Mollisols Soils Stabilization Using Lime Modified by Salts

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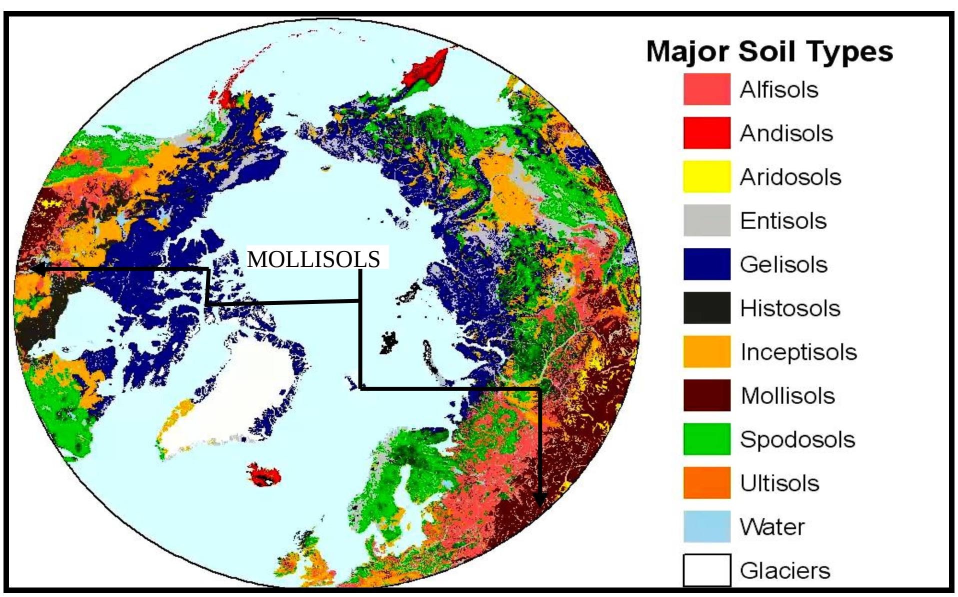
Abstract

Mollisols are one of the most abundantly found natural surface soils in the world. Due to presence of high organic content in these soils, its geotechnical engineering characteristics like bearing capacity, settlement, and slope stability etc. are feeble. In this research, an attempt was made to propose the best methodology of chemical stabilization of mollisols to extend its applications in geotechnical engineering. Mollisols showed high organic content and their characteristics was obtained using X-Ray diffraction (XRD) test. The test indicated the presence of clay minerals (montmorillonite and kaolinite), organic matters (magnesium diisopropoxide, 9H-Flourine etc.) and organic acids (tartaric acid, formylvanillic acid etc.) in mollisols. The geotechnical engineering properties of mollisols including grain size analysis, Atterberg limits, maximum dry density, optimum moisture content and unconfined compressive strength were determined. Mollisols samples were stabilized with lime and varying percentages (up to 10 %) of three chloride salts i.e sodium chloride (NaCl), potassium chloride (KCl) and calcium chloride ($CaCl_2$). The engineering classification of mixes remains unchanged by the addition of lime and salts. The results showed that when clay minerals were released from the affinity of organic matter and acids by addition of chloride salts, its reactivity with lime was enhanced resulting in improved stabilization. NaCl was observed to be the most promising chloride salt for effective stabilization of mollisols with lime.

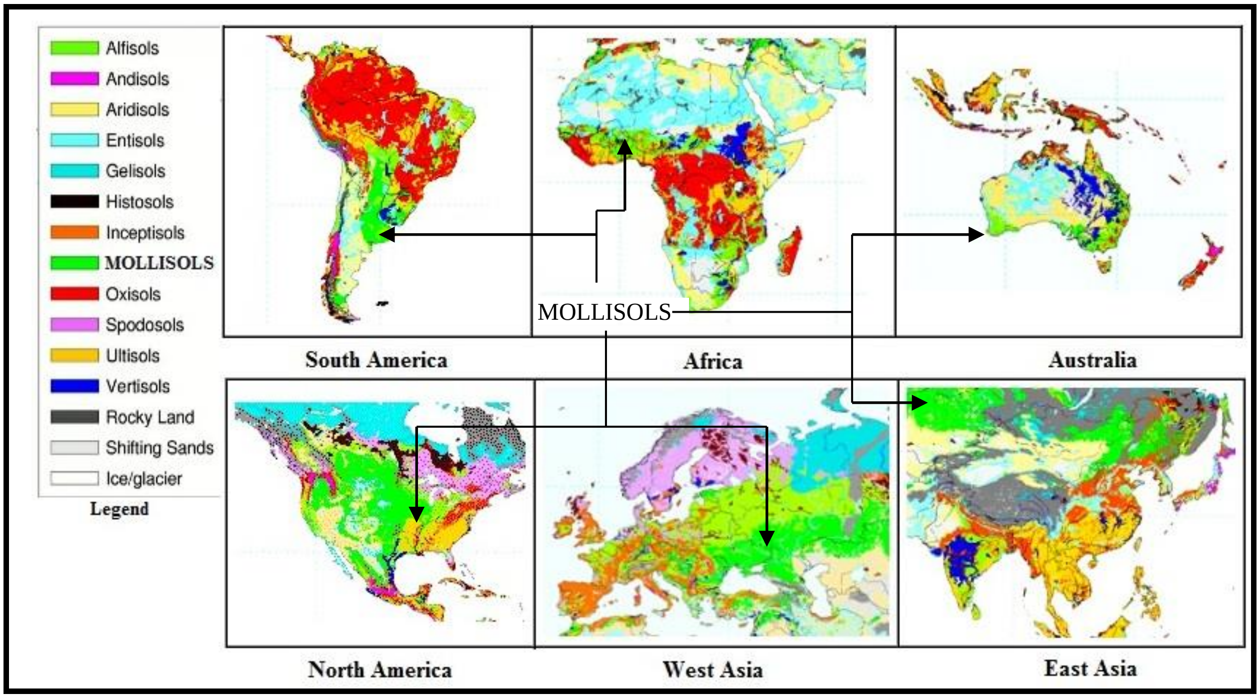
Key Words: Mollisols, soils, geotechnical engineering, lime, chloride salts, stabilization

