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Lime stabilization of highly plastic clayey soil for the impervious core of embankment dam: The case of Gidabo dam, Ethiopia

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Abstract

The stability of different parts of zoned embankment dam including the core has to be guaranteed during design and construction to ensure the overall stability of the structure. Selection of appropriate material is a very crucial step. Important material properties of the core are low permeability, erosion resistance and cracking resistance. Impervious clayey soils are a widely available and used materials for the construction of core of zoned embankment dams in Ethiopia. However, such soil is characterized by high compressibility, poor shear strength when compacted and saturated, difficult in moisture control during construction (poor workability) and requires slow rate of construction to allow dissipation of excess pore water pressure. Despite their undesirable characteristics, the use of locally found material is becoming more necessary for sustainability reasons. The present study has been, thus, conducted with intention to alter some of the undesirable characteristics of clayey soil using chemical additives. Six soil samples from Gidabo dam area were collected and different laboratory tests were conducted (i.e. Atterberg limits, permeability, compaction, 1D-consolidation, and undrained-unconsolidated (UU) triaxial) tests) on raw samples and after treatment with different percentage of hydrated lime. Seven days curing time and the lime addition ratios of 0 %, 2 %, 4 %, and 6 % by dry weight were considered. After lime treatment, the liquid limit, plasticity index and swelling potential decreased. The permeability also decreased by more than one order of magnitude from $4.47 * 10^{-6}$ to $3.63 * 10^{-7}$. The stiffness and compressibility of the soil increased and reduced, respectively. Lime content of 6% has been found to be the minimum lime percentage required to make soils of the study area desirable core fill material.

Keywords: *Lime, stabilization, highly plastic clay, embankment, impervious core*

1. Introduction

Dam, that is vital for the storage, requires a very detailed geotechnical investigation to ensure design of stable structure and also to select appropriate construction material at the vicinity of the construction site. There are two major types of dam: concrete dam and embankment, depending on the type of material used for construction (Fell et al., 2005). For small scale irrigation and water supply, embankment dam is more economical as construction materials are to be principally supplied near the dam site.

An embankment dam, which is sometimes called earth dam, is constructed from earth materials such as soil and rock excavated nearby. The zoned embankment dam has different part: shell, filter and impervious core. The materials used for different part of the dam vary based on the properties of the soil, such as grain size, permeability and density (Fell et al., 2005; Alonso & Cardoso, 2010). Rock fill materials (any type of rock) are commonly used for shells and granular materials are used for filters. Materials with low permeability, erosion resistant and intermediate to high plasticity to accommodate deformation without risk of cracking are more ideal to be used as a core fill (Fell et al., 2005). Asphalt, bituminous, concrete and clayey soils are among the different materials that meet the aforementioned properties to be used as impervious core. The major role of impervious core is to control seepage through the body of dame that can lead to failure.

In most developing countries, clayey soils are widely used for core of embankment dam because they are very economical and can be easily found in large part of the earth surface as a weathering product of parent rocks. Ethiopia is one of the countries with extensive coverage of expansive soil as a result clayey soil is widely used as a core fill material. For instance, Tendaho, Kesem, Koga, Ribb, Megech, Maqa dam, etc are among the different embankment dam in Ethiopia where clayey soil were used as a core fill material. Although using such soils for core material is more economical as compared to asphalt, bituminous and concrete, their optimal use as a core fill has been limited due to their undesirable properties (Yilmaz & Erzin, 2004), such as potential for high swelling and cracking, poor workability, low resistance to deformation, etc. According to Yilmaz & Karacan (1996), to use for core of an embankment dam, the materials preferred to fullfill the following properties: Maximum dry density (MMD) > 1.6 g/cm^3, optimum moisture content (OMC) = 15 – 20%, specific gravity (Gs) > 2.6, liquid limits (LL) = 40 – 50% and plasticity index = 14 – 20%.

