in predicting permeability of the OGFC mixes. VTM is more significant for sandstone based OGFC mixtures regression model in comparison to granite based OGFC mixtures regression model, where CA is more significant. Based on statistical significance parameters, the permeability regression model for sandstone based OGFC mixtures seems to be more significant as compared to permeability regression model for granite based OGFC mixtures.

The permeability prediction models in this research stand out in comparison to models developed in the past research on the basis of following vital aspects:

- The developed models are pertaining to permeability of OGFC mixtures, in particular.

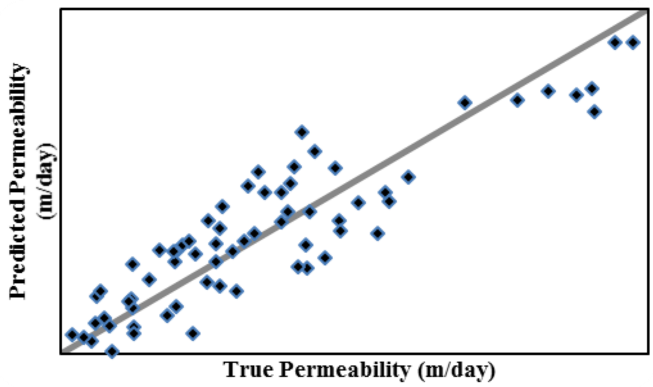

Fig. 5. Comparison of Predictive and True Permeability for Sandstone Based OGFC Mixtures.

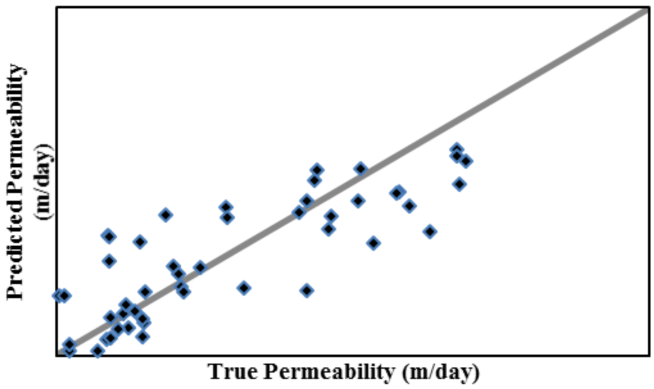

Fig. 6. Comparison of Predictive and True Permeability for Granite Based OGFC Mixtures.

- AC, one of the important factors in predicting permeability of OGFC mixtures, is included in the present model which obviates the possibility of omitting important model variable.
- The developed models exhibits good fit to experimental data which explains the variability of permeability due to change in VTM, AC and gradation.

Conclusions

Based on laboratory permeability data, regression analysis and its analysis conducted during the course of this study, the following conclusions are drawn:

- Permeability regression models have been developed for sandstone and granite based OGFC mixtures. These models can be used to predict permeability based on three primary variables AC, CA, and VTM.
- Permeability has positive relationship with VTM and CA.
- Permeability has negative relationship with AC.
- Increase of permeability with unit increase in VTM is 34 percent more in sand stone based OGFC as compared to granite based OGFC.

Recommendations

Permeability is an important performance measure of OGFC mixtures in design phase, regression models developed in this paper will be helpful in getting estimate of permeability values thereby improving the design procedure. In order to expand and further validate this research, it is recommended to select OGFC sections from light and heavily trafficked interstate/highways for field validation of permeability prediction models developed in this paper.

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