Effect of Wetting-Drying Cycles on Strength Behaviour of Lime Stabilized Expansive Soil

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Abstract. The behaviour of stabilized subgrade soil subjected to cyclic Wetting and Drying (W-D) in the region, where temperature and climatic variations are significant like Rajasthan (temperature rises up to 50°C), is essential for understanding its long-term durability. In the present study, effect of cyclic W-D on the strength behaviour of lime treated black cotton soil cured up to 28 days has been investigated. The objectives have been achieved by performing the detailed characterization of materials used and by investigating the Unconfined Compressive Strength (UCS) of soil treated with optimum lime content (6%). The lime treated sample cured up to 28 days has been selected by considering the fact that formation of cementitious compounds of Al-and Si-hydrates, which are mainly responsible for strength improvement, need longer time periods. The UCS has been determined for lime treated soil cured up to 28 days without and with subjected to W-D (up to 50°C) for one and four cycles. The results showed that the improvement in soil plasticity has been observed immediately after addition of lime. The strength of lime treated soil tested in drying state increases over the curing period and number of W-D cycles. The increase in strength can be attributed to the pozzolanic reactions which happen over the time and thereby, formation of compacted matrix with formation of cementitious compound.

Keywords: Black cotton soil, Lime, Micro-analysis, Strength, Wetting-Drying.

1 Introduction

Black Cotton Soil (BCS), also known as expansive soil, is a major soil group of India and is covered 20% land of country. BCS is predominated with smectite group of mineral such as montmorillonite and has characteristic of medium to high compressibility. Several damage and distress of structures constructed on BCS throughout the world have been encountered due to the cyclic swell-shrinkage behaviour upon temporal variation [1]. Hence, Wetting-Drying (W-D) cycles upon seasonal variation are key factor to be considered to control the induced damage of various civil engineering projects such as highways and pavements [2, 3]. Dempsey and Thompson [4] reported that materials used for construction should be sufficient enough to provide the adequate resistance to climatic conditions. However, suitability of material to be used as a construction material should be based on its mechanical and mineralogical properties under serve climatic conditions. During W-D cycles most of the engineering properties of the soils, especially their strength, are severely affected and as a result crack propagation and stability failure occur [5, 6]. Hence, proper study on effect of W-D cycles is necessary to evaluate the long-term behaviour of foundations [1]. Several ground improvement techniques such as traditional stabilizers (hydrated lime, portland cement, and fly ash); byproduct stabilizers (cement kiln dust, lime kiln dust, and other forms of byproduct lime); and nontraditional stabilizers (sulfonated oils, potassium compounds, ammonium chloride, enzymes, polymers, and so on) have been used to overcome with problem associated with climatic changes [7].

However, chemical stabilization, especially with lime, is considered as a one of the mostly adopted technique to improve the engineering properties of fine-grained soil due to its effective and economic usage [8, 9]. Modifications of properties of soil-lime mixtures are governed by four basic reactions i.e., a) Cation exchange; b) Flocculation/agglomeration; c) Carbonation; and d) Pozzolanic reaction [10, 11]. Cation exchange and flocculation/agglomeration occur rapidly and are mainly responsible for changes in plasticity, workability and engineering properties. Lime react with carbon dioxide to form relatively weak cementing agents [10]. Pozzolanic reaction is key phenomenon for the alteration in long-term soil properties of lime-treated soil. These pozzolanic reactions are responsible for the improvement in the strength and deformation behavior of soils [11]. However, durability of lime stabilized soil is always questionable against impact of successive W-D periods.

Based on few field studies of lime stabilized roads and earthfills by previous researchers, the successive W-D cycles can lead to the detrimental effect on the long-term efficiency of lime treatment [12, 13]. The laboratory studies have also been reported in literatures on samples reconstituted in the laboratory for lime stabilized soils subjected to number of W-D cycles. Rao et al. [1] that the formation of tension and surface cracks due to W-D cycles causes the damage of lime stabilized soil. The effect of W-D cycles on swell potential of chemically stabilized soil with fly ash is observed significant at first cycles and has unchanged afterward [14]. Similar observation is reported by Khattab [15] that the swelling potential of lime treated bentonite has not affected after a few number of W-D cycles. However, the advantageous effect of lime stabilized soils are partially lost after exposing it to several W-D cycles [9]. Further, Stoltz et al. [16] reported that progressive increase in the swelling properties of the material and a progressive loss of strength with increasing number of W-D cycles is observed in the clayey soil stabilized with quick lime. The development of crack in cemented structure due to the cyclic swell-shrinkage leads to the reduction in strength of stabilized soil subjected to W-D cycles [17, 18]. By and large, it has been concluded that cyclic W-D cycles of stabilized soil results the significant alteration in its long-term properties. This needs to be examined at micro-scale and has to be addressed properly prior to the application of chemical stabilization in field.

