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Strength improvement of weak subgrade expansive soil by using red ash and lime

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Abstract
Several studies have been conducted to minimize or eliminate the danger of damage to structures because of the heave and shrinkage of expansive soil. Road construction industries have attempted mechanisms to improve the ground dominated by weak soils. The methods of soil stabilization using different additives such as red ash and lime alone have been studied so far. However, stabilization using red ash or lime only is not efficient, economical, and eco-friendly.

This study was conducted to improve the strength of weak expansive sub-grade soil with locally available materials i.e., Red Ash (RA), and with a suitable proportion of Hydrated Lime (HL) for the required sub-grade strength parameter. Index property (i.e., gradation, Atterberg's limit test, linear shrinkage (LS), and free swell index (FSI)) and mechanical property tests (compaction, unconfined compressive strength (UCS), and California bearing ratio (CBR)) were conducted for both natural black cotton soil (NBCS) and soil treated with red ash and hydrated lime in per-defined combination. As per the test result, NBCS has a plasticity index (PI) of 61%, and under sieve analysis, more than 35% passes 75µm sieve, and the soil is classified as A-7-5 or A-7-6 and CH as per AASHTO and USCS respectively which is categorized under poor sub-grade materials. Also, the CBR value was 1.51%, which didn't meet the minimum sub-grade CBR strength value of 5% according to ERA 2013.

From the index property test result of treated soil, the LL, PI, LS, and FSI showed a continuous reduction with an increase in percentage red ash, hydrated lime, and a combination of red ash-hydrated lime compared with NBCS. The PI value observed < 20% and LS < 10%, for a higher percentage of red ash-hydrated lime combination. The MDD significantly increased with the addition of red ash and reduced with the addition of hydrated lime. The OMC value decreased for with the addition of red ash and hydrated lime on NBCS. As the curing days increase the value of UCS with the addition of red ash and hydrated lime. The CBR value slightly increased with increasing percent of red ash alone, and a much higher increment was obtained with the addition of hydrated lime. With finite element software Abacus simulation of pavement structure treated with hydrated lime and red ash the deformation of pavement structure reduces by 20% compared to natural untreated sub-grade material. Comparing cost for replacement method of stabilization with soil treatment by red ash and hydrated lime up to 10% saving in construction cost can be achieved.

Keywords: Black cotton soil, red ash**,** hydrated lime, plasticity index and CBR

Introduction

Expansive soil is one of the most abundant and problematic soils in Ethiopia. Its property significantly a change with variation in moisture content, it swells when it gets wet whereas shrinks when it gets dry. Road pavements constructed over this weak soil are highly susceptible to differential settlements due to poor shear strength and high comprehensibility. A list of countries of the world where expansive soil is widely reported includes the USA, Australia, Canada, India, Spain, Israel, Turkey, Argentina, Venezuela, South Africa, Ethiopia, Kenya, Mozambique, Morocco, Ghana, Nigeria etc. (Teferra and Leikun, 1999) [13]. A significant part of Ethiopia is covered by expansive black cotton soil. The aerial coverage of expansive soils in Ethiopia is estimated to be 24.7 million acres (Nebro, 2002) [10]. Also in the capital city, Addis Ababa, considerable areas of Bole, Akaki Kality, Kotebe, CMC, and Mekanisa, are covered by black cotton soils (Arega, 2012; Tsion and Uge, 2017) [1, 15]. The expansive soils of Ethiopia are derived from both groups (Teferra & Yohannes, 1986) [12]. Because of poor drainage, these soils are rich in soluble bases and silica (ERA, 2013b) [3]. Globally, soils rated CL or CH by USCS, and A6 or A7 by AASHTO may be considered potentially expansive (Nelson, and Miller, 1992) [11]. The unified Soil Classification System is the most popular system for use in all types of engineering problems involving soils. The system uses both the particle size analysis and plasticity characteristics of soils (Arora, 2004) [2].

