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Influence of industrial wastes and lime on strength characteristics of clayey soil

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Abstract. The stress-strain and volumetric behavior, shear strength parameters, permeability and stiffness of soft clayey soil stabilised with various proportions of molasses, waste foundry sand, and lime are investigated in this article using the variable head permeability test and consolidated drained triaxial test. The results of the tests showed that the permeability, stress-strain and volumetric behavior of the soft clayey soil were significantly enhanced by the addition of molasses, waste foundry sand, and lime. At all confining pressures, the volumetric strain was found to decrease with the inclusion of additives. The additives to soft clayey soil reduced cohesion to a limited extent whereas significantly increasing the angle of shearing resistance. Furthermore, scanning electron microscope (SEM) images of all the optimum composites demonstrate that with the additives, a composite with higher strength and density is observed, and the geotechnical properties of soft clayey soil are improved, thereby making it suitable as a subgrade material in pavement construction.

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1. Introduction

Expansive soil is a type of clayey soil that is prone to large volumetric variations caused by changes in water content. As expansive soils act differently than other types of soil, geotechnical engineers in particular have obstacles when working with them. Structures that are constructed on them are susceptible to damage as a result of their tendency to swell and shrink. Damage caused by swelling and shrinking behaviour of expansive soils owing to moisture fluctuations costs billions of dollars worldwide [1, 2]. Disruption caused by weak expansive soil is most evident on structures that are lightly stressed, such as single or double-story buildings, canal linings, earth retaining structures, pavements, etc.Soil stabilization is the technique of improving the engineering and index properties of poor soils [3, 4]. It is particularly of immense importance in civil engineering as it increases the shear strength of the soil and fulfils essential geotechnical requirements under specific environment. Efforts have been made in the past to stabilise expansive soils using a variety of materials such as molasses, waste foundry sand (WFS), construction demolition waste, cement, lime, polyurethane resin, and glass waste etc. [5–13]. It was observed that strength of expansive soil enhanced with the help of using these materials.

An enzyme is a biological system product that accelerates the chemical reactions in the cells by catalysis. Enzymes are hydrophilic organic catalysts that promote extremely particular chemical reactions under favourable circumstances [14]. According to a number of investigations, enzyme-based stabilisers result in maintenance-free roads with increased bearing capacity (UCS, CBR, and resilient modulus) [15–19]. The addition of molasses to sodic clay and soft murum soil modified structural strength of soil and proved to be economical in road construction [20]. The plasticity of the composite was reduced from 53 % to 19 % when 4 % molasses was added to the soil cement blend, and the CBR value was raised from 1 %

to 64 %. Lab tests conducted on mixtures of clayey soil and bio-enzyme revealed that the CBR value of the clayey soil was increased by 5–10 % in the presence of the bio-enzyme, compared to the CBR value of the untreated soil [21]. The unconfined compressive strength of kaolin clay increased from about 1.42 MPa to 2.04 MPa for samples with 0.1 wt% of fibres and 2.0 wt% molasses with respect to the dry weight of the soil [22].

The rapid development of industry has resulted in the production of a massive amount of waste, both solid and liquid. These wastes are often dumped on land or released into water bodies, without sufficient treatment, despite the fact that pollution control measures are required, and as a result they represent a significant source of environmental pollution and health hazard. High-quality silica sand, known as waste foundry sand (WFS) is a byproduct of the ferrous and non-ferrous metal casting industries. Because of its high thermal conductivity, it has been used for decades as a casting material for making moulds. The waste foundry sand is usually thrown away when the casting process is complete [23]. Every year, India produces nearly 1.8 million tonnes of waste foundry sands. More than 60 million tonnes of WFS were produced worldwide in 2016 and much of it was deposited in landfills [24]. The waste disposal problem of WFS might be overcome, and the environment would benefit, if it were utilized to stabilize expansive soils. Efforts to utilize WFS as a construction material have been increased significantly in recent years [25–29]. Standard proctor and CBR tests performed on combinations of lime, WFS, molasses, clayey soil and concluded that at 20 % WFS the CBR value of clayey soil was found to be the highest when compared with the other percentages of WFS used in the study [30]. Waste foundry sand materials (samples) from ten different industries were collected and investigated for use in road construction and as a structural fill. It was concluded that the finer sample may be used for the construction of the subbase layer of pavement [31].

The stabilization of clayey soil by the addition of lime is a method that is widely utilized across the globe to increase its suitability for construction. Lime is the oldest traditional stabilizer used for soil stabilization [32]. The term "lime stabilization" refers to the process of improving the quality of the soil by the incorporation of burned limestone products, such as calcium oxide (CaO) or calcium hydroxide (Ca (OH) ^{2}). Lime stabilization is used to strengthen sub-bases and subgrades in roads, to build railroads and airports, embankments, to exchange soil in unstable slopes, to backfill bridge abutments and retaining walls, to line canals, to enhance the soil under foundation slabs, and to make lime piles [33, 34]. Stabilization of the expansive soil with 6 % lime decreased soil swelling without increasing soil pressure [35]. Eastern Croatian clay soils were combined with lime, and the results demonstrated an improvement in the geotechnical properties of the clays [36]. The unconfined compressive strength (UCS) and small-strain dynamic characteristics of lime- and water-stabilized soft clay specimens revealed that increasing the lime concentration up to 10 % resulted in increasing the shear wave velocity (Vs), shear modulus (Gmax) and UCS values [37].

It has become clear from reviewing the existing research that using molasses and WFS individually in soil stabilization not only enhanced the geotechnical properties of clayey soils, but also proved to be environmentally friendly by resolving WFS disposal issues. Strength characteristics of composites and the shear response of clayey soils were significantly enhanced by the separate addition of molasses, WFS, and lime.

However, the shear response of clayey soil blended with molasses (M), waste foundry sand (WFS), and lime (L) in combination with each other has been understudied in the past. In the present study, a set of permeability tests and consolidated drained triaxial tests was carried out on clayey soil stabilized with molasses, WFS, and lime separately and in combination. The effect of adding different amounts of additives to clayey soil on deviator stress was examined. In addition, the strength ratio and stiffness of stabilized soil at different strain levels were compared with those of unstabilized soil.

2. Materials and Methods

The soil samples were takenfrom the side of NH-88 (Kangra-Shimla route) near the Jukhala village in the Bilaspur district of Himachal Pradesh, India. After sample collection in airtight bags, samples were transported to the laboratory. The soil samples were pulverized in the pulverizing machine after drying. Then they were sealed again in air-tight bags to avoid any variation in moisture content. The soil was classified as clayey soil of high plasticity (CH) according to Unified Soil Classification System (USCS). Tables 1 and 2 present the geotechnical characteristics and mineral composition of the soft clayey soil investigated in the research.

Molasses used in the study was obtained from Budhewal Co-Operative Sugar Mill Ltd., located in the Punjab region of Ludhiana. Table 3 shows the chemical characteristics of molasses. The waste foundry sand used in this work is a recycling waste from Shakti Foundries in Ludhiana (Punjab). WFS has a dark colour and a sandy texture due to the angular shape of the waste particles and the fines adhering to the sand particles. Dry sieve analysis in accordance with ASTM D6913-04 gave the gradation curve for WFS.

The effective size (D10), coefficient of curvature (Cc) and coefficient of uniformity (Cu) for the sand are 0.14 mm, 0.89 and 1.44 respectively, indicating that WFS is poorly graded in nature, with the majority of the particles falling into the fine sand range. Fig. 1 displays the particle-size distribution curve of the sand used in this study. The various geotechnical and chemical properties of WFS were tabulated in Tables 4 and 5. The powdered lime utilized in this investigation was purchased from a hardware store in Hamirpur, Himachal Pradesh. The chemical composition of lime is presented in Table 6.

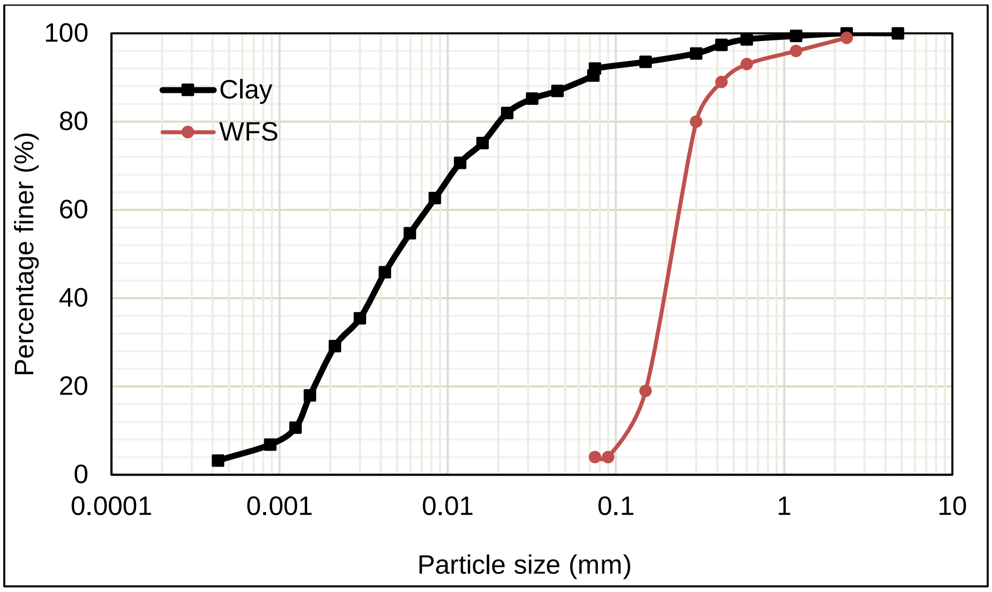

Figure 1. Particle size curve for soft clayey soil and WFS.

