World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:7, 2016

A Statistical Model for the Geotechnical Parameters of Cement-Stabilised Hightown's Soft Soil: A Case Study of Liverpool, UK

Hassnen M. Jafer, Khalid S. Hashim, W. Atherton, Ali W. Alattabi

Abstract**—**This study investigates the effect of two important parameters (length of curing period and percentage of the added binder) on the strength of soil treated with OPC. An intermediate plasticity silty clayey soil with medium organic content was used in this study. This soft soil was treated with different percentages of a commercially available cement type 32.5-N. laboratory experiments were carried out on the soil treated with 0, 1.5, 3, 6, 9, and 12% OPC by the dry weight to determine the effect of OPC on the compaction parameters, consistency limits, and the compressive strength. Unconfined compressive strength (UCS) test was carried out on cement-treated specimens after exposing them to different curing periods (1, 3, 7, 14, 28, and 90 days). The results of UCS test were used to develop a non-linear multi-regression model to find the relationship between the predicted and the measured maximum compressive strength of the treated soil (qu). The results indicated that there was a significant improvement in the index of plasticity (IP) by treating with OPC; IP was decreased from 20.2 to 14.1 by using 12% of OPC; this percentage was enough to increase the UCS of the treated soil up to 1362 kPa after 90 days of curing. With respect to the statistical model of the predicted qu, the results showed that the regression coefficients (R2) was equal to 0.8534 which indicates a good reproducibility for the constructed model.

Keywords**—**Cement admixtures, soft soil stabilisation, geotechnical parameters, unconfined compressive strength, multi-regression model.

I. Introduction

DUE to the rapid development of urbanization, there is a significant increment for the demand of soil as a construction material. Thus, the looking for sustainable alternative materials such as soft soils after mitigate their geotechnical properties to be suitable for the use in different civil engineering projects has become an important issue [1]. Moreover, the most important parameters that should be improved in soft soil stabilisation are soil strength, volume stability and compressibility [2]. Chemical stabilisation is the most accepted method to mitigate the unwanted soil properties to meet the specification of engineering projects; this technique can be applied by mixing undesired soils with chemical binders which react chemically with water to bind the soil particles resulting in stronger soil structure [3].

H. M. Jafer, Postgraduate Research Student, Liverpool John Moores University, School of the Built Environment. He is also with the Department of Civil Engineering, Faculty of Engineering, University of Babylon, Iraq (e-mail: H.M.Jafer@2014.ljmu.ac.uk).

Khalid S. Hashim and Ali. W. Alattabi are PhD student in the School of The Built Environment, Liverpool John Moores University, UK. They are also with the Department of Civil Engineering, Faculty of Engineering, University of Babylon, Iraq.

Dr. W. Atherton BEng (Hons) PhD FHEA, Programme Leader, is with the Department of Civil Engineering, Liverpool John Moore's University, Peter Jost Enterprise Centre, Byrom Street, Liverpool, L3 3AF, UK.

It is undeniable that the Ordinary Portland Cement (OPC) is the most common binder material used in soil stabilisation due its activity to improve the physical and geotechnical properties of soft soils significantly, and there are plentiful number of researchers have treated soft soils using OPC as a binder material by employing different procedures of soil stabilization such as deep and surface mixing as indicated in [4]-[7].

Cement stabilisation is the classical method for chemical stabilisation which is attributed to the agglomeration and flocculation phenomenon take place within the soil structure for both of short and long term along with the hydration reactivity happens among the water, cement and soil particles. The hydration reaction produces cementitious compounds which are called either calcium-silicate-hydrated (C-S-H) or calcium-aluminium-hydrated (C-A-H) dependant on the available type of pozzolanic compound in the treated soil and these cementitious compounds are responsible to improve soil properties and increase the soil strength [8]. However, cement stabilisation technique is very complex and it can be influenced by several aspects such as the existence of foreign materials such as the organic matter, the amount of natural moisture which affects the water-cement ratio, the percentage of the cement added to the stabilised soil and the curing condition such as the degree of temperature and the curing period [9]. The development in the strength of stabilised soil is dependant mainly on the physical and chemical properties of the treated soil and the type of its minerals. The experimental works conducted to measure the compressive strength of cement-stabilised soil is very essential to predict the sin-situ soil strength after treating with cement. However, the effect of the cement type on the improvement process was ignored in this study since it was proven that it has limited influence [10].

