LOSS OF CEMENTITIOUS ELEMENTS ON LIME STABILISED SOIL SAMPLES

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Abstract - Soil stabilisation with lime is used in many countries in the construction of road bases and sub-bases and for the treatment of subgrade soils. Studies have shown that the performance of stabilised soil layers can be affected by certain undesirable (deleterious) chemical reactions probably occurring on lime-treated soil. Carbonation is one of them. Carbonation referred to here has reference to the reaction that occurs between free lime and atmospheric carbon dioxide. Also called lime carbonation, the reaction referred to above of lime with carbon dioxide forms calcium carbonate instead of the cementitious CAHs and CSHs. The paper examines the existence of carbonation on two soil samples (sample one and two) treated with lime by conducting an Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), X-RD, SEM, EDS/EDX tests. The UCS of the soil decreases sharply at lime content of 6% for sample one while weak bonding due to the loss of cementitious element of the soil samples impacted on the CBR of the soil due to soil voids not so-closely tight, with EDS/EDX micro images showing the existence of the pores within the soil particles indicating the change in microstructure due to loss of cementitious element in soil (carbonation).

Keywords - Carbonation, Microstructural analysis, CBR Penetration, UCS, X-RD, SEM, EDS/EDX.

I. INTRODUCTION

1.1 Literature Review

The technique of soil stabilisation utilising lime - particularly hydrated lime - can be broadly classified into four different processes. These are referred to as lime soil stabilisation reactions (or lime soil chemistry) (Fang, 1991; Negi et al., 2013). Lime-soils reactions are complex and entail primarily, secondary and tertiary process. These reactions are:

- Cation exchange: The process where soil particle change positive bases with the environment in which the particles interacts (Aprile and Lorandi 2012).
- Flocculation and agglomeration: Prompted by the increased electrolyte content of the pore water due to ion exchange by the clay to the calcium during lime soils stabilisation process (Mallela, Quintus and Smith, 2004).
- Pozzolanic reaction :The reaction between soils silica and or alumina and lime to form various types of cementing agents (University of illinois at urbana-champaign, 2007) and,
- Lime carbonation: The reaction of lime, soil and water with carbon dioxide to form calcium carbonate. (Mallela, Quintus and Smith, 2004).

The following sub section of this paper focuses on the latter (i.e. lime carbonation). Lime carbonation: the reaction process where lime reacts with carbon dioxide to form calcium carbonate instead of the cementitious CAHs and CSHs (Mallela, Quintus and Smith, 2004). As reported by Jung and Bobet (2008), this is another process associated with lime-soils modification. During this process, calcium hydroxide is transformed into calcium carbonate as a result of the reaction between calcium hydroxide and atmospheric carbon dioxide gas (Cizer et al., 2006).

Cizer et al. (2006) talks of factors such as carbon dioxide diffusion through pores, calcium hydroxide and carbon dioxide dissolution in water, as well as the reaction of Ca+2 with CO3-2 ions to form the CaCO3 crystals as the main controllers of carbonation reactions. The latter (i.e.CaCO3) has reference to cementing material, with recommendations highly necessary to preclude or monitor its existence or formation. The 35th Southern African Transport Conference (SATC 2016) paper by Bhengu and Allopi (2016) mentions weak bonding, calcium carbonate being soluble salt eventually pulverizing when exposed to air for a long time period as further reasons having reference and association to carbonation.

A number of problems relating loss of cementitious content in stabilised soils – particularly due to carbonation - were reported in South Africa (Netterberg and Green, 1984; Green, Netterberg and Sampson, 1990; Gourley and Greening, 1999; Green, 2008; Bhengu and Allopi, 2016).

With carbonation associated with loss of cementitious, it may however results in long-term strength increases for soils stabilized with lime, on condition of slow process of carbonation slowly forms over a long period of time, thus leading to long-term strength increases (Samantasinghar, 2014). Several initiatives in trying to curb the effects of carbonation have been formulated. In relation to South African soils, a lot of publications having relation to ways of curbing carbonation have been made available (Netterberg and Green, 1984; Green, Netterberg and Sampson, 1990; Green, 2008). These include keeping stabilised materials as moist as possible, preventing carbonation by minimising the exposure of stabilised materials and improvement in

construction practices, for example compacting sooner with appropriate equipment to get higher density and lower permeability as well as improving of curing procedures and operations (Green, Netterberg and Sampson, 1990). Other initiatives include reviewing of designs and construction procedures to suit intended results (Bennett et al., 2002).

