Durability of enzyme stabilized expansive soil subjected to moisture degradation

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***Abstract*: Expansive soils are problematic and susceptible to ground movements, causing significant damage to overlying structures and reduction of bearing capacity. Geotechnical engineering has long recognized that the moisture variation triggers the expansive nature of soils resulting in its swell and shrinkage. Numerous stabilizing additives have been used to treat expansive soils such as lime, cement and fly ash. However, the use of bio-enzymes as a soil stabilizing agent is not currently fully understood. This study examines the durability performance of the enzymatic stabilization of expansive soils in road pavements subjected to moisture fluctuation. Number of experiments was performed under controlled conditions to investigate the mechanical and hydraulic response of stabilized soils subjected to cyclic moisture degradation at various initial moisture contents covering practical moisture ranges in applicable with road pavements. Results showed that strength of stabilized soils was considerably increased with the addition of enzyme based stabilizer, revealing its ability to maintain the material stiffness over moisture fluctuation. While wetting and drying tests had damaging effects on the UCS, enzyme based stabilization served to preserve soil strength effectively throughout the loading cycles. Results obtained from the mechanical/hydraulics tests were further elaborated using imaging analysis which provides an insight into the mechanism of enzyme based stabilization and the influence of moisture when using this novel stabilization approach. This research will substantially benefit geotechnical applications including cost-effective and sustainable road constructions.**

***Keywords*: Soil stabilization Enzyme Expansive soil Moisture damage Durability**

Introduction

Expansive soils are a problem worldwide, undergoing considerable volume changes; swelling on absorbing water and shrinking on evaporation. Moreover, moisture fluctuations cause distinct changes in soil strength. Gillott [23] identified the two primary mechanisms involved in swelling of expansive soils; inter-particle swelling and intracrystalline swelling. Inter-particle swelling occurs due to the relaxation of capillary tensile forces in clay particles when exposed to water. Intracrystalline swelling typically occurs in montmorillonite clay where water causes expansion of the crystal lattice. Because of this behaviour, overlying structures are undermined and severely damaged; distress in pavements are further intensified by moisture influence, resulting in durability issues and consequently premature failure. This alternating behaviour of shrink and swell causes greater economic loss than damage induced by natural disasters.

Soil stabilization is widely identified to improve durability, enhance the engineering properties and mitigate the volume change behaviour of the expansive soils. Various methods of stabilization have been used; these include either mechanical stabilization or chemical stabilization. Mechanical techniques densify the soil expelling air from the voids. Chemical techniques incorporate additives that improve the properties of problematic soils. Generally, chemical stabilizers are characterized as traditional and non-traditional additives. Traditional stabilizers include calcium-based stabilizers such as lime and cement. Non-traditional stabilizers include salts, acids, enzymes, lignosulfonates, petroleum emulsions, polymers and tree resins. Soil improvement using lime and cement are considered costly and less environmentally friendly. Large amounts of resources and energy are consumed during production, releasing large amounts of carbon emissions. Moreover, investigations revealed that cyclic wetting and drying causes the arresting volume change behaviour to be lost after the first wet-dry cycle, and consequently swelling potential increases after each cycle due to the formation of expansive material such as ettringite in calcium-based stabilized soils. Some of the drawbacks of calcium-based stabilizers have fostered the use of more sustainable and effective non-traditional stabilizers such as enzymes.

On the other hand, enzyme based stabilizers can provide an economical and sustainable alternative in soil improvement compared to traditional stabilizers. Scholen reported a successful bio-enzymatic application to a forest road in Oklahoma, producing a durable and dust free road. However, field studies and laboratory findings have been controversial, relating to the effectiveness of this technology. Various researchers reported that enzyme based stabilizers produce maintenance free roads with an increase in bearing capacity (UCS, CBR and resilient modulus), while Parsons and Milburn found that enzyme based stabilization produced no significant increase in soil strength. Chandler et al. suggests that the inconsistency of results among researchers can be attributed to differences in specimen preparation, type of enzyme and curing methods.

However, limited information is available on the durability and impact of moisture on enzyme stabilized soils. Parsons and Milburn have investigated enzyme treatment on freezing-thawing and wetting-drying cycles. Results showcased relatively low strength and failure during the first soaking phase. The study has not assessed the wet-dry durability and strength on enzyme stabilized lean clay, instead focused on silty sands and silts [33]. Moreover, researchers have studied the effect on enzyme treated soils on swell, permeability and capillary rise. Results revealed a reduced; swell, permeability and capillary movement. However, all these studies have been tested at the optimum moisture condition and have failed to investigate the durability of the enzyme stabilized soil with moisture fluctuations.

Enzymes are typically naturally occurring, concentrated liquid stabilizer derived from organic materials, however, the mechanism of enzyme based stabilization is contested. Marasteanu et al. identified that stabilization occurs through a cationic ex- change. Clay molecules are engulfed by enzyme cations, neutralizing it, resulting in a higher density. Moreover, Tolleson et al. suggested that catalytic bonding occurs as enzymes attach to the microbes present in the soil and forming tight covalent bonds. However, Scholen [43,44] identified that for effective enzymatic stabilization, organic molecules are required to attach to clay minerals thus preventing further absorption of water and formation of cementing bonds between particles. Rauch et al. [42] suggest that stabilization occurs through organic en- capsulation of clay molecules, by neutralizing the negatively charged clay molecules with the addition of enzymes to decrease the clays affinity for water, making it more stable. These various hypotheses highlight there is no agreed consensus; hence, it is crucial to identify the stabilization mechanism, particularly when investigating the durability of enzymatic stabilization.

Despite the reported benefits and advantages of bio-enzymes, engineers are apprehensive to apply it to practice. This reluctance is attributed to the lack of sound understanding of the stabilization mechanism, and the lack of long-term assessment of enzyme stabilized expansive clays and the effect of moisture fluctuations. This paper comprehensively investigates the durability of bio-enzymatic stabilization of expansive soil by carefully characterising the stabilization mechanism. First, number of micro-scale driven imaging tests were used to assess the internal microstructure and mechanism of stabiliza aims of the current study. Firstly, X-Ray Micro Computed Tomography (μ-CT) analyses were conducted to understand the internal micro- structure of compacted stabilized soil samples. Then a series of laboratory tests were conducted to examine the mechanical behaviour and its durability upon degradation; tests included compaction, direct shear test, unconfined compressive strength (UCS), resilient modulus (M_r) one-dimensional (1D) swell, permeability and consolidation tests. Tests were performed based on three moisture contents, optimum moisture (w_{opt}), equilibrium moisture condition [24,60] after drying to 5–6% residual moisture (w_{res}) and saturated conditions (w_{sat}). Detailed description of the tests including procedures, test conditions, test program and relevant standards, are provided herein.

