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(Review)

A Broad Review on Treatment of Expansive Soils Using Mixing and Reinforcement Inclusion Treatment Techniques: A Comprehensive Review

Ibrahim F. El-Demary[1]

[1] *Engineering Construction Department, Faculty of Engineering, Egyptian Russian University, Badr City, Cairo 11829, Egypt*

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ABSTRACT

Expansive soils are considered problematic soil due to the volumetric change occurrence because of moisture content variations. Such soils swell vertically and laterally as the moisture content increases inducing swelling pressures and strains damaging structures and causing distress to roadways. Yearly financial losses are reported due to expansive soil damages. Hung (2003) reported that the expansive soil damage in the USA led to an annual economic loss of 5.5 billion dollars in 1984 which increased to 7 billion dollars in 2003. These soils are estimated to cover 20% to 25% of the USA area. Ruwaih (1987) reported losses of millions of dollars due to buildings and pavement damage caused by swelling soils in the Kingdom of Saudi Arabia as the expansive soils cover about 800000 km^2 of the kingdom. In Egypt, severe damage is observed from expansive soils which are found in new desert cities, as the increase in population and economic growth fuel the development of such arid areas for urban expansion. These challenges have motivated the investigation of mixing and reinforcement inclusion techniques in this regard. The objective of this review article is to present two treatment techniques for treating expansive soils which are the mixing treatment technique and reinforcement inclusion treatment technique in order to eliminate the detrimental effect of such expansive soils on structures and make them more feasible for construction purposes. This paper contributes to the selection and application of mechanical and chemical treatment techniques.

Keywords: Expansive Soil, Mixing Techniques, Reinforcement Inclusion Techniques.

1-Introduction

Expansive soils are unsaturated soils that exhibit vertical swelling pressures and strains upon inundation with water. One problem that arises when constructing on clay is volumetric change due to swelling and/or shrinkage of the soil. These volumetric changes cause severe damage and economic losses which represents a challenge.

Al – Mhaidib (1999) noted that more than 400 one-story residential buildings constructed of rigid reinforced concrete frames at Al – Ghatt town suffered from cracks after being occupied. This is because of the increase in water content due to garden irrigation, domestic water infiltration within the soil due to the lack of public sewerage system and the prevention of moisture evaporation by the paving areas surrounding the buildings.

Buildings can be subjected to damage due to end lift caused by the induced swelling pressure resulting from the moisture content change of the soil at the perimeter of the building while at the centre of the building, the moisture content is unchanged causing extensive damage to buildings as shown in Figure (1).

Figure 1. Building damage due to end lift (Jones (2011))

The lateral swelling pressure induced by expansive soil behind a structure can cause severe damage to it as shown in Figure (2). Kassiff and Zeitlen (1962) noted the drastic damage of the lateral swelling pressure to pipelines buried in expansive clays. They stated that the cause of the very large stresses induced in the pipeline was the inequalities in the lateral and vertical swelling behavior.

Figure 2. Retaining wall collapse due to lateral swelling pressure (Dave (2010))

Zornberg and Gupta (2009) reported that in Texas the roads passing through expansive soil zones experience longitudinal cracks due to seasonal fluctuation of moisture content which caused volumetric changes in the soil.

Geotechnical engineers prefer mitigating the expansive soils' objectionable characteristics in situ by various choices of treatment techniques instead of soil replacement to cut costs.

Finally, the purpose of this paper is to extensively present the effectiveness of soil mixing treatment technique and reinforcement inclusion treatment technique in mitigating the swelling potential of expansive soils. This could be beneficial in addressing the issues associated with the practical application of these treatments to exclude the destructive effect of such soils on constructions and make aired areas encountering expansive soils more feasible for construction purposes.

2 - Mixing treatment technique

This method is specified to shallow treatment depths by mixing the expansive soil with the determined additive such as ordinary Portland cement, fly ash, lime, fibers, and lime–fly ash. The objective of the mixing treatment technique is the reduction of the expansion potential and swelling stress by modifying the soil chemistry.

2.1 - Fly ash stabilization

Zha et al. (2008) conducted an experimental study to investigate the effect of various fly ash contents, namely 0, 3, 6, 9, 12 and 15% by weight of the dry soil and the curing time on the free swell, swell potential and swell pressure of the expansive soil.

The free swell is the ratio of the difference between the volume of soil fraction in water and that in air, to the volume of soil in the air while the swell potential is the ratio of the free swell to the initial sample thickness multiplied by 100 to be expressed as a percent. The swelling pressure is the pressure needed to keep the sample volume constant after adding water.

The expansive soils were obtained from Hefei city in China, while the fly ash was brought from the Jinling Thermal Power Plant at Nanjing city of China which is classified as class F according to ASTM (C 618).

The samples were mixed at optimum moisture content and left for curing 24 hours, after which, it was compacted using the standard Proctor compaction effort of 592.8 kJ / m^3 to reach the maximum dry density. The tests were conducted according to the Chinese standard for soil testing in highway engineering (JTJ051-93).

To determine the effect of the curing time the samples were sealed in plastic bags and left for 7 days at 22 ^oC and 70% relative humidity.

Results showed that as the fly ash content increased the liquid limit, plasticity index and activity decreased, this is due to the increase of the silt and sand size fraction and the decrease of the clay size fraction which reduces the soil-specific surface area and consequently decreases the soil water absorption.

A significant decrease in the free swell from about 55% at 0% fly ash percentage to about 31% at 15% fly ash while the swell potential decreased from 11.4% at 0% fly ash percentage to about 7.2% at 15% fly ash content. The swelling pressure decreased from 240 kPa to 150 kPa on increasing the fly ash percentage to 15%.

The curing time significantly reduced the swelling pressure where a value of 63 kPa was reached after 7 days of curing compared to 150 kPa without curing at 15% fly ash content.

A decrease in the optimum moisture content and the maximum dry density was indicated as the fly ash percentage increased. This is attributed to the decreases in the thickness of the electric double layer as a result of the cation exchange between the fly ash and expansive soils which advances the flocculation of the soil particles giving the ability to compact the mixture at lower water content and hence reaching lower optimum moisture content.

Lees et al. (1982) and Bell (1996) related the reduction in the maximum dry unit weight as the additive percentage increased to the lower specific gravity of the additive compared to the soil.

Nalbantoglu (2004) conducted an experimental study to investigate the effect of fly ash on reducing the expansive soil swell potential. Two marine clay deposits obtained from two locations in North Cyprus: Degirmenlik and Tuzla villages having different physical properties were used as expansive soils in the study. The fly ash is obtained from Soma thermal power station in Turkey which is an industrial waste.

The soil was dried and passed through sieve # 40, then, mixed with fly ash with two percentages 15 and 25% by dry soil weight. The mixture was compacted at optimum moisture content and to maximum dry density using standard Proctor compaction effort. The samples were sealed and left for curing for periods of 0, 7, 30 and 100 days.

The standard oedometer was used to test the treated and untreated samples having dimensions of 20 mm in height and 76 mm in diameter by applying a seating pressure of 6.9 kPa and leaving it till equilibrium is reached.

For Degirmenlik soil results showed that as the fly ash percentage increased the liquid limit, shrinkage limit and plasticity index decreased. The reduction in swelling strain with 15 and 25 % fly ash content at 0 days curing period was about 74.5% and 81.1% respectively.

Concerning the swelling pressure, Degirmenlik soil mixed with 15 and 25% fly ash at 0 days curing period showed a reduction in swelling pressure of about 12.5 % and 27.1% respectively.

Moreover, as the curing time increased the reducing effect of the fly ash content on the swelling strain and swelling pressure increased, where cured soil for 30 days with 25% fly ash had a 100% reduction in swelling strain, likewise, a 100% reduction was achieved for the two fly ash contents at the same curing period.

For the Tuzla soil, results revealed that at 0 days curing period with 15% fly ash content the reduction in swelling strain was about 26.2%, nevertheless, increasing the fly ash content to 25% increased the swelling strain, and this increasing trend was reversed as the curing time increased.

The results indicated that as the fly ash content increased the reduction in the swelling pressure increased. Samples mixed with 15% fly ash at 0 days curing period showed a reduction in swelling pressure of about 43.8%, while an increase in the swelling pressure was demonstrated at 25% fly ash. This increasing trend was reversed as the curing time increased.

Regarding the curing time, it was witnessed that on increasing the curing period the fly ash efficiency increased, where at a 100-day curing period a reduction reaching 69.2% in the swelling strain was achieved in addition to a reduction of 84.4% in the swelling pressure was attained on using 25% fly ash content.

The reduction in swell potential is attributed to the cementation process of the fly ash that causes the clay particles to gather together leading to the decrease of the clay size fraction as the fly ash percent increase. This aggregation lowers the surface activity of the soil where it becomes more granular and consequently lowers the water absorption ability.

