Impacts of alkaline activated slag blended with Omani Sarooj on expansive soil

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ABSTRACT
Expansive soils exhibit substantial volume changes in response to variations in moisture content. Sarooj is the traditional Omani pozzolana obtained from calcination of clay. This study examines the effect of blends of Sarooj and alkaline activated ground granulated blast-furnace slag (GGBFS) on the strength of expansive soil obtained from Bayt Al Falaj, northeastern Oman. The physical properties of the soil sample were ascertained, unconfined compressive strength (UCS) was determined for binary and ternary mixes of the expansive soil, GGFBS and Sarooj, with and without the alkaline activator (Na_2SiO_3) at 6% binder content. The results revealed an increase in strength with the incorporation of Sarooj, and the Na_2SiO_3 impacted the strength for blends with binder contents and has no impact on untreated soil. The study established the potential use of Sarooj for soil stabilization purposes.

RÉSUMÉ
Les sols expansifs présentent des changements de volume substantiels en réponse aux variations de la teneur en humidité. Sarooj est la pouzzolane traditionnelle omanaise obtenue à partir de la calcination de l'argile. Cette étude examine l'effet des mélanges de Sarooj et de laitier de haut fourneau granulé activé alcalin (GGBFS) sur la résistance du sol expansif obtenu à Bayt Al Falaj, dans le nord-est d'Oman. Les propriétés physiques de l'échantillon de sol ont été déterminées, la résistance à la compression non confinée (UCS) a été déterminée pour les mélanges binaires et ternaires du sol expansif, GGFBS et Sarooj, avec et sans l'activateur alcalin (Na_2SiO_3) à une teneur en liant de 6 %. Les résultats ont révélé une augmentation de la résistance avec l'incorporation de Sarooj, et le Na_2SiO_3 a eu un impact sur la résistance des mélanges avec des teneurs en liant et n'a aucun impact sur les sols non traités. L'étude a établi l'utilisation potentielle de Sarooj à des fins de stabilization des sols.

1 INTRODUCTION

Expansive soils are soils that shrink and swell to the extremes! They exhibit significant volume changes in response to changes in their moisture content. They are also known as shrink-swell, shrinkable, heaving, and swelling soils. Expansive soil is a major threat to civil engineering infrastructures worldwide. It accounts for a $15 billion yearly damages in the United States, another $15 billion yearly damages in China, £400 million yearly damages in the United Kingdom, and previously accounts for cracks in 50,000 houses yearly in Australia (Jones and Jefferson 2012; Li et al. 2014), it is a global issue with preponderance in Arid and Semi-arid regions.

The significant volume changes cause distress and damages to structures founded on them. During the swelling stage soil expand and this constitutes uplift forces which counteract the foundation, the opposite happens when soil shrinks, and this leads to consolidation of soil and subsequent settlement of the overlying structure. The most critical settlements occurs when soils underlying the same structure settles at different rates leading to differential settlement (Mahedi et al. 2020; Sorochan et al. 2020; Taher et al. 2020).

In Canada, Regina clay (Saskatchewan) comes to the fore as a typical example of expansive soil. It evolved from weathered glacio-lacustrine sediments comprising residual wedge-shaped aggregates bounded by slickensides with hairline discontinuities. The volume changes which impair civil infrastructures are controlled by periodic saturation and desaturation occasioned by weather alternations. Damages to engineered facilities have gargantuan cost implications, for example the breakage rate in the 850 km long water supply network in the city has reached 0.27 breaks/km/year, costing more than $2 million in annual maintenance (Ito and Azam, 2013; Adem and Vanapalli, 2016).

Oman lies in the south-eastern corner of the Arabian Peninsula. It has an arid climate with topography primarily of deserts. Expansive soils cover wide geographical areas of Oman. In Northern Oman, it is composed of variable clay materials diverse in structure, lithology, and colour both vertically and laterally. These clay materials include argillaceous dolomitic limestones, marls and silty mudstones, bentonitic mudstones, altered conglomerates, and desert fill derived from these materials (Al-Rawas et al. 2006).

