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Resilient Modulus of Lime-bamboo ash Stabilized Subgrade Soil with Different Compactive Energy

Chijioke Christopher Ikeagwuani[1] and Donald Chimobi Nwonu[2]

[12]Civil Engineering Department, University of Nigeria, Nsukka, Enugu State, Nigeria

[1]Email: chijioke.ikeagwuani@unn.edu.ng

[2]Email: donald.nwonu@unn.edu.ng

ORCID iD: http://orcid.org/0000-0002-5106-4579

Correspondence: Donald Chimobi Nwonu; donald.nwonu@unn.edu.ng;

+2348065345122

Abstract

The resilient modulus (M_r) of natural subgrade materials have been extensively studied, however, for stabilized subgrade materials, the M_r requires adequate characterization to ascertain pragmatic performance. Furthermore, the soil M_r is known to be influenced by the soil physical state. A lime-modified expansive subgrade soil, admixed with varying percentages of bamboo ash (4, 8, 12, 16, and 20%) was understudied to determine its M_r with compaction attenuation. Two compactive energies, British standard heavy and British standard light were applied for determination of the stabilized soil M_r. The M_r was determined in accordance with AASHTO T307 guide. The results clearly showed that whilst M_r improved with additive content and increased deviator and confining stresses, the values diminished with compaction attenuation. A polynomial model relationship was developed for the M_r obtained using the two compactive energies. The results of the multiple regression analysis carried out using modified stress-based models from literature demonstrated the influence of compactive energy and additive content on the stabilized soil M_r.

Keywords: compactive energy; bamboo ash; lime-modified subgrade soil; multiple regression analysis; resilient modulus; stabilization

Introduction

As an expansive soil, tropical black clay (TBC) is prone to the characteristic volume change behaviour associated with such soils. Its alternate shrinkage and swelling behaviour with respective drying and wetting cycles is a consequence of the smectite group of clay minerals which dominate the clay fraction, predominantly montmorillonite (Mudgal et al.2014; Osinubi et al. 2010). However, the relevance of expansive soils in construction application is crucial due to their abundance in nature as indicated by Steinberg (2000).

When expansive soils are encountered on site, the cost of soil replacement could be prohibitive if the soil extends to considerable depth below the ground. Alternatively, the usual practice is the implementation of a stabilization mitigation strategy to improve the soil performance. Various stabilization techniques adopted for expansive soils abound in literature and is well reported in (Ikeagwuani and Nwonu 2019). The conventional additives applied are usually lime and cement, but their cost implication necessitates supplementing them with other relatively inexpensive additives. Wastes from agro-based materials have been found very useful in recent years for such supplementation purpose as seen in several research studies (Anupam et al. 2014; Ikeagwuani 2016; Ikeagwuani et al. 2017; Karatai et al. 2017; Osinubi et al. 2011; Osinubi et al. 2016; Phanikumar and Nagaraju 2018; Atahu et al. 2019). In view of this, bamboo ash (BA) was used as a supplementary additive for lime-modified TBC in this study.

Most often, stabilized soils find application in pavement construction, usually as subgrade materials. In pavement design, a key parameter for the design of the constituent layers of the pavement is the soil resilient modulus (M_r), based on the new mechanistic empirical pavement design guide (MEPDG) by NCHRP (2004). The soil physical condition, soil type and stress level, have been identified as the major factors that impact on the M_r of subgrade soils (Li and Selig 1994; Mamatha and Dinesh 2017). Compaction as a representative of the soil physical condition, has been identified to have a key influence on soil mechanical properties (Crispim et al. 2011), and the effect has been asserted to be consequent upon pore size variation with compaction level (Yaghoubi et al. 2016). This assertion is well supported by microstructural analyses (Crispim et al. 2011; Doris Asmani et al. 2011). Another study by Cetin et al. (2014), reported the influence of compaction method on the M_r of unbound granular materials. Impact and vibratory compaction methods were used, and the result showed that higher M_r values were achieved with the impact modified proctor method. In a recent study by Razouki and Ibrahim (2017), the M_r of a gypsum sand roadbed was improved by increasing the degree of compaction via the number of blows. The modified AASHTO compaction test was used, varying the number of blows in which 10, 30, 50 and 70 blows per layer were applied successively to increase the compactive energy.

