THE BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING
2022/17(2)

ISSN 1822-427X/eISSN 1822-4288
2022 Volume 17 Issue 2: 185–212
https://doi.org/10.7250/bjrbe.2022-17.565

# FEASIBILITY STUDY OF PETROCHEMICAL WASTE AND CEMENT USAGE FOR SALINE ROAD SUBGRADE STABILISATION

**MAHMOUD REZA KEYMANESH*, AMIN FALAMAKI, HADI GHODRAT**

*Department of Civil Engineering, Payame Noor University, Tehran, Iran*

Received 4 October 2021; accepted 28 January 2022

**Abstract.** The widespread distributions of saline soils in Iran cause a range of problems for road construction projects due to insufficient shear strength, salt solubility potential and swelling. This paper conducts experimental tests using different cement contents and a sort of petrochemical waste with two curing methods to stabilise saline soil samples. Strength, compressibility and chemical tests were conducted, X-ray diffraction analyses were performed, and scanning electron microscope pictures were prepared for basic materials and stabilised saline soil samples in this paper. The results indicate that both petrochemical soda ash waste and cement enhance the shear strength of saline soil, especially after 28 days of curing. However, the combination is more appropriate from the swelling and salt solubility potential viewpoint. The optimum combination of 2% cement and 5% of petrochemical soda ash waste, cured by method 2 for 28 days, results in the most significant shear strength enhancement (127%). Furthermore, a swelling quantity of the optimum combination is reasonably restricted. X-ray diffraction test results and scanning electron microscope pictures demonstrated that despite the presence of ettringite agents, the

* Corresponding author. E-mail: mrkeymanesh@pnu.ac.ir

Mahmoud Reza KEYMANESH (ORCID ID 0000-0003-0555-2755)
Amin FALAMAKI (ORCID ID 0000-0003-0158-0695)
Hadi GHODRAT (ORCID ID 0000-0002-9511-4689)

formation quantity of these minerals is negligible. The salt is well stabilised, and its solubility potential dramatically decreases.

**Keywords:** cement, petrochemical waste, road subgrade, saline soil, shear strength, solubility, swelling.

## Introduction

Saline soils are notable cases of problematic subgrades and poor quality in terms of resistance and compressibility features. Soil with a soluble salt content over a certain amount is called saline soil (Zhang et al., 2020). Generally, well-graded coarse-grain saline soils are quality materials for road construction from a bearing capacity and shear strength characteristics viewpoint, mainly when good compaction is performed (Zhang et al., 2019). However, soluble salt causes subgrade settlement, decreases the shear strength, and increases collapsibility risk due to rainfall or water table fluctuations. Moreover, salt expansion and uplift due to crystallisation of salt and ice in saline soils are likely, and roads and other infrastructure are seriously damaged. Ambient temperature and humidity affect the process of salt crystal formation and growth (Wang et al., 2020).

Changes in temperature and evaporation in the environment result in a large distribution of saline soil with a high level of soluble salt in Iran. Road construction on saline soil basements is widespread in this country because of transportation requirements and economic demands. Firuzabad–Farashband motorway needs to pass a salty soil of poorly classified silty sand on the Firuzabad salt dome (Fars province, Iran). Compliance with the requirements of the roadbed, such as high shear strength, stiffness and uniform deformation during the period of operation of the road, shall be guaranteed. Several treatment processes proposed by the experts should meet the demands of the high strength, rigidity, stability, and durability of the platform and provide the best economic considerations.

There are several achievements in using some stabilisers to modify the performance of saline soils as road subgrade. Researchers are interested in using construction materials, organic and inorganic waste and their combinations in various studies.

Some researchers have used lime as a low-cost and available stabiliser (Liu, & Zhang, 2012). Liu et al. (2019) discovered that adding lime to the saline soil led to the transformation of clay particles into sand and silt, and a bimodal pore size distribution was observed. Therefore, the unconfined compressive strength amount increased directly with lime content. They also found that the changes in soil characteristics occurred just after adding lime due to the quick cation exchange reaction. However, the pozzolanic reaction took place after a 28-day curing period.

Li et al. (2012) tried to use wheat straw as organic waste and lime to solidify inshore saline soils. They had to use an agent to treat wheat straw before using it as a modifier for saline soil. The treating agent was modified polyvinyl alcohol, which showed that it increases the resistance of wheat straw against corrosion and tensile forces. This study demonstrated that the brittle failure problem of modified saline soil decreased, and the effectiveness of using this type of organic modifier agent was approved.

Another solution to saline soil problems was fly ash as inorganic waste from factories (Li et al., 2015). The other study on fly ash as a modifier for improving the resistance properties of saline soils was carried out by Cheng et al. (2021). Different fly ash ratios are used in this study, and unconfined compressive strength tests and triaxial tests are applied. They discovered that the shear strength parameter was enhanced to the highest amount by using 15% of fly ash and a reference for appropriate use of improved saline soil as the road construction subgrade is provided. Moreover, gypsum waste was recycled by Kamei et al. (2012), and the residual particle, kyanite, was used to modify the durability and strength of soft saline clay.

A combination of inorganic materials and popular construction materials such as micro-silica and lime were used by Moayed et al. (2012). This study improved the bearing capacity and strength-deformation of saline soil layer by combining 2% lime with 3% micro silica. Tian et al. (2016) used different contents of cement, lime and fly ash to address the collapsibility of coarse grain chlorinated saline soils. Fly ash, sodium silicate and lime were used by Lv et al. (2018) to modify the geotechnical characteristics of saline soils. This combination has reduced the amount of sulphate in the modified salt soil and reduced the potential for salt expansion. Even, Parsaei et al. (2021) evaluated stabilisation of the expansive clay using a combination of cement with electric arc furnace waste ranging from 0% to 20% to reduce cement consumption as an environmentally friendly technique.

Based on the literature review, the researchers studied a number of treatment methods for saline soil subgrades. Moreover, various modifying agents, including construction materials and organic and inorganic waste, are used in saline soil stabilisation. However, using petrochemical waste as a modifier for saline soils has less been considered by the other researchers. These wastes are so abundant in quantity and accessible in oil-rich countries such as Iran, and their deposit is problematic for the environment. Therefore, using them as a stabiliser is economical and helpful in saving the environment.

In this context, a study was carried out on the saline soil subgrade of the under-construction Firuzabad–Farashband freeway located on the salt dome of Firouzabad (Fars province, Iran). This study aims to chemically solidify the saline soil subgrade using industrial waste, a petrochemical waste material made in the soda ash production unit of Shiraz Petrochemical Complex (Fars province, Iran). Petrochemical soda ash waste (PSAW) produces a significant volume stored in a depot adjacent to the plant. The geotechnical and microscopic properties were determined for both base material and treated saline soil, varying the dose of PSAW and cement and curing methods. The presentation and interpretation of the results provide a better understanding of the feasibility and effects of the use of mentioned industrial waste on the saline soil subgrade.

## 1. Materials

### 1.1. Study region

Natural saline soil used for this investigation is gathered from the subgrade of Firuzabad–Farashband highway constructed on the Firuzabad salt dome, a part of the Konarsiah and the Mangerak salt diaper (Figure 1). Konarsiah and the Mangerak salt diaper is located in the Zagros mountains in the south-west of Iran and contains about 200 exposed salt domes (longitude 52° 20’ 00” E to 52° 33’ 00” E and latitude 28° 40’ 00” N to 28° 53’ 00” N) (Ghanbarian, 2016; Talbot, 1990). Sampling is carried out from the coordination of longitude 52° 24’ 10” E and latitude 28° 47’ 11” N. The area is considered a semi-arid region, and the mean annual precipitation amount is about 400 mm. The environmental condition and water table level show that frost heave occurrence is unexpected or negligible. However, salt dissolving caused by rainfall and water table fluctuations is quite probable.


**Figure 1.** Study region and sampling location

## 1.2. Natural saline soil

The properties of saline soil achieved from laboratory tests are summarised in Table 1. As reported by the grading test (Figure 2) and Atterberg limits test, the saline soil is classified as SP-SM based on the unified soil classification system (USCS). Moreover, the in-situ moisture content of sampled soil is about 10%. Hence, the liquidity index (LI) of the soil is below zero and is based on description of Budhu (2020). It is

Table 1. Basic properties of natural saline soil

| Property | Characteristic |
|---|---|
| Unified soil classification | SP-SM |
| Passing #200, % | 34.00 |
| Particles less than 2 μm, % | 6.70 |
| Specific gravity | 2.63 |
| Plastic limit (PL), % | 22.02 |
| Liquid limit (LL), % | 24.19 |
| Plastic index (PI), % | 2.17 |
| Moisture content, % | 10.00 |
| Maximum dry density, g/cm$^3$ | 1.91 |
| Optimum water content, % | 11.00 |
| pH | 8.00 |
| Electrical conductivity (EC), ms | 13.67 |
| Salinity, ppt* | 7.36 |
| Total dissolved solids (TDS), ppt | 6.80 |
| Soluble salt content, % | 2.00 |
| Water-soluble sulphate in soil, % | 0.44 |

Note: *part per thousand.