Soil characterization

The soil was obtained from a land excavation site in Melbourne, Australia. Due to the geological and arid climatic conditions, the soils from the region are known to be reactive. The soil was pre-treated by oven drying to obtain uniform moisture content and consequently sieved through the No.4 (4.75 mm) sieve to remove gravels. Atterberg limits, specific gravity, hydrometer analysis and standard compaction were performed using the relevant tests according to the Australian Standards. Physical characteristics of untreated and stabilized soils are shown in Table 1. Particle size distribution (PSD) and compaction curve are presented in Fig. 1 and Fig. 2, respectively, whereas crystalline phases identified through X-ray diffraction (XRD) are illustrated in Fig. 3. As per the Unified Soil Classification System (USCS) and AASHTO soil classification system, the soil is classified as lean clay with sand (CL) and A7-6 respectively (fair to poor subgrade material). The XRD analysis showed that the soil contained illite, quartz, montmor- illonite and kaolinite. Based on the presence of the expansive clay mi- neral montmorillonite and the consistency limits, the soil is classed as having a medium-high degree of expansion [15,17,29,54]. This ex- pansive nature made the soil an optimal candidate for enzyme based stabilization to study its durability and performance due to moisture impact.

Enzyme soil stabilizer

The enzyme soil stabilizer used in this study was the commercially available Eko Soil. Eko Soil is a product that is non-toxic and bio-de- gradable, being produced from water and proteins derived from plants. Eko Soil is added to clay-based soils to increase the soil compaction and consequently the bearing capacity. Typically, dilution mass ratio (DMR) of 1:500 and application mass ratio (AMR) of 1% is specified in industry applications.

Sample preparation

Remoulded specimens were prepared for all the tests performed. Soil specimens were obtained from the soil compacted using Standard various types of man-made synthetic materials that may be used to stabilize and hence modify the properties of soils by injecting them inside the pores. The various types of materials he discusses about are micro fine cement, polyurethane, silicates, acrylamide, phenoplasts, epoxy etc.tion using enzyme based stabilizers. The effect of moisture fluctuation on the mechanical properties of stabilized expansive soil was then evaluated by concentrating on swelling, permeability, on solidation, compaction, unconfined compressive strength results and resilient modulus. The results of the research study are used to identify the effectiveness and durability of enzyme based stabilization in liable to road construction.

Literature Reviews:
Synthetic chemical grouts and social context:

Xanthakos et al. (1994) [1] has mentioned in his research paper all about

Karol et al., (2003) [2] carried out research over toxicity of various chemical grouts used in soil stabilization and their adverse effects in social contexts. He mentions in his research that except sodium silicate all the synthetic chemical grouts those were used at that time were toxic in nature. He mentioned a case study of 1974 in Japan which entails about a case of five water poisoning cases observed due to use of Acryamide as chemical grout to stabilize soil resulting in ban for use of all chemical grouts for soil treatment.

Cayan et al., (2008) [3] mentioned in his research paper all about the environmental concerns like rise of sea water level as a result of global warming whose one of the major reason is cement which is a very essential part of the civil infrastructure industry and also used as the one of the chemical grout to stabilize the weaker soils. And he also discusses about the very need to find out the revolutionary substitute which is in general biologically non-toxic, non-hazardous, and non-inflammable as compared to synthetic chemical grouts that in any way degrade the environment and hence questions the life possibility in near future.

BIO-MEDIATED SOIL IMPROVEMENT METHOD:

Mitchell and Santamarina (2005) [4] have outlined the biologically potential influences in the sub-surface that could modify the properties of soil and be utilized by geotechnical engineers. They defined this new field of harnessing the biological metabolism to 9 change the local geo-chemistry and improve the mechanical behaviour of soil as Bio-mediated technique of soil stabilization.

Whitman et al., (1998) [5] discussed about the microbes concentration with respect to the depth in the soil sub-surface. This review help us identify the depth up to which the enzymes can penetrate to stabilize the soil strata. He found that more than 109 cells per gram of soil exist in top one metre of soil and their concentration decreases in general as the depth increases. He mentioned that the lower limit of most soil stabilization applications with microbe concentration of around 106 cells per gram of soil exist at 30 metres of depth.

Madigan and Martinko (2003) [6] discussed about the geometric compatibility between the soil and the microbes in which they are grouted as a part of central issue for possibility of uniform stabilization of soil. They found that relatively small size of microbes of size range between 0.5 to 3μm are more effective for treatment

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EFFECT OF BIO-ENZYMES AND THEIR DOSAGES ON PROPERTIES OF VARIOUS TYPES OF SOILS.

Marasteanu et al. (2005) [7] has carried out tri-axial and resilient modulus tests on two combinations of soil which were stabilized with two different enzymes. Soil I had a specific gravity of 2.73 and 96 % of fines (75 % of clay) and plasticity index of 52%. While, Soil II had plasticity index of 9.4% and 60% of fines (14.5% of clay). Chemical analysis of only enzyme A was conducted, as the supplier of other enzyme B did not agreed for it. The chemical analysis for the enzymes was based on determination of pH, total organic carbon concentration, metals concentrations (e.g., Fe, Al, and Ca), and inorganic anion concentrations (e.g., NO3-, SO42- and Cl-). The pH of enzyme A was 4.77 and it had very high potassium (K) concentration and moderate to high concentrations of magnesium (Mg), calcium (Ca) and sodium (Na). The tests were conducted on a base (Base-1) as well to compare the results. The protein concentration in the undiluted enzyme A was found to be 9230 mg/L. The presence of protein alone does never entails that the solution will exhibit enzymatic activity for the substrates used. This identifies two possibilities: Product A is highly concentrate enzyme solution that may contain only a single type of enzyme or a group of them that catalyse reactions not being analysed in the various tests conducted or product A is unable to stabilize soil via by some enzymatic activity but rather by some other mechanism, might be due to their surfactant characteristics. 10

M B Mgangira et al. (2009) [8] has presented lab test results on the effect of enzyme based chemical liquid as soil stabilizer. Two soil samples were taken one with Ip of 7 % and the other with Ip of 35 %. Tests conducted included standard Proctor test, UCS tests and tests for Attenberg limits. Treatment with various enzyme dosage resulted in slight decrement of Ip of both soil. Enzyme based treatment of two soils in the other hand showed a mixed effect on the UCS. So, no significant and consistent improvement in the UCS could be attributed to the treatment.