From survey of literature, it is lucid that ample research has been conducted on the M_r of natural pavement materials. However, the same cannot be said for the behaviour of stabilized subgrade materials, as more studies are still required to describe the M_r of stabilized soils. Few models exist in literature that characterize the M_r of stabilized subgrade soils (Mamatha and Dinesh 2017; Rasul et al. 2018). This research work investigated the effect of compactive energy attenuation and additive content on the M_r of stabilized TBC by determination of the M_r using the British standard heavy (BSH) and British standard light (BSL) compactive efforts.

Materials and Methods

Materials

The TBC used for this study was obtained from Numan in Adamawa state, located on the geographical map of Nigeria at latitude 9°29’10’’N and longitude 12° 02’36’’E, using disturbed sampling method. The samples were collected at depths greater than 1m below ground level and stored in air-tight bags before being conveyed to the laboratory. The properties of the TBC sample determined in accordance with BS 1377 (1990) are shown in Table 1.

The bamboo used for production of BA as well as the lime used in this study was obtained commercially. The BA was a constituent of bamboo leaves, branches and the stem, burnt under controlled conditions to produce ash, and the combustion was conducted in two stages. The first stage was the carbonization phase (heating temperature of about 400°C), while the second stage was the carbon elimination phase (heating temperature of about 700°C). The chemical compositions of the materials used in this study are shown in Table 2.

Additive Mix Design

To achieve the aim of this research, lime modification was initially executed on the natural soil sample. This involved determination of the Atterberg limits of the lime-modified samples. The test was done in accordance with the specifications of BS 1377 (1990). The Casagrande apparatus was used, and the test was conducted on the specimens without curing. Lime was added to the natural soil sample in steps of 2% from 2-10% by weight of the air dried soil. The liquid limit, plastic limit and plasticity index were obtained. After the lime modification, 4% lime content produced the least plasticity index and was used during the determination of M_r.

Resilient Modulus Determination

Repeated load triaxial test was used to determine the M_r of the stabilized soil. The stabilized soil was a mixture of the natural soil sample, 4% lime and varying percentages of BA from 4-20% at 4% interval by weight of the air dried soil. The M_r was determined in accordance with AASHTO T307-99 (2007) using fifteen sequences of stress levels, consisting of five deviator stresses (12.4kPa, 25.6kPa, 38.3kPa, 51.7kPa and 66.5kPa) and three confining pressures (13.8kPa, 27.6kPa, and 41.4kPa). Each of the extruded cylindrical soil specimens of 100mm height by 50mm diameter was prepared at the respective optimum moisture content (OMC) and maximum dry density (MDD). The samples were cured for a day in a humidity controlled room to allow even distribution of moisture.

The M_r was determined using two compactive efforts, BSH and BSL. The BSH involved static compaction of the soil in 5 layers, using a Proctor mould of 944cm^3 and 4.5kg rammer, falling from a height of 0.45m. A total of 25 blows were applied to each compacted layer, giving a compactive energy level of 2681.41kN-m/m^3, using the formula according to Das (2014). For the compaction attenuation, BSL method was used in which the soil was statically compacted in 3 layers, using a Proctor mould of 944cm^3 and a 2.5kg rammer falling from a drop height of 0.3m. Each layer was also impacted with 25 blows of the rammer, giving a compactive energy level of 595.87kN-m/m^3.

The samples were preconditioned with 1000 cycles to prevent roughness at the diametric ends of the specimen and to better simulate the event occurring between compaction and heavy traffic condition, using deviatoric stress of 27.6kPa and confining pressure of 41.4kPa. For each of the 15 test sequence combinations, the standard 100 cycles was used after preconditioning. Each cycle consists of load duration of 0.1sec and a rest period of 0.9sec and the stress pulse shape was haversine in nature. The total resilient strain response of the specimen was measured for computation of the

M_r and the test was terminated once the permanent vertical strain exceeded 5%. The last five cycles were obtained and averaged to calculate the M_r for each test sequence.

