

# An Experimental Study to Mitigate Swelling Pressure of Expansive Tabuk Shale, Saudi Arabia

A. A. Embaby, A. Abu Halawa, M. Ramadan

**Abstract**—In Kingdom of Saudi Arabia, there are several areas where expansive soil exists in the form of variable-thicknesses layers in the developed regions. Severe distress to infrastructures can be caused by the development of heave and swelling pressure in this kind of expansive shale. Among the various techniques for expansive soil mitigation, the removal and replacement technique is very popular for lightly loaded structures and shallow foundations. This paper presents the result of an experimental study conducted for evaluating the effect of type and thickness of the cushion soils on mitigation of swelling characteristics of expanded shale. Seven undisturbed shale samples collected from Al Qadsiyah district, which is located in the Tabuk town north Kingdom of Saudi Arabia, are treated with two types of cushion coarse-grained sediments (CCS); sand and gravel. Each type is represented with three thicknesses, 22%, 33% and 44% in relation to the depth of the active zone. The test results indicated that the replacement of expansive shale by CCS reduces the swelling potential and pressure. It is found that the reduction in swelling depends on the type and thickness of CCS. The treatment by removing the original expansive shale and replacing it by cushion sand with 44% thickness reduced the swelling potential and pressure of about 53.29% and 62.78 %, respectively.

**Keywords**—Cushion coarse-grained sediments, expansive soil, Saudi Arabia, swelling pressure, Tabuk Shale.

## I. INTRODUCTION

EXPANSIVE soils are encountered in arid and semi-arid regions, where annual evaporation exceeds annual precipitation. The hazards caused by expansive soils have been recorded in many countries all over the world, including America, Australia, Canada, India, Iran, Mexico, and South Africa [1]. Expansive soils have been called the hidden disaster because their damage cost is greater than the combined damage from natural disasters such as floods, earthquakes, and hurricanes [2]. The damages regarding expansive soils have caused \$7 billion each year in the United State alone [3] and \$300 million during the period 1977-1987 in Kingdom of Saudi Arabia [4].

Expansive soils in Kingdom of Saudi Arabia have received wide attention of several researchers [5]–[10]. The shale is encountered in many parts of Saudi Arabia covering major zones of the central, north and northwestern parts of it. Clayey and silty shales were reported in Tabuk, Al Ghatt, Tayma,

Madinah Monawara, Hofuf, Sharawrah and Al Joaf [11]–[14]. Shale is the primary source of expansive soils in Al Qadsiyah, Al Masif and Al Rowdah, Tabuk districts [15]–[19].

There are various methods/techniques to reduce swelling in soils at the ground surface to prevent the damage caused to structures. Mitigation measures for expansive soils have been summarized and described by several authors [1], [20]–[25]. Among the various techniques of expansive soil mitigation, remove and replace technique has become prominent for lightly loaded structures and footings on expansive soils due to its effectiveness and adoptability. Removal of the upper expansive soil and replacing it with a non-expansive soil is one such method [26]. References [27]–[29] suggested that swelling pressure varies inversely as the thickness of the sand layer and directly as its density.

Reference [30] did research on the evaluation of the effectiveness of various design/mitigation procedures for reducing swelling and minimizing damage to pavements. They found that replacing the subgrade with inert (non-expansive) material is effective in reducing the pavement vertical movement. Then, remove and replace method has been used for the mitigation of expansive soils in different states like California, Texas and Colorado [31]. Removal and replacement of expansive material have been successful in the repair of some hydraulic structures to reduce uplift pressures. Repairs were made on the Friant-Kearn canal [32] and the Mohawk and Welton canals by over excavating the subgrade and replacing the expansive material with sand and lightly compacted gravel [33]. This remove and replace method was also used to reduce the expansion of clay by using a thick layer of the removed and replaced material to increase stress levels of underlying expansive clay. Hotlz [33] noted that the differential movements reduce by the presence of the replacement gravel layer.

The current study attempts to investigate the effectiveness of the abundant cushion of coarse-grained sediments on the mitigate or decay the swelling behavior of expansive Tabuk shale, KSA through conducting a series of large scale laboratory tests on seven undisturbed samples.

