Heaving Mechanisms in High Sulfate Soils

Mécanismes de soulèvement dans les sols à contenu élevé en sulfates

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ABSTRACT: Pavement distress caused by chemically treated sulfate soils are considered as major maintenance problems to highway agencies. In view of this, researchers across the world have conducted studies on heave mechanisms in chemically treated sulfate soils. Many of these studies are focused on soils with soluble sulfate contents below 10,000 parts per million (ppm). Heave mechanisms in soils with sulfate contents above 10,000 ppm still need to be understood as sulfate measurements indicate that the soil sulfate levels of certain regions are well above 10,000 ppm and may exceed 50,000 ppm in some cases. In order to understand the behavior of treated soils containing sulfates above 10,000 ppm, a research study was initiated. Two soils with different soil classification are studied. Lime is used as a chemical stabilizer for these soils. Chemical and mineralogical tests as well as engineering swell tests were conducted to compare the changes in swelling, mineralogical and chemical compositions of the soils from the lime-sulfate reactions. Results will explain the need to look for replace the classical treatments by alternate ones for these high sulfate soils for civil infrastructure projects.

RÉSUMÉ : La dégradation des chaussées causée par les sols à contenu de sulfates traités chimiquement sont considérés comme des problèmes d'entretien majeurs par les agences routières. Compte tenu de cela, les chercheurs du monde entier ont mené des études sur les mécanismes de soulèvement dans les sols à contenu de sulfates traités chimiquement. La plupart de ces études portent sur des sols à teneurs en sulfates solubles en inférieures à 10.000 parties par million (ppm). Les mécanismes de soulèvement dans les sols à teneurs en sulfates supérieures à 10.000 ppm doivent encore être étudiés car des mesures de taux de sulfates indiquent que les niveaux de sulfates du sol de certaines régions sont bien au-dessus 10.000 ppm et peuvent même dépasser 50.000 ppm dans certains cas. Afin de comprendre le comportement des sols traités à contenu de sulfates supérieurs à 10.000 ppm, une étude a été lancée. Deux sols réputés différents selon la classification des sols ont été étudiés. De la chaux a été utilisée comme stabilisant chimique de ces sols. Des tests chimiques et minéralogiques ainsi que des tests d'ingénierie du gonflement ont été menés pour comparer les gonflements, et la composition minéralogique et chimique des sols à la suite des réactions chaux-sulfate. Les résultats exposés expliqueront la nécessité de chercher des traitements alternatifs aux traitements classiques pour ces sols à contenu élevé en sulfates dans les projets d'infrastructures civiles.

KEYWORDS: Sulfate, Swell, Mellowing, Ettringite, Expansive Soil

1 INTRODUCTION

Chemical stabilization of expansive soils using lime and cement has been a favourite option for practitioners over the years (Hausmann, 1990). In last few decades, premature failure of roads, highways and infrastructure facilities around several parts of the globe lead to question the validity of calcium based stabilization. It was reported that when soils contain sulfate minerals such as gypsum ($CaSO_4.2H_2O$) and sodium sulfate (Na_2SO_4) in their natural formation and are treated with calcium based stabilizers, adverse reactions occur causing heave and pavement distress. (Mitchell 1986, Hunter 1988, Puppala et al. 1999, 2003, 2012). These adverse reactions are attributed to the formation of expansive minerals such as Ettringite ($Ca_6.[Al(OH)_6]_2.(SO_4)_3.26H_2O$) and Thaumasite ($Ca_6.[Si(OH)_6]_2.(SO_4).(CO_3)_2.24H_2O$). This phenomenon is termed as "Sulfate Induced Heave" in literature. Repair and re-construction of the the failed infrastructure is costing millions of dollars to the tax payers. Under favourable moisture, humidity and temperature conditons these minerals grow causing further swell. Lime/cement treatement of sulfate soils can be regarded as the man made expasive soil problem.

