Developed strength and engineering properties of stabilized organic soil using chemical admixture: A linear regression model

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
This study illustrates the developed strength and engineering properties of stabilized soils using chemical admixtures at varying curing periods. Organic soil samples were collected from four selected locations, namely, Teligati, Rangpur, Sonadanga and Khulna University campus, Bangladesh at a depth of 3, 2.5, 2 and 4 m, respectively, from the existing ground surface. Chemical admixtures such as cement, lime and bentonite were added to the organic soil specimens as a percentage of the dry soil mass at 5, 10, 15, 20 and 25 %. To check the validity of unconfined compressive strength (q_u) measured in the laboratory, SPSS 16.0 software was used to develop a linear regression model. The reliability and accuracy of the developed model were checked by comparing the predicted q_u against the measured values. Based on the regression analysis, R^2 values ranging from 0.909-0.984, 0.536-0.930 and 0.726-0.965 were observed for cement, lime and bentonite stabilized soil, respectively. Finally, the predicted q_u from the developed model was found to be nearly the same as the laboratory measured value and the degree of accuracy was more reliable.

RÉSUMÉ
Cette étude illustre la résistance développée et les propriétés d'ingénierie des sols stabilisés à l'aide des adjuvants chimiques à des périodes de durcissement variées. Des échantillons de sol organiques ont été recueillis auprès de quatre emplacements choisis, à savoir, Teligati, Rangpur, Sonadanga et le campus de l'Université de Khulna, au Bangladesh, à des profondeurs de 3, 2,5, 2 et 4 m respectivement. Des adjuvants chimiques, tels que le ciment, la chaux et la bentonite ont été ajoutés aux échantillons de sols organiques en tant que pourcentage de la masse du sol sec à 5, 10, 15, 20 et 25%. Pour vérifier la validité de la résistance en compression simple (qu) mesurée en laboratoire, le logiciel SPSS 16.0 a été utilisé pour développer un modèle de régression linéaire. La fiabilité et la précision du modèle développé ont été vérifiées en comparant la qu prédite avec les valeurs mesurées. En se basant sur l'analyse de régression, des valeurs de R2 allant de 0,909 à 0,984, 0,536-0,930 et 0,726 à 0,965 ont été observées pour le ciment, la chaux et la bentonite respectivement. Enfin, la qu prédite à partir du modèle développé est presque la même que la valeur mesurée au laboratoire et le degré de précision est plus fiable.

1 INTRODUCTION

Civil engineering projects located in areas with unsuitable soils is one of the most common problems in many parts of the world. Organic soils are well known for their low shear strength, high compressibility as well as high swell-shrinkage characteristics. Thus, they are inappropriate for building foundation or for other geotechnical works (Islam et al. 2013). The typical method to stabilize soils is to remove the unsuitable soil layer and replace it with a stronger civil engineering material. The high cost of this method has driven researchers to look for alternative methods and one of these methods is the process of soil stabilization (Kolias et al. 2005; Mleza and Hajjaji 2011). Soil stabilization is a technique introduced many years ago primarily to render the soils capable of meeting the requirements of the specific civil engineering projects. In addition, when the soils at a site are poor or when they have undesirable properties making them unsuitable for use in a geotechnical projects, they may have to be stabilized. In the last two decades, scientific techniques of soil stabilization have been introduced (Rogers et al. 1997).

Khulna is the third largest metropolitan city in Bangladesh, situated at the southwestern part of the country, near the world largest mangrove forest, Sundarbans. The sub-soil of this region consists of fine-grained soils with a considerable content of decomposed and semi-decomposed organic matter (Alamgir et al. 2006, Islam et al. 2009). To quantify the effect of such organic deposition on the adopted foundation system, it is required to establish the behavior of organic contents with the soil parameters of the stabilized organic soil (Islam et al. 2007). Moreover, in this region, the soft soil deposits extend to a considerable depth as a result of the recent alluvial deposits with organic composition that create problems for geotechnical engineers in designing economical foundations to construct the required infrastructure (Hasan and Islam 2013). Due to the presence of thick organic soil layers, the civil engineering construction in this region requires special attention to protect against possible shear failure as well as total and differential settlement. The term "organic soil" is used for describing soils with an organic content or soils that contain organic matter (Bujang et al. 2009; Tahia et al. 2012; Islam et al. 2013). Organic soil represents the extreme form of soft soil deposits and it is subjected to instability, shear failure and long term settlement.

Stabilizing of organic soil by adding admixtures always changes the physical and engineering properties of soil (Sharma et al. 2008). The quality of stabilized soil using different admixtures is affected by the quantity and type of admixture, soil moisture content, mixing and compaction method, curing time, temperature and soil minerals (Haut 2004; Islam et al. 2012). Because of the aforementioned parameters, a significant deviation between the laboratory measurements of the unconfined compressive strength of stabilized soils and the corresponding unconfined compressive strength from in-situ specimens is usually observed. Furthermore, the addition of admixture with soil, the water content of the stabilized soil decreases with the increase of the admixture content and the curing period (Costas and Chatziangelou 2008). The physical and mechanical properties of stabilized soils depend on several factors, mainly the properties of the base material and the environmental aspects (Hossain 2011).

