Matric Suction,Volume Change and Microstructural Characteristics of a Highly Expansive Soil Treated with Lime

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Abstract. This study examines the impact of lime treatment on matric suction, swelling and shrinkage response of a highly expansive soil, both at the macro and micro scales. The macro-scale investigations include the determination of compaction, compressibility, swelling pressure, DFSI, volumetric shrinkage and matric suction response of lime-treated expansive soil (0% to 6% of lime content). The alterations in the pore size and fabric of the soil at micro-scale were assessed using Scanning Electron Microscopy and Brunauer–Emmett–Teller gas adsorption technique. An increase in intra-aggregate pores followed by the reduction in inter-aggregate pores was evident from the microscopic observations. These microfabric changes led to an increase in matric suction within the compacted lime-treated specimens. In macro-level investigations, an amount of lime higher than the lime fixation point was found to be efficient to control the volumetric changes in the expansive soil. Addition of 6% lime reduced the compressibility and volumetric shrinkage of expansive soil by 86% and 84%, respectively. The rate of primary shrinkage of expansive soil was also observed to be reduced with lime addition owing to an increase in the water retention capacity. The swelling response of this highly expansive soil was completely nullified with only 4% lime whereas shrinkage could not be fully controlled even for higher lime content of 6%.

Keywords: Expansive soil; Matric Suction; Microstructural Alterations; Swelling; Shrinkage; Lime Treatment

1 Introduction

Expansive soils are known as problematic soils due to their tendency to swell and shrink owing to montmorillonite clay mineral (Nelson and Miller, 1997). These soils tend to swell on moisture ingress during the rainy season causing potential damage to the lightly loaded structures built over them such as highway and railway embankments, low-rise buildings, etc. On the other hand, during the summer season, these soils tend to shrink and leave large desiccation cracks which lead to the failure of the structures built over such soils (Di Sante et al., 2015). It is the first choice of practitioner engineers to avoid expansive soils in geotechnical construction activities and use some good borrow soil available in the nearby area for replacement. However, in large projects such as the construction of embankments for highways and railways, involving a huge amount of earth to be replaced, this becomes uneconomical (Bhuvaneshwari et al., 2014). On the other hand, it may not be possible that a good borrow soil is always readily available in the vicinity of the project site. Hence, avoiding expansive soils for construction is not practically feasible in many cases. Stabilization of expansive soils becomes mandatory in such cases. Chemical stabilization of expansive soils using lime is a conventional practice (Bhuvaneshwari et al., 2019). However, in most of the studies, the evaluation of the effectiveness of lime treatment is done based on the increase in the unconfined compressive strength, which is not an issue for unsaturated expansive soils (Kumar et al., 2007; Sharma et al., 2012). Expansive soils exhibit low strength problems only when they are completely saturated.

In the current study, the effectiveness of lime treatment on expansive soils is evaluated based on the changes in swell-shrink characteristics and microstructural alterations. As the embankment soil remains unsaturated most of the time, the effect of lime treatment on matric suction of expansive soil is also evaluated using the filter paper technique. Changes in the microstructure owing to lime treatment were used to understand the mechanics involved in the observed macro-level behavior. This study also examines the effect of the curing period on the swell, shrink, and the suction response of expansive soil.

2 Material Properties

The black cotton soil was collected from Nagpur, Maharashtra (India). The collected soil was moist and in the form of lumps, which was further air dried and pulverized to pass a 4.75 mm IS sieve. The geotechnical properties of Nagpur expansive soil are listed in Table 1. Fig. 1 depicts the grain size distribution of Nagpur expansive soil. The Nagpur soil consists of 56% clay, 38% silt, and 6% sand. It was classified as high plasticity clay (CH) as per IS system for soil classification. The degree of expansiveness of Nagpur soil was estimated to be very high as per Ranjan and Rao (2007).