1. Introduction

Mollisols are naturally available soils in globe with high organic contents over 2 % [1]. The high organic contents in these soils are due to biodegrading of vegetation, grass or roots. Figures-1(a), (b), (c) show the global, continental and in Pakistan presence of mollisols.



(a)



(b)

(c)

Fig. 1 Molisols existence in world (a) Global distribution (Courtesy US Department of Agriculture) (b) Continent wise presence (Courtesy US Department of Agriculture) (c) Mollisols in Pakistan (Courtesy Soil Survey of Pakistan)

Generically, mollisols are weak in its geotechnical engineering characteristics (settlement and bearing capacity). Therefore, from geotechnical point of view their use as foundation or subgrade material is not recommended unless stabilized. Various researchers [2, 3, 4, 5]in past have proved that effective stabilization of mollisols using different admixtures (lime, cement, bitumen, flyash etc) is not successful due to coating of organic acids on clay particles (montmorillonite, illite and kaolinite) as shown in Figure 2.

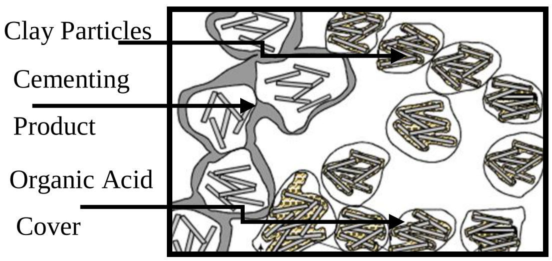


Fig. 2 Clay particles with organic acid cover

Lime was used effectively in the past by different researchers to stabilize clayey mollisols due to its cost effectiveness and ease of operation. Lime improved affinity with clay minerals than other commonly used admixtures for stabilization [6, 7, 8]. Recent research proved that chloride salts have strong potential to coagulate with cations present in organic acids to expose the clay particles [9]. If clay particles were exposed from the cover of organic acid than the probability of its reaction with lime increased which lead to a better stabilization of mollisols as shown in Figure 3.

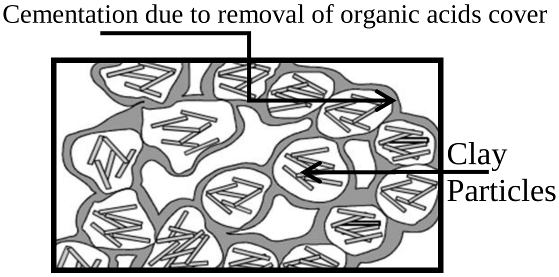


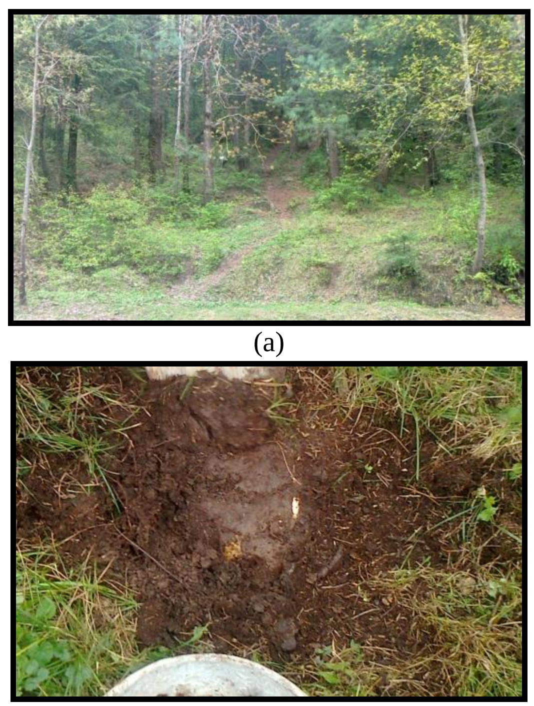
Fig. 3 Concept of Zhu et al. [9]

Suitability of most appropriate salt for stabilization of mollisols (diluting the organic acid cover) of Pakistan with lime for its use in geotechnical engineering works was desired. An attempt was made in this research to study the behavior of mollisols and lime mixes by introducing different chloride salts in it. The geotechnical properties like classification, compaction and unconfined compressive strength of different mixes were desired to be evaluated.