Peng et al. (2011) [9] has carried out UCS tests on three soil samples; coarse grained, fine grained and silty loam textures and named them as Soil I, Soil II and Soil III respectively. All the soil samples were stabilized with an enzyme (Perma-zyme) and quicklime. The samples were cured for 60 days in two dissimilar conditions; in sealed container and air-dry. In case of sealed container the moisture was preserved in the different samples throughout the curing period. While the samples that were put to air-dry condition were allowed to dry at room temperature. The enzyme was found to act effectively in air-dry curing for Soil I and Soil II as compared to quicklime where as it was found ineffective for Soil III in air-dry curing and for the three soil samples in sealed curing too. Quicklime on the other hand was found more effective than the enzymes as the water in the specimens was not allowed to vaporize which encouraged the hydration of quicklime.

Faisal Ali et al. (2012) [10] has focused in this research on the modification of engineering properties of three natural residual soils and mixed with various dosages of liquid chemical. A lot of lab tests such as consistency limits, compaction (OMC & MDD), UCS etc. were carried out to judge the performance & effectiveness of this chemical as a soil stabilizing agent. The result and analysis showed that the liquid stabilizer can reduce shrinkage by eliminating re-absorption of water molecules and reducing plasticity. It also reduces the OMC by exchanging and ionizing the water molecules on the surface of clay platelets; It raises the MDD by orderly re arranging and neutralizing the clay platelets and also increases the inter particle bridging.

Shukla M et al. (2010) [11] has experimented on an expansive soil treated and cured with an eco-friendly, organic, and non-toxic bio-enzyme stabilizer in order to evaluate its suitability in modifying the swelling potential of the expansive soils. The study shows that the bio enzyme stabilizer that was used found to be quite effective in reducing the swelling of an expansive soil on the wet side of optimum moisture content. 11

C.Venkatasubramanian et al. (2011) [12] has experimented on three different soil samples with four dosages for 2 and 4 weeks of curing after application of enzyme to find effect on various strength parameters. It is clear from the results that addition of bi-enzyme has significant effect in improving UCS values of chosen samples. The analysis showcased that the soil-stabilizing enzymes fasten the reactions between the clay and the organic cat-ions and catalyse the cat-ionic exchange without becoming the part of the end product.

A.U. Ravishankar et al. (2009) [13] has made comprehensive study on the effect of Terrazyme soil stabilizer with easily in abundant available laterite soil in South Kannada and Udupi districts .The soil does not satisfy the basic requirements (LL<=25% and Ip<=6%) to be used as a sound base course material in the pavements. To improve and modify the behaviour of soil the soil was initially blended with sand at various proportions unless until it matches the Atterberg's Limits for sub-base course of the pavement. The effect of enzyme on soil and the blended soil in terms of UCS and permeability are studied.

Mihai et al. (2005) [14] has carried out various tests (wet-dry, strength tests, leach testing, Atterberg's limits, freeze and thaw and strength tests) on soils (classified as SP, ML, CH, CL and SM) stabilized with cement, Permazyme 11-X, lime, and class C fly ash. UCS, stiffness, wet-dry, freeze-thaw, compaction and leaching tests were carried out on two silty soils (SM and ML) treated with Permazyme 11-X at a standard dosage.SM and ML soils had fines 30 % and 88%, LL 20% and 30% and Ip 3% and 7% respectively. Compaction tests for treated soils were carried out at moisture content 1% less than optimum value. But only 1% and 4% increase in dry density was found for SM and ML respectively. The soil samples for two soils after 28 days of curing were checked for stiffness and no improvement was found. Similarly for freeze-thaw very less improvement and for OMC-MDD & leaching test as well no improvement was found.

R.A. Velasquez et al. (2006) [15] has used chemical analysis and resilient modulus testing to study the effectiveness of sub-grade stabilization and the mechanism of action of two enzyme products (enzyme A & B).Two types of soils were investigated in in this study. Soil I with high % of fines (96.4% passing 200 μ sieve) and high clay content (75.2%) and Soil II with relatively low % of fines (59.7% passing 200 μ) and lower clay content (14.5%). Enzyme A and B improved soil workability and reduced the compaction effort at the time of sample preparation. Thus, lower effort was used to obtain the target density of the modified specimen as compared to untreated sample; the addition of enzyme A increased resilient modulus of soil 12

II by an average of 54% while it did not improve the resilient modulus of soil I; the addition of enzyme B to soils I and II had sound effect on the resilient modulus of soil. MR of soil I improved by an average of 69% and that for soil II it get raised by 77%; also, the resilient modulus increased as time of curing increased; Shear strength of soil I and Soil II were increased by an average of 9% and 23% respectively. While enzyme B raised the shear strength as 31% and 39% for soil I and II respectively. Hence it is known from analysis that % of fines and the chemical combination are the basic properties that may affect the mechanism of stabilization. Therefore, it is very necessary to give special look while selecting method of treatment for different types of soils.

Santamarina et al., (2001) [16] discusses about the monitoring of process of bio-mediation by non- destructive methods as they produce very less or no strain (resistivity case) so that the soil and the process of treatment remain undisturbed by measurements for accurate results. He mentions the following three geo-physical methods of non-destructive analysis to have real-time monitoring of biological, geotechnical and chemical components of soil sub-surface resulting in soil stabilization: velocity of shear waves, velocity of shear waves, resistivity method.

MONITORING OF PROCESS OF BIO-MEDIATION FOR SOIL STABILIZATION:

DeJong et al., (2006); Whiffin et al., (2007); Harkes et al., (2008) [17] have focussed on mainly the chain of reactions taking place especially the environment created by microbes of elevating the pH to generate supersaturated conditions that result in calcite precipitation which is the major cause of soil stabilization.

Jason T. DeJong et al. (2007) [18] have focussed completely on bio-mediated soil improvement method and mainly focusses on the various mechanisms of biological mediation which include bio-mineralization, bio-films and bio-gas generation which in turn results into soil stabilization.

EFFECT OF MAJOR ENVIRONMENTAL FACTORS ON BIOLOGICALLY INDUCED CEMENTATION FOR STABILIZATION OF SOIL:

Liang Cheng et al. (2016) [19] they studied the about influence the common environmental factors like temperature, oil contamination, freeze-thaw cycling, rainwater flushing, and urease concentration make when soil is treated by MICP technique so that the 13 efficiency of treatment in the most adverse condition can be known considering all these factors altogether.

Methodology

Number of experiments was conducted in this study to facilitate the Table 1

Table 1
Physical soil characteristics.