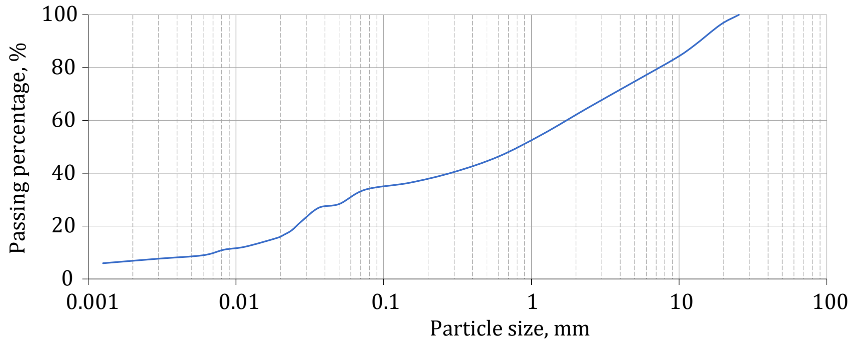



**Figure 2.** Grain-size distribution of saline soil

described as "semisolid-high strength, brittle with sudden expectable fracture".

Furthermore, considering Skempton activity number, the soil is classified as "inactive" from the clayey particle viewpoint, and swelling defects are negligible. The pH amount of the samples is about from 7.9 pH to 8.1 pH, and as stated in Slessarev et al. (2016), it is considered alkaline soil to some extent. The salinity number of samples is in the range of "very strongly saline", in agreement with Dahnke & Whitne (1988). Considering that the amount of water-soluble sulphate in the soil is more than 2000 ppm, the soil is classified as "high" sulphate soil in agreement with Puppala et al. (2004) descriptions. Also, the chemical composition of salts in soil is presented in section 3.4. Mineralogical studies and Figure 15.

## 1.3. Petrochemical soda ash waste (PSAW)

Salinity soda ash (sodium carbonate ) is majorly produced via the Solvey or ammonia soda process, and its ingredients are salt brine (from inland sources or the sea) and limestone. Soda ash has been produced

Note: sample dried, crushed and sieved.

**Figure 3.** Sample of petrochemical soda ash waste in the laboratory

**Table 2. Petrochemical soda ash waste and lime composition via X-ray fluorescence test**

| Material | Component and content, % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $CaO$ | $K_2O$ | $MgO$ | $SiO_2$ | $SO_3$ | $Al_2O_3$ | $Fe_2O_3$ | $Cl$ | $Na_2O$ | $P_2O_5$ | $SrO$ | L.O.I** |
| Petrochemical soda ash waste | 46.57 | 0.19 | 1.81 | 4.33 | 0.47 | 1.36 | 0.85 | 4.34 | 0.67 | 0.09 | 0.05 | 39.27 |
| Lime | 51.64 | 4.00 | 2.65 | 1.36 | 0.80 | 0.24 | 0.13 | – | – | – | – | 39.18 |

Note: * – *ASTM E1621-21 Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry*; **L.O.I – loss of ignition.

in Shiraz Petrochemical Complex, which is located near Shiraz (Fars province, Iran), via the following chemical reaction:

$$2NH_4Cl + Ca(OH)_2 \rightarrow 2NH_3 \uparrow + 2H_2O + CaCl_2.$$

This process has the main waste stream, which is mainly directed to sedimentation ponds where solid particles (PSAW) are settled. A bulk sample of settled solid particles is prepared (Figure 3), and its average composition is released via the X-ray fluorescence (XRF) test (Table 2). Based on the information presented in Table 2, PSAW elements are very similar to the lime, containing more than 46% quick lime.

### 1.4. Cement and water

Due to the high sulfate quantity of the saline soil samples, cement type V was used for sample preparation and related tests. The moisture content of prepared samples is adjusted via potable water. Distilled water was used to determine electrical conductivity (EC), total dissolved solids (TDS), salinity, pH, sulphate quantities, and solubility analyses.

## 2. Sample preparation and testing methods

### 2.1. Sample preparation

To sample preparation, firstly, PSAW was crushed via a rubber hammer and passed through sieve No. 30. The soil, cement and PSAW were oven-dried at 105 °C for at least 24 h and then cooled at the laboratory temperature. The moisture content of the samples was considered similar to the optimum moisture content of the soil. The soil used for sample preparation is finer than the No. 4 sieve. Various cement percentages (0%, 2%, 3%, 5%, and 7% by mass) and different percentages of PSAW (0%, 3%, 5%, and 7% by mass) were used for sample preparation, based on recommendations presented by Liu et al. (2019) and Zhang et al. (2020). All moulded samples were mixed manually to become homogeneous and packed in plastic bags to prevent moisture loss during the curing procedure. This study considers two curing methods: curing type 1 (CT1) and curing type 2 (CT2). In CT1, samples were put in an airtight container for at least seven to 28 days in 90% constant humidity and 20 ± 2 °C. Dissimilarly, in CT2, prepared samples were cured in laboratory humidity (about 15%) and the average temperature of 20 ± 2 °C for at least seven days to 28 days. Direct shear and unconfined compressive tests were carried out on the samples, and damaged specimens were used for other tests.

## 2.2. Testing methods

Physical, chemical and mechanical specifications of natural saline soil, PSAW and modified saline soil are studied via several tests, as stated in Table 3. The devices, methods and procedures used to conduct the tests are presented below.

Grain size composition test and Atterberg limits determination test were carried out for natural saline soil based on *ASTM D422-63(2007) e2 Standard Test Method for Particle-Size Analysis of Soils* (withdrawn 2016). Proctor compaction tests were conducted for all specimens to determine optimum moisture content and maximum dry density by *ASTM D698-12(2021) Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))*. The quantities of pH, EC, TDS, soluble salt content and water-soluble sulphate in soil for saline soils are determined by standard methods.

Moreover, the saline subgrade specification with different PSAW and cement contents and the two different curing methods are studied via direct shear test and unconfined compression test (*ASTM D3080/D3080M-11 Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions* (withdrawn 2020); *ASTM D2166/D2166M-16 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*). The direct shear tests were executed using an ordinary direct shear test device with a shear box of 10×10 cm, and the horizontal displacement speed was 1 mm per minute (*ASTM D3080/D3080M-11*). Moreover, the dimension of unconfined compression test samples was 38.1 cm in diameter and 76.2 cm in height.

Then, the swelling potential and salt solubility of modified samples were investigated. One-dimensional swell-consolidation tests were performed in an oedometer on the samples to study the effect of stabilisation agents on the swelling potential. The specimens were oven-dried and different contents of PSAW and cement in combination with saline soil were used for sample preparation of these tests.

Next, more investigations on the samples modified by different contents of PSAW and cement were carried out to determine the effect of stabilisation on the saline soil salt solubility. To conduct this part of the study, oven-dried pieces of prepared samples for the direct shear tests were used.

Finally, XRD and microstructure analyses were done using SEM pictures taken from the non-modified and modified samples to discover the formation of internal linking strands. The main aim of carrying out XRD tests is to determine ettringite mineral formation and to study the influence of the stabilisation mechanism by PSAW and cement.

The samples prepared for direct shear tests were used for these tests. Scanning electronic microscopy was carried out to investigate changes to the natural and modified saline soil samples. Due to these studies, natural saline soil samples and modified ones with 5% PSAW and 2% of cement, and 5% PSAW. The modified samples with PSAW were cured with the CT2 curing method for 28 days. Also, the ones were modified with cement and PSAW were cured with the CT1 curing method for 28 days. Cube specimens with 1 cm length were trimmed flat and vacuum coated with a layer of gold of 200 mm to 300 mm thickness. The gold layer causes EC of specimens (Al-Rawas, & McGown, 1999).