In addition, for checking the validity of q_u of different stabilized soils measured in the laboratory, SPSS 16.0 software was used to develop a linear regression model. For developing this model under laboratory conditions the parameters of water content, w (%), liquid limit, w_L (%), cement content, C (%), lime content L (%), bentonite content, B (%), sand content, S (%) and curing time, CT (days) which strongly affect its value were considered. Model shows high values of regression coefficient (R^2) and the comparative assessment indicates that the developed model provides a very good agreement with the measurements. This study focused on: (i) investigating the effect of admixture contents on q_u values; (ii) investigating the effect of the curing period on q_u; (iii) evaluating the changes of the liquid limit (w_L) in relation to variations in mixing water content, admixtures content and organic content (OC); (iv) investigating the effect of organic content on q_u values; (v) observing the changes of compaction properties at varying admixture contents and organic content and (vi) developing a new model of linear regression analysis through SPSS 16.0, based on the measured q_u values in the laboratory.

2 MATERIALS AND METHODOLOGY

The preparation of stabilized soil samples in the laboratory within a short period of time is very difficult using chemical admixtures such as cement, lime and bentonite (Sharma et al. 2008). Therefore, a mechanical study of cement, lime and bentonite stabilized soil was carried out in the laboratory to understand the mechanical behaviors of the stabilized soils. Organic soil samples were collected for laboratory tests at a depth of 3, 2.5, 2 and 4 m from the existing ground surface from the four selected locations in Khulna region, namely, Teligati, Rangpur, Sonadanga as well as Khulna University (KU) campus, Khulna, Bangladesh, respectively. The physical and index properties of the collected soil samples were investigated in the laboratory through the ASTM (2004) standard methods and are presented in Table 1.

Table 1. Physical and index properties of organic soil used in this study

Properties	Teligati	Rangpur	Sona-danga	KU Campus
Organic content (%)	66	53	32	71
Water content (%)	96	87	65	126
Liquid limit (%)	145	122	95	170
Plastic limit (%)	65	57	45	80
Specific gravity	1.23	1.46	1.71	1.12
Compressive strength (kPa)	45	54	65	38

The cement particles are heterogeneous substances, containing tri-calcium silicate (C_3S), di-calcium silicate (C_2S), tri-calcium aluminate (C_3A), and the solid solution described as tetra-calcium alumino-ferrite (C_4AF). Di-calcium silicate (C_2S) is responsible for the progressive strength of cement. In this study, when preparing stabilized soil in the laboratory, the amounts of cement, lime and bentonite ranged from 5-25 % as a percentage of dry soil mass. The basic ingredients of cement used in this study obtained from the laboratory tests are given in Table 2. Moreover, the basic ingredients of the lime and bentonite used in this study are also given in Table 3.

Table 2. Physical properties of cement used in this study

Physical properties	Values
Normal consistency (%)	22.40
Initial setting time	2 hours 10 minutes
Final setting time	4 hours 10 minutes
Fineness	0.60

The properties of used water were observed to be clear and free from harmful salts, alkalis, acids or organic matter. In general, the potable water is also satisfactory for stabilization of soil using cement, lime and bentonite.

Table 3. Basic ingredients of lime and bentonite used in this study

Basic Ingredients of Lime	Composition (%)	Basic ingredients of bentonite	Composition (%)
Calcium oxide	50	Magnesium	25
Magnesium oxide	35	Aluminum	35
Aluminum oxide	3	Silica	67
Silica	22	Iron	3

The collected undisturbed soil samples were first brought to the laboratory and spread out over the floor for air-drying. The air-dried soil samples were broken down and ground as fine as possible using a wooden hammer without applying unnecessary pressure. The soil powder passed through a # 40 standard sieve to remove large particles. Air dried soil powder free from foreign materials used as the main ingredient to prepare stabilized soils.

The water content of the air dried soil samples was measured at a range of 3.75- 5.5 %. To ensure a uniform mixture of soil with cement, lime and bentonite, a mixture was prepared free from lumps and other foreign particles. The soil paste was then poured in to the cylindrical plastic mould using fingers so that no air voids were entrapped into the soil sample. After six hours, the specimen was removed from the cylindrical mould and it was tightly wrapped in polythene bags to prevent the loss of moisture through evaporation from the stabilized soil. After 24 hours, the wrapped specimens were placed under water at room temperature until testing at the designated period of 1, 3, 7, 14 and 28 days. For investigating the effect of chemical admixtures using liquid limit test, samples were prepared independently at mixing water contents of 100 and 50 %. To investigate the compaction behaviors of stabilized soil, the prepared soil samples were compacted in the laboratory in accordance with standard and modified proctor test methods. The flow chart of laboratory investigations for unconfined compression, liquid limit and compaction tests is shown in Figure 1.