This paper focuses on the investigation of geotechnical properties of cement-stabilised soft soil with different percentages (0, 1.5, 3, 6, 9, and 12%) of the dry weight and cured for different periods of curing with short and long periods (1, 3, 7, 14, 28, and 90 days). Additionally, this paper presents the development of a statistical model using multi-regression modelling to evaluate the relationship between the measured and the predicted of UCS value using SPSS program. The effect of OPC treatment on the consistency limits and the compaction parameters of the stabilised soil in this study were also investigated.

II. Materials

A. Soil Sample

The treated soil was exported from the bank of the River Alt which is located in Hightown to the north of Liverpool in the UK. This type of soil covers a very large area of the Hightown as well as the coastal area of the river which can be used as full materials in different construction projects. Fig. 1 shows the maps of Liverpool and the corresponding site where the soil samples used in this study were extracted.

Table I illustrates the main physical and chemical of the soft soil used in this study. It can be seen that the soil is composed from 13.08% sand, 43.92% silt, and 43.0% clay. Liquid limit (LL) and IP were measured and they were found to be equal to 44 and 20.22 respectively. From values of the parameters illustrated in Table I and according to the Unified Soil Classification System (USCS), the soft soil used in this study is an intermediate plasticity silty clay with sand (CI).

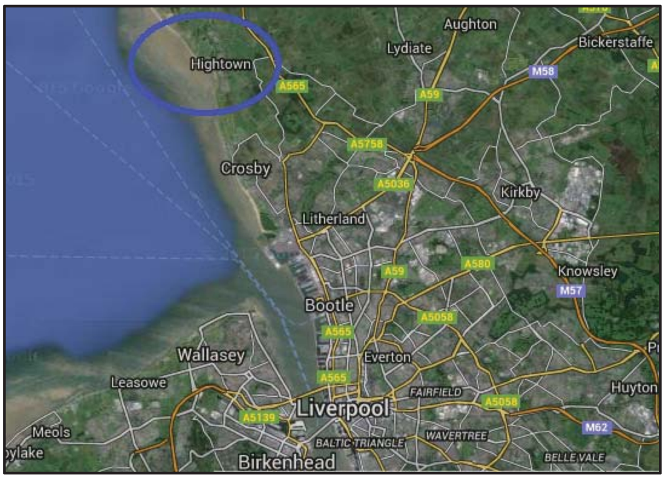

Fig. 1 Satellite images of the site of extraction of the soft soil used in the study

TABLE I
Main Physical and Engineering Properties of the Soft Soil

Property	Value
Natural Moisture Content %	36.8
LL %	44
Plasticity Index (PI)	20.22
Sand %	13.08
Silt %	43.92
Clay %	43.00
Maximum Dry Density (MDD) g/cm^3	1.57
Optimum moisture content (OMC) %	23
pH	7.78
Organic Matter Content %	7.95
Unconfined Compressive Strength for Undisturbed Soil qu (kPa)	66.46

g/cm^3= gram/cubic centimeter, kPa = kilopascal.

B. OPC

The OPC used in this study was a commercially available cement type CEM-II/A/LL 32.5-N and it was brought from Cemex Quality Department, Warwickshire, UK. Fig. 2 shows the particle size distribution curve of the OPC used in this study which was obtained from using the laser particle analyser. The major oxides of the used OPC are listed in Table II which were measured by conducting the X-Ray Florescence Spectrometry test (XRF).

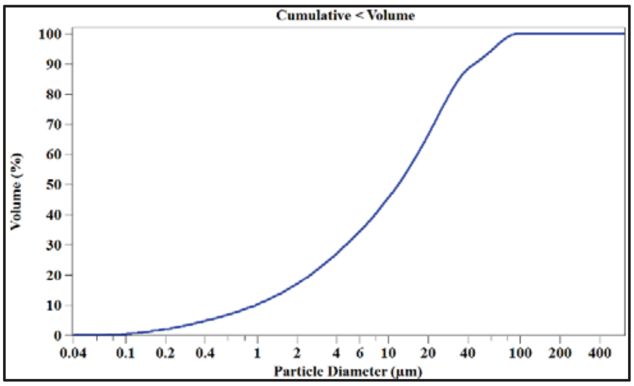

Fig. 2 Particle size distribution curve of the cement used in this study

From Fig. 2, it can be seen that the particles of the OPC used in this study are ranging between 0.1 and approximately 50 micrometres which would enhance the pozzolanic reactivity between cement and soil particles and this increases the production of the cementitious compound which develop the soil strength. Additionally, the fine particles of additives fill the voids in soil body which decrease the soil permeability and this improve the soil property against the swelling and shrinkage stresses [3].