Table 1. Geotechnical properties of Nagpur expansive soil

Properties	IS Code Followed	Value
Specific gravity	IS 2720 (Part III/ Sec 1)-1980	2.75
Liquid limit (%)	IS 2720 (Part V)-1985	84
Plastic limit (%)	IS 2720 (Part V)-1985	27
Plasticity index (%)	IS 2720 (Part V)-1985	57
Shrinkage limit (%)	IS 2720 (Part VI)-1972	10
Differential free swell index (%)	IS 2720 (Part XL)-1977	125
Maximum dry density (g/cc)	IS 2720 (Part VII)-1980	1.46
Optimum moisture content (%)	IS 2720 (Part VII)-1980	30

Commercially available hydrated lime ($Ca(OH)_2$) was used as a chemical stabilizer to treat the Nagpur expansive soil in this study. The dosages of lime varied from 0% to

6% at intervals of 1%. In the previous studies, the amount of lime was found to be ± 2% to 3% of the initial lime consumption (ICL) value of the chosen soil (Sharma et al., 2012; Bhuvaneshwari et al., 2019). The ICL was defined as the minimum amount of lime required to fully satisfy the negative charges of clay minerals present in the soil. Eades and Grim (1966) suggested a pH-based method to determine the ICL value of given soil. The ICL value for the Nagpur expansive soil was found to be 3%, above which pH did not change significantly (Fig. 2). The lime content above 6% was caused difficulty in specimen preparation due to its brittle nature, hence the amount of lime was kept limited to 6%.

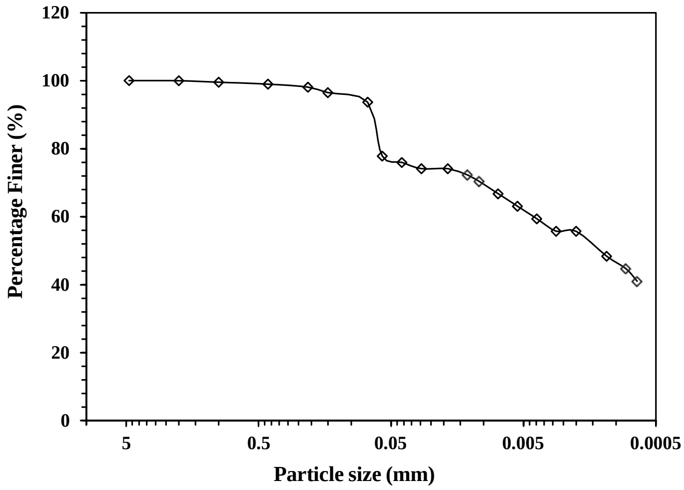

Fig. 1. Grain size distribution curve of Nagpur expansive soil.

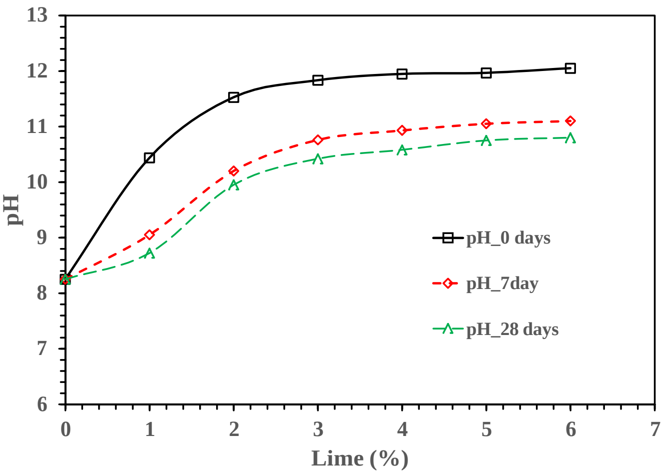

Fig. 2. Effect of lime on pH of Nagpur expansive soil.

3 Experimental Program

A series of light compaction tests were performed on Nagpur expansive soil treated with 0%, 3%, and 5% lime content using mini proctor apparatus (Sridharan and Sivapullaiah, 2005). The soil and lime were mixed in the dry state followed by the addition of water. Compaction was performed immediately after mixing water to avoid any effects of delayed compaction. The compaction curves are presented in Fig. 3. The change in compaction parameters due to lime treatment was found to be less than 5%, hence it was decided to prepare all the specimens at 95% of maximum dry density (1.39 g/cc) and optimum moisture content (30%) of the untreated Nagpur expansive soil. All the compacted specimens were prepared using the moist tamping technique in three equal layers. The prepared specimens were shrink-wrapped twice and kept in desiccators to allow curing for 7 and 28 days. The weight of the specimens was recorded at the beginning and end of each curing period to check for any moisture loss during the curing process, and if it is found more than 1g, the specimen was discarded.

