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Eco-friendly soil stabilization: a combined approach using lime and waste eggshell powder

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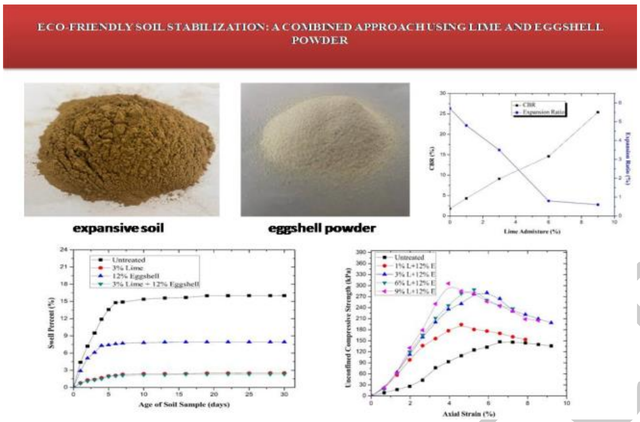
Graphical abstract



Abstract

In recent years, geotechnical engineers preferred environmentally friendly and sustainable techniques to improve the engineering characteristics of expansive soil. This paper focuses on the comparative study of the enhancement in engineering properties of expansive soil using lime and waste eggshell powder. A series of laboratory tests such as unconfined compressive strength test, pH test, free swell index test, swelling pressure test, California – Bearing Ratio test and Atterberg's limit test were performed for evaluating the engineering behaviour of expansive soil with lime and waste eggshell both individually and together. The experimental test results showed that the combined admixtures significantly improve the engineering characteristics of the soil. The maximum value of compressive strength at the inclusion of 9% lime and 12% waste eggshell powder was observed to be 306 kPa. The swell pressure of the treated soil showed up to a reduction to 2.32 at the inclusion of 3% lime and 12% waste eggshell powder. In all the tests, the combined admixtures exhibited greater efficiency when compared to the individual inclusion of lime and waste eggshell. Thus, the investigation results confirmed the efficient use of lime and waste eggshell powder at optimum percentages as soil-stabilizing material and made them suitable for field applications.

Keywords: Lime, waste eggshell powder, expansive soil, stabilization

1. Introduction

The expansive soil is considered to be the most problematic soil in the geotechnical field (Kulanthaivel *et al*. 2021). Expansive soils were mostly found in the states of Maharashtra, Andhra Pradesh, Gujarat, Madhya Pradesh, Odisha, Narmada, Tapi, Godavari, and Krishna River valleys (Indiramma *et al*. 2019). It offers high swelling and shrinkage, lower strength and higher settlement behaviour (Kulanthaivel *et al*. 2022). The expansion and swelling nature of the clay soil depend on the aqueous solutions being in contact with the clay particles (Ikeagwani *et al*. 2019). The volume change could be observed for about 30% with the extensive damages with respect to the expansion behaviour (Nyankson *et al*. 2013). These significant volumetric fluctuations posed a greater danger for the construction industry and other applications. These adverse effects may affect the construction works either during or after the completion of projects (Kulanthaivel *et al*. 2022, Kulanthaivel *et al*. 2020). In addition to that the dual and intrinsic swell–shrink behaviour may lead to damage to highway infrastructure projects and railway projects (Kulanthaivel *et al*. 2022). The differential settlement might be responsible for the heaving and cracking being developed in pavements on expansive soil (Selvakumar *et al*. 2022). These problems also caused severe cost issues and environmental concerns in the case of renovation and rehabilitation (Kulanthaivel *et al*. 2021). There are multiple strategies and methods available for the stabilisation of expansive soils. It is essential to choose materials that are cost–effective and with greater sustainability criteria (James, 2020). To stabilise, the soil characteristics must be analysed since the characteristics related to strength parameters are likely to be varied even if present in the same field (Tiwari and Satyam, 2020). Several methods like replacing the expansive with non–expansive soil, sustaining the same water content and especially soil stabilisation were analysed (Dang *et al*. 2016). Soil stabilisation could be highly beneficial to reduce the change in volume behaviour when provided with varying moisture contents (Cheng *et al*. 2018).

Lime is included in the expansive soil as one of the additives. Lime was chosen as it significantly improved the engineering properties of expansive soil. In addition to that the waste materials can also be used for the stabilisation of expansive soil. The properties of waste materials like sturdiness, strength and high deterrent nature are required to improve the strength parameters in clay soil (Hasan *et al*. 2021). The waste eggshell is utilised because it was observed to be energy-efficient, most economical and environmentally sustainable. This could be highly beneficial since it can reduce the cement level in concrete production (Zaini *et al*. 2021). The waste eggshell powder was utilised as a replacement for cement, concrete, and especially as a soil stabiliser in the construction field (Sathiparan, 2021).

The present study involves the utilisation of lime and waste eggshell powder for stabilising the expansive soil. The lime was included in percentages of 1%, 3%, 6% and 9% in the soil samples whereas in the case of waste eggshell powder, the percentages were taken as 0%, 4%, 8%, 12%, and 16% respectively. A series of experiments such as unconfined compressive strength test, California Bearing Ratio test, Expansion Ratio test, swelling pressure test, free swell index test, pH test and Atterberg's limit tests were carried out to check the suitability of lime and eggshell powder as expansive soil stabilized admixture.

2. Materials and methods

2.1. Expansive soil

The expansive soil used in the current research was collected from Chemmancheri, Chennai. The soil was found to contain a high amount of clay minerals. The index properties of the expansive soil were examined and provided in Table 1. As per the Indian Standard Soil Classification system, the soil was classified as high-plasticity clay. Table 2 elucidates the chemical composition of the expansive soil. A pictographic view of expansive soil is shown in Figure 1.

