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Geotechnical behaviour of lime treated sulphatic soils

Comportement géotechnique de sols sulfatés traités au calcaire

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ABSTRACT
This study has been under taken to understand the influence of sulphate content on two extreme types of fine-grained soils, namely montmorillonitic black cotton soil and kaolinitic red earth stabilised with optimum lime content of 6%. . It has been observed that unusual increase in liquid limit and plasticity index of both types of lime treated soils occurs in the presence of sulphate. However, only the shrinkage limit of expansive soil decreases in the presence of sulphate. Compressibility of lime treated soil containing sulphate increases significantly after curing for one year. The strength of both the lime treated soils decreased considerably due to alteration of soil lime reactions products to swelling ettrengite type of compounds in the presence of sulphate. The strength decrease is more for expansive montmorillonitic black cotton soil than in kaolinitic red earth soil. Use of barium chloride in the proportion of two times the weight of sulphate overcomes the adverse effects of sulphate in lime stabilised soils.

RÉSUMÉ
Cette étude a été menée pour comprendre l'influence des teneurs en sulfate sur deux type de sol à texture fine, les sols noirs à montmorillonites et les sols rouges à kaolinite, chacun stabilisé avec une teneur en calcaire optimum de 6%. Les résultats indiquent, en présence de sulfate, une surprenante augmentation de la limite liquide et de l'indice de plasticité dans les deux types de sols, mais une diminution de la limite de retrait seulement dans les sols gonflants. La compressibilité des sols contenant du sulfate et traité au calcaire augmente de manière significative après un an de séchage. La force des deux sols traités au calcaire diminue considérablement en raison de la transformation des produits de réaction du calcaire du sol en composé de type ettrengite en présence de sulfate. La diminution de la force est plus forte pour les sols noir à montmorillonite gonflante que pour les sols rouges à kaolinite. L'utilisation de chlorure de barium dans des proportions pondérales doubles du sulfate empêche les effets défavorables du sulfate dans les sols stabilisés au calcaire.

1 INTRODUCTION

Natural sulphatic soils are omni present in many parts of world. Sulphate may also be introduced into the soil environmental problems. Many different soils including sulphatic soils are often treated with lime to improve their geotechnical properties. In fact, with the advent of technology to apply lime by improved methods such as lime slurry pressure injection technique, its use to improve the properties of fine-grained soils is increasing. The mechanism of improvement is by cation exchange, flocculation and pozzolanic reactions. Additives such as inorganic salts have been used to further improve the effect of lime. One main reason restricting the use of lime stabilisation of soil is the presence of sulphate. When the sulphatic soils are treated with lime some unexpected behaviour has been reported. Sulphate induced heave has been reported after considerable lapse of time.. The formation of ettringite has been reported as the main reason for these adverse effects. The weak sulphate mineral undergoes significant heave when subjected to hydration severely affecting the performance of stabilised bases and subgrades in the pavement systems. (Hunter, 1988; Mitchell and Dermatas 1990; Petry and Little 1992; Rajendran and Lytton, 1997; Rollings et al, 1999, Puppala et al, 2001). Similar problems occur when sulphatic soils are treated with cement treated soils. However, no comprehensive data is available on the role of mineralogy, the amount of sulphate content, the effect of percentage of lime and the effect of duration etc. Understanding this will enable to evolve methods to mitigate the problems of ettringite. An experimental study has been taken up to study the effect of sulphate on two extreme types of fine-grained soils, one containing expansive montmorillonite mineral and another having non-expansive kaolinite mineral as principle clay mineral.

2 SOILS USED

The properties of the soils used are given in Table 1.