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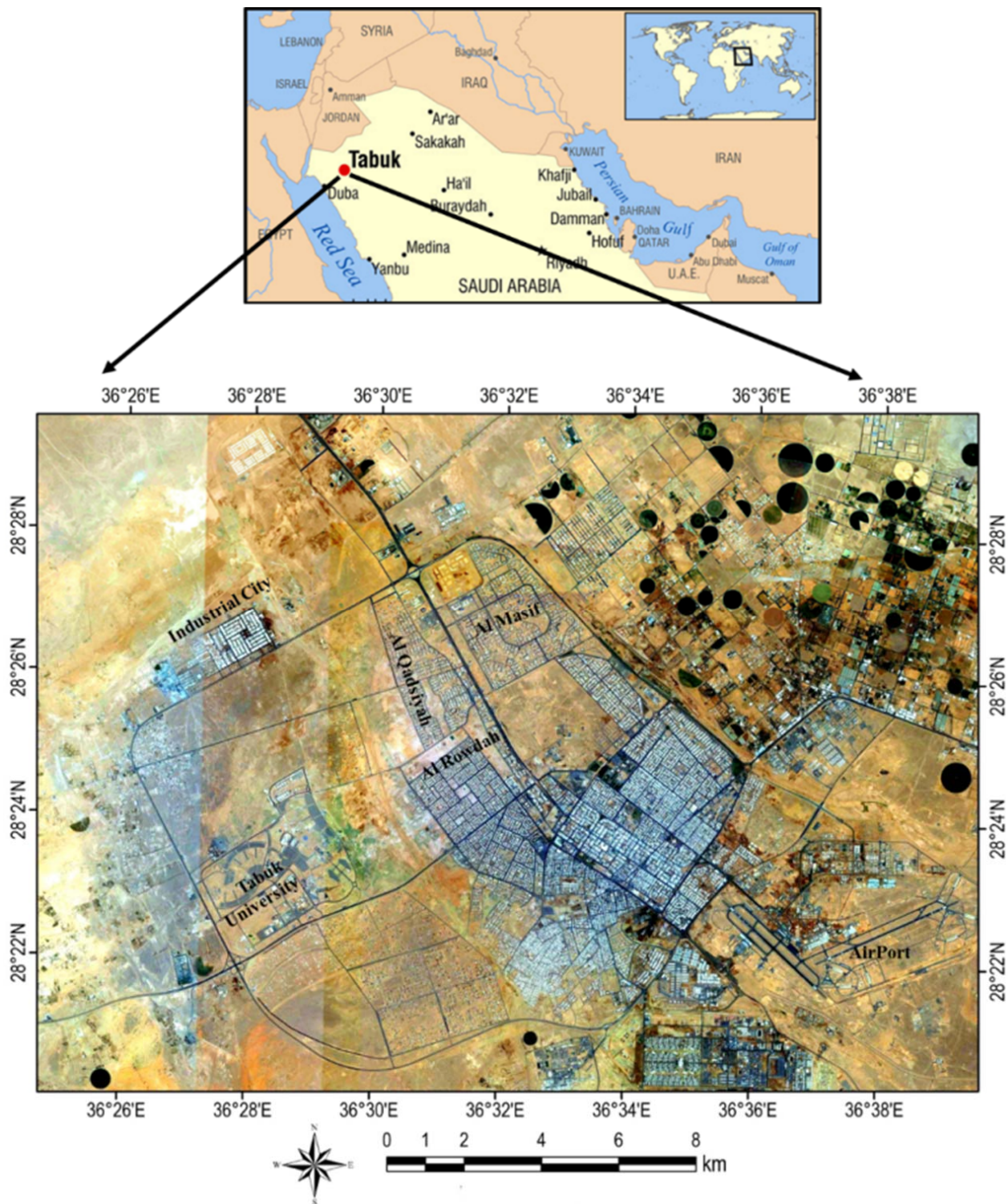


Fig. 1 Location map of Tabuk city, Kingdom of Saudi Arabia "KSA" (from Landsat-8 OLI bands 753 RGB, captured 2015)

## II. LOCATION AND GEOLOGICAL SETTING

Tabuk town is located in the northwestern part of the Kingdom of Saudi Arabia between latitudes 27.50° - 28.50° N, and longitudes 36.00° - 7.00° E (Fig. 1). Al Qadsiyah district is

more vital and residential neighborhood in Tabuk city, where there are many government and private buildings (schools, universities and hospitals, etc.). It is one of the most affected districts from expansion soil hazards, where many of the

buildings show the fissures and cracks in the walls, as well as in the boundary walls, walkways and the streets (Fig. 2).