Due to the aforementioned reasons, the clayey soils in natural state are least preferred material for core of embankment dam (Wanger, 1957) and need to be avoided whenever possible. However, in some places, finding better alternative material may be difficult due to different reasons like shortage of budget. In addition, for both environmental and economic reasons and in a context of circular economy, it is necessary to use local material for construction works. Hence, there is a need to find a remedial measure or technique to improve the engineering properties of clayey soils, particularly highly plastic, to make them suitable materials for a core of embankment dam.

The most widely recognized form of soil stabilizations, in road construction, is lime treatment as it alters undesirable characteristics of clay minerals (Diamond & Kinter, 1965; Choquette et al., 1987; Verhasselt, 1990; He et al., 1995; Bell, 1996; Al-Rawas et al., 2005; Al-Mukhtar et al., 2010; Eisazadeh et al., 2012; Pomakhina et al., 2012; Maubec et al., 2017; Guidobaldi et al., 2017; Vitale et al., 2017). However, the potential effectiveness of this technique for the embankment core material need to be checked before implementation in actual field projects. The minimum percentage of lime that need to be added to attain the optimum properties and meet the limits to be used as a core material is among issues that need to be addressed. For fulfillment of this goal, it is necessary to compare the relative desirability as a core material of raw and lime treated clayey soil samples under controlled condition. The present paper, thus, aimed to alter the undesirable characteristics of clayey soils using hydrated lime ($Ca(OH)_2$) and to determine the optimum (minimum) lime percentage. The case of Gidabo dam is considered in this study and the necessary soil samples (red clay soil) have been collected from the dam site.

2. Materials and methods

2.1. Location of the project area

The project area is located in the Southern Ethiopia, Abaya-Chamo sub-basin of the Rift Valley about 17 km from Dilla town. The dam site is accessible via Addis Ababa – Dilla asphalt road, which is about 360 km and Dilla-Gidabo dam site weather road, which is about 17 km. It is geographically located between 6°20' to 6° 25' N and 38° 05' to 38°10' E (Figure 1).

2.2. Materials

For Gidabo dam and irrigation project, two clay burrow sites (from upstream (site 1) and downstream (site 2)) were selected as potential sources for the core material (Figure 1). A total of six disturbed soil samples were collected from the two clay burrow sites (three from each) for the present study. The hydrated lime used for the present experiment, with purity > 97%, was supplied by Derba Cement plc.

2.3. Experimental approach

A series of index and engineering property tests were carried on disturbed and remolded soil at optimum moisture content before and after lime treatment. For lime treatment, desired amount of lime (2%, 4% and 6% by weight of dry soil) was mixed with the air dried soil in the dry state until an even distribution of lime in mixture was obtained. Then, mixed by adding water to reach the optimum moisture content. Then, the mixture is stored in airtight plastic bag at room temperature for 7 days before and after compaction depending on the type of test. The quantity of lime to be added is calculated according to the following expression:

$$Lime\ \% = \frac{\text{Mass of lime}}{\text{Mass of lime} + \text{Mass of Soil}} * 100\%$$