	Untreated soil	Enzyme stabilized soil
Specific gravity	2.7	2.7
Liquid limit (LL) %	48	49
Plastic limit (PL) %	18	17
Plasticity index (PI) %	30	32
Maximum dry density (MDD) (g/cm^3)	1.62	1.67
Optimum moisture content (OMC) (%)	22.9	21.2
Permeability (m/s)	6.83×10^{-10}	1.03×10^{-10}
Passing sieve number 200 (%)	74.7	
Unified soil classification	CL*	
AASHTO soil classification	A7-6	

* Note: CL = lean clay with sand.

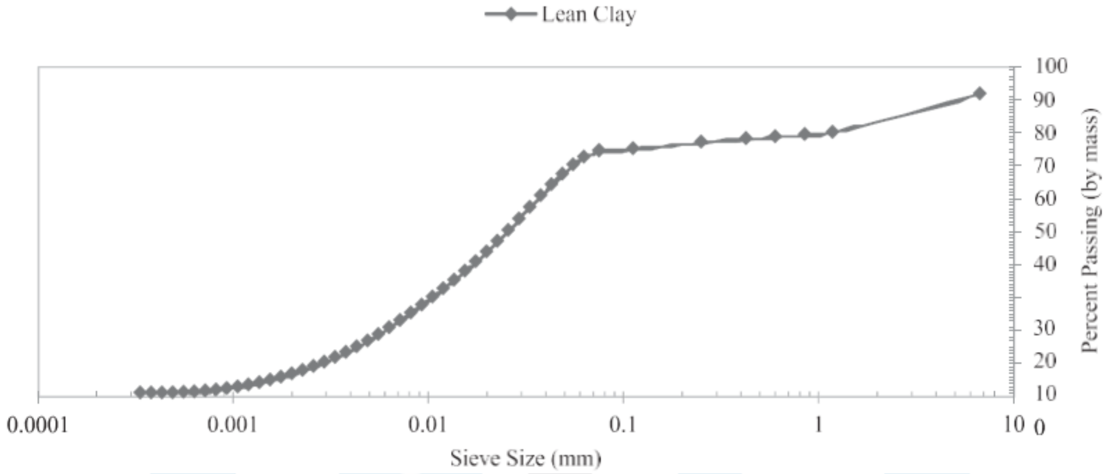

Fig. 1. PSD curve.

Proctor compaction performed in accordance with AS 1289.5.1.1 [4] at the respective moisture contents. The µ-CT, swell and shear strength specimens were then trimmed to size. Treated samples were prepared with the enzyme at DMR of 1:500 and AMR of 1%. Firstly, soil was pre- moistened to the initial moisture content of OMC – (AMR/DMR) + 2% and allowed to cure in a sealed airtight container for 48 h. The diluted stabilizer was then mixed into the soil at the selected AMR and allowed to stand for 1 h before compaction. All samples were compacted within ± 2% of the MDD. Compacted samples were tested after a 4- day curing period in airtight containers.

Testing Programme

The behaviour of stabilization on the internal microstructure was examined using µ-CT on soil specimens at w_{opt} conditions. In order to assess the influence of moisture on enzyme stabilized soil, a series of tests were conducted on soil specimens at various moisture contents. After curing, the compacted samples were trimmed to size if required, before testing. In this study, three moisture contents were investigated, w_{opt}, equilibrium moisture condition [24,60] after drying to 5–6% w_{res} and w_{sat} conditions, to reflect and accurately predict how the subgrade soils react to seasonal changes in moisture content [18]. The experi- mental plan is summarized in Table 2 and elaborated below.

X-Ray Micro Computed Tomography (µ-CT)

µ-CT analysis was performed to non-destructively evaluate the density, volume and porosity fractions [26]. Samples for µ-CT analysis was obtained using UCS samples, which were compacted and cured 4- days before trimming to about 20 mm3. µ-CT analysis was conducted using the Bruker Skyscan 1275 Micro CT apparatus. Samples were scanned at 20 µm resolution, using an X-ray tube with a copper filter at a voltage of 100 kV, current of 100 mA and a copper filter. CTAn soft- ware was used to analyse the µ-CT porosity and microstructure of tested specimens.

California bearing ratio (CBR)

Soaked and unsoaked CBR testing was conducted following AS 1289.6.1.1 [5] using a standard compaction hammer. Subgrade CBR is typically expressed from soaked conditions to assess the strength of subgrade material used in road design and construction.

Unconfined compressive strength (UCS)

UCS testing was performed in accordance with AS 5101.4 [7]. Samples were prepared in cylindrical moulds (105 mm diameter,

