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Modeling unconfined compressive strength of fine grained soils: Application of dynamic cone penetration to predict foundation soil strength

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Abstract

Evaluating the strength of soil foundation and is a critical requirement in every civil infrastructure. For cohesive soils, the foundation soil strength and settlement are determined in terms of undrained shear strength. In many cases, unconfined compressive strength (UCS) is used as an undrained condition of the triaxial shear test. However, this test is time-consuming, it needs huge effort and needs care comparing to the dynamic cone penetration test. Recently, dynamic cone penetration tests (DCP) have been using as an alternative to predict subgrade strength parameters. In this study, DCP and atterberg limits are used to predict UCS using simple and multiple regression analysis. Thirty tests were conducted at different depths and locations in the town. The established equations are validated using sets of data. The result obtained from validation shows that the established empirical correlation can be useful in the quick determination of UCS when there is a financial limitation, lack of equipment, and time to conduct UCS in the current study area.

Keywords: *Bearing capacity, DCP, UCS, Regression analysis, Undrained condition*

1. Introduction

The evaluation of foundation soil strength is a critical step in the design of flexible pavements and civil infrastructures. Before starting any civil infrastructure, determining the foundation bearing capacity is mandatory. A proper site investigation should have been done to be safe and economical in every activity related to engineering works. To do so, there are many methods, by which the strength of subsoil is to be evaluated. In building construction, the total load of the structure must safely be transferred to the foundation soil, while in the case of pavement construction the load from traffic must safely be transferred to subgrade soil.

For cohesive soils, where the undrained condition of the foundation is considered, unconfined compressive strength, the simple type of triaxial test is widely used to determine the undrained shear strength of the soil. For building constructions, this test is used to determine the bearing capacity of foundation soil. In flexible pavement design, unconfined compressive strength is used with other factors such as climate conditions, traffic load, and traffic intensity, to evaluate the bearing capacity of the foundation soil [1].

Unconfined compressive strength can be carried out by taking the sample directly from the site or by remolding the sample in a laboratory. This process cannot be easily determined in the field, time-consuming, need huge effort and care to conduct the test [2]. Recently, to avoid such complexity, and due to its low cost of operation and simplicity to address the quality of pavement layers effectively, many pavement engineers and geotechnical experts have been using in-situ tests. These in-situ techniques provide structural parameters used in engineering design such as load-bearing capacity and deformation properties easily [3]. Dynamic cone penetration is one of these in-situ techniques. DCP tests require a short time to conduct, analyze and interpret the test results.

The dynamic cone penetration test (DCPT) has many advantages over the other methods as it provides soil strength with a depth continuously. Comparing to other test instruments it is cheap, simple, and easy to operate and interpret the test result [3]. Many researchers concluded DCP is a reasonable and advantageous apparatus used to evaluate the strength of subgrade soil materials [3], [4].

In our country, only a few pieces of research were done concerning correlations of Dynamic cone penetration with Unconfined compressive strength which is limited to a specific area. The aim of this study is to develop a correlation of unconfined compressive strength for locally used subgrade soil material in Jimma town. This correlation study is very important to estimate UCS, especially for preliminary investigation of projects where there is a financial limitation, lack of test equipment, and limited time to conduct UCS tests for the study area. The finding of this study contributes an important role in introducing the science of using dynamic cone penetration for the evaluation of subgrade soil strength.

2. Literature Reviews

Dynamic Cone Penetrometer was developed for the first time in South Africa in 1956 as a technique to evaluate a pavement in in-situ conditions. It consists of a hammer with 9 kg, free-falling from 510 mm, and a steel rod with a diameter of 15.88 mm [5]. Later in 1991, it was modified to a steel rod with a diameter of 16 mm, hammer weight of 8 kg, and falling height of 575 mm. To read the depth of penetration additional steel reading device is attached to the lower shaft of the apparatus. The diameter of the cone attached at the bottom end of the steel rod is greater than that of the steel rod to ensure resistance to penetration exerted on the cone [6].

2.1. Factors Affecting DCP Results

The study done on the effects of variables on the determination and operation of DCP shows that, for fine-grained soil density, classification, moisture content and confining pressure are the factors that affect the value of DCP. When the density of the soil increases the penetration index decreases, and with increases in moisture content the penetration index decreases. DCP values of the upper layer may be affected by vertical confinement [7-8].