II. MATERIALS AND METHODS OF TESTING

2.1. Sample preparations

Bags of naturally occurring soil samples were collected from two pre identified locations in the parts of the province of KwaZulu Natal in South Africa (i.e. Umlazi and Mkuze South and North part of the province respectively). The soil samples for laboratory analyses were typically air dried in preparation for receiving lime for the below stated laboratory tests.

2.2. Tests conducted on soils and testing procedures

Both tests relating to engineering properties and micro structural properties identification for soil samples were conducted in studying the carbonation variables on the treated soil samples with lime. For engineering properties of the soil identification, tests such as consistency limits (Atterberg tests), Maximum Dry Density and Optimum Moisture Content determination, UCS and CBR Penetration were prime tests conducted. These tests were conducted in relation to South African Technical Methods of Highway 1 (TMH1) under subsections, method A1, A2, A3, A7, A9, and A14 with complementation from SANRAL materials testing manuals.

III. PRESENTATION AND DISCUSSION OF RESULTS

3.1 Consistency limits

Soil properties helping in the classification and properties identification of soil are presented in table 1 and are discussed below. Table 1 shows consistency limits results for the two soil samples tested. As per the results, it can be seen that upon lime application, the plasticity of the soil decreases. One of the attributes to the above relates to a decrease in the liquid limit and the increase in the plastic limit of the soil.

Property	Sample 1	Sample 2
Liquid limit (%)	32	23.43
Plastic limit (%)	21.25	10.61
Linear shrinkage (mm)	4.21	4.24
Plasticity index (raw) (%)	10.98	12.82
Plasticity index (Lime-treated) (%)	8.42	10.72

Table 1: Consistency index properties of the soil

3.2 Grading analysis of the soil

Figure 1 and 2 shows the grading curves for sample 1 and 2 respectively. According to the grading analysis on the two soil samples indicated that sample one is a well graded soil containing particles of a wide range of sizes and has a good representation of all sizes, with sample two being the semi-well graded soil samples as per the grading analysis test.

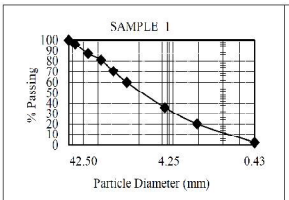


Figure 1: Particle size distribution for sample one

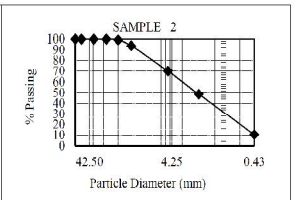


Figure 2: Particle size distribution for sample two

3.3 Maximum Dry Density (MDD) & Optimum Moisture Content (OMC)

An analysis on the maximum dry density and the optimum moisture content of the lime treated two soil samples at different contents of lime performed to determine the relationship between the moisture content and the dry density of a soil for a specified compactive effort was conducted. The result of series of tests conducted at lime contents of 2%, 4%, 6%, 8% and 10% on the ASSTHO Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC) are presented in table 2 below.

Sample Number	Maximum Dry Density & Moisture content	2% Lime	4% Lime	6% Lime	8% Lime	10% Lime
1	MDD kg/m³ & OMC	1702.8 20%	1702.8 20%	1740.6 20%	1749.2 20%	1672 19%
2	MDD kg/m³ & OMC	1667.2 22%	1643.0 20%	1670.1 20%	1677.4 20%	1645.59 20%

Table 2: Maximum Dry Density and Optimum Moisture Contents of lime stabilized soil samples.

The results of the compaction tests conducted on the soil samples showed that the addition of lime resulted in the improvement in the characteristics of the natural two soil samples. The two soil samples displayed their respective maximum dry densities ranging from 1643 kg/m³ to 1749.2 kg/m³ and their respective optimum moisture contents ranging from 19% to 22%. With constant comp active effort, the addition of different lime contents indicated highest values of the MDD with corresponding values of OMC for sample one (1) at lime content of 8% by weight of soil. For both soil samples 1 and 2, results showed that further addition of lime decreases the density with constant or increasing moisture content.
Lime content at range of 6% - 8% indicates density increase of the stabilized soil samples. The dry density of the soil samples showed a decrease with

constant optimum moisture content at lime content of 4% for sample number two.