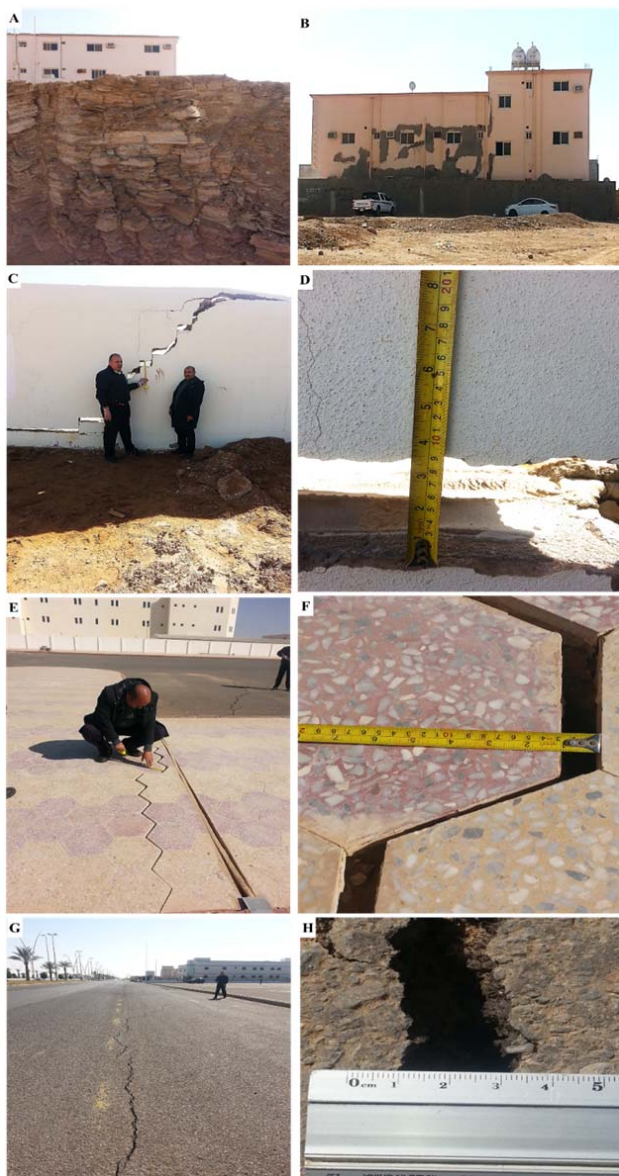


Fig. 2 Some effects of expansive shale: (A & B) longitudinal cracking and failure in housing, (C & D) boundary wall, (E & F) walkways and (G & F) roadway, Tabuk, KSA

Based on the drilling boreholes, the lithology of the subsurface is divided into four layers (Fig. 3). Starting from the top; the first layer, a surficial transported silt, clay, sand soil has a thickness range 0.5-2 m; the second layer consists of weathered shale with thickness range 0.5-3 m, the third layer consists of brownish gray laminated silty and clay shale interbedded with thin lamination of sandstone and lenses of gypsum, the thickness of the layer ranges from 3 to 20 m. The fourth layer is fine to medium sandstone bed-rock. Some of these layers are represented in some areas and absent in

another. In some localities such as Al Qadsiyah (present investigation) and Al Masif districts, the first and second layers are absent and buildings are constructed directly on shale, which represents the expansive soils in this region.

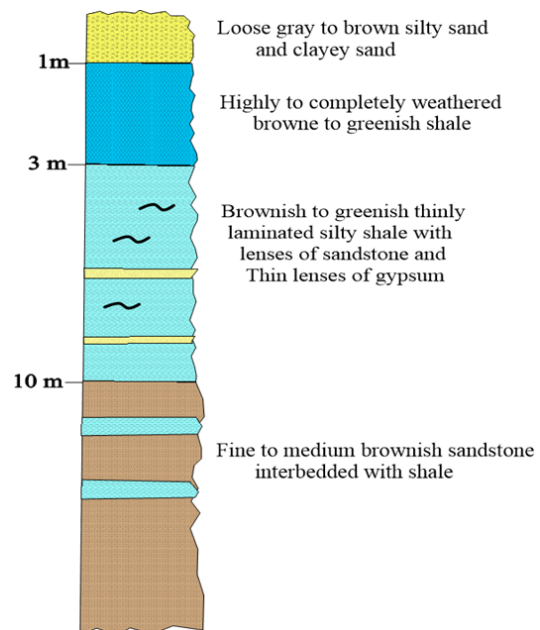


Fig. 3 Lithological log of subsurface layers at Al Qadsiyah district, Tabuk, KSA

### III. MATERIALS AND METHODS

#### A. Sample Preparation

The undisturbed shale specimens were taken from excavated test pit from Al Qadsiyah district of Tabuk town, KSA. Test pit (2.0 m x 4.0 m) was excavated using a Poclairn from shale rock surface to a depth of -1.0 m below the ground surface; the excavated surface was clean and leveled from loose materials. Seven molds were penetrated inside shale by using hydraulic pressure smoothly and gently. Excavate the soil around the molds and then pick up the molds from the soil. The molds were leveled from both sides, kept on perforated base and covered with wax. The molds were stored at 25 °C in a humidity chamber of the geotechnical lab.

#### B. Shale Material Prosperities

The physical, geotechnical and mineralogical properties of the shale set were measured and analyzed (Table I, Fig. 4). The shale was composed of predominantly silt size of about 68.6%, clay size of about 27.9% and 3.5% sand. It is classified as silt of low plasticity (ML) according to the Unified Soil Classification System (USCS). The shale samples have natural average moisture content of about 3.2%. The average liquid, plastic, plasticity index and shrinkage limits were 44%, 35%, 13%, and 16%, respectively. The activity of the shale and free swell were 0.6 and 19%, respectively. The results of the Atterberg limits and free swell tests (Table I) indicated that the shale had low to medium swelling potential [34]–[38]. Active

zone is the total thickness of shale which affected by changes in moisture content [39]. It ranges from 2 to 3.5 m in the study area. Mineralogical analyses of the studied shale were conducted by using X-Ray Diffraction (XRD).

The XRD patterns indicate that the predominant clay minerals constituents of the shale are kaolinite with minor amounts of illite (Table I, Fig. 4). The expansive lattice-type clay mineral (i.e., montmorillonite) cannot be traced in it.

*C. Cushion Coarse-Grained (Replacement Soil) Materials Properties*

The treatment procedure used two different CCS types (sand and gravel) with different thickness as replacement materials. The properties and grain size distribution of the cushion sediments are listed and represented in Table II and Fig. 5. The median grain size of sand and gravel are 0.15 mm and 7.22 mm, respectively. Sand and gravel are well sorted (poorly graded). The cushion replacement samples were classified according to American Association of State Highway and Transportation Officials (AASHTO) as granular materials,

groups A-3 and A-1-a of sand and gravel, respectively.