TABLE II
Main Oxides in the OPC Used in the Study

Oxide Symbol	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3
Percentage (%)	66.12	24.91	1.73	1.67	1.32	2.66

C. Statistical Program

A multi regression functional of the statistical program SPSS-23 was used in this study. The results of UCS test was utilised in this program to find a relationship between the measured and predicted q_u of the soil treated with different percentages of OPC and exposed to different curing period. SPSS was used to develop a new statistical model to evaluate UCS dependant on two factors (percentage of the added cement and the length of curing period)

III. Experimental Works

A. Methodology

After the identification of the materials used in this study, soil samples were air dried then pulverised to small particles using wooden hammer to be ready for experimental works. The investigated geotechnical parameters of the cement-stabilised soil used in this study were compaction parameters (MDD and OMC) which were determined by conducting the standard Proctor test, the consistency limits (LL, plastic limit

(PL) and IP), and UCS to measure the maximum soil strength q_u. Fig. 3 shows the flow chart of testing regime conducted in this study.

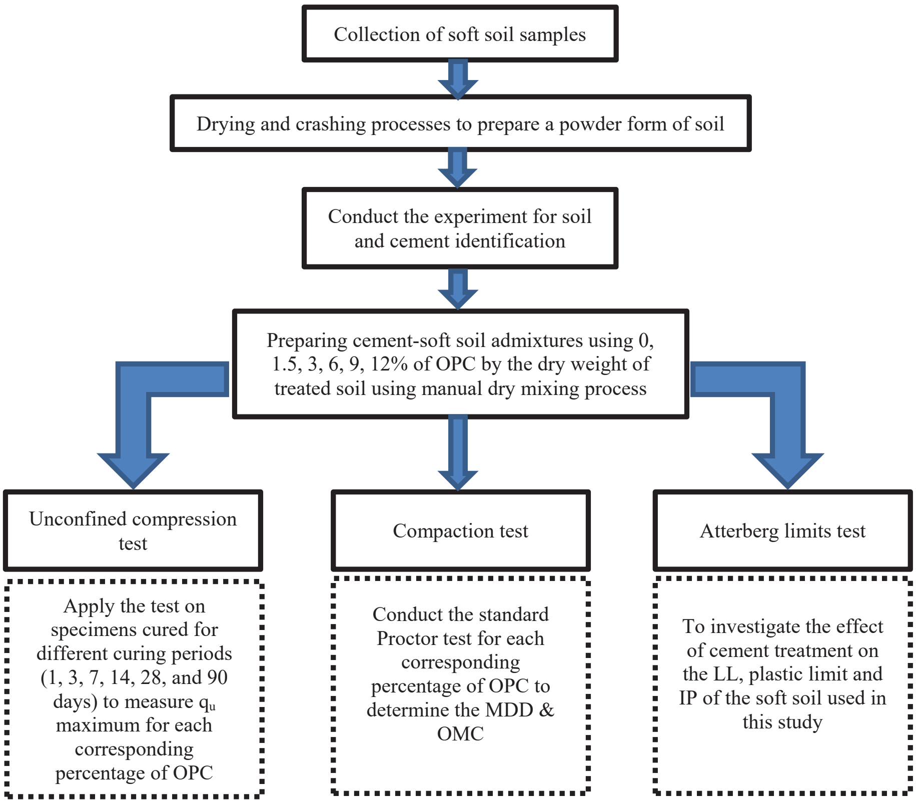

Fig. 3 Flow chart of testing regime adopted in the study

B. Samples Preparation and Testing Conditioning

The samples for both consistency limits and compaction parameters tests were prepared by mixing different percentages of OPC with the soft soil manually. The mixing process was continued for approximately 5 minutes until getting a homogeneous colour for the mixture, then the tests were conducted after adding the tab water to the mixture immediately. LL test was conducted by falling cone method using cone penetrometer apparatus according to the British standard BS 1377-2:1990 [11]. The compaction test was conducted using standard Proctor test method to measure the MDD and OMC for each corresponding percentage of OPC in accordance with British standard BS 1377-4:1990 [12].