Furthermore, tests indicated that increasing the curing time increased the sand size particles in the soil making it respond as a granular soil with a lower ability to absorb water.

The tests designated a decrease in the cation exchange capacity of the soil as the fly ash percentage increased, this indicates changes in the mineralogy of the treated samples.

Kumar and Sharma (2004) conducted an experimental program to investigate the fly ash effect on the engineering properties of expansive soil. Fly ash contents of 0, 5, 10, 15 and 20% were mixed by the dry weight of the expansive soil. Atterberg limits, free swell index and one-dimensional oedometer swelling potential test were used.

The obtained results showed that as the fly ash content increased the liquid limit decreased while the plastic limit increased, resulting in a decrease in the plasticity index by about 50%.

By increasing the fly ash content, the free swell index decreased continuously reaching a reduction percentage of about 50% on using 20% fly ash content. The swell potential and swelling pressure were reduced by about 50% by adding 20% fly ash.

Results of the standard compaction test demonstrated a reduction in the optimum moisture content an and increase in the maximum dry unit weight as the fly ash content increased, where a decrease of about 25% in the optimum moisture content and an increase of 5% in the maximum dry unit weight was observed on using 20% fly ash content.

Hayder A. Hasan (2012), conducted an experimental study on samples collected from Karbala City south of Baghdad to investigate the effect of various fly ash contents on the soil swelling potential. The index properties of the soil before adding the fly ash is as summarized in Table (1). The Fly ash was collected from the Baghdad Electrical Power Station with its chemical composition presented in Table (2).

Table (1): Properties of expansive soil

Property	Quantity
Specific Gravity	2.68
Liquid Limit (%)	74
Plastic Limit (%)	31
Plasticity Index (%)	44
Swelling Strain (%)	48
USCS Classification	CH

Table (2): Chemical composition of fly ash

Chemical Content	Percentage
Sio_2	42.3
Al_2O_3	12.5
Fe_2O_3	9.5
CaO	13.5
SO_3	17.3
Dissolved salts	4.9

The soil was oven dried and pulverized after which it was mixed with the chosen amount of fly ash then water was added to the mixture and mixed till it became homogenous. Atterberg limits test and one-dimensional oedometer swelling potential test were conducted on the samples in accordance with ASTM D4318-00 and ASTM D4546-96 respectively.

Results showed that the liquid limit and plastic limit decreased with increasing the fly ash content resulting in a decrease in the plasticity index.

It was noticed that as the fly ash content increased the swelling pressure and the swelling strain decreased. Figure (3) presents a correlation between fly ash content with swelling strain and swelling pressure.

The fly ash additive enhances the flocculation of the clay fabric and enriches the aggregation of the clay particles. Moreover, fly ash additive reduced the clay size fraction in the soil in view of the flocculation of the clay particles by cementation. Consequently, the fly ash inclusion made the soil more granular.

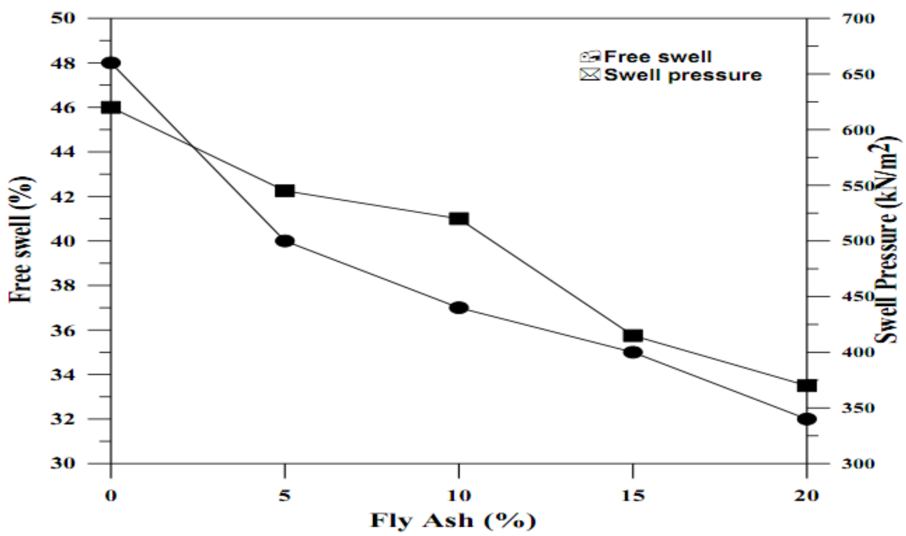


Figure 3. Fly ash content versus swelling strain and swelling pressure, (Hayder A. Hasan (2012))

2.2. Lime - Fly ash stabilization

Zha et al. (2008) investigated the effect of lime-fly ash additive and the curing time on the free swell, swell potential and swell pressure of the expansive soil by performing laboratory tests. The materials used in the study were expansive soils from Hefei City in China. Table (3) summarizes the soil properties. The fly ash was obtained from the Jinling Thermal Power Plant at Nanjing city of China classified as class F according to ASTM C 618 and powder lime containing about 70 % quick lime.

The fly ash contents were 0, 3, 6, 9, 12 and 15% while the lime contents were 0, 1, 2, and 3% by weight of the dry soil.

Table (3) shows the soil properties and swelling potential values.

Property	Quantity
Liquid Limit (%)	60
Plastic Limit (%)	28
Plasticity Index (%)	32
Swell Potential (%)	6.82
Swelling Pressure (kPa)	240
Free Swell (%)	55.5
USCS	CH

The specimens to be tested were mixed with water at optimum moisture content and allowed to cure for 24 hours, then it was compacted to the maximum dry density using the standard Proctor compaction effort of 592.8 kJ / m^3.

The tests were carried on according to the Chinese standard for soil testing in highway engineering (JTJ051-93). Sealed samples in plastic bags were cured for 7 days at 22 ^oC and 70% relative humidity.

Results showed a continuous decrease in the liquid limit, plasticity index and soil activity as the lime-fly ash content increased in addition to the change in the soil classification from clay with high plasticity (CH) to silt with high plasticity.

The free swell decreased significantly by mixing the lime-fly ash additive with the expansive soil, this decreasing trend continued as the additive content increased, and the free swell reached about 29% at maximum additive content (3% lime and 15% fly ash) compared to 55% for untreated sample. The swell potential decreased Markey on using the additive, where a swell potential of about 5% at maximum additive contents compare to 11.4% for untreated samples.

The swelling pressure decreased from 240 kPa to 90 kPa on mixing the soil with the maximum additive content.

Concerning the curing time impact on the additive efficiency the swelling pressure was reduced greatly, knowing that the swelling pressure was 90 kPa at maximum additive content with no curing time, while after curing for 7 days it reached 30 kPa.

This is attributed to the decrease in the diffuse double layer thickness, the flocculation of clay particles and the increase in the silt and sand size portion in the soil due to the agglomeration of fine clay particles (Sivapullaiah et al.1996), in addition to the decrease in the activity which indicates a decrease in the soil affinity to absorb water.

It is demonstrated from the standard proctor compaction tests that the optimum moisture content and the maximum dry density decreased as the additive content increased.

This is because of the cation exchange between the lime-fly ash and expansive soils which decreased the thickness of the electric double layer leading to the progress of soil particle flocculation allowing the compaction of the mixture at lower water content and consequently reaching lower the optimum moisture content. Lees et al. (1982) and Bell (1996) noted that the low specific gravity of the additives is the reason for the reduction in the maximum dry unit weight as the additive percentage increased.

Omer Hamza (2014) performed a study to investigate the effect of lime–fly ash additive on mitigating the swelling potential of expansive soils. Two soil samples were collected from different areas in Sudan: Madani in Gezira and Gedarif. The soil properties and swelling potential are shown in Table (4).

Table (4): shows the soil properties and swelling potential values.

Property	Median Soil	Gedarif Soil
Liquid Limit (%)	69	78
Plastic Limit (%)	34	38
Plasticity Index (%)	35	40
Free Swell (%)	120	188
Swelling Pressure (kg / cm^2)	17	28.5

The lime material was obtained from Kassala, while the fly ash material was collected from Gary Electrical Station in North Khartoum. The lime content ranged from 3% to 15 % and the fly ash content ranged from 5% to 10%.

Several experimental tests were conducted namely; the Atterberg limits test, free swell test and one-dimensional oedometer test. The free swell test and one-dimensional oedometer test were conducted in accordance with BS 1377 (1990) standard.

Results indicated that the lime–fly ash additive decreased the Atterberg limits till converting the soil to a non-plastic soil as its percentage increased. Similarly, the free swell showed a steep reduction in its value. Tables (5 and 6) summarize the obtained results. Moreover, the swelling pressure was seized on using the additive mixtures. Table (7) presents the swelling pressure values.