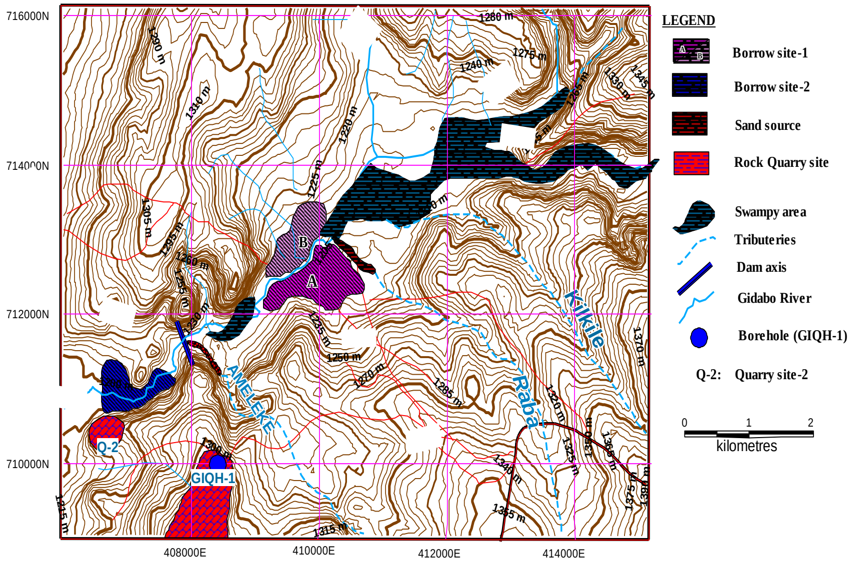

Figure 1. Map showing the material source sites. Burrow site 1 and 2 are a source for clayey core material.

All the tests (i.e. grain size distribution, liquid limit, plastic limit, compaction, permeability, strength, and consolidation) were conducted according to ASTM standards. Both liquid limit (based on Casagrande method) and plastic limit tests have been performed on soil fraction passing 0.425 mm sieve, after adding a considerable amount of water to moist the soil grain and left for hours.

The swelling characteristics of the soil is assessed by determining the free swelling index. The test is performed by slowly pouring 10 cm3 of dry soil which has passed the No. 40 (0.425mm) sieve in to 100 cm3 graduated cylinder filled with distilled water. After 24 hours, final volume of the suspension is recorded. Hence, free swell index is calculated using the following expression:

$$Free\ Swell\ Index\ \% = \frac{\text{Final volume} - \text{Initial volume}}{\text{Initial volume}} * 100\%$$

The standard proctor compaction tests were done on the investigated soil according to ASTM D698-98 method A to determine optimum moisture content at which maximum compacted dry density achieved. For the test, soil fraction passing the No. 4.75 mm sieve was soaked overnight. Then, they were compacted in a cylindrical mold of 944 cm^3 volume (10 cm diameter and 12 cm height) standard proctor mold by repeated blows from the mass of a hammer 2.5 kg falling freely from a height of 30.5 cm. The soils were compacted in three layers, each layer being subjected to 25 blows.

Permeability and mechanical tests (consolidation and triaxial compression tests) were conducted on one selected soil sample after compaction at optimum moisture content. After compaction, specimens were taken out from the molds and cured at 20°C for 7 days. Permeability of the studied samples were determined from the falling head permeability tests following ASTM D-2434 standard. Before the commencement of the test, the soil was saturated by allowing water to flow continuously through it from the standpipe. One-dimensional (1-D) consolidation tests were performed in accordance with ASTM D2435, on specimens trimmed from remolded samples. The test specimens were loaded at twenty-four hour intervals using a load-increment ratio of two, and they were unloaded at twenty-four hour. The triaxial test is the most commonly used method for determining the shear strength of soils in the laboratory. The test was conducted on 38 mm diameter cylindrical sample. The test specimen were prepared from remolded soil which is extruded hydraulically by pushing the soil in to 38 mm diameter tubes and 76 mm in height.

3. Result and discussion

3.1. Result

3.1.1. Initial soil sample characterization

The basic physical properties of the studied soil samples are outlined in Table 1. All the soil samples under the study are fine grained soil with > 80% of the grains passed through sieve # 200 and liquid limit and plasticity index greater than 50% and 30%, respectively. According to unified soil classification plasticity chart, the studied soils lies above A-line (Figure 6) which means the soils are clayey soil with high plasticity (CH). The free swell index ranges from 70% to 90%, which is a typical characteristics of expansive soil. The amount of swelling is known to be dependent on the clay mineral types. Soil which contain sufficient amount of montimorillonite tends to swell when they absorb moisture and shrink when they lose moisture.

The maximum dry density (MDD) for the soils under the investigation achieved at relatively higher moisture content (24 – 35%), suggesting poor compaction characteristic of the soil. The permeability coefficients of the tested samples ranges from $2.51 * 10^{-6}$ to $9.45 * 10^{-6}$. The soils are categorized as low to very low permeable soil (Head, 1985). The consolidation characteristic of the soil was assessed in terms of the consolidation index (Cc). The obtained value of 0.24 for the tested soil is generally a characteristic of medium to high compressible clay soils.