In view of the past sulfate induced failures researchers have developed "Threshold Sulfate Levels" beyond which calcium based stabilization is to be cautioned. Berger et al., 2001 stated that sulfate levels below 0.3 percent can be safely treated with calcium stabilizers. Sulfate levels between 0.3 percent to 0.8 are to be handled with caution and sulfate levels greater than 0.8 percent should be avoided. Puppala et al., 2003 indicated that sulfate levels below 1000 ppm are of no concern and soils with sulfate levels between 1000-2500 ppm can be treated with additional amount of lime. Sulfate levels above 2,500 ppm are to be completely avoided. Harris et al., 2004 confirmed that in soils with sulfate levels greater than 7,000 ppm lime stabilization is not a viable option. There is no conclusive agreement between the threshold sulfates since in most cases of sulfate induced failures sulfate contents varied from as low as 320 ppm to as high as 43,500 ppm.

Based on previous recommendations researchers have studied heave mechanisms and developed alternative stabilization techniques for treating sulfate soils. Many of these studies were focused on soils with sulfate contents below 10,000 ppm. However, a further understanding about the soils with sulfate contents above 10,000 ppm and higher is needed. Researchers named these soils as "High Sulfate Soils". In view of this aspect the current study focuses on heaving mechanisms and remedial options for high sulfate soils. Two soils from the state of Texas with sulfate contents above 20,000 ppm are considered in the current study. These soils were lime stabilized using mellowing technique and various engineering and mineralogical tests were conducted to understand the swell shrinkage characteristics of chemically stabilized high sulfate soils. Based on test results and analysis recommendations about the validity of mellowing technique, an attempt to look for alternative treatments was made.

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Test Soils and Basic Tests

Criteria for selection of the test soils is as follows: soils have to belong to different geological formation and classification. Based on these criteria Sherman and Childress, Texas soils were sampled for the testing program. As per USCS classification, Sherman soil is classified as 'CH' whereas Childress is classified as 'MH' soil. Gypsum is the sulfate source for both the soils. Soluble sulfate contents were determined using the TxDOT method (Tex-145-E, Colorimetric method). A 1:20 initial soil/water dilution ratio is used in this method. Turbidity caused by the presence of sulfate is determined using "Colorimeter" and converted in to ppm. Soluble sulfate content of Childress and Sherman soils are 24,000 ppm and 44,000 ppm respectively. Based on the classifications mentioned above these two soils are termed as "high sulfate soils".

Hydrated lime is used as the stabilizer for the soils understudy. Lime dosage is determined as per "Eades and Grim" test. Test soils were treated with various percentages of lime and pH test was conducted. The dosage at which soil pH reaches a value of 12.4 is considered as the optimum lime dosage. The optimum dosage of lime for both soils is 6% by dry weight. Optimum moisture content and dry density of natural and treated soils were obtained by conducting standard proctor tests as per ASTM standard procedures (ASTM D-698). It was observed that maximum dry density decreased and optimum moisture content increased up on lime treatment. Classification and standard Proctor test results are summarized in Table 1.

Table 1. Classification and Proctor Test Results

Soil	Atterberg Limits			Untreated Soil		6% Lime Treated Soil	
	LL	PL	PI	OMC (%)	MDD, psf	OMC (%)	MDD, psf
Sherman	72	30	42	27	89	28	87
Childress	71	35	36	21	103	22	96

Note: LL – Liquid Limit; PL – Plastic Limit; PI – Plasticity Index; OMC – Optimum Moisture Content; MDD- Maximum Dry Density

A series of chemical tests were conducted on test soils to determine the cation-exchange capacity (CEC), specific surface area (SSA) and total potassium (TP). Based on the mineralogical test results, clay mineralogy of the test soils was assessed as per the procedure outlined by Chittoori and Puppala (2011). Clay mineralogy indicated the dominance of Montmorillonite mineral in Sherman soil and Kaolinite mineral in Childress soil. Both soils exhibited swell potential upon hydration.

2.2 Engineering Tests and Mineralogical Tests

Engineering tests were performed on untreated test soils to assess the swell, shrinkage and strength characteristics. These tests include three dimensional (3-D) volumetric swell, shrinkage and unconfined compressive strength (UCS) tests. As alumina and silica constitute the chemical composition of Ettringite and Thaumasite, measurement of alumina and silica is essential. Alumina and silica that participate in the sulfate reactions are called "reactive alumina and silica". Reactive alumina and silica measurements were conducted as part of the mineralogical tests. All the engineering tests were conducted at optimum moisture content (OMC) and wet of optimum moisture content (WOMC) corresponding to 95% of maximum dry density. Wet of optimum moisture content is 2% and 3% higher than the optimum moisture content for Childress and Sherman soils.