The main objective of this research was to investigate the effect of various percentages of salts with lime on engineering classification, compaction characteristics and strength of mollisols available in Pakistan to extend its application in geotechnical engineering.

2. Test Materials & Methods:

The mollisols presence in Pakistan was confirmed through an extensive literature survey from the database of departments like Agriculture Department, Geological Survey of Pakistan, Soil Survey of Pakistan etc. Mollisols were found in the northern areas of Pakistan especially in the surroundings of Murree district. Shallow test pits up to the depth of 2 m were dugout at Phagwari, Ghora Gali and Angoori town of Murree district for collection of representative samples of mollisols as shown in Figure 4. The representative mollisols samples were collected from said sites and transported for evaluation of its properties at Geotechnical Engineering Laboratory, Department of Civil Engineering, University of Engineering and Technology, Lahore.



(a)

(b)

Fig. 4 Sampling locations of mollisols from Murree district (a) Broader view (b) Closer view

The organic matter content of mollisols was determined through loss on ignition (LOI) test Method A [10] using relation given in Eq. 1:

LOI = [(Oven – Dry soil weight – ash weight)/(oven – dry soil weight)] x 100 (1)

To evaluate the solubility of minerals and mobility of hydronium ions in the mollisols, pH test was performed using pH meter and silver chloride electrode system [11]. The mineralogy and organic content composition in mollisols were evaluated by x-ray radiography (XRD) test [12]and XPERT-PRO software.

Representative mollisols samples were subjected to sieve analysis [13], hydrometer analysis and Atterberg Limits [14] for determination for its respective engineering classification by unified [15]and American Association of State Highway and Transportation Officials (AASHTO) systems. The compaction and strength characteristics of mollisols were determined by performing modified proctor compaction [16] and unconfined compression tests [17].

Review of extensive literature regarding selection of possible salts that can help in enhancement of lime affinity for stabilization of mollisols was conducted. Three chloride salts were selected and their chemical composition was evaluated.

Determination of geotechnical properties of mollisols samples mixed with different combination of lime and saltsby tests like Atterberg Limits, modified proctor compaction and unconfined compression were carried out. The samples for unconfined compressive strength were remolded in laboratory at maximum dry density and optimum moisture content obtained from the modified laboratory compaction test. Unconfined compressive strength of mixes was evaluated up to 28 days of curing time. Evaluation of the effect of lime and salts combinations on the engineering classification, compaction and unconfined compressive strength of mollisols was made. Selection of the salts possible optimal combination with lime for the best stabilization of mollisols was proposed. Determination of California bearing ratio (CBR) in soaked and unsoaked condition for optimal combination of mollisols, lime and salt was determined [18].

3. Results and Discussion

The organic content found by loss on ignition tests performed on mollisols samples was 8 %. Soils having over 2 % organic matter are rated as high organic mollisols [19]. Hence, high organic content of mollisols is confirmed. The mollisols exhibited hydronium ion concentration (pH) of 7.6, which reflected slight alkalinity [11].

To cover the variations in angle of exit with respect to incoming x-ray beam 2Theta position was employed during XRD test. The XRD test results (Figure 5) reveal the presence of montmorillonite and kaolinite as clay minerals. Illite as clay mineral was not observed in the samples. Magnesium diisopropoxide, 9H-Flourine, 3-(p-Toluenesulfonyl)-4-cyano-5-methylthioisothiazole etc. are the major identified constituents of the organic matter of mollisols. The results of XRD test show the various organic acids present in the mollisols soil like tartaric acid, formylvanillic acid, phenylenediacetic acid, dimethylacrylic acid, pentyloxybenzoic acid, glycolic acid, mesaconic acid, picolinic acid along with other compounds of benzene. The complex mixture of different acids containing humic, carboxyl and phenolate groups behaves functionally as dibasic acid and occasionally as tribasic acid.

The typical grain size distribution curve of the mollisols is shown in Figure 6. Grain size distribution represents that mollisols sample comprised of small fractions of medium coarse sand with 10 % fine sand, 54 % silt and 34 % clay contents. Mollisols sample showed plasticity index of 17 % with 49 % and 32 % as representative liquid and plastic limits values. Based on the results of grain size distribution and Atterberg limits the mollisols are classified as organic silty clay of low plasticity (OL) according to Unified soil classification system and A-7 as per AASHTO soil classification system. The maximum dry density of mollisols was obtained as 16.6 kN/m^3 with optimum moisture content of 14.6 %. The unconfined compressive strength of mollisols remolded at maximum dry density and optimum moisture content was found 280 kPa.