Table 1. Index properties of expansive soil

Index properties	Expansive soil
Sand, %	2.61
Silt, %	42.7
Clay, %	54.69
Free Swell Index, %	125
Liquid Limit, %	200
Plastic Limit, %	79
Plasticity Index, %	121
California Bearing Ratio (CBR), %	1.8
Expansion Ratio, %	5.7
Unconfined Compressive Strength (UCS), kPa	147
pH	7.96
Soil Classification (as Per IS)	CH
Optimum Moisture Content, %	18
Maximum Dry Density, g/cc	1.73

Table 2. Chemical composition of the expansive soil

Chemical composition	Expansive soil (%)
SiO_2	65.2
Fe_2O_3	6.47
Al_2O_3	14.32
CaO	1.15
MgO	0.85
Na_2O	2.41
K_2O	0.80
TiO_2	1.45
SO_3	0.04
P_2O_5	0.36
LoI	5.48

Table 3. Chemical composition of lime

Chemical composition	Lime (%)
SiO_2	0.43
Al_2O_3	0.25
CaO	77.9
MgO	21.2
Na_2O	0.2
SO_3	0.1

Figure 1. Pictographic view of expansive soil

2.2. Lime

Lime was considered to be taken as quicklime, and CaO was used for the treatment of the expansive soil. It was obtained from Global Enterprises, Kerala. The specific gravity and pH of lime are 2.49 and 2.8 respectively. The water absorption capacity of lime is 18%. The melting temperature of lime is 2600 ^{0}C. The chemical composition of lime is represented in Table 3.

2.3. Waste eggshell powder

The crude chicken waste eggshells were gathered from the SKM Egg products, Erode. The crude chicken waste eggshells were then cleaned, allowed to air dry for seven days, crushed, and then heated for one hour at 800^{o}C in a chamber heater to create the final product in powder form. The acquired eggshell refuse was free from proteins and organic material. In order to create a thin powder with a particle size smaller than 75 microns, it was further ground and sieved. To produce Egg Shell Admixture (ESA), this material was calcined at a temperature of 500°C for 15 minutes in a muffle oven. The chemical composition of the waste eggshell powder is represented in Table 4. A pictographic view of the waste eggshell powder is represented in Figure 2.

Figure 2. Pictographic view of waste eggshell powder

Table 4. Chemical composition of waste eggshell powder

Chemical Composition	Waste eggshell Powder (%)
SiO_2	0.06
CaO	68.21
Al_2O_3	0.03
K_2O	0.07
MgO	0.81
Fe_2O_3	0.06

2.4. Unconfined compressive strength test

The unconfined compressive strength experiment was calculated according to IS 2720 (Part 10) (1973). Static compaction was used to generate a cylindrical specimen provided with a height of 76 mm and a diameter of 38 mm. The samples were made as per the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) obtained. The sample was subjected to 1.2 mm/min of stable strain rate. The inclusion of lime and waste eggshell powder was considered in terms of 0%, 1%, 3%, 6%, 9% and 0%, 4%, 8%, 12%, and 16% respectively to the dry soil weight. The soil samples were left for curing and tested at 3, 7 and 28 days under standard conditions.

2.5. California bearing ratio test

The CBR experiment was carried out according to IS: 2720 (Part 16): 1987. The samples were made with respect to the maximum dry density and optimum moisture content attained from the modified proctor test. The inclusion of lime and waste eggshell powder was considered in terms of 0%, 1%,3%, 6%, 9% and 0%, 4%, 8%, 12%, and 16% respectively to the dry soil weight. The specimens after draining were kept on the loading machine such that the penetration resistance can be measured by the load application at a rate of 1.25 mm per minute. The CBR value was computed corresponding to 2.5 mm penetration for the soil samples included with lime and waste eggshell powder. The load penetration curve was obtained.

2.6. Swell pressure test

The swell pressure was determined according to IS 2720(Part 41):1977. The swelling pressure test setup consists of a loading unit of 5 tonnes and a proving ring with a 200 kg capacity. The samples after the inclusion of lime and waste eggshell powder were prepared. In addition to that, the untreated samples were also tested. The specimens were prepared such that 3% of lime and 12% of waste eggshell powder were included in the expansive soil individually and in the combined form. The accurate measurement of change in vertical load was recorded from the proving ring. The strain gauge readings recorded the volumetric variation with the swelling. The soil sample was then extracted to get the moisture content variation across the sample.

2.7. Free swell index test

The soil sample passed through trough a 425-micron IS sieve was used for this test. The two graduated cylinders of 100 ml volume were taken. The distilled water and kerosene were filled in each of them respectively. The inclusion of lime and waste eggshell powder was considered in terms of 0%, 1%,3%, 6%, 9% and 0%, 4%, 8%, 12%, and 16% respectively to the dry soil weight. 10 g of soil sample for each percentage of xanthan gum and guar gum was utilized for the investigation. The samples transferred in cylinders were stirred to make a saturated medium without any entrapped air. The initial volume of each sample was noted, and the setup was left undisturbed for 24 hours. Then the final volumes of each sample with the inclusion of lime and waste eggshell powder were also noted. This free swell index experiment was performed as per IS 2720 (Part 40) – 1985.

2.8. pH test

The pH tests were performed according to IS 2720 – 26 (1987). The soil samples were taken that includes untreated and soil treated with lime and waste eggshell powder. The specimens were prepared such that 3% of lime and 12% of waste eggshell powder were included in the expansive soil individually and in the combined form. The pH meter was calibrated to 4.0, 7.0 and 9.2 as standard reference values for each specimen. The pH values for slurries were noted after a period of 1.5 hours.

2.9. Atterberg's limits test

The soil specimens were tested to reveal the liquid limit, plastic limit and plasticity index of both the samples with the inclusion of 1%,3%, 6% and 9% lime and 0%, 4%, 8%, 12%, 16% waste eggshell powder along with the untreated sample. The liquid limit was obtained using the Casagrande apparatus whereas to attain the plastic limit of the soil, the specimens were rolled to 3mm diameter and oven-dried. The experiments for liquid limit and the plastic limit difference between liquid limit and plastic limit.