Mellowing technique has been successful in stabilizing soils with sulfate concentration up to 7,000 ppm (Harris et al., 2004). Applicability of mellowing for high sulfate soils has not been studied so far. To assess the validity of mellowing technique in high sulfate soils both the soils are treated with 6% lime and corresponding moisture from the proctor curve. Lime treated soils were mellowed for periods of 0 and 3 days in a moisture controlled environment. Since lime treatment makes the soil dry, to compensate for the moisture loss during the mellowing process, additional 3% moisture is provided for 3 day mellowed soils. Another reason for provision of additional moisture is to increase the solubility of gypsum and early depletion as the sulfate reactions occur during the mellowing period. After the elapsed mellowing periods, soil samples were recompacted and engineering tests were conducted. Data from the engineering tests is compared with untreated soils to witness the sulfate reactions occurring in high sulfate soils. Reactive alumina and silica measurements were performed on the samples subjected to swelling and loss of aluminates and silicates were calculated. A brief description of the tests conducted is given below:

2.2.1 Three Dimensional Volumetric Swell (3-D Swell) Test

3-D swell tests were conducted on natural and treated soils to determine the maximum possible volumetric swell which is a combination of vertical and radial swell. These tests are conducted on 4 in. (101.6 mm) diameter and 4.6 in. (116.8 mm) height samples. The samples are prepared using a gyratory compactor machine. Porous stones are placed at the top and bottom of the sample and a rubber membrane is placed around the sample. The samples are double inundated and a dial gauge is placed on the top of the sample to record the vertical swell with time. Vertical swell readings are collected with time until there is no further swell for 24 hours. Radial swell of the sample is measured after the completion of the test using a pi-tape. Double inundation provides the worst possible scenario in field where the soil is 100% saturated and maximum swell is expected in this case. Researchers across United States and UK have successfully used double inundation technique for measuring the volumetric swell.

2.2.2 Three Dimensional Volumetric Shrinkage Test

3-D shrinkage tests were conducted as per the procedure developed by Puppala et al., 2004 to measure the decrease in the total volume of soil specimens due to the loss of moisture content in field samples during a dry spell. In order to replicate the worst possible conditions, drying from a compacted state to completely dry state is considered in this test. Soil samples were compacted to 2.26 in. (57 mm) diameter and 5 in. (127 mm) height using a static compaction machine. Initial sample height and diameter are measured at three locations and averaged. Samples are prepared at optimum and wet of optimum moisture contents and dried on bench top for 12 hours followed by oven drying for 24 hours. Steps used in sample preparation and extraction are similar to the UCS sample except the sample sizes are different. After 24 hours, samples are removed from the oven and sample dimensions are taken. Volumetric shrinkage is calculated as the difference of initial and final volume divided by the initial volume expressed in percentage.

2.2.3 Unconfined Compressive Strength (UCS) Test

Unconfined Compressive Strength (UCS) tests were conducted as per ASTM D 2166 method. The main intention of these tests is to determine the strength changes during the mellowing process. Soil samples are treated with lime and allowed to mellow for 0 and 3 days. After the mellowing period soil samples were compacted to 2.8 in diameter (70 mm) and 5.6 in. (140 mm) height and moist cured in a 100% relative humidity environment for 7 days. After the curing period soil samples are loaded to failure at a constant strain rate of 1.27 in/minute in a triaxial compression machine.

2.2.4 Reactive Alumina and Silica Measurements

Reactive alumina and silica are the aluminum and silica present in amorphous or poorly crystalline Al/Si phases including amorphous alumino silicate, organically complexed alumina and hydroxyl-Al polymers present in Montmorillonite interlayers. Reactive alumina and silica measurements were conducted by a procedure modified after Foster (1953). To determine the reactive alumina and silica, 15g of soil was mixed with 150 ml of 0.5 N NaOH and heated. Once the solution starts boiling, heating is discontinued and the solution is allowed to cool, followed by centrifuging at 8000 rpm. After centrifuging the extract is filtered using a 0.1 µm membrane type filter paper. The extract obtained was stored in a plastic bottle and the ICP analysis was performed on a clear extract. If the extract obtained in the last step is not clear it is treated for organics and iron oxides which inhibit the alumina and silica measurements in ICP analysis.