According to American society for testing and materials (ASTM) standards, grain size analysis (ASTM D6913-04, ASTM D422-63), pH (ASTM D4972-18), Atterberg limits (ASTM D4318-10), permeability (ASTM D5084-03), and consolidated drained (CD) triaxial compression tests (ASTM D7181-11) were performed on soft clayey soil, clay-molasses mix, clay-WFS mix, clay-lime mix, clay-molasses-WFS-lime mix, clay-molasses-lime mix, and clay-molasses-WFS-lime mix.

Using two 100 ml cylindrical beakers, one with distilled water and the other with 30 gm of soil mixed in 75 ml of distilled water, the pH of soft clayey soil alone and soil combined with varied amounts of molasses, WFS, and lime were tested in the lab. Soil and distilled water were combined and stirred every 15 minutes for an hour, following which the pH was recorded using an electronic pH metre inserted in the beaker. The laboratory tests confirmed that Atterberg limits of the soft clayey soil and stabilized soil conformed to standards. The samples used to determine the liquid limit and plastic limit were screened using a 0.425 mm sieve. The liquid limit of the sample is the water content corresponding to 25 blows determined using Casagrande test apparatus and plastic limit is the moisture content at which soil begins to crumble when rolled into a 3 mm diameter thread using a ground glass plate. The plasticity index of the soil is the numerical difference between the liquid and plastic limits.

To investigate the drainage properties of soft clayey soil and different composites of unstabilized and stabilized clayey soil a variable head permeability test was performed. A mould with a diameter of 100 mm and a height of 125 mm was used to conduct the variable head permeability test, and the sample was compacted in three layers at maximum dry density equal to optimum moisture content using 25 blows at each layer. The samples were soaked after preparation until water constantly came out of the mould. The starting and final heads were recorded, as well as the time it took for the heads to decrease, keeping the head difference constant. The triaxial tests were performed in a Perspex cell on 76×38 mm cylindrical materials compacted to the maximum dry density at optimum moisture content. The consolidated drained triaxial test was carried out in two stages: first, the sample was placed in the triaxial cell, confining pressure was applied, and drainage was allowed; secondly, an additional axial stress (also known as deviator stress) was applied, allowing drainage to occur, resulting in shear stresses in the sample. The sample was subjected to increasing axial stress until it failed. Applied stresses, axial strain, and sample volume change were all monitored during both phases.

Table 1. Geotechnical properties of clayey soil.

Soilproperties	Value
Soil type	CH
Liquid limit	55%
Plastic limit	20%
Plasticity index	35%
Specific gravity	2.6
Differential free swell index	35%
Optimum moisture content	16.5%

Table 2. Mineral composition of clayey soil.

Mineralcomposition	Content (%)
Oxygen, O	45.4
Silicon, Si	18.5
Aluminium, Al	8.69
Carbon, C	10.9
Iron, Fe	1.42
Potassium, K	1.86
Magnesium, Mg	2.30
Titanium, Ti	2.51

Table 3. Chemical properties of molasses used.

Constituents	Result
Color	Black
Brix	83.2
pH (1:1 at 20 ºC)	5.6
Specific Gravity	1.39
Viscosity	17500 mPa-s
Moisture	21.76%
Total sugar	47.83%
Invert sugar	10.20%
Sulphated sugar	15.50%
Ca	1.63%

Table 4. Geotechnical properties of WFS.

Property	Value
Specific Gravity	2.64
Optimum moisture content	8.20 %
Maximum dry density	1.59 g/cc

Table 5. Chemical properties of WFS.

Chemical composition	Percentage
SiO_2	84.90
Al_2O_3	5.21
Fe_2O_3	3.32
CaO	0.58
MgO	0.67
SO_3	0.29
MnO	0.08
TiO_2	0.19
K_2O	0.97
P_2O_5	0.05
Na_2O	0.50
Loss of ignition	2.87

Table 6. Chemical composition of lime used.

Chemicalcomposition	Content (%)
SiO_2	2.1
Al_2O_3	1.3
Fe_2O_3	1.2
CaO	82.8
MgO	0.3
SO_3	0.4
Na_2O	0.4
K_2O	-
C	2.2
$CaCO_3$	4.3
Impurities	5.0
Loss of ignition at 800°C	-

3. Results and Discussion

The following sections provide a summary of the effect of varying molasses, WFS, and lime percentages on pH, Atterberg limits, permeability, and shear strength parameters of soft clayey soils.

3.1. pH tests

The influence of molasses, WFS, and lime on soft clay pH is discussed in this section. pH of clayey soil treated with 5, 10, 15, and 20 % molasses was measured. Fig. 2 depicts the change in clay pH as a result of the addition of molasses. Soft clayey soil had a pH of 7.56, which was somewhat alkaline, whereas molasses had a pH of 5.8, which was slightly acidic. When molasses was added to soft clay, the pH of the composite decreased and reached neutral (pH = 7) at 10 % molasses concentration, and continued to drop as the molasses percentage was increasing. Molasses with a concentration of 10 % may be used for fixation in clay-molasses mixtures. Because molasses has a lower pH than soft clayey soil, it causes the pH of the mixture to drop when it is added [38].

Fig. 3 depicts the change in soft clay pH as a result of the addition of WFS (10, 20, 30, and 40 %). Soft clayey soil had a pH of 7.56, which was somewhat alkaline, whereas WFS had a pH of 6.42, which was slightly acidic. When WFS was added to soft clay, the pH of the composite decreased and reached neutral (pH = 7) at 20 % WFS concentration, and continued to drop as the WFS percentage was increasing. WFS with a concentration of 20 % may be used for fixation in clay-WFS mixtures. Because WFS has a lower pH than soft clayey soil, it causes the pH of the mixture to drop when it is added [39].

As shown in Fig. 4, the pH of the soft clay-lime mix rises as the lime concentration rises. The alkaline nature of lime causes a rise in pH with its addition. At 9% lime concentration in clay-lime combination, a maximum pH of 12.2 (pH of commercial lime employed in this research, which includes some impurities) was attained, suggesting that it might be utilized for soil stabilization. According to ASTM-C977, if the pH of the soil is 12.40 or above, the lowest proportion that yields a pH of 12.40 is the optimum lime concentration. When lime was added to soft clay, a reaction between the lime and the soil particles occurred, resulting in cation exchange up to a specific lime content, at which point the pH reached its maximum value, beyond which further lime dose had no effect on the pH value [40–42].

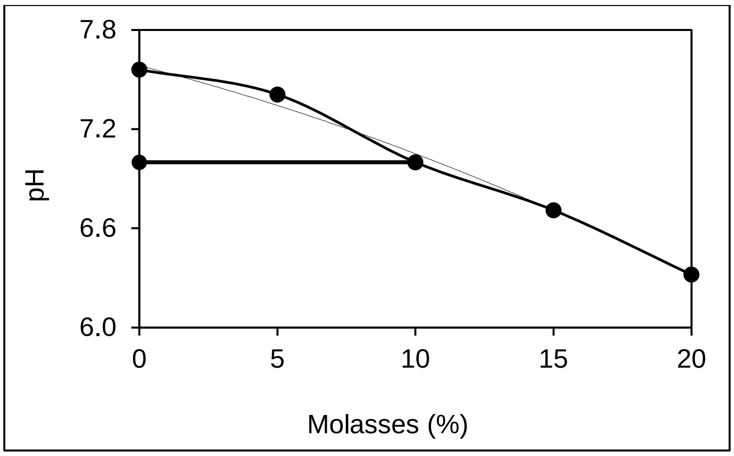

Figure 2. pH of clay-molasses mixes.

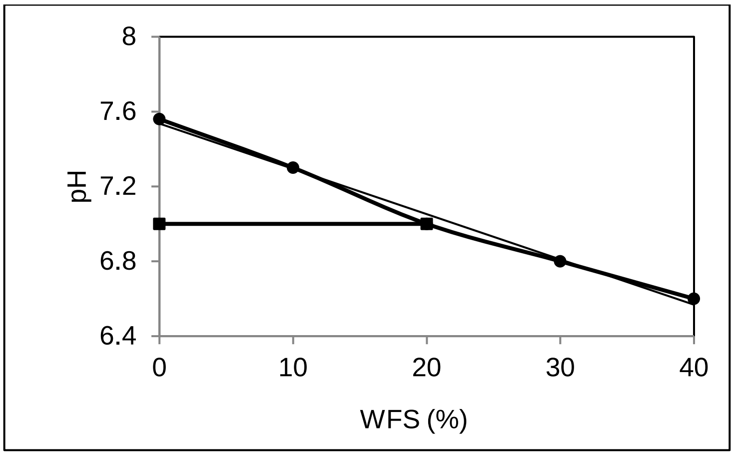

Figure 3. pH of clay-WFS mixes.