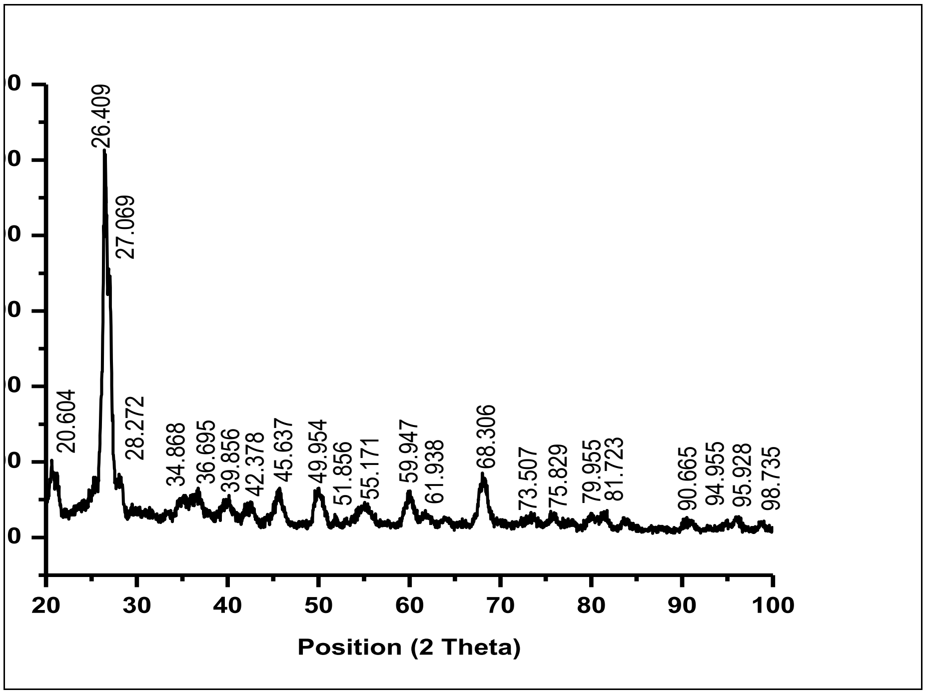


Fig. 5 XRD trend observed during testing of mollisols

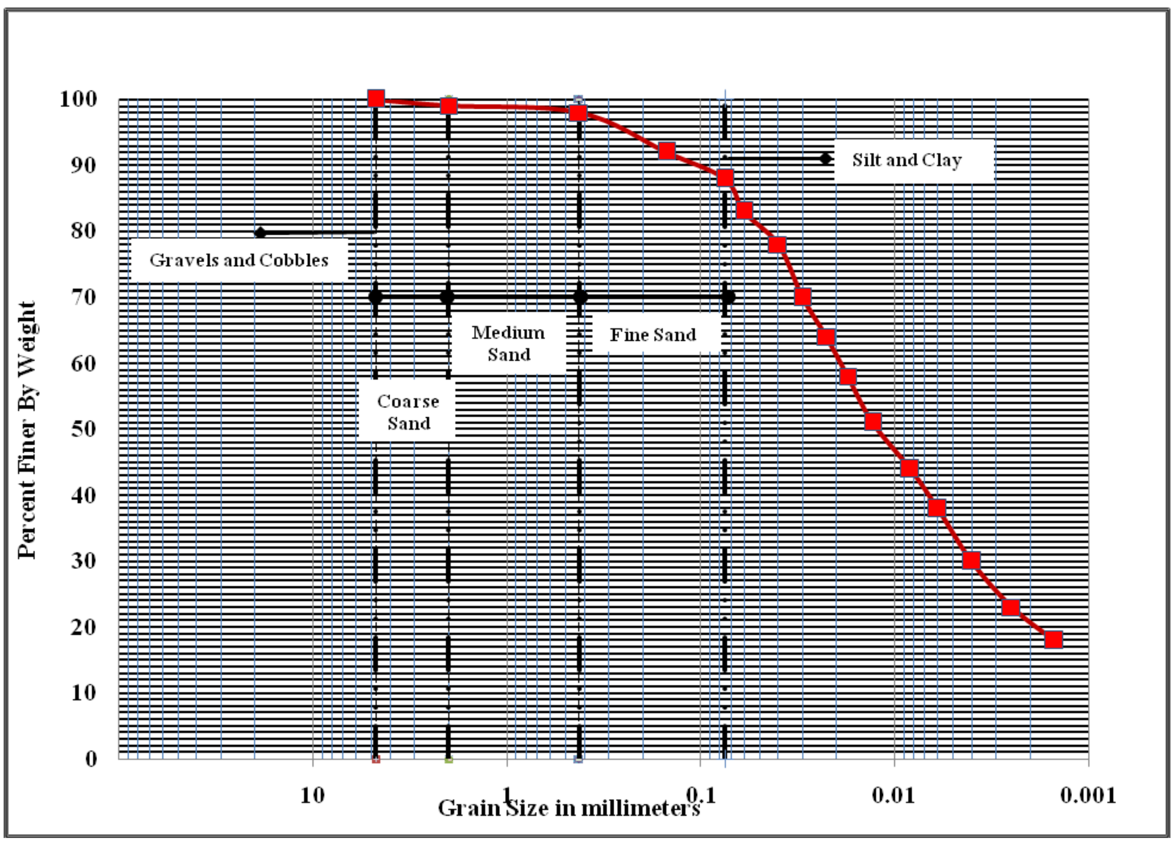


Fig. 6 Typical grain size distribution curve of mollisols

OL / A-7 soils are rated as poor subgrade material in terms of capacity and settlement behavior [1]. Lime is one of the most suitable stabilizer agents for silty clay soils[19]. Slaked lime was selected as main stabilizer of silty clay used in this research as cement can cause water and soil pollutions by leaching of organic matter [6]. Further, lime is more sensitive to organic contents than cement. The slaked lime having over 95 % calcium hydrxoide [$Ca(OH)_2$] content was used in the research [20]. During mixing of lime with mollisols, the percentage of lime was kept 10 % of the total weight of mollisols [21].