3.4 Unconfined compressive strength of lime stabilized soil (UCS)

The unconfined compressive strength test was conducted to determine the undrained strength of the soil samples tested under unconfined conditions according to the Technical Methods of Highway 1 (TMH1) and other complimentary soil science standards by SANRAL (Materials Testing Manual).

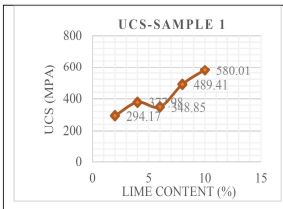


Figure 3: Sample 1 UCS @ 2%, 4%, 6%, 8% & 10% lime contents at 7th day of curing.

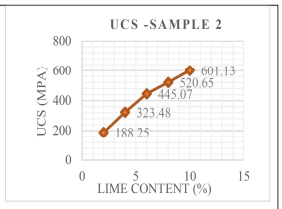


Figure 4: Sample 2 UCS @ 2%, 4%, 6%, 8% & 10% lime contents at 7th day of curing.

The result of the Unconfined Compression Strength test conducted on the two naturally occurring soil samples stabilized with 2% 4% 6% 8% and 10% lime contents, compacted at the respective MDD and OMC, and cured for seven days in accordance with TMH1 (1996) are shown in Figure 3 & 4 respectively. The result indicate that the UCS (one engineering property of the soil) of the soil sample can be significantly improved by lime stabilization. Constant increase in strength was indicated by the lime stabilized material for sample two at each lime content with highest strength recorded at lime content as 601.13Mpa at lime content of 10% after curing for seven days. Sample one indicated a slow grow in strength compare to sample two. It can be noted from Figure 3 that the UCS of the soil decreases sharply at lime content of 6%. One contributory factor directly impacting on this is carbonation which might have promoted the loss of cementitious content in stabilized soil sample taking place while soil samples were mixed lime was mixed and during the curing.

The above implies that carbon dioxide diffused through pores (both of the curing membrane and that of the soil sample), calcium hydroxide and carbon dioxide dissolution in water, as well as the reaction of Ca+2 with CO3-2 ions to form the CaCO3 crystals forming carbonation reactions.

3.5 California Bearing Ratio (CBR)

The California bearing ratio (CBR) test was conducted by measuring the load required to penetrate surface of the compacted soil samples, at different compactive efforts (i.e. 55 CBR mechanically compacted, 25 CBR mechanically compacted, and 55 CBR manually compacted). The results of the CBR tests on lime contents of 2% 4% 6% 8% and 10%. Lime treated soil samples recorded inconstant results for soil samples that were tested. Some recorded improved results with highest at 17.52KN CBR values, with lowest being 2.57KN both for sample two, at different comp active efforts. The inconsistency in CBR values tested soil samples in a direct indication of the principal chemical reactions taking place during lime-soil stabilization namely Cation exchange, flocculation and agglomeration, lime carbonation, pozzolanic reactions. Weak bonding due to the loss of cementitious element of the soil samples, calcium carbonate being soluble salt eventually pulverizing due to being exposed to which might have found its way through the curing membrane and eventually the membrane of the soil sample thus promoting carbonation. This has an impact on the CBR of the soil due that the fact of not so-closely tight soil voids loss of cementitious powder.

3.6 X-Ray Diffraction, SEM & EDS/EDX

Soil minerals play a significant role in dictating the suitability and the behaviour of the soil for various land uses, be it engineering /construction activities or agricultural activities. Figures 5-10 shows the XRD graphs for both soil samples treated with lime different lime variations. X-ray diffraction technique provided detailed information about the atomic structure of crystalline of the two soil samples that were lime treated and tested. The Y-axis shows the counts (number of X-rays received and processed by the detector) and the X-axis shows the energy level of those counts. From XRD, soil tested consisted of Quartz, albite, microcline, montmorillonite, biotite, rutile and chrysotile, as identified from the peaks for minerals that were present in the soil. SEM (Scanning Electron Microscopy) and EDS/EDX (Energy Dispersive Spectroscopy) analysis was also carried out on the tiny soil samples after the unconfined compression tests. Lime treatment changed significantly the soil fabric depending on curing time and water content, thus justifying the chemical reactions taking place when soil is mixed with lime soil. Figure 11 to figure 20 shows the SEM and EDS/EDX micrographs of treated soil samples. As can be seen from figure 11 to figure 20, soil particles treated with different content of lime were observed and displayed flaky texture. Flaky texture confirms the formation of needle-like crystalline formations in the soil sample such as ettringite. The EDS/EDX micro images, when closely looked shows the existence of the pores within the soil particles indicating the change in microstructure due to loss of cementitious element in soil (carbonation).