Table 1: Basic properties of soil samples from the six burrow sites

	Soil samples					
Property	TP-1	TP-2	TP-3	TP-4	TP-5	TP-6
Specific Gravity	2.7	2.69	2.75	2.65	2.76	2.69
Liquid limit (%)	62.4	68	71.5	65	56	66
Plastic limit (%)	28.9	32.4	26.7	24.2	24	19
Plasticity index (%)	33.5	35.6	44.8	40.8	32	47
Maximum Dry Density (g/cm^3)	1.59	1.55	1.52	1.57	1.37	1.49
Optimum Moisture Content (%)	27.8	26	26.8	24.5	35	35
Free swelling index (%)	80	75	90	70	80	70
Sand (%)	8	5	5	7	9	8
Silt (%)	32	38	40	36	39	38
Clay (%)	60	57	55	57	52	54

3.1.2. Lime treated soil

a) Effect of lime on soil plasticity and swelling

The effect of lime on the consistency limits (i.e. liquid limit, plastic limit and plasticity index) of the soil is shown in Figure 2. With increasing lime content from 0% to 6%, the liquid limit decreased markedly compared to plastic limit, which shows slight increasing trend. The overall effect leads to decrease in plasticity index value. Similarly the free swelling index decreased after lime treatment (Figure 3). The results of both tests clearly reveal that lime treatment is effective in decreasing water retaining capacity of clayey soil.

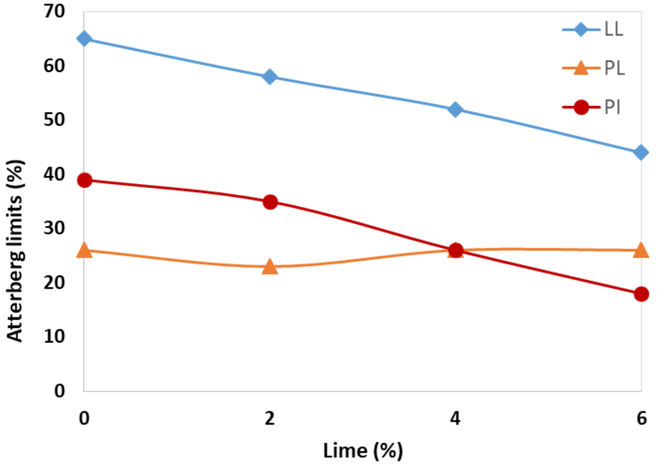

Figure 2. Influence of lime on atterberg limits (the values are an average of the six soil samples). LL = liquid limit, PL = plastic limit and PI = plasticity index

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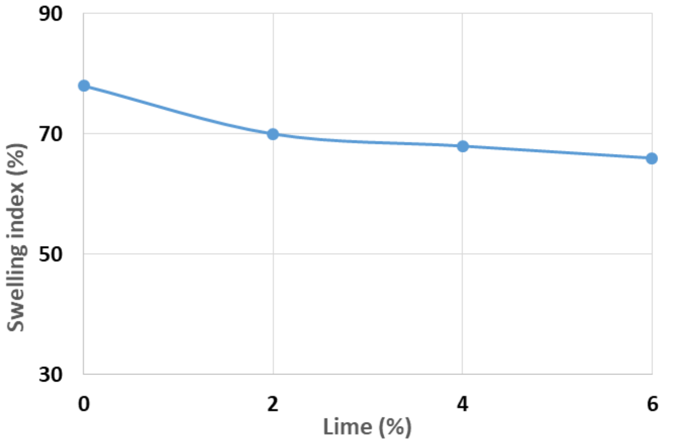

Figure 3. Influence of lime on free swelling index (the values are an average of the six soil samples)

b) Compressibility characteristics

The comparison of 1-D consolidation curves of untreated and lime treated (4 and 6% dry weight) soils are presented in Figure 4. The initial void ratio of untreated soil sample is higher than the lime treated soil sample and it decreases with increasing the percentage of stabilizer. The compression index (i.e. the slope of the linear portion of void ratio – log stress curve) also decreased from 0.24 to 0.175 with increasing lime percentage to 6%, implying the compressibility property of the soil improved after lime treatment.