The specimens of UCS test were prepared by pressing the soil-cement paste in fixed volume mould using manual hydraulic jack to produce specimens with standard dimension (36 mm in diameter and 76 mm in height) as shown in Fig. 4. Then the specimens were labelled and wrapped with cling film, then stored in humidity cabinet for curing under 20±2°C in temperature and 100% humidity. UCS test was conducted using a triaxial testing machine by maintaining the lateral pressure to be equal to zero and in accordance to British standard BS 1377-7:1990 [13].

Fig. 4 Preparing of UCS test specimens

IV. Results and Discussion

A. Results of Experimental Works

The effect of cement stabilisation on the compaction parameters of the soil treated in this study is shown in Fig. 5. It can be seen that the MDD decreased and the OMC increased with the increase of the amount of the added cement to the soil. This is attributed to the flocculation and the agglomeration took place between clay particles in the soil and cement. Fig. 6 shows the relationship between the added percentage of OPC and the consistency limits of the stabilised soil. It can be seen that the value of LL increased fist with increase of OPC percentage up to 6% then staid constant for 9% then started to decrease slightly with the use of 12% OPC. On the other hand, significant increments were observed with respect to PL for the soil treated with OPC up to 9% then there was also slight decrease for 12% OPC. These differences in the rates of increments for LL and PL led to significant decrease in IP which decreased from 20.2 for untreated soil to 14.1 by using 12% of OPC.