3 RESULTS AND DISCUSSON

3.1 Results of the Testing Program

3.1.1 Three Dimensional (3-D) Swell Test

3-D swell tests were conducted on natural and treated soils as per the procedure described above. Natural swell of Sherman and Childress soils at optimum moisture content is 16.2% and 7.5% respectively. The observed swell is less at wet of optimum moisture content. Additional swell tests were conducted on both the soils at 7-day mellowing. Results of the swell testing are presented in Figure 1 and Figure 2. It can be observed from the figures that for both the soils at 0 days mellowing, the treated swell is higher than the natural swell indicating the dominance of sulfate reactions over stabilization reactions which is common in lime treated high sulfate soils. In case of Sherman soil, the observed swell is below the natural swell for 3-day mellowing which further decreased with 7-day mellowing indicating the effectiveness of mellowing in Sherman soil. In Childress soil, with 3-day mellowing the reduction in swell is observed though it is not significant since the treated swell is higher than the natural swell. With 7-day mellowing, the treated swell further increased indicating mellowing is not effective for Childress soil. Reasons for this behavior are explained in the subsequent sections.

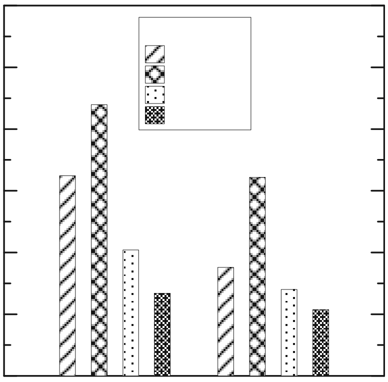

Figure 1. 3-D Volumetric Swell (SHERMAN Soil)

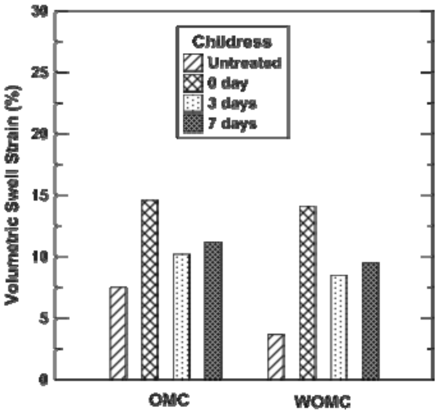

Figure 2. 3-D Volumetric Swell (Childress Soil)

3.1.2 3-D Shrinkage Test

3-D volumetric shrinkage tests were conducted on natural and treated soils at optimum and wet of optimum moisture contents. 3-D shrinkage test results are shown in Table 2.

Table 2. 3-D Shrinkage Test Results

Soil	**Natural**		**6%L, 0 day mellowing**		**6%L, 3 day mellowing**	
	OMC*	**WOMC***	**OMC***	**WOMC***	**OMC***	**WOMC***
Sherman	-15.8	-20.0	-7.6	-8.9	-6.3	-9.4
Childress	-14.3	-15.4	-2.4	-2.6	-3.1	-4.0

Note*: Negative sign indicates shrinkage

From Table 2, it can be observed that volumetric shrinkage reduced with lime treatment irrespective of the sulfate content. Volumetric shrinkage is higher at WOMC condition owing to the high moisture at wet of optimum than optimum. Volumetric shrinkage of the 3 day mellowed soils is slightly higher than the 0 mellowed soils due to additional moisture provided during the mellowing process. It can be concluded that sulfate heave reactions do not have significant influence on the shrinkage behavior of lime treated soils.

3.1.3 UCS Test Results

Unconfined compressive strength (UCS) tests were conducted on natural and treated soils (0 day and 3 day mellowing). The results of UCS tests are presented in Table 3. From Table 3. it can be observed that UCS strengh of treated soils is 2-5 times higher than the natural soil. There was a slight decrease in strength in case of 3 day mellowed samples which could be attributed to the addition of extra moisture during mellowing.