The present work emphasizes the effect of wetting-drying cycles on the lime stabilized soil. The objective was achieved by performing the unconfined compressive strength of cured lime treated expansive soil up to 28 days. Further, samples cured for 7, 14 and 28 days are taken to examine the effect of varying wetting-drying cycles. Physical properties of untreated and lime treated soil are also determined.

2 Materials Used and Methodologies Followed

2.1 Materials Used

The Black Cotton Soil (BCS) used for the present study is collected through open excavation below 1.5 m depth from Shivdaspura (303903) village, Jaipur district of Rajasthan, India. The geotechnical properties of BCS and methodologies followed are presented in Table 1. The combined curve of wet sieving and hydrometer analysis shows (Fig. 1) the presence of predominant amount of sand sized particle (4.75 – 0.075 mm) of 11.0%, silt sized particle (0.075 – 0.002 mm) of 13.0% and clay sized particle (<0.002mm) of 76.0%. The liquid limit and plastic limit of BCS are found to be 43% and 15.18% and hence, the difference of liquid limit and plastic limit i.e. plasticity index (PI) is 27.18%. Based on the Indian Standard plasticity chart for soil classification, Black cotton soil is classified as clay of low plasticity (CL). The specific gravity and pH of BCS are 2.39 and 7.5, respectively.

Scanning Electron Microscope (SEM) image of BCS [Fig. 2a] illustrates several voids with honeycomb networking patterns. The X-ray Diffraction (XRD) analysis of soil shows the presence of montmorillonite, aluminum oxide and quartz as predominant minerals (Fig. 2b). Energy Dispersive X–ray Spectroscopy (EDAX) is performed for the chemical composition to observe the element present in black cotton soil. It is observed that black cotton soil is predominated with Silica (Si) and Aluminum (Al) with minor amount of magnesium (Mg) and Sodium (Na) [Table 2].

Hydrated Lime ($Ca(OH)_2$), a laboratory reagent, has been used for the treatment of soil.

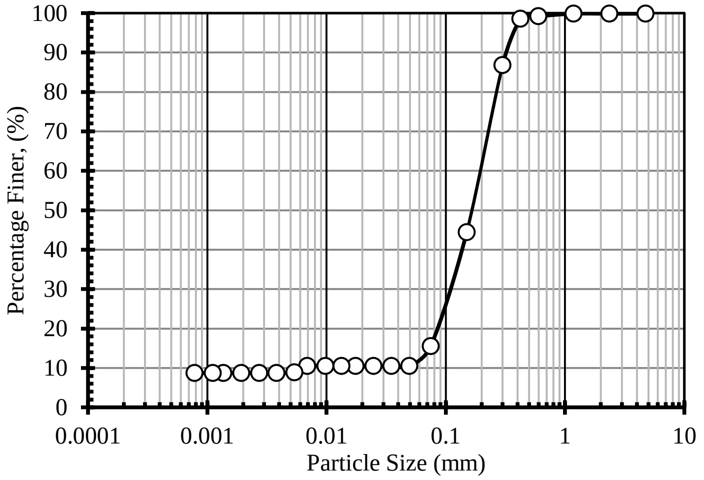
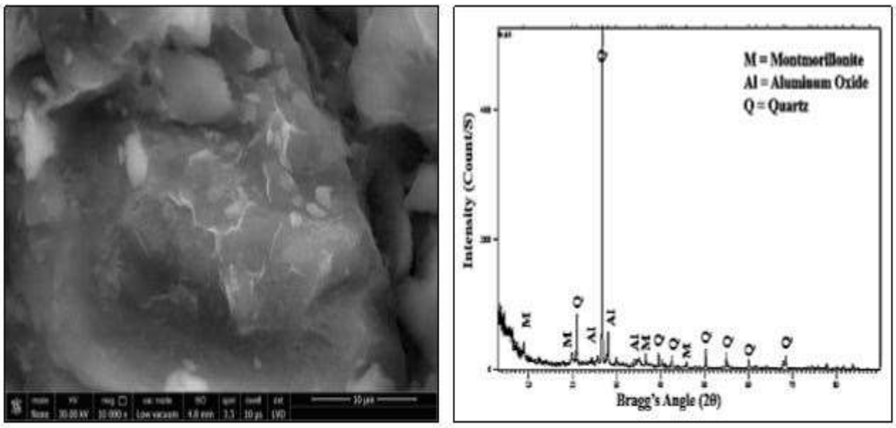