Table (4): Atterberg limits and free swell percentage for Median soil

Lime (%)	Fly ash (%)	L.L (%)	P.L (%)	P.I (%)	Free Swell (%)
0	0	69	34	65	120
3	5	68	43.2	24.8	90
5	5	60.2	45.9	14.3	80
8	5	Non-Plastic			70
12	5	Non-Plastic			65
15	5	Non-Plastic			55
3	10	61.5	50.1	11.4	80
5	10	Non-Plastic			75
8	10	Non-Plastic			65
12	10	Non-Plastic			60
15	10	Non-Plastic			55

Table (6): Atterberg limits and free swell percentage for Gedarif soil

Lime (%)	Fly ash (%)	L.L (%)	P.L (%)	P.I (%)	Free Swell (%)
0	0	69	34	65	120
3	5	79.9	51.5	28.4	114
5	5	Non-Plastic			80
8	5	Non-Plastic			80
12	5	Non-Plastic			50
15	5	Non-Plastic			60
3	10	74.9	50.3	24.6	60
5	10	Non-Plastic			90

8	10	Non-Plastic	80
12	10	Non-Plastic	78
15	10	Non-Plastic	65

Table (7): Swelling pressure for Median and Gedarif soil

Lime (%)	Fly ash (%)	Median Soil	Gedarif soil
0	0	17	28.6
8	5	0	0
5	10	0	0

2.3 Lime stabilization

Mohammed and Elsharief (2015) performed an experimental study on three types of expansive soils collected from different locations in Sudan mixed with variable contents of construction-hydrated lime.

Samples were prepared by adding lime in increments of 0.5% by weight to the tested soil up to 10.5% for Soil 1, 5.5% for Soil 2 and 9.5% for Soil 3, then mixed carefully with distilled water and left for two hours to cure.

The liquid and plastic limit tests were carried out for each increment using the falling cone method and B.S. 1377-1990 test procedures.

Results showed that the addition of lime to the natural samples decreased their liquid limit, increased their plastic limit and accordingly reduced their plasticity index.

It was concluded that the addition of lime to the soil successfully reduced the plasticity.

Due to the variability in the soil's mineralogical composition and fine content, they showed a different response to the lime addition. Results revealed that the lime had a great effect on reducing the plasticity of the montmorillonite clays, unlike the kaolinite clays.

Mateos (1964) and Bhasin et al. (1978) reported that the swelling of expansive soils can be controlled effectively using lime by physicochemical modifications. Wang et al. (1963) and Bell (1988) reported that increasing the lime content decreases the liquid limit of the soils. Herrin and Mitchell (1961) and Barker et al. (2006) stated that on adding lime to the soil the plastic limit usually exerts an increasing trend.

Dash and Hussain (2012) performed an experimental study to investigate the effect of lime additives with variable contents of 1, 3, 5, 9 and 13% by weight of dry soil on the swelling manner and plasticity characteristics of the soil.

Six soils were prepared by mixing expansive bentonite (ES) with non-expansive soil (NES) which consisted mainly of silt to obtain a wide range of plasticity. Table (8) introduced the properties of the six soils.

Table (8) presents the soil properties.

Soil	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
100% ES	459.9	53.7	406.2
80% ES + 20% NES	351.9	49.4	302.5
60% ES + 40% NES	248.2	38.1	210.1
40% ES + 60% NES	178.8	30.7	148.1
20% ES + 80% NES	99.2	28.7	70.5
100% NES	45.3	25.9	19.4

Several curing periods were considered in the study which were 0, 3, 7, 21, and 28 days. The soil and lime were mixed with water to form a slurry and left for the required curing period after which the liquid and plastic limit tests were executed.

The specimens to be tested in the oedometer were prepared at optimum moisture content; an extra quantity of water corresponding to 32 % of the lime weight was added to compensate for the lime hydration. The soil was compacted statically in the oedometer ring to the maximum dry density.

A surcharge of 5 kPa was applied to the sample then it was inundated and left for 30 days. Curing took place during the swell test, as it is estimated that the pozzolanic reaction of the lime takes 28 days so the swell test was left for 30 days.

For all the soil samples it was observed that as the lime content increased the liquid limit decreased, the reducing effect was more pronounced on the 100 % bentonite soil sample and this effect decreased as the non-expansive soil content increased.

Figures (4a and b) presents the relationship between the liquid limit and the lime content for different curing periods for 100% ES and 100 NES soils respectively. The responses of the other soil mixes are intermediate to these trends.

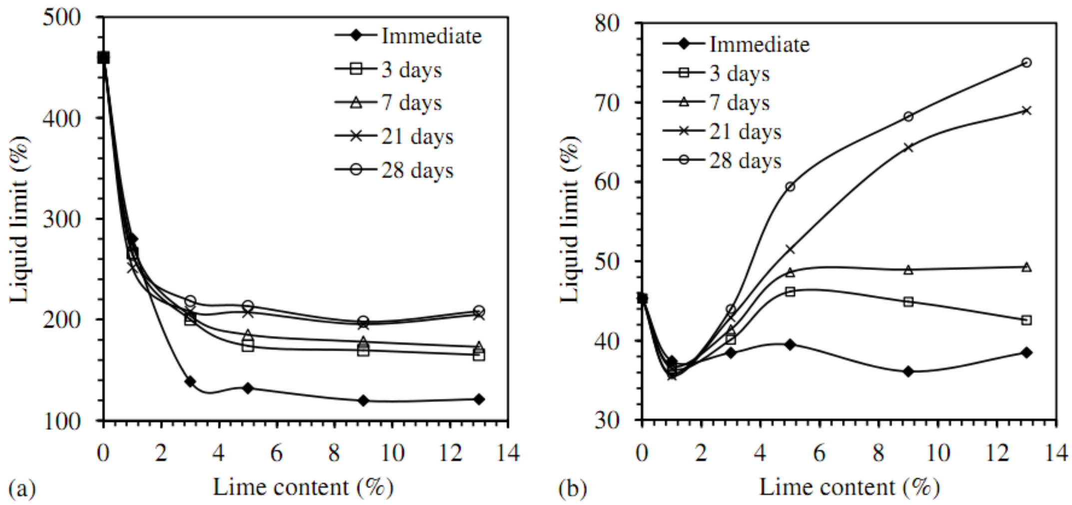


Figure 4. (a) Relationship between the liquid limit and the lime content for different curing periods for 100% ES soil, (b) Relationship between the liquid limit and the lime content for different curing periods 100 NES soils, (Dash and Hussain (2012))

This is attributed to the increases in the electrolyte concentration in the pore fluid due to the release of the Ca^{+} by adding lime which decreases the diffuse double-layer thickness. The liquid limit continued to decrease until a 3% lime content after which there was not much reduction in the liquid limit.

The liquid limit showed an increasing trend for soils having a high content of silica-rich non-expansive soil mixed with 13% lime and cured for 21 and 28 days.

The plastic limit increased at a faster pace until 3% lime content then it slowed down at lime content from 3 to 5%. Only for soils having more than 80 % non-expansive soil and cured for long periods (21 and 28 days) an obvious increase in the plastic limit was observed.

The plasticity index of all the soils decreased as the lime content increased, for the bentonite sample the plasticity index decreased from 400 to 50% indicating that the soil had changed which was confirmed from the plasticity chart as the mixed soils with lime crossed the A- line to the silt zone.

The reason that soils containing a big amount of non-expansive soil and cured for long periods showed an increasing trend in the plasticity index, was due to the too much creation of silica gel that increases the soil capacity for holding water.

Results obtained from the one-dimensional oedometer test showed a stepped reduction in the swell strain as the lime content increased till reaching a lime content of 5%. The reduction in swell strain was up to about 99% at 5% lime content. This reduction was due to the decrease in the diffused double-layer thickness because of the increased electrolyte concentration.

By increasing the lime content over 5% the swell strain started to increase again, this is attributed to the formation of the silica gel which changed the nature of the non-expansive soil to be moderately swelling soil inducing a swell strain of 5.5% at 13% lime content.

A significant increase in swell strain was observed at 9% lime content for soils containing non-expansive soil portion of 40% and greater, while for lower contents of a non-expansive fraction of 5% a significant swell strain was demonstrated. Table (9) presents a summary of the swelling potential for different soils.