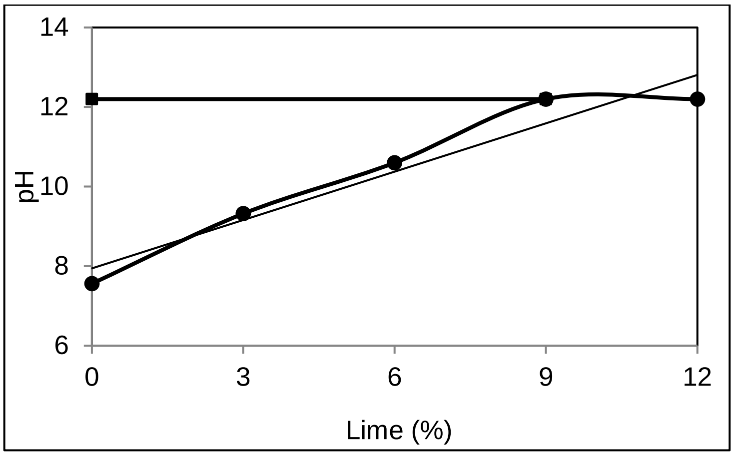

Figure 4. pH of clay-lime mixes.

3.2. Consistency limit tests

For soft clayey soil the liquid limit was 55 % and plastic limit was 20 % and from plasticity index chart it was observed that clayey soil can be categorized as CH (clay of high plasticity) (Fig. 5). Adding molasses (at 5 %, 10 %, 15 %, and 20 % concentrations) to soft clayey soil lowered the plasticity index (Ip) from 35 % to 21 %. Noteworthy, Ip value dropped more significantly when 10 % molasses was used compared to other percentages of WFS. The points of the curve in the plasticity index chart shifted from the high plastic (CH) zone to the intermediate plastic clay (CI) zone, as shown in Fig. 5. Similar trend was observed in the past by some researchers [6, 43]. The Ip in soft clayey soil was lowered from 35 % to 29 % after WFS (10, 20, 30, and 40 %) was added. It is worth noting that the percentage of WFS at which the Ip value dropped the most was 20 %. Fig. 5 shows a shift from the high plastic (CH) to the intermediate plastic clay (CI) region on the plasticity index chart. Similar trend was observed in the past by some researchers [39, 44]. The plasticity index (Ip) dropped from 35 % to 9 % with the addition of lime (3, 6, 9, and 12 %) to the soft clayey soil. It is important to note that the Ip value dropped significantly at 9 % lime compared to other lime concentrations. Variations in the plasticity index chart are depicted in Fig.5, where the points of the curve moved from the high plastic (CH) zone to the MI zone sufficiently below the A-line. Similar trend was observed in the past by some researchers [45, 46].

A combination of molasses and WFS reduced the Ip value of clayey soil to 17 %, by keeping molasses content constant at 10 % and varying the WFS content (10, 20, 30, and 40 %). Low plastic clay (CL) is represented by a variation in the plasticity index chart shown in Fig. 5. When WFS was added to soft clayey soil containing 10 % molasses and 10 % WFS, the plasticity index of the composite dropped, and it continued to drop considerably as higher percentages of WFS were added. As a result, the combination C: M: WFS:: 80: 10: 10 may be considered the optimum combination for soil stabilization from clay-molasses-WFS mix.

Plasticity index was reduced from 10 % to 3 % when soft clayey soil was treated with molasses and lime, by keeping molasses content at 10 % and varying lime content (3, 6, 9, and 12 %). The points of the plasticity index curve in Fig. 5 deviate from the standard chart by shifting to the MI region below the A-line. The plasticity index of the composite decreased when 6 % lime was added to clayey soil with 10 % molasses, followed by a considerable increase in the value of the Ip the next percentages of lime, suggesting that the combination C: M: L:: 84:10:6 is the optimal combination for soil stabilization from clay-molasses-lime mix.

Plasticity index value was reduced from 14 % to 8 % when WFS and lime were added to clayey soil, with WFS held constant at 20 % and varying lime content. The points of the plasticity index curve in Fig. 5 deviate from the plasticity index chart by shifting to the MI region below the A-line. The plasticity index of the composite decreased with the addition of lime 6 % to clayey soil containing 20 % WFS, followed by a considerable improvement in the value of the plasticity index for the subsequent percentages of lime, suggesting that the combination C: WFS: L:: 74:20:6 may be considered the optimum combination for soil stabilization from clay-WFS-lime mix.

Adding molasses, WFS, and lime to clayey soil lowered the Ip value down to 2 %, by keeping 10 % molasses, 20 % WFS constant, and varying lime content. The points of the curve in Fig.5 of the plasticity index chart shift to the ML region, which is sufficiently below the A-line. The plasticity index of the composite decreased with the addition of 3 % lime to clayey soil containing 10 % molasses and 20 % WFS, followed by a considerable increase in the value of the Ip for the next percentages of lime, suggesting that the combination C: M: WFS: L:: 67: 10: 20: 3 may be the optimum combination for soil stabilization from clay-molasses-WFS-lime mix.

From the above performed tests it was concluded that the geotechnical characteristics of soft clayey soil were improved significantly with the following proportions:

- 10 % molasses in clay-molasses mix;
- 20 % WFS in clay-WFS mix;
- 9 % lime in clay-lime mix;
- 10 % molasses and 10 % WFS in clay-molasses-WFS mix;
- 10 % molasses and 6 % lime in clay-molasses-lime mix;
- 20 % WFS and 6 % lime in clay-WFS-lime mix;
- and 10 % molasses, 20 % WFS and 3 % lime in clay-molasses-WFS-mix.

Hence all these mentioned combinations, considered optimum combinations, were further subjected to permeability test and consolidated drained triaxial tests.

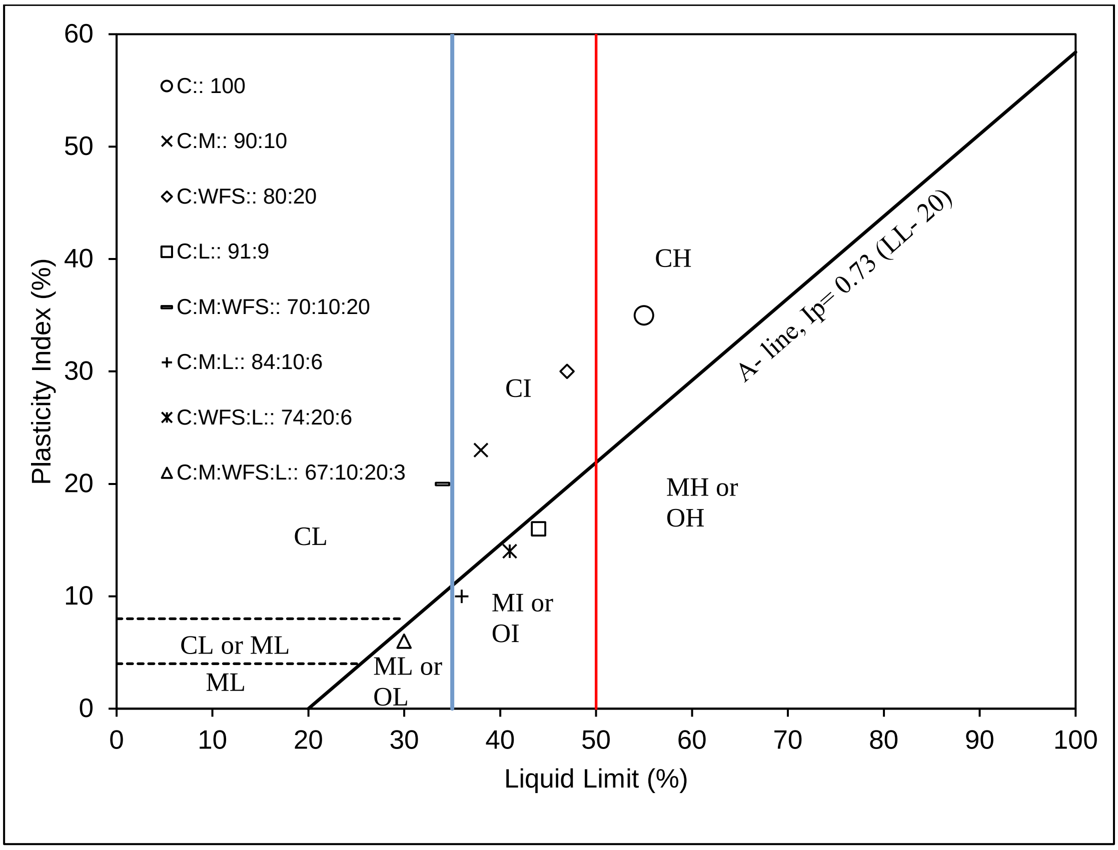

Figure 5. Plasticity index chart showing additives effect on classification of soft clayey soil.

3.3. Permeability tests

Permeability tests were conducted to assess the drainage characteristics of soft clayey soil alone and combined with optimum contents of molasses, WFS, and lime. The coefficient of permeability (k) of soft clayey soil was 3.4×10^{-8} cm/sec. On adding optimum percentage of molasses (10 %) individually the coefficient of permeability of soft clayey soil decreased and it increased with the addition of optimum percentages of WFS (20 %), and lime (9 %). Fig. 6 shows the coefficient of permeability values observed for soft clay and optimum combinations.