The presence of expansive soils in construction sites such as road alignments is problematic, unless proper care is taken during the planning, location, design, and construction of such infrastructure (Arega, 2012) [1]. Many roads and foundations of light buildings have been reported due to these soils that inflicted billions of dollars in damages and repairs annually to earth structures and facilities (Gidigasu, 2013) [5]. Many reports revealed that road pavements on this type of soil failed before their expected design life causing loss of the country's budget. Roads constructed on unsuitable sub-grade will fail in the form of heave depression cracking unevenness. Stabilization of unsuitable material economically brings down the growing cost of soil stabilizers. According to Krazynski (1980), there is a need to incorporate an economical soil stabilization process before roads are constructed, since experience has clearly shown that the cost of repairs (of bad roads) is very much higher than the cost of a proper initial design, and the results are much less satisfactory. Furthermore use of waste material and natural fiber for improving soil properties is advantageous because they are cheap, locally available, and eco-friendly (Shihab, 2020) [16]

General objective

The main objective of this study is to evaluate the suitability of red ash and hydrated lime as stabilizing agents for weak expansive sub-grade soil.

Materials and Method

This section deals with sample source, material collection, sample preparation and laboratory experiments on using treated and untreated soil. Material source and sample collection is a primary step in the experimental study to commence laboratory tests. An important prerequisite for selecting the target source of expansive sub-grade soil, their variable properties under moisture change, and the selection of locally available materials for improvement sub-grade is a necessary activity. Materials used in this study were presented in the following sub-section. The index and mechanical property was conducted to determine the characteristics of natural and red ash and lime treated soil.

Sampling and Data Collection

Sample preparation and laboratory experiments were carried out according to ASTM and AASHTO soil testing standard procedures. Also, the original black cotton soil was collected from Addis Ababa specific location at Addis Ababa Science and Technology University compound. The sufficient mass of red ash was collected from nearby source and also hydrated lime was purchased from well-known local supplier.

Experimental Study

After detailed reviews on previous related literature quality tests were conducted through experimental tests based on ERA, AASHTO, and ASTM standards. In this experimental research, the design of the experiment was organized to minimize wastage of laboratory test time due to many combinations of additive percentages, Soil modifying and proportioning were done by using different percentages of Red Ash (RA) ranging from 5 to 30% with five percent increment alone and mixed with 3 and 5% Hydrated Lime (HL). UCS, standard proctor compaction, and CBR tests are then performed for that proportion of RA and HL which have shown significant improvement while performing the index tests. The percentages of RA and HL for this specific study are 15%, 20% and 30%. It was desired to make an easy comparison between the results obtained using RA, HL, and combination. Accordingly, it was designed to blend expansive black cotton soil with RA and HL. The experimental design is summarized in the Table 1.

Table 1: Experimental design

Test type												
Mix				Index property					Mechanical Properly			
No	HL (%)	RA (%)	BCS (%)	Gs	LL	PL	LS	PSI	Compaction	UCS	CBR	CBR Swell
1	0	0	100	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	3	0	97	/	✓	✓	✓	✓	✓	✓	✓	✓
3	5	0	95	✓	✓			✓	✓	✓	✓	✓
4	0	5	95	✓	✓	✓	✓	✓				
5	0	10	90	✓	✓	✓	✓	✓				
6	0	15	85	✓	✓	✓	✓	✓	✓	✓	✓	✓
7	0	20	80	✓	✓	✓	✓	✓	✓	✓	✓	✓
8	0	30	70	✓	✓	✓	✓	✓	✓	✓	✓	✓
9	3	5	92	1	✓	✓	✓	✓				
10	3	10	87	I	✓	✓	✓	I				
11	3	15	82	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	3	20	77	✓	✓	✓	.	✓	✓	✓	✓	✓
13	3	30	67	✓	✓	✓	✓	✓	✓	✓	✓	✓
14	5	5	90			✓	✓	✓				
15	5	10	85	✓	✓	✓	✓	✓				
16	5	15	80	✓	✓	✓	✓	✓	✓	✓	✓	✓
17	5	20	75	✓	✓	✓		✓	✓	✓	✓	✓
18	5	30	65	✓	✓	✓	✓	✓	✓	✓	✓	✓

Index property tests

To meet the objective of the study index property of tests such as particle-size distribution, specific gravity test, and Atterberg's limit test was conducted. The test standard procedure of ASTM D422, ASTM D4318, ASTM D 854 were used for particle size analysis, Atterberg's limit and specific gravity test respectively. Soil passing through No. 40 sieve (425μm) was used to conduct index property tests excluding specific gravity and particle size analysis. The sample preparation pictures was as shown on Figure 1.

