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ORIGINAL PAPER

Study the possibility of treating saline soils using cement-activated fly ash

Safa Hussain Abid Awn[1] · Hassan Obaid Abbas[2]

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Abstract

One of the most serious problems facing geotechnical engineers is the presence of saline soil because of its collapsing behavior which causes engineering problems for the foundations of the buildings constructed on it. These soils contain chloride salts that are quickly soluble in water when subjected to any sores of water, thus breaking the bonds between the molecules. Three types of saline soils with different salt content (7%, 25%, and 43%) were examined. The possibility of improving their ultimate bearing pressure was investigated using Portland cement-activated fly ash with different mixing proportions (5%, 10%, 15%, and 20%). The results of an experimental study conducted that mixing soil with 5% of this additive increased ultimate bearing pressure three times at the dry test and 6 times at the soaking test. This additive is considered economical and applicable for treating such problematic soil.

Keywords Saline soil · Soil stabilization · Fly ash · Portland cement

Introduction

Saline soils constitute about 7% of the Earth's land area (Lai et al. 2020). Salinity occurs due to the withdrawal processes of rivers and oceans, weathering, and unplanned irrigation of crops (Lai et al. 2020). The salts are formed as a result of the union of the chloride ion with other elements, including magnesium, calcium, potassium, or sodium, forming quick-dissolving salts (Ren et al. 2021). The human side plays a major role in changing the geographical map of the distribution and increase of saline soil areas. This may be due to the failure to follow modern methods of watering crops scientifically and the existence of a defect in the drainage system that leads to an increase in the concentration of salts in groundwater as a result of human intervention and ill-considered water management in dams (Sale and Kawy 2021). The bulldozing operations of agricultural lands and cutting down trees also contribute to increasing the salinity of the soil (Cheng et al. 2021), as happened to vast areas of Mesopotamia, after razing vast lands and cutting down palm trees, which contribute to the absorption of salinity from the soil (Nabil 1998). The ill-considered irrigation operations contribute to an increase in the salinity of the soil because the water contains dissolved salts (Truc and Mihova 2020), and as a result of leaving it for long periods under the sun's rays, these areas dry out and the salts accumulate in the soil, as shown in Fig. 1.

It can be seen from Fig. 1 that pure crystalline salts are present at the ground surface because of capillary action. The salty water evaporates, leaving the salts on the surface. The salinity rate in some sedimentary plain areas close to water bodies and open lands may reach 70%. This ratio starts to go down with depth. This situation appears in areas with water bodies that are prone to drought, as in the marshlands in southern Iraq, in addition to following the wrong irrigation methods in flooding agricultural lands for crops that depend on this method, such as rice and other crops. In some regions (southeast of Tunisia), given the semi-arid to arid climatic conditions, groundwater is an essential resource to meet the growth needs of social and economic development. To ensure sustainable development and conservation of water resources, it is necessary to make an accurate estimate of the current recharge and identify potential areas

Responsible Editor: Zeynal Abiddin Erguler

✉ Hassan Obaid Abbas
temimi71@yahoo.com

1 Department of Airports and Highways Engineering, Faculty of Engineering, University of Diyala, Baqubah, Diyala, Iraq

2 Department of Civil Engineering, Faculty of Engineering, University of Diyala, Baqubah City, Baqubah, Diyala, Iraq

Fig. 1 Accumulation of salts on the surface of the saline soil (south of Iraq)

of precipitation in order to accurately assess the regional water balance. In this context, a study showed a preliminary assessment of groundwater recharge in the Gabes basin in relation to the identification of potential recharge zones for groundwater aquifers, as the groundwater in some areas has a high or unacceptable salt content, which affects the environmental and geographical balance of the region (Abdelkarim et al. 2022). This problem is exacerbated by poor drainage of excess water, in addition to the use of saline water to irrigate crops (Haeri and Valishzadeh 2021). The presence of saline soils constitutes a real challenge for the geotechnical engineer due to the occurrence of engineering problems for the soil due to the rapid dissolution of the salts that permeate its particles (Ted, et al. 1985), which leads to the occurrence of engineering and construction problems for the foundations of the buildings and facilities erected on them due to the weakness of the soil as a result of changing its engineering properties after wetting it, as shown in Fig. 2.