Results and Discussion

Resilient Modulus of Natural Soil

The M_r of the natural soil is shown in Figs 1 and 2 for BSH and BSL compaction respectively, at various levels of confinement and deviator stress, and the figures exhibited a similar trend. From the trend, the soil M_r increased with the increase in confining stress due to the stiffening effect of confinement imparted to the soil. However, the M_r decreased with increase in deviator stress, indicative of drop in the soil resilience at higher stress levels for both compaction methods. A similar trend was reported by Rasul et al. (2018) for A-7-5 soil. The drop is attributable to the strain softening effect imparted due to load-induced failure of the natural soil and led to the loss in the soil compact nature. This causes increase in the recoverable deformation with attendant decrease in the M_r (Georgees et al. 2018). More so, with compaction attenuation (that is, decrease in compactive energy), the presence of larger voids in the specimens compacted using the BSL, further reduced the M_r in comparison with those of BSH . The result is in agreement with that reported by Razouki and Ibrahim (2017).

Resilient Modulus of Stabilized Soil

For the stabilized soil, the M_r is also represented in Figs 1and 2 for BSH and BSL compaction respectively, at different confinement levels and deviator stress. The figures show a similar trend in which the M_r of the soil increased with increase in confinement and deviator stress. Furthermore, with increase in BA content, the M_r rose to attain its peak values at 12%BA, after which a gradual drop was observed. The increase in the M_r with additive content can be attributed to hydration of the ions (calcium and silicate) in the additives to form cementitous compounds, which are responsible for improving the M_r of the stabilized soil (Kang et al. 2014). More so, the flocculation and agglomeration of soil-lime-BA particles modifies the stabilized soil skeleton into coarse particulate granules, which make compaction expedient, owing to their friable nature (Firoozi et al. 2017).

In addition, the water requirement of the hydration reaction induced self-dessication in the soil-lime-BA mixture, which causes drop in hydration, resulting to the prevalence of drier condition within the soil matrix. As reported by other researchers (Tastan et al. 2011; Qian et al. 2014), the soil M_r improves at drier conditions. The trend is similar to that obtained by Tastan et al. (2011) for Lawson soil (P.Isle).

The observed drop in M_r after the 12% BA content can be adduced to the exhaustion of the available lime in soil-lime-BA mixtures for the formation of cementitious compounds. On further addition of BA, silicon dissolution increases, with a corresponding consumption of OH^- from the lime, which ultimately results to decline in alkalinity of the clay-pore fluid media. Al-taie et al. (2016) showed that the resultant effect is a discontinuation in cation exchange, flocculation, agglomeration, and pozzolanic reaction. With compaction attenuation, the values of M_r were smaller, as similarly observed for the natural soil, which can be explicated in terms of loss in the soil compact nature due to the prevalence of larger voids in the specimens compacted using BSL method. The result is consentient with that of Razouki and Ibrahim (2017).

Regresion Analysis using Stress-based Models

Constitutive models are often used for prediction of M_r values as level 2 design input parameter based on the recent MEPDG (NCHRP, 2004). Most of these models are stress-based and generally attempt to incorporate the effect of loading and confinement. In view of this, three parameter stress-based models are ostensibly robust as they include the overall effects of stress and confinement. Three pioneer models in literature which incorporate the effects of stress and confinement are the models by Uzan (1985), Witzack and Uzan (1988) and Pezo et al. (1991). However, these models have inherent limitations in the prediction of M_r for isotropic soil conditions. Ni et al (2002), proposed an improved model based on confining pressure and deviator stress, to surmount the limitations associated with the aforementioned models.

Consequently, the model by Ni et al (2002) and the octahedral shear stress model recommended in the MEPDG by NCHRP (2004) were used in this study to predict the soil M_r under different compaction energies. The models are as shown in equations (1) and (2):

$$M_r = K_1 P_a \left(\frac{\sigma_3}{P_a}+1\right)^{K_2} \left(\frac{\sigma_d}{P_a}+1\right)^{K_3} \tag{1}$$

$$M_r = K_1 P_a \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{K_3} \tag{2}$$

Where for a cylindrical specimen, σ_3= confining pressure, representing the minor principal stress; σ_d = deviator stress; θ is the bulk stress $=\sigma_d + 3\sigma_3$; τ_{oct} is the octahedral shear stress = $\frac{\sigma_d\sqrt{2}}{3}$, and K_1, K_2 & K_3 are the model parameter constants.