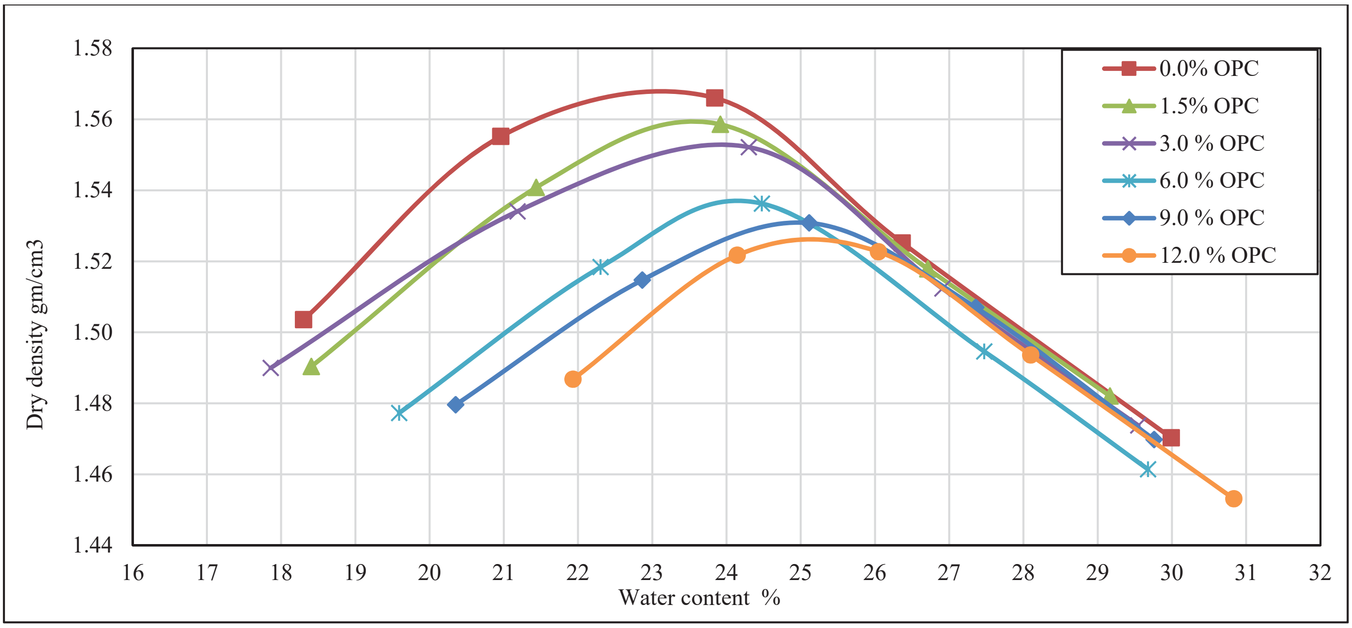

Fig. 5 Compaction parameters curves for the soil treated with OPC

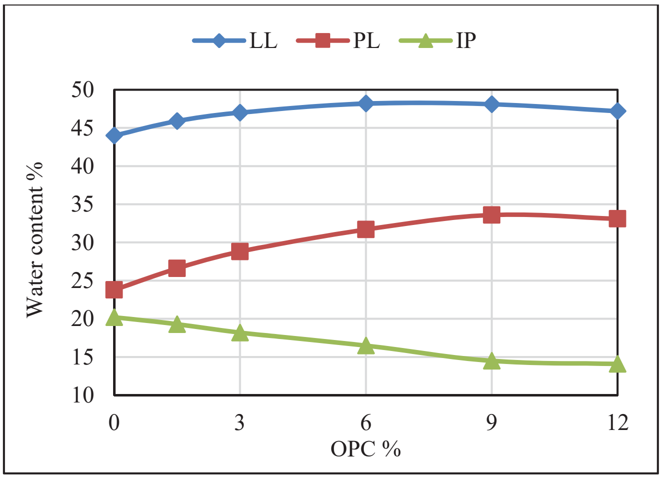

Fig. 6 Effect of OPC on the Atterberg limits

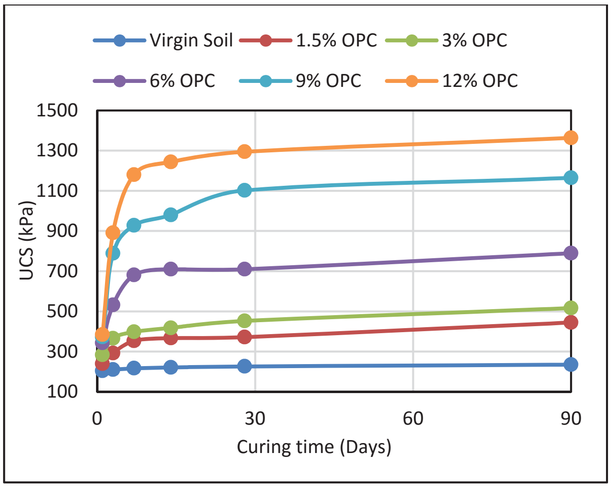

Fig. 7 Development of UCS for the soil treated with OPC

The maximum values of UCS of the soft soil specimens treated with different percentages of OPC and exposed to different lengths of curing periods are shown in Fig. 7. The results of UCS test indicated that soil strength was improved significantly especially for the OPC percentages beyond 6%. However, no significant improvement in UCS were observed for curing period longer than 28 days for all percentages of OPC. Overall, the UCS of the soft soil used in this study was improved significantly with the cement treatment when it increased from 200kPa for untreated soil to 1364kPa with the use of 12% OPC and after 90 days of curing.

B. Development of the Statistical Model

The current section of work concerns the development of a statistical model depending on the obtained results from experimental work. This model has been developed using multiple regression technique. The latter can be defined as pack of techniques that helps to develop a relationship between a dependent variable with set of independent variables [14]. In fact, multiple regression technique is not applicable for small sets of data and there more than one key assumption must be check before performing this technique where, [15] recommended the following formula to calculate the minimum required data size:

$$S > 50 + 8V \quad (1)$$

where S and V are data size and number of independent parameters, respectively.

Construction of a multiple regression model must be passed through the following steps [14]:

1- Check the main assumptions of the multiple regression model, which include the presence of multicollinearity, outliers, normality, linearity, and homoscedasticity of residuals. The presence of these parameters negatively influences the reliability of the constructed model.
2- Evaluating the constructed model.
3- Check the statistical significance of the independent variables.

In order to check the mentioned assumptions and to develop a reliable multiple regression model, SPSS-23 and Excel software were used.