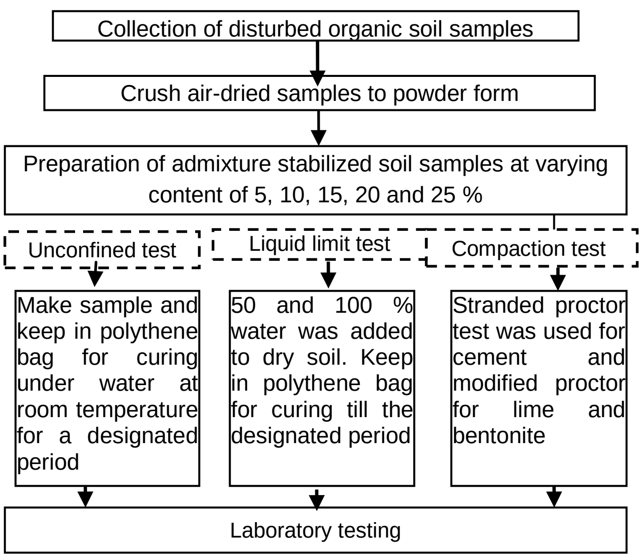


Figure 1. Flow chart of laboratory investigations

3 RESULTS AND DISCUSSIONS

The effect of chemical admixtures in terms of admixture content and curing period of unconfined compressive strength, liquid limit and compaction behaviors of stabilized soils prepared in the laboratory were analyzed and results are discussed in the following sections.

3.1 Unconfined Compressive Strength

The strength behavior of the stabilized soil samples prepared in the laboratory by using cement, lime and bentonite at varying admixture content from 5 to 25 % for the curing periods of 14, 28 and 3 days are shown in Figures 2, 3 and 4, respectively. Moreover, studies are carried out to examine the effect of chemical admixtures in terms of admixture content and curing period as well as the influence of organic content on the magnitude of q_u of the stabilized soils and hence discussed in followings.

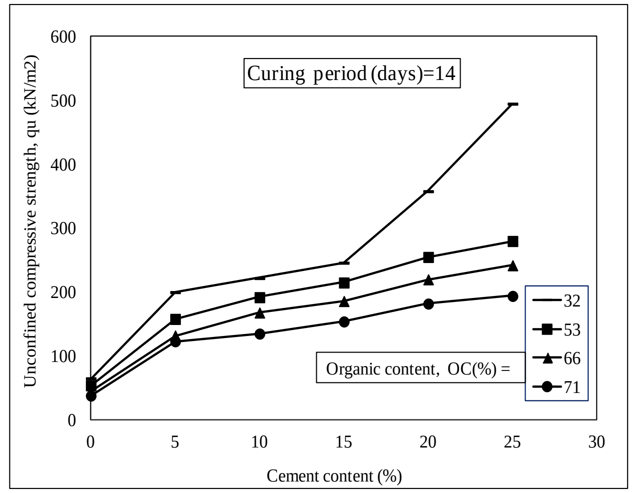


Figure 2. Compressive strength of cement stabilized soil at varying organic content after curing period of 14 days

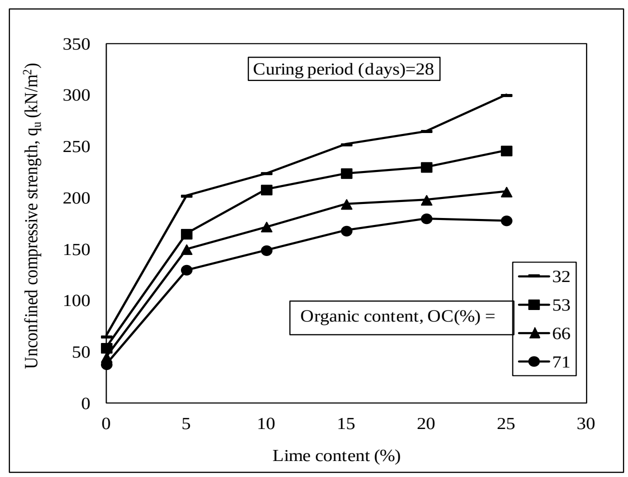


Figure 3. Compressive strength of lime stabilized soil at varying organic content after curing period of 28 days

The effect of cement content from 5 to 25 % on the values of q_u of the cement stabilized soils at varying organic content of 32 to 71 % were investigated and presented in Figure 2. Figure 2 depicts the magnitude of q_u increases in relation to the increase of cement content of stabilized soil at a particular curing period of 14 days. Moreover, it should be noted that for a particular amount of organic content say 32 %, the values of compressive strength increases as 65-310, 65-395, 65-435, 65-495 and 65-540 kN/m^2 for the cement stabilized soils at varying curing periods of 1, 3. 7, 14 and 28 days, respectively. The stabilized soil at 28 days shows comparatively the higher amount of strength (540 kN/m^2) than that of other curing periods. Moreover, Figure 2 shows for cement content of 0-25 % of the stabilized soil at 14 days curing periods, the q_u values were ranging from 65-495, 54-280, 45-242 and 38-194 kN/m^2 for the organic content of 32, 53, 66 and 71 %, respectively. Result reveals compressive strength decreases with the increase of organic content in the stabilized soil. Additionally, it should be noted that with the increasing of organic content, the compressive strength decreases because the organic matter in soil has the low shear strength and high compressibility behaviours. Moreover, Figures 2 to 4 reveals that the values of q_u increases in relation to the increasing of elapsed period of admixture stabilized soil for all the percentages of organic content. Figure 3 depicts the magnitude of q_u increases in relation to the increases of lime content, while, decreases with the increase of organic content in the stabilized soil. Additionally, it was also observed that for a particular amount of mixing lime content say 20 % and curing period 28 (not shown here), the values of compressive strength decreases as 265, 230, 198 and 180 kN/m^2 for organic content 0f 32, 53, 66 and 71 %, respectively.