3. Results and discussion

3.1. Effect of lime on the unconfined compression strength of the expansive soil

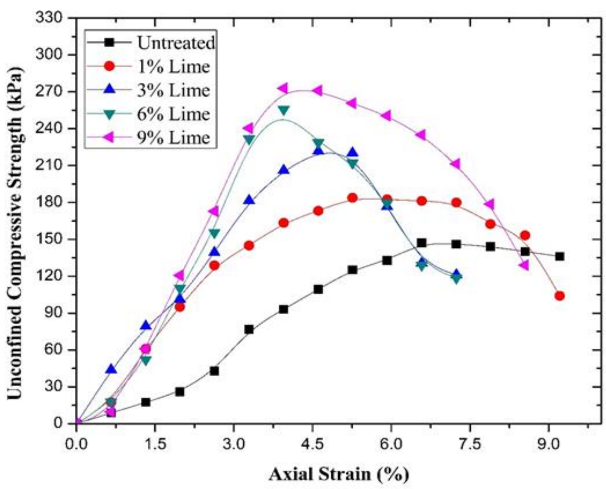


Figure 3. Effect of lime on the unconfined compression strength of the expansive soil

The variation of unconfined compressive strength of the expansive soil after the treatment with lime is shown in Figure 3. According to the rise in lime concentration in the expansive clay soil, the UCS was determined to have increased. The soil samples were kept under curing and tested at 3, 7 and 28 days. The UCS values obtained at 7 day curing period for untreated, 1%, 3%, 6% and 9% of lime were 147 kPa, 184 kPa, 222 kPa, 256 kPa and 273 kPa respectively. The cation exchange between the metal ions on the clay surface and the calcium ions in the lime caused this rise in strength to be seen. The clay particles thereafter become rough with high brittle nature and less plastic behaviour (Dang *et al*. 2016). The pozzolanic reactions that take place due to the presence of lime result in the dissolution of silica and alumina on the clay surface. Eventually, calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) which are the new cementitious compounds formed after the treatment with lime were formed. These compounds after crystallisation tend to increase the compressive strength of the expansive soil. The unconfined compressive strength of the black cotton soil treated with lime provided consistent results with the present study (Sahoo and Pradhan, 2010). The UCS obtained for soft expansive clay treated with quick lime and waste is comparatively similar to the results attained from the treatment with lime in expansive clay (Khazaei and Moayedi, 2017). Therefore, lime could effectively increase the strength parameters of the expansive soil after treatment.

3.2. Effect of waste eggshell powder on the unconfined compression strength of the expansive soil

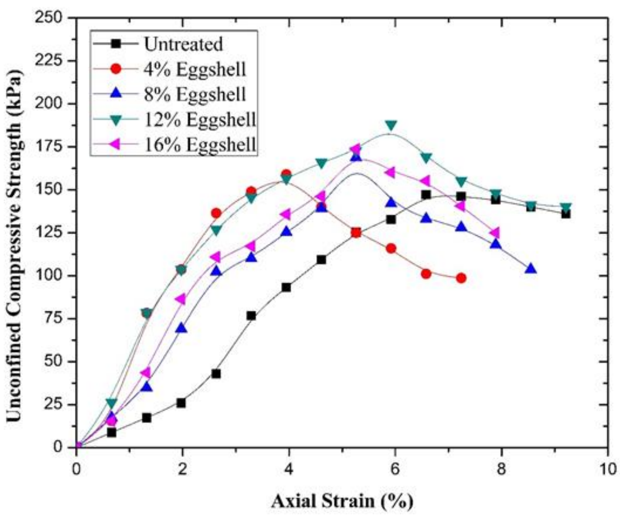


Figure 4. Effect of waste eggshell powder on the unconfined compression strength of the expansive soil

The variation in the UCS with respect to the inclusion of waste eggshell powder is shown in Figure 4. The UCS was found to be increased with an increase in waste eggshell shell powder composition in the expansive soil. The soil samples were kept under curing for 3, 7 and 28 days. The UCS values obtained at 7-day curing period for untreated, 4%. 8%, 12% and 16% inclusion of waste eggshell powder were found to be 147 kPa, 159 kPa, 169 kPa, 188 kPa and 174 kPa respectively. The strength increment was observed because of flocculation and agglomeration taking place between the particles of waste eggshell powder and the clay particles. In addition to that, pozzolanic reactions take place which enhance the strength of the expansive soil by producing CSH and CAH compounds. An optimum strength improvement was observed at 12% inclusion of waste eggshell powder and further inclusion of the additive was found to decrease the strength which was comparatively greater than the expansive soil. Hence, strength improvement was observed with respect to the increase in the percentages of waste eggshell powder in expansive soil. The results of the UCS obtained were observed to be quite similar to the results obtained for expansive soil treated with waste eggshell ash (James *et al*. 2020). The UCS of this study was found to be higher than the results obtained for the clay soil treated with waste eggshell powder and wastes (Alzaidy, 2019). Hence, utilising waste eggshell powder could enhance the strength similar to other additive inclusions.