Table (9) Summary of swell potential for different soils

Soil	Lime Content (%)					
	0%	1%	3%	5%	9%	13%
100% ES	97.10	18.60	1.46	0.72	7.25	10.30
80% ES + 20%	48.10	11.90	0.87	1.04	5.96	6.80
60% ES + 40%	34.20	5.15	0.63	0.85	0.98	5.68
40% ES + 60%	26.30	0.71	0.00	0.13	0.38	9.52
20% ES + 80%	3.89	0.22	0.00	0.10	0.17	8.95
100% NES	0.25	0.05	0.06	0.01	1.35	5.54

The explanation for this phenomenon is that soils exhibiting higher content of coarse-grained particles tend to have voids that are filled with the silica gel, as the gel volume exceeds the voids volume the swelling starts. This shows that the swelling of soils mixed with lime is influenced by the grain size.

Ingrid Belchior et al., (2017) investigated the effect of lime additive on the swelling potential of Eagle Ford clay found in Texas, United States. The new geotechnical centrifuge test was used in the study that allows testing multiple specimens simultaneously in a very short time.

Hydrated high-calcium lime with 94% of Ca (OH)2 was used in the study. The lime content was in the order of 0.5, 1, 2, 3 and 4% of dry soil weight.

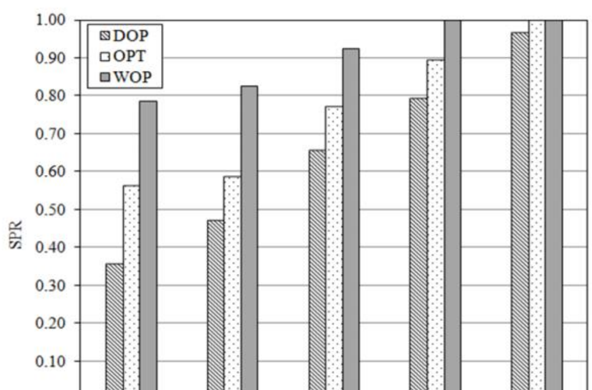
The samples were prepared at different densities and water content. The compaction density varied between relative compaction of 94% (RC 94%) and relative compaction of 100% (RC 100%) of the maximum dry density. The compaction moisture content varied between dry of optimum (DOP), optimum (OPT) and wet of optimum (WOP) moisture content.

A parameter, named Swelling Potential Reduction Ratio (SPR) was presented in the study which measures the reduction of the swelling potential made by hydrated lime additive regarding to swelling potential in natural soil. SPR will be zero for untreated Eagle Ford clay and will be one when the reduction in swelling potential is 100%. Equation (1) defines the SRP.

Therefore, the higher SPR is, the lime treatment can be considered more efficient.

$$SRP = 1 - \frac{Sp\ (n\%\ HL)}{Sp\ (0\%\ HL)} \tag{1}$$

Results showed that only 2% of lime was needed to seize the swelling potential for samples compacted with wet of optimum (WOP) moisture content, while 4% of lime was required to prevent swelling of samples compacted at dry of optimum (DOP) moisture content. Figure (5) presents a histogram of the outcomes.

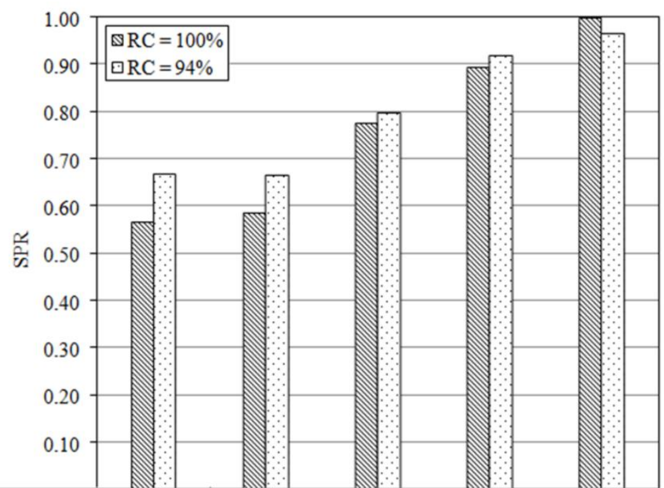


HL (%)	0.5	1	2	3	4
DOP	0.36	0.47	0.66	0.79	0.97
OPT	0.56	0.59	0.77	0.89	1.00
WOP	0.79	0.82	0.92	1.00	1.00

Figure 5. Swelling potential reduction ratio (SPR) at different moisture contents,

(Ingrid Belchior et al., (2017))

It was noticed that efficiency of lime additive to reduce the swelling potential increased as the dry density decreased except for the 4% of hydrated lime. Figure (6) shows a histogram for the findings.



HL(%)	0.5	1	2	3	4
RC = 100%	0.57	0.59	0.77	0.89	1.00
RC = 94%	0.67	0.67	0.80	0.92	0.97

Figure 6. Effect of relative compaction on swelling potential reduction ratio (SPR) for different lime contents, (Ingrid Belchior et al., (2017))

2.4 Cement stabilization

Abdullah, and Alsharqi (2011) investigated the effect of mixing Portland cement with expansive soil on the swell potential characteristics. Several cement contents were utilized in the study (1, 2, 3 and 4%) and two curing periods of 7 and 28 days were applied.

The oedometer was used to evaluate the swelling pressure and strain in accordance with ASTM (D 4546) Method A and Method C. The specimens were compacted statically to the desired dry unit weight.

The swelling strain was obtained by applying Method A as the specimens were allowed to swell under a surcharge pressure of 6.9 kPa, while the swelling pressure was determined by applying Method C where the specimen height was kept constant by increasing the loads on the sample.

Results showed that the addition of cement reduced the swell strain greatly, where adding 2% cement and curing for 28 days reduced the swell strain from 7.4% to 0.4%, similarly, the vertical swelling pressure was reduced from 333 kPa to 20 kPa.

Mahamedi Abdelkrim and, K hemissa Mohamed, (2013), executed a laboratory study on expansive silty clay obtained from a site located in Sidi -Aissa city (wilaya of M’sila, Algeria) to evaluate the efficiency of Portland cement additive in mitigating the swelling potential of the soil. Table (10) presents the expansive soil properties.

Table (10): Properties of expansive soil

Property	Quantity
Liquid Limit (%)	43.8
Plastic Limit (%)	19.04
Plasticity Index (%)	24.76
Swelling Pressure (kPa)	195
Free Swelling (%)	18.44
USCS Classification	CL

Serval Portland cement contents were used, namely: 1, 2, 3, 4, 5, 6, 7 and 8% by weight. Finely crushed dried soil was mixed with the cement content at dry conditions, and then water was added at the optimum water content.

The obtained results showed that the swelling pressure and its corresponding free swelling decreased significantly on cement addition. This is due to the cementing effect causing soil stabilization, as it seems that the cement content over 3% makes the clay insensitive to swelling. Figure (7) presents the swelling pressure versus the cement content, while Figure (8) presents the free swelling versus the cement content.

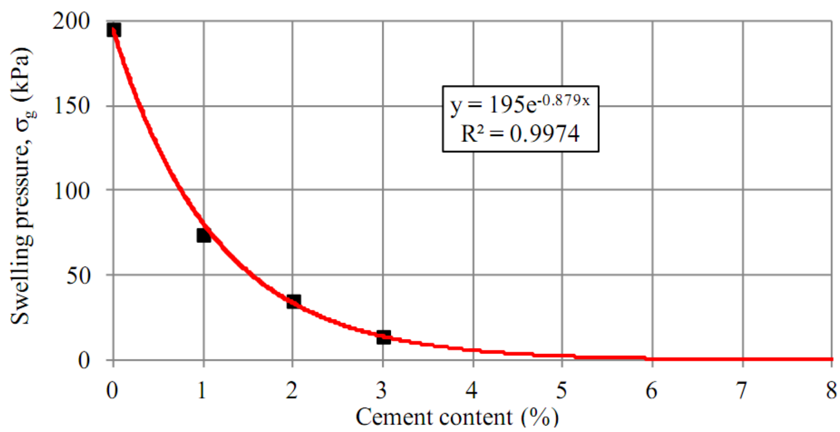


Figure 7. Swelling pressure versus the cement content, (Mahamedi Abdelkrim and, K hemissa Mohamed, (2013))

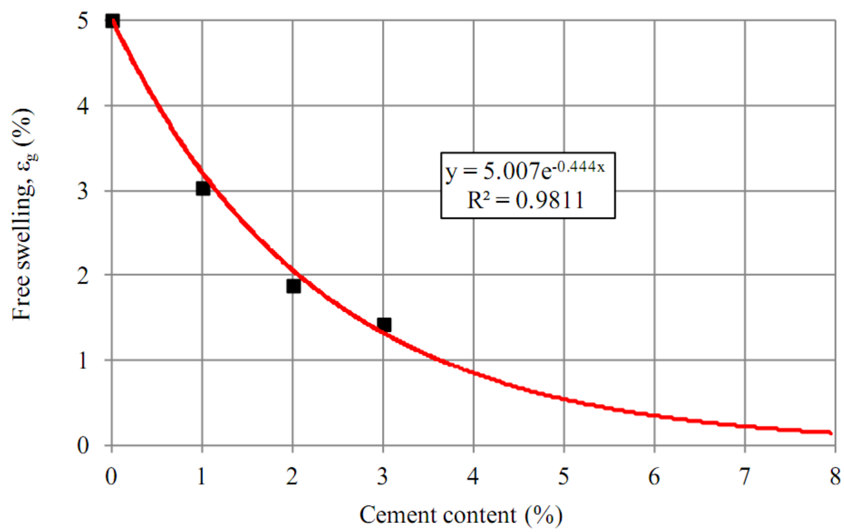


Figure 8. Free swelling versus the cement content, (Mahamedi Abdelkrim and, K hemissa Mohamed, (2013))

Alaa D. Almurshedi et al., (2019) performed an experimental study on expansive soil collected from the province of Karbala in Iraq to evaluate the effect of cement dust on the soil swelling potential. The soil properties are presented in Table (11).