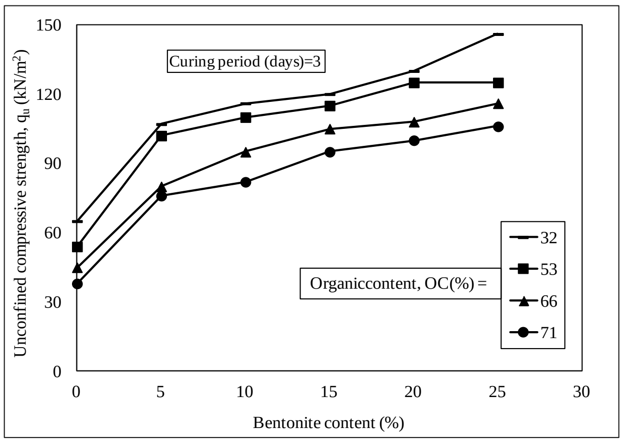


Figure 4. Compressive strength of bentonite stabilized soil at varying organic content after curing period 3 days

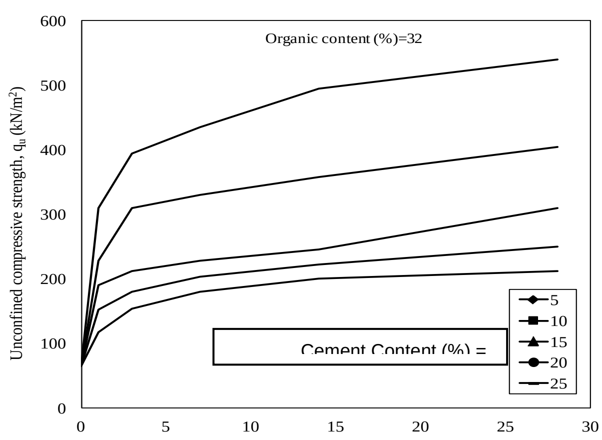


Figure 5. Variation of compressive strength with curing period of cement stabilized soil (OC=32%).

Based on Figure 4, it can be noted that the values of compressive strength increases in relation to the increasing of bentonite content. For bentonite content of 0-25 % of the stabilized soil at 3 days curing periods, the q_u values were ranging from 65-146, 54-125, 45-116 and 38-105 kN/m^2 for the organic content of 32, 53, 66 and 71 %, respectively (Figure 4). Based on the results of admixture content for stabilizing of organic soil, it can be concluded that for a particular amount of organic content and curing period, cement admixture shows comparatively the higher strength than that of other admixtures (lime and bentonite).

The development of compressive strength in cement, lime and bentonite stabilized soil for the curing period of 1 to 28 days, at varying content from 5 to 25 % is presented in Figures 5 to 8. Figure 5 shows the variation of q_u of cement stabilized soil of organic content 32 % at varying curing periods from 1 to 28 days. Studies are carried out to characterize the q_u of the stabilized soils in relation to the changes of curing period and organic content. Figure 5 shows for a particular amount of organic content say 32 % of the cement stabilized soil, the values of compressive strength increases from 65-213, 65-250, 65-310, 65-405 and 65-540 kN/m^2 for the curing periods of 1, 3, 7, 14 and 28 days, respectively.

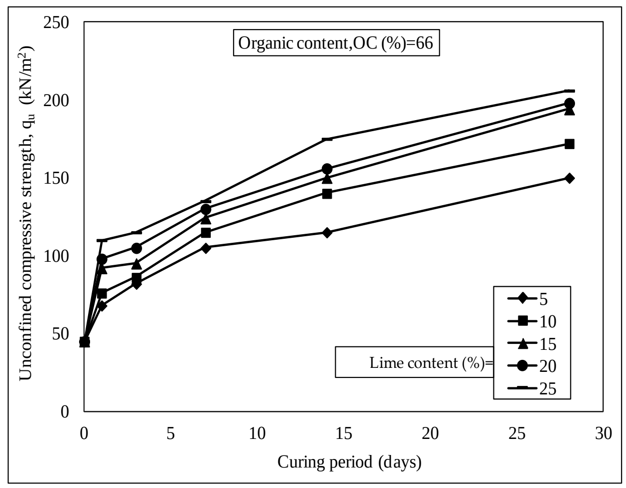


Figure 6. Variation of compressive strength with curing period of lime stabilized soil (OC=66%).

It was also observed that q_u increases with the increasing of curing period and cement content as well as it shows the maximum value of q_u at maximum percentage of cement content (25%) at 28 days of curing period (Figure 5). Here it can also be noted that the values of compressive strength increases in relation to the increasing of curing periods for the other amount of organic content of the cement stabilized soils. . Additionally, based on Figures 6 to 8, it can be also seen that q_u increases with the increasing of elapsed period up to the end of this study and the similar trend was also observed by Bergado (1996). The values of compressive strength of lime stabilized soil for the organic content of 66 and 32 % are presented in Figure 6 and Figure 7, respectively. Figure 6 and 7 reveals for a particular amount of lime content say 10 % and specific curing period 14 days, the values of strength were found to be 140 and 190 kN/m^2 for organic content of 66 and 32 % in soil, respectively. Here, it should be noted that (compare the Figures 6 and 7), considering the stabilized of soil with lime at varying organic content, Figure 7 shows the higher values of q_u than Figure 6 that means stabilized soil at lower organic content reveals the higher value of q_u in relation to the increasing of curing period.