Regression analysis was performed on the M_r values obtained for both the natural and stabilized soil using equations (1) and (2). The relationship between the measured and predicted values of M_r obtained using equations (1) and (2) showed poor predictive capability of the models, based on the R^2 values of 0.024. This can be asserted to be as a result of the fact that the effect of other factors which affect the M_r of stabilized expansive soils (such as compactive energy, additives, curing time, et cetera were not accounted for by the models. Consequently, a modified model was developed in this study to incorporate the influence of the different compactive energies applied and the additive used. The modified nonlinear stress-based equations developed in this study are as shown in equations (3) and (4) respectively.

$$M_r = K_1 P_a \left(\frac{\sigma_3}{P_a}+1\right)^{K_2} \left(\frac{\sigma_d}{P_a}+1\right)^{K_3} \left(\frac{E_c}{h\gamma_{max}}\right)^{K_4} (A+1)^{K_5} \tag{3}$$

$$M_r = K_1 P_a \left(\frac{\theta}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{K_3} \left(\frac{E_c}{h\gamma_{max}}\right)^{K_4} (A+1)^{K_5} \tag{4}$$

Where the parameters defined previously retain their usual meaning, E_c= compactive energy in kN-m/m^3, γ_{max} = maximum dry unit weight in kN/m^3, h= rammer height of drop in m, A = BA content in %, $K_1 - K_5$ = regression coefficients.

In equations (3) and (4), the compactive energy was normalized using the product of the maximum dry unit weight and the rammer height of drop. The results of the regression analysis using equations (3) and (4) are represented in Figs 3 and 4, showing the relationship between measured and predicted values of M_r. From the figures, the regression constants have been determined and are all positive, and the coefficient of determination obtained depicts good predictive capability for the equations developed in this study.

Josh and Malla (2006) pointed out some facts about the model parameter constants for prediction of M_r of natural soils. The authors asserted that since K_1 is in direct proportion with M_r, K_1 values would always be positive since M_r does not take negative values. Also, K_2 always need to be positive in order for the stiffening effect of confinement to yield higher values for M_r, however, K_3 has to take negative values for the shear effect to weaken the soil and reduce the M_r. The aforementioned conditions for the values of K_1, K_2 and K_3 are based on the generic knowledge that M_r values decrease with loading and increases with confinement.

However, for the stabilized soil in this study, it is perspicuous that the values of all the model parameter constants were positive. The descrepancy can be explicated from the trend observed for the M_r of the stabilized soil, in which the values increased with increase in deviator stress, confinement, compactive energy and additive content. This ensures strain hardenening effect imparted to the stabilized soil, which improved the $M_r$values, and consequently yielded positive values for the model parameter constants of the stabilized soil, since more of the data points are for the stabilized soil.

Polynomial Model

To establish a relationship between the M_r obtained using the two compactive energies adopted in this study, a phenomenological model was developed. The M_r obtained using the BSL method, $M_{r,BSL}$ was expressed as a function of the M_r obtained using BSH method, $M_{r,BSH}$. As adopted by Saberian et al. (2017), a quadratic polynomial was found to best approximate the relationship between soil geotechnical properties and additive content. Similarly, a degree two polynomial was found to be plausible for the relationship between $M_{r,BSL}$ and $M_{r,BSH}$. The established relationship is represented in equation (5) below

$$M_{r,BSL} = a \times (M_{r,BSH})^2 + b \times \left(M_{r,BSH}\right) + c \tag{5}$$

Where a $(kPa)^{-1}$, b, and c (kPa) are all fitting parameters.

The quadratic function, representing the relationship in equation (5) is shown in Fig 5. From the figures, all the fitting parameters required for predicting the $M_{r,BSL}$ have been determined, and the data was fitted with R^2 value of 0.708.

Conclusion

Repeated load triaxial tests were performed on stabilized expansive soil (tropical black clay) with different compactive energies, to determine the M_r of the stabilized soil with compaction attenuation. The natural soil was pre-modified with 4% lime content, before further modifications with BA content (4, 8, 12, 16 and 20%) by weight of the air dried soil. It was discovered that the M_r of the natural soil improved significantly on addition of BA. The following salient points were drawn as the conclusion from the results of this study:

1. The natural soilM_r decreased with deviator stress, while the M_r of the stabilized soil increased with deviator stress, depicting a strain hardening effect imparted to the soil by the additive.