Table 3. UCS Test Results (psi)

Soil	**Natural**		**6%L, 0 day mellowing**		**6%L, 3 day mellowing**	
	OMC	**WOMC**	**OMC**	**WOMC**	**OMC**	**WOMC**
Sherman	33	19	81	60	70	46
Childress	23	16	108	78	103	56

3.1.4 Discussion

Reactive alumina and silica measurements on natural (untreated soils) and treated soils (after the samples have been subjected for swell testing) at different mellowing periods were performed as per the procedure outlined above. Table 4 shows the results of these tests and the loss of alumina and silica in treated soils at different mellowing time periods. It can be seen from the Table 4 that the initial reactive alumina and silica contents are very low in Childress soil when compared to that of Sherman soil. The main intent of mellowing is to allow the Ettringite formation reactions in initial stages. During remixing and compacting the initial Ettringite is broken and further Ettringite formation is hence not possible due to the lack of reactive sulfates.

It is reported in the literature that Ettringite formation depends on the amount of reactive alumina present in the system. For example, low alumina contents in soils favor the trisulfate hydrate (Ettringite) formation. High alumina contents, on the other hand, lead to simultaneous formations of pozzalonic and ettringite reactions. As a result, attractive forces formed from pozzalonic formation will resist the disruptive forces caused by Ettringite hydration reactions. This explains low heaving in high alumina soil (Sherman soil) of the present research.

Low initial reactive alumina contents coupled with high sulfate contents in Childress soils are attributed to large heaving and here the mellowing is deemed ineffective primarily due to low alumina content in the soil. Also, the loss of alumina and silica at both 0 day and 3 day mellowing periods were higher in case of Childress soil compared to Sherman soil. Though the loss of alumina and silica is less in 3-day mellowed soils, this soil still exhibited high swelling due to high sulfate content (44,000 ppm) present.

Table 4. Reactive Alumina and Silica (ppm) in present soils

Soil	**Untreated (Natural)**		**6%L, 0-day mellowing**		**6%L, 3-day mellowing**	
			% loss		**% loss**	
	Al(ppm)	**Si(ppm)**	**Al**	**Si**	**Al**	**Si**
Sherman@OMC	279	137	58	66	53	64
Sherman@WOMC	279	137	57	64	52	63
Childress@OMC	76	13	63	54	61	46
Childress@WOMC	76	13	62	62	58	54

Also, authors have made attempts to link the formation and growth of Ettringite to the compaction density/void ratio of the soil specimens. Based on specific gravity and maximum dry density (@OMC condition), the compaction void ratio is calculated. Compaction void ratios of Childress and Sherman soils are 0.52 and 0.86, respectively. In soils with high void ratio (Sherman), the initial Ettringite formation, growth and heaving on hydration can be accommodated in the soil matrix provided there is no further nucleation of new compounds. If there had been further Ettringite growth, heave would have been higher in Sherman soil. In soil with low void ratio such as the present Childress soil, the dense soil matrix could not accommodate both initial Etringite formation and their growth on hydration and as a result, this soil exhibited higher heaving.

Overall, both alumina amounts and compaction void ratio conditions contribute to soil sulfate heaving and this information is used in the development of alternate chemical treatments for high sulfate soils.

4 CONCLUSIONS

1. In Sherman soil containing sulfates of 30,000 ppm or less, the mellowing effectively reduced the swell potential. Childress soil, containing larger amounts of sulfates of more than 30,000 ppm, exhibited sulfate induced heaving even at longer mellowing periods.
2. Volumetric shrinkage behavior is unaffected by the presence of sulfates and mellowing periods indicating that the shrinkage behavior was succesfully reduced with lime treament.
3. Low alumina contents facilitated Ettringite formation and heaving (Childress soil) whereas at high alumina contents both Ettringite and pozzolonic reactions occur simultaneously but due to dominance of pozzolonic reactions less heave is observed in this case (Sherman soil).
4. Compaction void ratio is an important parameter that need to be emphasized in lime treament of sulfate soils because Ettringite induced heaving is more critical in dense soil matrix compared to loose matrix.

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