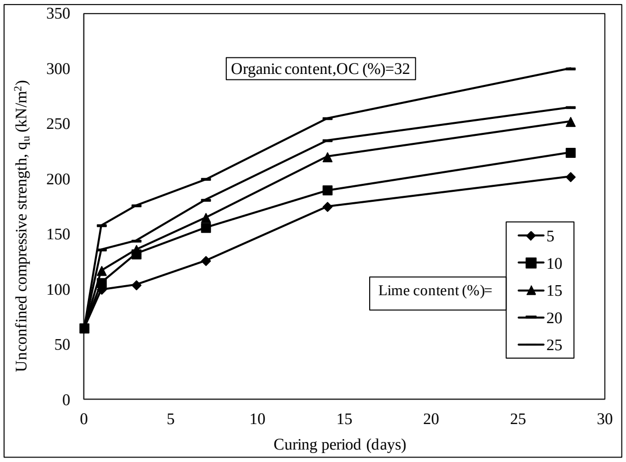


Figure 7. Variation of compressive strength with curing period of lime stabilized soil (OC=32%)

In contrast, the compressive strength of lime and bentonite stabilized soils at varying organic content is shown in Figure 7 and Figure 8, respectively. Based on Figures 7 and 8, it was observed that for a particular amount of lime and bentonite content say 10 %, particular organic content (32 %) and specific curing period 7 days, the values of strength were to be found as 156 and 126 kN/m^2 for lime and bentonite content, respectively. Based on the comparison of Figures 7 and 8, it can be depicted that lime stabilized soil comparatively shows the higher compressive strength than that of bentonite stabilized soil at maximum mixing content and curing period. However, cement stabilized soil had the highest compressive strength against the counterpart i.e. lime and bentonite stabilized soil for all the curing period (Figure 5).

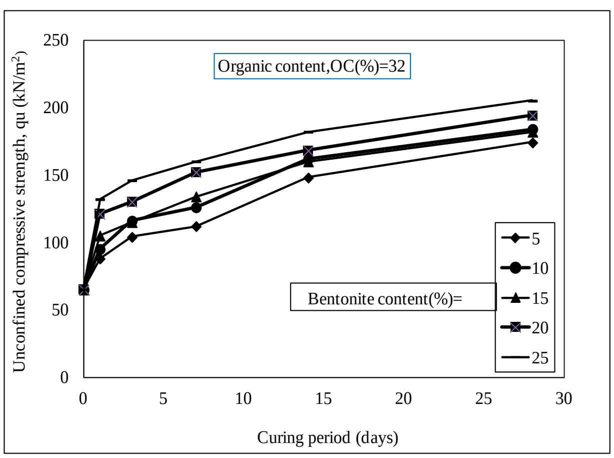


Figure 8. Variation of compressive strength with curing period of bentonite stabilized soil (OC=32%)

3.2 Compaction Properties

A series of test were conducted to investigate the effect of different types of admixture content on the compaction characteristics of organic soil. The samples were compacted in accordance with the standard proctor test for cement and bentonite stabilized soils, as well as modified proctor test for lime stabilized soils. The variation of dry unit weight and optimum moisture content in soil with the addition of varying percentage of cement, lime and bentonite of 5, 10, 15, 20 and 25 % are evident in Figures 9, 10 and 11, respectively. Based on Figure 9, it was observed the maximum dry unit weight of 1295, 1255, 1235, 1195 and 1140 (kg/m^3) with the corresponding optimum moisture content of 51.15, 53.17, 56.41, 58.12 and 66.16 % for the cement content of 25, 20, 15, 10 and 5 %, respectively. He it can be noted that the values of maximum dry unit weight decreases in relation to the decreasing of cement content. However, the maximum dry unit weight was to be found (1255 kg/m^3) for the maximum cement content of 25 %. Here it can be also noted that the optimum moisture content increases with the decreasing of cement content in soil.

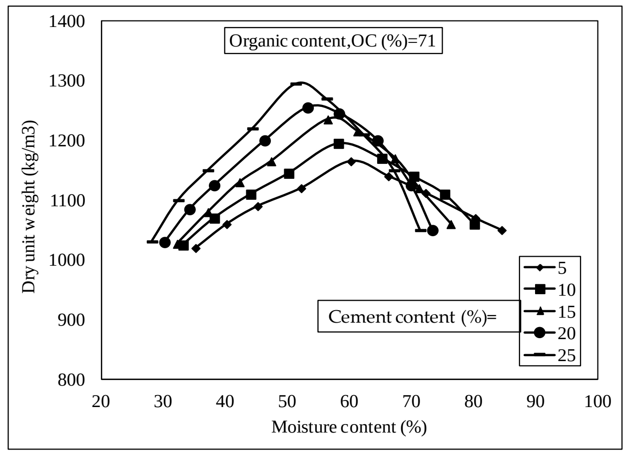


Figure 9. Effect of cement content on dry unit weight of stabilized soil at varying organic content