Fig 1: Sample preparation for index property test

Mechanical property tests

Under this category major engineering property tests such as standard proctor compaction tests, California Bearing Ratio tests, and Unconfined Compressive Strength tests were carried out for natural black cotton soil and also BCS with a selected optimum percentage combination of RA and HL. The tests are conducted following ASTM D698, ASTM D1883, and ASTM D 2166-13, for standard proctor compaction, CBR, and UCS respectively. Also the sample pictures of specimen preparation steps for the mechanical property test was as shown on Figure 2.

Fig 2: Sample preparation, compaction, CBR and UCS test

Result and Discussion

Index and mechanical property test result of natural black cotton soil

Characterization and identification of the expansiveness of the target natural soil before applying stabilizer ingredients is the primary step of this research. The particle size distribution curve indicated that almost 87.80% of the soil passes through the No 200 sieve (0.075 mm) as shown on

Figure 3, the liquid limit and plastic limit of the natural black cotton soil was obtained as 108% and 47% respectively exhibiting the plasticity index of 61%. From the standard proctor compaction test, the optimum moisture content (OMC) and the maximum dry density MDD of the natural black cotton soil (NBCS) were found as 37.40% and 1.24 g/cm. The soil under the study has the ultimate strength (qu) of 384.34 kPa and 451.25 kPa and corresponding strain of 3.29% and 2.21% for zero days and 7 days of curing respectively. The CBR value of the natural BCS was obtained as 1.51% with 13.5% CBR swell. The summary of engineering property test result for natural black cotton soil was as shown on Table 3. According to the particle size distribution test result almost 58% of the total mass of soil is finer than 0.002mm which is classified as clay and the specific gravity of the natural soil was 2.68. The summary of the index property test result for NBCS was shown on the Table 2.

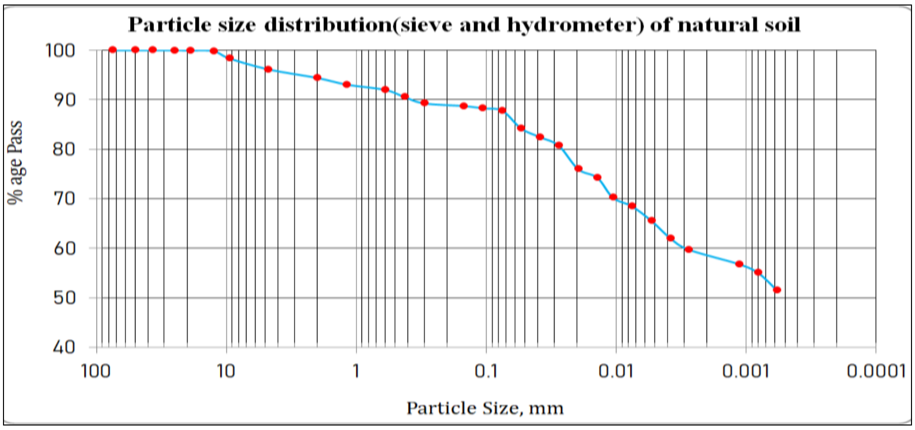

Fig 3: Particle size distribution curve for natural black cotton soil

Table 2: Summary of index property test results

Parameters	Unit	Results
Specific Gravity	-	2.68
Liquid limit (LL)	%	108
Plastic limit (PL)	%	47
Plasticity index (PI)	%	61
Particles larger than 4.75mm	mm	3.85
Coarse Sand (4.75mm-0.425mm)	mm	5.59
Fine Sand (0.425mm-0.075mm)	mm	2.78
Silt (0.075-0.002mm)	mm	29.43
Clay smaller than(0.002mm)	mm	58.35

Table 3: Summary of mechanical property test result for NBCS

S. No	Property	Results
1	AASHTO Soil Classification	A-7-5 or A-7-6
2	Unified Soil Classification	CH
3	Free Swell,%	130
4	Maximum Dry Density, g/cm3	1.24
5	Optimum Moisture Content,%	37.4
6	Unconfined Compressive Strength. kPa (0 day curing)	384.34
7	Unconfined Compressive Strength. kPa (7 days curing)	451.25
8	California Bearing Ratio (CBR),%	1.51
9	CBR Swell,%	13.5