TABLE I  
PROPERTIES OF THE IN SITU SHALE, AL QADSIYAH, TABUK, KSA

Properties	Characteristics	Properties	Characteristics
Liquid limit LL (%)	44	Particle size distribution	
Plastic limit, PL (%)	35	Clay (%)	27.9
Plasticity Index PI	13	Silt (%)	68.6
Shrink limit SL (%)	16	Sand (%)	3.5
Water content (%)	3.2	Classification USCS	Silt (ML)
Activity	0.6		
Free swell (%)	19		
Dry unit weight (kg/cm <sup>3</sup> )	2.19	X-ray diffraction analysis	Kaolinite 73%
Specific gravity	2.73		Illite 7%
Compression index	0.0112		
Swelling pressure Oedometer test (kg/cm <sup>2</sup> )	8.0	Swelling pressure large-scale test (kg/cm <sup>2</sup> )	2.23
Active zone depth	2-3.5m		

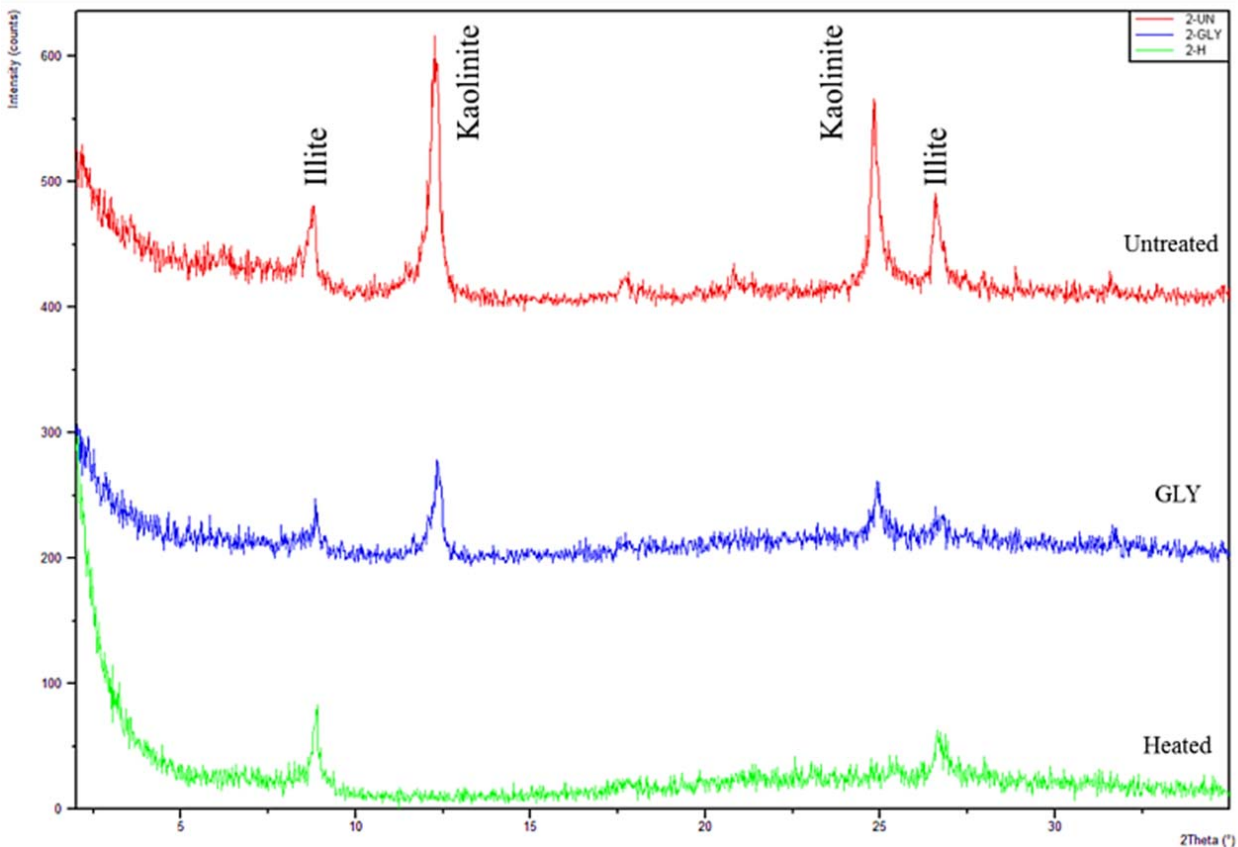


Fig. 4 Completed signal quantification with labeled peaks of expansive Tabuk shale, Al Qadsiyah district, Tabuk, KSA