Hassan [9] found that in-situ density, moisture content, confining pressure, and type of soil are the factors that can influence the rate of DCPI for fine-grained soils. As confining pressure rises, the DCPI declines for a given field density. At the field, moisture content fluctuates within the boundary of plastic limit and liquid limit. As the in-situ natural moisture content varies, the in-situ density also varies. This variation of moisture content and density of the natural soil results in an increase and decrease of the strength of the soil [10].

Recently, findings have investigated that varying plastic limits and liquid limits have resulted in significant changes in the shear strength of the soil. In addition to this, particle size and clay mineral content play a great role in shear strength mobilization. This indicated that consistency limits, particle gradation, and arrangement of the soil are highly influencing factors on the shear strength of the soil [11-12]. Many literatures have tries to clarify the relationship between unconfined compressive strength and liquidity index. They found that, there is a wide variation with fluctuation of liquidity index [11-13].

2.2. Prediction of Undrained Shear Strength

Depending on the results obtained from laboratory studies, many researchers conclude that DCPI values can be correlated to the unconfined compressive strength (UCS). A study found that DCPI and UCS have a strong association by establishing an equation, which is best suited to predict UCS, where DCPI is with a unit of inches/blows [7]. According to Mukesh [14], the relation between UCS of a subgrade, DCP, modified liquid limit, and moisture content is determined from regression analysis of results obtained from experimental investigation.

In Ethiopia, Alemayehu [15], found that there is a good relationship between field DCP and UCS around Alemgena town in Ethiopia. The study established correlation equations for red and black soils. The study done in Addis Abeba for fine-grained soils observed that UCS can statistically be correlated to DCPI with a coefficient of determination of 0.711, and 0.524 for red and black clay soils respectively as shown in Table 1 [16].

Temnit concluded that the unconfined compression strength (UCS) is highly influenced by DCPI, bulk unit weight and natural moisture content (NMC), and liquidity Index (LI) [17]. Another research done in our country revealed that UCS is significantly influenced by DCP and Liquidity index. The prediction equations are obtained for red and black soils in Debre Markos soil [18].

Table 1: Equations developed by previous works

Researcher	Developed equation	Soil type	R^2
Alemayehu [15]	$UCS = -24.56*\ln(DCPI) + 223.05$	Black clay	0.805
	$UCS = -58.59*\ln(DCPI)+308.04$	Red clay	0.831
Anteneh [16]	$UCS = -197\ln(DCPI) + 735.5$	Red clay	0.711
	$UCS = 895.8*DCPI^{-0.56}$	Black clay	0.524
Fitsum [17]	$UCS = -209.5*\ln(DCPI) + 800.5$	Red clay	0.802
	$UCS=-7.1661*(DCPI) +416.82$	Black clay	0.821
Gediyon [18]	$UCS = -115.59*\ln(DCPI) +456.41\ LI + 645.70$	Black clay	0.676

3. Experimental study

3.1 Description of study area

The experimental testing program was conducted in Jimma city, which is located at an elevation of 1780 m above sea level, found in Oromia regional state, Ethiopia. Jimma is known for its humid climate with high precipitation; warm temperature and mean annual rainfall of 1500 mm and annual evaporation of 1456 mm. reddish-brown residual soils and alluvial soils (brownish-gray and grayish-white clay) are the two types of soils are found abundantly in the town.

3.2 Sample preparation, Test Procedures and Data analysis

3.2.1 Sample preparation

After in-depth visual observation, test pit locations are selected in the town. At the field, DCP, natural moisture content, and sand replacement test for field in-situ density were carried out. The samples were taken for unconfined compressive strength using Shelby tube and extracted in the laboratory. In the laboratory, sieve analysis, atterberg limits, compaction, and UCS tests were carried out. The laboratory tests were performed in Jimma Institute of Technology Geotechnical Laboratory.

3.2.2 Test Procedures

DCP test was carried out to determine the in-situ soil strength according to ASTM-D6951-3 standard procedure on existing subgrade at in-situ density and natural moisture. The DCP test instrument consists of the steel rod with 16 mm diameter on which steel cone with 20 mm base diameter and 60^0 point angle is attached at the bottom with a free-falling hammer with 8 kg from a height of 575 mm with due care. DCPI is determined as the average ratio of penetration in mm to the number of blows. The dynamic cone penetration index (DCPI) obtained from the field was varies from 12.2 to 58.8 which differs from place to place.