The collapse of those soils increases with the increase in the proportion of salts and their components (Alqasemi et al. 2021). There are quick-dissolving salts such as sodium chloride and medium-soluble salts such as magnesium or calcium chloride. Extensive studies are looking at the collapse of saline soils and serious attempts to find solutions to it by mixing it with chemical additives such as light or aromatic compounds and other physical stabilizers such as soil reinforcement or compaction. Significantly, these techniques are good for treating the breakdown of saline soils when exposed to wetting; several researchers have used fly ash to improve organic soil (Nath and Md. Keramat Ali Molla, Grytan Sarkar 2017) or fine sand (Siavash, et al. 2017). In semi-arid climatic conditions (such as central Tunisia), groundwater is a critical resource for meeting the needs of social and economic development. For the conservation of water resources and sustainable development, it is necessary to conduct an accurate estimation of groundwater quality to accurately evaluate the hydro geochemical properties of the water (Missaoui et al. 2023).

An experimental study was conducted to treat ordinary soil with cement Fly ash for layers in road construction. The soil sample for the laboratory test was taken from Cu Chi province, Southern Vietnam with a specific gravity 2.65 and a plasticity index of 12.18%.The fly ash used in this study meets the requirements in accordance with ASTM C618.

Fig. 2 The failure of the structure as a result of the presence of saline soil under the foundation

Five proportional mixtures were used in this work with varying amounts of ordinary Portland cement in quantities of 8% cement with fly ash content between 2%, 4%, and 6%. The study showed that the addition of 8% cement and 2% fly ash to the soil increases the compressive strength to 7.6 MPa as shown in Fig. 3. In addition to that, the splitting tensile strength is greater than 0.45 MPa, satisfying the base layer of road construction requirement according to current Vietnamese standards. The results of the study provided a shred of evidence for capable of using fly ash for road construction in the context of an increase in the fly ash generated in thermal power plants (Nguyen and Phan 2021).

This study aims to study the behavior of saline soils, their formation, factors that help their spread, and to know their engineering properties such as compressibility and bearing capacity by conducting a number of laboratory tests on them.

The scope of this study is limited to investigate the possibility of improving the compressibility of saline soils and increasing their ultimate bearing capacity using fly ash powder activated by Portland cement, which is mixed with the soil in different mixing proportions. Three types of natural saline soils with different salt content were used. Laboratory tests were carried out using a laboratory model designed for this purpose. Tests were carried out on the three soils, in both dry and wet conditions, to find out the possibility of improving such problematic collapsible soil.

Experimental work

This study includes conducting laboratory tests using a model, in addition to the traditional tests for the three soils used. The properties of the cement-activated fly ash used as a stabilizer for these soils were also studied, and tests were conducted on it.

Tested soil

In this study, natural soils brought from three different regions of Diyala Governorate in the State of Iraq were used. All laboratory tests were performed on these three types of saline soils. Disturb and undisturbed samples were taken from these areas at a depth of 1 m. The physical examinations of the soils used were carried out. Table 1 shows the results of the physical test for the three soils. Table 2 shows the chemical tests carried out on the three soils. The grain size distribution curves for the three soils are shown in Fig. 4.

Fly ash

The crushed iron residues resulting from factories (fly ash), which accumulate a lot and are usually neglected and disposed of, have been used because they contain undesirable materials in industries. They are inert materials that have been activated after mixing with Portland

Table 1 Physical properties of soils

Property	Soil 1	Soil 2	Soil 3
Soil type	SM	SM	SM
Gs	2.48	2.47	2.41
L.L	16	17	15
P.L	N. P	N. P	N. P
Ø dry	25	29	36
C kN/m^2	5	8	12
Ø wet	23	27	29
γ max kN/m^3	17.3	16.7	17.8
Optimum moisture content %	15	11	15
Collapse potential % at natural condition	11	20	32