Macro level investigations consisted of the determination of time swell response and swell pressure as per IS 2720 (Part-41), compressibility characteristics using 1D consolidation tests (according to IS 2720-Part 15), differential free swell index (as per IS 2720 (Part XL), pH (IS 2720- Part 26), and matric suction using contact filter paper technique as per ASTM D5298-16. The specimen dimensions and procedure for matric suction determination were followed as given in Pandya and Sachan (2018). Shrinkage tests were conducted as per IS 2720 (Part VI) with continuous monitoring of the weight of the slurry specimens, which helped in observing the effect of lime on water retention tendency. To explain the mechanics involved in macro-level observations, a few micro-level investigations were conducted such as X-Ray diffraction (XRD), Scanning electron microscopy (SEM), and Brunauer–Emmett–Teller (BET) gas adsorption technique on selected specimens.

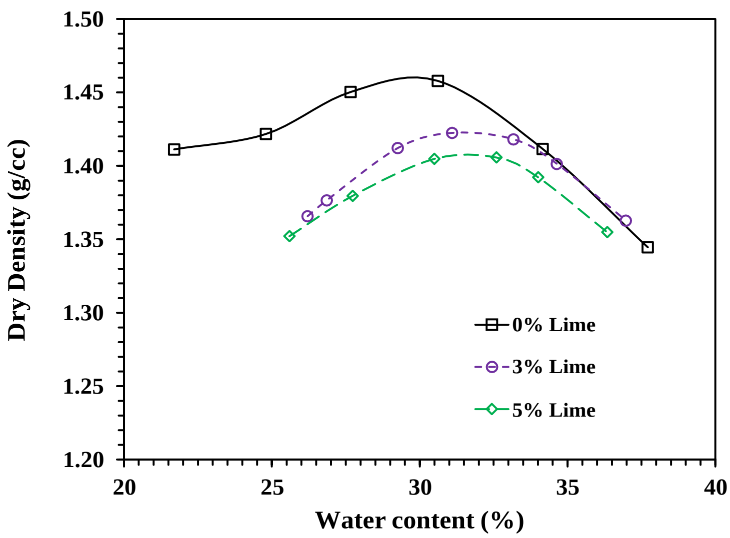

Fig. 3. Compaction curves of untreated and lime-treated Nagpur expansive soil.

4 Results and Discussion

4.1 Effect of lime treatment on matric suction and microstructure of Nagpur expansive soil

The contact filter paper technique was adopted for the determination of matric suction using compacted specimens. Fig. 4 depicts the effect of lime content and curing period on matric suction of Nagpur expansive soil. Matric suction of untreated soil was determined to be 1387 kPa. A gradual increase in the matric suction was observed up to 3% lime content (equal to ICL value) followed by a rapid increase on further addition of lime, for 7 and 28 days cured specimens. A 168% increase in the matric suction was observed with the addition of 6% lime for 28 days of the curing period. The microstructural changes that occurred in the specimens due to soil-lime reactions caused an increase in the matric suction.

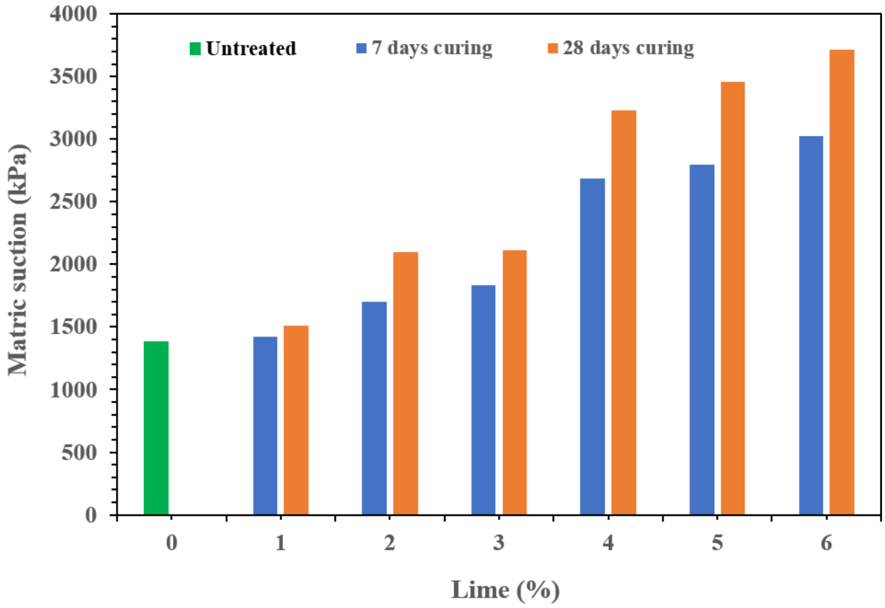

Fig. 4. Effect of lime content and curing period on Matric suction of Nagpur expansive soil.