Fig. 1. Particle size examination of BCS

Table 1. Geotechnical Properties of untreated and lime treated BCS

Property	**BCS**	**BCS + 6% Lime**	**Procedure Followed**
Particle Size Analysis			
Sand (4.75 - 0.075 mm), %	11.00	–	IS-2720 (Part-4) [19]
Silt (0.075 - .002 mm), %	13.00	–	
Clay (<0.002 mm), %	76.00	–	
Specific Gravity			
Specific Gravity	2.37	2.49	IS-2720 (Part 3) [20]
Atterberg's Limit			
Liquid Limit, %	45.93	43.00	IS-2720 (Part 5) [21]
Plastic Limit, %	15.18	30.79	IS-2720 (Part 5) [21]
Plasticity Index, %	27.18	15.13	
Shrinkage Limit, %	11.65	21.96	IS-2720 Part 6 [22]
Soil Classification	CL	CI	IS 1498 [23]
Compaction Characteristics			
Max. Dry Density, gm/cc	1.59	1.45	Sridharan and Sivapullaiah [24]
Optimum Water Content, %	21.56	27.75	
pH			
pH Value	7.5	11.5	IS 2720 (Part 26) [25]



(a.) (b.)

Fig. 2. a) SEM and b) XRD analysis of BCS

Table 2. Chemical composition analysis of BCS

Element	Atomic %
O	66.41
Si	15.38
Al	12.62
Fe	3.85
K	0.67
Mg	0.54
Na	0.53
C	0.00
Total	**100.00**

2.2 Methodologies Followed

The standard procedures followed to determine the physical properties (particle size analysis, specific gravity, Atterberg's limits, compaction characteristics and pH) of untreated and lime treated soil are presented in Table 1. The Optimum Lime Content (OLC) used in the present work was determined as per Eades and Grim [26]. The pH value of OLC (i.e. 6%) was observed to be 11.5.

Unconfined compressive strength (UCS) tests are performed on parent soil and lime treated soil at different curing periods up to 28 days. The 76 mm height and 38 mm in diameter cylindrical static compacted specimens are prepared at maximum dry density (ρ_{max}) and Optimum Water Content (OWC). The samples are kept in air tight desiccators maintaining relative humidity more than 95% by proper wrapping in polyethylene bags up to a desired curing period. Samples are also checked for loss in water content by measuring weight after each curing periods and are rejected, when the variation is more than 0.5%. UCS tests are performed according to IS 2720 (Part 10) [27] under a constant strain rate of 1.25 mm/minute. The average of peak stress values of two identical tested samples is taken as unconfined compressive strength, if the difference in peak stress values is more than 10%.

Fig. 3. Sample preparation for wetting and drying process

The process of drying and wetting is performed in laboratory with great deal of accuracy. The UCS samples cured for 7, 14 and 28 days are taken for W-D process. The whole process of W-D are summarized in Fig. 3. The wetting process starts by covering the sample with filter-paper and then allowing it to soak for 24 hours at room temperature 27 °C. After 24 hours of wetting, it is removed from the soaking bucket and is placed in oven for 24 hours by maintaining the temperature of oven to 50 °C. The summation of both wetting and drying for 48 hours is considered as a one W-D cycle. The samples are allowed to cool at room temperature for 2 hr. after completing each cycles. The UCS test has been done on the samples subjected to one and four cycles in drying state to examine the effect of W-D on the strength behaviour of lime treated soil.