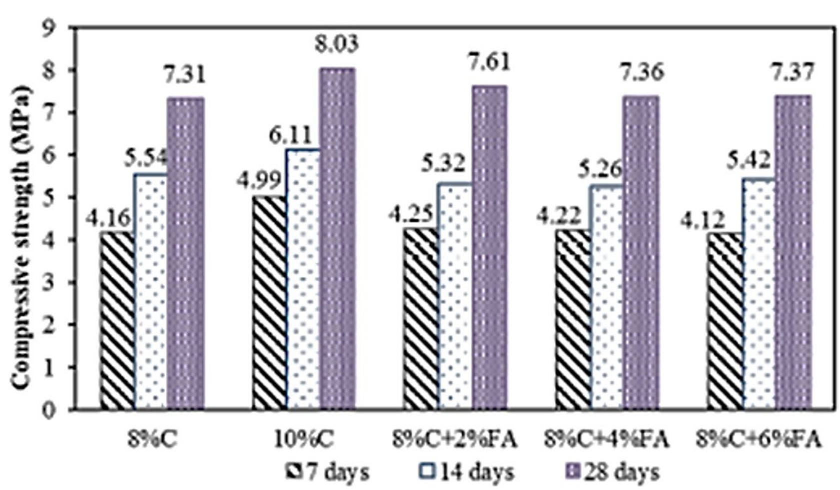

Fig. 3 Ultimate confined stress for natural clayey soil stabilized by fly ash with cement. (After D. T. Nguyen and Phan 2021), (Nguyen and Phan 2021)

Table 2 Minerals constitute the three soils used in this study (checked in the National center for Construction Laboratories and Research (NCCLR-Iraq))

Chemical component symbols	Percentage (%)		
	Soil 1	Soil 2	Soil 3
CL	0.044	0.831	0.884
CaO	17.043	18.586	19.551
SiO_2	38.146	36.351	35.010
Al_2O_3	14.082	15.429	14.076
SO_3	1.313	1.298	1.441
K_2O	5.284	5.125	5.287
TiO_2	0.851	0.855	0.851
Fe_2O_3	20.056	18.442	19.783
P_2O_3	1.515	1.456	1.359
V_2O_5	0.163	0.163	0.160
Cr_2O_3	0.119	0.113	0.105
MnO	0.334	0.318	0.338
NiO_2	0.033	0.032	0.036
CuO	0.036	0.033	0.027
ZnO	0.044	0.029	0.028
Y_2O_3	0.010	0.009	0.010
ZrO_2	0.068	0.065	0.067
Loss of ignition (L.O.I)	14.21	13.5	8.24
Total soluble salts T.S.S %	21	32	45

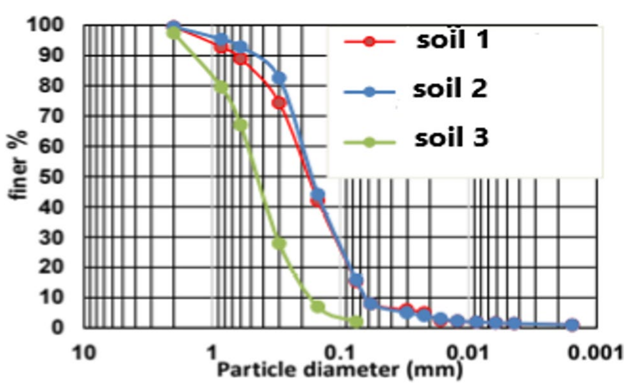

Fig. 4 Grain size distribution curve for soils used in study

cement to increase adhesion with soil particles. Different mixing ratios of this additive were used to mix it with saline soil in proportions (0%, 5%, 10%, 15%, and 20%) activated by 5% of Portland cement, to show how effective it is in reducing the collapse of this soil when soaked or wetted by water or in the dry state. Table 3 shows the main properties of fly ash used in the study.