In presence of water, $Ca(OH)_2$ dissociated into Ca^{+2} ions and OH^- ions. These bivalent calcium ions replaced the monovalent cations from the surface of clay particles causing a reduction in the thickness of the double diffused layer and flocculation of clay particles. After these initial surface modifications, the remaining calcium ions caused the formation of pozzolanic reaction products which hardened with curing time. These pozzolanic reaction products were found to be calcium aluminate hydrate (CAH), calcium silicate hydrate (CSH), and calcium silicate aluminate hydrate (CASH), which can be observed in XRD results (Fig. 5). The microstructural changes due to these pozzolanic reaction products are illustrated in Fig. 6 and Fig. 7. A typical scanning electron microscopic image of a specimen treated with 5% lime and 28 days curing is shown in Fig.6. The observed aggregation of clay particles in SEM images, indicated a reduction in the macroporosity (interaggregate pores) and increase in the microporosity (intra-aggregate pores) within the soil mass.

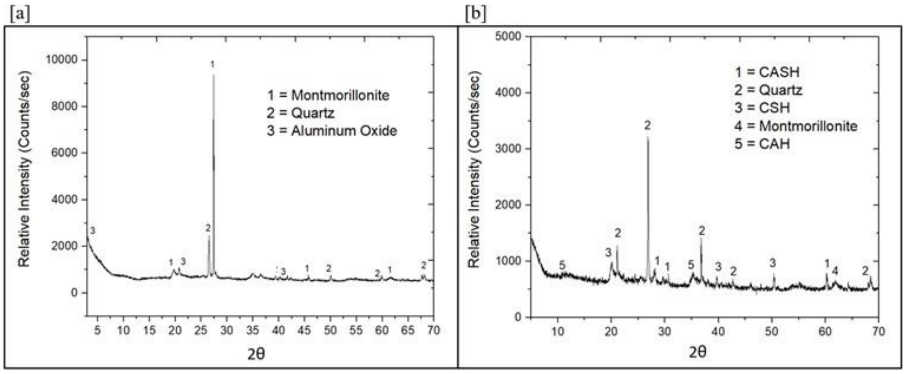

Fig. 5. Mineralogical composition using XRD test for [a] untreated specimen and [b] 5% lime treated specimen after 28 days of curing.

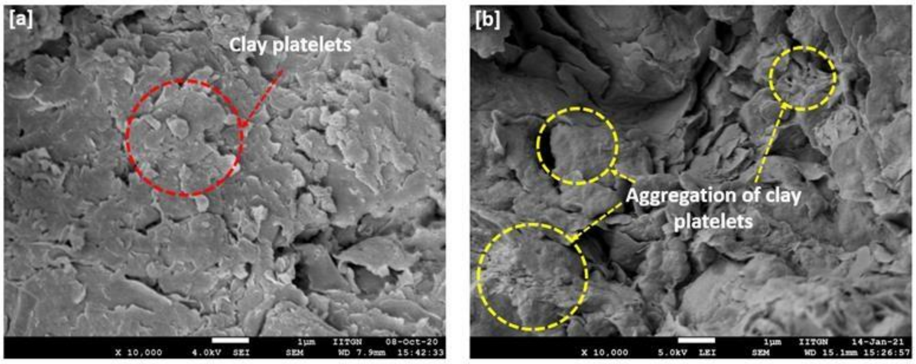

Fig. 6. SEM images of [a] untreated soil and [b] 5% lime-treated specimen after 28 days of curing.

The results from the BET gas adsorption test on the same specimen also validated these microstructural alterations (Fig.7). The pore volume corresponding to higher pore diameters (i.e., macropores) reduced and corresponding to smaller pore diameters (i.e., micropores) increased. The increase in micropores resulted in the generation of the higher number of capillaries with the smaller pore diameter as compared to untreated soil mass exhibiting an increase in matric suction values. The surface area per unit mass determined for untreated soil using BET analysis was 52.5 m^2/g, which was reduced to 6.7 m^2/g (almost 87% reduction) on treatment with 5% lime for 28 days of curing.