**Table 3. Conducted tests and sample descriptions**

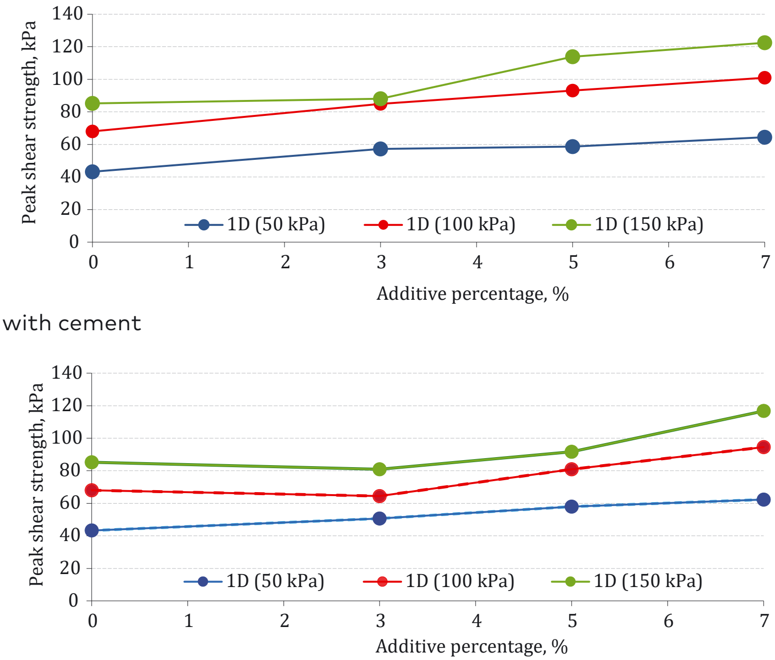
| Test type | Number of tests | Modifier content, % | | Curing type | Curing time, days |
|---|---|---|---|---|---|
| | | Cement | Petrochemical soda ash waste | | |
| Standard Proctor compaction | 1 | 0 | 0 | no | 1 |
| | 1+1+1 | 0 | 3, 5, 7 | no | 1 |
| | 1+1+1 | 3, 5, 7 | 0 | no | 1 |
| | 1+1 | 2 | 5, 7 | no | 1 |
| Direct shear test | 3+3+3 | 0 | 3, 5, 7 | no | 1 |
| | 3+3+3 | 3, 5, 7 | 0 | no | 1 |
| | 3+3+3 | 0 | 3, 5, 7 | CT2 | 28 |
| | 3+3+3 | 3, 5, 7 | 0 | CT1 | 28 |
| | 3+3+3+3+3+3 | 2 | 5, 7 | no, CT1, CT2 | 1, 28 |
| Unconfined compression test | 1+1+1+1+1+1 | 0 | 3, 5, 7 | CT2 | 1, 28 |
| | 1+1+1+1+1+1 | 3, 5, 7 | 0 | no, CT1 | 1, 28 |
| | 1+1+1+2+2+2 | 2 | 3, 5, 7 | no, CT1, CT2 | 1, 28 |
| Swelling study | 1 | 0 | 5 | no | – |
| | 1 | 5 | 0 | no | – |
| | 1 | 2 | 5 | no | – |
| Salt stabilisation study | 1+1+1 | 0 | 3, 5, 7 | CT2 | 28 |
| | 1+1+1 | 3, 5, 7 | 0 | CT1 | 28 |
| | 1+1 | 2 | 5, 7 | CT2 | 28 |
| X-ray diffraction (XRD) | 1+1 | 0 | 0, 5 | CT2 | 28 |
| | 1 | 2 | 5 | CT1 | 28 |
| Scanning electron microscope (SEM) | 1+1 | 0 | 0, 5 | CT2 | 28 |
| | 1 | 2 | 5 | CT1 | 28 |

Note: CT1 – curing method type 1; CT2 – curing method type 2.

# 3. Result and discussion

## 3.1. Shear strength of stabilised saline soil

The effect of using different contents of PSAW or cement as an additive for stabilising saline soil under various confining pressures is stated in Figure 4. The samples are one day and without a cure. The results show that the peak of shear strength increases up to 44% if PSAW content is increased to 7%. Changes to the maximum shear strength increase as the PSAW increases. However, this is negligible when the PSAW is 3%. Subsequently, by increasing the PSAW to 5%, the slope of the curve increases substantially. The slope of the curve goes down again after 5%. This finding shows that using 5% PSAW to improve saline soil is more appropriate than less or more. Considering the similarities between PSAW and lime, the results are comparable to Liu et al. (2019) from a mineral and ingredient point of view. Their study observed increased shear resistance by increasing the percentage of lime. The function of the cement combined with the saline soil is the same. The value of the increase in maximum shear strength for 1-day samples is about 49%. in 1-day samples, the time for pozzolanic




**a)** with cement

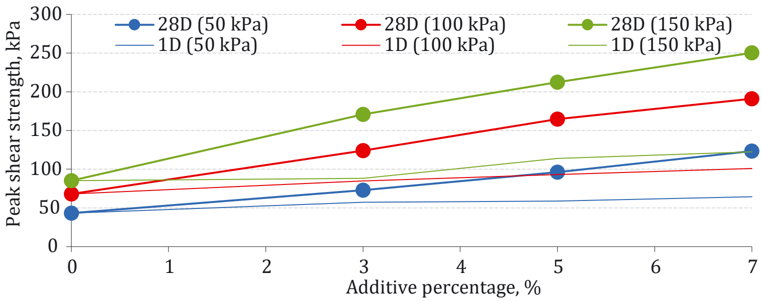
**b)** with petrochemical soda ash waste

**Figure 4.** Effect of stabilisation on shear strength (without curing)

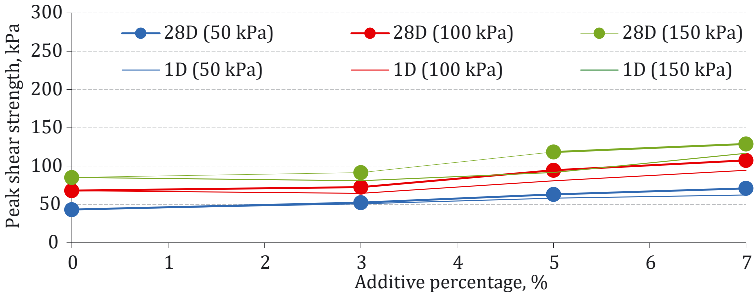
reactions is insufficient. The failure behaviour of saline soil modified with PSAW is ductile. Similarly, the failure behaviour for cement-treated is ductile too.

A part of the prepared samples was considered to be cured by CT1 for seven days. On the seventh day of curing, the samples were extruded from the airtight container. Dimension measurement of samples shows that a reduction of about 2 mm on each side occurs, which signifies shrinkage in cured samples. The samples stabilised with only PSAW and cured in the airtight container were destroyed entirely, and the results are unreportable. Therefore, mentioned samples were cured with the CT2 curing method. The results indicate that the shear strength enhancement of stabilised saline soil samples was insignificant. It established that 7-day curing with the CT2 method brings about minor changes in the shear strength of stabilised saline soil samples with different percentages of PSAW. Based on the tests, the authors decided to utilise the CT1 curing method only for the samples containing cement as a modifier.

The results of stabilised samples by various percentages of cement or PSAW after 28 days with the CT1 or CT2 curing method are presented in Figure 5. For the samples stabilised by different contents




**a)** by cement (C)



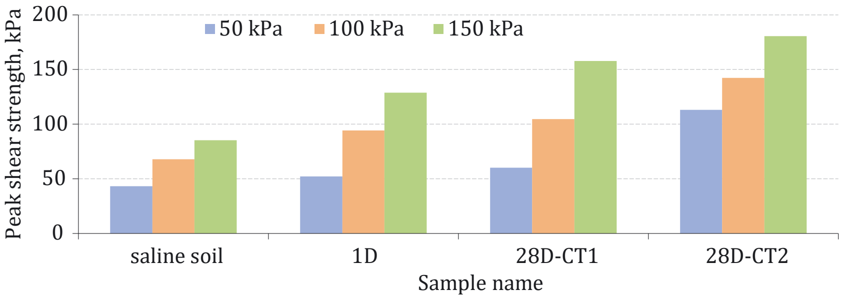

**b)** by petrochemical soda ash waste (W)

**Figure 5.** Effect of curing time on shear strength

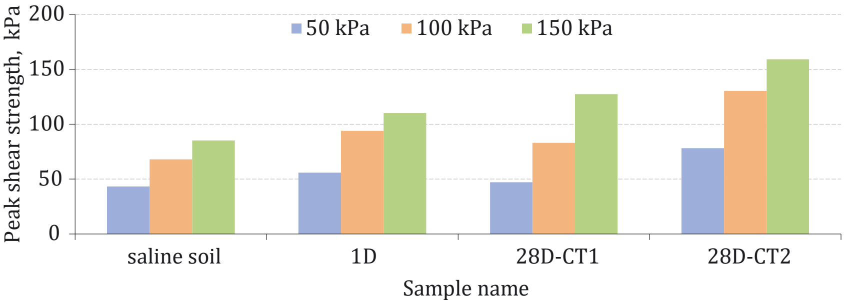
of PSAW, a moderate increase in shear strength (between 3% to 30%) was observed, and failure behaviour was ductile. On the other hand, stabilised samples by cement indicate that considerable changes (between 70% to 370% increase) in the shear strength of samples occur after 28 days of curing with the CT1 method.