Field Emission Scanning Electron Microscope (FESEM) coupled with Energy Dispersive X–ray Spectroscopy (EDAX) is performed to examine microstructural and chemical composition of soil. Small amount of oven dried soils is mounted on the aluminum mounting disc (also called SEM stubs) with the help of carbon tape. Prior to SEM examination, the sample was coated with 100 Å thin layer of gold palladium for 38 second using a sputter coater, polaron E5100 at 10^{-3} Torr Vacuum. The gold coating is done in order to avoid charging problem during imaging.

The X-ray diffraction (XRD) spectrometer is performed to determine the mineralogical composition of the BCS by using graphite mono-chromator and Cu-Kα radiation. The scanning angle of the sample for 2θ is 3° to 90°. The data file which is developed by the Joint Committee on Powder Diffraction Standards (JCPDS) [28] is used to identify the presence of various minerals in the sample.

3 Results and Discussion

3.1 Physical Properties and Compaction Characteristics of Lime Treated Soil

The effect of optimum lime content on the physical properties (Atterberg’s limits, specific gravity and compaction characteristics) are listed in Table 1.

The specific gravity of soil-lime mixture is observed to be increased than that of soil. The increase in specific gravity is attributed to the aggregation of soil particle due to ionic exchange between soil and lime. The plasticity index of soil reduces significantly with reduction in liquid limit and increase in plastic limit with addition of lime. The change in plasticity of soil with addition of lime is due to the reduction in thickness of double diffuse layer. Addition of lime causes an increase in electrolyte concentration of pore fluid and replacement of monovalent ions present in the soil with divalent calcium ion [29]. However, the increase in plastic limit of soil is due to the increase in viscosity and charge concentration, resulting an enhancement in an interparticle shear resistance [30]. However, change in fabric of soil to flocculated structure with addition of lime is responsible for increase in shrinkage limit [31].

The compaction characteristics (maximum dry density and optimum water content) of untreated and lime treated soil are shown in Fig. 4 and are presented in Table 1. The results show an increase in optimum water content with reduction in maximum dry density of soil with addition of lime (Fig. 4). The aggregation and agglomeration of soil with addition of lime result in reduction in dry density of lime treated soil. However, formation of flocculated matrix and thereby, increase in water holding capacity leads to the increase in optimum water content. Similar observations were made by earlier researchers with lime treated soil [11, 29, 30].

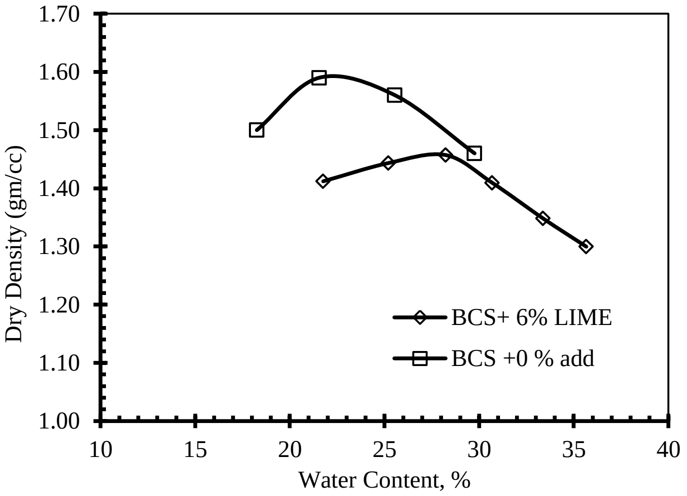


Fig. 4. Compaction characteristics curves of BCS and lime treated soil

3.2 Strength Behaviour of Lime Treated Soil Subjected to W-D Cycles

Fig. 5 shows the unconfined compressive strength (UCS) of lime treated soil cured for different curing period for 7, 14 and 28 days before and after W-D cycles.

The UCS of BCS is obtained to be 207 kPa. However, improvement in strength is observed with lime treatment and is enhanced continuously with curing periods up to 28 days. The increase in strength of lime treated soil is due to the consumption of lime in pozzolanic reactions to form the cementitious compounds and hence, formation of compacted matrix.