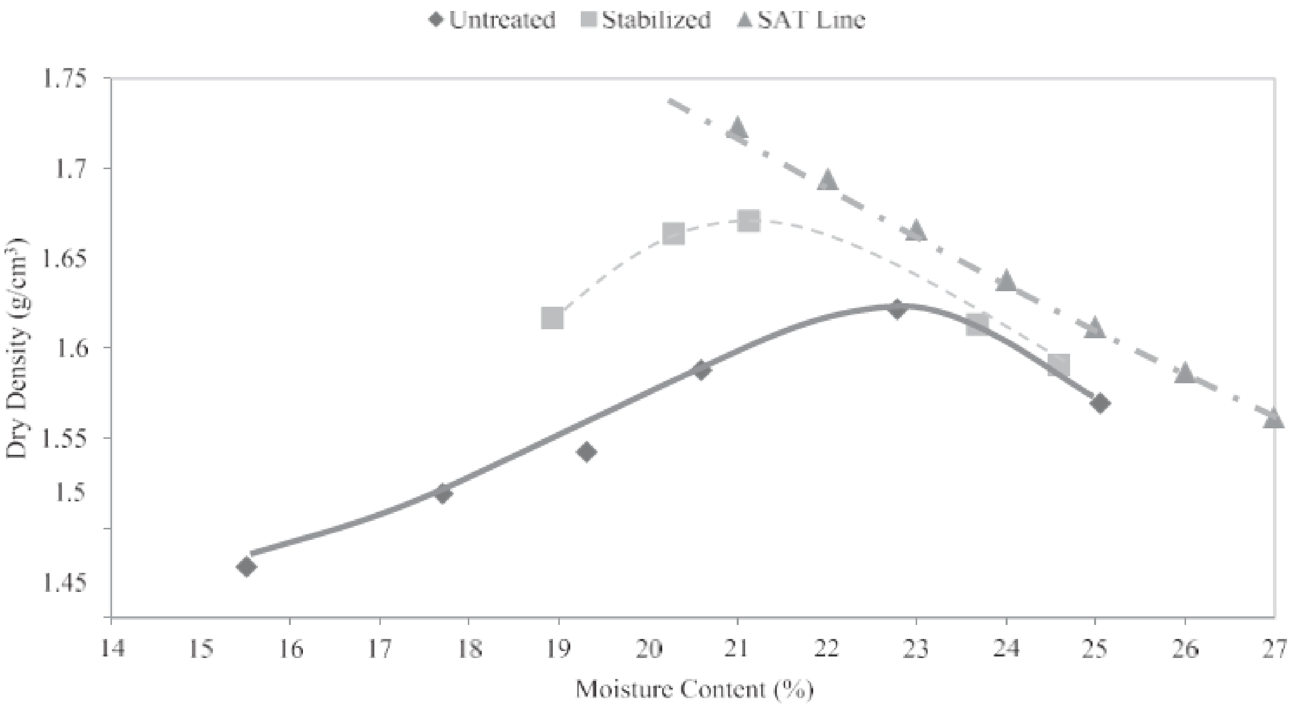

Fig. 2. Standard compaction curve.

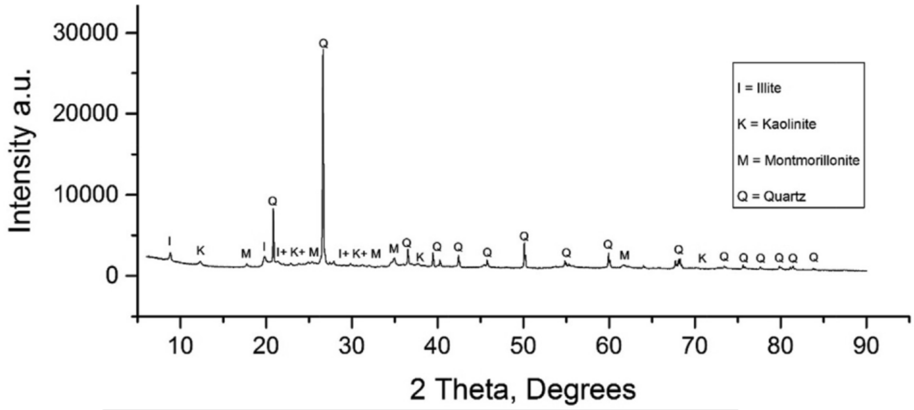

Fig. 3. XRD of tested soil.

115 mm height) and compacted using Standard Proctor compaction, and tested up to failure or 15% strain under a constant deformation of1 mm/min [7,9].

Wetting and drying test

Following the curing period, compacted soil samples were subjected to wetting and drying cycles adapting the ASTM D559 [8] procedures to investigate the durability of enzyme based soil stabilization. Throughout testing, specimens were wrapped around a rubber mem-brane and placed between two porous stones to aid in handling. In the current study, up to 5 wetting-drying cycles were applied to simulate a major rainfall event that has induced flooding followed by dry condi- tions over a ten-year period. Each cycle consisted of 1-hour saturationin the vacuum chamber at 52 cmHg, followed by 24-hour immersion in water at room temperature and then drying the soil at 100 °C for 24 h. Compared to the ASTM D559 [8], wetting periods included vacuum saturation and increased wetting time up to 24 h to ensure samples were completely saturated simulating a flooded condition, common to many parts of Australia. The drying temperature was maintained at 100 °C to reach typical site moisture conditions (equilibrium moisture content) within the 24-hour drying period. Samples were exposed to 0,1, 3 and 5 cycles prior to the compressive strength testing and volume change assessment. Volume change values reported in this study were determined by measuring the average height and diameter at 3 pointson the soil sample. The compressive strengths were determined in the drying state.

Permeability

Falling head permeability test was performed on untreated and stabilized soil samples in accordance with AS1289.6.7.2 [6]. Test specimens were prepared in UCS cylindrical moulds (101.6 mm diameter, 116.43 mm height) and compacted to its respective OMC and MDD using a standard compactive effort. The specimen was saturated using the vacuum chamber previously described. Once saturated, the parameter was attached to the falling head apparatus. At regular intervals, reading of the standpipe was taken until the permeability became constant.

Direct shear testing

Direct shear testing was performed in accordance with ASTM D3080 [64]. Specimens were prepared by trimming compacted samples to direct shear box size (60 mm length × 60 mm width × 20 mm height). Direct shear tests were performed by applying a shearing rate of 0.025 mm/min until the soil failed or reached a maximum horizontaldisplacement of 20 mm. The shearing rate was determined after a number of preliminary tests conducted at OMC condition by monitoring the change in volume (i.e. volumetric strain) and moisture content (Table 3). The selected shearing rate was able to minimize the shear induced volume changes and subsequent changes in suction while es- tablishing constant water content due to the very low permeability of clay. Direct shear specimens were tested at the applied normal stressesof 50 kPa, 100 kPa, 150 kPa and 200 kPa to determine the effective shear stresses at failure using Bishop [65] effective stress equation. Soil suction was estimated from the PSD using the Arya and Paris model [66]. The normal stresses and shear stress at failure were then plotted to determine the Mohr-Coulomb failure envelopes.

One dimensional swell

ASTM D4546 [10] procedure was employed to determine the swell pressure using the consolidation apparatus. Test method A 'wetting- after-loading' was used in this study. The compacted soil specimen was cut to size of the consolidation ring (50 mm diameter and 20 mm height) and prepared according to moisture contents of w_{opt}, w_{res} and w_{sat} as previously described. Various vertical loads were first applied to the specimens to produce a range of stresses (1 kPa, 5 kPa, 12.5 kPa,50 kPa, 100 kPa and 200 kPa). The samples were inundated with water taking deformation readings until primary swell/collapse was completed.

Table 2
Summary of experimental tests performed.

Test	Soil treatment	DMR	AMR (%)	Compacted dry density (g/cm³)	Moisture content (%)
μ-CT	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}
CBR	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}
UCS	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}, w_{res}, w_{sat}
Wetting/drying	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}
Permeability	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}
Direct shear	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}, w_{res}, w_{sat}
1D swell	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}, w_{res}, w_{sat}
Resilient modulus	Untreated, stabilized	1:500	0, 1	1.62, 1.67	w_{opt}, w_{res}, w_{sat}

Table 3
Scheme to determine shear rate.