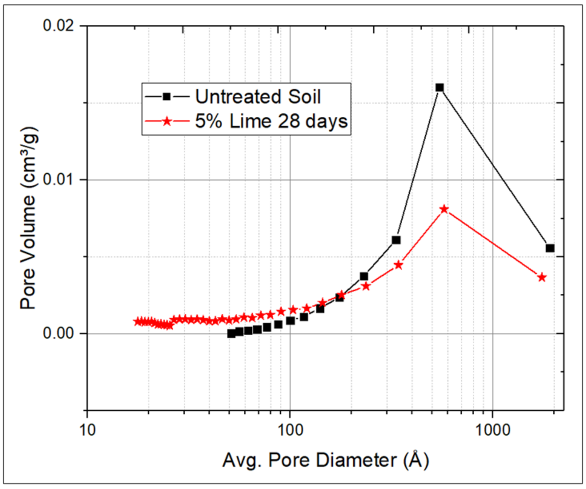

Fig. 7. Pore volume distribution in untreated specimen and specimen treated with 5% lime after 28 days of curing.

4.2 Effect of lime treatment on swelling and compressibility characteristics of Nagpur expansive soil

Swell potential and swell pressure of untreated and lime-treated compacted specimens were determined using the consolidometer method as per IS 2720 (Part-41). The compacted specimen was allowed to swell under a constant seating pressure of 5 kPa until the swelling dial gauge reading became constant. The swelling dial gauge reading was continuously monitored during the whole swelling process. Fig. 8 depicts the effect of lime treatment on the time-swell response of Nagpur expansive soil.

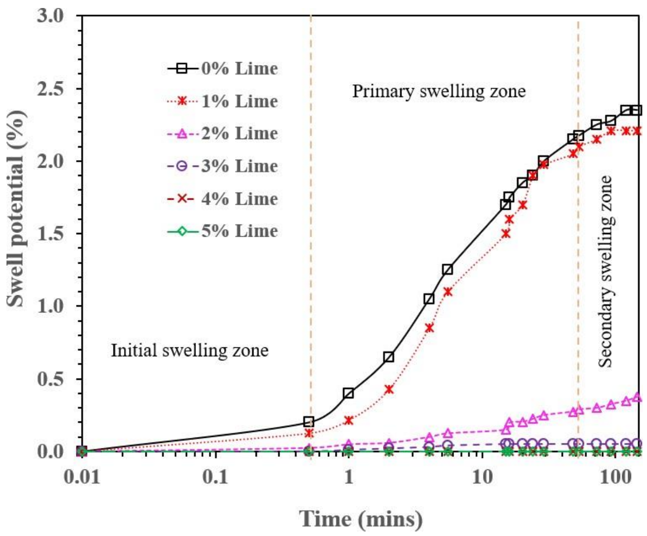

Fig. 8. Effect of lime content on the time-swell response of Nagpur expansive soil

The swelling was observed to be fully controlled by the addition of only 4% lime content within just seven days. Hence, these tests were performed on 0 to 5% lime-treated specimens for seven days of curing only. Fig. 8 shows that the time swell response follows an S-shaped trend. The whole swelling process can be divided into three parts, (i) initial swelling, (ii) primary swelling, and (iii) secondary swelling. The rate and amount of swelling are maximum in the primary swelling region.

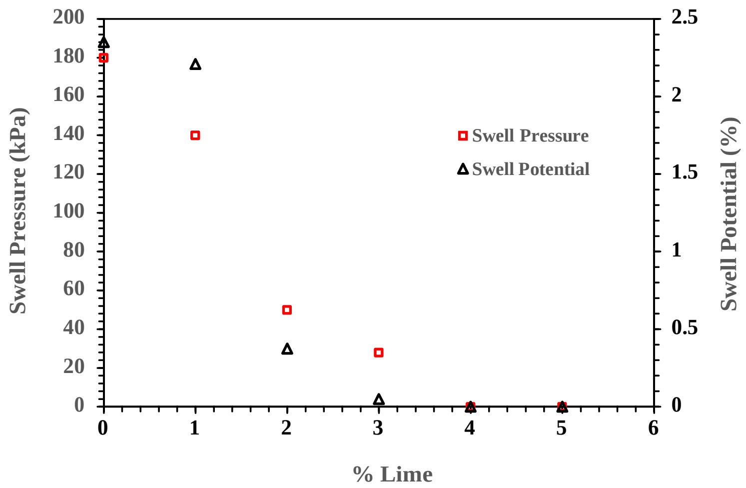

Fig. 9. Effect of lime content on swell pressure and swell potential of Nagpur expansive soil