2. With compaction attenuation, there was significant drop in the M_r of both the natural and stabilized soils, and the relationship between the M_r obtained using compactive energy of 595.87kN-m/m^3 was expressed as a quadratic function of the M_r obtained using a compactive energy of 2681.41kN-m/m^3 through a polynomial model.
3. Multiple linear regression analysis performed on the M_r of the stabilized soil, irrespective of the compactive energy applied, using two constitutive stress-based models, showed poor predictive capability. The coefficient of determination obtained after fitting the M_r values using the model based on confining pressure and deviator stress, and also the octahedral shear stress model recommended in the MEPDG was 0.024. The poor prediction was due to the failure of the models to account for the effect of other factors which affect the M_r of stabilized expansive soils (such as compactive energy, additives, curing time, et cetera).
4. In order to incorporate the influence of compaction attenuation and additive effect, the two stress-based models were modified. The modified models gave good predictive capability. The coefficient of determination obtained after fitting the M_r values using the modified model based on confining pressure and deviator stress, and also the modified octahedral shear stress model recommended in the MEPDG were 0.863 and 0.864 respectively. This lucidly elucidates the signifance of incorporating the influence of compactive energy and additive content in resilient models for stabilized soils.

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Figure Captions.

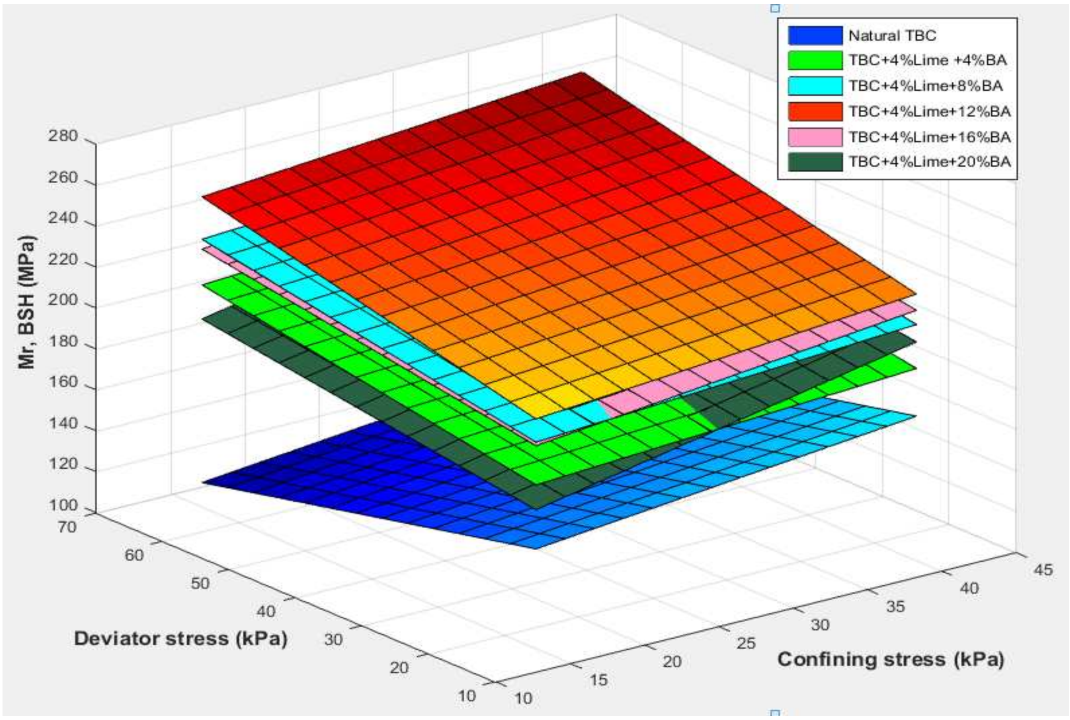
Fig 1 Variation of $\mathrm{M}_{\mathrm{r,BSH}}$ with deviator and confining stresses at different BA content

Fig 2 Variation of $\mathrm{M}_{\mathrm{r,BSL}}$ with deviator and confining stresses at different BA content

Fig 3 Correlation of measured and predicted M_{r} using the modified Ni et al. (2002) model

Fig 4 Correlation of measured and predicted M_{r} using the modified octahedral shear stress model

Fig 5 Polynomial relationship between $\mathrm{M}_{\mathrm{r,BSL}}$ and $\mathrm{M}_{\mathrm{r,BSH}}$