Based on the ASTM D1140-97, the wash method or wet sieve analysis was conducted to determine the particle size analysis. The Casagrande method was employed to determine the liquid limit of the soil as per ASTM D 4318, while the plastic limit was taken as moisture content of the soil rolled on a glass plate until the treads reach 3 mm in diameter. Using the results of these laboratory tests soil classifications were performed according to both AASHTO and USCS standards.

A modified compaction test was carried out to determine the maximum dry density and optimum moisture contents of the soil according to ASTM D 1557 procedure.

3.2.3 Data analysis

The laboratory results obtained during the investigation were analyzed using correlation and regression analysis. The data variables are classified into two as dependent and independent variables. The normality of the data obtained from laboratory and field tests was analyzed using SPSS software for normality to check the normality of the data. Depending on the significance value of Shapiro-Wilk, the data with significance greater than 0.05 are taken as normal data. Accordingly, for this study, the significance value of the Shapiro-Wilk Test is greater than 0.05, which shows that the data are normally distributed.

The correlation coefficient of correlation between UCS and DCP was observed. The correlation analysis shows that the coefficient of correlation between UCS and DCP was high indicating that there is a good relationship between the two variables. Taking the confidence level for the statistical analysis as 95%, the p-value of the correlation between UCS and DCPI is less than 0.05, which indicates that there is strong evidence for the correlation.

3.3 Summary of the test results

According to the AASHTO classification system, the soils were classified as A-7-5 and A-7-6, which are clayey soils, while the soil fails under CH and MH according to USCS classification. This implies that the soils of the study area are highly clayey fine-grained soils. The liquid limit value of soil samples considered for this study ranging from 93.5 up to 56. Whereas plasticity limit value ranges from 24 up to 51, and plasticity index values of 24% up to 58.5% were obtained.

Using the data obtained during compaction tests, compaction curves were drawn to show the peak MDD and OMC values. The result obtained from the laboratory varies from 1.36 to 1.48 g/cm3 for maximum dry density and from 23.6 % to 30.6 % for optimum moisture content. From CBR data analysis, it has been observed that the ranges of UCS values for these ranges from 1.25 % to 10.5%. The dynamic cone penetration index (DCPI) obtained from the field was varies from 12.2 to 58.8 which differs from place to place. The summary of the laboratory and field tests is presented in Table 2.

Table 2: Summary of the field and laboratory test results

Test	Range of values
Maximum dry density (g/cc)	1.36- 1.48
Optimum moisture content (%)	23.6 – 30.6
Liquid limit (%)	56 – 93.5
Plastic limit (%)	24 - 51
UCS (%)	1.25 – 10.5
In-situ density (kN/m3)	9.12 – 12.98
Natural moisture content (%)	35 - 59
DCPI (mm/blows)	12.2 -58.8

3.4 Statistical Analysis

In this study, the data collected from field and laboratory tests were summarized using descriptive statistics. Quantitative data analysis method was followed as evaluation criteria in developing regression models to predict unconfined compressive strength. Statistical software for social science (SPSS) was used in performing statistical analyses and model development. The correlation coefficients were obtained using Pearson correlation to evaluate the relationship between variables. In this study, the variables having p-value less than 0.05 were taken as significant.

3.4.1 Scatter plots

The relationship and strengths between variables can observed from a critical section called scatter plots. In developing correlations, it is the first step is creating a scatter plot of the data, to visually assess the strength and form of relationship between the variables. If the points are very close to each other, a good amount of correlation can be expected between the two variables. The scatter plots of UCS versus other independent variables are shown in Fig. 1 to Fig. 7.

As show in Fig. 2, the relationship between UCS and DCPI is examined with logarithmic type, and it has been observed that there is a strong relationship between these variables as the points are very close to the trend line.

The scatter plots of unconfined compressive strength with dynamic come penetration index and other influencing factors are shown on Fig. 1 up to Fig. 7. The coefficients of determination of the associations are significant showing that DCPI have a strong relationship with these factors.

