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Suitability of Rice Husk Ash to Improve Geotechnical Properties of Soil for Embankments

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Abstract: This study investigates the applicability of Rice Husk Ash (RHA) as an alternative material for soil improvement. The soil was obtained from a borrow pit located in Kuduvil, Sri Lanka (7°16'36.0"N 81°45'32.8"E) and RHA was collected from a power plant belonging to the Bio energy Solution (Pvt) Ltd, located in Oluvil, Sri Lanka (7°19'28.1"N 81°50'54.0"E). The soil was blended with RHA in weight percentages ranging from 0% to 18% at an increment of 3% to study the improvement of particle size distribution analysis, liquid limit, plastic limit, specific gravity, California Bearing Ratio (CBR), Maximum Dry Density (MDD), Optimum Moisture Contend (OMC) and Unconfined Compressive Strength (UCS) of the samples. Results showed a good improvement in particle size distribution with increasing percentage of RHA. As the RHA percentage increased from 0% to 18%, the liquid limit and plastic limit increased from 36% to 62.5% and 19.7% to 42.4%, respectively. Further, the MDD decreased from 1,980 kg/m^3 to 1,610 kg/m^3 whereas the optimum moisture content increased from 8% to 16.25%. In addition, CBR increased by up to 30% from 7.6% to 15% of RHA, and decreased subsequently. Similarly, UCS increased at 6% of RHA, followed by a decrease thereafter. It was revealed that 9% of RHA amendment provided an optimum mix proportion yielding overall the best results. Furthermore, a series of correlations between CBR and geotechnical properties were derived using multiple linear regression analysis.

Keywords: CBR, Compaction; Embankment, Geotechnical competent; Rice Husk Ash; Soil Improvement;

1. Introduction

1.1 Background

Sri Lanka is one of the developing countries in the world. Road network is one of the key factors for the economy of a country. Further, it has an extensive road network for inland transportation with more than 100,000 km of paved roads (RDA, 2019).

Further, the construction of highways showed a rapid growth in the recent past in Sri Lanka due to various projects such as the construction of expressways, widening and improvement of highways, improvements of rural roads under the *i*Road project and the improvement of a 100,000 km roads project. Hence, it is observed that there is a huge requirement for suitable materials in highway maintenance and construction. In the modern era, researchers study to reuse by-product materials to improve soil properties and utilize them with a view of sustainable development. Application of RHA improves construction materials by enhancing strength and durability, reducing cement usage, lowering costs, and contributing to sustainability through reduced carbon emissions.

1.2 Aim

This study is to examine the suitability of RHA to improve soil available in Ampara District, Sri Lanka for road constructions and applications.

1.3 Objectives

- To study the geotechnical properties of soil and RHA.
- To determine the immediate effect on geotechnical properties of selected different mixed proportions of soil and RHA.
- To investigate the optimum mixing ratio which yields the best geotechnical properties for embankment applications.

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- To develop statistically meaningful relationships between CBR and easily measurable geotechnical properties of soil and RHA mixes.

1.4 Signification of the Study

Soil is known as one of the basic materials with low cost for construction of any type of road. Hence, scarcity of suitable materials becomes one of the major issues in the construction field day by day, and it costs unwanted delays in many projects. Hence, replacing soil is a very expensive option. Therefore, improvement in soil properties can be used to overcome this issue. Although similar studies had been carried out across the globe by using various additives, no studies have yet been carried out by using RHA with similar chemical compositions.

1.5 Scope

This study is limited to examine the soil properties taken from the "Kuduvil" borrow pit (7°16'36.0"N 81°45'32.8"E) by adding different percentages of RHA taken from "Bio energy Solution (Pvt) Ltd" (7°19'28.1"N 81°50'54.0"E) to study the engineering properties of the mix and determine the optimum mix percentage. The scope is to find out only the engineering properties and not to examine any chemical properties. Further, soil behavior varies depending on the region of borrow pits and the properties of RHA vary depending on the state of burning.

Since the initial objective is to evaluate the immediate effects of varying percentages of RHA on soil properties, focusing on CBR and UCS values at standard curing conditions. However RHA, being pozzolanic in nature, can exhibit significant changes in strength and performance over time due to ongoing reactions.

2. Literature Review

2.1 Atterberg Limits

Several studies have demonstrated that chemical and waste-based stabilizers significantly modify soil plasticity characteristics. Alam and Rayhan (2015) reported reductions in liquid limit (LL) from 45.19% to 33.05% and plastic limit (PL) from 18.46% to 16.44% with cement–glass dust stabilization. Similar decreasing trends in LL, PL, and plasticity index (PI) with quarry dust addition were observed by Indiramma and Sudharani (2016), while Thirumalai et al. (2017) reported a reduction in LL from 21% to 17%. Ahamed (2014) documented reductions in LL and PI of up to 47% and 13%, respectively, whereas Yadu et al. (2011) noted a progressive decrease in PI with increasing fly ash and rice husk ash (RHA) contents. Guttikonda and Abhilash (2018) further observed that increasing NaCl content led to decreased LL and PI with a marginal increase in PL. Fattah et al. (2013) attributed the general reduction in LL and increase in PL in soil–RHA mixtures to cation exchange and the formation of cementitious calcium silicate compounds, a mechanism consistent with other reported findings. Overall, these studies collectively confirm that stabilizer addition reduces soil plasticity through physicochemical interactions, thereby improving workability and moisture resistance.