The addition of molasses to soft clayey soil caused an increase in the force of attraction between soil particles, which, in turn, reduced the amount of pore space between them resulting in a reduction of the soil permeability. The percentage of coarser particles in WFS was more than in clayey soil which may be the cause of the rise in permeability value of soft clayey soil after the addition of WFS. The pozzolanic interaction between lime and clay particles may be the cause of rise in permeability value observed after the addition of molasses and lime to clayey soil. Similar trend was observed in the past by some researchers [47, 48].

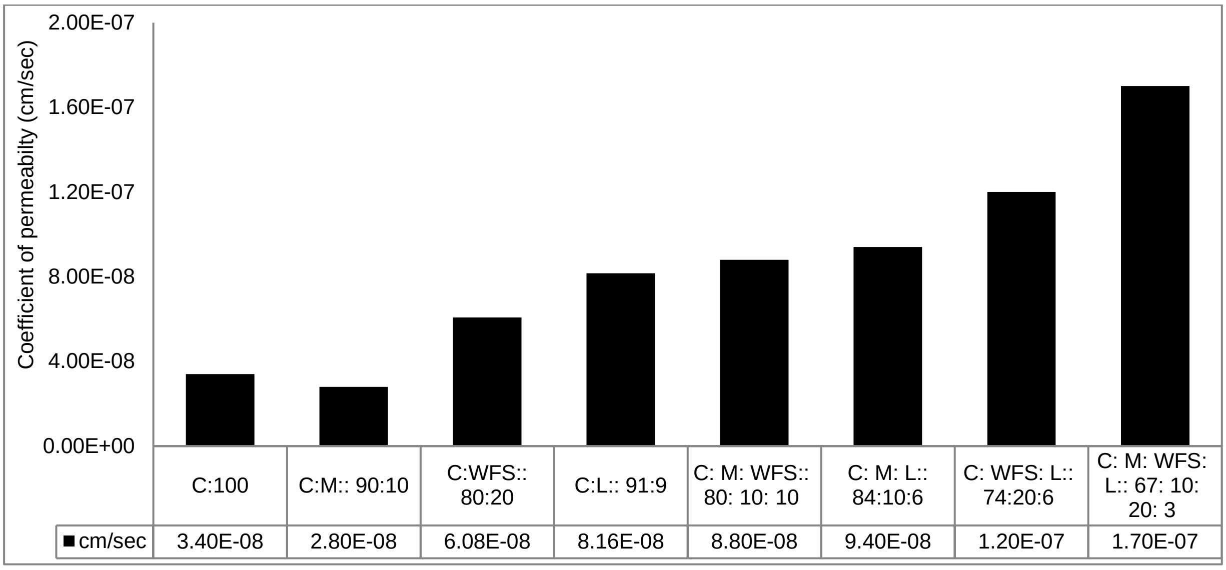

Figure 6. Permeability coefficient values of soft clay and optimum combinations.

3.4. Consolidated drained triaxial tests

3.4.1. Stress-strain curves from triaxial tests

Fig. 7–9 show typical stress–strain curves for soft clayey soil and optimum combinations of clayey soil blended with molasses, WFS, and lime at confining pressures of 49.03 kPa, 98.06 kPa, and 147.1 kPa, respectively. A significant increase in deviator stress was seen when clayey soil was stabilized using molasses, WFS, and lime, when compared to unstabilized clayey soil. With the addition of the optimum combination (C:M:WFS:L:: 67:9:20:3), the maximum deviator stress enhanced by 185 % for confining pressure of 49.03 kPa, 203 % for confining pressure of 98.06 kPa, and 179 % for confining pressure of 147.1 kPa. The deviator stress enhanced with increasing confining pressure for the samples stabilized with optimum percentages of additives (molasses, WFS, and lime), as shown in Fig. 10. The substantial impact of molasses, WFS, and lime as stabilizers occurred at high strain values, but at low strain (up to 2 %), the stabilization with these additives had no significant effect on the axial stress–strain behavior of the samples. Similar trend was observed in the past by some researchers [49–51].

3.4.2. Volumetric strain behavior

Fig. 11 shows volumetric strain curves on soft clayey soil stabilized with varied molasses, WFS, and lime concentrations for a confining pressure of 98.06 kPa. For moderate strains, the volumetric strain during shearing remained relatively constant and increased strain levels resulting in a higher volumetric strain reduction. The soft clayey soil showed the most significant reduction in volumetric strain. When the stabilization of soil was done using additives, decreased rate of volumetric strain was observed more for clay:molasses:WFS:lime mix followed by clay:WFS:lime mix, clay:molasses:lime mix, clay:molasses:WFS mix, clay:lime mix, clay:WFS mix, and clay:molasses mix. For soft clayeysoil, the rate of change in volumetric strain increased significantly up to strains of 10 %, after whichit decreased. The rate of change in volumetric strain was significantly lower for soil stabilized with molasses, WFS, and lime when compared to soft clayey soil.

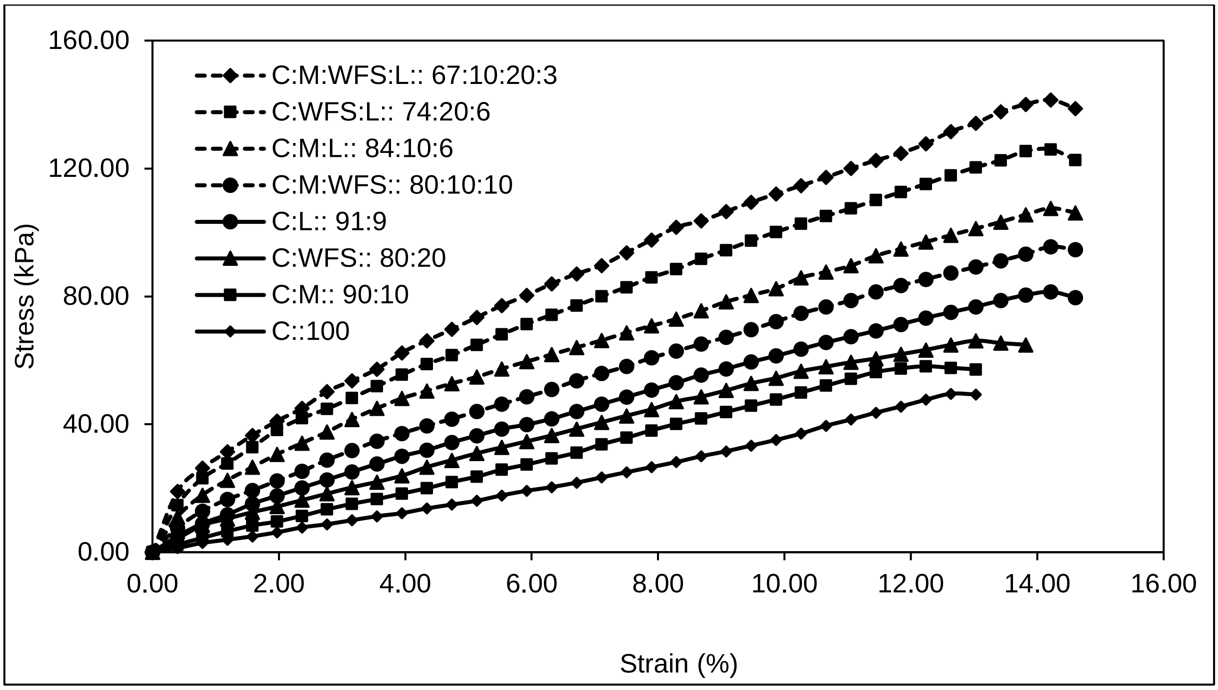

Figure 7. Deviator stress versus axial strain for soft clay and optimum combinations for confining pressure 49.03 kPa.