A slight delay in the primary swelling was observed in lime-treated specimens. However, these three zones of swelling were only visible up to 3% lime content, beyond which the swelling became negligible. Once the swelling of the specimen was over, it was loaded incrementally up to 800 kPa to determine the swell pressure. Fig. 9 shows the variation of swell pressure and swell potential with lime content.

Table 2. DFSI and compression index of untreated and lime-treated soil

Lime (%)	DFSI (%)		Compression Index	
	7 Days	28 Days	7 Days	28 Days
0	125		0.29	
1	121	119	0.28	0.27
2	114	109	0.26	0.26
3	78	71.2	0.08	0.07
4	60	54	0.06	0.06
5	45	40	0.05	0.04
6	39	38	0.05	0.05

The swell pressure of untreated soil was found to be 180 kPa, which was reduced to 28 kPa with the addition of 3% lime within seven days of the curing period. However, further addition of lime resulted in zero swell pressure. The swell potential values also followed a similar trend with lime content. Another important parameter to study the swelling nature of the soil is differential free swell index (DFSI) values. DFSI was measured for all lime percentages and curing periods (7 and 28 days). As reported in Table 2, a decrease of 69% was observed in the DFSI value with 6% lime treatment within seven days. However, the curing period did not impact the swelling nature significantly. This could be because the reduction in plasticity nature of soil due to surface modifications does not depend on the curing process. The curing process only hardens the pozzolanic reaction products which impart strength and stiffness to the soil mass. The increased stiffness was evident from a reduction in compression index resulting from lime addition as indicated in Table 2.

4.3 Effect of lime treatment on shrinkage parameters and water retention characteristics of Nagpur expansive soil

The efficacy of lime treatment in controlling the shrinkage behavior of expansive soils has not been studied much. In this study, shrinkage tests were conducted on slurry specimens as per IS 2720 (Part VI). A slight modification in the procedure was done to observe the changes in water content with time, throughout the shrinkage process. Fig. 10 depicts the variation of volumetric shrinkage and shrinkage limit with lime content and curing period.

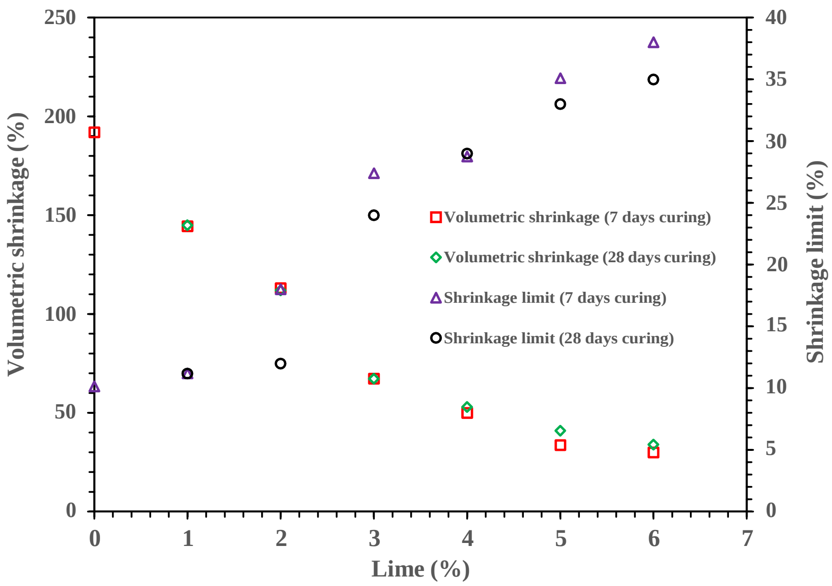

Fig. 10. Effect of lime content and curing period on volumetric shrinkage and shrinkage limit of Nagpur expansive soil

The volumetric shrinkage of untreated soil was 192%, which was reduced by 84% with the addition of 6% lime content. However, the curing period did not show any significant impact on shrinkage behavior. An increase in the shrinkage limit from 10% (for untreated soil) to 38% (for 6% lime) also indicated a significant reduction in the shrinkage potential of soil due to lime treatment. A similar trend was observed in the reduction in shrinkage ratio as well (Fig. 11).