3.3. Effect of combination of lime and waste eggshell powder on the unconfined compression strength of the expansive soil

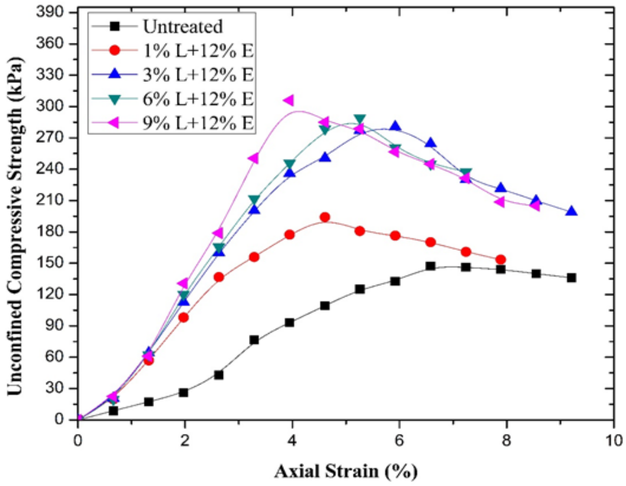


Figure 5. Effect of the combination of lime and waste eggshell powder on the unconfined compression strength of the expansive soil

The variation in the UCS after the inclusion of combined lime and waste eggshell powder is shown in Figure 5. With respect to an increase in the addition of mixed additives, it was found that the UCS of the expansive soil had risen. The samples were cured and tested at 3, 7 and 28 days such that the variation in the strength can be compared for the individual additive inclusion and their combination. The 12% inclusion of waste eggshell powder was considered as further addition of waste eggshell eventually decreased the strength. The UCS attained for the untreated sample was 147 kPa. The UCS values obtained for the addition of 12% of waste eggshell powder in each percent inclusion of 1%, 3%, 6% and 9% lime were observed to be194 kPa, 281 kPa, 289 kPa and 306 kPa respectively. In comparison with the results obtained from the individual addition of lime and waste eggshell powder, the inclusion of combination of additives exhibited higher strength in expansive soil. The UCS attained in the case of expansive clay after the inclusion of lime and waste eggshell powder was found to be significantly greater when compared to the results obtained from the treatment with lime and plastic waste strips (Amena and Chakeri, 2022). The result attained from the expansive soil treated with polypropylene, saw dust ash and waste eggshell powder was found to be consistent with the UCS attained from the current study (Wani *et al*. 2019).

3.4. Effect of lime on the California bearing ratio and expansion ratio of the expansive soil

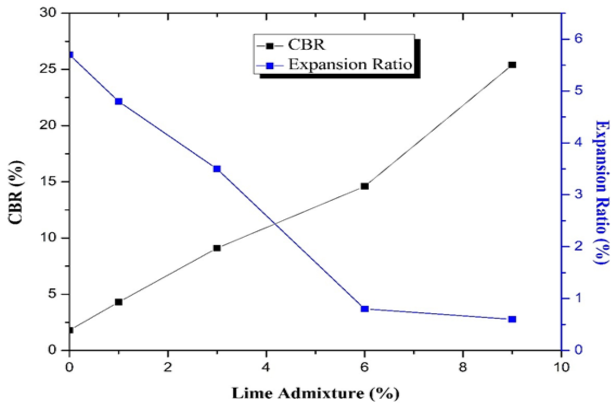


Figure 6. Effect of lime on the California Bearing Ratio and expansion ratio of the expansive soil

The variation in the California Bearing Ratio (CBR) and expansion ratio with respect to the inclusion of lime into the expansive soil is shown in Figure 6. The CBR values were found to increase with the increase in lime content in the expansive soil. The expansion ratio of the expansive decrease eventually with the addition of lime at specific percentages. The observations made for 0%, 1%, 3%, 6% and 9% inclusion of lime were found to be 1.8%, 4.3%, 9.1%, 14.6% and 25.4% respectively. The expansion ratios for the expansive soil treated with 0%, 1%, 3%, 6% and 9% of lime were found to be 5.7, 4.8, 3.5, 0.8 and 0.6 respectively. The change in CBR was observed due to the pozzolanic reactions occurring in the clay particles of expansive soil after the lime addition (Tiwari and Satyam, 2020). This ultimately enhances the strength of the expansive soil which in turn increases the CBR of the treated soil samples. The CBR results attained from the present study were found to be higher than the results obtained from the expansive soil treated with lime and fly ash (Dahale *et al*. 2017). The results attained from expansive soil treated with lime and quarry dust were found to be consistent with the CBR from the present study (Sabat, 2013).

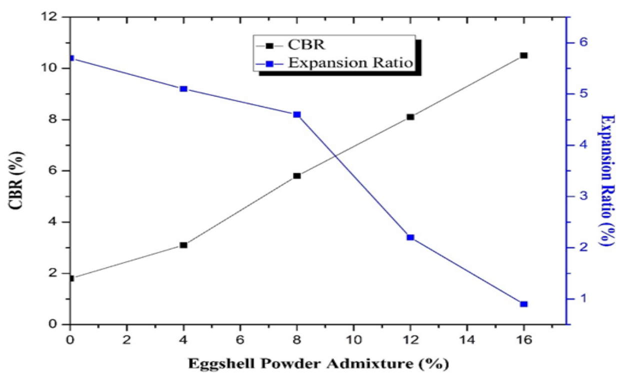


Figure 7. Effect of waste eggshell powder on the California Bearing Ratio and expansion ratio of the expansive soil

3.5. Effect of waste eggshell powder on the California bearing ratio and expansion ratio of the expansive soil

The variation in the CBR and expansion ratio with respect to the increase in the composition of the waste eggshell powder is shown in Figure 7. The CBR increased with the further inclusion of waste eggshell powder into the expansive soil. The expansion ratio decreased with an increase in the lime content as observed in the figure. The CBR obtained for 0%, 4%, 8%, 12% and 16% inclusion of waste eggshell powder in expansive soil were found to be 1.8%, 3.1%, 5.8%, 8.1% and 10.5% respectively. The expansion ratios of the expansive soil after the addition of 0%, 4%, 8%, 12% and 16% of waste eggshell powder were found to be 5.7, 5.1, 4.6, 2.2 and 0.9 respectively. The increase in CBR was observed in accordance with the chemical reactions occurring between the CSH compound formed and the clay particles of expansive soil. This tendency of increase in the CBR ultimately indicated the strength gain in the expansive soil after treatment. The CBR attained for the expansive soil treated with waste eggshell powder was found to be significantly higher than the results obtained from the expansive soil treated with waste eggshell powder and plastic wastes (Alzaidy, 2019). The results obtained from the treatment with waste eggshell powder were observed to be greater when compared with the results attained from the black cotton soil treated with waste eggshell powder – gum Arabic (Haruna *et al*. 2017).