Soil properties	Shear rate (mm/min)	Change in moisture content (%)	Volumetric strain (%)
w_{opt} condition - normal stress 200 kPa	0.01	7.8	3.3
	0.02	6.1	3.4
	0.025	2.8	2.9

Resilient modulus

Specimens for resilient modulus test were prepared using the stan- dard proctor hammer. The mould used to prepare the resilient modulus specimens had a height of 200 mm and a diameter of 100 mm. Specimens were compacted in 3 layers such that the compacted height of the soil was 67 ± 2 mm in the first layer and 133 ± 2 mm in the second layer, and the third layer was compacted to finish flush with the top of the mould. The procedure described in AASHTO T 307-99 [1] was followed for the resilient modulus testing using the loading se- quence for subgrade soil.

Conclusions:

This study investigates assessing the durability of enzyme based soil stabilization for expansive soils subjected to moisture degradation is applicable with the soil. A series of lab tests was con- ducted to assess the impact of moisture on the engineering properties of enzymatically stabilized clay soils. Results showed the addition of en- zyme stabilizer has been able to showcase considerable improvement in strength and hydraulic characteristics of soil. Stabilization has also been effective to improve the water permeability resistance. Strength results also revealed the enzyme based stabi- lizers ability to maintain the material stiffness over moisture fluctua- tions, ensuring its durability. The results from the wetting and drying tests further showcased the durability effects. Even though the control soil samples undergo crack propagation, volume reduction, shape changes and reduction in UCS results with an increase in the number of wetting and drying cycles, the addition of the enzyme stabilizer in ex- pansive soils limits these changes, preserving strength and durability in its applications. Moreover, treated soil samples had undergone a re- duction in swell across the varying moisture contents, revealing the stabilizers ability to inhibit swell. These results provide an insight into the mechanism of stabilization and the influence of moisture when using this novel stabilization approach. Hence the study shows the enzyme based soil stabilization has been effective to improve and maintain the strength and hydraulic characteristics, which is beneficial for sustainable road construction. It is to be noted that differing enzyme stabilizers and mix proportions can yield different results which pri- marily depend on the field soil type/condition. However, it is re- commended that enzyme based stabilization be used in conjunction with another additive to provide greater improvements in the strength

References

[1] American Association of State Highway Transportation Offcials (AASHTO). Standard method of test for determining the resilient modulus of soil and aggregate materials. 2017, AASHTO: Washington, D.C.

[2] Agarwal P, Kaur S. Effect of bio-enzyme stabilization on unconfined compressive strength of expansive soil. Int J Res Eng Technol 2014;3(5):30–3.

[3] Amadi AA. Enhancing durability of quarry fines modified black cotton soil subgrade

[4] with cement kiln dust stabilization. Transportation Geotechnics 2014;1(1):55–61. https://doi.org/10.1016/j.trgeo.2014.02.002.

[5] AS 1289.5. Methods of testing soils for engineering purposes, in 5.1.1 Soil com- paction and density tests - Determination of the dry density/moisture content re- lation of a soil using standard compactive effort. 2017, Standards Australia Limited: Sydney, Australia.

[6] AS 1289.6. Methods of testing soils for engineering purposes, in 6.1.1 Soil strength and consolidation tests - Determination of California Bearing Ratio of a soil. 2014, Standards Australia Limited: Sydney, Australia.

[7] AS 1289.6. Methods of testing soils for engineering purposes, in 6.7.2 Soil strength and consolidation tests - Determination of permeability of a soil - Falling head method for remoulded specimen. 2001, Standards Australia Limited: Sydney, Australia.

[8] AS 5101.4. Methods of for preparation and testing of stabilized materials, in Method 4 Unconfined compressive strength of compacted materials. 2008, Standards Australia Limited: Sydney, Australia.

[9] ASTM D559. Standard test method for wetting and drying compacted soil-cement mixures. ASTM International: West Conshohocken, PA, United States; 2015.

[10] ASTM D2166. Standard test method for unconfined compressive strength of cohe- sive soil. ASTM International: West Conshohocken, PA, United States; 2016.

[11] ASTM D4546. Standard test method for one-dimensional swell or collapse of soil. ASTM International: West Conshohocken, PA, United States; 2014.

[12] Behnood A. Soil and clay stabilization with calcium- and non-calcium-based ad- ditives: A state-of-the-art review of challenges, approaches and techniques. Transportation Geotechnics 2018;17:14–32. https://doi.org/10.1016/j.trgeo.2018. 08.002.

[13] Bell F. Stabilisation and treatment of clay soils with lime: Part 2-some applications. Ground Eng 1988;12(2):22–30.

[14] Celik E, Nalbantoglu Z. Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils. Eng Geol 2013;163:20–5. https://doi.org/10.1016/j.enggeo.2013.05.016.

[15] Chandler N, Palson J, Burns T. Capillary rise experiment to assess effectiveness of an

[16] enzyme soil stabilizer. Can Geotech J 2017;54(10):1509–17. https://doi.org/10. 1139/cgj-2016-0511.

[17] Chen FH. Foundations on expansive soils. Amsterdam: Elsevier; 1988.

[18] Cokca E, Erol O, Armangil F. Effects of compaction moisture content on the shear strength of an unsaturated clay. Geotech Geol Eng 2004;22(2):285. https://doi.org/ 10.1023/B:GEGE.0000018349.40866.3e.

[19] Dakshanamurthy V, Raman V. A simple method of identifying an expansive soil. Soils Found 1973;13(1):97–104. https://doi.org/10.3208/sandf1972.13.97.

[20] Drumm EC, Reeves JS, Madgett MR, Trolinger WD. Subgrade resilient modulus correction for saturation effects. J Geotech Geoenviron 1997;123(7):663–70. https://doi.org/10.1061/(ASCE)1090-0241(1997) 123:7(663).

[21] EkoSoil. Eko Soil Manual. Melbourne, Australia; 2015

[22] Eujine GN, Chandrakaran S, Sankar N. Accelerated subgrade stabilization using enzymatic lime technique. J Mater Civil Eng 2017;29(9):04017085–4017087. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001923.

[23] Eujine GN, Chandrakaran S, Sankar N. Influence of enzymatic lime on clay mineral behavior. Arab J Geosci 2017;10(20):454–62. https://doi.org/10.1007/s12517- 017-3238-z.

[24] Fredlund DG, Rahardjo H. Soil mechanics for unsaturated soils. United States of America: John Wiley & Sons; 1993.

[25] Gillott JE. Clay in engineering geology. 2nd ed. New York: Elsevier; 1968.

[26] Giummarra GJ. Unsealed roads manual: guidelines to good practice. 3rd ed. Vermont South: ARRB Group; 2009.

[27] Guney Y, Sari D, Cetin M, Tuncan M. Impact of cyclic wetting–drying on swelling behavior of lime-stabilized soil. Build Environ 2007;42(2):681–8. https://doi.org/ 10.1016/j.buildenv.2005.10.035.