Geotechnical engineers have devised different approaches to improving properties of weak soils and making them viable for different construction purposes. However, the most common and cost-effective method is by the incorporation of additives onto soils, known as (chemical) stabilization. Soil stabilization methods enhance numerous engineering characteristics of soil. The resultant soil possesses increased stiffness, durability, and strength with a reduction of shrinkage/swelling and plasticity, yielding an improved material suitable for engineering use (Al-Alawi et al. 2020). The usage of stabilized soil in lieu of weak and problematic soils can have significant environmental and economic benefits (Moradi et al. 2018; Moradi et al. 2019; Mustapa et al. 2021).

Cement and lime are the foremost materials utilized in chemical stabilization of soils. However, with increasing awareness of sustainability, other naturally available materials have been employed to improving properties of weak soils (Adedokun et al. 2019; Ali et al. 2020; Asmeel et al. 2021). With the adoption of calcine clay as cementitious materials in concrete technology and its further implementation as alkaline activated binders in geopolymers, there is a high possibility of its favourable usage in soil stabilization processes either alone or in binary/ternary mixes (Adjaottor et al. 2019; Hollanders et al. 2016; Schulze and Rickert 2019).

Sarooj is a local Omani term depicting an artificial cementitious material obtained by traditional calcination of raw clayey soil along with dry logs of date trees(Hago and Al-Rawas 2008). It has been used for more than 3600 years for cementing purposes in buildings, hydraulic structures, and defence infrastructures. In recent times, its usage has been limited to the restoration of castles, forts, monuments and historical buildings (Al-Rawas et al. 2001; Al-Saidy et al. 2017; Meddah et al. 2020). It is one important heritage of Oman that is yet to get the deserved attention.

The properties of Sarooj are a function of the composition of the constituent clay, its binding nature is a resultant effect of the reaction between alumina and silica akin to Portland cement, its pozzolanic reactivity depends on its burning temperature and duration, fineness, shape, density, and particle size distribution(Al-Rawas and Hago 2006; Al-Rawas et al. 2005; Al-Rawas et al. 2001; Hago and Al-Rawas 2008; Hago et al. 2002; Meddah et al. 2020). Previous research on Sarooj has been on the characterisation, the production process and application in concrete technology as cement replacement with lime, cement, or mortar based on its identified pozzolanic properties but has not gotten sufficient applications in geotechnical research.

Alkaline activation (geopolymerisation) of binders, using a wide variety of Alumino-silicate source materials such as slag, metakaolin, fly ash, palm oil fuel ash etc. in lieu of cement is a trending research trend in concrete technology (Salami et al. 2022; Yusuf et al. 2014). Alkaline activation is a polycondensation of aluminium and silica alternately tetrahedrally interlinked by sharing all the oxygen atoms. The process starts when the high hydroxyl concentration of the alkaline medium favours the breaking of the covalent bonds Si–O–Si, Al–O-Al, and Al–O–Si from the vitreous phase of the source material, transforming the silica (SiO_2) and alumina (Al_2O_3) ions in colloids and releasing them into the solution. This transforms the materials to a well-structured alumino-silicate polymerised framework (Nodehi and Taghvaee, 2021).

Furthermore, the incorporation of calcinated clays as supplementary cementitious materials (SCMs) in concrete technology is another promising research niche which bring forth a substantial lowering of environmental impacts of cement and concrete. Calcining clays leads to the formation of an active metastable state material with high pozzolanic activity. A complete removal of hydroxyl groups upon calcination results in a collapsed and disarranged metastable structure with low crystallinity that can be used as partial substitute of the clinker. The pozzolanic activity depends on the dehydroxylation degree and the available surface for reaction to produce a cementing compound like C-S-H and some alumina-hydrated phases (Martirena et al. 2017; Schulze and Rickert 2019; Scrivener et al. 2018; Tironi et al. 2012).