Table 1: Chemical composition of salts

Properties	Salts Name		
	Halite	**Ionic halide**	**Metal halide**
Molecular formula	NaCl	$CaCl_2$	KCl
Molecular weight (g/mol)	58.44	147.01	74.55
Boiling point (°C at 1013 hPa)	1413	1600	1420
Melting point (°C)	801	772	773
Density (g/cm³ at 20°C)	2.16	1.85	1.98
Assay (%)	99.5	99 – 105.0	99.5
Acidity or alkalinity (meq/g)	0.0005	-	0.0005
pH (5 % at 20°C)	5.0 to 8.0	4.5 – 8.5	5.0 to 8.0
Heavy metals as lead (Pb) (ppm)	2	5	5
Hexacyanoferrates (ppm)	1	-	-
Insolubility in water (ppm)	50	-	100
Loss on drying (%)	0.5	-	-
Insoluble matter (%)	0.01	-	-
Oxidizing substances (%)	0.003	-	-
Nitrogen (N) (ppm)	5	-	20
Bromide (Br) (ppm)	50	0.05	0.05
Iodide (I) (ppm)	10	20	20
Sulphate (SO_4) (ppm)	40	0.01	50
Phosphate (PO_4) (ppm)	5	-	5
Barium (Ba) (ppm)	10	0.005	10
Arsenic (As) (ppm)	0.4	-	0.5
Copper (Cu) (ppm)	2	-	2
Calcium (Ca) (ppm)	20	-	10
Potassium (K) (ppm)	50	0.01	-
Iron (Fe) (ppm)	1	0.001	2
Nickel (Ni) (ppm)	10	-	-
Sodium (Na) (ppm)	0.02	-	-
Ammonium (NH_4) (ppm)	0.005	-	-
Magnesium (Mg) (ppm)	0.005	-	20
Strontium (Sr) (ppm)	0.1	-	-

The organic matters present in mollisols reduce the chemical affinity of lime during stabilization process [6]. The adverse effect of organic matter during stabilization with lime can be mitigated by increasing the concentration of chloride salts in mixes [8]. Three chloride saltsi.e. sodium chloride (NaCl), calcium chloride ($CaCl_2$) and potassium chloride (KCl) were selecteddue to their in abundance availability around the globe. Table 1 summarizes the composition and properties of these salts.Among the three salts, $CaCl_2$ exhibits maximum molecular weight and also showed utmost boiling point. The melting points, assays and pH of all salts were found in close proximity. NaCl was observed more water soluble than other salts. An only very small trace of insoluble matter and oxidizing substances was observed in NaCl in comparison with other salts. Nickel and magnesium were the only noticeable elements observed in NaCl and KCl respectively.

The testing matrix of mollisols and lime mixed with chloride salts evaluated during the research are summarized in Table 2. The percentages of chloride salts were kept as 2.5, 5 and 10 % of the total weight of mollisols lime mix[8].

Table 2: Testing matrix with nomenclature

Sr.	Samples	Atterberg Limits (ASTM D-4318)	Modified Proctor Test (ASTM D-698)	Unconfined Compression Test (ASTM D-2166). Curing time (days)		
				0	**7**	**14**
S1	Untreated Mollisols	X	X	X	X	X
S2	Mollisols + 5% Lime	X	X	X	X	X
S3	Mollisols + 10% Lime	X	X	X	X	X
S4	Mollisols + 10% lime + 2.5% $CaCl_2$	X	X	X	X	X
S5	Mollisols + 10% lime + 5% $CaCl_2$	X	X	X	X	X
S6	Mollisols + 10% lime + 10% $CaCl_2$	X	X	X	X	X
S7	Mollisols + 10% lime + 2.5% NaCl	X	X	X	X	X
S8	Mollisols + 10% lime + 5% NaCl	X	X	X	X	X
S9	Mollisols + 10% lime + 10% NaCl	X	X	X	X	X
S10	Mollisols + 10% lime + 2.5% KCl	X	X	X	X	X
S11	Mollisols + 10% lime + 5% KCl	X	X	X	X	X
S12	Mollisols + 10% lime + 10% KCl	X	X	X	X	X

The results of Atterberg limits of different mixes tabulated above are shown in Figure 7. It is eminent from Figure 7 that slightreduction in the liquid limit (49 to 41 %) and plastic limits (32 to 27 %)values of the mixes was observed by the addition of all salts in 2.5 to 10 %. The engineering classification of the mollisols remains unchanged after addition of lime and salts. Previous researches also showed that by addition of salts in mollisols the Atterberg limits show insignificant variations [22].