After 28 days, PSAW increases the shear strength of saline soil samples, although this increase is less than the samples stabilised by cement. On the other hand, by increasing the amount of cement, the shear strength of the specimens after 28 days increases significantly. This increasing trend for the samples in which PSAW stabilised is negligible, and it is true that amounts more than 5% have an insignificant influence on increasing shear strength. This process demonstrates that a blend of cement and PSAW has logical outcomes.

The effects of curing type and sample age on the shear strength of samples stabilised with different combinations of cement and PSAW are stated in Figure 6. Adding 2% of cement and 5% of PSAW to the saline soil without curing measurement increases the shear strength




**a)** C2W5 – saline soil + 2% cement + 5% petrochemical soda ash waste




**b)** C2W7 – saline soil + 2% cement + 7% petrochemical soda ash waste

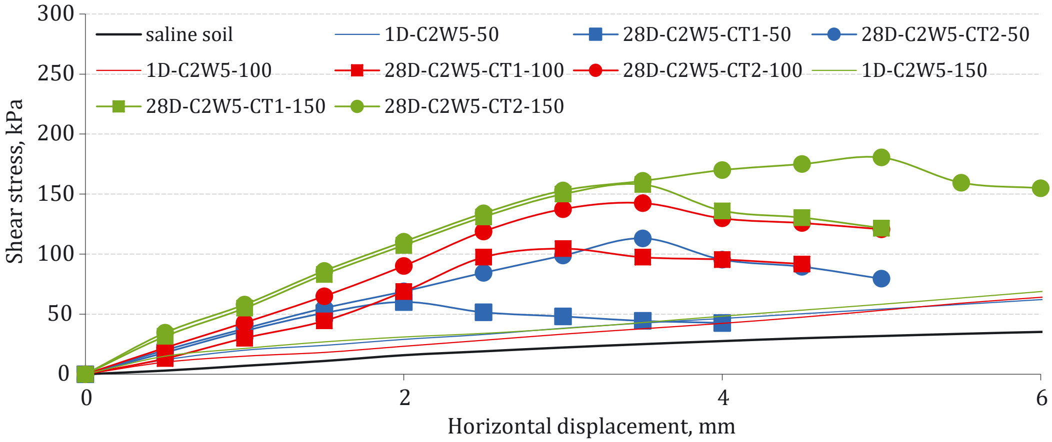
**Figure 6.** Effect of curing method on shear strength stabilised samples

of the mixture to about 37% on average. The shear strength of samples increases by about 60% in CT1 and 127% in the CT2 curing method. The samples cured with the CT2 method become stronger against shear stress to about 70%. It indicates that pozzolanic reactions occur more considerably in the CT2 curing method. Similar tests for the samples prepared with saline soil plus modifiers including 2% and 7% of cement and PSAW, respectively stated in Figure 6. The trend of strength increase is similar to C2W5 samples but lower in amount. Adding 2% of cement and 7% of PSAW to the saline soil samples without curing measurements increases their shear strength to 32%. Although using two more per cent of PSAW, the shear strength of modified samples without curing decreased by about 11% on average.

Moreover, sample curing with the CT1 method cannot increase shear strength, especially in lower confining pressures. Similarly, when the age of the samples increases to 28 days, the shear strength of cured ones with either CT1 or CT2 curing methods cannot boost the average amount of shear strength. Therefore, more than 5% PSAW causes reverse function in the strength of stabilised samples.

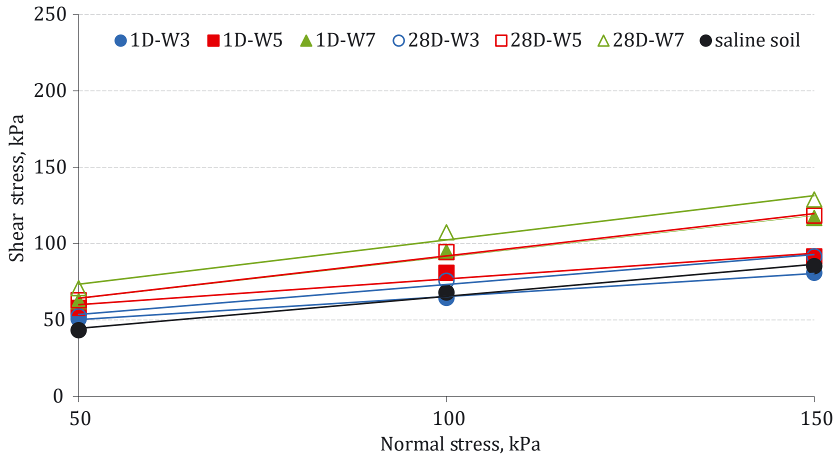
Figure 7 stated that the failure behaviour of saline soil stabilised with a combination of cement and PSAW without curing is ductile and similar to natural saline soil. On the other hand, the failure behaviour of the cured samples with CT1 and CT2 changed after 28 days into brittle.

The Mohr-Coulomb failure line of saline soil modified by different contents of cement and PSAW cured in different curing times and

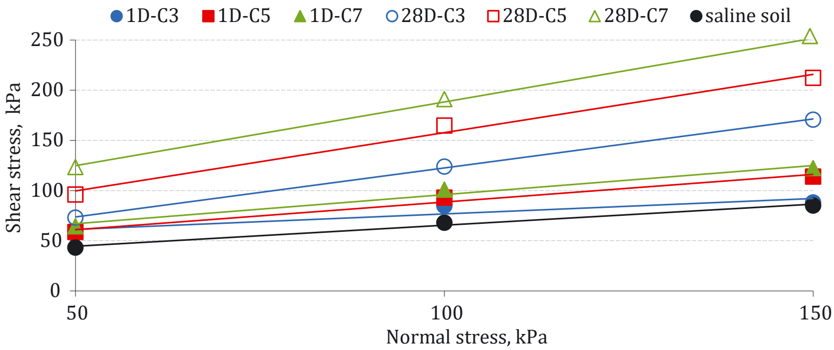



Note: C2W5 – saline soil + 2% cement+ 5% petrochemical soda ash waste;
CT1– curing method type 1; CT2 – curing method type 2.

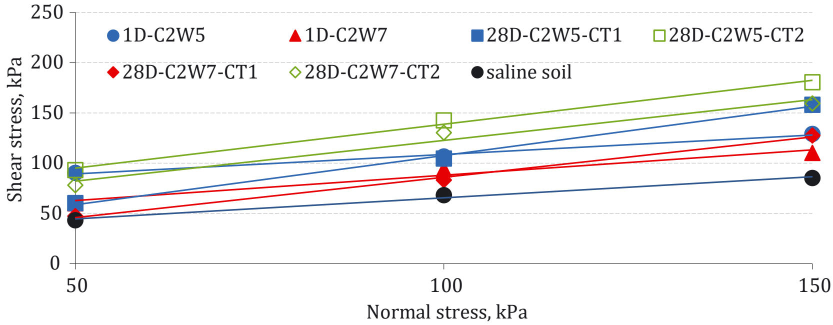
**Figure 7.** Failure behaviour of stabilised samples




**a)** petrochemical soda ash waste (3%, 5%, and 7%)




**b)** cement (3%, 5%, and 7%)



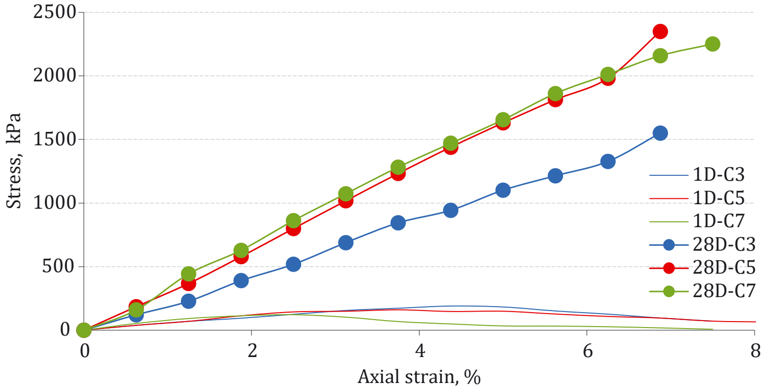

**c)** cement (2%) + petrochemical soda ash waste (5% and 7%)

Note: W – petrochemical soda ash waste (PSAW); C – cement.