The UCS of cured lime treated soil for different period after first and fourth cycles tested in drying state is shown in Fig. 5. It is interesting to note that UCS of samples after first W-D cycle increases compared to strength of lime treated soil before W-D cycle. The strength after first cycle increases by 1.04, 1.36, 1.43 folds compared to strength of lime treated soil at 7, 14 and 28 days, respectively This may be attributed to the availability of more water for pozzolanic reaction during wetting process. However, drying process at 50°C temperature also leads to accelerate the ionic reactions to gain the strength. Further, enhancement in strength of sample after first W-D cycle is observed with an increase in curing periods up to 28 days. However, significant improvement in strength is seen in the sample cured for 28 days. This is due to the availability of sufficient time for pozzolanic reactions.

The strength of lime treated soil after four cycle exhibits drastic improvement in the strength at any curing periods than that of measured after first and before W-D cycle. The strength after four cycle increases by 2.10, 2.40 and 2.23 folds that of measured at samples of same curing periods of 7, 14 and 28 days before W-D cycles. It has been attributed that increase in W-D process leads to accelerate the hydration process and thereby, formation of cemented and compacted soil matrix. Similar observation were made by Aldaood et al. [32] for lime-stabilized gypseous soils subjected to W-D cycles. However, strength of lime treated soil subjected to wetting-drying cycles also needs to be examined in wetting state to understand its durability.

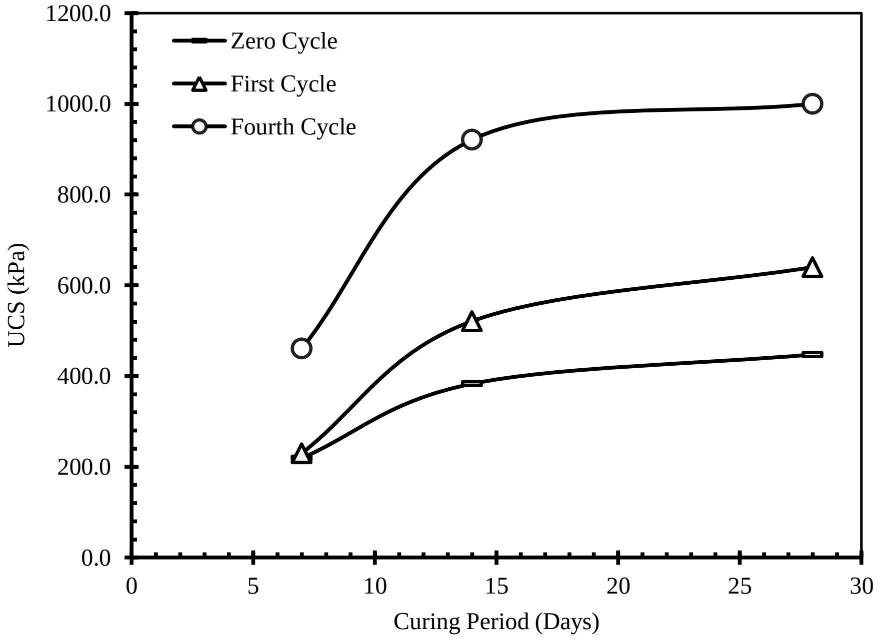


Fig. 5. Unconfined compressive strength of lime treated soil subjected to wetting and drying cycles

4 Conclusion

It is known that lime treatment of soils causes an improvement in their plasticity and an enchantment in strength behaviour. However, the present study is extended to understand the durability of cured lime treated soil for certain periods subjected to repeat climatic changes (i.e. wetting-drying cycles). Based on present study and findings, key conclusion can be drawn as follows:

1. Improvement in the soil plasticity and increase in shrinkage limit of lime treated soil are due to the cation exchange process and reduction in thickness of double diffuse layer. However, flocculation and aggregation of soil particle with addition of lime results the reduction of dry density and increase in optimum water content.
2. Strength of soil enhances with lime treated and with increase in curing periods. However, wetting by submerging the sample in distilled water for

24 hour and drying it in 50°C leads to increase the strength of lime treated soil tested in drying state at any curing periods. Further enhancement in strength is seen with increase in number of W-D cycles of cured lime treated soil for more periods.

3. The strength behaviour of lime treated soil in wetting state of wetting-drying cycles needs to be examined to understand its durability.

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