[28] Hashemi MA, Massart TJ, Salager S, Herrier G, François B. Pore scale character- ization of lime-treated sand–bentonite mixtures. Appl Clay Sci 2015;111:50–60. https://doi.org/10.1016/j.clay.2015.04.001.

[29] Imbabi MS, Carrigan C, McKenna S. Trends and developments in green cement and concrete technology. Int J Sustain Built Environ 2012;1(2):194–216. https://doi. org/10.1016/j.ijsbe.2013.05.001.

[30] Ismael NF, Behbehani M. Influence of relative compaction on the shear strength of compacted surface sands. Int J Environ Sci Dev 2014;5(1):8–11.

[31] Khemissa M, Mahamedi A. Cement and lime mixture stabilization of an expansive overconsolidated clay. Appl Clay Sci 2014;95:104–10. https://doi.org/10.1016/j. clay.2014.03.017.

[32] Lin B, Cerato A. Investigation on soil-water characteristic curves of untreated and stabilized highly clayey expansive soils. Geotech Geol Eng 2012;30(4):803–12. https://doi.org/10.1007/s10706-012-9499-0.

[33] Marasteanu MO, Hozalski RM, Clyne TR, Velasquez R. Preliminary laboratory in- vestigation of enzyme solutions as a soil stabilizer. St. Paul Minnesota Department of Transportation; 2005.

[34] Naagesh S, Gangadhara S. Swelling properties of bio-enzyme treated expansive soil. Int J Eng Stud 2011;4(2):555–60.

[35] Parsons RL, Milburn JP. Engineering behavior of stabilized soils. Transp Res Rec 2003;1837(1):20–9. https://doi.org/10.3141/1837-03.
[36] Patel U, Singh S, Chaudhari S. Effect of bio enzyme–terrazyme on compaction,
[37] Consistency limits and strength characteristics of expansive soil. Int J Res Eng Technol 2018;5(3):1602–5.
[38] Pedarla A, Chittoori S, Puppala AJ. Influence of mineralogy and plasticity index on the stabilization effectiveness of expansive clays. Transp Res Rec 2011;2212(1):91–9. 10.3141%2F2212-10.
[39] Phanikumar BR. Effect of lime and fly ash on swell, consolidation and shear
[40] strength characteristics of expansive clays: a comparative study. Geomech Geoeng 2009;4(2):175–81. https://doi.org/10.1080/17486020902856983. Popescu ME. A comparison between the behaviour of swelling and of collapsing soils. Eng Geol 1986;23(2):145–63. https://doi.org/10.1016/0013-7952(86) 90036-0.
[41] Punthutaecha K, Puppala AJ, Vanapalli SK, Inyang H. Volume change behaviors of expansive soils stabilized with recycled ashes and fibers. J Mater Civil Eng 2006;18(2):295–306. https://doi.org/10.1061/(ASCE)0899-1561(2006)
[42] 18:2(295).
[43] Puppala AJ, Banavathu N, Intharasombat N, Qasim S. The effects of using compost as a preventive measure to mitigate shoulder cracking: laboratory studies. The University of Texas 2006.
[44] Puppala AJ, Manosuthikij T, Chittoori BC. Swell and shrinkage characterizations of unsaturated expansive clays from Texas. Eng Geol 2013;164:187–94. https://doi. org/10.1016/j.enggeo.2013.07.001.
[45] Rauch A, Harmon J, Katz L, Liljestrand H. Measured effects of liquid soil stabilizers on engineering properties of clay. Transp Res Rec 2002;1787(1):33–41. https://doi. org/10.3141/1787-04.
[46] Rauch A, Katz L, Liljestrand H. An analysis of the mechanisms and efficacy of three liquid chemical soil stabilizers. Center for Transportation Research; 2003.
[47] Scholen DE. Non-standard stabilizers. Washington, D.C.: Springfield, VA. Federal Highway Administration; 1992.
[48] Scholen DE. Stabilizer mechanisms in nonstandard stabilizers. Sixth international conference on low-volume roads. Minneapolis, Minnesota; 1995. p. 252–60.
[49] Shah K, Shah M. Soil stabilization using terrazyme. Int J Adv Eng Res Dev
[50] 2016;3(12):359–65.
[51] Shaka PM, Shaka SM. Laboratory investigation on black cotton soils and red soil stabilized using enzyme. Int J Res Eng Technol 2016;3(6):325–30.
[52] Shamrani MA, Mutaz E, Puppala AJ, Dafalla MA. Characterization of problematic
[53] expansive soils from mineralogical and swell characterization studies. GeoFlorida 2010: Advances in analysis, modeling & design. Florida; 2010. p. 793–802. Doi: 10. 1061/41095(365)78.
[54] Shankar AR, Mithanthaya R, Lekha B. Laboratory studies on bio-enzyme stabilized lateritic soil as a highway material. Workshop on non-conventional materials/ technologies. New Delhi; 2012. p. 109–23.
[55] Shankar AR, Rai HK, Mithanthaya R. Bio-enzyme stabilized lateritic soil as a
[56] highway material. Indian Roads Congress J 2009;70(2):143–51.
[57] Sheng D, Gens A, Fredlund DG, Sloan SW. Unsaturated soils: From constitutive modelling to numerical algorithms. Comput Geotech 2008;35(6):810–24. https:// doi.org/10.1016/j.compgeo.2008.08.011.
[58] Shojaei Baghini M, Ismail A, Karim MR, Shokri F, Firoozi AA. Effect of styr- ene–butadiene copolymer latex on properties and durability of road base stabilized with Portland cement additive. Constr Build Mater 2014;68:740–9. https://doi.org/ 10.1016/j.conbuildmat.2014.06.061.
[59] Simons KB. Limitations of residential structures on expansive soils. J Perform Constr Fac 1991;5(4):258–70. https://doi.org/10.1061/(ASCE)0887-3828(1991) 5:4(258).
[60] Sobhan K, Das BM. Durability of soil-sements against fatigue fracture. J Mater Civil Eng 2007;19(1):26–32. https://doi.org/10.1061/(ASCE)0899-1561(2007) 19:1(26).
[61] Sridharan A, Prakash K. Classification procedures for expansive soils. P I Civil Eng- Geotech 2000. https://doi.org/10.1680/geng.2000.143.4.235.
[62] Ta'negonbadi B, Noorzad R. Stabilization of clayey soil using lignosulfonate. Transportation Geotechnics 2017;12:45–55. https://doi.org/10.1016/j.trgeo.2017. 08.004.
[63] Tingle J, Newman J, Larson S, Weiss C, Rushing J. Stabilization mechanisms of nontraditional additives. Transp Res Rec 2007;1989–2(1):59–67. Doi: 10.3141%2F1989-49.
[64] Tolleson R, Shatnswi M, Harman E, Mahdavian E. An evaluation of strength change on subgrade soils stabilized with an enzyme catalyst solution using CBR and SSG comparisons. South Carolina State University; 2003.
[65] Velasquez RA, Marasteanu MO, Hozalski RM. Investigation of the effectiveness and mechanisms of enzyme products for subgrade stabilization. Int J Pavement Eng 2006;7(3):213–20. https://doi.org/10.1080/10298430600574395.
[66] Venkatasubramanian C, Dhinakaran G. Effect of bio-enzymatic soil stabilisation on
[67] unconfined compressive strength and California bearing ratio. J Eng Appl Sci
[68] 2011;6(5):295–8.
[69] Yang S-R, Lin H-D, Kung JHS, Huang W-H. Suction-controlled laboratory test on resilient modulus of unsaturated compacted subgrade soils. J Geotech GeoEnviron 2008;134(9):1375–84. https://doi.org/10.1061/(ASCE)1090-0241(2008)
[70] 134:9(1375).
[71] Yong RN, Ouhadi VR. Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils. Appl Clay Sci 2007;35(3):238–49. https://doi. org/10.1016/j.clay.2006.08.009.
[72] Zheng J-L, Zhang R, Yang H-P. Highway subgrade construction in expansive soil areas. J Mater Civil Eng 2009;21(4):154–62.