As per AASHTO LL, less than 35% indicates low plasticity, between 35% and 50% intermediate plasticity, between 50% and 70% high plasticity, and between 70% and 90% very high plasticity, therefore, these values indicate that the soil is highly plastic clay. Accordingly, the soil falls under the A-7-5 or A-7-6 class based on the AASHTO soil classification system. Most black cotton soils are classified as A-7-5 and A-7-6 by the AASHTO Classification System with group index values varying from 13 - 89 and CH and CL on the Unified Soil Classification System (Gidigasu, 2013) [5]. Soils under this class are generally classified as a material of poor engineering property to be used as a sub-grade material. From the index property test result, the natural soil under the study has a high liquid limit, plasticity index, and free swell values (see also Table 3) which were found higher than recommended values by local standard (i.e. LL < 60% and PI < 30%, ERA 2013). According to the Ethiopian Roads Administration (ERA) pavement design manual sub-grades are classified based on the laboratory-soaked CBR tests on samples compacted to 97% AASHTO T180 standard specification. The sub-grade strength for design is assigned to one of six strength classes reflecting the sensitivity of thickness design to sub-grade strength, the classes are defined as shown in Table 4 below.

Table 4: Sub-grade classes (ERA, 2013) [3]

Design CBR	S2	S3	S4	S5	S6
Range,%	3 - 4	5 - 8	9-14	15-29	30 +

This displays that, the soil sample does not satisfy the requirements as a sub-grade material and is determined to be unsuitable for sub-grade in road construction. The soil generally fell below the standard recommendations for most geotechnical construction works. Therefore, the soil requires initial modification and/or stabilization to improve its work-ability and engineering property.

Index and mechanical property test result of red ash and hydrated lime treated soil

The index property such as specific gravity, liquid limit, plastic limit, and free swell index test was performed to determine the effect of red ash (RA) and hydrated lime (HL) on the physical characteristic of expansive soil under the study. The index property test result is summarized in Table 5. In this section, the optimum content of red ash and the combination of red ash with hydrated lime was also determined from index property test results so far. From the test result, it is observed that the liquid limit and plasticity index values showed a continuous decrease with the percent

red ash, the reduction was found highly significant after the addition of hydrated lime; the highest percent of reduction was obtained when black cotton soil mixed with 30% red ash combined with 5% hydrated lime which is about 44% reduction and also the plasticity index reduced from 61% to 13%, which is 79% reduction when compared to untreated black cotton soil.

Table 5: Summary of index property test results of treated soil

S. No	Mk Proportion			Index property test result					
	BCS (%)	IL (%)	RA (%)	Gs	LL (%)	PL (%)	P1 (%)	LS (%)	FSI (%)
1	100	0	0	2.68	108	47	61	32	130
2	97	3	0	2.65	82	44	38	21	91
3	95	5	0	2.61	74	47	27	13	76
4	95	0	5	2.71	106	47	59	31	125
5	90	0	10	2.75	102	46	56	29	112
6	85	0	15	2.78	100	48	52	28	103
7	80	0	20	2.8	95	46	49	27	91
8	70	0	30	2.84	87	44	43	24	87
9	92	3	5	2.65	SO	45	35	20	84
10	87	3	10	2.67	77	43	34	19	78
11	82	3	15	2.71	75	45	30	17	73
12	77	3	20	2.73	74	46	28	15	70
13	67	3	30	2.74	73	49	24	13	67
14	90	5	5	2.57	77	52	25	10	73
15	85	5	10	2.59	74	51	23	9	68
16	80	5	15	2.61	70	50	20	8	64
17	75	5	20	2.68	66	49	17	6	61
18	65	5	30	2.73	61	48	13	5	57

The BCS partially replaced by 15, 20 and 30% RA combined with 3 and 5% HL showed significant improvements on PI, LS, and FSI, to save time and energy the mechanical property test of the treated soil was conducted at the mentioned proportion of RA and RA-HL. For comparison, the tests were also performed for BCS with 15%, 20%, and 30% RA alone and BCS with 3% and 5% HL alone. From the test result, the liquid limit and plasticity index values showed a continuous decrease with the percent red ash, the reduction was found highly significant after the addition of hydrated lime; the highest percent of reduction was obtained when black cotton soil mixed with 30% red ash combined with 5% hydrated lime which is about 44% reduction and also the plasticity index reduced from 61% to 13%, which is 79% reduction when compared to untreated black cotton soil (see also Table 5 and Figure 4). The decline in percentage may be due to the non-plastic properties of red ash and probably due to high polarization properties and reduced surface activity of hydrated lime as a result of flocculation and agglomeration of clay particles caused by cation exchange. The specific gravity was found to decrease with the addition of 3% and 5% hydrated lime, whereas the value significantly increased with percent red ash. The reason may be due to the lightness of hydrated lime and the heaviness of red ash compared to natural black cotton soil (see Figure 6).