Atterberg limits, Free swell index and swelling pressure values were determined for the treated and untreated samples.

Table (11): Properties of expansive soil

Property	Quantity
Specific Gravity	2.61
Liquid Limit (%)	88
Plastic Limit (%)	33
Plasticity Index (%)	55
Swelling Pressure (kPa)	195
Free Swelling (%)	18.44
USCS Classification	CH

Five different percentages of cement dust were utilized in the study which were 4, 8, 12, 16 and 20%.

The soil was dried and ground, after which it was mixed with cement dust and the optimum water content. The soil mixtures were cured for 7, 14, 21 and 28 days.

Samples were compacted in moulds in accordance with the Standard Proctor Compaction test. A Shelby tube that is 50 mm in diameter was used to extract the samples. The obtained samples were cut into 100 mm long.

Results revealed a significant decrease in all the Atterberg limits as cement dust contents increased. This is because cement dust is a soft and very fine matter which occupies the voids between soil particles instead of water which will reduce the water content of the treated soils. The pronounced effect of cement dust on the consistency limits is shown in Figure (9).

Low consistency limits are considered favourable due to their low swelling potential.

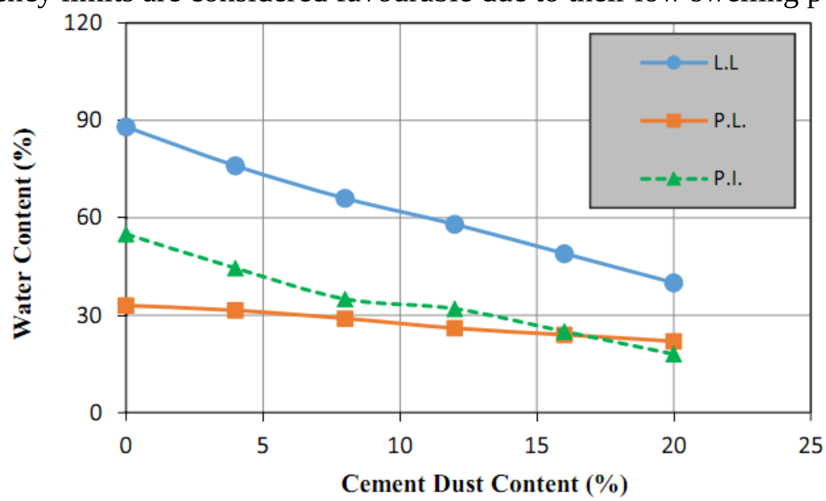


Figure 9. Effect of cement dust on the consistency limits, (Alaa D. Almurshedi et al., (2019))

Concerning the curing time effect, it was observed that the plasticity index decreased considerably as samples were cured for a longer time. Figure (10) shows the effect of curing time on the plasticity index with different cement dust content. The figure reveals that the plasticity index decreased at a small rate at cement dust content of about 4% to 8%, whereas the plasticity index decreased at a greater rate at cement dust content of 12% to 20% for all curing periods.

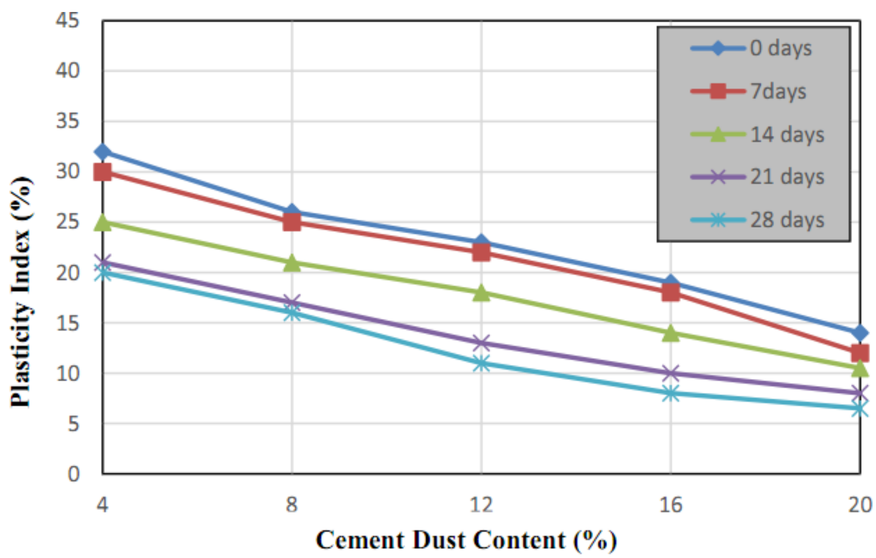


Figure (10) Effect of curing time on the plasticity index with different cement dust content, Alaa D. Almurshedi et al., (2019)

The Free Swelling Index (FSI) was determined for the cured samples, as samples were soaked in distilled water and kerosene for 24 hours, after which the height of sediment columns in water (Vw) and in kerosene (Vk) were recorded. Equation (2) presents the calculation of the deferential Free Swelling Index.

$$FSI = (V_W - V_k) / V_k \qquad (2)$$

It was observed that the curing periods had an obvious decreasing effect on the (FSI) for all cement dust contents except cement content of 8%. Figure (11) introduces the Swelling Index versus cement dust content for different curing periods. A significant reduction in the (FSI) was noticed as it reached about 75%.

A significant reduction in the swelling pressure was detected as the cement content increased which reached 43%. Figure (12) shows the relation between the swelling pressure and the cement dust content.

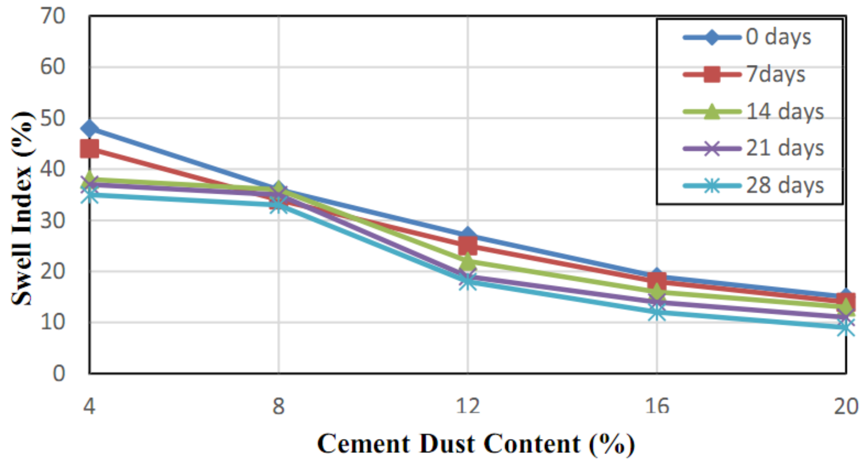


Figure 11. Swelling Index versus cement dust content for different curing periods, Alaa D. Almurshedi et al., (2019)

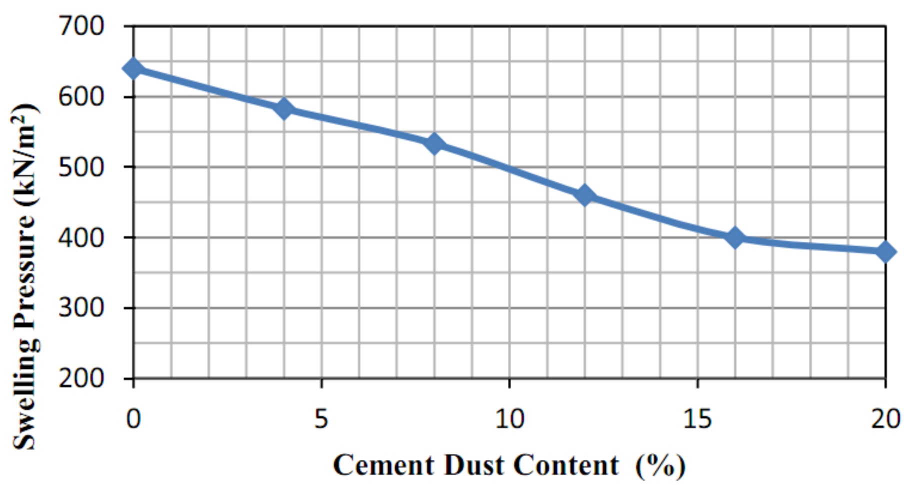


Figure (12) Swelling pressure versus the cement dust content, Alaa D. Almurshedi et al., (2019)

2.5 Polypropylene fiber stabilization

Loehr (2000) investigated the effect of polypropylene fibers inclusion on the free swell displacements of expansive soil by performing several tests using the standard oedometer.