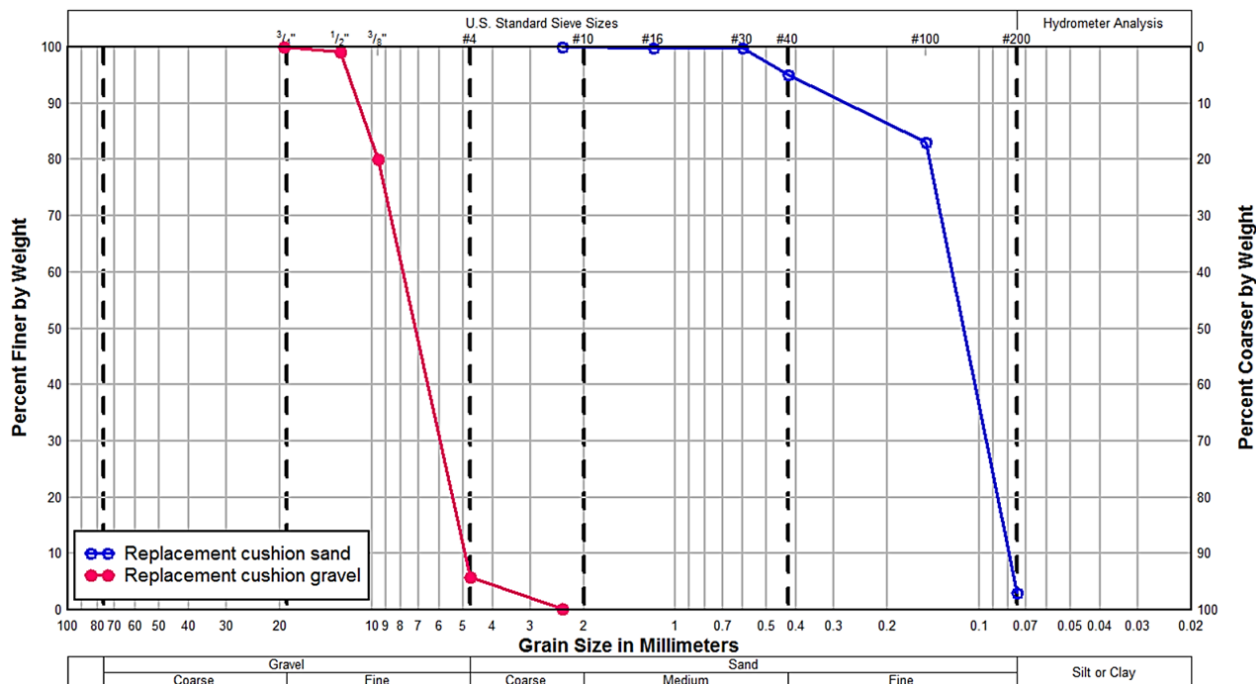


Fig. 5 The particle size distribution of the cushion sediments used in replacement; sand and gravel

IV. TEST SETUP AND PROCEDURE

The test essentially depends on direct measurement of the vertical rise of a shale sample placed under some surcharge and in contact with water inside the mold. In the current laboratory large-scale test, seven molds (15 cm diameter, 30 cm high) with perforated base were used. Typical test arrangements with CCS are shown in Fig. 6. The swelling and consolidation tests were carried out for the seven molds, which contain undisturbed shale samples, as follows:

- 1) The wax removed from molds and leveled from both sides at the laboratory.
- 2) The sample length inside the mold and the weight of the molds were measured to estimate the dry density.
- 3) The seating loads 7 kPa that closely corresponded to the in situ effective stress acting on the soil were applied on the samples inside the molds.
- 4) Different thicknesses from CCS types, as in Table II, were added in the seven molds (Fig. 6).
- 5) Last mold No. 7 was kept as natural shale without any treatment materials to compare the effect of the treatment by replacement cushion sediments.
- 6) All the molds were occupied by surcharged weight according to the depth of sample at site (7 kPa) and submerged in water tank and fixed a dial gage (0.01mm) on each mold (Fig. 6). The water tank and room temperature were maintained at constant 25 °C.
- 7) On the first day, the dial gage reading was taken after each hour and after the first day; the swelling readings were recorded after 24 hours for 24 days.
- 8) After reaching to constant or very little change in swelling for each mold the test was stopped and the final swell

readings were recorded.

TABLE II  
PROPERTIES OF CUSHION REPLACEMENT SEDIMENTS

Replacement type	Sand	Gravel
Median grain size (mm)	0.15	7.22
Soil description	Poorly graded	Aggregate
USCS classification	SP	GP
AASHTO classification	A-3	A-1-a
Mold Sample No.	1 2 3 4	5 6
Replacement thickness (%)	44 33 22 44	33 22

- 9) The molds were removed from the water tank and then the gradual loads were applied to bring the samples in their original condition (before swelling) and recorded the load as swelling pressure.
- 10) After this, the moisture content was determined at every 2 to 3 cm depth for each mold.
- 11) The relation between long time (hour) and swell (%) for all molds to determine the best thickness and the type of cushion was shown.

V.RESULTS

The percentage of change (reduction or increase) in any swelling characteristic was evaluated by comparing its value before and after soil treatment as [24]:

$$\text{Swelling\%} = \frac{\text{Value before treatment} - \text{Value after treatment}}{\text{Value before treatment}} \times 100$$

Swelling pressure was calculated from load applied to bring the samples in their original thickness. The differential

swellings between different cushion type and thickness with time are graphically presented (Fig. 7, Tables III & IV).



Fig. 6 Seven undisturbed shale molds (6 treatments and 1 without) with different type and thickness of replacement CCS used for treatment (A); seven molds submerged in a water tank and fixed a dial gage (0.01mm) for measurement of swelling (B); Al Qadsiyah district, Tabuk, KSA

From Fig. 7, the potential swelling curve has two stages. The first stage of swelling is initially very fast. It starts when the sample is flooded. It corresponds to a macroscopic swelling governed primarily by the permeability of the strata and the gradient of suction. On the other hand, the second stage is slow and progressive microscopic swelling up to the time needed to stability. This phase is a progressive process of clay minerals and cations adsorbed; this hydration is due to the available water in the pores. It was observed that swelling continues to occur for about 600 hours, beyond that there is very little or no change in swelling.