Further to the above mentioned, the EDS/EDX show elements found in the soil, majority of the soil chemical elements evaluated were significantly influenced by use of lime to the three soil samples. Chemical elements, ordered by their atomic number (number of protons), electron configurations, and recurring chemical properties from the SEM on the

soil samples treated with different lime contents were identified in the soil samples tested. These (elements) ranged from Magnesium (Mg), Potassium (K), Calcium (Ca), Titanium (Ti), Iron (Fe), Aluminium (Al), Silicon (Si) Oxygen (O), Carbon (C) to Sodium (Na). With limestone being the source of Ca and Mg and in the presence of water the carbonates dissolve and the Hydroxide, some of the elements listed above form part of the chemical composition making up the hydrated lime used for this experiment.

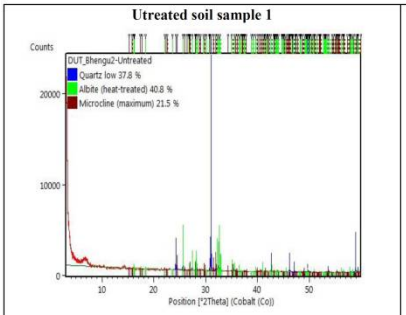


Figure 5: Sample 1 -Untreated

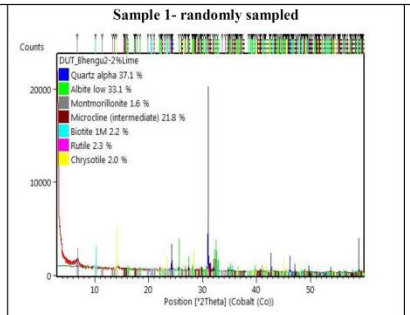


Figure 6: XRD Graph, sample 1 randomly sampled

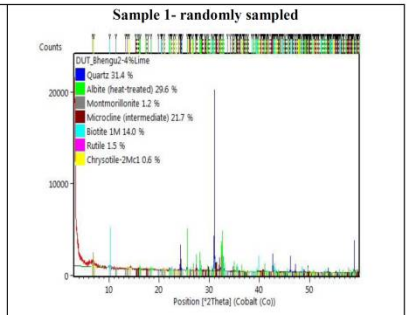


Figure 7: XRD Graph, sample 1 randomly sampled

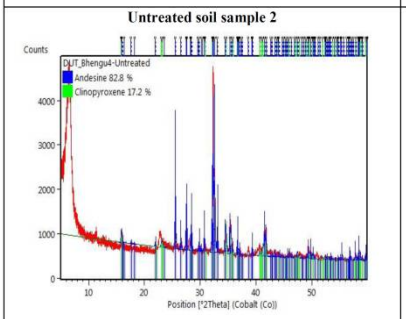


Figure 8: Sample 2 -Untreated

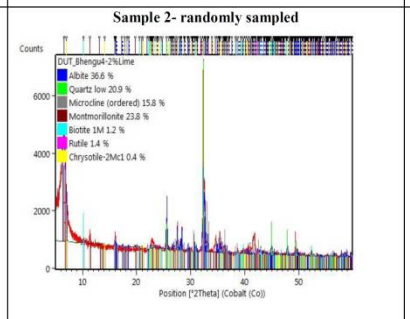


Figure 9: XRD Graph, randomly sampled

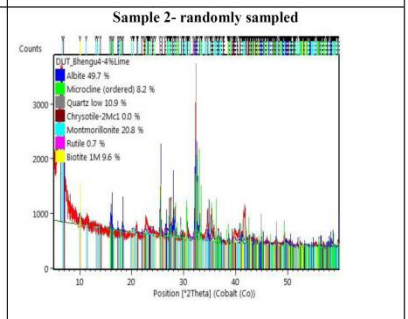


Figure 10: XRD Graph, randomly sampled

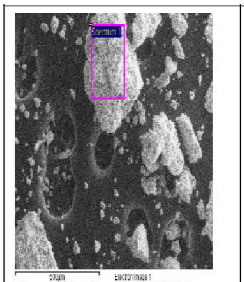


Figure 11 : Sample 1-2%Lime

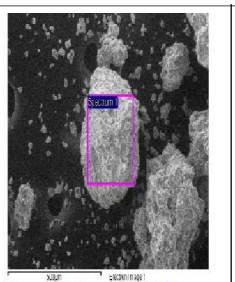


Figure 12: Sample 1-4%Lime

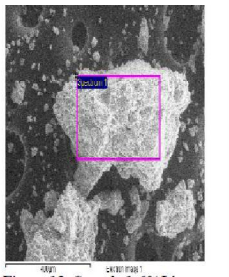


Figure 13: Sample 1-6%Lime

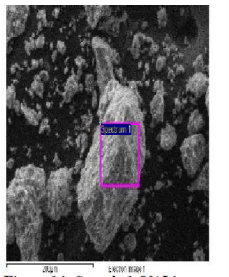


Figure 14: Sample 1-8%Lime

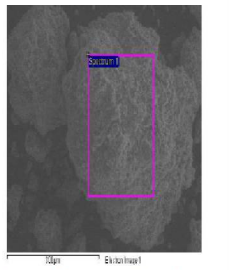


Figure 15: Sample 1-10%Lime

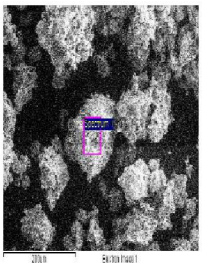


Figure 16: Sample 2-2%Lime

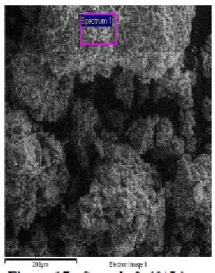


Figure 17 : Sample 2-4%Lime

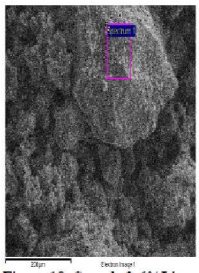


Figure 18: Sample 2-6%Lime

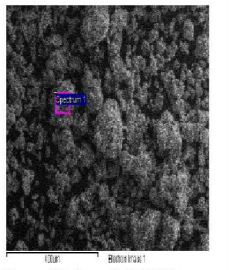


Figure 19: Sample 2-8%Lime

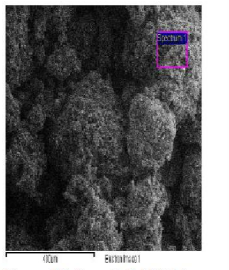


Figure 20: Sample 2-10%Lime

CONCLUSION