The results of modified proctor compaction tests performed on different mixes listed in Table 2 are shown in Figure 8. By the addition of 5 and 10 % lime in mollisols, the optimum moisture content (OMC) of the mixes showed slight increase while maximum dry density (γ_d) showed slight decrease with reference to OMC and γ_d of untreated mollisol. Considering S3 mix as standard, by the addition of different salts (NaCl, KCl and $CaCl_2$) both the γ_d and OMC of mixes slightly increased. By the addition of only lime in mollisols the compacteddry density of mix slightly decreased. However, by the addition of different salts with lime in mollisols the compacted dry density of mixes slightly improved. Similar results regarding variation in density were also reported in literature [19, 22, 23]. It is worth mentioning that chemical reaction (curing and rate of hydration dependent) of lime with mollisols was not achieved during compaction tests. Therefore, the worth of the compaction test in the study is only for the determination of typical range of maximum dry density and optimum moisture content for remolding.

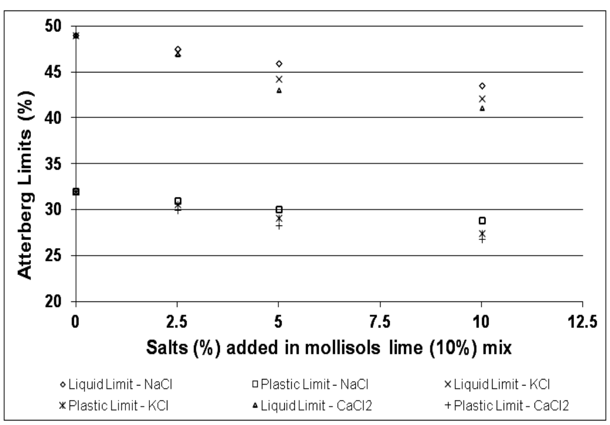


Fig. 7 Variation in Atterberg limits of mollisosls lime mix by addition of salts

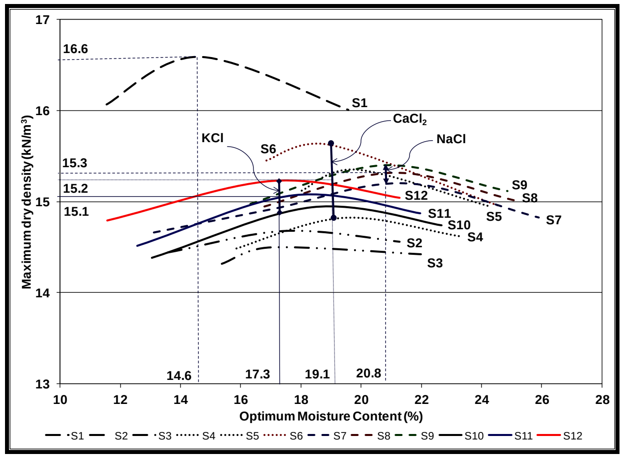
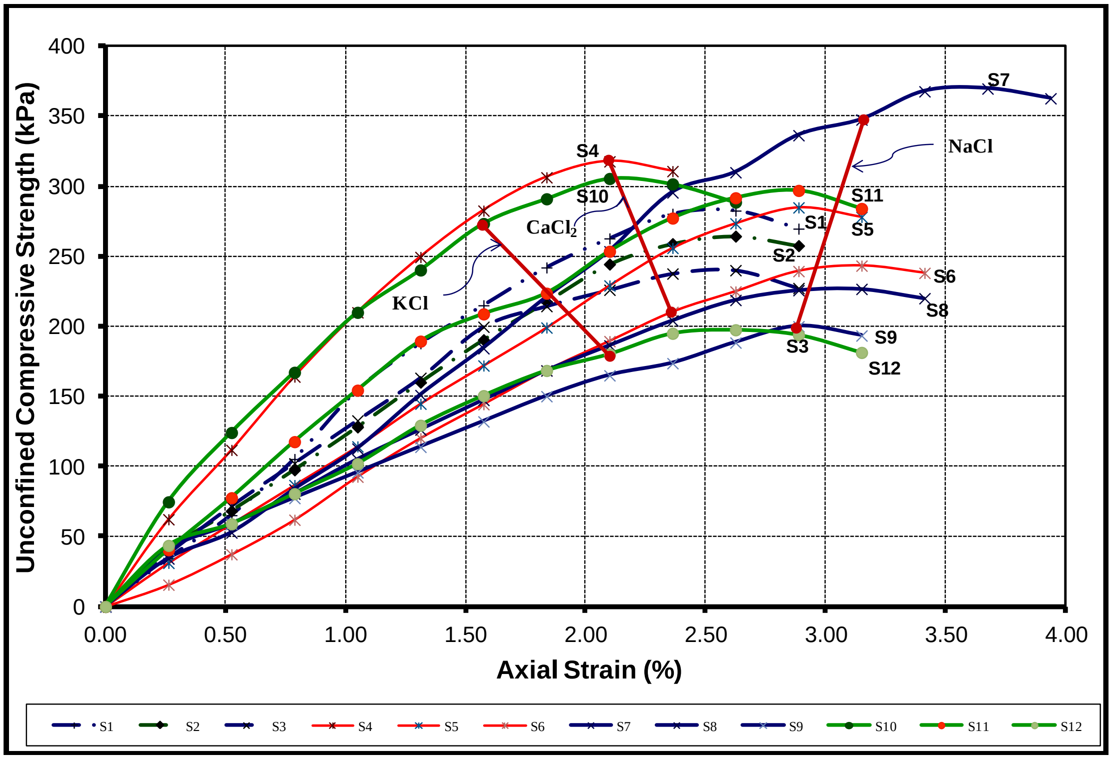