Results showed that the fiber inclusions within the expansive soil reduce the swell displacements significantly.

Puppala and Musenda (2007) reported that discrete and randomly oriented polypropylene fiber reinforcement reduced the expansive soil vertical swelling pressure.

Soğancı (2015) performed an experimental study to investigate the effect of polypropylene fiber on expansive soil. The fiber contents used in the study were 0, 0.5, 0.75 and 1% of air-dried soil. The samples were prepared at the optimum moisture content and left 24 hours for curing then it was compacted statically to the maximum dry unit weight.

The standard oedometer was used to test the samples which had an internal diameter of 50 mm and a height of 19 mm. A surcharge pressure of 7 kPa was applied to the inundated samples. After reaching equilibrium the samples were loaded till reaching the initial void ratio.

Results showed that the free swell expressed as percentage swell decreased as the fiber content increased, where the reduction in the percentage swell was about 37.5, 43.1 and 54.1% on using 0.5, 0.75 and 1% fiber contents respectively.

Ikizler et al. (2009) investigated the effect of fibers on the swelling characteristics and index properties of expansive soil. Atterberg limits, Standard Proctor test and one-dimensional swell potential test were utilized in the study. High swelling potential bentonite consisting mainly of sodium montmorillonite was used as the expansive soil, with its properties introduced in table (12).

Table (12): Properties of expansive soil

Property	Quantity
Specific Gravity	2.51
Liquid Limit (%)	635
Plastic Limit (%)	66
Plasticity Index (%)	569
Swelling Pressure (kPa)	195
Free Swelling (%)	18.44
USCS Classification	CH

Two types of polypropylene fibers (fibrillated polypropylene fiber (F) and multifilament fiber (M) with several mixing contents of 0.2, 0.3, 0.4 and 0.5% by dry soil weight were used in the study.

The specimens were prepared at optimum moisture content and compacted in the oedometer ring to the maximum dry density. After inundating the specimen volume was kept constant by increasing the vertical pressure till no more swell was observed then the test was terminated.

Results showed that at 0.2% multifilament fiber (M) additive, the liquid limit and the plasticity index decreased, however, by increasing the fiber content the liquid limit and the plasticity index started to increase but still it was less than the values of untreated soil.

For the fibrillated polypropylene fiber (F), the liquid limit and the plasticity index decreased as the fiber content increased. Figure (13) presents a histogram summarizing the outcomes.

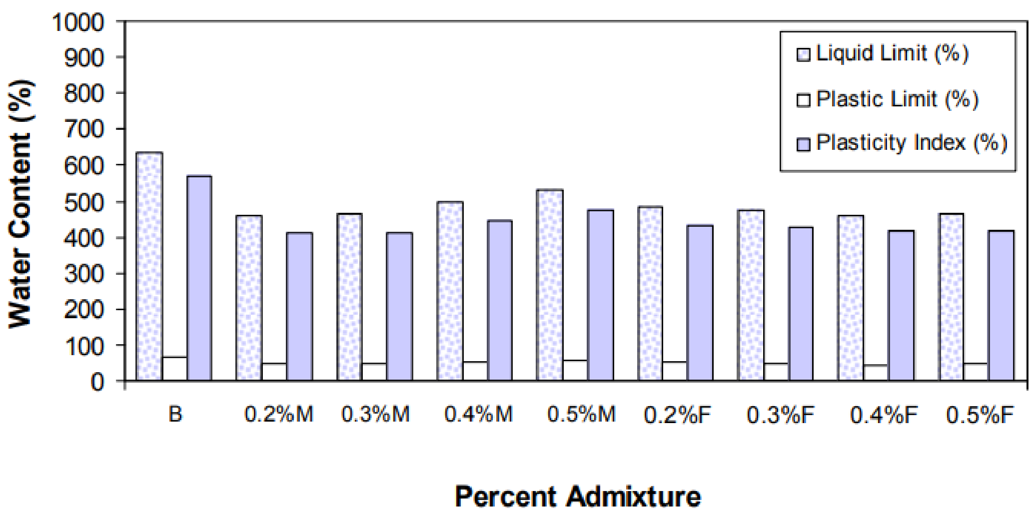


Figure 13. Consistency indices for the two fiber types with different contents, (Ikizler et al. (2009))

The swelling pressure was reduced by using a multifilament fiber (M) additive with a mixing content of 0.2 %. In spite of increasing the additive content, the reduction percentage decreased showing no effect at 0.5% fiber content. This demonstrated the less effectiveness of the treatment at higher fiber contents. It was concluded that a fiber content of 0.2 to 0.3 % would be best for reducing the swelling pressure.

For the fibrillated polypropylene fiber (F) additive, the swelling pressure continued to decrease as the fiber content increased. On comparing the two fiber types the multifilament fiber (M) is more efficient in reducing the swelling pressure than the fibrillated polypropylene fiber (F). The swelling pressure values is presented in Figure (14).

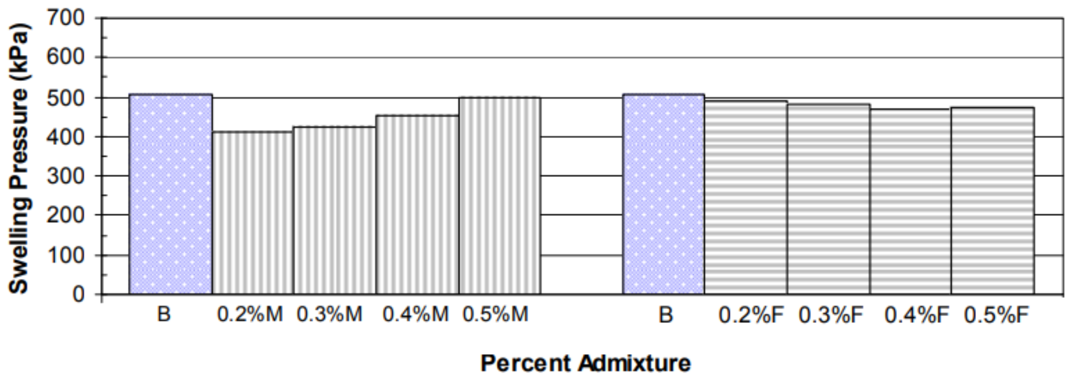


Figure 14. Swelling pressure for the two fiber types with different contents, Ikizler et al. (2009))

Malekzadeh and Bilsel (2012) conducted free swell tests on expansive soil mixed with variable contents of polypropylene fibers to study its effect on the soil swelling characteristics. The fiber contents were 0.5, 0.75 and 1% by dry weight of soil and the standard oedometer apparatus was used in the study.

The specimens were prepared at optimum moisture content and left for 24 hours for curing, then the fibers were mixed with the soil, after which the matrix was compacted statically in the oedometer ring. The specimens were allowed to swell under a surcharge pressure of 7 kPa.

Results showed that on using fiber contents of 0.5 and 0.75% the swell strain increased, however, increasing the content to 1% reduced the swell strain.

Loehr et. al. (2000) stated that on testing reinforced samples with fibers having a diameter of 10.2 cm the swell percentage decreased as the fiber content increased while testing the soil samples with a diameter of 6.4 cm led to an increase in the swell percentage. This observation indicated that sample size influences the results.

3. Reinforcement inclusion technique

The technique of inserting inclusions within the expansive soil mass is used for the treatment of greater depths. This is attained by the installation of geogrid reinforced columns or sand columns within the expansive soil. The reinforcement inclusion technique can be applied to shallow depths by the embedment of geogrids within the expansive soil.

3.1 Geogrid embedment

Zornberg and Gupta (2009) reported that roads passing through zones encountering expansive soils in Texas suffered longitudinal cracks due to volumetric changes in the soil as a result of seasonal fluctuation of moisture content.

In the dry season the soil moisture content under the shoulder decreases, while it remains constant under the pavement centerline causing shrinkage of the soil under the shoulder and leading to settlements, on the other hand, in wet seasons the soil moisture content under the shoulder increases causing the soil to heave while at the pavement centerline, the moisture content remains unchanged.