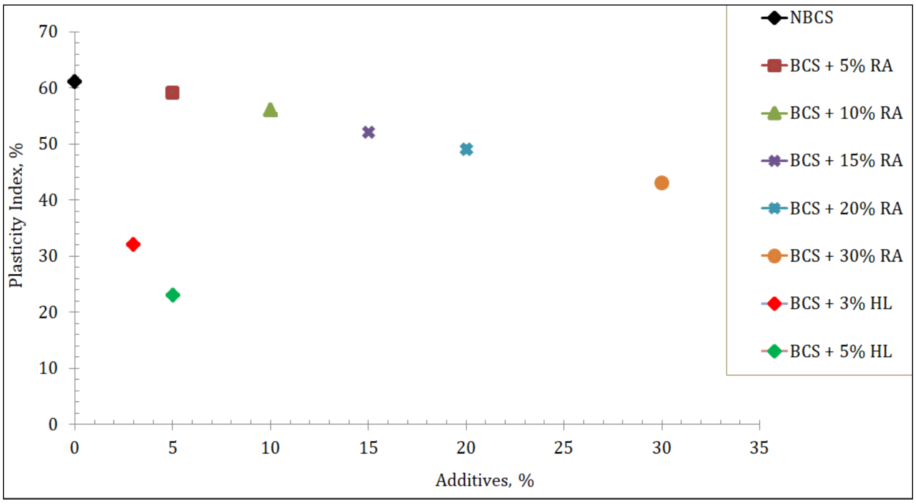

Fig 4: Effect of RA and HL alone on PI of BCS

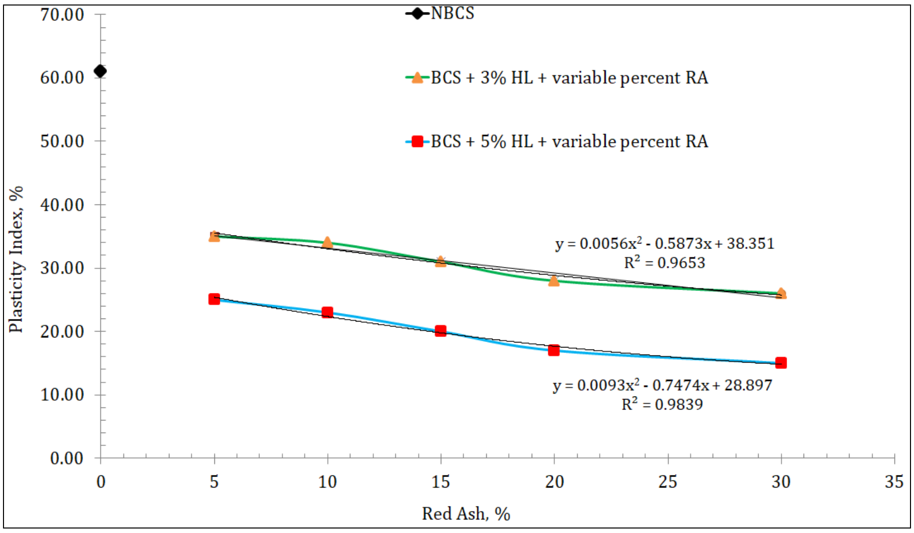

Fig 5: Effect of combined RA and HL on PI of BCS

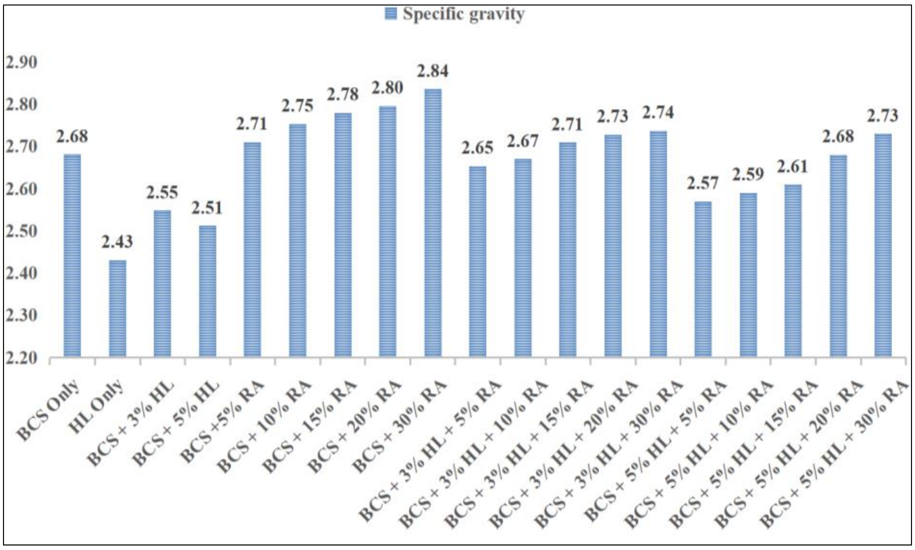

Fig 7: Specific gravity test result for NBCS and treated soil

The free swell of black cotton soil treated with red ash and hydrated lime was determined. The test was conducted following the USBR test procedure. The effect of red ash and hydrated lime on the free swell index of the expansive soil is shown in Figure 8. The reduction in the free swell index value observed is directly proportional to the quantity of red ash and hydrated lime added to the soil. The combined effect of red ash and hydrated lime resulted in a significant reduction. The highest reduction was from 130% to 56% which is about 132% compared to untreated soil.

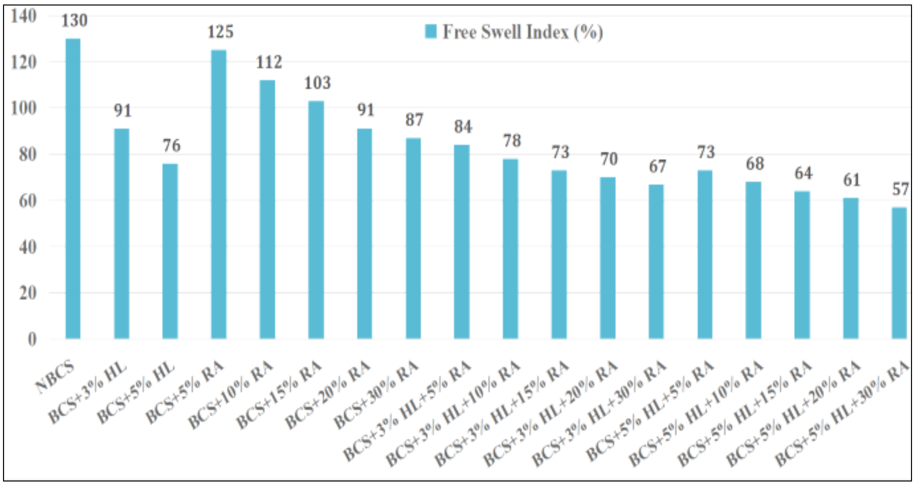

Fig 8: Free swell index test result for NBCS and treated soil

The effect of combination of red ash and hydrated lime on mechanical properties is discussed in this section.

Accordingly, the MDD and OMC of NBCS were obtained at 1.24 g/cm^3 and 37.40% respectively. When the percentage of red ash increased from 15% to 30% about 8% increment in MDD was obtained, on the other hand, MDD decreased from 1.24 to 1.19 g/cm^3 with a percent increment of hydrated lime alone compared to untreated black cotton soil. The MDD significantly increases up to 8.0% and 6.5% for BCS mixed with constant 3% and 5% HL combined with varying RA respectively. The Optimum Moisture Content (OMC) for the soil treated with combined RA and HL is presented in Table 6, comparatively With NBCS the OMC of treated soil was found reduced, the reduction was significant for smaller percent red ash mixed with constant hydrated lime. The UCS value for NBCS was found as 384.34 kPa and 451.25 kPa for no curing and 7 days of curing respectively.