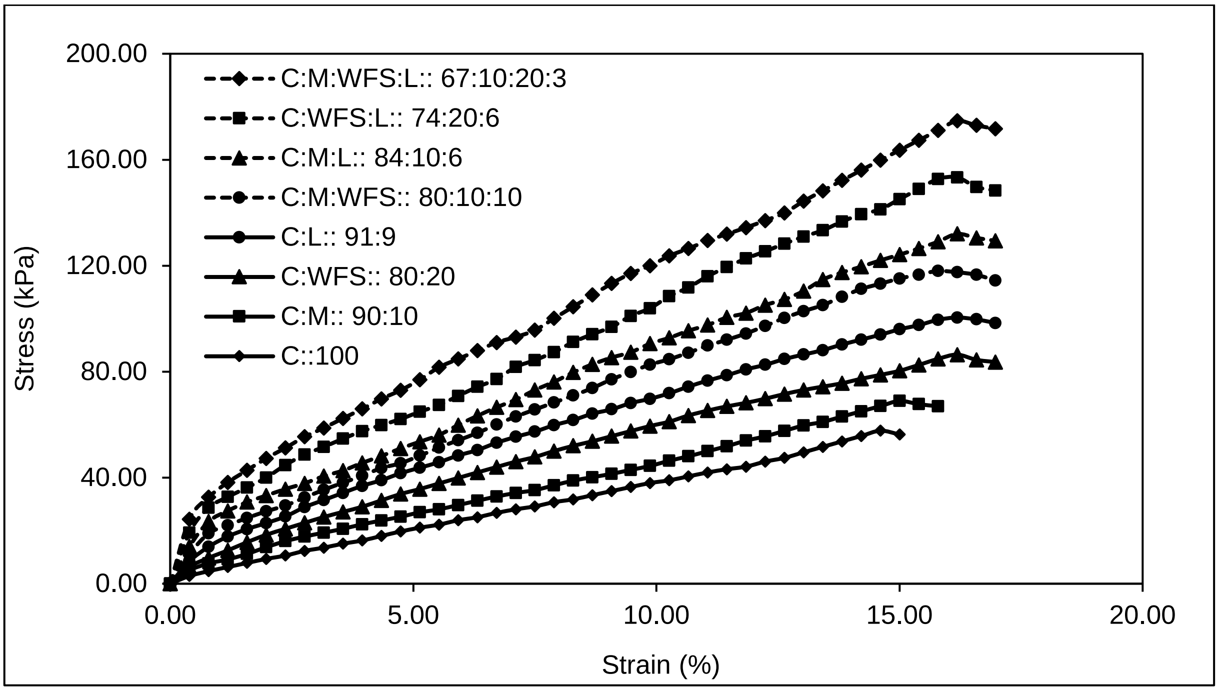

Figure 8. Deviator stress versus axial strain for soft clay and optimum combinations for confining pressure 98.06 kPa.

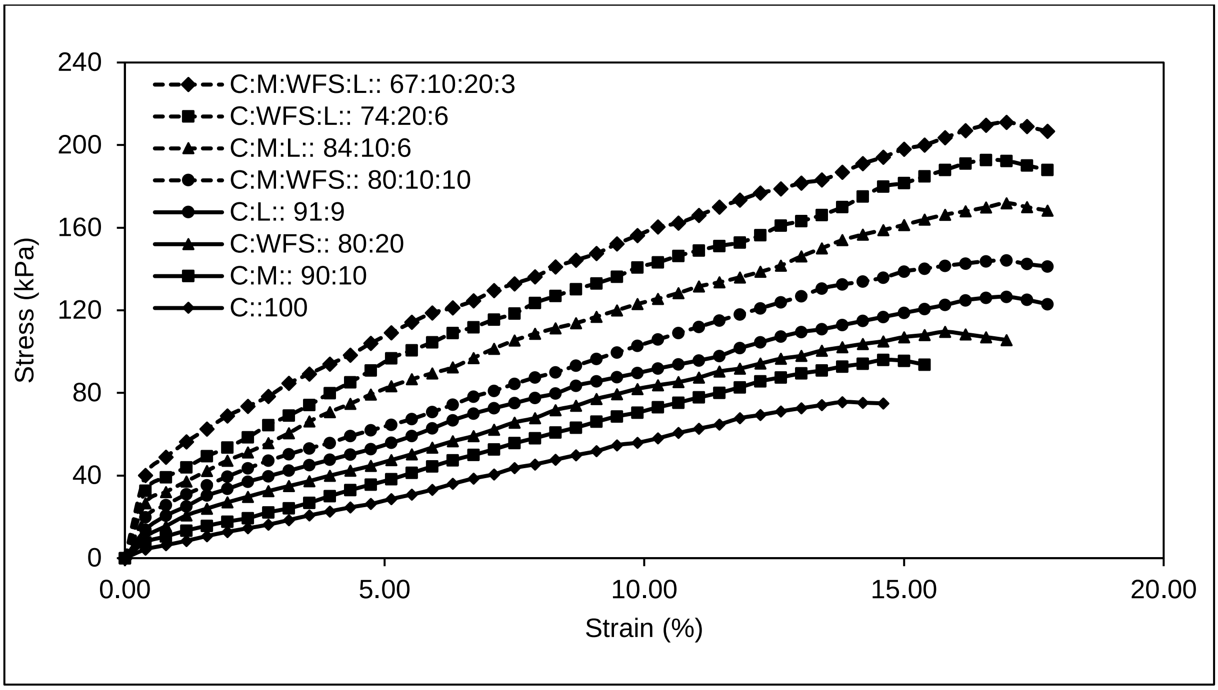

Figure 9. Deviator stress versus axial strain for soft clay and optimum combinations for confining pressure 147.1 kPa.

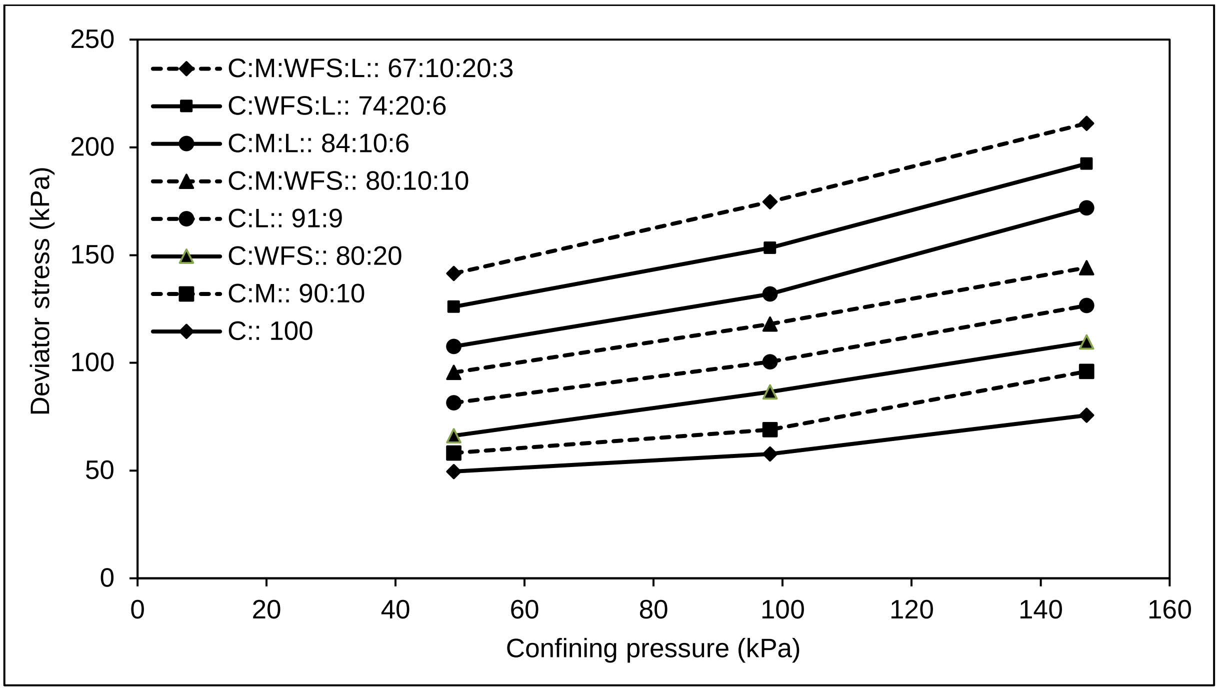

Figure 10. Deviator stress versus confining pressure for soft clay and optimum combinations.

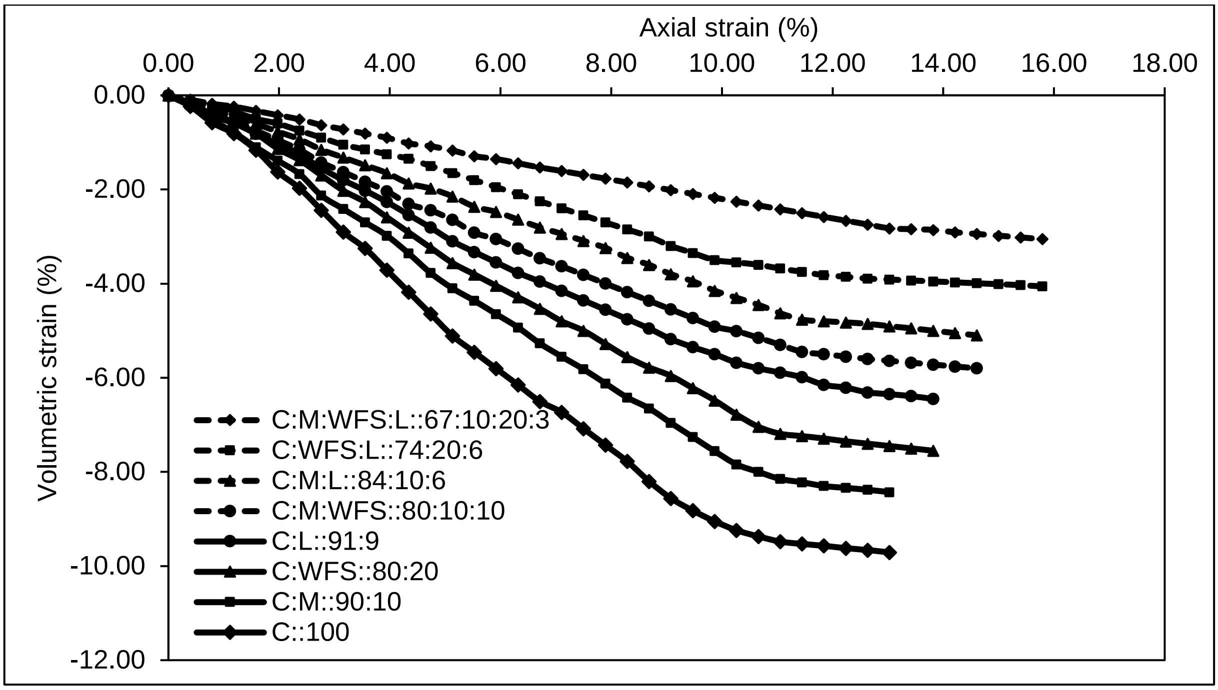

Figure 11. Volumetric strain-axial strain curves for soft clay and optimum combinations at confining pressure 96.06 kPa.