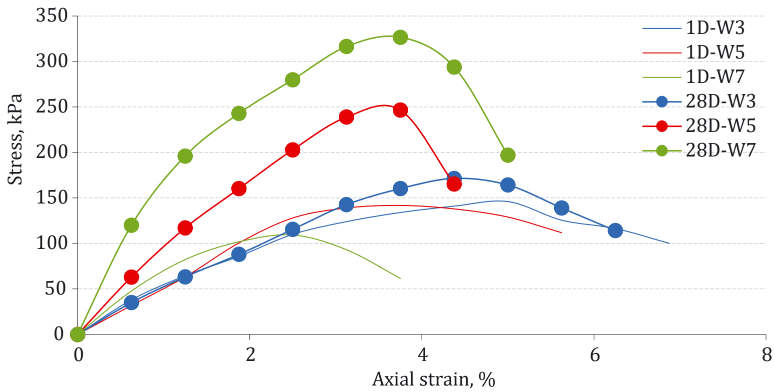
**Figure 8.** Mohr-Coulomb failure line of modified saline soil samples

methods are presented in Figure 8. Using different percentages of PSAW significantly increased the cohesion of 1-day stabilised samples. However, it had little effect on the internal friction angle. On the other hand, increasing the PSAW value by more than 5% increases the internal friction angle and internal locking of saline soil particles. With the curing of the samples, the cohesion change is negligible. Only the internal friction angle increased. Increasing the age of the stabilised specimens has a negligible effect on increasing the pozzolanic reactions and only increases the internal locking of the specimen.

For 1-day specimens stabilised by cement, an increase in the amount of cohesion and internal friction angle is quite evident. Also, the CT1 curing method and increasing the age of the samples have significantly




**a)** cement (C)

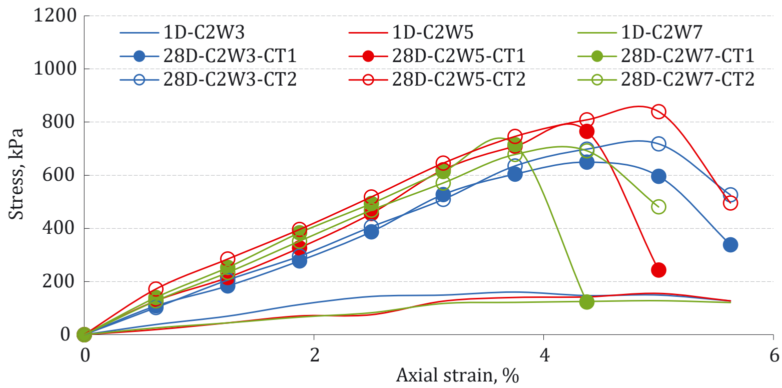



**b)** petrochemical soda ash waste (W)

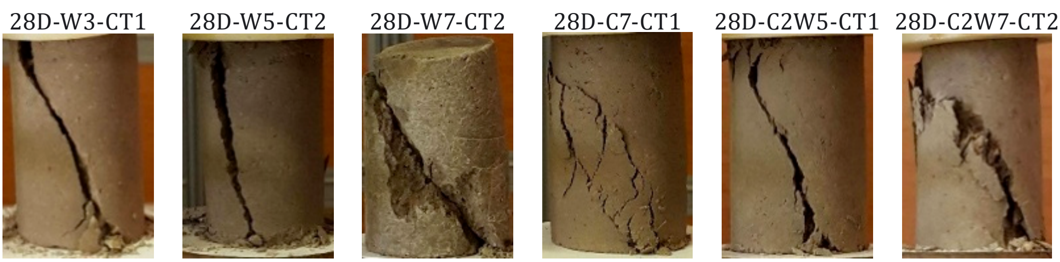
**Figure 9.** Unconfined compressive strength of stabilised samples

increased the cohesion parameters and the internal friction angle of these stabilised samples. Therefore, the CT1 curing method has increased the shear strength parameters of the sample during 28 days due to pozzolanic reactions and the formation of internal connections between soil particles and cement. In 1-day samples stabilised with 2% cement and 5% or 7% PSAW, cohesion increased significantly, especially for samples containing 5% PSAW. CT2 curing method has a much more significant effect on increasing cohesion than CT1. This analysis proves that using 2% cement and 5% PSAW with curing by the CT2 method for 28 days increases the cohesion parameter significantly and the internal friction angle of the stabilised sample.

The results of the unconfined compression test (*ASTM D2166/ D2166M-16*) indicate that the failure behaviour of 1-day samples stabilised by different contents of PSAW gradually changes into brittle when the PSAW percentages or samples age (Figure 9). Moreover, adding different contents of PSAW causes an increase in the undrained shear




**a)** unconfined compressive strength test results




**b)** failure modes of differently prepared samples

**Figure 10.** Simultaneous effect of modifiers on unconfined compressive strength

strength of the samples to about 34% on average. Also, the CT2 curing method until 28 days shows considerable effects on the amounts of undrained shear strength (about 97% on average). Similar tests on the samples prepared with different cement contents show that undrained shear strength boosts the average amount of about 60% (Figure 9). However, the CT1 curing method after 28 days significantly enhances undrained shear strength. The failure behaviour completely changes into brittle and sample deterioration suddenly occurs too high and loud. Therefore, both cement and waste increase the shear strength of saline soils.

The considerable enhancement, similar to the results of unconfined compression tests of saline soil samples stabilised by cement, is more than the requirements of road construction. Hence, different compositions are prepared (Figure 10). Adding 2% of cement and 3%, 5%, and 7% of PSAW to the saline soil increases the undrained shear strength to about 50%. CT1 curing method after 28 days enhances the amount of undrained shear strength to more than 3.8 times compared to saline soil. At the same time, the 28-day CT2 curing method boosts this parameter by about 4.1 times on average. The cumulative study of direct shear and unconfined compression tests indicates that saline soil modified with 2% of cement and 5% of PSAW, cured with the CT2 curing method after 28 days, brings about the best results from a shear strength viewpoint. Failure modes of differently prepared samples for unconfined compression tests are shown in Figure 10.

## 3.2. Swelling studies

Natural saline soil specifications (1.2 section) presented that the soil in this investigation is inactive from a clayey particle viewpoint, so swelling defects are unexpected. However, since the saline soil is classified as “high-sulphate”, the interaction between calcium ions of applied stabilisation agents and inactive sulphate and aluminium content of the saline soil and ettringite crystals formation is expected. Ettringite crystals formation causes disruptive volumetric changes and loss of mechanical strength for the stabilised saline soil. Therefore, swelling studies were conducted by the authors.

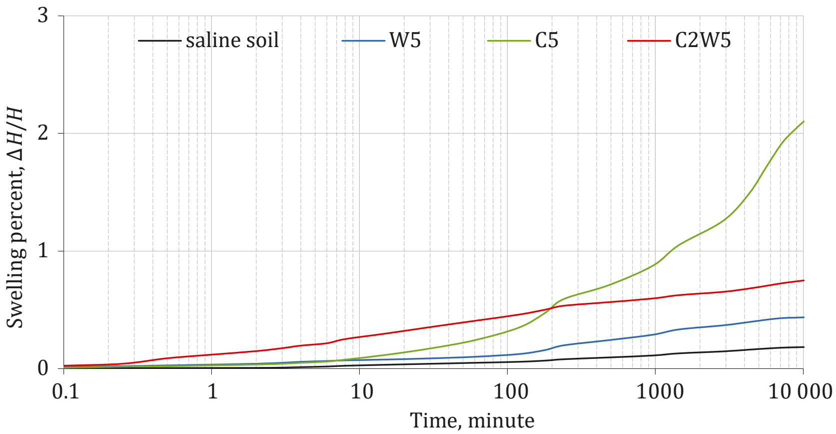
As stated in Figure 11, natural saline soil is inactive from the swelling viewpoint because the swelling per cent (the ratio of the increase in thickness ($\Delta H$) to the original thickness ($H$) expressed as a percentage) is about 0.2% after seven days. For the C5 sample, a significant swelling percentage occurred, which was about 2.1%, and the W5 sample swelling was too low (about 0.44%). In comparison, it is about 0.75% for the C2W5 specimens. The swelling potential of natural saline soil and C2W5 samples are "low", and the C5 is "moderate" based on the classification presented by Seed et al. (1962). However, the United States Bureau of Reclamation (USBR) is considered all of them as "low" from a swelling potential viewpoint.

## 3.3. Salt solubility stabilisation studies

Electrical conductivity (EC), total dissolved solids (TDS), and pH changes of natural saline soil samples versus soil-washing numbers are presented in Figures 12 and 13a. These diagrams show that EC and TDS amount rapidly decrease with increasing soil-washing, and the results are similar to Li et al. (2016) findings. The first and second washing numbers solved a significant amount of salt in the non-stabilised soil sample. Nevertheless, the soluble salt content declined during the third and fourth washing. Hence, the first and second phases have a more significant impact on other phases.