Table 3 Properties of fly ash used as additive in this study

Chemical composition	Percentages (%)
Al_2O_3	38.95
SiO_2	52.32
FeO_2	8.02
SO_3	0.37
L.O. I *	0.34

L.O.I Loss of ignition

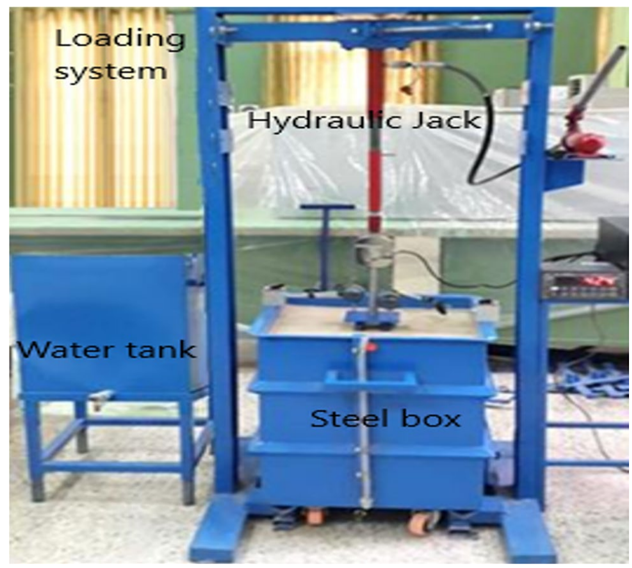

Fig. 5 Tools and equipment used in the study

Tools and equipment used in the study

Figure 5 shows that the set of laboratory model and apparatus used in this study consists of the following parts:

1. Steel box
2. Loading device
3. Loading control
4. Square footing

Steel box

A box with dimensions of 500 × 500 × 700 mm made from steel with a thickness of 2 mm, made of galvanized billet to prevent corrosion, was used in the study. The sides of container were reinforced with horizontal stiffened bars to strengthen the sides of the steel box. The model was provided from the base with swivel wheels to facilitate its movement and soil replacement after each examination. A mechanical lever is installed that regulates the water level in the immersion check of the model. Water is supplied through a 250-l water tank placed next to the test device and connected to it by a rubber tube, to ensure a continuous supply of water during the immersion test.

Loading device and control

An integrated loading system was designed that simulates the loading of a site foundation, consisting of two vertical iron supports, 2-m high and 5-mm thick, perforated from the top with several holes to control the level of the height of the jack and fixed from the bottom with screws. A hydraulic jack was used, connected to a manual control handle, and equipped with a load-setting or loosening system. It is fixed from the top of the loading structure by screws. The jack was provided with an electronic loading spring placed between the base and the jack, and the readings of the applied pressure were checked and were calibrated before starting the tests to ensure the accuracy of the readings.

Steel footing

A square iron pallet of 5-mm thickness and 130-mm width was used to represent a square foundation for all examinations.

Testing methodology

There are a number of steps that were adopted in the examination of saline soils in two cases, the dry test and the soaking test, for laboratory samples of treated and untreated soils with fly ash:

1- The soil is prepared by grinding and drying it and then passing it through Sieve No. 4 to isolate the unsuitable large parts in the examination.
2- The relative density used is 85%, the soil unit weight used 16 kN/m^3 is for all soils used in the study, and the moisture content was fixed in any of the laboratory samples (8.8% humidity).
3- The treated soil was prepared by mixing natural saline soil with different percentages of fly ash (0%, 5%, 10%, 15% and 20%) and activated with 5% cement.
4- The density of soil is controlled by dividing the soil into three groups, stacking each group at a height of 100 mm using a manual steel pestle, equalizing the surface of the soil, then placing the second layer and repeating the same steps.
5- After completing the third layer, the surface of the soil is equalized, and the square footing is placed in the center of the model, considering the levelness of the layer and it is without voids and large soil particles.
6- The load cell is placed between the foundation and the jack, loading is started first until the lever touches, and the first pressure reading was started. Then, the zero reading is recorded, and the load starts were started at double levels.
7- The settlement reading for the footing is taken through the dial gage that is fixed on the two edges of the base until the model reaches failure. This is the first stage of the examination, which is the dry test.
8- In the soaking test, the model samples are soaking with water feeding from a water tank shown in Fig. 3. The water level was controlled using a water control system fixed to the upper part of steel container. The soaking time of the sample was fixed for 48 h to ensure complete dissolution of salts inside the sample for saline soils to investigate the problem of saline. The steps of soaking test is as in the dry test described in the previous six steps.