3.4.3. Effect of additives on deviator stress

Fig.12–14 illustrate the influence of altering optimum percentages of molasses, WFS, and lime in clayey soil for confining pressures of 49.03, 98.06, and 147.1 kPa for two axial strain values 6 % and 12 %. It was observed that the deviator stress of the optimum combinations was substantially higher when compared to the unstabilized soil.

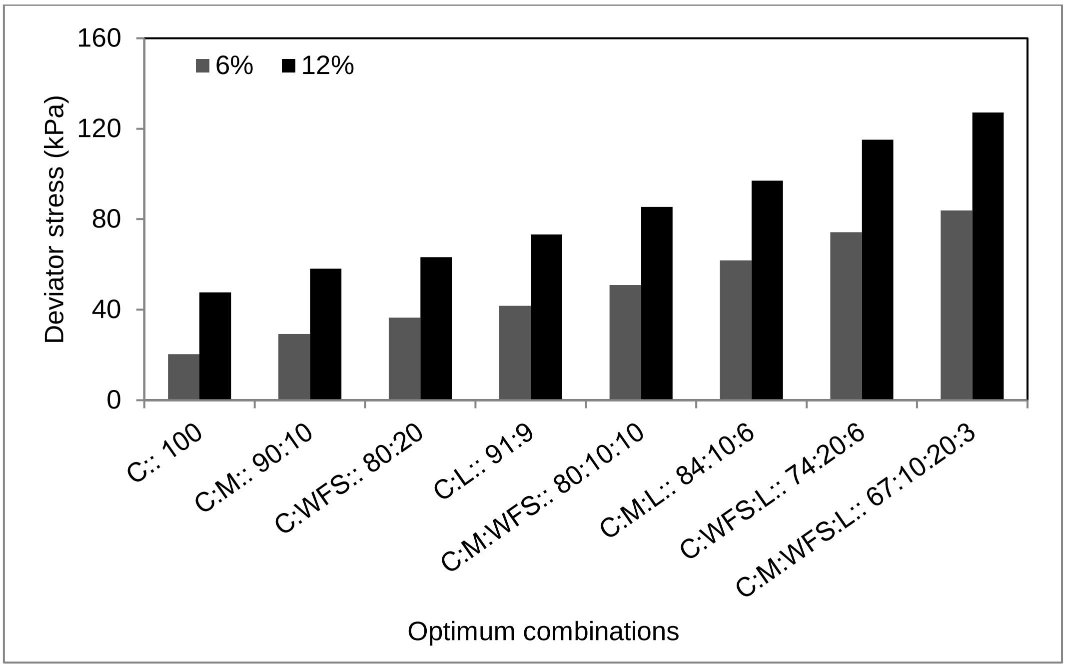

Figure 12. Maximum deviator stress for soft clay and optimum combinations of the composites (confining pressure 49.03 kPa).

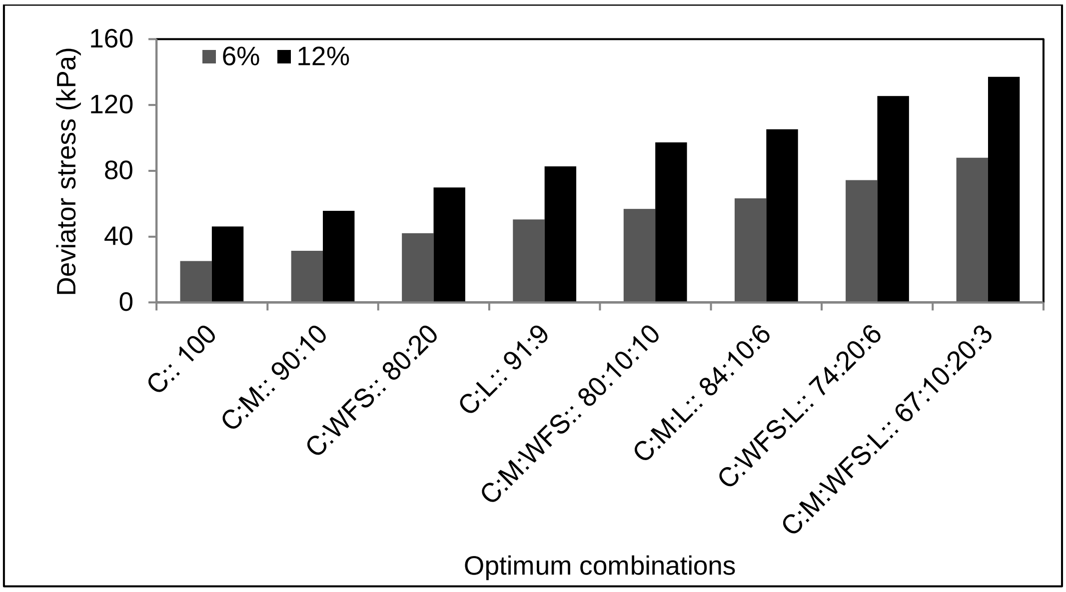

Figure 13. Maximum deviator stress for soft clay and optimum combinations of the composites (confining pressure 98.06 kPa).

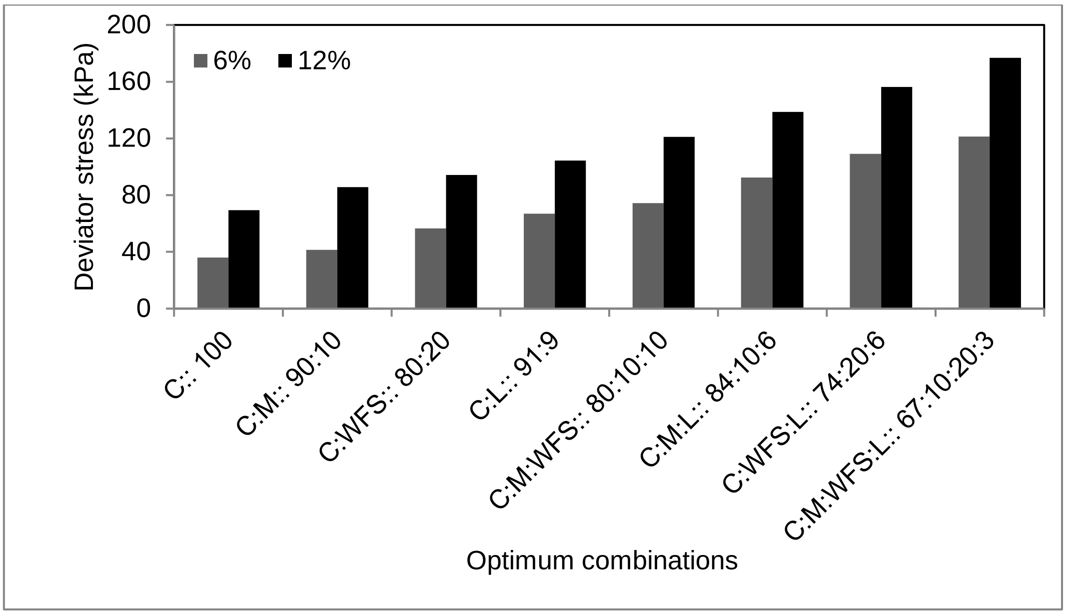

Figure 14. Maximum deviator stress for soft clay and optimum combinations of the composites (confining pressure 147.1kPa).

3.4.4. Shear strength parameters

The p-q diagram for unstabilized clayey soil and stabilized soil is shown in Fig. 15. The shear strength characteristics of clayey soil were shown to be significantly influenced by the addition of molasses, WFS, and lime.

As shown in Fig. 16, the friction angle increases as the percentage of additives in unstabilized clayey soil varied. The friction angle was greatly improved when molasses, WFS, and lime content blended with soft clayey soil. As the percentage of molasses, WFS, and lime increased, there was a fairly linear shift in the friction angle; hence, it ranged from 17° to 29.68°. The friction angle was around 14.86° for soft clayey soil. The friction angle value increased by 19.4 % on addition of 10 % molasses content, 35.5 % on addition of 20 % WFS content, 50.6 % on addition of 9 % lime content, 67.8 % for soil stabilized with 10 % molasses, and 10 % WFS content, 80.5 % for soil stabilized with 10 % molasses, and 6 % lime content, 98.02 % for soil stabilized with 20 % WFS, and 6 % lime content and 113.8 % for soil stabilized with 10 % molasses, 20% WFS, and 3 % lime content, when compared to un-stabilized soil.