3.6. Effect of combination of lime and waste eggshell powder on the California bearing ratio and expansion ratio of the expansive soil

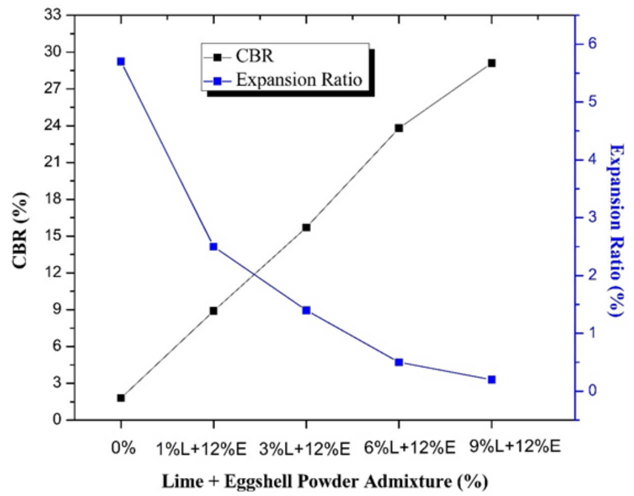


Figure 8. Effect of the combination of lime and waste eggshell powder on the California Bearing Ratio and expansion ratio of the expansive soil

The variation in the CBR with respect to the increase in the lime and waste eggshell combined at a specific percentage is shown in Figure 8. The CBR was found to be increased with an increase in the addition of additives after combination. The expansion ratio of the expansive soil was observed to be decreased after the further inclusion of combined lime and waste eggshell powder. The optimum dosage of waste eggshell powder in the expansive soil was observed to be 12% which was attained from unconfined compression test. The CBR values for 1%, 3%, 6% and 9% lime each included with 12% of waste eggshell powder were found to be 8.9%, 15.7%, 23.8% and 29.1% respectively. The values of expansion ratio of the expansive soil treated with 1%, 3%, 6% and 9% lime where each sample was added with 12% of waste eggshell powder were found to be 5.7, 2.5, 1.4, 0.5 and 0.2 respectively. The results obtained for the combination of lime and waste eggshell powder were observed to be higher in comparison with the results obtained for the inclusion of additives individually for both cases of CBR and expansion ratio test. The expansion ratio values attained from the present study were found to be quite higher than the previous studies (Bapiraju, 2019). The CBR values were found to be consistent with the results attained from expansive soil treated with coir fibre, waste eggshell powder and steel fibre (Srinivasan *et al*. 2021).

3.7. Effect of lime, waste eggshell powder & combined lime and waste eggshell on the swelling pressure of the expansive soil

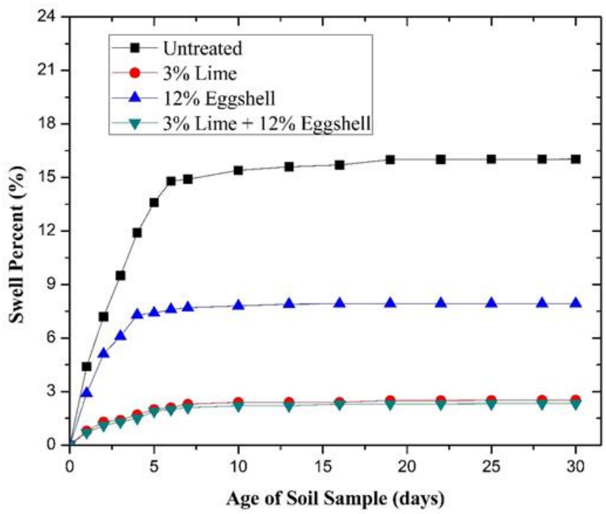


Figure.9. Effect of lime, waste eggshell powder & combined lime and waste eggshell on the swelling pressure of the expansive soil

The variation in the swell pressure with respect to the increase in the lime composition in the expansive soil is shown in Figure 9. The swell pressure for the soil samples were tested at 0, 1, 2, 3, 4, 5, 6, 7, 10, 13, 16, 19, 22, 25, 28 and 30 days and the results were compared. The swell pressure for the untreated expansive soil was 4.4% whereas the expansive soil treated with 3% of lime decreased to 2.53% at the end of 30 days. A reduction in swell pressure was observed due to a reduction in the permeability of the treated expansive soil that eventually decrease the water affinity into the soil mass (Tiwari and Satyam, 2020). Hence, the tendency to swell decreases with the addition of 3% lime into the expansive soil. The reduction of swell pressure in the expansive soil treated with lime was found to be greater than the results obtained from the lime-treated expansive soil from Oman (Al-Rawas *et al*. 2005). The variation in the swell pressure with respect to the addition of waste eggshell powder at different ages is shown in Figure 9. The swell pressure for the soil samples were tested at 0, 1, 2, 3, 4, 5, 6, 7, 10, 13, 16, 19, 22, 25, 28 and 30 days and the results were compared. The waste eggshell powder was included in a dosage of 12%. The swell pressure decreased to 7.93% at the end of 30 days after the inclusion of waste eggshell powder. The reduction in swell pressure was observed after the inclusion of waste eggshell powder due to agglomeration and flocculation mechanism occurring between clay and waste eggshell particles. The variation in swell pressure after the inclusion of both lime and waste eggshell powder at specific percentages is shown in Figure 9. The swell pressure for the soil samples were tested at 0, 1, 2, 3, 4, 5, 6, 7, 10, 13, 16, 19, 22, 25, 28 and 30 days and the results were compared. The CBR values were found to increase as there was an increase in the composition of the combined lime and waste eggshell powder. The dosages chosen to be added in the case of lime and waste eggshell powder were 3% and 12% respectively. The swell pressure of the untreated expansive soil specimen was found to be 16.03% at the end of 30 days whereas for the soil specimen treated with 3% lime and 12% waste eggshell powder was found to be 2.32%. The results obtained from the expansive soil after the treatment with combined additives were found to be significantly less compared to the individual addition of lime and waste eggshell powder. This indicated the improvement in the stabilisation of the expansive soil effectively and efficiently.