Carbonation effect on lime stabilised soil was investigated .The concluding remarks in relation to the entire study are presented as below. As per the experimental results, it can be seen that many of the important properties of soils can be enhanced by the addition of lime, however the factors such as loss of cementitious content in stabilised materials leading the formation of calcium carbonate when lime treated soils are in the open air might have promoted by carbonation. The results showed that carbonation to varying degrees and loss of strength occurred in all the strength-age relations. The result for the Unconfined Compression Strength (UCS) test showed increase in strength as was indicated by the lime stabilized material for sample two at each lime content with highest strength recorded at lime content

as 601.13Mpa at lime content of 10% after curing for seven days, with sample one indicating slow grow in strength compare to sample two. It can be noted, one contributory factor directly impacting on this (latter) is carbonation, promoting the loss of cementitious content in stabilized soil sample during mixing and during the curing. Weak bonding due to the loss of cementitious element of the soil samples due to soil samples being exposed to air finding its way through the curing membrane and eventually the membrane of the soil sample thus promoting carbonation led to an impact on the CBR of the soil due not so closely tight soil voids loss of cementitious powder.

Lastly, some of the EDS/EDX micro images showed the existence of the pores within the soil particles indicating the change in microstructure due to loss of cementitious element in soil (carbonation). More studies on carbonation of soil treated with cementitious elements, particularly lime need to be conducted, to reveal factors such as humidity, room temperature, the curing effect time and other so as to fully understand carbonation particularly in understanding the extent to which moisture can be due to carbonation.

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