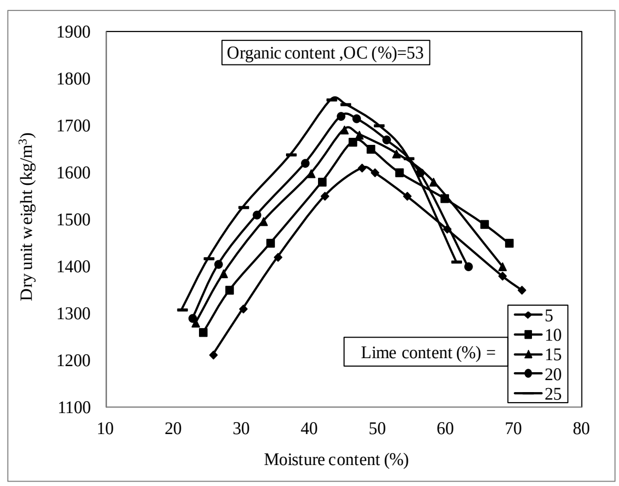


Figure 10. Effect of lime content on dry unit weight of stabilized soil at varying organic content

Based on Figures 9 to 11, it was observed that the values of dry unit weight of cement, lime and bentonite stabilized soil increases, while, the optimum moisture content decreases with the increasing of cement, lime and bentonite content. However, the value of dry unit weight decreases and optimum moisture content increases with the increasing of organic content of soil.

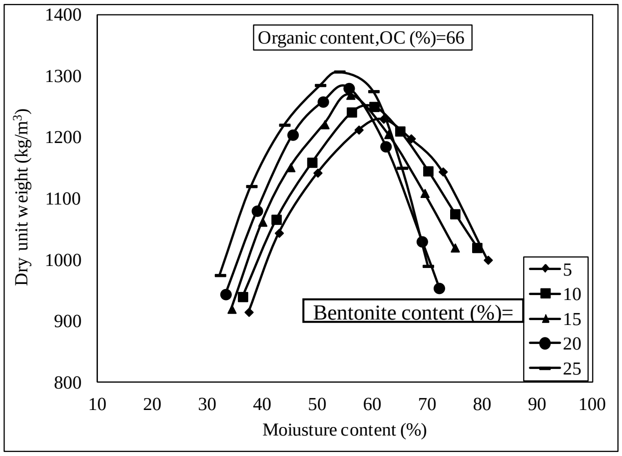


Figure 11. Effect of bentonite content on dry unit weight of stabilized soil at varying organic content

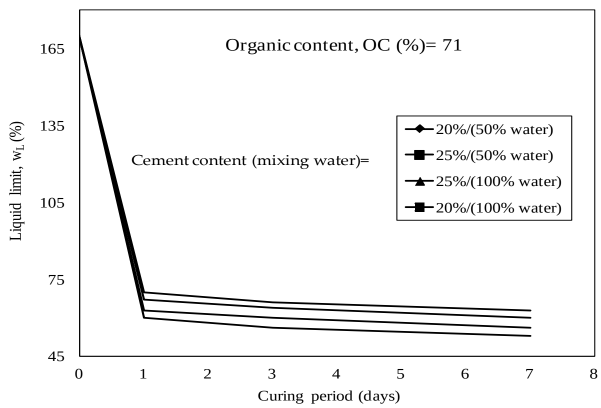


Figure 12. Effect of cement content on liquid limit of stabilized soil at varying mixing water and curing period

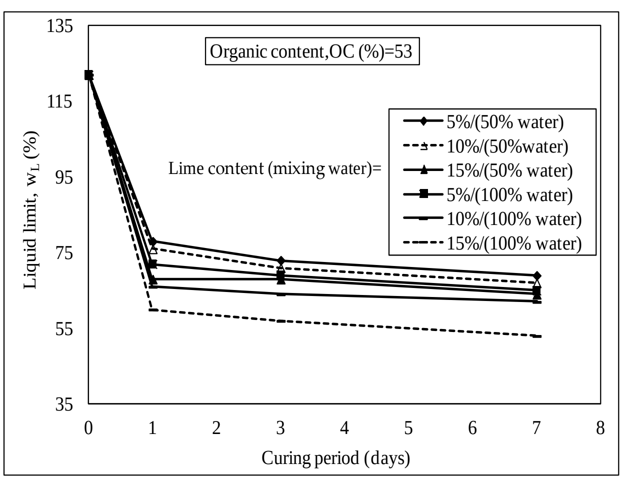


Figure 13. Effect of lime content on liquid limit of stabilized soil at varying mixing water and curing period

3.3 Liquid Limits

In the laboratory, for investigating the effect of admixture content, curing period and organic content on the values of liquid limit (w_L) of soil, the stabilized soil samples were prepared independently with mixing water content of 100 and 50 %. The variation of w_L with increasing of elapsed period from sample preparation at the varying percentages of cement, lime and bentonite content of 5, 10, 15, 20 and 25 %, is evident in Figures 12 to 14. Figure 12 depicts the values of w_L in cement stabilized soil were ranging from 170-53 and 170-60 for decreasing of curing period of 0-7 for mixing water content 100 and 50 %, respectively. Based on Figures 12 to 14 it was observed that w_L decreases with the increasing of elapsed period.