2.2 Specific Gravity

Thirumalai et al. (2017) reported an increase in the specific gravity of black cotton soil with the addition of quarry dust and granite waste due to replacement of highly plastic clay minerals with denser materials. Similar trends were observed by Karthik et al. (2014), who found that specific gravity increased with fly ash content up to 5% and then stabilized at about 2.7. In contrast, Yadu et al. (2011) and Fattah et al. (2013) reported a reduction in specific gravity with the addition of fly ash and rice husk ash, attributed to their lower inherent specific gravity, particularly RHA (~2.04).

2.3 Proctor Compaction

Musa & Alhaji (2007) reported that MDD generally decreases and OMC increases with increase in RHA content (2 – 8%) at specified cement contents. Guttikonda & Abhilash (2018) stated that OMC increases and MDD decreases as the percentage of NaCl increases for their study. Yadu et al. (2011) stated that OMC increases and MDD decrease with increasing percentage of RHA. The decrease in MDD can be attributed to the replacement of soil by FA and RHA. In addition, Fattah et al. (2013) reported that MDD decreases with an increase in the RHA content and the OMC increases with an increase in the RHA content. Singh & Maan(2017) concluded that OMC and MDD decrease with the addition of RHA and fly ash. Basha et al. (2005) stated that RHA increased the OMC and decrease the amount of the MDD corresponding to increasing in cement and RHA percentages.

Principally, an increase in dry density indicates an improvement. Unfortunately, both cement and RHA, instead, reduce the dry density. Sabat & Nanda (2011) also reported that, irrespective of the increase in the percentage of addition of RHA, MDD goes on decreasing. When 20% of RHA was added to expansive soil, MDD of soil decreases to 15.5 kN/m^3 from 16.1 kN/m^3, which is due to the attribution of lower value of specific gravity (2.3) of RHA as compared to higher specific gravity (2.61) of expansive soil. Similarly, OMC increases irrespective of the percentage addition of RHA. When 20% of RHA was added to expansive soil, OMC increased to a value of 23% from 21%. The increase in OMC may be caused by the absorption of water by the RHA. This trend is in line with the conclusion of Musa & Alhaji (2007) that MDD decreases due to the attribution of relatively lower specific gravity (2.25) of RHA that replaces the soil of relatively higher specific gravity (2.69). Indiramma & Sudharani (2016) reported that, as the percentage of quarry dust increases, MDD increases and OMC decreases. A similar trend was observed by Reddy & Prasad (2017). Raj & Gopinath (2015) studied about strength improvement of lateritic soil using fly ash and tire chips and reported that dry density increases with an increase in fly ash content up to 6% and thereafter decreases, and dry density increases up to 1.31 times for the addition of 6% fly ash. Ahamed (2014) reported that the dry density increases as the fly ash is raised to 15%, then reduced to 1.53 at 20%. The optimum moisture content decreases to 15%, and thereafter it starts to increase. The results of Indiramma & Sudharani (2016), Raj & Gopinath (2015), and Reddy & Prasad (2017) are compatible with each other. Pandey & Rabbani (2017) studied soil stabilization by using cement and reported that the OMC of the mixture (soil and cement) increases with increasing cement content. Alam & Rayhan (2015) reported a reduction in OMC and variation in MDD. Further, Harshita (2018) concluded that OMC reduces from 14.87% to 10.89% with an increment in the percentage of lime from 0% to 9%. Beyond that addition, there is a slight increase in OMC. Further, Musa & Alhaji (2007), Guttikonda & Abhilash (2018), Yadu et al. (2011), Fattah et al. (2013) and Singh & Maan (2017) and Basha et al. (2005) have observed the same trend in their results.

2.4 California Bearing Ratio

Karthik et al. (2014) concluded that the bearing capacity of borrowed soil is 10 kg/mm^2, the CBR value of the soil is 3.1, pavement thickness for soil is 12 inches, the stabilized soil with 6% of fly ash reaches the bearing capacity of 35 kg/mm^2 and CBR of stabilized soil is 4.82. Decreased pavement thickness value due to the stabilization is 8.5 inches. Venkateswarlu et al. (2015) reported that CBR increased to 6.7 from 1.2 at 10% of QD to the expansive soil. Raj & Gopinath (2015) stated that for 6% fly ash, the maximum CBR obtained is 5.51 which is 1.42 times greater than the original soil.

Further, Ahamed (2014) reported that soaked CBR value significantly increased as ash content in the soil mixture increased. The slight reduction in CBR occurs when the soil-ash mixture contains more than 15% of ash for their study about fly ash utilization in soil stabilization.