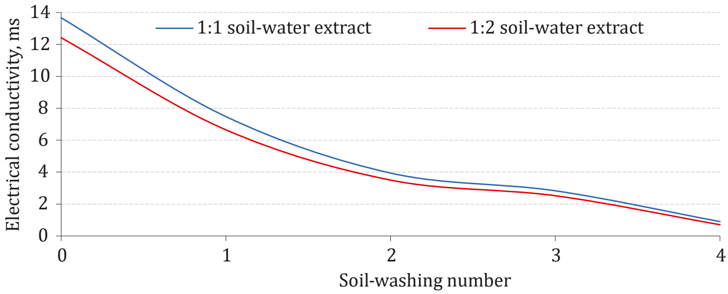
Moreover, the findings of this study demonstrate a too weak correlation between pH changes and soil-washing numbers.

Moreover, the soluble salt content of non-modified saline soil tends to zero after four times of soil washing (Figure 13b). after four soil-washing numbers in four phases, the entire salty structure removes from the soil, and all the soil particle connections destroy. It is observed that the soil at this stage completely changes into sludge without any resistance. Before

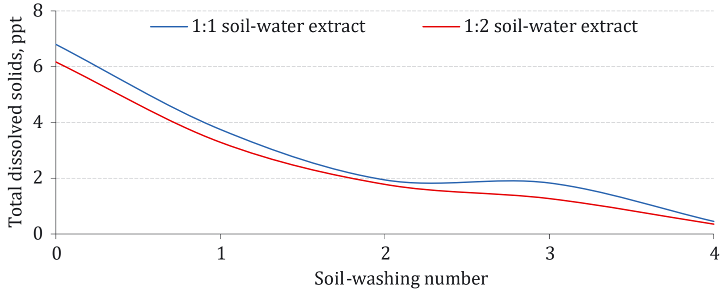



Note: modifier 5% of petrochemical soda ash waste (W5), 5% of cement (C5) and 2% of cement plus 5% of petrochemical soda ash waste (C2W5).

**Figure 11.** Swelling potential

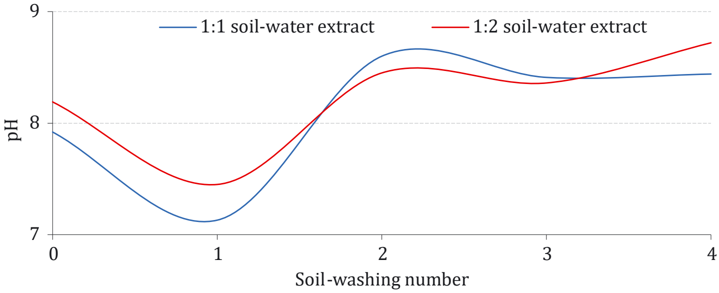



**a)** electrical conductivity (EC)

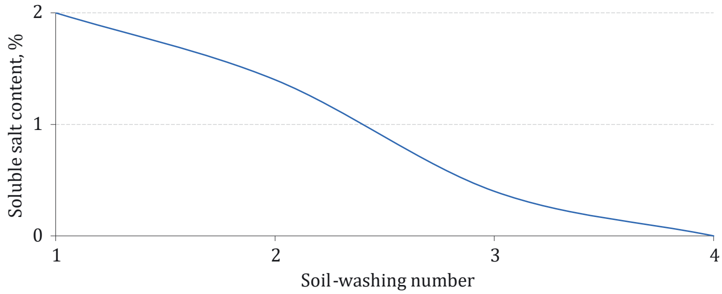



**b)** total dissolved solids (TDS)

**Figure 12.** Salt solubility parameters of natural saline soil




**a)** pH



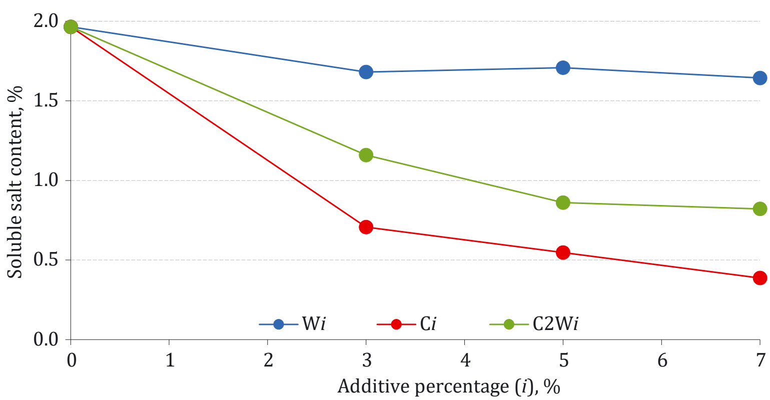

**b)** soluble salt content

**Figure 13.** pH and soluble salt content of natural saline soil

these tests, the probes of EC and TDS and pH meter are calibrated with standard buffer solutions and the temperature of the tests is set to 25 °C.

Figure 14 shows that samples that have been stabilised with PSAW still lose a great deal of salt after washing. Furthermore, the increase in PSAW content has a negligible impact on this issue. Because the samples that were stabilised with 3% PSAW are almost identical to the stabilised results with 7% PSAW, it is concluded that PSAW has an insignificant effect on the stabilisation of saline soil samples against salt dissolution. In contrast, samples that were stabilised with cement showed a different trend. Test results indicate that cement effectively prevents salt dissolution in samples. Only with 3% cement did the amount of soluble salt in the samples reach 0.7%. This downward trend continues with more percentages of cement but shows less slope. It proves that less than 3% of the cement is more efficient than more cement.

On economic issues, samples that were stabilised with 2% cement and stabilised with 3%, 5% and 7% PSAW were tested (Figure 14). The downward trend in salt dissolution is seen, but it is lower than the strength of samples, which have been stabilised by cement and more significant than the ones stabilised just by PSAW. Salt stabilisation in saline soil just by PSAW is inappropriate, but cement salvages salt structures because of pozzolanic reactions. However, using only cement to stabilise salt is uneconomic. Therefore, the most logical result comes from the combination of 2% cement and 5% PSAW (Figure 14).




Note*:* W*i* – saline soil + *i*% petrochemical soda ash waste; C*i* – saline soil + *i*% cement; C2W*i* – saline soil + 2% cement + *i*% petrochemical soda ash waste.

**Figure 14.** Soluble salt of modified saline soil

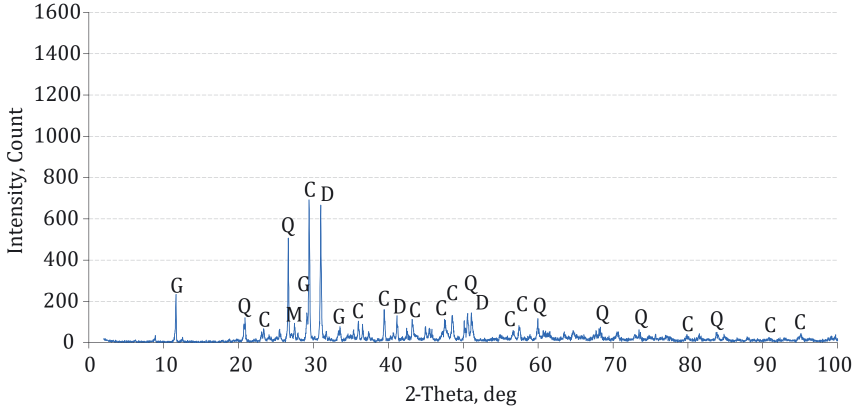
## 3.4. Mineralogical studies

Swelling studies show that sulphate-heave per cent in both natural saline soil and stabilised samples with different contents of PSAW and cement is negligible. Also, it seems that the possibility of ettringite mineral formation is ignorable. Therefore, more investigations are suggested. Selected soil samples were used for conducting XRD tests.