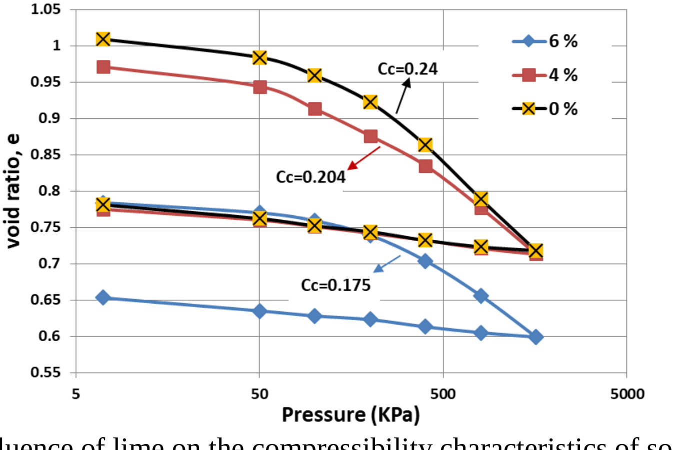

Figure 4. Influence of lime on the compressibility characteristics of soil (TP-1)

c) Shear resistance

The aim of the UU triaxial shear resistance measurements is to assess the improvement of mechanical stability of core material as a result of lime treatment. The results obtained after treatment with different percentage of lime at seven days curing period and compacted at OMC are reported on the Figure 5. With increasing the lime percentage, the strain-stress curve shifted upward indicating the maximum stress that the specimen can sustain improved after lime treatment. In addition, the treated soil become stiffer or less deformed as indicated by increase of the slope of pre-peak curve.

d) Hydraulic conductivity

The coefficient of permeability, k (determined from falling head test) is used to study the permeability characteristics of treated soil samples. The permeability decreased significantly by one order of magnitude, from 4.47 * 10^{-06} (low permeable) to 3.63 * 10^{-07} (very low permeable), after lime treatment (Figure 6). The effect is more pronounced at lower percentage of lime (2%) and the effect become less with increasing lime content.

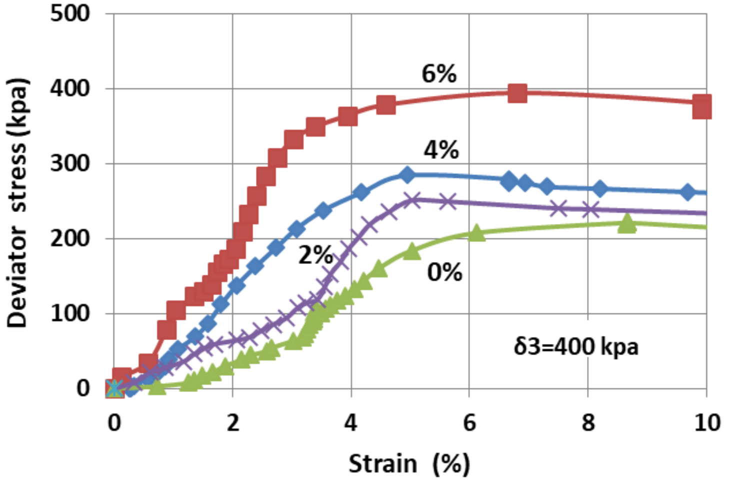

Figure 5. Influence of different lime content on the compressive strength of soil (TP-1)