Alkaline activation of calcined clay for stabilization of weak soils is a recent invention and still evolving, it is a direct transformation of clay minerals without the addition of external aluminosilicates. Al-Swaidani et. al (2019a; 2019b) observed that addition of 2% nano-calcined clay reduced Plasticity index (PI) by 50%, increased the angle of internal friction by about 20%, and also led to a reduction in swelling and compressibility of the natural clay soil. Obonyo et al (2014) experimented geopolymerisation on two lateritic soil samples, the results from micro-structural tests demonstrated the effectiveness of the calcined laterite to act as nucleation sites and extend the geopolymerization to the matrix composites products with low porosity, good strength and good stability in water, it was concluded that quality laterites is promising solid precursor for sustainable, environmentally-friendly, and cost-efficient binding materials.

Although universal, the problem of expansive soils is real, relevant, significant, and immediate to Oman. Thus, a meticulous characterisation of expansive soil within the locale is essential. Next is to devise a means of appropriate in-situ treatment to neutralize the shrink-swell behaviour and the attendant negative effects on built infrastructure. Chemical stabilization of the soil is a probable method to achieve this. Sarooj is a locally produced cementitious material with innate pozzolanic property that could be activated via geopolymerisation to stabilize the soil. This study examines the impact of addition of blends of Sarooj and alkaline-activated GGBFS on the geotechnical properties of expansive soil obtained from Bayt Al Falaj, Muscat, northeastern Oman.

2 METHODOLOGY

2.1 Materials

Expansive soil sample was collected from Bayt Al Falaj (23.6134°N, 58.5401°E), Governorate of Muscat, Sultanate of Oman. Omani Sarooj sample was collected from Nakhal Fort (23.3946ºN, 57.82854ºE), Nakhl, Al Batinah South Governorate, Sultanate of Oman. The restoration of the fort at this location was being carried out using Omani Sarooj and the research collected the sample from the contractor. GGBFS sample was collected from a coal-fired power plant in Duqm, Al Wusta Governorate, Oman. Alkaline Sodium Silicate, Na_2SiO_3 containing 34% of Sodium Silicate was utilised as the activator.

2.2 Experimental Tests

The particle size distribution test was conducted according to BS EN ISO 17892-4:2016 using standard sieves for both. expansive soil and Sarooj samples. Liquid limit and plastic limit tests were carried out according to BS EN ISO 17892-12: 2018, specific gravity test was conducted according to BS EN ISO 17892-3:2015, shrinkage limit tests according to BS 1377-2: 1990, pH test according to BS 1377-3: 1990 standard, and Standard Proctor Compaction test was conducted according to BS 1377-4: 1990 standard.

The unconfined compressive strength (UCS) test was carried out in accordance with the BS EN ISO 17892-7: 2017 standard. The tests were performed on samples of 50 mm diameter and 100 mm height, compacted at 100% MDD at a strain rate of 1.2 mm/min. A fixed binder content of 6% was maintained for all samples. Tests were carried out after 1, 7 & 28 days. The samples were kept in plastic boxes and stored at room temperature until their respective test days (Figure 1), a pair was made and tested for each sample to ensure consistence and guarantee correctness of the readings, the samples were loaded until failure and readings recorded. Table 1 shows the details of the mixes.

Table 1. Details of the sample mix

Label	Expansive Soil (g)	Sarooj (g)	GGBFS (g)	Water (g)	Na_2SiO_3 (g)
A	660	-	-	65	-
B	620	40	-	65	-
C	620	-	40	65	-
D	620	20	20	65	-
E	650	-	-	65	7
F	600	50	-	65	7
G	600	-	50	65	7
H	600	25	25	65	7