TABLE III  
THE SWELL PERCENT OF SHALE FOR DIFFERENT CUSHION TYPE AND THICKNESS OF AL QADSIYAH DISTRICT, TABUK, KSA

Mold No.	Replacement Soil		Swell (%)	Swell Pressure (kg/cm <sup>2</sup> )	Final Moisture Content (%)
	Type	Thickness* (%)			
1		44	1.63	0.83	10.80
2	Sand	33	1.93	0.96	11.80
3		22	2.6	1.11	12.20
4		44	1.86	1.35	11.65
5	Gravel	33	2.25	1.55	12.50
6		22	2.77	1.70	13.89
7	Without	----	3.48	2.23	13.93

\* The replaced thickness related to original length (9 cm) of the shale sample in the mold.

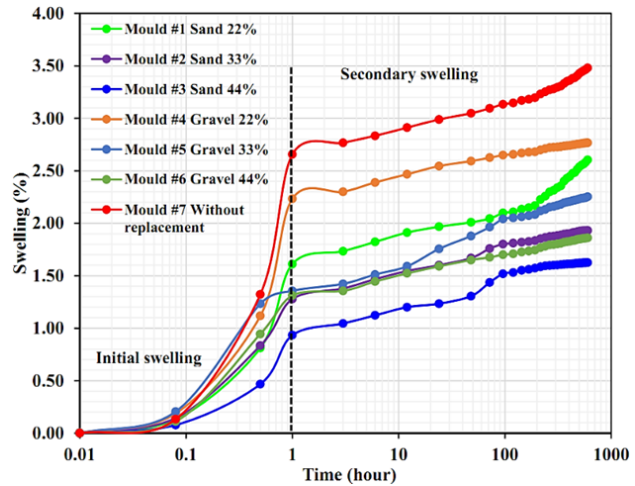


Fig. 7 Shale swelling (%) versus logarithmic time (hour) for variable type and thickness of the cushion replacement sediments, Al Qadsiyah district, Tabuk, KSA

TABLE IV  
THE REDUCTION OF SWELL AND PRESSURE PERCENT OF SHALE FOR DIFFERENT CUSHION TYPE AND THICKNESS OF AL QADSIYAH DISTRICT, TABUK, KSA

Mold No.	Replacement Soil		Reduction %	
	Soil Type	Thickness, %	Swell, %	Swell Pressure, kg/cm <sup>2</sup>
1		44	53.29	62.78
2	Sand	33	44.49	56.95
3		22	25.14	50.22
4		44	46.50	39.46
5	Gravel	33	35.28	30.49
6		22	20.49	23.77

The results of the testing program show that replacement by cushion sand controls the swelling effectively (Fig. 8). The thickness of replacement cushion affects the swelling behavior. The cushion sand type with 44% thickness reduces swelling more than other cushion type and thickness (Tables III & IV).

## VI. CONCLUSION

The swelling pressure test of natural and undisturbed shale specimens from Al Qadsiyah district by using Oedometer indicates that swelling pressure is 8 kg/cm<sup>2</sup>. This result is obtained in the laboratory for a confined small sample. The actual swelling pressure in the field is far less and can be taken as one third of this value [40], [41]. The swelling pressure for non-confined field condition, in our case that depends on the above value, is 2.66 kg/cm<sup>2</sup>. The swelling pressure value obtained from the laboratory large-scale test is 2.23 kg/cm<sup>2</sup>, this value is suggested as a design value for this particular area.

The swelling potential decreases by increasing the replacement thickness of all types of cushion (Fig. 8). The final swelling percent of original, expansive shale is reduced by about 53.29% in the case of using cushion sand replacement with thickness of 44% (Fig. 8 and Table IV).

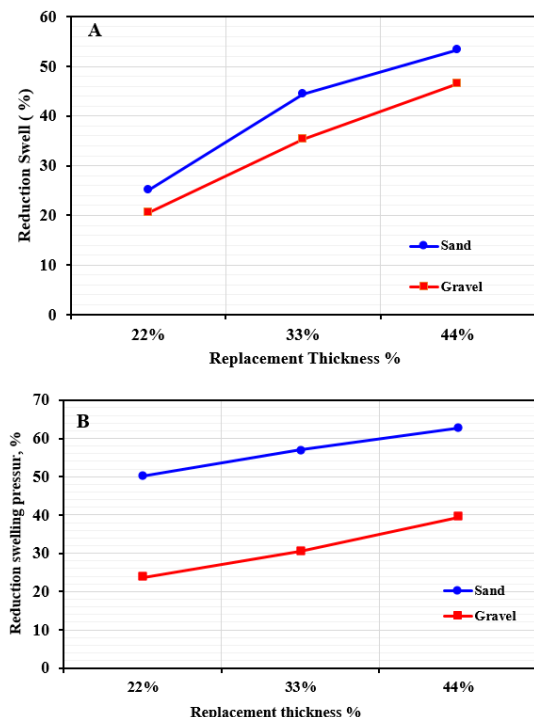


Fig. 8 Effect of thickness and type of cushion on reduction of Tabuk shale swelling % and swelling pressure %, Al Qadsiyah district, Tabuk, KSA

The sand cushion replacements with all thicknesses decrease the swelling potential more than the gravel cushion types with all thicknesses. The reduction of swelling percent with sand cushion 33% thickness and gravel cushion 44% thickness are nearly similar; the swelling reduction is 44.5% and 46.5%, respectively.