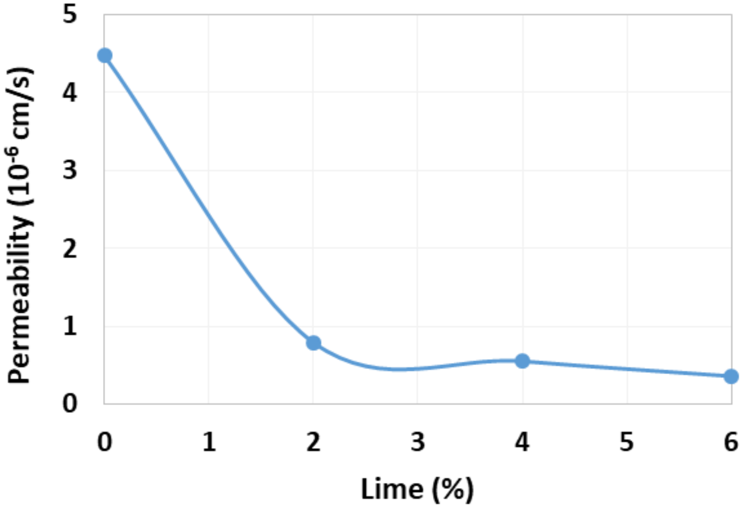

Figure 6. Influence of lime content on the hydraulic conductivity of soil (TP-1)

3.2. Discussion

The studied soils are characterized by high plasticity, high compressibility and medium to high swelling potential. These properties make such kind of clayey soil less suitable for construction of road, building, dams and other engineering structures. However, the low permeability and self-sealing stability makes it cost effective alternative material for engineering barrier and for the core of embankment dam. Apart from permeability, factors like Maximum dry density (MMD), optimum moisture content (OMC), specific gravity (Gs), liquid limits (LL) and plasticity index (PI) governess the suitability of clayey soil for embankment core material (Yilmaz & Karacan, 1996). Except the specific gravity, the other properties of the studied soil do not meet the specified engineering requirement to be used as core fill material. It suggests compaction alone is not sufficient in improving the property of clayey materials since it does not alter the chemistry of clay minerals.

After lime treatment with different lime content, the engineering and index properties of the studied soils are improved. The classification after treatment is summarized in Figure 7. The untreated soil and 2% and 4% lime treated soils grouped as CH (high plasticity inorganic clay), while the soil is grouped to CL (Low plastic inorganic clay) after 6% lime treatment. The CL soil is characterized by medium compressibility, has fair shear strength and good workability as compared to CH soils. According to engineering use chart of Wanger (1957) for core of embankment dam, CH soils rated 7 (very low level of desirability), while CL soil rated 3 (Good level of desirability). Blending with granular material such as sand is an alternative method to improve the property of clayey soil. However, it increases the permeability of the soil.

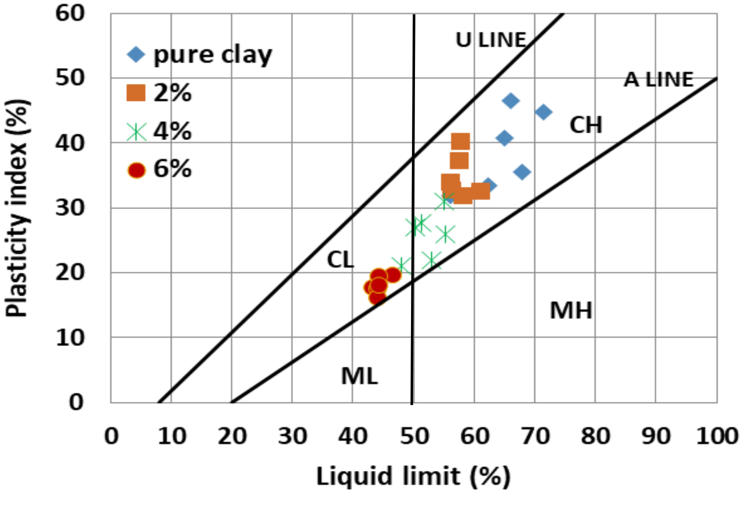

Figure 7. USCS classification of raw soil sample and after treatment with lime

The liquid limit and plasticity index are compared with the limit suggested by Yilmaz & Karacan (1996) in Table 2. Similar to untreated sample, 2% and 4% lime treated soils are also failed to satisfy the limits as the values of liquid limit and plasticity indexes are over the suggested limits. In the case of 6% lime treated soil, however, the parameters meet the limits. Therefore, 6% lime has been found to be the minimum lime content required to stabilize the soils of the study area for the desired purpose. The presence of lime nodules in the 7 days cured sample reveals the water content near the optimum moisture content is not enough to dissolve all the lime to keep the pore water pH higher enough to initiate pozzolanic reaction during the curing period.