Results and discussion

Dry model test results

Figures 6, 7, and 8 show the relationship between the applied load and settlement for square foundation resting on saline soils. Three saline soils with different salinity percentages (7%, 25%, and 43%) were examined at dry state. Soils were

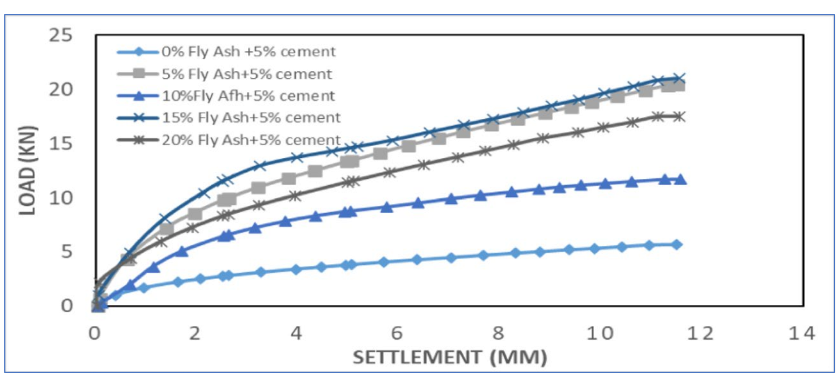

Fig. 6 Load-Settlement curve for first soil with 7% salinity, treated with different percentages of fly ash activated by Portland cement (dry test)

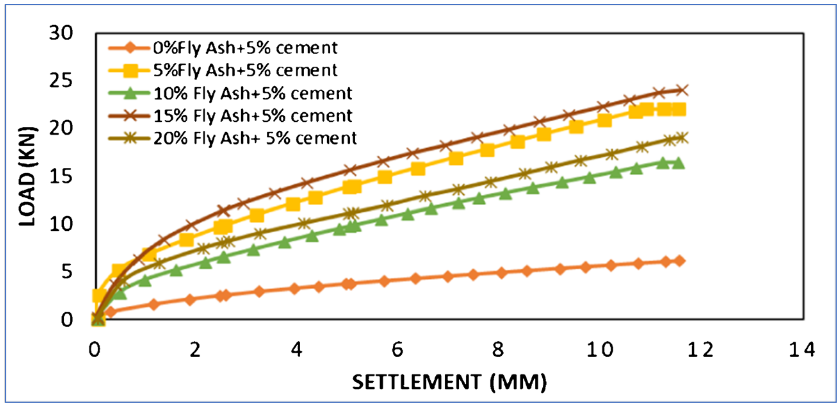

Fig. 7 Load-Settlement curve for second soil with 25% salinity, treated with different percentages of fly ash activated by Portland cement (dry test)

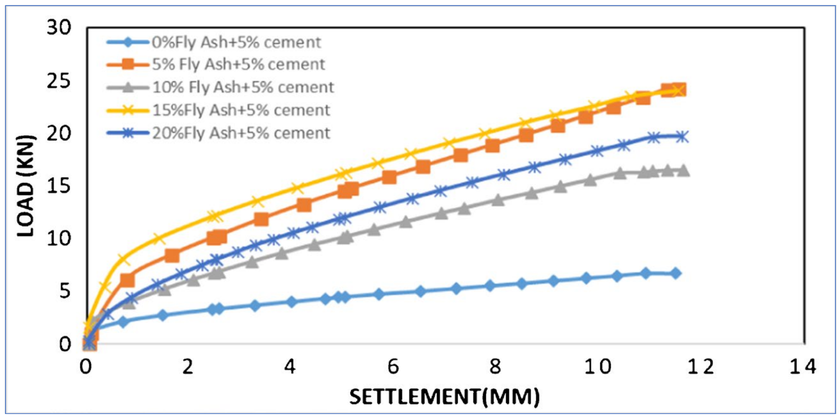

Fig. 8 Load-Settlement curve for third soil with 43% salinity, treated with different percentages of fly ash activated by Portland cement (dry test)