The swelling pressure of the undisturbed shale sample 2.23 kg/cm<sup>2</sup> can be mitigated or reduced to 0.83 kg/cm<sup>2</sup> (Table IV) with replacement of the sand cushion thickness (44%). Consequently, the treatment by replacement cushion sand with thickness of 44% is the best condition.

The reduction change in swell percent and pressure (kg/cm<sup>2</sup>) increases by increasing the thickness of the replacement and increases in cushion sand more than gravel. The swelling pressure 2.23 kg/cm<sup>2</sup> can be mitigated or reduced to 0.83 kg/cm<sup>2</sup> with treatment by cushion sand replacement by 1.5 m thickness.

#### VII. RECOMMENDATIONS

1- The swelling pressure value of Al Qadsiyah shale obtained from the laboratory large-scale test is 2.23 kg/cm<sup>2</sup>, this value is suggested as a design value for this particular area. In the case of light structures, the dead loads are less than 2.23 kg/cm<sup>2</sup>, it recommends replacing expansive shale by cushions sand (fine to medium size) with thickness 1.5 m to mitigate or reduce the swelling pressure to 0.83 kg/cm<sup>2</sup>, this value is suggested as a design value of uplift pressure of Tabuk shale.

- 2- When using cushion gravel/sandy soils as replacement layer caution should be exercised, as these are permeable soils. Such cushions make water infiltrate into lower underlying expansive soil layers that could lead to expansion. Consequently, it is recommended that, the plastic horizontal barrier should be placed at the top of a sand cushion in case of treating expansive soil with a replacement layer in order to eliminate water seepage into the subsurface shale layer.
- 3- In addition, using replacement of expansive shale by sand cushion (fine to medium grain size) is recommended because this type is available and abundant in the Kingdom of Saudi Arabia The cost of replacement by sand can be more economical than the other replacement types or stabilization procedures, since it does not require special construction equipment such as discs, harrows, mixers, or spreaders.

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#### REFERENCES

- [1] F. H. Chen, Foundations on expansive soils. 2<sup>nd</sup> ed. Amsterdam: Elsevier, 1988, 463p.
- [2] D. E. Jones and W. G. Holtz, Expansive soils-the hidden disaster. Civil Engineering, ASCE, vol. 43, no. 8, pp. 49-51, 1973.
- [3] D. R. Snethen, Expansive soils: where are we? Ground failure, No. 3. National Research Council Communication on Ground Failure Hazards, National Research Council, Washington, DC, 1986, pp. 12-16.
- [4] A. Al-Muhaidib, Characteristics of expansive soil in the Kingdom of Saudi Arabia. Journal of King Saud University (Engineering Sciences), vol. 16, no.1, pp. 1-34, 2003.
- [5] D. E. Slater, Potential expansive soils in Arabian Peninsula. American Society for Civil Engineering. Geothermal Engineering, vol. 109, no. 5, pp. 744-746, 1983.
- [6] A. Dhowian, I. Ruwaih, and A. Erol, The distribution and evaluation of the expansive soils in Saudi Arabia, Proc. 2nd Saudi Eng. Conf. King Fahd University of Petroleum and Minerals, Dhahran, 1985, 4: pp. 1969-1990.
- [7] T. Al-Refeai, and D. Al-Ghamdy, Geological and geotechnical aspects of Saudi Arabia. Geotechnical & Geological Engineering, vol. 12, no. 4, pp. 253-276, 1994.
- [8] A. Al-Muhaidib, Swelling behaviour of expansive shales from the Middle Region of Saudi Arabia. Geotechnical & Geological Engineering, vol. 16, no. 4, pp. 291-307, 1998.
- [9] T. Elkady, and M. Abbas, Shear strength behavior of highly expansive soil. GeoCongress 2012, pp. 2532-2541.
- [10] I. A. Ruwaih, Experiences with expansive soils in Saudi Arabia. Proceedings of 6th International Conference on Expansive Soils, New Delhi, India, 1987, pp. 317-322.
- [11] S. N. Abduljawwad, and R. Ahmed, Expansive soil in Al-Qatif area. Arabian Journal for Science and Engineering (AJSE). Vol. 15, no. 2A, pp. 133-144, 1990.