Reddy & Prasad (2017) found out that soaked CBR values increase from 1.39 to 2.15. Beyond that, it decreases, and 20% of sugarcane straw ash was observed as the optimum percentage. Sabat & Nanda (2011) observed that when 10 % of RHA was added, the soaked CBR of soil increases to 2.6% from 1.98%. With the increase in different percentages of marble dust, the soaked CBR of soil further increased to 7.8% from 2.6% when 20% marble dust was added. Further addition of marble dust reduced the soaked CBR of the soil. The soaked CBR reduces to 6.5% when 30% marble dust was added to expansive soil stabilized with 10% RHA. The soaked CBR achieved the highest value for a 20 percentage of marble dust addition.

An initial reduction in CBR values was noticed by Musa & Alhaji (2007) with the inclusion of 2% RHA then, the value increased to its maximum at 6% of RHA. Yadu et al. (2011) found that the CBR value of raw soil increases with the addition of RHA and FA. Therefore, generally, CBR values increase with the addition of RHA or FA.

2.4.1 Developing a correlation for CBR

Rakaraddi & Gomarsi (2015) established a relationship between CBR with different soil properties by using simple relation and Multiple Linear Regression Analysis (MLRA). For simple relation, graphs were plotted with CBR against different soil parameters and drew suitable trend lines with higher correlation coefficients. In this research, any correlation with an R^2 with values more than 0.80 is considered as the best fit.

For MLRA, CBR is considered as the independent variable and soil properties such as gravel (G), fines (F), sand(S), LL, PL, MDD and OMC are considered as the dependent variables. This analysis was carried out using standard statistical software.

2.5 Unconfined Compressive Strength

Pandey & Rabbani (2017) stated that the Unconfined Compressive Strength (UCS) of stabilized soil increases when increasing the quantity of cement in a mixture. Indiramma & Sudharani (2016) reported that UCS increases with an increment in the percentage of quarry dust.

Reddy & Prasad (2017) stated that there is an improvement in UCS. Thirumalai et al. (2017) observed that UCS improved in black cotton soil after adding 20% of quarry dust and granite waste. Further, Raj & Gopinath (2015) concluded that the UCS value increases with an increase of fly ash content up to 6% and then decreases.

Sabat & Nanda (2011) observed that when 10%RHA was added, UCS of soil increased to 72 kN/m^2. The addition of different percentages of marble dust had accountable effects on the UCS of the RHA stabilized expansive soil.

A variation of UCS with an increase in RHA from 0% to 12% for 7 days, 14 days and 28 days curing period was investigated by Musa & Alhaji (2007) and reported a sudden initial reduction in UCS as the RHA was mixed to the natural soil (recorded UCS value of natural soil is 290 kN/m^2). Increment in the UCS values reported for the subsequent addition of RHA at between 6 – 8%, after that it was reduced between 10 – 12% of RHA addition. Yadu et al. (2011) reported that the strength of the soil increases with the addition of FA and RHA. The initial increase in the UCS with the addition of RHA is attributed to the formation of cementitious compounds between the CaOH present in the soil and the pozzolana present in the FA and RHA. The decrease in the UCS values after the addition of 12% FA and 9% RHA may be due to the weak bond formation between the soil and the cementitious compounds.

Fattah et al. (2013) reported an increment in the UCS values for the subsequent addition of RHA and the maximum was achieved between 6 – 8% of RHA. After that, UCS dropped at 9% RHA. The subsequent increase in UCS value is due to the formation of cementitious compounds between the pozzolans present in the RHA and CaOH present in the soil and RHA. Then, the UCS values decreased after the addition of 8% RHA as weak bonds were formed between the soil and the cementitious compounds as results of surplus RHA was not used in any reaction. Basha et al. (2005) stated that RHA slightly increases the strength.

2.6 Chemical Composition

Tharshika et al. (2019) used the same rice husk, which was used for this study for the evaluation of RHA and water treatment sludge in masonry unit production. RHA was obtained from Bio energy Solution Limited, Sri Lanka. The RHA used for this study was burnt at a temperature between 600 to 800 °C during the process of biomass production and no further treatment was performed at the plant.

2.6.1 Characterization of RHA

It was revealed in the XRF analysis that the RHA has a prominent amount of silicon (74.4%), potassium (5.1%) and iron (3.9%) oxides. In addition to that, due to the uncontrolled burning process of biomass production, loss on ignition (LOI) is approximately 10%. Further most importantly, pozzolanic activities were determined by the high amorphous silica content characteristic of RHA and low bulk unit weight and high external surface area were observed due to high porous particles that RHA consists. RHA behaves like fly ash and blast furnace slag regarding development of strength in cementitious binders. However, the pozzolanic reaction occurred at later stages than the other supplementary cementitious materials due to the higher silica content.