Table 2. Comparison of the average index properties value with the limit values for core material suggested by Yilmaz & Karacan (1996)

Test type	**Limit for core material**	**Lime %**			
		0%	2%	4%	6%
Specific gravity	≥ 2.6	2.71	-	-	-
MMD (g/cm^3)	≥ 1.6	1.52	-	-	-
OMC (%)	15 - 20	29	-	-	-
LL (%)	40 - 50	65	58	52	44
PI (%)	14 - 20	39	35	26	18

As the results of this work clearly shows, lime treatment is efficient technique in altering undesirable characteristics of high plastic clay soils. The modification of the properties of the lime treated soil is due to two-stage reaction mechanism initiated by lime addition: short-term and long-term reactions (Diamond and Kinter, 1965; Choquette et al., 1987; Verhasselt, 1990; He et al., 1995; Bell, 1996). Immediately as the lime mixed with soil and water, cation exchange begins to take place between the metallic ions associated with the surfaces of the clay particles and the free calcium ions of the lime, which reduces the double layer thickness (film of water) around the clay particles. The compression of diffused electrical double layer in turn leads to the decrease of repulsive potential between clay particles, thus the particles being attracted closer to each other to form flocks. The overall effects are flocculation and particle aggregation, decrease reactivity with water and plasticity, improved workability and reduced volume change characteristics.

The long term reaction, unlike to the immediate effect, is initiated by alkaline environment (pH > 12.4) produced by the addition of lime. The high pH facilitates dissolution of clay particles that releases Si and Al, which together with Ca precipitated as hydrated cementious phases (like calcium silicate hydrates (C-S-H) and calcium silicate aluminate hydrate (C-S-A-H). The cementation process bounds individual grains together and significantly increases the mechanical strength (increase in stiffness and decrease in compressibility characteristics) of the lime treated soil. The decrease in hydraulic conductivity (k) is also a result of change in the soil texture or decrease of pore size due to cementious gel that formed by pozzolanic reaction. The decrease in permeability has advantage in reducing the risk of internal erosion and ensuring dam stability.

4. Conclusion

This paper presents the effect of lime treatment on the engineering properties of clayey soils that are selected to be used for the construction of core of Gidabo embankment dam. All the soil samples taken from the six identified burrow sites are classified as fine grained high plastic soil (CH) according to USCS classification system. CH soils are characterized by high swelling-shrinkage potential, high compressibility, poor workability and low shear strength when compacted and saturated with water. These properties make CH soil undesirable for construction of core of embankment dam. After lime treatment, however, the engineering properties of the soil improved (i.e. water holding capacity and plasticity reduced, the compressibility reduced, the strength, stiffness and compaction characteristics improved). The minimum lime content required to make the soil of the study area desirable core fill material has found to be 6%. Generally, the relative desirability of the soil for the impervious core of embankment dam is improved to rank 3 (Good level of desirability) after 6% lime treatment from rank 7 (very low level of desirability). This improvement in engineering properties is due to alteration of the surface chemistry of the clay particles in short-term and cementation of soil particles by calcium silicate and aluminate hydrates in the long-term.

The main conclusion of this work is, although the red clayey soil found nearby Gidabo dam site and other similar soil types (CH) have some undesirable characteristics, it can be used for the core fill material after mixing with lime (≥ 6%) and compaction at controlled water content (i.e. near to optimum moisture content). In terms of water content, it is recommended to treat the soil at water content higher than optimum moisture content to dissolve the lime nodules.

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