Table 6: Summary of mechanical property test of treated soil

S.no	Mix proportion			Mechanical Property					
				Compaction		ISCS (kPa)		CBR	CBR Swell (p6)
	BCS (%)	HL (%)	R.A. (%)	MDD (g/cm ^{3})	OMC (%)	0 day curing	7 days curing		
1	10 C	0	0	1.24	34.40	384.34	451.21	1.51	13.5
2	97	3	0	1.21	35.87	360.38	537.5	6.84	1.95
3	95	5	0	1.19	39.11	343.6	582.3	12.23	1.22
4	85	0	15	1.31	30.31	370.8	421.3	2.98	10.21
5	80	0	20	1.32	32.71	365.6	405.3	3.86	8.14
6	70	0	30	1.35	30.01	315.2	396.4	4.05	4.83
7	82	3	15	1.30	31.05	363.5	485.8	7.24	1.75
8	77	3	20	1.29	33.61	358.9	460.7	8.04	1.62
9	67	3	30	1.32	34.80	343.2	455.3	9.47	1.06
10	80	5	15	1.25	32.60	342.6	583.2	13.41	0.95
11	75	5	*20*	1.31	35.70	326.5	564.7	16.29	0.53
12	65	5	30	1.34	36.20	304.3	541	18.58	0.25

The decrease in UCS value for treated soil in no curing condition indicated that the partial replacement of highly cohesive BCS with relatively non-cohesive red ash and insufficient reaction period for HL may cause the breaking of cohesive force between the BCS particles, on the other hand, improvement in UCS value with curing period is due to provision of sufficient reaction time and high pozzolanic hydrated lime (see also Table 6). As it is observed from the figures the CBR value of NBCS was obtained as 1.51% with a corresponding percent CBR swell of 13.5% after 4 days of soaking which is classified as weak sub-grade material. For treated soil the CBR value slightly increased with the percent red ash, the same trend was also observed for the CBR swell value. When treating the expansive soil up to 30% red ash only the CBR increased from 1.51% to 4.05%, after adding 3% and 5% HL the value increased to 9.47% and 18.58% respectively. The CBR swelling also decreased from 13.5% to 4.83 for BCS replaced up to 30% RA alone; however, after adding 3 and 5% HL the CBR swelling reduced to 1.06 and 0.25 respectively (See also Table 6).

Conclusion

From this thesis's experimental test result the following conclusions were drawn:

- The index property test result indicated that the black cotton soil under the study can be categorized as poor and weak expansive soil as per both AASHTO and USC system
- The liquid limit, plasticity index, linear shrinkage, and free swell index of treated BCS showed a continuous reduction with increasing in percentage RA, HL, and combination of RA-HL compared with NBCS.
- The specific gravity increased with percent RA while the value decreased with a percent increase in HL compared to natural black cotton soil.
- The MDD significantly increased and reduced with the addition of red ash alone and HL alone respectively, however, the value showed a slight increase with RA and HL combination compared with natural black cotton soil.
- The OMC value showed relative reduction and increment for BCS mixed with RA alone and HL alone compared with NBCS, for the mix containing a combination of RA-HL the OMC is much higher than NBCS at 5% HL with 20 and 30% RA.
- The UCS of treated soil decreased with increasing amounts of red ash alone and hydrated lime alone and a combination of RA-HL almost for all mixes for zero-day curing.
- After 7 days of curing the UCS value showed an increment with percent hydrated lime and mix containing a combination of RA-HL.
- The CBR value showed a continuous slight increment with percent RA alone, however significant increment was obtained for BCS mixed with HL alone and RA-HL combination.
- The CBR swell value slightly reduced with a percent increase in RA, however much significant reduction in CBR swell was observed for mix containing HL and RA-HL combination compared to natural black cotton soil.
- The minimum CBR for sub-grade class S4 was obtained using 30% RA combined with 3% HL, which is taken as optimum value based on the strength.
- A 10% saving cost was obtained by stabilizing weak sub-grade expansive black cotton soil with 30% RA combined with 3% HL.

Recommendation

In this thesis work it has been observed that both index and mechanical properties of the expansive soil were slightly improved with increase in red ash alone, however the minimum requirement for sub-grade strength (CBR > 5% ERA, 2013) was not fulfilled even using higher percent of red ash alone. The significant improvement was obtained with hydrated lime for all cases. Due to financial constraints and time limitations, the present thesis work did not cover the whole aspects of expansive black cotton soil treatment with red ash and hydrated lime. As a result, findings should be considered suggestive rather than absolute for filed applications.

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