Table 1 - Chemical Composition of RHA

Elements	Mass % in RHA
SiO_2	74.4
K_2O	5.1
Cao	3.9
Fe_2O_3	3.9
SO_3	0.7
TiO_2	0.7
MgO	0.8
LOI*	10.5

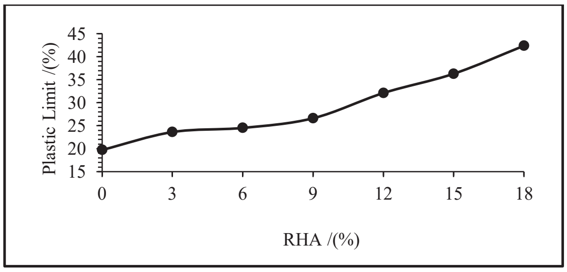

Figure 1-Variation of Plastic Limit with RHA

3. Methodology

The raw soil sample (A) blended with 3%, 6%, 9%, 12%, 15% and 18% of RHA by weight were subjected to laboratory tests B, C, D, E, F, and G, respectively, to find the geotechnical engineering properties. The following laboratory tests were carried out according to the standard procedures.

- Particle Size Analysis.
- Atterberg Limits.
- Specific Gravity.
- Proctor Compaction.
- California Bearing Ratio.
- Unconfined Compressive Strength.

4. Data Analysis and Interpretation of Results

4.1 Results for Particle Distribution

Fine particles in RHA are higher than that of soil. Fine particles in samples A and B (raw sample & sample with 3% RHA) are less than the specified limits. Hence, further addition of RHA increases the fine particles in the sample. Therefore, the passing percentage of the sample increases as the percentage of RHA in the sample increases. As a result, fine particles in samples C, D, E, F and G (addition of 6%, 9%, 12%, 15% and 18% of RHA, respectively) increase and satisfy the requirement of specification limits.

4.2 Results for Atterberg Limits

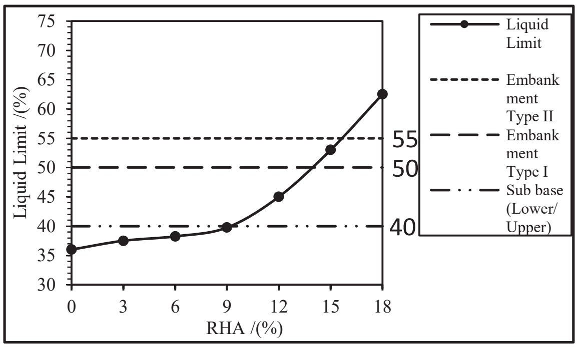

Figure 2 - Variation of liquid limit with RHA

Laboratory tests to find Atterberg limits of soil have been carried out for varying percentages of RHA i.e. from 0% to 18% at an increment of 3% and the results are presented in Figure 2, Figure 3 and Figure 4. The liquid limit and plastic limit of RHA treated soil increase with the addition of RHA due to the replacement of the soil grains with the RHA particle and higher water holding capacity of RHA.

The liquid limit increases from 39% to 69.5%.Meanwhile, the plastic limit of soil alone is 19.7% and upon the addition of RHA content plastic limit increases from 19.7% to 42.4%. Further, the cationic exchange reaction adduced for the liquid limit is also applicable here. plastic index also increases except 3% addition of RHA. Similar results are reported by Basha et al. (2005).

4.3 Results for Specific Gravity

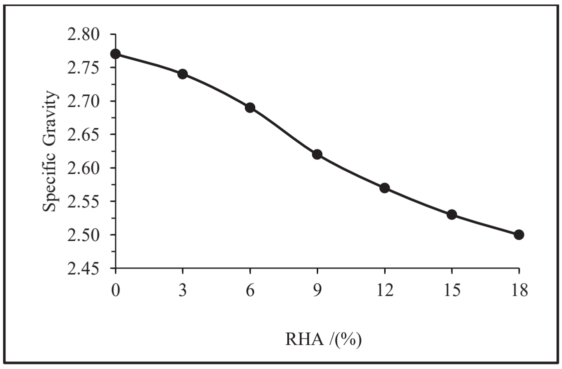

Figure 3 - Variation of specific gravity with RHA

It was observed that the specific gravity of the sample decreases with the addition of RHA. The subsequent reduction in the specific gravity is attribution of lower value of the specific gravity of RHA. The results are in agreement with Yadu et al. (2011) and Fattah et al. (2013).

4.4 Results for Proctor Compaction Test

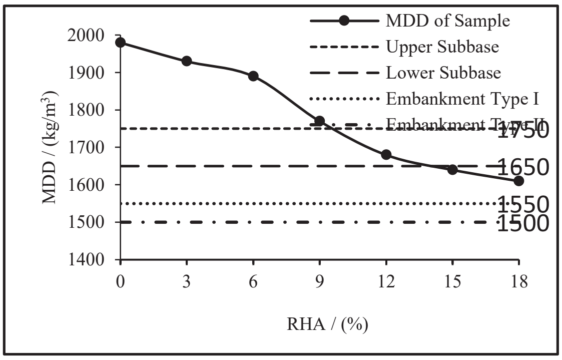

Figure 4 - Variation of MDD with RHA

The MDD of the raw sample is 1,980 kg/m^3. The decrease in the MDD can be attributed to the soil replaced by RHA in the mixture, which has relatively lower specific gravity compared to that of the soil. Due to this reason, MDD decreases from sample A to G with the addition of RHA.