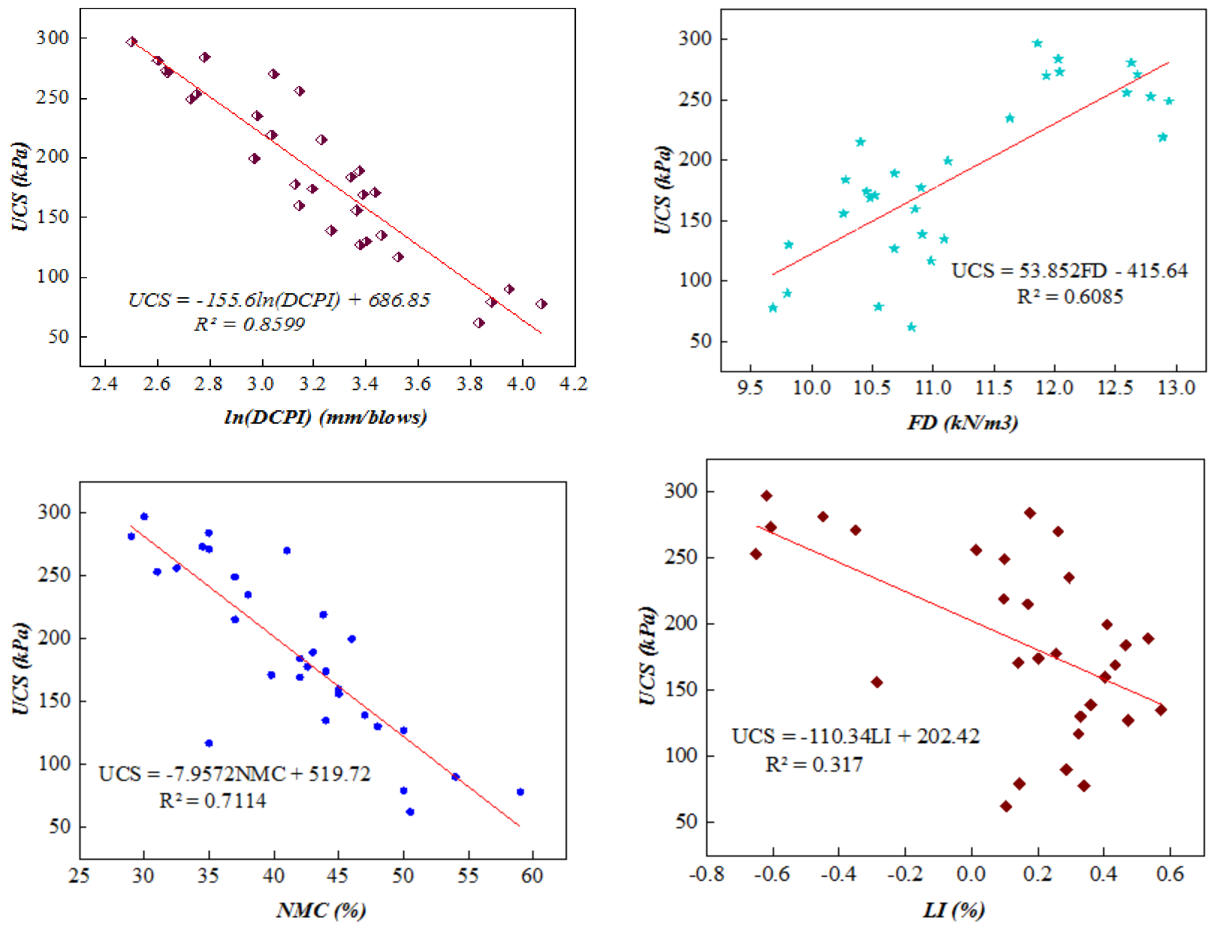

Figure 1: Scatter plots of UCS against DCPI, FD, NMC, and LI

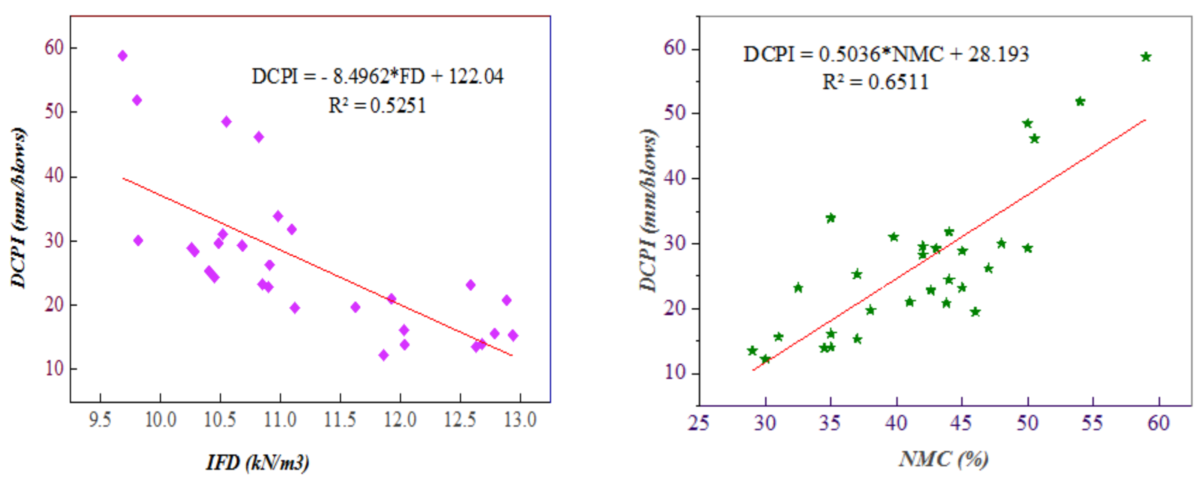

Figure 2: Scatter plots of DCPI against FD, and NMC

3.3.2 Simple linear regression analysis

Linear regression analysis was used to formulate the predicting equation. Simple linear regression was performed to establish the model equation used to predict UCS from factors that highly affect the variable. Multiple linear regression analysis was carried out to evaluate the impacts of various simultaneous factors on dependent variable (UCS). Finally, the developed model was evaluated using the coefficient of determination (R^2).

The results of simple linear regression is summarized in Table 3. The significance and model fitting of the developed equation between dependent variable (UCS) and independent variables (DCPI, FD, NMC, LI) are investigated by R^2 value. The coefficient of determination for correlation of UCS with DCPI, FD, NMC, and LI are 0.855, 0.6085, 0.711, and 0.317 respectively. This indicates that the relationship of unconfined compressive strength with dynamic cone penetration index, field density and natural moisture content is strong and that of LI is weak. This shows the reliability of DCPI to predict undrained shear strength of cohesive soils than conducting the labor intensive, costy and time consuming UCS test. In addition to DCPI, it have been observed that field density, and natural moisture content are the variables influencing the values of UCS.

Table 3: summary of simple linear regression analysis

Dependent variable	*Independent variable*	*Developed equations*	*R2*
UCS	DCPI	UCS = -155.6*ln(DCPI) + 686.85	0.8599
	FD	UCS = 53.85*FD - 415.64	0.6085
	NMC	UCS = -7.957*NMC + 519.72	0.711
	LI	UCS = -110.34*LI + 202.42	0.317

In addition to that of UCS, the effects of in-situ soil parameters on dynamic cone penetration index has been evaluated. The result shows that the effects of field density and natural moisture content are significant since field density and natural moisture content are correlated to DCPI with coefficient of determination of 0.525 and 0.652 respectively.