- [12] S. N. Abduljawwad, Swelling behavior of calcareous clays from the eastern province of Saudi Arabia. *Journal of Engineering Geology*, vol. 27, pp. 333-351, 1994.
- [13] S. Azam, Engineering behaviour of clay-bearing calcium sulphate in Dammam Dome, eastern Saudi Arabia. *Bull Eng Geol Environ*, vol. 67, pp. 521–528, 2008.
- [14] M. A. Dafalla, and M. A. Al-Shamrani, Performance-based solutions for foundations on expansive soils- Al-Ghatt region, Saudi Arabia. *GEOCHIANGMAI 2008*, Chiangmai, Thailand.
- [15] A. W. Dhowian, Characteristics of expansive clay-shale in the northern region of Saudi Arabia. *Proceedings of the 5th International Conference on Expansive Soils*, Adelaide, South Australia, 1984, pp. 316-320.
- [16] A. O. Erol, and A. Dhowian, Swell behavior of arid climate shale from Saudi Arabia. *Journal of Engineering Geology*, vol. 23, pp. 243–254, 1990.
- [17] A. A. Sabtan, Geotechnical properties of expansive clay shale in Tabuk, Saudi Arabia. *Journal Asian Earth Science*, vol. 25, no. 5, pp. 747-757, 2005.
- [18] M. A. Dafalla, and M. A. Al-Shamrani, Expansive soil properties in a semiarid region. *Research Journal of Environmental and Earth Sciences*, vol. 4, pp. 930-938, 2012.
- [19] M. A. Dafalla, E. Mutaz, M. Al Humimidi, L. A. Oumar, and M. Al-Shamrani, Shale failure and cracking in a semi-arid area. *International Journal of GEOMATE*, vol. 5, no. 2, pp. 696-699, 2013.
- [20] S. Clemence, and A. Finbarr, Design considerations for collapsible soils. *Journal of Geotechnical Engineering*, ASCE, vol. 107, pp. 305-318, 1981.
- [21] D. G. Fredlund, and H. Rahardjo, *Soil mechanics for unsaturated soils*. New York: John Wiley & Sons, 1993.
- [22] J. D. Nelson, and D. J. Miller, *Expansive soils: problems and practice in foundation and pavement engineering*. New York: John Wiley & Sons, 1992.
- [23] R. W. Day, *Expansive Soils: Recent advances in characterization and treatment* 1st ed., Taylor & Francis, 2006.
- [24] S. M. El-Kholy, Improving the characteristics of expansive soil using coarse-grained soil. *Journal of Engineering and Computer Sciences*, Qassim University, vol. 1, no. 2, pp. 71- 81, 2008.
- [25] E. S. Abu Seif, Efficiency of quicklime in reducing the swelling potential of pulverized expansive shale, Northern Jeddah, Saudi Arabia. *Bull Eng Geol Environ*, vol. 74, pp. 637–650, 2015.
- [26] *International Building Code (IBC) and International Residential Code (IRC)*, 2006.
- [27] B. Satyanarayana, Swelling pressure and related mechanical properties of black cotton soils. PhD Thesis, IISc, Bangalore, 1966.
- [28] R. K. Katti, Search for solutions to problems in black cotton soils. *First Indian Geotechnical Society Annual Lecture*, *Indian Geotechnical Journal*, vol. 9, no. 1, pp. 1–88, 1978.
- [29] A. Aly, Assessment of drying-wetting cycles for mitigation the potential of expansive soil in Upper Egypt. *Journal of Applied Sciences Research*, vol. 12, pp. 2277-2284, 2009.
- [30] R. Lytton, C. Aubeny, and R. Bulut, Design procedures for pavements on expansive soils (Project Number 0-4518), 2004, Report 0-4518-1, vol.1.
- [31] *California Building Standards and Codes for Residential Structures*. 2010.
- [32] W. G. Holtz, and G. J. Gibbs, Engineering properties of expansive clays. *Transactions of the American Society of Civil Engineers*, vol. 121, pp. 641-677, 1956.
- [33] W. G. Holtz, Expansive clays properties and problems. *Quart, Colorado School of Mines*, vol. 54, pp. 89–117, 1959.
- [34] H. B. Seed, R. J. Woodward, and R. Lundgren, Prediction of swelling potential for compacted clays, *Journal of Soil Mechanics and Foundation Engineering Division*, ASCE vol. 88, pp. 53–87, 1962.
- [35] D. H. Van Der Merwe, The prediction of heave from the plasticity index and percentage clay fraction of soils. *Civil Engineers in South Africa*, vol. 6, pp. 337–342, 1964.
- [36] M. Carter, and S. P. Bentley, *Correlation of soil properties*. Pentech Press, London, 1991.
- [37] A. Sridharan, and K. Prakash, Classification procedures for expansive soils, *Geotechnical Engineering*, *Proc. ICE (UK)*, 2000, vol. 143, pp. 235–240.
- [38] J. K. Mitchell, and K. Soga, *Fundamentals of soil behavior*, III ed, John Wiley and Sons, Inc., New York, 2005.
- [39] J. D. Nelson, D. D. Overton, and D. B. Durkee, Depth of wetting and the active zone. *Proceedings of the Geo-Institute Shallow Foundation and Soil Properties Committee Sessions at the ASCE 2001, Civil Engineering Conference*, Houston, Texas, October, 2001, pp. 10–13.
- [40] M. A. Al-Shamrani, and A. I. Al-Muhaidib, Prediction of potential vertical swell of expansive soils using a triaxial stress path cell. *Journal of Engineering Geology*, vol. 32, pp. 45-54, 1999.
- [41] M. A. Al-Shamrani, and A. W. Dhowian, Experimental study of lateral restraint effects on the potential heave. *Journal of Engineering Geology*, vol. 69, pp. 63-81, 2003.