Hence, minimum MDD requirements for embankment type II, type I, lower sub base and upper sub base are 1,500 kg/m^3, 1,550 kg/m^3, 1,650 kg/m^3 and 1,750 kg/m^3, respectively according to the standard specifications.

Hence, samples A, B, C and D satisfy the requirement for upper sub-base, sample E satisfies the requirement for lower sub-base and the rest of the samples satisfy the requirement for embankment type I.

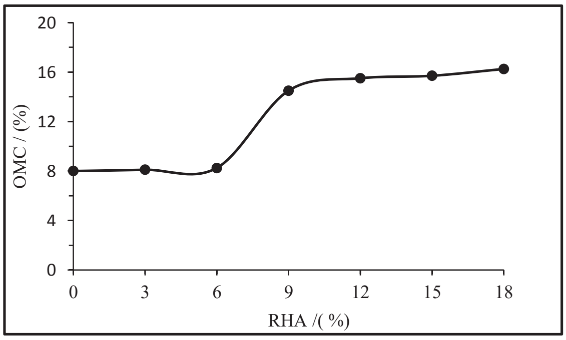

Figure 5 - Variation of OMC with RHA

Optimum moisture content increases as RHA contents increase. The increase is due to the addition of RHA, by which the quantity of free silt and clay fraction and coarser materials are decreased and larger surface areas are formed and these processes need water to take place. Therefore, more water is needed for the compaction of the soil and RHA mixtures. Further, the increase in the optimum moisture content may be due to the absorption of water by the RHA. These results are compatible with the findings of Musa & Alhaji (2007), Guttikonda & Abhilash (2018), Yadu et al. (2011) and Fattah et al. (2013).

4.5 Results for CBR

Figure 7 illustrates the variation of soaked CBR with the increase in RHA from 0 to 18%. CBR values of soaked samples increase with the addition of RHA up to 15%, after which the values decrease.

Existence of water supports to further the formation of the cementitious compounds between the soil and RHA which may be the reason for the increment in CBR. Subsequent addition of RHA after 15% decrease the CBR due to surplus RHA that was not mobilized in soil – RHA reaction. Further, 5%, 7%, 15% and 20% of CBR values are required for embankment type II, embankment type I, lower sub-base and upper sub base, respectively, according to the standard specifications

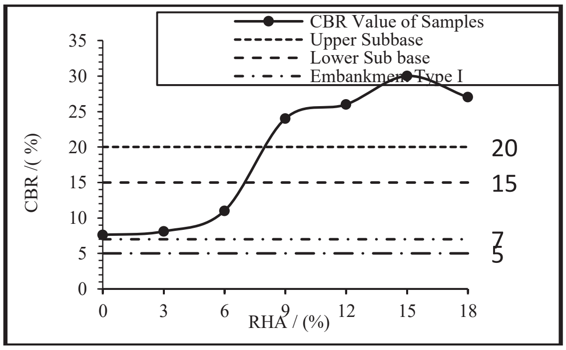

Figure 6 - Variation of soaked CBR with RHA

Therefore, samples A, B and C satisfy the requirement for embankment type II and embankment type I, meanwhile samples D, E, G, and F satisfy the requirement of the upper sub base.

4.6 Results for UCS

The UCS increases up to 6% of RHA addition. The subsequent increase in the UCS is attributed to the formation of the bond between the soil and RHA. This decrease in the UCS values after the addition of 6% RHA, may be due to the excess RHA introduced to the soil.

Due to this, it forms weak bonds between the soil and the RHA. The results are in agreement with Pandey & Rabbani (2017), Indiramma & Sudharani (2016), Reddy & Prasad (2017), Thirumalai et al. (2017), Raj & Gopinath (2015) and Sabat & Nanda (2011). Further, the maximum value for UCS and CBR were obtained at 6% and 15% of RHA addition, respectively.

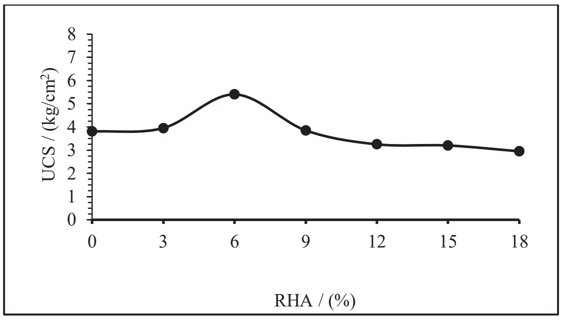

Figure 7- Variation of soaked UCS with RHA

This may be due to the different size distribution of particles used for both tests. Material passing through a 19.0 mm sieve was used for the CBR test while those passing through 425 μm sieve were used for the UCS test. Therefore, the material used for CBR is well graded and can be packed better than those used for UCS. As a result, CBR could be increased with a higher percentage of RHA than that for UCS. In addition, CBR tests were carried out after the soaking and a UCS test was carried out without soaking. Hence, the presence of water helps to further the formation of the cementitious compounds between the soil and RHA. As a result, the CBR can be increased up to a higher percentage of RHA than UCS due to the availability of water for hydration. The two factors above, in combination, are presumed to increase the optimum percentage of RHA for CBR as compared to UCS.