3.3.3 Multiple linear regression analysis

While developing prediction equation using multiple linear regression, adjusted R-square and significance of the variables are analyzed. The interdependency of the independent variables is analyzed using variance inflation factor (VIF) value. Variance inflation factor shows the ratio of overall model variance to the variance of a model that includes only the single independent variable.

After deep analysis, the independent variables that significantly contributes to the prediction of unconfined compressive strength are dynamic cone penetration index and liquidity index. The significance value and collinearity of the variables was checked. The significance value of the model is 0.000, and adjusted R^2 = 0.81, indicating that the model can predicts the UCS in better way. The result shows VIF value is 1.27, which indicates the interdependency between DCPI and LI is very weak. The following model equation was developed in multiple linear regression analysis.

$$UCS = 319 - 4.72\,DCPI - 38.0\,LI,$$

Where, Adjusted R-square = 0.81, significance = 0.000, and VIF = 1.27.

4. Validation

It is not recommended to use the developed equations directly with out evaluating for validation.
The developed equation was evaluated using six control samples tests. The control test evaluation results indicated that the variations between the actual control test results and the predicted UCS values are minimum. This shows that Unconfined compressive strength of fine grained soil can be predicted from the developed equation.

Both equation developed using simple linear regression and multiple linear regression was evaluated depending on the control test values. The variations between the actual values of UCS and the predicted values using the developed models were observed. According to the result of prediction models (Model 1 and Model 2), the variation of the Model-1 and model-2 are within ranges of 8 % - 19 % and 9 % – 19 % respectively.