Initially, the minimum required data points were checked using (1); this assumption has been met as 108 data points has been used in the current statistical analysis, while the required points are 66 (two independent variables were used). Then, the presence of the multicollinearity has been checked by determining the tolerance value (Table III) where, [14] recommended that the multicollinearity presents within the studied data when the tolerance value is less than 0.1. Thus, the multicollinearity is not present as the tolerance value of the collected data was 1.0. The presence of outliers in the experimental data was examined by determining the Mahalanobis distances, which must be less than 13.82 (for two independent variables) [14], the maximum Mahalanobis distances in the present investigation was 7.04 that indicate the absence of outliers within the collected data. Finally, the existence of normality, linearity, and homoscedasticity of residuals (all these parameters are related to the distribution of data points) was investigated by examine the normal distribution of data, where 99% of the standardised residuals must be within the range of 3.0 to -3.0 [14]. The obtained results showed that less than 1% of the studied data were exceeded the mentioned range.

TABLE III
RESULTS OF THE STATISTICAL ANALYSIS

Parameter	Tolerance	Max. Mahalanobis Distance	R2	Adjusted R2	Standardized residual		Beta	Sig.
					Max.	Min.		
Age	1.000	13.82			1.65	-3.1	0.272	0.000
OPC	1.000		0.853	0.849			0.883	0.000

The following model has been developed, using SPSS-23, depending on the experimental data:

$$USC = 138.63 + OPC * 74.29 + Age * 3.122 \quad (2)$$

The second step that includes evaluation of the constructed model, is step examine the ability of the model to explain the relationship between the dependent variable and the independent variables. Coefficient of determination (R^2) is efficient tool to evaluate the constructed model, where the higher the R^2 (close to 1), the higher the accuracy of the regression model [15]. The obtained results from the statistical analyses, Table III, showed that the R^2 value was 0.85, which is an acceptable value [14].

Finally, the contribution of each independent variable to the constructed model has been investigated by calculating its statistical significant (*Sig.*) and *Beta* value. The term *Sig.* indicates whether the studied independent variable contributes to the model or not, any independent variable with *Sig.* value more than 0.05 will not contribute to the model, but it play an important role in the prediction process when its *Sig.* value is less than 0.05 [14]. While *Beta* value indicates the relative importance of each independent variable within the constructed model, the higher the *Beta* value, the higher relative importance [14]. According to the results of Table III, all the studied parameters significantly contribute to the constructed model, as their *Sig.* values are less than 0.05. At the same time, it can be seen that the OPC (independent variable) plays the most important role in the model as its *Beta* value is about three times that of age. Fig. 8 shows high correlation between the obtained predicted results, using the model, and the experimental ones, where it can be seen that the R^2 value is about 0.85.

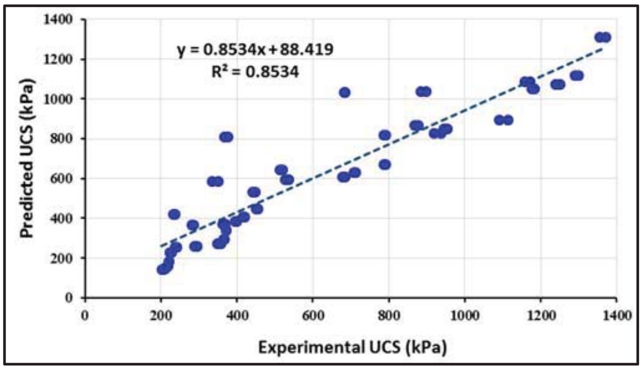

Fig. 8 Experimental UCS vs Predicted UCS

V. CONCLUSIONS

This study evaluates the geotechnical parameters of cement-stabilised soft soil through conducting the experimental works for compaction parameters, consistency limits and UCS. Additionally, this paper provides a statistical model to predict the compressive strength of the stabilised soil for different percentages of OPC and lengths of curing period dependant on the measured data from the experiments. According to the findings of this research study, the following conclusions can be drawn:

- The results of compaction test indicated that MDD decreased with increase of the added percentage of OPC.

On the other hand, the OMC increased with the increase of OPC due to the increase of water demand for cement hydration.