Table 1. Properties of Soils

Property	Black Cotton Soil	Red Earth
Specific Gravity	2.7	2.7
Liquid Limit, %	81	49
Plastic Limit, %	33.5	27
Shrinkage Limit, %	9	16
Plasticity Index, %	47.5	22
Clay content, %	35	35
CEC, meq/100g,		
Total,	30.1	13.5
as Sodium,	9.3	0.8
as Calcium,	10.2	2.0
as Potassium,	0.5	8.9
as Magnesium	10.1	1.8
Primary Clay mineral	Montmorillonite	Kaolinite
Sulphate	(trace)	(trace)

The black cotton soil used in this investigation was obtained from Davangere, Karnataka State, India. The soil was collected by open excavation, from a depth of one meter from ground level. The red earth used in this investigation was obtained from around Soil Mechanics, Laboratory, Indian Institute of Science, Bangalore, India. The soil was collected by open excavation, from a depth of one meter from ground level. The soils were dried and passed through IS sieve size of 425 micron. *21 Lime and Sodium/Calcium sulphate used*

Chemically pure hydrated lime and sodium sulphate are obtained from Glaxo Laboratory, India and used in the investigation.

2.2 Preparation and curing of samples

Soil was mixed with optimum lime content of 6 % and varying sodium or calcium sulphate contents (up to 3 % by weight of soil) and was brought to its liquid limit consistency.

For consolidation tests, the tests were conducted using stainless steel rings of 76.2 mm in diameter and 25.4 mm in height. The inside of the rings was lubricated with silicon grease to minimize the side friction between the rings and the soil specimen. The rings were placed on a 10-mm thick porous stone. Bottom filter paper was placed on the porous stone to avoid soil particles to clog the pores of the porous stone. The filter paper was then placed over the top of the soil samples. The entire assembly was mounted in the consolidation cell and positioned in loading frame. The consolidation tests were conducted at room temperature (27^0 C) with a loading increment ratio of unity. For tests on cured samples, the samples prepared in the consolidation rings were cured for 1 year before starting the consolidation test.

For triaxial tests the wet soil was remoulded into stainless steel tubes of 38.1mm diameter and length of 150 mm. The tubes were covered with polythene sheets and were kept in a air tight container to prevent carbonation. After the remoulded sample gained sufficient strength, they were extruded with sample extractor. The samples were trimmed normal to its axis horizontally to a height of 76.2 mm. The samples were then covered with a wet cotton cloth and cured in air tight plastic container for periods varying from 7 days to 365 days.

Conventional triaxial testing was carried out to measure the consolidated undrained strength along with pore water pressure measurement on the cured samples. Readings of deviator load, pore water pressure, and axial deformations were taken. The test was continued until the deviator load reached a maximum level and dropped. The test was carried out at least on three identical samples under the effective cell pressures of 100 kPa to 300 kPa. Using the test data, stresses and strains were computed and deviator stresses versus axial strain plots were drawn. From these plots, peak stresses were taken. Using these values and pore water pressure total and effective strength parameters were obtained using modified Mohr-Coulomb's plot.

3 RESULTS AND DISCUSSION

Presence of sulphate modifies the soil lime reaction products. Sulphate reacts with lime to form calcium sulphate and sodium hydroxide increasing the pH of the system. Increased pH enables to dissolve more silica from soil which intern reacts with calcium to from more calcium silicate hydrate gel, which is responsible for cementation of particles. However, in the presence of sulphate these reaction products are modified to swelling ettrengite type of compounds by the following chemical reactions:

$$6Ca^{2+} + 2\ Al(OH)^-_4 + 4(OH)^- + 3(SO_4)^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2\ (SO_4)_3\ 26H_2\ O \qquad (1) \quad \text{(ettringite)}$$

$$Ca_6[Al(OH)_6]_2(SO_4)_3\ 26H_2O + 2H_2SiO^{2-}_4 + 2CO^{2-}_3 + O_2 \rightarrow Ca_6[Si(OH)_6]_2\ (SO_4)_2(CO_3\ )_2 24H_2\ O + 2Al\ (OH_4)^- + (SO_4)^{2-} + 4OH^- + 2H_2O \qquad (2) \quad \text{(thaumasite)}$$

The effect of the alteration of soil lime reactions in the presence of sulphate on basic and engineering properties of soil is presented in the following sections.