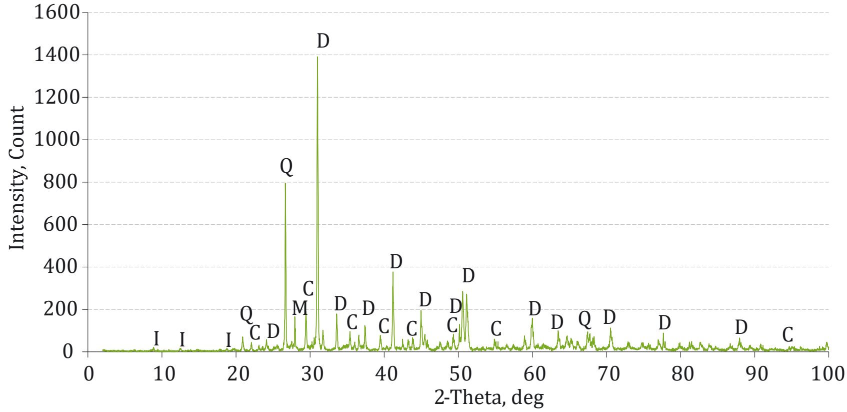
The results of the XRD test are stated in Figure 15. The results indicate that there was calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), gypsum ($CaSO_4{\cdot}2H_2O$), quartz ($SiO_2$), and halite (NaCl) in the saline soil samples. Gypsum was observed just in the sample of natural saline soil. Other minerals such as microcline ($KAlSi_3O_8$), illite ($(KH_3O)Al_2Si_3AlO_{10}(OH)_2$) are shown in the diagrams too, but they have a low frequency. It is good to say that saline soil samples contain clay minerals and feldspar (Na, Ca and K). The saline soil is classified as "high-sulphate", and the elements such as calcium, aluminium and sulphate were discovered in both natural saline soil and stabilisation agents (cement and PSAW). Nevertheless, ettringite formation in the samples stabilised by different contents of cement and PSAW is unremarkable. As stated in Figure 15, the peaks at 9.6 Å, 5.6 Å and 3.26 Å (equals to 2 angle of 9.2°, 15.8° and 27.3°, respectively) are insignificant. Hence, the amount of ettringite mineral formed is negligible (1 Å = 0.1 nm). The names of observed minerals, their chemical formulas and abbreviations are presented in Table 4. The intensity of each mineral is stated in Figure 15.

**Table 4. Observed minerals in X-ray diffraction test results**

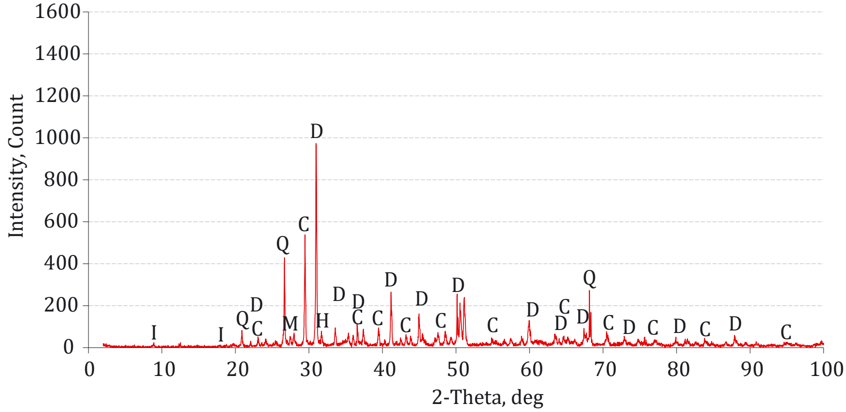
| Mineral name | Chemical formula | Abbreviations |
|---|---|---|
| Gypsum | $CaSO_4{\cdot}2H_2O$ | G |
| Quartz | $SiO_2$ | Q |
| Calcite | $CaCO_3$ | C |
| Microcline | $KAlSi_3O_8$ | M |
| Dolomite | $CaMg(CO_3)_2$ | D |
| Illite | $(KH_3O)Al_2Si_3AlO_{10}(OH)_2$ | I |
| Halite | NaCl | H |




**a)** saline soil




**b)** saline soil + 5% petrochemical soda ash waste




**c)** saline soil + 2% cement + 5% petrochemical soda ash waste

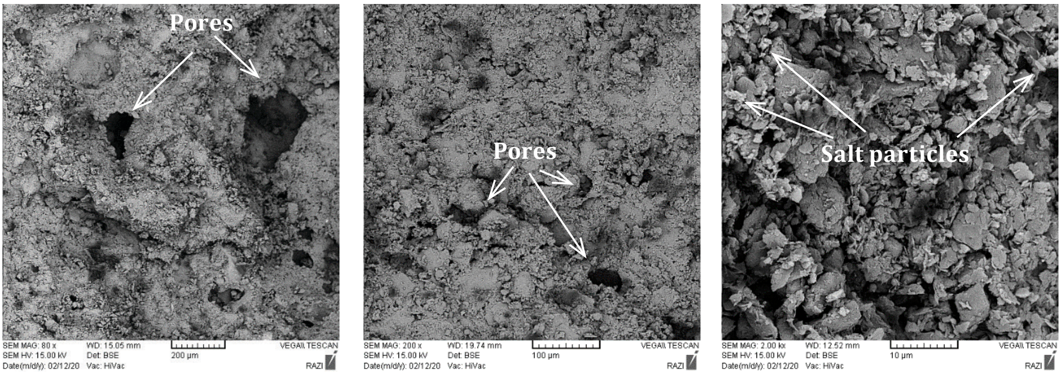
Note: Table 4 presents abbreviations, mineral names and their chemical formulas.

**Figure 15.** X-ray diffraction

## 3.5. Microstructure analysis

The microstructure of natural saline soil (Figure 16) shows that while the particles have nonuniform size, they are connected in a relative porous form, and the fulfilment of pores by finer particles is unexpected.

The W5-CT2 sample in saline soil was modified with 5% petrochemical soda ash waste on the 28th day of curing type 2. Scanning electron microscope pictures of this sample (Figure 17) indicate that PSAW particles fill in the pores of natural saline soil, so sample porosity significantly decreases. Also, PSAW particles and saline soil particles are wrapped and stacked together, forming coarser particles. Therefore, a more compacted combination obtains. However, still, some tiny pores are visible. In Figure 17, the determination of the calcium-enriched zone shows that a significant percentage of PSAW particles are settled on the surface of soil particles (about 17% of average weight).




80 times 200 times 2000 times

**Figure 16.** Microstructure of saline soil


80 times 200 times 2000 times

**Figure 17.** Microstructure of W5-CT2

Moreover, because of the white colour of PSAW, this combination colour tends to be brighter than the natural saline soil colour. A combination of saline soil with 2% cement and 5% PSAW cured with the CT1 curing method (the C2W5-CT1) shows a compacted formation with too low porosity and without major cracks (Figure 18). The internal structure is relatively compact, and the style of modified saline soil with cement and PSAW is dense from a framework point of view. The cement modification results in a denser combination and more strength product because of the solidification process. Also, Figure 18 indicate ettringite development during reactions. As stated in Figures 16 and 17, stabilised salt particles are negligible in the natural saline soil sample and the sample prepared with 5% of petrochemical soda ash waste.

On the other hand, salt particles were detectable in SEM pictures prepared from the samples modified with 2% cement and 5% PSAW. It is the result of successful salt stabilisation. Moreover, too little formation of needle-shaped crystal ettringite was discovered during the prepared sample's reaction with 2% of cement and 5% of PSAW (Figure 18). Despite the presence of calcium, magnesium, silicon, aluminium and potassium plus sulphate ions, which were observed in chemical test results of saline soil, the formation of this complicated mineral was too small and negligible.

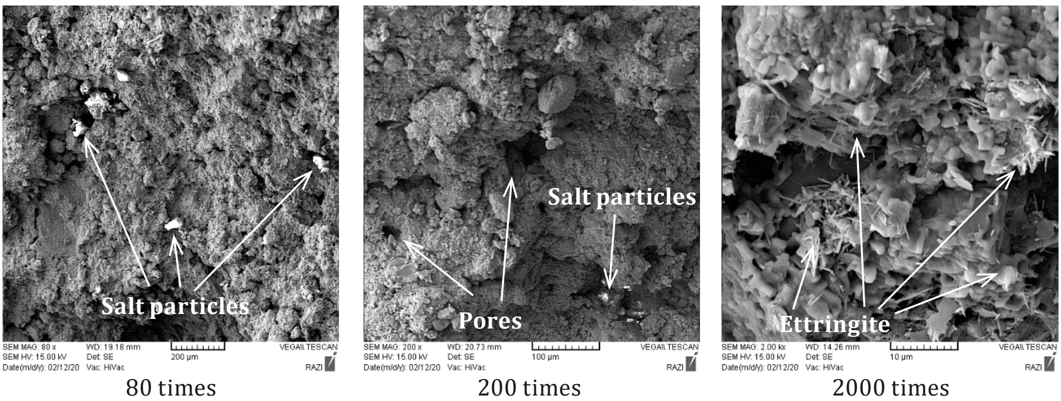



**Figure 18.** Microstructure of C2W5-CT1

## Conclusions

An experimental investigation was conducted to study saline soil subgrade physical, chemical and mechanical specifications stabilised with different percentages of modifiers such as petrochemical soda ash waste and cement with two different curing methods.