treated with the addition of cement-activated fly ash with different percentages (0%, 5%, 10%, and 20%). The results show a pronounce improvement in the ultimate bearing capacity for saline soils treated with that additive. The fly ash activated by Portland cement works in general to fill the voids in the saline soil because of its high surface area surrounding the soil particles due to the softness of the particles of this additive, which increases the bonding with the soil particles, as the cement works with the aforementioned mixing ratios to strengthen the bonds and increase the adhesion between the ash volatiles and soil particles to form a dense and solid mass.

The optimum mixing ratio is 5%, where the bearing capacity of the soil increased more than 3 times for all soils, while the percentage of the increase was slight by adding more than this percentage. This behavior is attributed to the increase in the bonding forces between the dry soil particles in the presence of the additive, which leads to improve its bearing capacity and reduce settlement, in addition to the effect of Portland cement, which increase the adhesive forces between soil molecules.

It can be seen that the improvement of the dry saline soil became less by adding a mixing ratio of 20% of the additive due to the lack of interdependence of the mixture of the soil with the additive and the decrease in its effectiveness by reducing the compressibility of the soil model, so it is useless to put high percentages of it, and it may cause future problems for the foundations built on the soil, especially for the higher percentages of cement mixed with ash due to the impact of the foundations of buildings built on these soils and their interaction with concrete, which leads to cracks in it and thus its failure.

Soaking model test results

Laboratory samples of saline soils were examined in case of wetting from any external source to identify the efficiency of adding cement-activated fly ash and the percentages of improvement in their tolerance. The results showed a clear improvement in the bearing capacity of the saline soil immersed in water after mixing it with this additive in general.

In Fig. 9, it is noted that the amount of improvement increased in the maximum bearing capacity of the first soil, which contains 7% of salts, after mixing it with different percentages of fly ash activated by Portland cement. The highest levels of improvement were by using 5% of the additive and mixing it with the soil, where the bearing capacity of the soil immersed in water increased 6 times more when compared to the untreated model. The presence of fly ash in addition

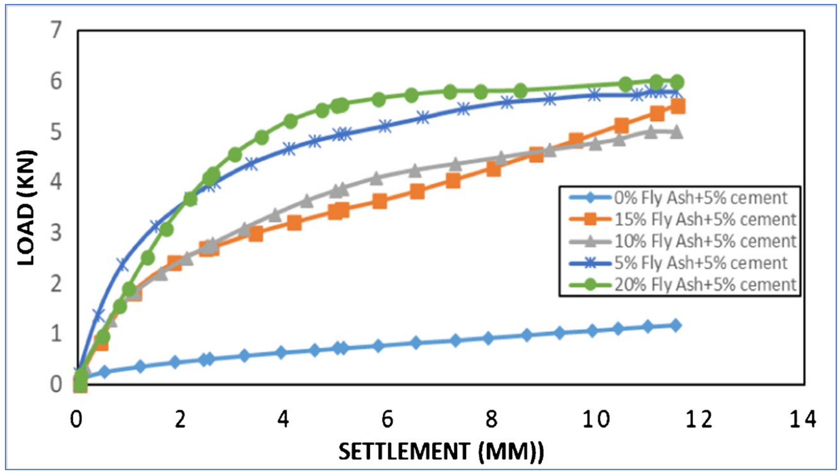

Fig. 9 Load-Settlement curve for first soil with 7% salinity, treated with different percentages of fly ash activated by Portland cement (soaked test)

to the cement material as a binder, which is activated after exposure to wetness from the flooded soil, works to increase the bonding and cohesion between the soil particles and fly ash on the one hand, and to increase the bonds of cohesion and sticking to the same soil particles at the same time.

In Fig. 10, it is noted that the improvement is clear with regard to the model for soil with a salt content of 25% after mixing it with 20% of fly ash activated with cement; the results showed that the maximum load-bearing capacity for immersion increased by about 5 times compared to the untreated model, and this increase is attributed to the increase in the area of the surface of the additive and its rapid interaction with Portland cement in the presence of water that permeates the soil particles, which leads to increased bonding and adhesion with the additive to form a strong medium of this mixture.