4.7 Developing a Numerical Model for CBR

The results obtained from the laboratory tests are tabulated in Table 2.The relationship between soaked CBR and other geotechnical properties is plotted from Figure 8 to Figure 13 to generate mathematical equations.

From Figure 8, CBR = - 192.4 + 8.35 (LL) - $0.078(LL)^2$------ (15), and the coefficient of correlation $R^2 = 0.871$.

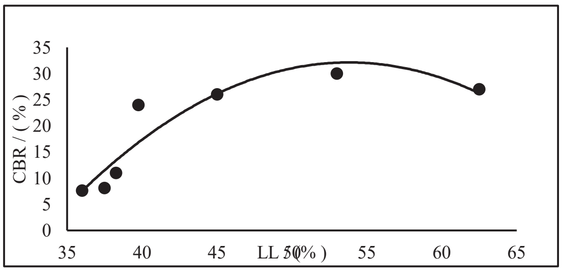

Figure 8 - Correlation between CBR and LL

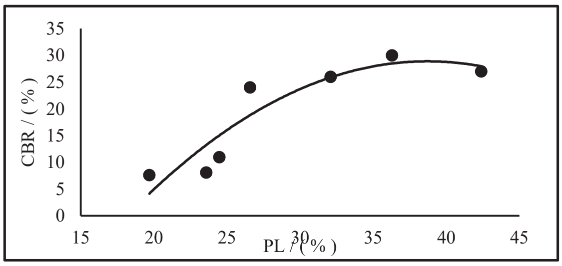

Figure 9 - Correlation between CBR and PL

Table 2 - Engineering properties of the samples

Soil / (%)	100	97	94	91	88	85	82
RHA/ (%)	0	3	6	9	12	15	18
Particle size of (D_{50}) / (mm)	4.57	4.42	4.23	4.06	3.89	3.66	3.47
LL/ (%)	36.00	37.50	38.25	39.75	45.00	53.00	62.50
PL / (%)	19.70	23.60	24.50	26.60	32.10	36.30	42.40
PI / (%)	16.30	13.90	13.75	13.15	12.90	16.70	20.10
MDD /(kg/cm³)	1980	1930	1890	1770	1680	1640	1610
OMC / (%)	8.00	8.10	8.25	14.50	15.50	15.70	16.25
CBR / (%)	7.6	8.1	11.0	24.0	26.0	30.0	27.0
Specific Gravity	2.77	2.74	2.69	2.62	2.57	2.53	2.50
UCS Value / (kg/cm²)	3.80	3.95	5.40	3.85	3.25	3.20	2.95

From Figure 9, CBR = -73.6 + 5.23(PL) - $0.068(PL)^2$ ---------- (16), the coefficient of correlation $R^2 = 0.853$.

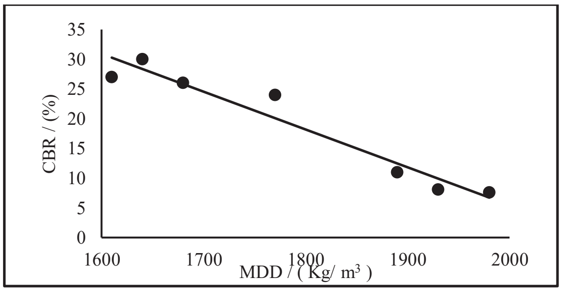

Figure 10 - Correlation between CBR and MDD

From Figure 10, CBR = 132.4 – 0.064 (MDD) ----- (17), the coefficient of correlation $R^2 = 0.939$.

Table 3 - Comparison of CBR for Simple Relation

Soil / (%)	**93**	**89.5**	**86**
RHA / (%)	**7**	**10.5**	**14**
Particle size of (D_{50}) / (mm)	4.21	4.05	3.72
LL / (%)	38.5	43.0	48.0
PL / (%)	25.2	29.3	33.5
PI / (%)	13.3	13.7	14.5
MDD / (kg/m^3)	1845	1730	1660
OMC / (%)	10.50	15.00	15.50
CBR / (%)	**16.5**	**25.0**	**28.0**
Specific Gravity	2.66	2.60	2.55
UCS Value / (kg/cm^2)	4.60	3.50	3.20

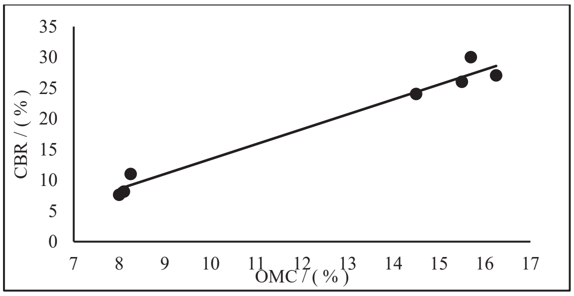

Figure 11 - Correlation between CBR and OMC

From figure 11, CBR = -10.70 + 2.42 (OMC) ------- (18), the coefficient of correlation R^2 = 0.972.