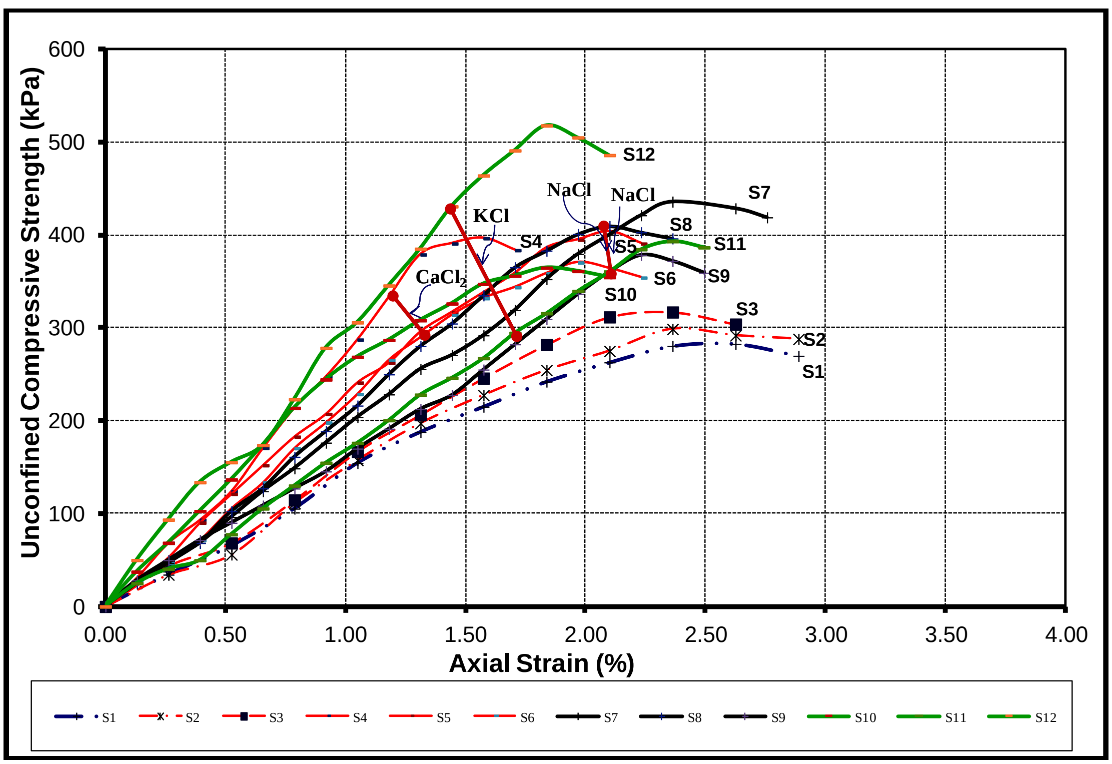
Fig. 8 Variation in modified proctor test characteristics of mollisols with addition of lime and salts

Figures 9 (a), (b) and (c) show the variation of unconfined compressive strength of different mixes at 0, 7 and 14 days curing duration. For 0 days curing duration, minor variation of unconfined compressive strength (200 to 300 kPa) was observed in tested mixes. The patterns of the strength versus (vs) strain were random reflecting initiation of reaction in the mixes. Hence, no specific conclusion can be drawn from it. Figure 9 (b) shows the strength pattern of mixes cured at remolded moisture content for 7 days at 72 F^0. It is eminent that the addition of lime and different saltsimprove the strength carrying capacity of mollisols. An average of over 100 kPa improvement in strength of samples has been observed. More promising trends have been observed with NaCl in comparison with $CaCl_2$ and KCl. Figure 9 (c) reflects the strength achieved by mixes cured at remolded moisture content for 28 days at 72 F^0. Mollisols lime mix with NaCl salt as an additive showed maximum unconfined strength. Other mixes stabilized with salts like $CaCl_2$ and KCl also showed reasonably good strengths. In stabilized samples the reduction in axial strain against increase in unconfined compressive strength (plastic zone) has been observed. The main reason of showing less plasticity by all the salts modified samples shows the maturity with age in sequences of hydration, flocculation, agglomeration and pozzolanic reactions.Further, it can be seen that the addition of salt chemically improve the reactivity of the lime with mollisols in achieving more strength.