In Fig. 11, the results show the relationship between the percentage of the additive and the bearing capacity of the third salt soil (43%) immersed in water. The results showed that the soil continued to improve in its bearing capacity, especially when mixing 5% of the additive, while the improvement was limited to mixing the soil with 20% of the additive. This is due to the fact that the fly ash material itself has high compressibility if it is present in large proportions due to its weakness and lack of bonding between its particles and the presence of voids between them, but with its presence in a limited amount and by the action of cement as an active and binder material, its tolerance increases, as it is at this rate (5%). It forms with the soil immersed in water, a strong medium that is resistant to collapse, and its tolerance increases due to the increase in the bonds of interaction with cement and its interference with soil particles by filling the voids and thus increasing the density of the treated soil.

Figure 12 shows the relationship between the percentages of salt and the maximum bearing capacity of soils treated with 5% of the cement-activated fly ash additive; it can be seen that the maximum bearing capacity increases small to moderate with increasing salinity percentage for the dry samples of saline soils treated with 5% of fly ash. On the other hand, the opposite was observed for soaked samples treated by the additive with the same ratio. The increase in the amount of tolerance of dry soil with the increase in the percentage of salinity is due to the increase in the bonds and interdependence of the salt with the soil particles and

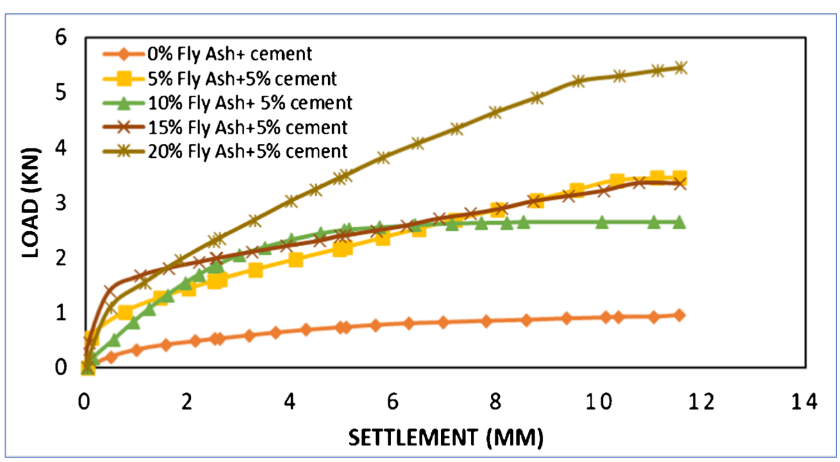

Fig. 10 Load-Settlement curve for second soil with 25% salinity, treated with different percentages of fly ash activated by Portland cement (soaked test)

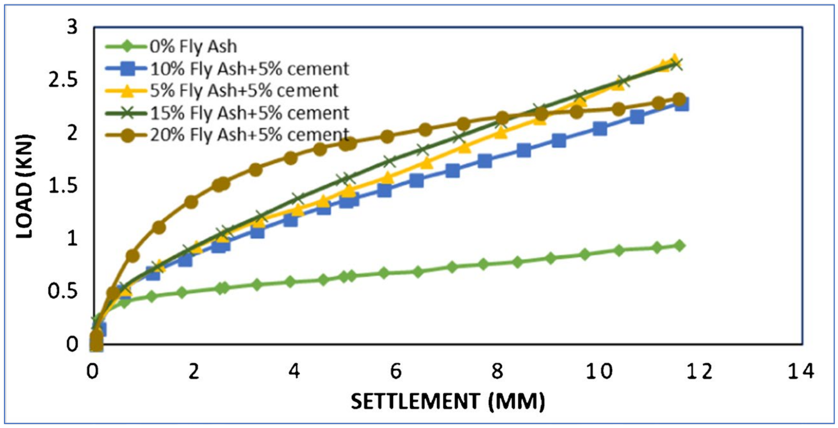

Fig. 11 Load-Settlement curve for third soil with 43% salinity, treated with different percentages of Fly ash activated by Portland cement (soaked test)