Similarly, from figure 12, CBR = 254.0 – 89.25 (SG) -------- (19), the coefficient of correlation R2 = 0.921

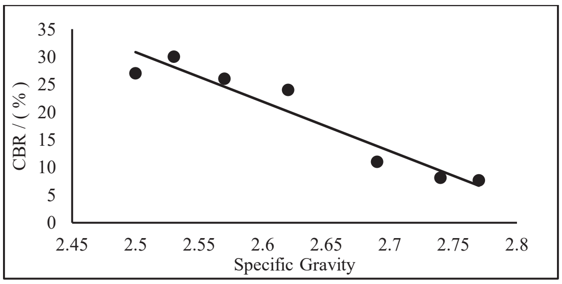

Figure 12 - Correlation between CBR and SG

From Figure 13 graph, CBR = 162.2 – 64.18 (UCS) + 6.69(UCS) ^{2} ----- (20), the coefficient of correlation R^2 = 0.623. Since it is less than 0.8, this is not a best fit.

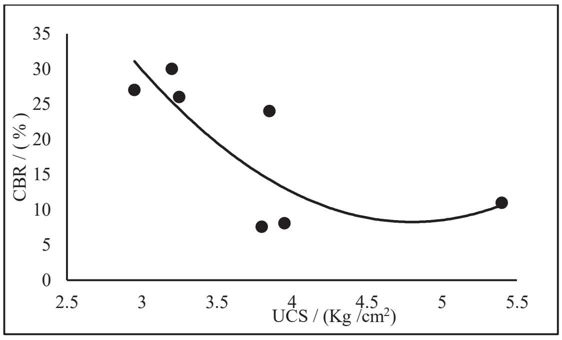

Figure 13 - Correlation between CBR and UCS

4.7.1 Multiple Linear Regression Analysis (MLRA)

From the statistical analysis by using the "Minitab" application, the following relationships are derived.

CBR = 254 – 0.47 LL – 0.73 PL – 47.6 D50, R^2 = 0.91 …(21)

CBR = 277.6 + 0.74 LL – 2.12 PL – 0.128 MDD, R^2= 0.99...(22)

CBR = 25.8 – 0.016 MDD + 1.831 OMC, R^2 = 0.97 …(23)

CBR = 46.1+ 5.2D_{50} – 0.0376 MDD + 1.54 OMC, R^2 = 0.97(24)

CBR = 148.1 + 21.3D_{50} – 0.122 MDD + 0.70 UCS,R^2= 0.96 ...(25)

CBR = 495.3 +42.2 D50 – 0.75UCS – 244.7 SG, R2= 0.98...(26)

CBR is correlated with more than one and less than four geotechnical properties of the sample. The P-value of the regression models in the analysis of variance table are less than 0.05. This shows the model estimated by the regression procedure significant at the level of 0.05.

The R2 - values indicate the variance in CBR of a particular equation. These values explain how the model fits the data well. The T - value measures the size of the difference relative to the variation in your sample data. T is simply the calculated difference represented in units of standard error. The greater the magnitude of T, the greater the evidence against the null hypothesis.

4.8 Comparison of Theoretical Values and Practical Values

Theoretical values obtained from the simple relation equations and MLRA are compared with the practical values that were obtained from the laboratory tests for 7%, 10.5% and 14% addition of RHA.

4.8.1 Comparison for simple relationships

Equations 15 to 20 are derived by using simple relation for CBR. Theoretical values and practical values are compared as follows.

Where $\% \ of error$ = (Theoretical value – Practical .value) /Practical .value X 100

4.8.2 Comparison for Multiple Linear Regression Analysis (MLRA)

Equations 21 to 26 are derived by using MLRA for CBR. Theoretical values and practical values are compared as follows.

Table 4: Comparison of CBR for simple relation

Eqn. No	Equation	Theoretical values for CBR	Practical values for CBR	Error / (%)
For 7 % of RHA				
15	CBR = -192.4 + 8.35 (LL) – 0.078 $(LL)^2$	13.95	16.5	-15.5
16	CBR = -73.6 + 5.23 (PL) – 0.068$(PL)^2$	16.42		-0.5
17	CBR = 132.4 – 0.064 (MDD)	15.32		-7.2
18	CBR = -10.7 + 2.42 (OMC)	14.69		-11.0
19	CBR = 254 – 89.25 (SG)	16.60		0.6
20	CBR = 162.2 -64.18 (UCS) +6.69 $(UCS)^2$	8.60		-47.9
For 10.5 % of RHA				
15	CBR = -192.4 + 8.35 (LL) – 0.078 $(LL)^2$	23.06	25.0	-7.8
16	CBR = -73.6 + 5.23 (PL) – 0.068$(PL)^2$	22.85		-8.6
17	CBR = 132.4 – 0.064	22.61		-9.6
18	CBR = -10.7 + 2.42 (OMC)	25.57		2.3
19	CBR = 254 – 89.25 (SG)	22.40		-10.4
20	CBR = 162.2 -64.18 (UCS) +6.69 $(UCS)^2$	19.56		-21.8
For 14% of RHA				
15	CBR = -192.4 + 8.35 (LL) – 0.078 $(LL)^2$	29.49	28.0	5.3
16	CBR = -73.6 + 5.23 (PL) – 0.068$(PL)^2$	27.05		-3.4
17	CBR = 132.4 – 0.064 (MDD)	27.06		-3.4
18	CBR = -10.7 + 2.42 (OMC)	26.78		-4.4
19	CBR = 254 – 89.25 (SG)	26.41		-5.7
20	CBR = 162.2 -64.18 (UCS) +6.69 $(UCS)^2$	25.36		-9.4