Unconfined Compressive Strength (kPa)
Axial Strain (%)
S7
NaCl
S4
S10
S11
CaCl2
S1
S5
S2
KCl
S6
S8
S9
S3
S12

Fig. 9(a)



Unconfined Compressive Strength (kPa)
Axial Strain (%)
S12
NaCl
NaCl
S7
KCl
S8
S4
S5
S11
CaCl2
S6
S9
S10
S3
S2
S1

Fig. 9(b)

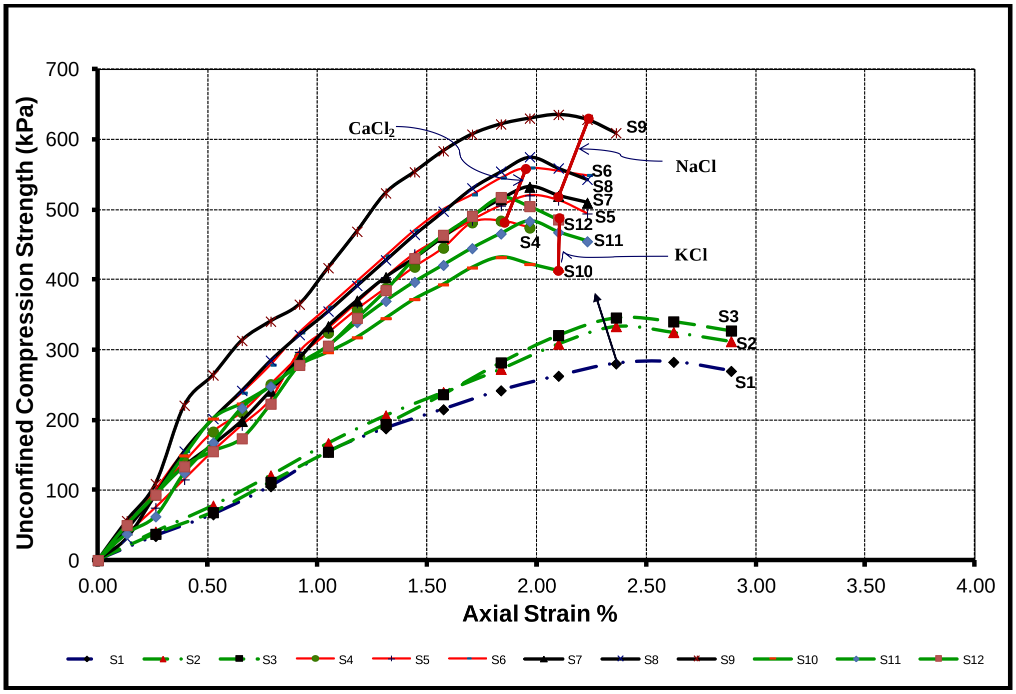


Fig. 9(c)

Fig. 9 Variation in unconfined compressive strength of mollisols soil samples (a) 0 days (b) 7 days (c) 14 days

Various researchers [7, 24] proposed to use lime as a stabilizer when its addition increase approximately the unconfined compressive strength of the soil 340 kPa after 28 days. As per this recommendation, it can be seen in Figure 9 (c) that the mix of mollisols with 10 % lime and 10 % NaCl is observed to be the best combination in term of strength vs strain behavior. Hence, the combination among the mixes can be rated as best in term of strength performance achieved in 28 days. In order to extend the application of research for the subgrades materials used in common/low cost roads construction. The CBR of the original mollisols in soaked and unsoaked condition was determined and compared with CBR of the mix having mollisols, 10 % lime and 10 % NaCl. The results are tabulated in Table 3.

Table 3 Comparison between CBR of unstabilized and stabilized mollisols

Description	CBR (ASTM D-1883)	
	Soaked	Unsoaked
Original mollisols	03	05
Stabilized mix	12	16

It can be narrated from Table 3 that CBR of the stabilized mix achieved is about 3 to 4 times higher than the original soil. Hence, the stabilized mix has potential to be utilized in practice as subgrade in common/low cost roads with light traffic loadings.

4. Conclusions and Recommendations

Following conclusions can be drawn from findings:

1. The chloride salts (NaCl, KCl and $CaCl_2$) has potential to dilute the bonding of organic acids covering the clay minerals (montmorillonite and kaolinite) in mollisols thus facilitating the lime reaction desired for stabilization.

2. The mollisols soils mixed with lime (maximum 10%) and salts (maximum 10% of NaCl, KCl and $CaCl_2$) do not show change in its engineering classification i.e Atterberg limits.

3. Addition of lime (maximum 10 %) in mollisols reduces the maximum dry density and increase optimum moisture content. However, additions

of salts (10 % NaCl, KCl and $CaCl_2$) in mollisols lime mix improve the compacted dry density of soils.

4. Mollisols soil sample stabilized with lime (10 %) and sodium chloride (10 %) is the most optimum blend observed in term of achieving unconfined compressive strength (over 630 kPa) at 28 days.
5. The optimum blend of mollisols with lime (10 %) and sodium chloride (10 %) showed over three times improved CBR performance in comparison with original mollisols. Hence, the mix has potential to be used as subgrade in ordinary / low cost roads.

While using soilsfor geotechnical purposes the salt contents are desired to be controlled in mixes. This research has shown that by the addition of lime and different salts in mollisols its strength characteristics can be improved. However, the suitability of these mixes in term of salt contents after the occurrence of chemical reaction needs further evaluation. For that purpose it is recommended to conduct chemical analysis of mixes accompanied by XRD for evaluation of mineralogical changes take place in samples during and after stabilization.

5. Acknowledgement

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