1. This investigation proves that petrochemical soda ash waste and cement as modifiers enhance saline soil shear strength in first-day samples to lower than 50%. However, the influence of petrochemical soda ash waste was weaker than cement. As part of this study, it became apparent that the petrochemical soda ash waste contains specific compositions similar to lime. This industrial waste has also increased the shear resistance of saline soils. Moreover, the influential role of cement in increasing the resistance of saline soils becomes clear. Consequently, the function of cement and petrochemical soda ash waste in the samples without curing is similar.

2. The two different curing methods used in this study demonstrate that the curing type 1 brings about more good results for the samples containing only cement as a modifier. Curing type 2 is suitable for the samples that contain petrochemical soda ash waste. The effect of sample age was considerable on the shear strength of the samples modified by cement. Curing type 2 curing method, achieved quickly in road construction job sites. Required facilities and equipment are simply attainable. A cumulative review of the results achieved from the direct shear test and unconfined compression tests resulted in the most reasonable shear strength (about a 127% increase). This increase occurs in saline soil samples stabilised by 2% cement and 5% of petrochemical soda ash waste and cured by curing method type 2 for 28 days (28D-C2W5-CT2).

Therefore, the mentioned combination, 28D-C2W5-CT2, is considered the optimum modification formula. It was concluded that most of the increase in shear strength was due to increased cohesion parameters and was influenced by pozzolanic reactions. Increasing the amount of petrochemical soda ash waste by more than 5% affected the internal friction angle. This study proved that the shear strength would increase considerably after curing with curing type 1 and curing type 2 methods or increasing the age of stabilised materials. However, failure behaviour tends from ductile to brittle, and a sudden failure is probable. However, this function meets the road construction criteria.

3. This study showed that a mixture of different per cent of petrochemical soda ash waste with a maximum of 3% of cement helped stabilise saline soil against salt solubility. Moreover, "28D-C2W5-CT2"

meets the best achievements from a shear strength viewpoint and addresses the salt solubility problem of saline soil.

4. Finally, X-ray diffraction test results and scanning electron microscope pictures proved that considerable enhancement of shear strength properties in 28D-C2W5-CT2 was due to the formation of an internal connection between saline soil particles and calcium concentration. X-ray diffraction tests demonstrated the presence of ettringite formation elements. Nevertheless, ettringite minerals formed were negligible. Therefore, a swelling problem for 28D-C2W5-CT2 is unexpected. Consequently, the salt concentration in different zones of mentioned stabilised samples, observable in scanning electron microscope pictures, demonstrated that the saline soil was well stabilised against salt dissolution.

## REFERENCES

Al-Rawas, A. A., & McGown, A. (1999). Microstructure of Omani expansive soils. *Canadian Geotechnical Journal*, *36*(2), 272-290. https://doi.org/10.1139/t98-111

*ASTM E1621-13, Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry*

*ASTM D2166/D2166M-16 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*

*ASTM D3080/D3080M-11 Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions* (withdrawn 2020)

*ASTM D422-63(2007)e2 Standard Test Method for Particle-Size Analysis of Soils* (withdrawn 2016)

*ASTM D698-12(2021) Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3))*

*ASTM E1621-21 Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry*

Budhu, M. (2020). *Soil mechanics and foundations,* 3rd edition. New York: Wiley. 761 p.

Cheng, Z., Cui, G., Yang, Z., Gang, H., Gao, Z., Zhang, D., & Xi, C. (2021). Improvement of the salinised soil properties of fly ash by freeze-thaw cycles: an impact test study. *Sustainability*, *13*(5), 2908. https://doi.org/10.3390/su13052908

Dahnke, W. C., & Whitney, D. A. (1988). Measurement of soil salinity. *Recommended Chemical Soil Test Procedures for the North Central Region*, *499*, 32-34.

Ghanbarian, M. A. (2016). Structural analysis of the Konarsiah and the Mangerak salt domes and its influence in ground water contamination, Zagros foreland folded belt, SW Iran. *International Journal of Environmental Sciences*, *7*(1), 70-82. https://doi.org/10.6088/ijes.7007

Kamei, T., Ahmed, A., & Shibi, T. (2012). Effect of freeze–thaw cycles on durability and strength of very soft clay soil stabilised with recycled Bassanite. *Cold Regions Science and Technology*, *82*, 124-129. https://doi.org/10.1016/j.coldregions.2012.05.016

Li, H., Shen, H., & Shen, J. (2015). Shearing strength and durability of hypersaline soil solidified with fly ash. *Journal of Lanzhou University of Technologies*, *41*, 140-144. (in Chinese)

Li, M., Chai, S. X., Zhang, H. Y., Du, H. P., & Wei, L. (2012). Feasibility of saline soil reinforced with treated wheat straw and lime. *Soils and Foundations*, *52*(2), 228-238. https://doi.org/10.1016/j.sandf.2012.02.003

Li, M., Chai, S., Du, H., & Wang, C. (2016). Effect of chlorine salt on the physical and mechanical properties of inshore saline soil treated with lime. *Soils and Foundations*, *56*(3), 327-335. https://doi.org/10.1016/j.sandf.2016.04.001

Liu, Y. P., & Zhang, Y. (2012). Analysis and Treatment for Diseases of Sulphate Saline Soil Subgrade in Xinjiang Area. *Transport. Standardisation*, *3*, 69-72. (in Chinese)

Liu, Y., Wang, Q., Liu, S., ShangGuan, Y., Fu, H., Ma, B., ... & Yuan, X. (2019). Experimental investigation of the geotechnical properties and microstructure of lime-stabilised saline soils under freeze-thaw cycling. *Cold Regions Science and Technology*, *161*, 32-42. https://doi.org/10.1016/j.coldregions.2019.03.003

Lv, Q., Jiang, L., Ma, B., Zhao, B., & Huo, Z. (2018). A study on the effect of the salt content on the solidification of sulphate saline soil solidified with an alkali-activated geopolymer. *Construction and Building Materials*, *176*, 68-74. https://doi.org/10.1016/j.conbuildmat.2018.05.013

Moayed, R. Z., Izadi, E., & Heidari, S. (2012). Stabilisation of saline silty sand using lime and micro silica. *Journal of Central South University*, *19*(10), 3006-3011. https://doi.org/10.1007/s11771-012-1370-1

Parsaei, M., Vakili, A. H., Salimi, M., Farhadi, M. S., & Falamaki, A. (2021). Effect of electric arc and ladle furnace slags on the strength and swelling behavior of cement-stabilised expansive clay. *Bulletin of Engineering Geology and the Environment*, *80*(8), 6303-6320. https://doi.org/10.1007/s10064-021-02316-0

Puppala, A. J., Griffin, J. A., Hoyos, L. R., & Chomtid, S. (2004). Studies on sulphate-resistant cement stabilisation methods to address sulphate-induced soil heave. *Journal of Geotechnical and Geoenvironmental Engineering*, *130*(4), 391-402. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:4(391)

Seed, H. B., Woodward Jr, R. J., & Lundgren, R. (1962). Prediction of swelling potential for compacted clays. *Journal of the Soil Mechanics and Foundations Division*, *88*(3), 53-87. https://doi.org/10.1061/JSFEAQ.0000431

Slessarev, E. W., Lin, Y., Bingham, N. L., Johnson, J. E., Dai, Y., Schimel, J. P., & Chadwick, O. A. (2016). Water balance creates a threshold in soil pH at the global scale. *Nature*, *540*(7634), 567-569. https://doi.org/10.1038/nature20139

Talbot, C. J. (1990). Allochthonous salt spreading. In *Symposium on Diapirism with Special Reference to Iran* (pp. 507-510).

Tian, H., Qi, Z., & Qing, M. (2016). Experimental study on chemical improvement of coarse particle saline soil. *Site Investig. Sci. Technol. 5*–7+27, (in Chinese)

Wang, J., Wang, Q., Lin, S., Han, Y., Cheng, S., & Wang, N. (2020). Relationship between the shear strength and microscopic pore parameters of saline soil with different freeze-thaw cycles and salinities. *Symmetry*, *12*(10), 1709. https://doi.org/10.3390/sym12101709

Zhang, S., Yang, X., Xie, S., & Yin, P. (2020). Experimental study on improving the engineering properties of coarse grain sulphate saline soils with inorganic materials. *Cold Regions Science and Technology*, *170*, 102909. https://doi.org/10.1016/j.coldregions.2019.102909

Zhang, W., Ma, J., & Tang, L. (2019). Experimental study on shear strength characteristics of sulphate saline soil in Ningxia region under long-term freeze-thaw cycles. *Cold Regions Science and Technology*, *160*, 48-57. https://doi.org/10.1016/j.coldregions.2019.01.008