3.8. Effect of lime on the free swell index of the expansive soil

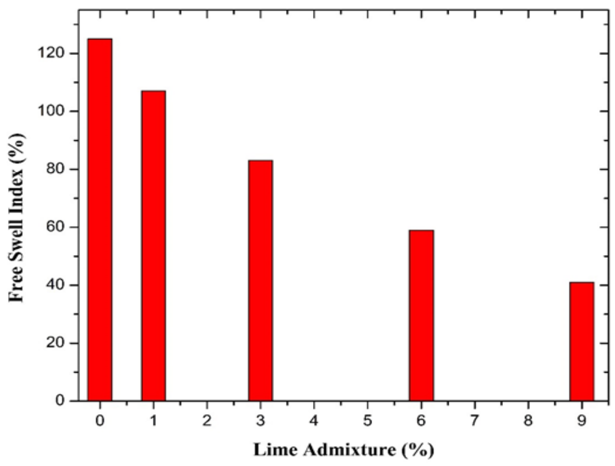


Figure 10. Effect of lime on the free swell index of the expansive soil

The variation in the free swell index (FSI)of the expansive soil after the treatment with different dosages of lime is depicted in the Figure 10. The FSI for the expansive soil tends to reduce with the inclusion of lime. The swell index for 0%, 1%, 3%, 6% and 9% inclusion of lime content were observed to be 125%, 107%, 83%, 59% and 41% respectively. The reduction in the free swell index was observed due to the presence of divalent and trivalent cations that tend to enhance flocculation in the particles of expansive soil thereby lessening the surface area and affinity to water for the soil specimens (Indiramma *et al*. 2019). The reduction in the free swell index of the expansive soil treated with lime was found to be consistent with the results obtained from the previous studies (James and Pandian, 2016).

3.9. Effect of waste eggshell powder on the free swell index of the expansive soil

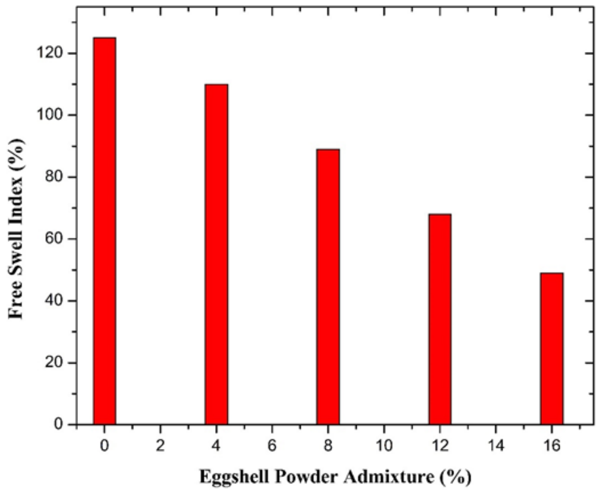


Figure 11. Effect of waste eggshell powder on the free swell index of the expansive soil

The variation in the FSI of the expansive with respect to different dosages of waste eggshell powder inclusion is shown in Figure 11. The swell index values of expansive soil were observed to be reduced with an increase in the composition of the waste eggshell powder. The FSI for expansive soil treated with 0%, 4%, 8%, 12% and 16% of waste eggshell powder were found to be 125%, 110%, 89%, 68% and 49% respectively. The addition of waste eggshell powder into expansive soil eventually reduced the clay fraction gradually thereby increasing the sand fraction in the soil sample (Nyankson *et al*. 2013). The swell index percentage of the expansive soil treated with lime was quite lower than the results attained from the soil treated with waste eggshell powder and bacillus subtilis (Sugata *et al*. 2020).

3.10. Effect of combination of lime and waste eggshell powder on the free swell index of the expansive soil

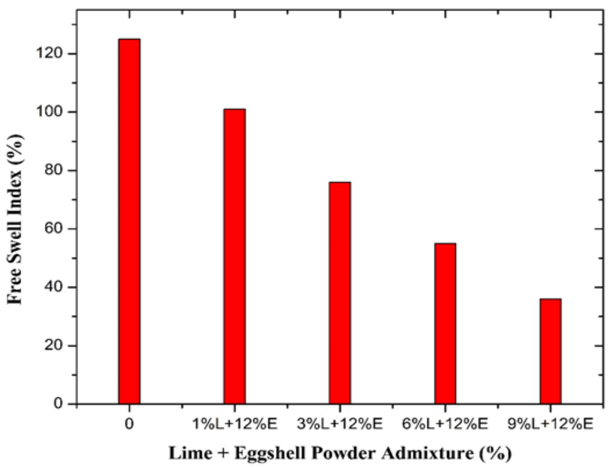


Figure 12. Effect of the combination of lime and waste eggshell powder on the free swell index of the expansive soil

The variation of the free swell index of expansive soil with respect to the addition of combined lime and waste eggshell powder is shown in Figure 12. The swell index values of expansive soil decreased significantly after the inclusion of different dosages of lime with 12% waste eggshell powder as it was observed to exhibit higher strength. The FSI for expansive soil treated with 0%, 1%, 3%, 6% and 9% along with 12% of waste eggshell powder were found to be 125%, 101%, 76%, 55% and 36% respectively. The results of FSI obtained from this experiment were found to be quite lower than those obtained from the inclusion of lime and waste eggshell individually at different percentages into expansive soil. The results obtained for the inclusion of combined lime and waste eggshell were observed to be considerably the same as the study related to the inclusion of lime and marble dust (Makebo, 2019).