3.1 *Effect on basic properties*

It was found that the optimum lime content of both the soils was 6%. It has been reported that unusual increase in liquid limit and plasticity index of both types of lime treated soils occurs (Sivapullaiah et al., 1995;). However, while the shrinkage limit of expansive soil decreases in the presence of sulphate that of red earth is fairly unaffected. These change, during shorter periods of curing, are due to changes in cation exchange, change of fabric etc. (Tables 2, 3)

Table 2 : Index properties of Lime treated Black Cotton Soil with Sulphate after curing

Curing Period in days	0	7	30
Liquid Limit, (%)			
B C Soil alone	97.0	97.0	97.0
6% lime	68.0	102	100
0.5% Ca SO_4	70.0	86.0	88.0
1% Ca SO_4	73.0	93.0	93.6
3% Ca SO_4	76.0	100.0	101.5
0.5 % Na_2 SO_4	78.6	97	106.0
1% Na_2 SO_4	78.9	122.5	116.0
3% Na_2 SO_4	82.7	137.5	119.5
Plastic Limit, (%)			
B C Soil alone	36.0	36.0	36.0
6% lime	53.5	63.0	68.5
0.5% Ca SO_4	53.5	61.5	63.0
1% Ca SO_4	56.0	63.0	63.6
3% Ca SO_4	57.0	62.5	64.0
0.5% Na_2 SO_4	56.0	61.0	68.0
1% Na_2 SO_4	52.5	73.00	62.3
3% Na_2 SO_4			
Shrinkage Limit, (%)			
B C Soil alone	8.6	8.6	8.6
6% lime	35.6	45.4	45.4
0.5% Ca SO_4	36.1	41.0	43.0
1% Ca SO_4	38.0	46.0	47.0
3% Ca SO_4	39.5	49.5	49.5
0.5% Na_2 SO_4	35.1	40.8	42.0
1% Na_2 SO_4	35.1	40.0	42.0
3% Na_2 SO_4	33.0	46.3	46.0

3.2 E*ffect on volume change behaviour*

Oedometer swelling of lime treated expansive soil occurs in two different phases (Fig. 1). The first one is flocculation swelling and the second is due to adsorption of sulphate.

Table 3 : Index properties of Lime treated Red Earth

Curing Period in days	0	7	30
Liquid Limit			
Red Earth alone	49.7	49.7	49.7
6% lime	49.4	56.9	61
1% Ca SO_4	50	63	70
3% Ca SO_4	51	85	93
1% Na_2 SO_4	54	75	83
3% Na_2 SO_4	61	98	100
Plasticity Index			
Red earth alone	21.5	21.5	21.5
6% lime	22.4	20.4	22.2
1% Ca SO_4	36.5	43.6	23.4
3% Ca SO_4	37	48.2	34.7
1% Na_2 SO_4	33	38.2	38.5
3% Na_2 SO_4	33.4	45.5	42
Shrinkage Limit			
Red earth alone	16.4	16.4	16.4
6% lime	32.8	35.7	36.5
1% Ca SO_4	35.2	47	44
3% Ca SO_4	30.2	44	45
1% Na_2 SO_4	28.8	42.0	42
3% Na_2 SO_4	30.1	33	35.2

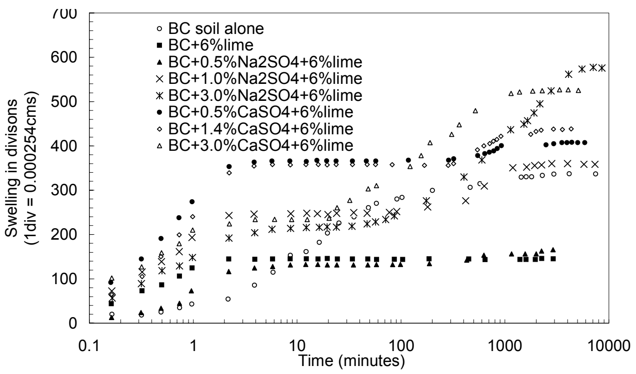

Fig.1 Oedometer swelling with time for lime treated black cotton soil with different sulphate contents

For lime treated red earth the swelling in the presence of sulphate occurs only in one stage. For flocculated kaolinite, the initial swelling is absent (Fig. 2).