Natural TBC
TBC+4%Lime +4%BA
TBC+4%Lime+8%BA
TBC+4%Lime+12%BA
TBC+4%Lime+16%BA
TBC+4%Lime+20%BA
Mr, BSH (MPa)
280
260
240
220
200
180
160
140
120
100
Deviator stress (kPa)
70
60
50
40
30
20
10
Confining stress (kPa)
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15
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25
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40
45

Fig. 1

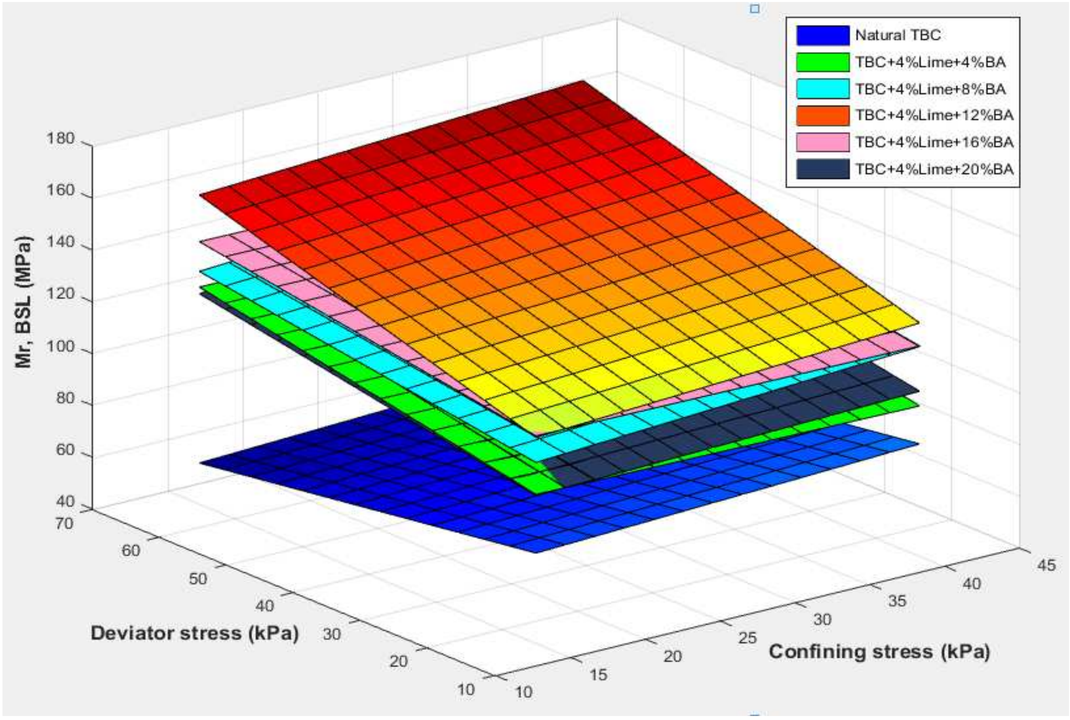
Natural TBC
TBC+4%Lime+4%BA
TBC+4%Lime+8%BA
TBC+4%Lime+12%BA
TBC+4%Lime+16%BA
TBC+4%Lime+20%BA
Mr, BSL (MPa)
180
160
140
120
100
80
60
40
Deviator stress (kPa)
70
60
50
40
30
20
10
Confining stress (kPa)
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Fig. 2