Such longitudinal cracks result from the induced tensile stresses caused by flexure of the pavement section during the dry season, this is confirmed by the visualization of the open wide longitudinal cracks at the end of the dry season and the partial closure of such cracks at the wet season.

Such cyclic movements cause substantial damage to the pavement as experienced by the Texas Department of Transportation (TxDOT).

Zornberg and Gupta (2009) reported that in 1996 road FM 1915 located in Milam County, Texas suffered longitudinal cracks due to the existence of high-plasticity clay. Two sections with base layer thicknesses of 0.2 and 0.127 m were treated by embedding a geogrid layer at the interface between the subgrade and the base layer. These sections were compared to a control section with a base layer thickness of 0.2 m.

Observations indicated that geogrid reinforced sections did not suffer any longitudinal cracks, while the control section showed significant longitudinal cracks.

Zornberg and Gupta (2009) demonstrated the geogrid reinforcement mechanism by evaluating road section FM 542, sited in Leon County, Texas. The road shoulder was upgraded to serve as an alternative traffic lane. The subgrade was stabilized by lime in addition to embedding a reinforced geogrid layer between the subgrade and the base layer.

Longitudinal cracks were observed in the shoulder section before the road was opened to traffic. A trench was excavated to investigate the defect, which revealed that the contractor used a shorter geogrid roll which did not cover the whole section as seen in Figure (15). The crack was located directly at the edge of the shorter-than-required geogrid reinforcement.

This incident confirmed the effectiveness of the geogrid reinforcement in mitigating the swelling soil damage in addition to relocating the cracks away from the reinforced zone.

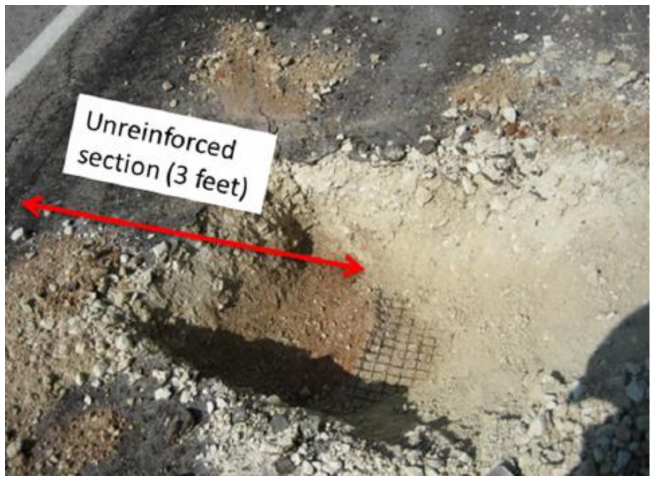


Figure 15. Incomplete coverage of the shoulder section by the geogrid layer induced a longitudinal crack, (Zornberg and Gupta (2009))

Stalin et al. (2010) performed an experimental study to investigate the effect of geogrid, geomenbranes and geotextiles embedded to mitigate swelling characteristics of expansive soils. This was done by varying the reinforcement orientation and the number of layers. Table (13) shows the expansive soil properties.

Table (13): Properties of expansive soil

Property	Quantity
Specific Gravity	2.70
Liquid Limit (%)	62
Plastic Limit (%)	28
Plasticity Index (%)	34
Free Swelling Index (%)	78

The soil sample of height 80 mm was statically compacted to the maximum dry density and at the optimum moisture content in a mould of diameter 150 mm. Geosynthetics were placed in the sample at the decided locations as required before the soil is subjected to compaction.

The expansive soil was compacted statically to the maximum dry density (1.64 kN / m^3) at the optimum moisture content (18%) in a mould having a diameter of 150 mm and a height of 80 mm. The geosynthetics were placed horizontally prior to soil compaction at the middle of the specimen in the case of using one layer, while in the case of placing two layers, the geosynthetics were positioned such that it divided the specimen height into three-thirds.

Dial–time readings were recorded after applying a surcharge pressure of 5 kPa and inundating the specimen till reaching equilibrium.

For the case of one-layer embedment, the time-swell relationship results showed that at 4000 min the reduction in swelling was 38% for the geomembrane, 17% for the geogrid, 8% for the geocomposite and 6% for the geotextile.

This reduction is attributed to passive resistance. The same order was observed for the case of using two horizontal layers where a reduction of 52%, 28% and 10% in swelling was reached on using geomembrane, geogrid, geocomposite and geotextile respectively.

It is seen that the usage of two horizontal layers of geosynthetics is more efficient in reducing the swelling percentage. This is due to the mobilized friction between the soil and geosynthetic material.

Geomembrane was found to control the swelling of clay greatly compared to geogrid, geotextile and geocomposite. This may be related to the mechanism of passive resistance developed below the geomembrane layer because of the swelling of underlying clay. The reduction of percentage swell was in the order of geomembrane < geogrid < geotextile < geocomposite.

Placing the geosynthetics in the vertical direction reduced the swelling more than the horizontal placement for all the geosynthetic types except the geomembrane.

3.2 Geogrid column reinforcement

Al-Omari et al. (2016) reported that the use of geogrid-reinforced columns to reduce the free swell of the expansive soil is based on the induced tensile bond on the soil-geogrid interface which limits the soil particle movements. Such developed bonds can be attributed to friction, adhesion and interlocking.

Zornberg (2010) reported that as the shear strain reaches as certain value, a shear band develops near the surface between the soil and the geosynthetics. The reinforcement mechanism is based on the anti-sliding effect created at the soil-reinforcement interface.

The friction and interlocking are two criteria occurring at different stages, this is because the friction is developed as a result of the relative displacement between the soil and the geosynthetic material, while interlocking is developed at large displacement situations due to the interaction between the soil and the geogrid.

Based on a large scale pull-out test, Hoared (1979) noted that the shear band is developed after the soil particles are rolled and crushed. The interface consists of the shear band which is approximately 5 to 6 times the average size of the soil particle and the contact surface.

Al-Omari et al. (2016) performed an experimental study using a large-scale oedometer and CBR mould to investigate the effect of embedded cylindrical geogrid reinforced columns with variable diameters (20, 30 and 50 mm) and different stiffness (120, 40 kN / m) on the expansive soil swell potential. The CBR mould had a diameter of 152.4 mm and a height of 177.8 mm.

Three expansive soils were tested which were, bentonite base-Na, bentonite Base-Ca and a mixture composed of 30% kaolinite and 70% bentonite base-Na having plasticity indices of 100, 79 and 82% respectively and inducing variable swell potentials.

The kaolinite was obtained from the State Company for Geological Survey and Mining in Baghdad city while the two bentonite types were obtained from Kirkuk City North of Iraq.

The geogrid reinforced columns were filled with sand or the same expansive clay.

Standard oedometer tests were conducted on the control samples prepared at optimum moisture content and compacted statically in a 50 mm diameter ring. The samples were allowed to swell under a pressure of 7 kPa.

The large samples prepared in the CBR mould were compacted statically in three layers of 20 mm each, reaching a sample height of 60 mm. The samples were compacted at the dry side of the compaction curve.

A hole was drilled in the expansive soil so as to insert the geogrid reinforced column. A hopper at a calibrated height was used to control sand raining so as to reach a unit weight of 15.2 kN / m^3 corresponding to the void ratio of 0.76 and relative density of 23%.

Due to the long time required for the samples to accomplish the swelling a time of 15 days was adopted for all the test groups in the CBR mould.

Results showed that the reduction in void ratio and height for treated samples was smaller than that of untreated samples during loading, furthermore, it was observed that the rate of reduction was high for untreated samples and it was small for the treated samples.

This is attributed to the reinforcement effect of the geogrid which strengthens the soil, where the tensile bond is developed on the soil-reinforcement interface, which restricts the movement of soil particles. This bond could be due to adhesion, interlocking or friction.

It was noted that the free swell was reduced significantly on using the geogrid columns. The geogrid stiffness has a small share in reducing the free swell, while, results indicated that the geogrid diameter has a pronounced effect on reducing the free swell, this is because as the diameter increases the column surface area increases which enhances the interlocking between the soil and the geogrid.

A factor, named the improvement factor (IF) was presented in the study. It was defined as the difference between the final swell of the unreinforced sample (Wu) and the final swell of the reinforced sample (Wr) divided by the final unreinforced swell. Equation (3) presents the (IF) factor.

$$\mathrm{IF} = \frac{Wu - Wr}{Wu} \qquad (3)$$

The improvement factors ranged from 30 to 60%, depending on the plasticity index, type of fill material and geogrid stiffness.

Filling the geogrid reinforcement column with sand was more effective in reducing the free swell than filling it with the same expansive clay since sand is more permeable and less compressible than clays.