Fig. 17 shows that stabilised soil cohesion value (range from 19.92 to 13.89 kPa) is lower than soft clayey soil cohesion value (about 21.771 kPa). The cohesion value decreased by 8.5 % on addition of 10 % molasses content, 12.36 % on addition of 20 % WFS content, 19.06 % on addition of 9 % lime content, 24.48 % for soil stabilized with 10 % molasses, and 10 % WFS content, 28.34 % for soil stabilized with 10 % molasses, and 6 % lime content, 32.11 % for soil stabilized with 20 % WFS, and 6 % lime content and 36.19 % for soil stabilized with 10 % molasses, 20 % WFS, and 3 % lime content, when compared to un-stabilized soil.

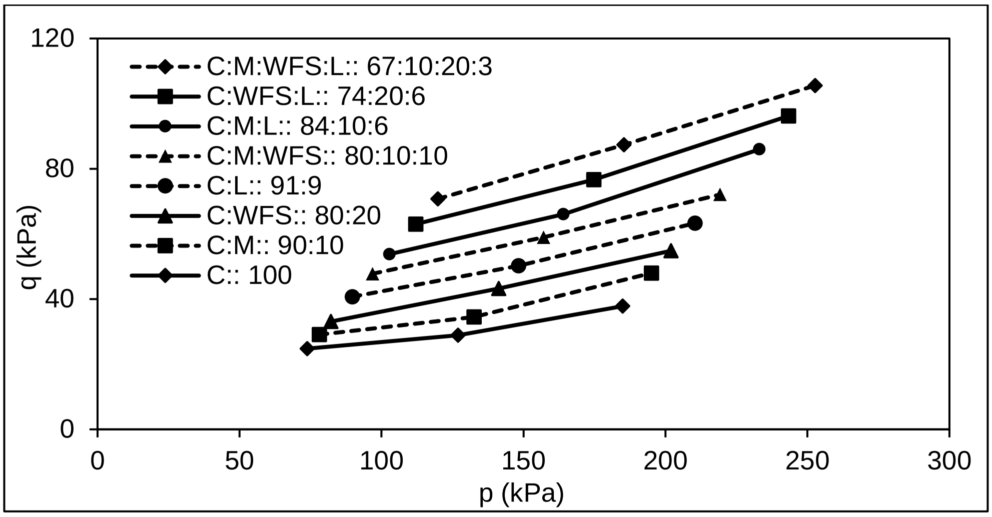

Figure 15.p-q diagram for the soft clay and optimum combinations.

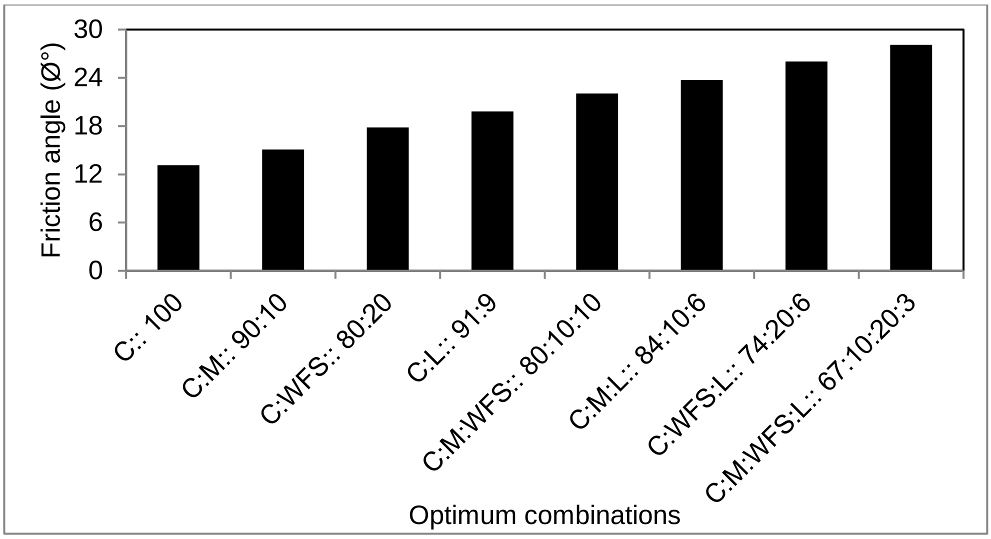

Figure 16. Effect of optimum content of molasses, WFS, and lime on friction angle of soft clayey soil (confining pressure 98.06 kPa).

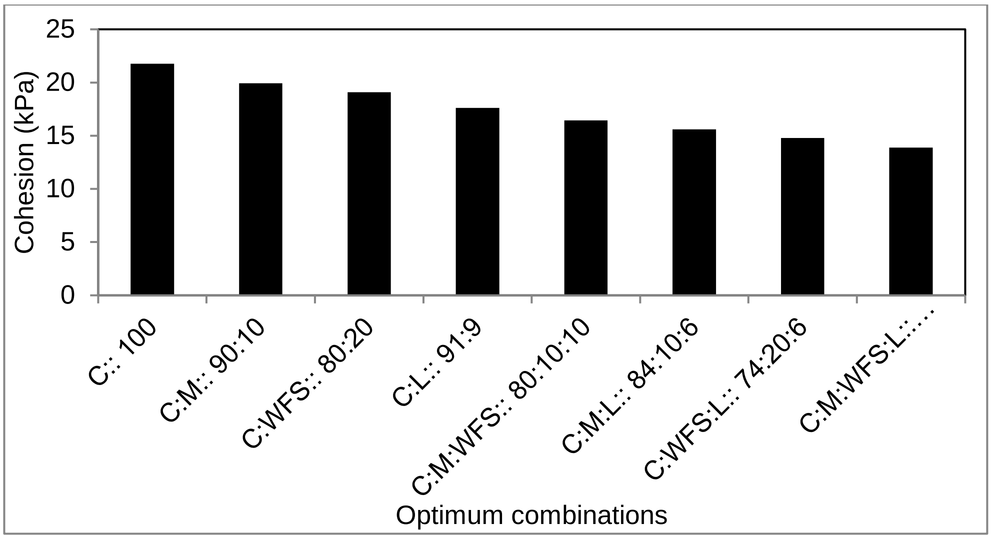

Figure 17. Effect of optimum content of molasses, WFS, and lime on cohesion value of soft clayey soil (confining pressure 98.06 kPa).

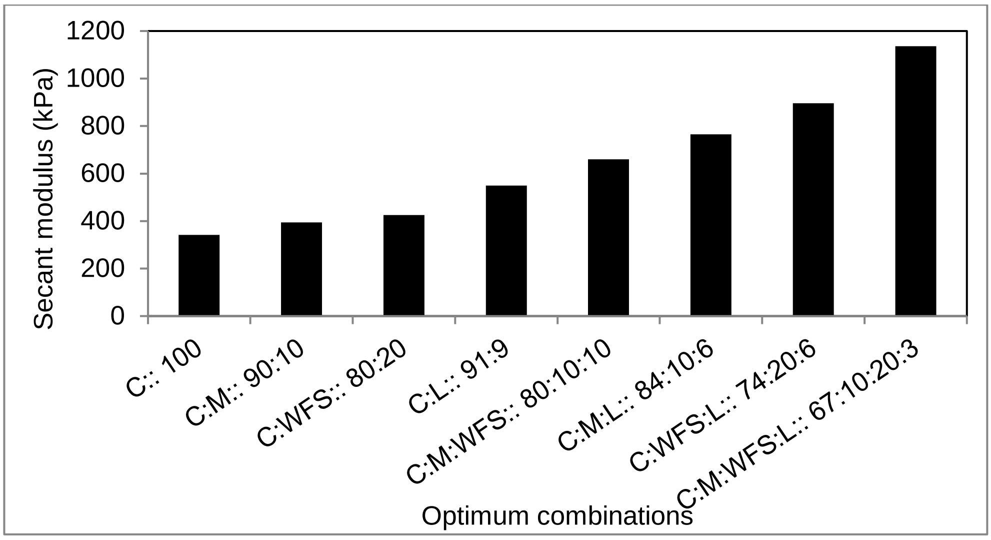

Figure 18. Secant modulus versus soft clayey soil and optimum combinations of the composites (confining pressure 49.03 kPa).

3.4.5 Effect of stiffness

For a confining pressure of 49.03 kPa, Fig. 18 depicts the difference between the secant modulus of soft clayey soil and stabilized clayey soil with the optimum content of molasses, WFS, and lime at lower strain levels (3 %). Initially, for clay-molasses and clay-WFS mixes, the rate increment in secant modulus was low; for clay:lime mix, clay:molasses:WFS mix, clay:molasses:lime mix, and clay:WFS:lime mix, the rate of increment in secant modulus value was somewhat higher; but for clay:molasses:WFS:lime mix, the secant modulus increased abruptly. The percentage increase in stabilized soil was 15.5 % for clay:molasses mix; 24.3 % for clay-WFS mix; 60.8 % for clay:lime mix; 93 % for clay:molasses:WFSmix; 123.7 % for clay:molasses:lime mix ;162 % for clay:WFS:lime mix; and 232 % for clay:molasses:WFS:lime mix soil. For red clayey deposits, [52] found that as confining pressure and saturation increased, the stiffness value also improved.