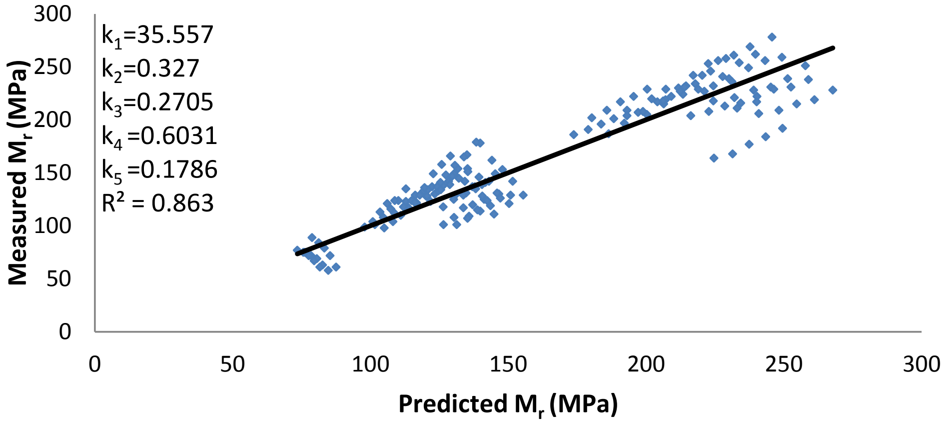

Fig. 3

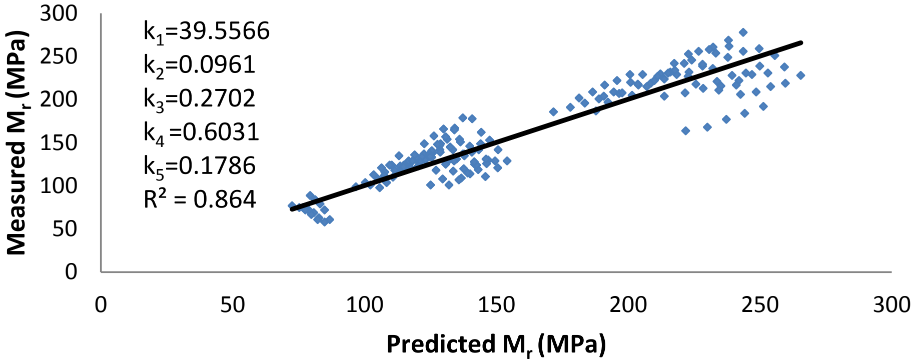

Fig. 4

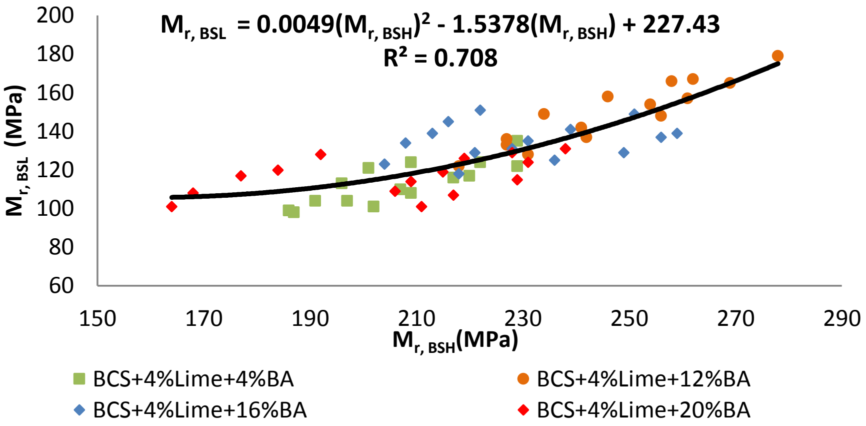

Fig 5.

Table 1. Properties of the Natural Soil

Property	**Description**
Specific gravity	2.75
Sand content	18%
Silt content	21%
Clay content	61%
Natural moisture content	12.4%
Liquid limit	70.4%
Plastic limit	24.9%
Plasticity index	45.5%
Shrinkage limit	14%
Optimum moisture content (BSL)	18%
Maximum dry density (BSL)	15.1kN/m^3
Optimum moisture content (BSH)	15.2%
Maximum dry density (BSH)	17.5kN/m^3
AASHTO classification	A-7-6
USCS classification	CH
Colour	Black
pH	7.01

Table 2. Chemical Composition of Materials Used

Composition	**Soil (%)**	**Lime (%)**	**BA (%)**
Silicon oxide	64.3	-	85
Iron oxide	3.6	0.2	0.56
Aluminium oxide	5.1	12.19	6.56
Phosphorus oxide	-	0.25	0.30
Sodium oxide	1.06	-	-
Potassium oxide	1.52	-	5.30
Calcium oxide	5.67	80.5	0.34
Magnesium oxide	2.31	6.8	0.64
Titanium oxide	1.86	-	-
Manganese oxide	15.79	-	0.48
Nitrogen oxide	-	≤0.004	-
Sulphur oxide	-	≤0.10	0.20
Minimum assay (after ignition)	-	98	-
LOI	1.87	≤2	-