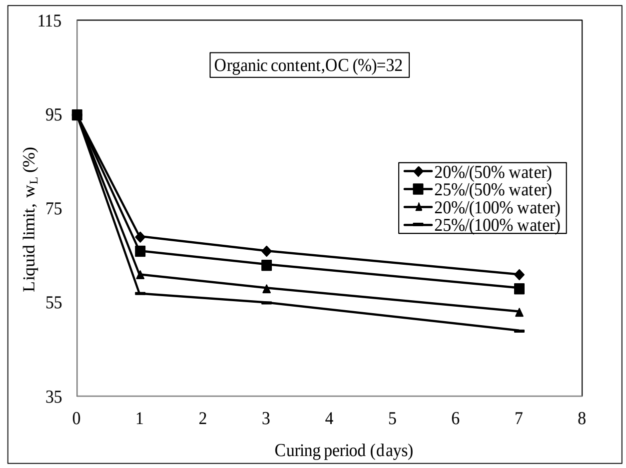
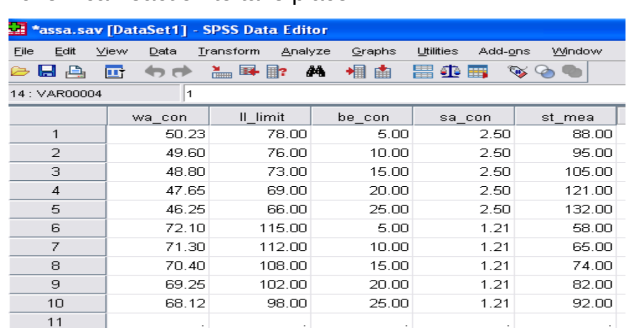


Figure 14. Effect of bentonite content on liquid limit of stabilized soil at varying mixing water and curing period

Additionally, the values of w_L of stabilized soil were to be found decreases with the increase of cement, lime and bentonite content. The soil with 100 % mixing water had a comparatively higher w_L than soil specimens with 50 % mixing water. Based on the caparison of Figures 12 to 14, it was observed that the cement stabilized had the larger amount of w_L than that of lime and bentonite stabilized soils. However, it was not possible to conduct any more w_L test after 7 days of curing as the soil samples have become too hard. Here, it is notable that for a particular soil-cement/lime/bentonite mixed, there is a better reduction in w_L when more water is made available for the chemical reaction to take place.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	wa_con	ll_limit	be_con	sa_con	st_mea
1	50.23	78.00	5.00	2.50	88.00
2	49.60	76.00	10.00	2.50	95.00
3	48.80	73.00	15.00	2.50	105.00
4	47.65	69.00	20.00	2.50	121.00
5	46.25	66.00	25.00	2.50	132.00
6	72.10	115.00	5.00	1.21	58.00
7	71.30	112.00	10.00	1.21	65.00
8	70.40	108.00	15.00	1.21	74.00
9	69.25	102.00	20.00	1.21	82.00
10	68.12	98.00	25.00	1.21	92.00
11	.	.	.	.	.

Figure 15. Variables for model of SPSS analysis

4 ANALYSIS OF REGRESSION MODEL

Based on the laboratory results and using SPSS 16.0 statistic program a linear regression model was developed which correlates the compressive strength (q_u) of cement/lime/bentonite stabilized soils to the variables water content, w (%), liquid limit, w_L (%), cement content, C (%), lime content L (%), bentonite content, B (%), sand content, S (%) and curing time, CT (days). The coefficient of a_1, a_2, a_3, a_4, a_5 and a_6 were used for developing of regression liner equations. The developed equation for cement stabilised soil are as follows by the Equation 1.

$$q_u = a_1 + a_2(w) + a_3(w_L) + a_4(C) + a_5(CT) + a_6(S) \quad [1]$$

In order to obtain a more accurate regression model, the curing time (CT) was left out as a descriptor variable in the regression equation. The model that gives the best correlation is the following shown in Equation 2.

$$q_u = a_1 + a_2(w) + a_3(w_L) + a_4(C) + a_5(S) \quad [2]$$

4.1 Cement Stabilized Soil

For regression analysis, water content, liquid limit, admixture content and sand content were considered as the independent variables, while, the values of measured compressive strength were considered as a dependent variable is evident in Figure 15. Moreover, to depict the validity of the measured strength against the computed values, the following Equation 3 for cement stabilized soil was developed using the unstandardized coefficients.

$$q_u = 1100.275 - 28.410(w) + 6.314(w_L) + 5.106(C) - 57.427(S) \quad [3]$$

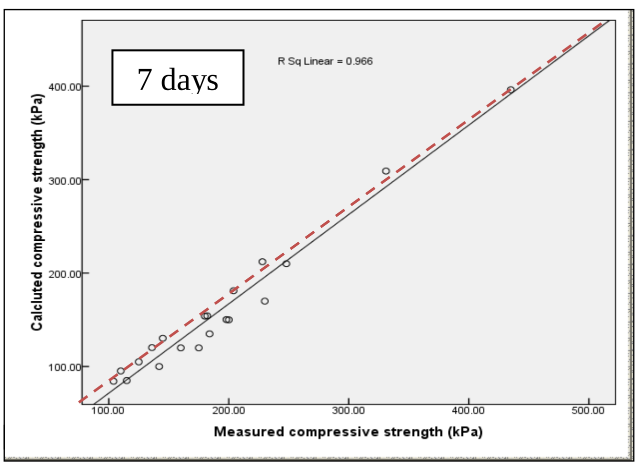

Figure 16. Cross plot of computed and measured compressive strength of cement stabilized soils at curing period 7 day using Equation 3

The cross plot of the values of computed compressive strength obtained from the application of Equation 3, against the measured values using the linear regression model. Figure 16 illustrate a plot of the values of computed compressive strength with measured values using the linear regression model for cement stabilized soil at curing period of 7 days. The red dot straight line in the Figure 16 represents the line of perfect equality, where the values being compared are exactly equal. The correlation coefficient (R^2) at 95% confidence interval is 0.966, meaning roughly that 96.6% of the variance in strength is explained by the model. This value is statistically significant and therefore suggests that measured and computed strength are comparable.