- Cement stabilisation was found very effective to improve Atterberg limits of Hightown's soft soil. Both of LL and PL increased with increase of OPC but the increments occurred in LL were less than those for PL, thus the values of IP decreased which lead to enhance the soil strength against the stresses of swelling and shrinkage. Overall, IP was decreased from 20.2 to 14.1 by using 12% OPC.
- The results of UCS test indicated an increase in the soil strength with continuous increase in OPC as well as in the increase of curing time. Additionally, the results of UCS test revealed that there was clear development in the soil strength beyond 6% of OPC. However, the most of the developments gained in soil strength were achieved between 14 and 28 days of curing.
- With respect the early age strength (1 and 3 days) the results indicated that significant improvement was achieved for soil treated with 6% and above of OPC.
- The constructed model showed a very good reproducibility with R^2 of 0.85. In addition, the comparison between the predicted and the experimental results indicated that the constructed model can be reasonably applied to explain the influences of the OPC and the length of curing period on the UCS, which in turn enables the users to design new mixtures, using the mentioned materials, without the need for experimental work.

ACKNOWLEDGMENT

The first (corresponding), second and fourth authors would like to express their acknowledgment to the Iraqi ministry of high education and scientific research, the University of Babylon - college of engineering/Babylon – Iraq, and the University of Wasit-Faculty of engineering/ Wasit - Iraq for the financial support for this study. Also, the first author would like to express his deep gratitude to the third author (Dr. William Atherton) for his supervision and support for this work.

REFERENCES

[1] Sariosseiri, F. & Muhunthan, B. 2009. Effect of Cement Treatment on Geotechnical Properties of Some Washington State Soils. *Engineering Geology* 104 (1-2): 119-
[2] Modarres, A., and Nosoudy, Y. M. (2015) Clay Stabilisation Using Coal Waste and Lime – Technical and Environmental Impact. *Applied Clay Science*, pp. 1-8.
[3] Jafer, H. M., Atherton, W., Ruddock, F. M. & Loffil, E. 2015. Assessing the Potential of a Waste Material for Cement Replacement and the Effect of Its Finennes in Soft Soil Stabilisation. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 9(8), 794-800.
[4] Jauberthie, R.; Rendell, F.; Rangeard, D. and Molez, L. 2010. Stabilisation of estuarine silt with lime and/or cement. Applied Clay Science, 50, 395-400.
[5] Farouk, A. and Shahien, M. M. 2013. Ground improvement using soil–cement columns: Experimental investigation. *Alexandria Engineering Journal,* 52**,** 733-740.
[6] Onal, O. 2014. Lime Stabilization of Soils Underlying a Salt Evaporation Pond: A Laboratory Study. Marine Georesources & Geotechnology, 33, 391-402.
[7] Rios, S.; Cristelo, N.; Viana da Fonseca, A. and Ferreira, C. 2016. Structural Performance of Alkali-Activated Soil Ash versus Soil Cement. Journal of Materials in Civil Engineering, 28, 04015125.
[8] Makusa, G. P. 2012. Soil Stabilization Methods and Materials in Engineering Practice. Luleå, Sweden: Luleå University of Technology.
[9] Eskisar, T. (2015). "Influence of Cement Treatment on Unconfined Compressive Strength and Compressibility of Lean Clay with Medium Plasticity." Arabian Journal for Science and Engineering 40(3): 763-772.
[10] Ahnberg, H., S. E. Johansson, H. Pihl, and T. Carlsson "Stabilising effects of different binders in some Swedish soils". Ground Improvement, Vol. 7, pp 9-23, 2003.
[11] British Standard 1990a. BS 1377-2:1990, Methods of test for soils for civil engineering purposes - Part 2: Classification tests. London: UK: British Standard Institution.
[12] British Standard 1990b. BS 1377-4-1990, Methods of test for Soils for civil engineering purposes - Part4: Compaction-related tests. London: UK: British Standard institute.
[13] British Standard 1990c. BS 1377-7-1990- methods of test for Soils for civil engineering purposes - Part 7: Shear strength tests (total stress). London: UK: British Standard institute.
[14] Pallant, J. (2005). SPSS Survival Manual. Australia, Allen & Unwin.
[15] Tabachnick, B. G. and L. S. Fidell (2001). Using Multivariate Statistics. Boston, Allyn and Bacon.