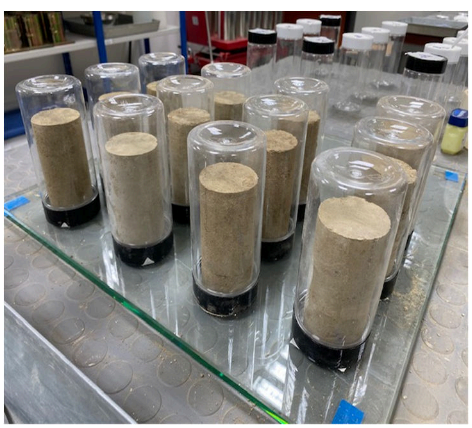

Figure 1. Curing of UCS samples

3 RESULTS AND DISCUSSIONS

Figure 2 shows the particle size distribution of both the expansive soil and Sarooj. The expansive soil is well graded with coefficient of curvature and uniformity c_v and c_u of 2.4 and 15 respectively. Table 2 presents the results of the physical tests on expansive soil and Sarooj and the classification based on the results. A thorough review of the properties revealed the need for improvement of the soil, for example A-2-7(0) AASHTO classification indicates its unsuitability for highway construction.

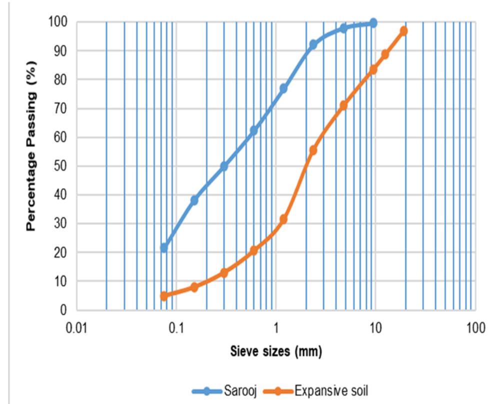

Figure 2. Particle size distribution curve of Sarooj and expansive soil

Table 2. Geotechnical properties of expansive soil and Sarooj

Property	Expansive Soil	Sarooj
Natural Moisture Content (%)	24.34	16.10
Specific Gravity (Mg/m^3)	2.73	2.66
Liquid Limit (%)	41.56	40.04
Plastic Limit (%)	28.97	33.43
Plasticity Index (%)	12.59	6.61
Linear Shrinkage (%)	10.4	2.9
pH	8.04	8.29
AASHTO soil classification	A-3 (0)	A-2-7(0)
USCS soil classification	SW	SC
Maximum Dry Unit Weight (kN/m^3)	24	16.5
Optimum Moisture Content (%)	10	22

Figure 3 shows the maximum stress values obtained from the UCS tests for samples without the alkaline activator. For the samples cured for one-day, the untreated soil has the lowest compressive strength, the increase of compressive strength was 37.8%, 140%, and 66.7% by adding Sarooj, GGBFS and Sarooj + GGBFS respectively. At 7 days of curing, the increase in compressive strength was 11.4%, 108.6%, and 78.6% by adding Sarooj, GGBFS and Sarooj + GGBFS respectively over the untreated expansive soil sample. At 28 days of curing, the increase in strength was 12.5%, 295.8%, and 145.8% with the addition of Sarooj, GGBFS and Sarooj + GGBFS respectively.

Basically, the increase in strength with the addition of Sarooj is an indication of its suitability for soil improvement purposes. The mechanism for this behaviour needs to be unravel through further tests such as microstructural investigations. The highest improvement was observed with the addition of GGBFS, this is an affirmation of earlier studies on using it for soil improvement. The binder mixes of GGBFS + Sarooj have medium improvement for all the days, it implies that Sarooj has lower strength improvement capability when compared with GGBFS, the extent and rationale of which need further investigations to unveil. Generally, there is an increase in the strength of treated samples with increased curing days which is an indication continuous interaction of the binders with soil as days progresses, the limiting period can also be delineated with further investigations.