Table 5- Comparison of CBR for MLRA

Eqn. No	Equation	Theoretical values for CBR	Practical values for CBR	Error/ (%)
For 7 % of RHA				
21	CBR = 254 – 0.47LL – 0.73 PL – 47.6 D_{50}	17.1	16.5	3.6
22	CBR = 277.6 +0.74 LL - 2.12 PL – 0.128 MDD	16.5		0.0
23	CBR = 25.8 – 0.016 MDD + 1.831 OMC	15.5		-6.1
24	CBR = 46.1 + 5.2 D_{50} – 0.0376MDD + 1.54OMC	14.8		-10.3
25	CBR = 148.1 + 21.3D_{50} - 0.122MDD + 0.7 UCS	15.9		-3.6
26	CBR = 495.3 + 42.2 D_{50} – 0.75 UCS – 244.7SG	18.6		12.7
For 10.5 % of RHA				
21	CBR = 254 – 0.47LL – 0.73 PL – 47.6 D_{50}	19.6	25.0	-21.6
22	CBR = 277.6 +0.74 LL - 2.12 PL – 0.128 MDD	25.9		3.6
23	CBR = 25.8 – 0.016 MDD + 1.831 OMC	25.6		2.4
24	CBR = 46.1 + 5.2 D_{50} – 0.0376MDD + 1.54OMC	25.2		0.8
25	CBR = 148.1 + 21.3D_{50} - 0.122 MDD + 0.7 UCS	25.8		3.2
26	CBR = 495.3 + 42.2 D_{50} – 0.75 UCS – 244.7SG	27.4		9.6
For 14% of RHA				
21	CBR = 254 – 0.47LL – 0.73 PL – 47.6 D_{50}	29.9	28.0	6.8
22	CBR = 277.6 +0.74 LL - 2.12 PL – 0.128 MDD	29.6		5.7
23	CBR = 25.8 – 0.016 MDD + 1.831 OMC	27.6		-1.4
24	CBR = 46.1 + 5.2 D_{50} – 0.0376MDD + 1.54OMC	26.9		-3.9
25	CBR = 148.1 + 21.3D_{50} - 0.122 MDD + 0.7 UCS	27.1		-3.2
26	CBR = 495.3 + 42.2 D_{50} – 0.75 UCS – 244.7SG	26.9		-3.9

From table 4 and table 5, the theoretical values are approximately the same as that of practical values. Therefore, the above equations can be used to calculate the CBR value from the other soil properties depending on the data available.

5. Conclusions and Recommendations

5.1 Conclusions

- As the addition of RHA increases from 0% to 18%, fine particles of samples increase. Therefore, the particle size of the samples with more than 6% of RHA satisfies the required ranges.
- The MDD of the raw sample is 1,980 kg/m^3. MDD decreases as the percentage of RHA increases. Hence, samples up to 9% of RHA addition still satisfy the requirement for upper sub-base, and up to 12% of RHA addition can be used for lower sub-base and rests can be used for embankment filling.
- A variation of soaked CBR with an increasing percentage of RHA increases up to 15% then it decreases. As a result, samples up to 6% of RHA can be used for embankment filling and the rest of the samples can be used as sub-base materials.
- LL increases as the percentage of RHA increases, hence, the sample up to 9% of RHA still satisfies the requirement of specification for sub-base and the plastic index of the sample satisfies the range between 3% and 12% of RHA addition.

- The UCS and USS increase up to 6% of RHA addition. The UCS value increases subsequently due to the bond formation between the soil and RHA up to 6% RHA. Then decreases due to the surplus RHA introduced to the soil which forms a weak bond between the RHA and the soil.
- Considering the above test results, a sample with 9% of RHA is the optimum proportion to be used for the best results.
- The relationship for CBR with another soil parameter can be derived by using simple relation and MLRA.

5.2 Recommendations for Future Studies

The following factors are also to be taken into account.

- Incomplete burning of RHA due to mechanical issues in the plant.
- Properties of other borrow pits may be different.
- Excess use of RHA may leach out and pollute the groundwater.
- Comprehensively address long-term performance and time-dependent variations in CBR and UCS.

Therefore, the following arrangements or precautions can be followed.

- Mechanical setup for complete burning of RHA should be arranged.
- Properties of adjacent borrow pits can be studied and compared with the results.
- An optimum proportion of RHA should be recommended to get the best results and to avoid leaching.

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