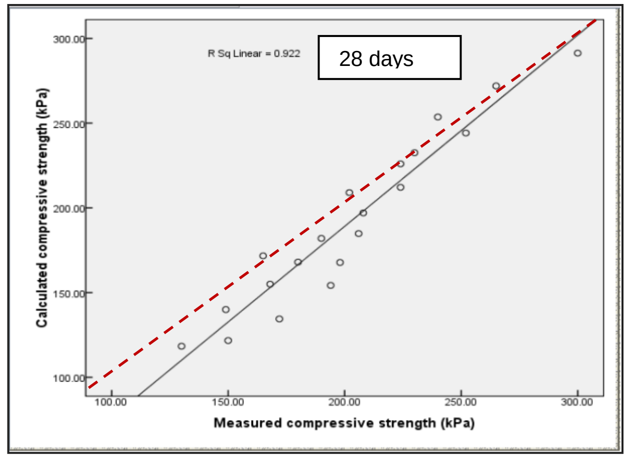

Figure 17. Cross plot of computed and measured compressive strength of lime stabilized soils at curing period 28 days

4.2 Lime Stabilized Soil

The following Equation 4 was developed for lime stabilized soil using the unstandardized coefficients.

$$q_u = 446.657 - 6.208(w) + 2.322(w_L) + 3.619(L) - 59.742(S) \quad [4]$$

The Figure 17 shows the comparison of measured and computed compressive strength of lime stabilized soil. The red dot straight line in the figure represents the line of perfect equality, where the values being compared are exactly equal. The correlation coefficient (R^2) at 95 % confidence interval is 0.922, meaning roughly that 92.2 % of the variance in compressive strength is explained by the model. The predicted unconfined compressive strength from the developed model was found to be nearly the same as the laboratory measured value and the degree of accuracy was more reliable.

4.3 Bentonite Stabilized Soil

The following Equation 5 was developed of bentonite stabilized soil using the unstandardized coefficients.

$$q_u = 745.548 - 10.699(w) + 1.781(w_L) + 1.194(B) - 106.089(S) \quad [5]$$

The Figure 18 shows the comparison of measured and computed q_u of bentonite stabilized soil. The red dot straight line in the figure represents the line of perfect equality, where the values being compared are exactly equal. The correlation coefficient (R^2) at 95% confidence interval was 0.726, meaning roughly that 72.6% of the variance in strength is explained by the model. This value is statistically significant and therefore suggests that the measured and calculated values of q_u are comparable.

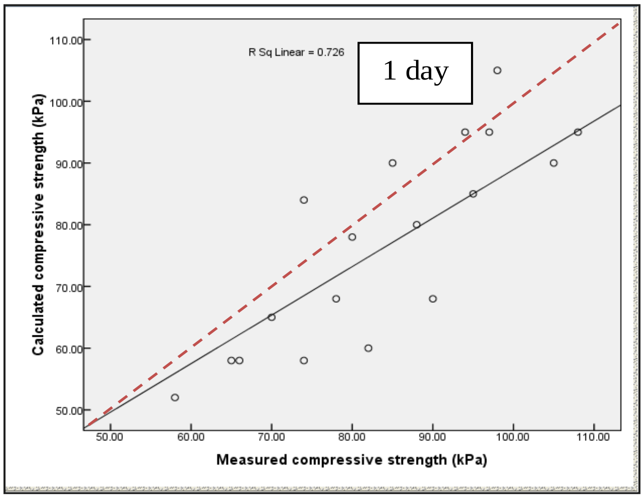

Figure 18. Cross plot of computed and measured compressive strength of bentonite stabilized soils at curing period 1 day using Equation 5

5 CONCLUSSION

The results reveal that the addition of chemical admixtures improved the engineering properties of stabilized soils, especially after a long curing period. The unconfined compressive strength of stabilized soil increases significantly with the increase of cement, lime and bentonite content. However, it was also found that the greater the organic content in the soil negates the positive effect of the cement, lime and bentonite content in improving the mechanical properties of soil. Additionally, the liquid limit of stabilized soil was found to decrease with the increase of cement, lime and bentonite content. The soil with 100 % mixing water had a comparatively higher liquid limit than soil specimens with 50 % mixing water. Moreover, the maximum dry density increases while optimum water content decreases with the increase of admixture content in the stabilized soil. The results indicated an appreciable improvement in the stabilized soils. Finally, the predicted unconfined compressive strength from the developed model was found to be nearly the same as the laboratory measured value and the degree of accuracy was more reliable.

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