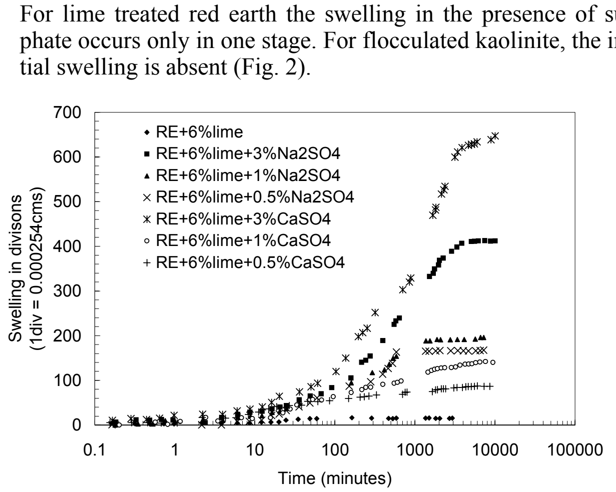

Fig. 2. Oedometer swelling with time for lime treated red earth with different sulphate contents

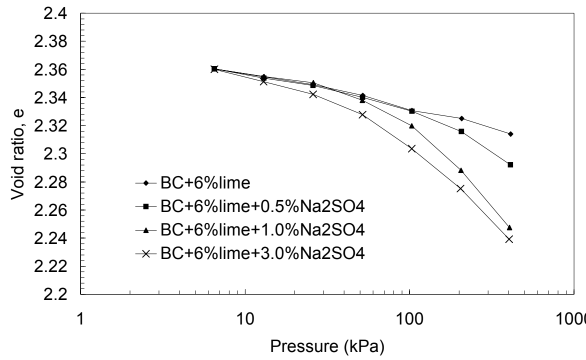

Fig.3 Void ratio- pressure curves for lime treated black cotton soil in the presence of sulphate after curing for one year

Fig. 3 shows the void - pressure relationships for lime treated black cotton soil in the presence of 0.5, 1 and 3% of sodium sulphate after one year of curing. It can be seen that the total compression, with increase in effective stress from 6.25 to 400 kPa, increases as the concentration of sulphate increases.

Fig. 4 shows the void - pressure relationships for lime treated red earth in the presence of 0.5, 1 and 3% of sodium sulphate after one year of curing. It is observed that the increase in the compressibility with 0.5 and 1% of sodium sulphate is negligible where as it is very high in the presence of 3% of sodium sulphate. It is known that lime reacts better with black cotton soil containing montmorillonite than with red earth containing kaolinite mineral. The cementitious compounds produced are altered even in the presence of small concentration of sodium sulphate in black cotton soil where as high concentration is required in the presence of red earth.

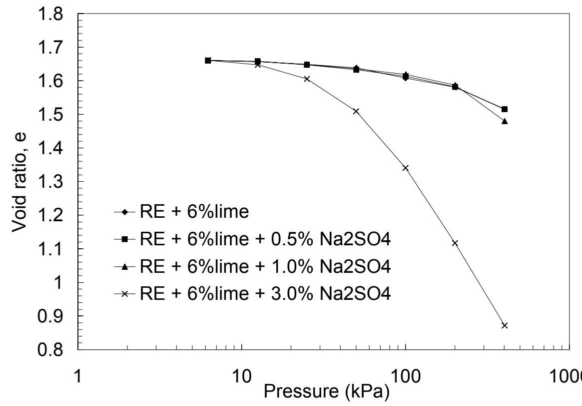

Fig.4 Void ratio- pressure curves for lime treated red earth in the presence of sulphate after curing for one year