3.11. Effect of lime, waste eggshell powder & combined lime and waste eggshell powder on the ph of the expansive soil

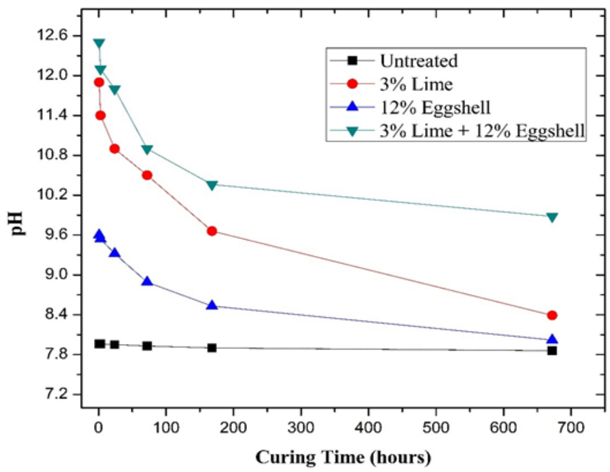


Figure 13. Effect of lime, waste eggshell powder & combined lime and waste eggshell powder on the pH of the expansive soil

The variation of pH with respect to the increase in the lime content in expansive soil is shown in Figure 13. The specimens for pH test were considered to be cured and tested at 1, 3, 24, 72, 168 and 672 hours. The pH of the expansive soil after the inclusion of 3% lime at 1, 3, 24, 72, 168 and 672 hours were 11.9, 11.4, 10.9, 10.5, 9.66 and 8.39 respectively from 7.96, 7.96, 7.95, 7.93, 7.9 and 7.86. Therefore, the addition of 3% lime considerably reduced the pH values thereby improving the stabilisation of expansive soil. The increase in pH was found to be occurring because of the cation exchange reaction taking place after the inclusion of lime into the soil sample. This gradually decreased the gap between the soil particles and hence reduced the swell potential of the expansive clay soil (Cheng *et al*. 2018). The pH of the expansive soil treated with lime was found to be similar to the results obtained from earlier studies (Cheng *et al*. 2018 and Al-Mukhtar *et al*. 2010). The variation in pH after the inclusion of waste eggshell powder in clay soil is elucidated in Figure 13. The expansive soil was treated with 12% of the waste eggshell powder. The soil specimens were cured for specific periods such as 1, 3, 24, 72, 168 and 672 hours. The pH obtained for those curing periods were 9.6, 9.54, 9.32, 8.89, 8.53 and 8.02 respectively whereas in the case of untreated expansive soil, the values were found to be 7.96, 7.96, 7.95, 7.93, 7.9 and 7.86 respectively. The variation in pH with respect to the addition of a specific dosage combination of lime and waste eggshell powder is shown in Figure 13. The expansive soil was treated with 3% lime and 12% waste eggshell powder for the curing periods such as 1, 3, 24, 72, 168 and 672 hours. The pH values attained for 3% lime and 12% waste eggshell powder inclusion in the expansive soil specimens were found to be 12.5, 12.1, 11.8, 10.9, 10.36 and 9.88 respectively. The results obtained from the combination of lime and waste eggshell powder were found to be effective in comparison with the results attained from the lime and waste eggshell included separately. The results obtained for expansive clay soil after the treatment with combined lime and waste eggshell powder were found to be consistent with the results obtained for expansive clay soil after treatment with combined lime, jaggery and gallnut powder (James *et al*. 2018).

3.12. Effect of lime on the Atterberg's limit of the expansive soil

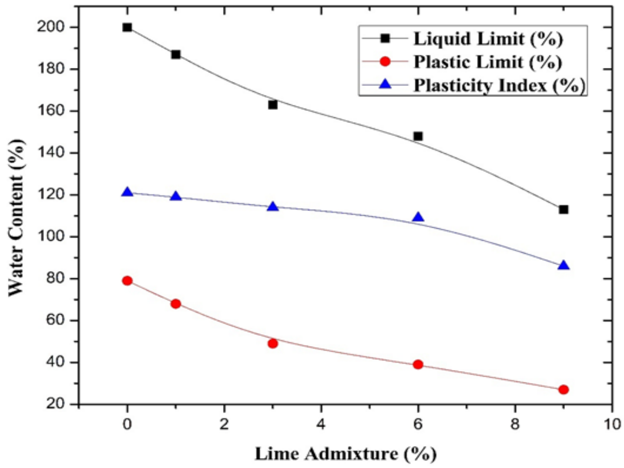


Figure 14. Effect of lime on the Atterberg's limit of the expansive soil

The variation in Atterberg's limit after the inclusion of lime is shown in Figure 14. The Atterberg's limits which include liquid limit, plastic limit and plasticity index was represented in graphs with respect to the addition of lime. The liquid limit for 0%, 1%, 3%, 6% and 9% inclusion of lime were found to be 200%, 187%, 163%, 148% and 113% respectively. The liquid limit decreased with the respective increase in lime content. The variation of plastic limit in case of addition of 0%, 1%, 3%, 6% and 9% of lime was found to be 79%, 68%, 49%, 39% and 27% respectively. From the figure, it can be observed that the plastic limit decreases with an increase in lime content in the expansive soil. Eventually, the plasticity index of the treated expansive soil varies as 121%, 119%, 114%, 109% and 86% respectively. The reduction in Atterberg's limit was observed to occur simultaneously when tested after the addition of additive. The decrease in clay percentage in the expansive soil and the formation of diffused double layer after treatment with lime were found to be responsible for the reduction in liquid limit, plastic limit and hence the plasticity index (Indiramma *et al*. 2019). The Atterberg's limits of the present study were found to be higher than the results obtained from the expansive soil after the treatment with lime and natural pozzolans (Cheng *et al*. 2018).