3.5. Microstructure

The addition of optimum proportions of additives was studied for their effects on the clayey soil structure using the scanning electron microscope (SEM) approach. Plate-like structures and numerous cavities can be seen in the SEM picture of the clayey soil (Fig.19). When the proper amount of molasses (about 10 percent) was mixed with clayey soil, a jelly-like structure formed (Fig. 20) and the gaps in the soil were filled, leading to an increase in the composite's strength. When clayey soil was mixed with the optimum percentage of waste foundry sand, a compact structure was created (Fig. 21), which helped in boosting the composite's strength. By adding lime to the clayey soil at the optimum content of 9 %, the void ratio was reduced because the finer particles of lime helped to fill the gaps, creating a denser and thread-like structure (Fig. 22), which in turn increased the strength of the composite.

Fig. 23 is a SEM image of a composite consisting of clay, molasses, and WFS, showing that the voids present in the composite were reduced and a compact structure was formed. When compared to clay-molasses or clay-lime composites, the SEM image of the clay-molasses-lime composite (Fig. 24) shows a more uniform and compact structure. Fig. 25 displays the result of combining WFS with lime, which is a denser structure than both clay-WFS or clay-lime composites alone. In Fig. 26, a thick micro-structure was observed that was formed when clay blended with molasses, WFS, and lime. Hence it can be concluded that by combining the right proportions of molasses, WFS, and lime with clay, a composite with increased strength and a more compact structure is produced, which in turn enhances the geotechnical properties of clay.

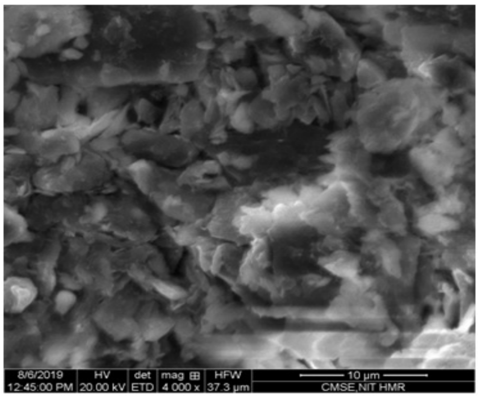

Figure 19. SEM image of clay.

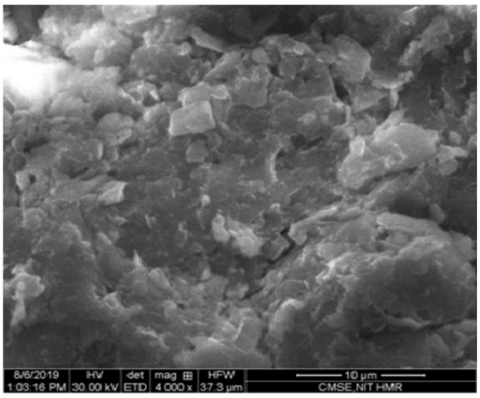

Figure 20.SEM of clay-molasses.

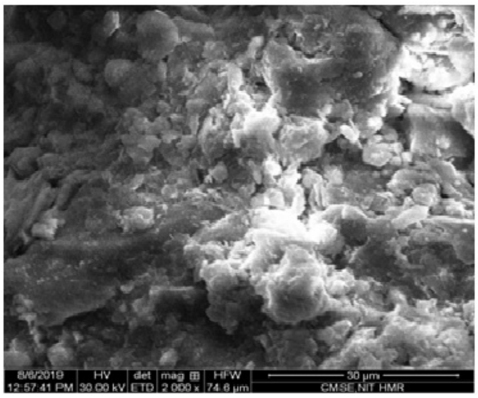

Figure 21.SEM of clay-WFS.

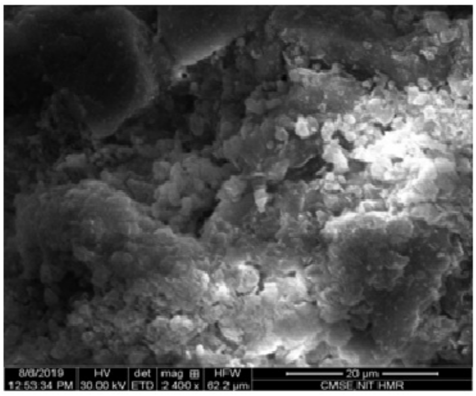

Figure 22. SEM of clay-lime.

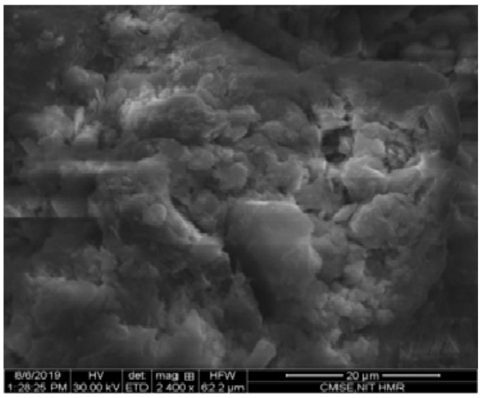

Figure 23. SEM of clay-molasses-WFS

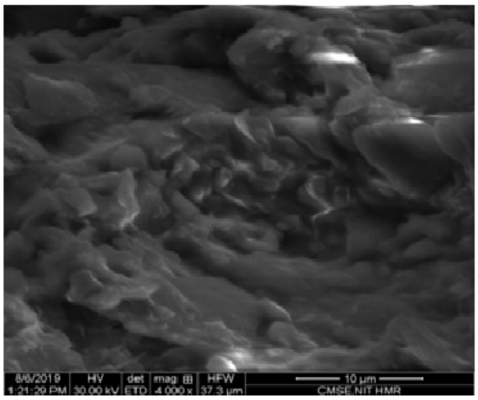

Figure 24. SEM of clay-molasses-lime.

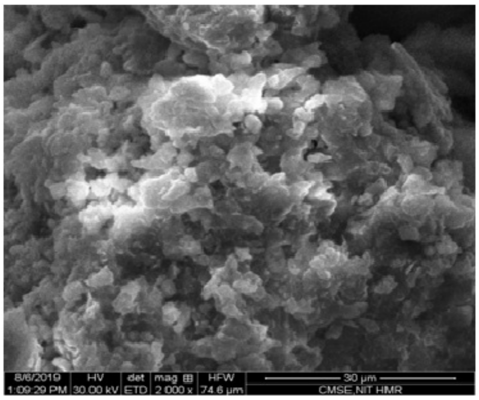

Figure 25. SEM of clay-WFS-lime.

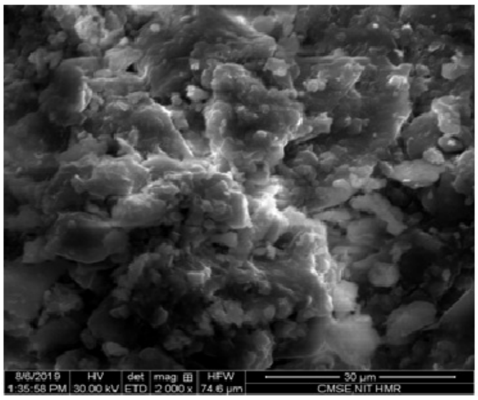

Figure 26. SEM of clay-molasses-WFS-lime.

4. Conclusion

Atterberg limits tests and pH tests on soft clayey soil and stabilized clayey soil were conducted to study about the behavior of soft clayey soil. The engineering characteristics of both soft clayey soil and optimum combinations were studied using permeability and consolidated drained triaxial tests. The following conclusions were drawn from this study:

1. The pH of soft clayey soil decreased with the addition of molasses and WFS and reached neutral value at 10 % molasses and 20 % WFS. The alkaline nature of lime caused a rise in pH of soft clayey soil with its addition and reached a maximum of 12.2 pH with 9 % lime.

2. The addition of molasses, WFS, and lime separately and in combination to each other decreased the plasticity index value of the soft clayey soil. For clay-molasses-WFS mix 10 % WFS, for clay-molasses-lime mix 6 % lime, for clay-WFS-lime mix 6 % lime and for clay-molasses-WFS-lime mix 3 % lime was found to be satisfactory to improve the workability of the clayey soil.

3. The considerable improvements in the deviator stress of soft clayey soil are obtained by 9 % lime, followed by 20 % WFS and 10 % molasses. Furthermore, among the optimum combinations, the clay-molasses-WFS-lime mix showed the most significant improvements in the deviator stress of soft clayey soil, followed by the clay-WFS-lime mix, the clay-molasses-lime mix, and the clay-molasses-WFS mix.

4. Scanning electron microscope (SEM) results showed that addition of molasses and WFS filled the voids between the soft clayey soil particles rendering a compact composite thus improving the strength characteristics. A combination of all the three additives in optimum proportion produced a composite possessing higher strength and dense structure, the geotechnical characteristics of clayey soil were improved making it suitable as a foundation material.

Based on the findings of this study, it is evident that clayey soil can be adequately stabilized for use as a foundation material. The significance of the results is that in contrast to other lime stabilization cases where larger amounts of lime (and invariably higher construction costs) were involved, the findings show that smaller amounts of lime (and thus lower construction costs) used in this study can provide a stronger foundation material. Optimum stabilization of clayey soil was achieved with 10 % molasses, 20 % WFS, and only 3 % lime.

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