3.3 Effect on strength

Table 4 shows the effect of concentration of sodium sulphate and calcium sulphate on the peak stress of lime treated black cotton soil after curing for different periods. It can be seen that the peak stress of lime treated soil in the absence of sulphate increases significantly with curing period at a cell pressure of 100 kPa, whereas the strength of lime treated soil decreases considerably after curing for long period in the presence of sulphate. It was observed that the same trend is followed at other cell pressures viz., 200 and 300 kPa. With lime alone the peak stress is very high because of cementation of particles by pozzolanic compounds produced. These compounds are altered to ettringite leading to breakage of cementation bonds. However, the effect of concentration does not follow a definite order.

Table 4: Peak Stress Values for lime treated black cotton soil at a cell pressure of 100 kPa

Sulphate Content	Peak Stress (k Pa), after curing for		
	7 days	30 days	365 days
0%	320	640	1100
0.5% Na_2SO_4	240	400	380
1% Na_2SO_4	400	1040	140
3% Na_2SO_4	330	460	310
0.5% $CaSO_4$	800	680	580
1 % $CaSO_4$	560	940	280
3% $CaSO_4$	700	900	340

Table 5 shows the effect of concentration of sodium sulphate on the peak stress of lime treated red earth with curing. With lime alone the peak stress increases continuously with curing period. This is because of cementation of particles by pozzolanic compounds produced. The peak stress increases and then decreases with curing period with any sulphate content. As sulphate content increases the strength increases for curing periods of 7 days and 30 days. The strength decreases after curing for 365 days.

Table 5: Peak Stress Values of lime treated red earth at a cell pressure of 100 kPa.

Sulphate Content	Peak Stress (kPa), after curing for		
	7 days	30 days	365 days
0%	202	546	599
1% Na_2SO_4	666	1032	642
3% Na_2SO_4	1048	1106	606

4 REMEDIAL MEASURES

Serious attempts are being made to mitigate the problems of sulphate in soil in the stabilisation of soils. One of the methods reported recently is by Puppla et al. (2004). In the present investigation, the use of barium chloride to counter the effect of sulphate explored. The strength of lime treated black cotton soil containing sulphate and barium chloride has been studied. The stress-strain curves of lime treated soil without sulphate, with sulphate and with sulphate and barium chloride after one year of curing have been shown in Fig. 5 (333). The peak stress of lime treated black cotton soil with sulphate and barium chloride is very close to that of soil with lime alone indicating that the adverse effect of sulphate has been effectively countered. The weight of barium chloride used has been twice the weight of sulphate.

5 CONCLUSIONS

Unusual increase in liquid limit and plasticity index of lime treated black cotton soil and red earth soils occurs in the presence of sulphate.

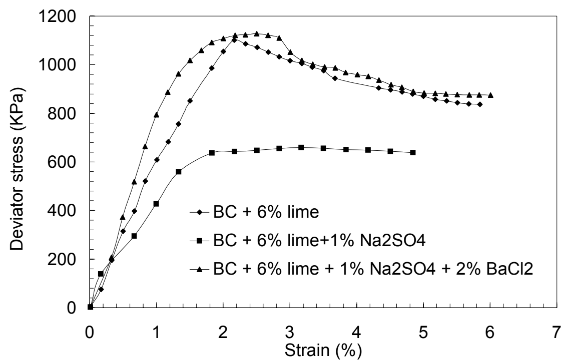

Fig.5 stress - strain curves of lime treated black cotton soil with and without barium chloride after curing for one year at a cell pressure of 100 kPa.

Oedometer swelling of soils exhibited swelling due to adsorption of sulphate by soil. Lime treated black cotton soil also exhibits swelling due to flocculation of soil particles. Compressibility of soils increases significantly in the presence of sulphate after one year of curing due to conversion of soil-lime pozzolanic reaction compounds into ettrengite. The strength of lime treated soils decreases after curing for long period in the presence of sulphate. Addition of barium chloride remediates the effect of sulphate.

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