3.13. Effect of waste eggshell powder on the Atterberg's limit of the expansive soil

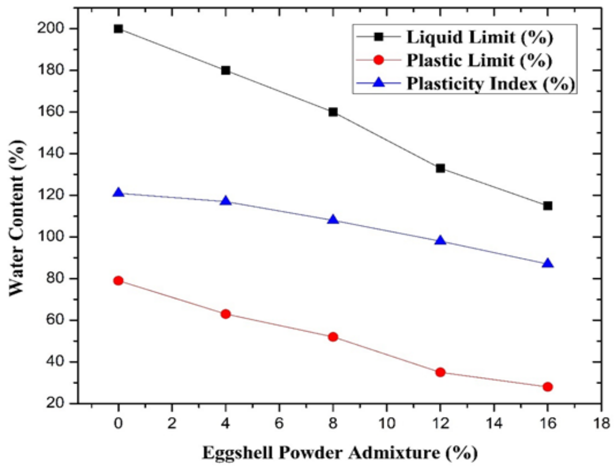


Figure 15. Effect of waste eggshell powder on the Atterberg's limit of the expansive soil

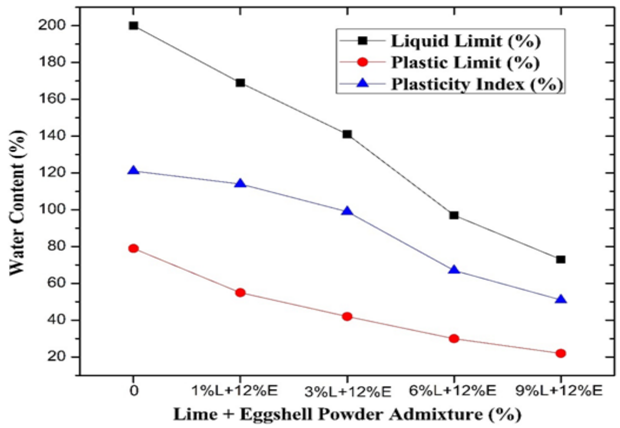


Figure 16. Effect of the combination of lime and waste eggshell powder on Atterberg's limit of the expansive soil

The variation of Atterberg's limit with respect to the addition of waste eggshell powder at specific percentages was shown in Figure 15. The values of Atterberg's limit were found to be reduced with the respective inclusion of waste eggshell powder as observed from the figure. The liquid limit of the treated expansive after the treatment with 0%, 4%, 8%, 12% and 16% of waste eggshell powder were found to be 200%, 180%, 160%, 133% and 115% respectively. The plastic limit for the treated expansive soil with 0%, 4%, 8%, 12% and 16% inclusion of waste eggshell powder varies as 79%, 63%, 52%, 35% and 28% respectively. This eventually affects the plasticity index as it varies with respective percentage inclusion as 121%, 117%, 108%, 93% and 87%. Therefore, there is a reduction in liquid limit and plastic limit and ultimately resulting in the variation in plasticity index with the respective inclusion of waste eggshell powder into the clay. In the process, the cations at the surface of the soil were found to be substituted by calcium. This eventually enhanced flocculation and aggregation making the treated expansive soil less plastic (Sathiparan, 2021). The present study exhibited effective results when compared to the results obtained from the lime-stabilised expansive soil treated with waste eggshell powder (Soundara and Vilasini, 2015).

3.14. Effect of combination of lime and waste eggshell powder on atterberg's limit of the expansive soil

The variation in the liquid limit, plastic limit and plasticity index with respect to the inclusion of lime and waste eggshell powder at specific percentages were shown in Figure 16. The expansive soil is treated with 1%, 3%, 6% and 9% of lime in addition to 12% of waste eggshell powder at specific percentages of lime inclusion. The liquid limit varied as 200%, 169%, 141%, 97% and 73% respectively after adding lime and waste eggshell powder. The plastic limit of the treated expansive soil varied from 79%, 55%, 42%, 30% and 22% respectively. Hence, the respective plasticity index values were found to be 121%, 114%, 99%, 67% and 51%. The Atterberg's limits such as liquid limit, plastic limit and plasticity index were observed to be decreased after the addition of lime and waste eggshell powder at specific combinations. The combined lime and waste eggshell powder exhibited better results in comparison with the results obtained from the individual addition of additives. The effective reduction was observed as it involved two additives and they exhibited different functions to enable efficient stabilisation of expansive soil. The results attained were consistent with the results obtained from the earlier studies (Anoop *et al*. 2017).

4. Conclusion

The soil stabilisation characteristics which were improved after the inclusion of lime, waste eggshell powder and combined lime and waste eggshell powder were analysed and elucidated by conducting a series of experiments. The following findings were offered as a result of the current investigation.

- The unconfined compressive strength of the expansive soil increased after the inclusion of additives. The UCS of the expansive soil with respect to the addition of 9% lime, 12% waste eggshell powder and combined admixtures were found to be 273 kPa, 188 kPa and 306 kPa respectively. A higher strength was attained for the combined inclusion of lime and waste eggshell powder.
- The California Bearing Ratio of the expansive soil increased after the inclusion combination of lime and waste eggshell powder. The expansion ratio of the expansive soil reduced efficiently after the inclusion of lime and waste eggshell powder in a combined form than the individual inclusion.

- A significant decrease in swell pressure was observed to 2.32% after the combined inclusion of lime and waste eggshell powder.
- The free swell index of the expansive soil with respect to the 9% lime, 12% waste eggshell powder and combined inclusion of lime and waste eggshell powder were observed to be 41%, 49% and 36% respectively. A higher improvement was identified in the case of the combined inclusion of additives.

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