Model-1: $UCS = -155.6 \cdot \ln(DCPI) + 686.85$

Model-2: $UCS = 319 - 4.72\,DCPI - 38.0\,LI$

Table 4: Comparison of Actual and predicted UCS values

Control test	**Actual values**			**Model-1**	**Model-2**
	UCS (kPa)	DCPI (mm/blows)	LI %)		
1	125.7	31.5	0.528	150.0	150.3
2	103.5	46	0.267	91.1	91.7
3	246	14.8	-0.565	267.6	270.6
4	130.6	32.8	0.417	143.7	148.4
5	168.4	25.1	0.409	185.4	185.0
6	214.9	17.6	0.100	240.6	232.1

The comparison between the laboratory Unconfined compressive strength and the UCS values obtained from prediction models are shown in Table 4. Graphically, the variations are shown in Figure 4.

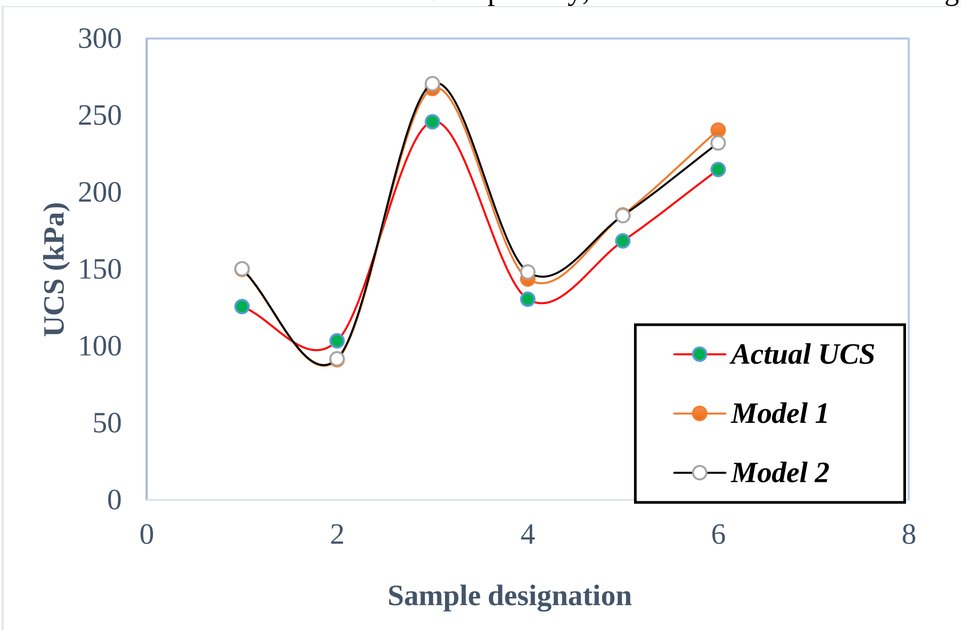

Figure 4: Comparison of Actual and predicted UCS values

5. Conclusion

The objective of this study is to introduce the application of dynamic cone penetration to predict the undrained shear strength of the soil in study area. Field dynamic cone penetration , unconfined compressive strength, density and natural moisture content tests and laboratory atterberg, compaction and grain size analysis tests were carried out. Data obtained from laboratory and field tests are analysed using simple and multiple linear regression. The following conclusions were made:

- The unconfined compressive strength is highly influenced by the field condition i.e. UCS is strongly correlated to dynamic cone penetration index (DCPI), field density (FD), natural moisture content (NMC) and slightly to liquidity index (LI).
- The study come up with two prediction models. Model-1 is developed using simple linear regression between UCS and DCPI. The logarithmic equation with R^2 value of 0.86 is selected. Model-2 developed from multiple linear regression analysis between UCS and the factors that highly affects the dependent variable. After indepth analysis by checking for multicollinearity, and significance values the equation with high R^2 value is choosed. The selected equation correlates UCS to DCPI and liquidity index.

Model-1: $UCS = -155.6*\ln(DCPI) + 686.85 \quad R^2 = 0.86 \quad signif. < 0.05$

Model-2: $UCS = 319 - 4.72\ DCPI - 38.0\ LI \quad R^2 = 0.81 \quad signif. < 0.05$

- The developed models are validated using control tests which are not included in raw data for model fitting. Small variations are observed between the actual laboratory values of UCS and the predicted values from established equations.

Recommendation

- The study recommends that, the developed equations are best suited to the study area. However, since both UCS and DCP are dependent on material properties and field conditions, the equations should be used with cautions.
- In addition to this, the study considers all types of soils found in the town. So that it is recommended that it is better if more researches are done on different types of soils by increasing the sample sizes.

Conflict of interest

The authors report that there is no conflict of interests concerning this publishing

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