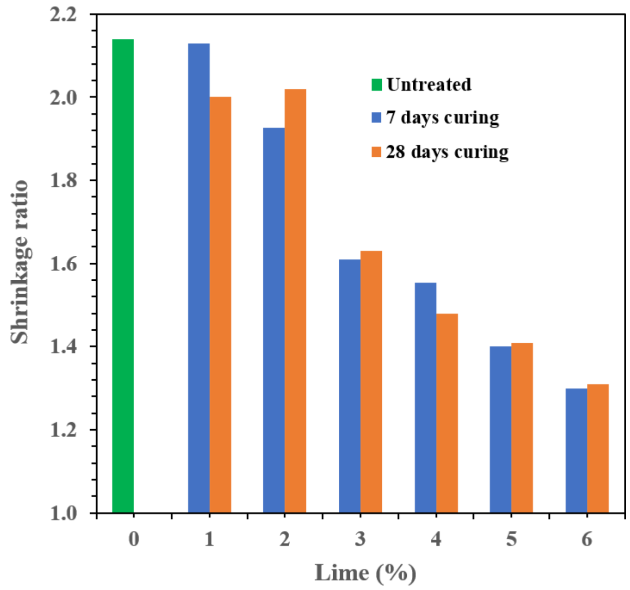

Fig. 11. Effect of lime content and curing period on shrinkage ratio of Nagpur expansive soil

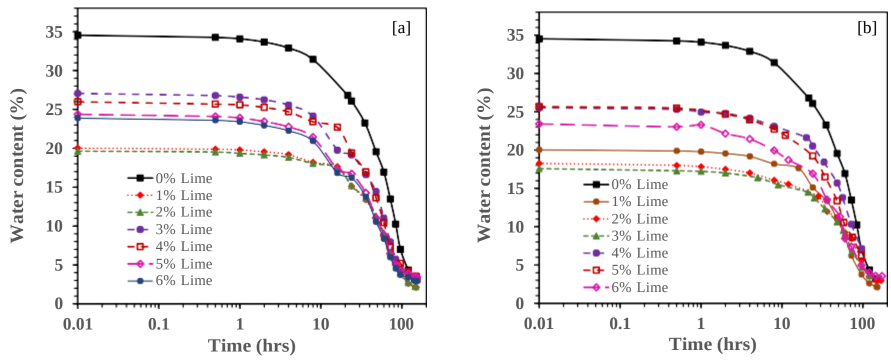

Fig. 12. Effect of lime content on water retention behavior of Nagpur expansive soil [a] after 7 days curing [b] after 28 days curing

Fig. 12 depicts the water retention curves for untreated as well as lime-treated soil specimens. In both Fig. 12 a and b, the slope of the water retention curve was observed to decrease due to lime treatment, which indicated a higher water retention capacity of lime-treated soil as compared to the untreated specimen. However, no clear trend was observed for soil treated with different lime contents (0%-6%).

5 Conclusions

The present study evaluated the effect of lime treatment on swelling, shrinkage, and compressibility behavior along with the matric suction. Commercially available hydrated lime was used in dosages varying from 0% to 6%. Microstructural alterations caused by lime treatment were also investigated for typical specimens to explain the phenomenon occurring at the macro level. It was found that 4% lime was enough to fully control the swelling nature of the Nagpur expansive soil in only seven days, however, only an 84% decrease was noticed in the volumetric shrinkage. The shrinkage limit of the soil increased from 10% to 38%, with the addition of 6% lime. The results of SEM and BET gas adsorption analysis indicated that the microporosity of soil increased due to lime treatment. The increased amount of micropores also rendered higher matric suction in lime-treated specimens despite using the same dry density and water content. Based on this study, 4% lime was sufficient to significantly control both swelling and shrinkage nature of the Nagpur expansive soil within seven days of the curing period. A higher amount of lime unnecessarily increased the matric suction values without giving much effect to swell-shrink nature. The results of this study also indicated that the increase in matric suction caused by the lime treatment could not impart more swelling tendency to the soil, unlike untreated soils. This is because of additional bonding between particles due to pozzolanic reaction products, which oppose the swelling process.

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