3.3 Sand column reinforcement

Aparna, et al., (2014) executed an experimental study to investigate the effect of sand column installation within the expansive soil mass on the induced swell strain. Black cotton soil and fine river sand were utilized in the research.

The expansive soil was mixed with variable initial moisture contents (14, 18, 22, 26, 30, 36, 40 and 44%) and compacted to a dry density of 15 kN / m^3 in three layers in a cylindrical mould having a diameter of 100 mm and a height of 128 mm.

A hole was made in the soil using an auger and a casing pipe to install the sand columns having diameters of 25, 37.5 and 50 mm. The sand was compacted in layers to the required density.

Porous plates and filter papers were placed below and above the sample in addition to the placement of a collar. A heave stake was mounted on the sample, over which a dial gauge was placed to measure the swelling heave.

The whole test setup was placed in a water tank and heave dial readings were recorded till stabilization.

Results showed a step reduction in the swelling heaves on increasing the sand column diameter. A great reduction was observed on testing soil with the lowest mixing moisture content (14%), where a reduction of 11.5, 23 and 42% was reached on using sand column diameters of 25, 37.5 and 50 mm respectively.

This is attributed to the replacement of the expansive soil by non-expansive soil. It was observed that as the moisture content increased the swelling strain decreased.

Muhannd W. Majeed et al., (2018) conducted research to demonstrate the influence of sand column reinforcement on the swelling characteristics and consistency limits of expansive soil.

The sand column had three diameters which were 1, 1.5 and 2 cm, with three sizes of sand 0.850, 1.18, and 2.36 mm.

The expansive soil was gotten from the State Company, of Geological Survey and Mining in the form of powder. Table (14) introduced the expansive soil properties.

Table (14): Properties of expansive soil

Property	Quantity
Specific Gravity	2.84
Liquid Limit (%)	160
Plastic Limit (%)	62
Plasticity Index (%)	98
Swelling Pressure (kPa)	195
Free Swelling (%)	18.44
USCS Classification	CH

Results showed a step reduction in the free swell value as the sand column diameter increased, similarly as the sand particle size increased for each sand column diameter the free swell value decreased. Table (15) presents a summary of the obtained free swell values.

It can be observed that the improvement percentage in suppressing the free swell ranged from 10.0 to 68.7% which is considered significant.

Table (15): Effect of the sand column on free swell values

Diameter of sand column, cm	The free swell of treated soil, mm			The free swell of untreated soil, mm	Original sample height, mm
	Sand size, mm				
	0.85	1.18	2.36		
1	5.4	5.35	3.83	6	12
1.5	4.5	3.18	2.48	6	12
2	2.7	2.21	1.88	6	12

The swelling pressure was evaluated by inundating the samples and preventing them from swelling by increasing the applied stresses till equilibrium was reached. It was noticed that as the sand column diameter increased the swelling pressure decreased, moreover, for the same sand column diameter the swelling pressure decreased as the sand particle size increased. Table (16) presents the swelling pressure values.

Table (16): Effect of the sand column on the swelling pressure values

Diameter of sand column, cm	Swelling pressure of treated soil, (kN / m^2) Sand size, mm			Swelling pressure of untreated soil, (kN / m^2)
	0.85	1.18	2.36	
1	23.32	19.06	8.32	24.66
1.5	19.45	15.25	6.88	
2	1634	10.00	6.10	

It can be observed that the improvement percentage in controlling the swelling pressure ranged from 5.4 to 75.3% which is considered significant.

4. Discussion

The browse treatment techniques in the paper demonstrated their feasibility in mitigating the swelling potential of the expansive soils. However, the choice of the treatment technique should be judged with the following aspects: (1) Economic factors (2) Expected control of volume changes by comprehending different treatment options (3) Site situations such as degree of expansiveness, moisture fluctuations, degree of fissuring, and permeability (4) Project nature (5) Allowable movement of the foundation (6) Type of distresses (7) Extent of distress associated damage (8) Time frame vacant for treatment.

Thus, an appropriate understanding of the challenge and the implementation efforts possibly will lead to the more effective performance of structures on expansive soils.

Mixing treatment technique and reinforcement inclusion treatment technique can be considered cost-saving practices compared to soil replacement procedure, moreover, it reduces the dependence on natural material resources needed for the replacement process.

Fly ash and cement dust are considered a byproduct that is induced from coal-burning in power plants and cement production factories. Those materials pollute the environment, being industrial waste which is a problem facing industrial countries.

Accordingly, making benefit of such materials in mitigating swelling potential is considered a win-win situation.

Fly ash, lime and polypropylene fibre are cheap materials that can have an enormous economic impact by making areas encountering expansive soils in new desert cities suitable for construction.

On comparing the improvement percentage in controlling the swelling characteristics of expansive soils for the additives used in the mixing treatment technique, it was clearly noticed that the lime and cement had better results in mitigating the swelling of the soil than the other additives, although, economic aspect should be well-thought-out on using cement additive in practical applications.

Sand column reinforcement demonstrated a superior reducing effect on the swelling of the soil than the geogrid column reinforcement, this makes the sand column reinforcement a competitor alternative to the geogrid column reinforcement considering the cost and effectiveness in field implementations.

From the observed results, it can be noticed that the mixing treatment technique utilizing lime and cement was the most effective treatment technique in mitigating swelling characteristics of expansive soils compared to reinforcement inclusion treatment technique.

The reinforced inclusion columns can be an effective and cheap treatment solution in situations where expansive soils extend to great depths which threaten the structure's safety.

5. Conclusion

This paper has presented a detailed review of studies performed on two treatment techniques which were the mixing treatment technique and reinforcement inclusion treatment technique.

In the mixing treatment technique, several additives were utilized such as fly ash, lime–fly ash, lime, cement and polypropylene fiber, while in the reinforcement inclusion treatment technique inclusions such as geogrid embedment, geogrid column reinforcement, sand column reinforcement was employed.

The primary motive of this article was to understand comprehensively the physical, chemical and microstructural changes occurring to the expansive soils treated with these additives in addition to the reinforcement effect of the inclusions that impacts the expansive soil swelling potential to make them suitable for construction purposes.

Based on the reported observations, the following major conclusions can be drawn:

1) Mixing treatment technique and reinforcement inclusion treatment technique showed a significant effect on reducing the swelling characteristics of the expansive soil.

2) Lime and cement additives were more efficient than fly-ash or polypropylene fiber additives in controlling the swelling characteristics of the soil, as their improvement percentage in mitigating swelling reached about 100%, while the fly-ash and the polypropylene fiber provided an improvement of about 50%, however, cement additive is more expensive compared to other additives which should be considered in practical application.

3) Curing period had a significant impact on increasing the effectiveness of the utilized treatment additives, where about a 60% increase in the efficiency of such additives was noticed on curing the samples for several days compared to 0 curing time, thus curing period must be considered in implementing mixing treatment to maximize the benefit.

4) If lime content exceeded its optimum value, the soil swelling characteristics will surge due to the formation of the silica gel which changes the nature of the soil.

5) The geosynthetic materials used as embedment in expansive soil can be ordered according to their effectiveness in mitigating swelling characteristics of expansive soil as:

   Geocomposite, geotextile, geogrid and geomembrane

6) Sand column reinforcement showed a greater stabilization effect than the geogrid column reinforcement in treating expansive soils, as it provided an improvement percentage of about 75% compared to about 60% on the usage of geogrid column reinforcement, this makes the sand column reinforcement advantageous, considering cost saving and effectiveness.

7) The effectiveness of the geogrid column reinforcement in controlling the swelling characteristics of expansive soil was nearly the same as the effectiveness of the fly ash and the polypropylene fiber additive, which makes it cheaper to use those additives.

8) Placing the geosynthetics in the vertical direction reduced the swelling more than the horizontal placement for all the geosynthetic types except the geomembrane.

Further research is recommended to be undertaken to further develop the findings of this paper which may include:

1. Investigating the scale effects on the performance of the treatment techniques including full-scale field investigation and large scale laboratory testing.
2. Applying numerical modelling on the soil-geosynthetic materials interaction and soil-sand column reinforcement interaction, taking into consideration unsaturated soil conditions and anisotropy of the clay and inserts.
3. Evaluating drainage conditions and rate of swelling for different treatment techniques.
4. Studying the effect of effective overburden pressure at inundation on the swelling pressure, swelling strain, and modulus of treated soils.
5. Utilizing different types of geosynthetics with different grades and stiffness.
6. Evaluating the effect of the expansive soil constituents and clay fabric on the treatment techniques results.
7. Results of the recommended work should be correlated with the actual field performance of–situ section constructed with the same respective soil mixing additives, percentage, geosynthetic type, orientation, and number of layers.

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