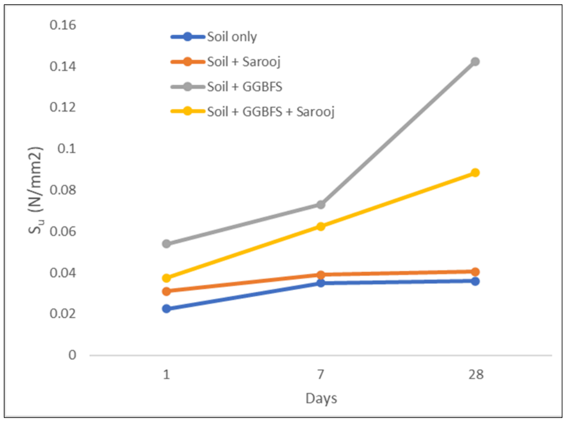

Figure 3. UCS values for samples without alkaline activator

According to Figure 4 which depicts the UCS values for samples containing Na_2SO_3 as the alkaline activator, the untreated sample has the lowest strength after one-day curing, the compressive strength increased by 26.9%, 104.5%, and 80.6% for samples with blends of Sarooj, GGBFS and Sarooj + GGBFS respectively. At 7 days of curing, the increased strength was 30.1%, 117.8%, and 78.1% respectively, with the addition of Sarooj, GGBFS and Sarooj + GGBFS respectively. At 28 days, the increase of the compressive strength of samples with binders of Sarooj, GGBFS and Sarooj + GGBFS respectively are 29.3%, 370.7%, and 206.7% respectively.

The alkaline activated samples also consistently maintained the trend of increased strength with increase in number of curing days. Also at 28 days, there is significant increase in the compressive strength for all treated samples when compared to similar samples without the addition of alkaline activator. This indicates that the alkaline medium of Na_2SO_3 improved the reaction or the mechanism between the binders and the soil and was responsible for the enhanced strength. However, there was no or marginal increase in strength at 1 day and 7 days when compared with samples without alkaline activator, this implies that the Na_2SO_3 has a delayed interference in the mechanism responsible for the upsurge in the compressive strength. The exact timeline of interaction and the rate can equally be investigated in a more controlled investigation with variable parameters. It is equally significant to note that the presence of GGBFS and/or Sarooj is needed for Na_2SO_3 to positively impact the strength because the addition of the alkaline activator to untreated expansive soil sample has no effect on the UCS values irrespective of the number of curing days.

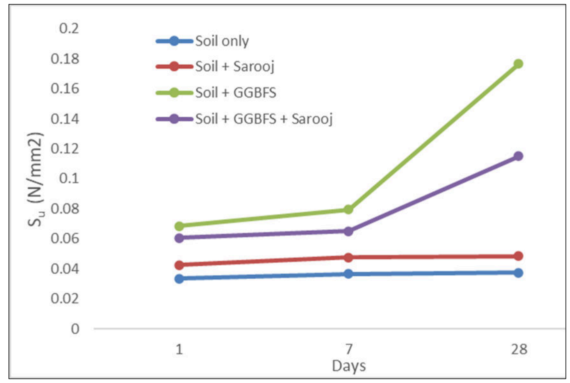

Figure 4. UCS values for samples with alkaline activator

4 CONCLUSIONS

Expansive soil is one of the problematic soils that cause damages to various civil engineering infrastructures because of its high swelling and shrinking potentials. This study investigated the suitability of blends of Sarooj and alkaline-activated GGBFS for the stabilization of expansive soil. The physical properties and strength properties of the selected expansive soils were determined. It was found that the soil needs to be improved before it could be used for some specific engineering purposes. A fixed binder content of 6% was utilised for the UCS tests varying Sarooj, GGBFS, and Sarooj + GGBFS with and without Sodium Silicate alkaline activator tested after curing for 1, 7 and 28 days.

The addition of Sarooj increased the strength of the soil, likewise, is the addition of Sarooj + GGBFS, and GGBFS only. The inclusion of the alkaline activator yielded significant upsurge in strength at 28 days for samples with binders and has no effect on untreated soil sample. Further investigations at micro levels, variations of parameters and more controlled conditions are needed to fully grasps the mechanism responsible for the gained strength, its rate, limits, and viable environmental conditions required. However, the current study has successfully established the potential of Sarooj for improvement of compressive strength of expansive soil, and hence its stabilization.

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