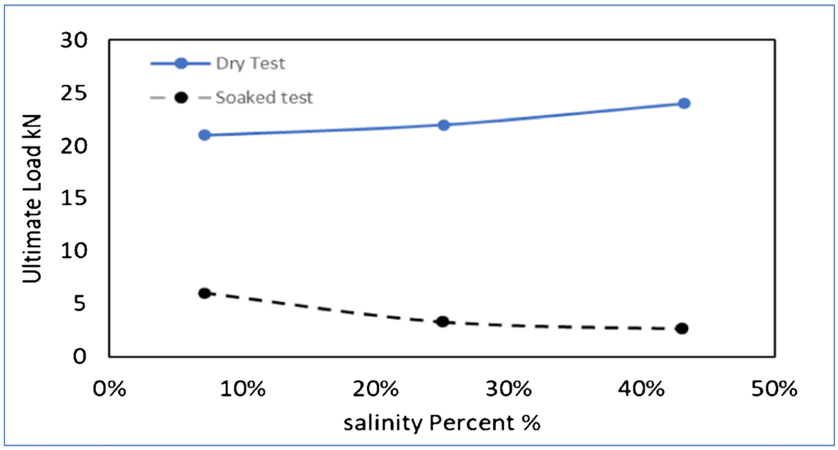

Fig. 12 Effect of soil salinity on ultimate load capacity for all treated soils with 5% fly ash activated with 5% Portland cement, at dry and soaking conditions

its permeation into the voids and the increase in its density in the presence of the additive in this proportion, while the effect of the presence of water when soaking the saline soil treated with the additive was clear in reducing the ultimate capacity of the soil by increasing the percentage of salts it contains due to the solubility of the salt particles surrounding the soil particles when immersed in water and thus increasing the compressibility of the soil and reducing its bearing capacity. However, the improvement of this soil was good, especially after mixing it with 5% of the additive, as it gave promising results to treat these types of problematic collapsible soils.

The results of this study are consistent with that of a previous study in which the same additive was used in close proportions but on different soils (Nguyen and Phan 2021), where the effectiveness of cement-activated fly ash in improving the load-bearing capacity of clay soils soaked in water was investigated, and the results showed that 2% of cement-activated fly ash was the highest in improvement, as shown in the Fig. 4. By adding this percentage of fly ash, the improvement becomes modest, and this supports the findings of this study, which shows 5% of fly ash with 5% cement is the optimal percentage in improving the properties of saline soils, as it increased 3 times for the dry test and 6 times for the soaked test compared with the untreated model. The increase in the percentage of the additive does not significantly affect the improvement, and the improvement may be slight. This is consistent with the previous study referred to reference (Nguyen and Phan 2021).

Conclusions and recommendations

It can be concluded from this study that saline soil is natural soil that does not suffer from any structural problems when it is in a dry state. Problems are well manifested, when exposed to hydration from any water source, causing sudden collapse of the saline soil. An additive of fly ash activated by cement was used, since these materials are widely available. It was observed through this study that the optimum percentage of this additive is 5%, where the soil bearing capacity increased about 3 times in relation to the dry model and 6 times in relation to the soaked model. The fly ash material is considered an inert and weak material if it exists independently, and it can be activated by mixing it with Portland cement and adding it in appropriate proportions to the saline soil. The study demonstrated the effectiveness of this additive in improving the compressibility and increasing ultimate pressure of saline soils. The submersion of this type of soil increases the subsidence of the foundation on which it is built, especially for soils with a high salt content. So, mixing saline soil with this additive gives acceptable results for improvement such problematic soil.

It is recommended in the event of the possibility of replacing a part of saline soil before constructing the foundations of the buildings or adopting other supportive treatments such as compaction in addition to fly ash or soil reinforcement. Thus, precautions must be taken when constructing buildings near drains and conveying channels.

Declarations

Conflict of interest The authors declare no competing interests.

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