https://doi.org/10.1061/(ASCE)0899- 1561(2009) 21:4(154).
[73] Zornberg JG, Azevedo M, Sikkema M, Odgers B. Geosynthetics with enhanced lateral drainage capabilities in roadway systems. TransportationGeotechnics 2017;12:85–100. https://doi.org/10.1016/j.trgeo.2017.08.008.
[74] ASTM D3080. Standard test method for direct shear test of soil under consolidated
[75] drained conditions. West Conshohocken, PA, United States: ASTM International; 2011.
[76] Bishop AW. The principle of effective stress. Teknisk Ukeblad 1959;106(39):859–63.
[77] Arya LM, Paris JF. A physicoempirical model to predict the soil moisture char-
[78] acteristic from particle-size distribution and bulk density data. Soil Sci Soc Am J 1981;45(6):1023–30. https://doi.org/10.2136/sssaj1981.
[79] 03615995004500060004x.
[80] Xanthakos, P.P.; Abramson L.W. and Bruce D.A., (1994), "Ground Control and Improvement" John Wiley and Sons, New York, NY, 910.
[81] Karol, R.H., (2003), "Chemical Grouting and Soil Stabilization" Marcel Dekker, New York, NY, 558.
[82] Cayan, D.R.; Bromirski P.D.; Hayhoe K.; Tyree M.; Dettinger M.D. and Flick R.E., (2008), "Climate change projections of sea level extremes along the California coast", Climate Change 87 (Suppl 1), S57–S73.
[83] Mitchell, J.K.; Santamarina J.C., (2005), "Biological considerations in geotechnical engineering", J. Geotech. Geoenviron. Eng. 131 (10), 1222–1233.
[84] Whitman, W.B.; Coleman D.C.; Wiebe W.J., (1998), "Prokaryotes: the unseen majority" Nat. Acad. Sci. (95), 6578–6583.
[85] Madigan, M.T.; Martinko J.M.; (2003), "Brock Biology of Microorganisms", eleventh edition, Prentice Hall, Upper Saddle River, NJ, 992.
[86] Marasteanu, M.O.; Hozalski R.; Clyne T.R. and Velasquez R (2005), "Preliminary laboratory investigation of enzyme solutions as a soil stabilizer", Minnesota Department of Transportation, Research Services.
[87] Mgangira, M.B. (2010), "Evaluation of the effects of enzyme-based liquid chemical stabilizers on sub-grade soils" CSIR, Built Environment, Pretoria.
[88] ix. Peng, H. T.; Su, H. T.; Zhang, X. P. & Wang, J. (2011), "An experimental comparison of compressive strengths of soils stabilized with enzyme and ground quicklime", Advance Material Research 280: 9-12.
[89] Ali, F. (2012), "Stabilization of Residual Soils Using Liquid Chemical" Civil Engineering Department, Faculty of Engineering, National Defence University of Malaysia, Kuala Lumpur, Malaysia.
[90] Shukla, M.; Bose, S. and Sikdar, P. (2010), "Enzyme for stabilization of soil in road construction a cost effective approach", IRC Seminar, "Integrated development of rural and arterial road networks for socio-economic development", New Delhi.
[91] Venkatasubramanian, C. and Dhinakaran, G. (2011), "Effect of bio-enzymatic soil stabilization on unconfined compressive strength and California bearing ratio", Journal of Engineering and Applied Sciences: 6(5):295-298.
[92] 59
[93] Shankar, A. U.; Rai, H. K. and Mithanthaya, R (2009), "Enzyme stabilized Lateritic Soil as a Highway material", Indian Roads Congress Journal.
[94] Mihai; Ray, O.M.; Timothy, H.; R.C. and Raul, V. (2005) "Preliminary laboratory investigation of enzyme solutions as a soil stabilizer", MN/RC – 2005-25 Report. Minnesota Department of Transportation.
[95] Velasquez, R.A.; Marasteanu, M. O. and Hozalski, R.M. (2006), "Investigation of the effectiveness and mechanisms of enzyme products for sub-grade stabilization", International Journal of Pavement Engineering, 7:3, 213-220.
[96] Santamarina, J.C.; Klein, K.A. and Fam, M.A., (2001), "Soils and Waves", John Wiley & Sons, ltd., 455.
[97] DeJong, J.T.; Fritzges, M.B. and Nusslein, K., (2006), "Microbial induced cementation to control sand response to undrained shear", ASCE J. Geotech. Geoenviron. Eng. 132(11), 1381–1392.
[98] DeJong, J.; Mortensen, B., and Martinez, B (2007), "Bio-Soils Interdisciplinary Science and Engineering Initiative", 85 pp. http://www.sil.ucdavis.edu/biosoil-outcomes.htm.
[99] Liang cheng; Mohamed A.Sahin, and Donovan Mujah (2016). "Influence of environmental conditions on microbially induced cementation for soil-stabilization" J. Geotech. & Geo-environ. Eng., 10.1061/ (ASCE) GT.1943-5606.0001586.