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Improvement in shear strength characteristics of desert sand using shredded plastic waste

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Abstract. In the Kingdom of Saudi Arabia, the shallower depth of the earth's crust is composed of loose dune or beach sand with soluble salts. The expansive behavior of salt bearing soil, fluctuation of ground water table and extreme environmental conditions offer a variety of geotechnical problems affecting safety and serviceability of the infrastructure built on it. Despite spending money, time and other resources on repair and rehabilitation, no significant attention is paid to explore the root causes of excessive differential settlement and cracking to these facilities. The scientific solution required to ensure safety and serviceability of the constructed infrastructure is to improve the strength and durability properties of the supporting ground. In this study, shredded plastic is employed as a low cost and locally available additive to improve strength characteristics of the desert sand. The study shows a remarkable increase in the shear strength and normal settlement of the soil. A seven (07) degree increase in angle of internal friction is achieved by adding 0.4 percent of the shredded plastic additive. The effect of different proportions and sizes of the plastic strips is also investigated to obtain optimum values. Such a long-lived solution will seek to reduce maintenance and repair costs of the infrastructure facilities laid on problematic soil along with reduction of environmental pollutants.

Keywords: loose sand; geotechnical investigation; shredded plastic; shear strength; angle of internal friction

1. Introduction

Shallow soil profiles of the Arabian Peninsula show that the area is covered up mainly by dune or beach sand. The soil in the shallower depth, which bears the foundations for most of the infrastructure, is in loose state with soluble salts and is generally termed as Sabkha (Bauman *et al.* 2013). Various salts occur in either the dissolved form in soil moisture or as salt crusts on the surface. Chemical analyses have shown that salt precipitation in Middle East desert regions is dominated by sulphates, chlorides and carbonates of calcium, sodium and magnesium (Al Sayari and Zotl 1978, Akili and Torrance 1981, Stipho 1981, 1983). The Sabkha soils are usually formed in hot, semi-arid to arid climates and are associated with shallow ground water table (Al-Homidy 2017). When it is wet, the Sabkha soil becomes very weak and even a medium weight vehicle will easily sink in it (Renfro 1994). The presence of high salt content, fluctuation of ground water table and extreme environmental conditions lead to large changes in density, consistency, strength, swelling and shrinkage characteristics of the soil (Hossain and Ali 1988, Al-Amoudi 1992, James and Little 1994). Expansive behavior of the salt bearing soil along with salt crystallization leads to differential settlement and cracking of the pavement structures (Bubshait 2001). Some researchers have comprehensively reported compression zone and settlement induced damages to newly constructed roads in Kingdom of Saudi Arabia and other desert regions (Aiban 1994, AL-Abdul Wahhab and Ramadhan 1990). Excessive settlement and cracking of the infrastructures built on Sabkha soil has also been reported (Al-Hashemi *et al.* 2018).

Since the oil boom and economic transformation, the Kingdom of Saudi Arabia is expeditiously developing infrastructure facilities. Road network has been extended abnormally to connect sparse settlements. It is quite often to see that important earth structures are constructed by locally available low-quality material. Pavements constructed by such poor-quality material undergo wear and tear immediately after construction and repeated repair work starts much earlier than the design life (Fig. 1). Mostly, the maintenance is done by replacing the wearing course of the pavement without exploring the root causes of differential settlement and cracking which is mainly contributed by the poor condition of the supporting soil. The scientific solution to ensure safety and serviceability of the constructed infrastructure is to improve strength and durability properties of the ground.

The soil is very complex and highly heterogenic engineering material which usually demands for a methodical enhancement of its mechanical properties. Soil stabilization is aimed at improving load bearing capacity and/or strength, reducing absolute and differential settlements, and mitigating liquefaction during a seismic activity (Makusa 2013). It can be achieved by mechanical or chemical stabilization methods. Mechanical stabilization includes different approaches towards effective compaction, consolidation and inclusion of non-degradable fibers and geosynthetics reinforcement to improve strength properties

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Fig. 1 Settlement of the soil and damage to the roads in the Kingdom of Saudi Arabia

(Raj 2005, Azadegan *et al.* 2012, Mallela *et al.* 2004, Ramadas *et al.* 2011). In the chemical stabilization, different cementitious additives (like cement, lime, bitumen, polymers, fuel ash and other chemicals) are used which react with the soil minerals to meet required strength properties (Raj 2005, Alawaji 2001, Viswanadham *et al.* 2009). The basic principles have remained same since the first introduction of both the stabilization techniques however; development of new materials and equipment have been taking places of old practices.

Uses of traditional practices and materials in both mechanical and chemical stabilization techniques have some cons, if not many. For example, mechanical stabilization significantly affects ground water condition and the vegetation growth (DeJong *et al.* 2006). Soil compaction often alters soil physical properties including water infiltration and distribution, gaseous movement, and nutrient uptake, which results in changes in root elongation and plant-available water (Barzegar *et al.*, 2016). Similarly, use of traditional chemical additives (like cement and lime) are expensive as well as their production and utilization is not environment friendly due to emission of carbon dioxide and pollution of ground water (Qureshi *et al.* 2017 and 2014). It has been reported that 5% of the global carbon dioxide emissions are induced by the cement industries (Worrell *et al.* 2001). By performing Unconfined Compression Tests on sand samples stabilized with cement, Shooshpasha and Shirvani (2014) concluded highly brittle behavior of the stabilized soil. When soil treated with lime or any calcium-based additives containing soluble sulfate salt, soil distress, heaving and disintegration may occur, resulting in strength loss (Mitchell 1986, Hunter 1988, Nair and Little 2011). Behavior of excessive soluble salts in the surface soil is quite different and challenging towards the cementitious additives. Alternatively, different sustainable approaches have emerged in the field of geotechnical engineering which make use of environment friendly materials, such as geosynthetics, biopolymers, processed and unprocessed environmental wastes, and biological treatment of the soil. Khatami and O'Kelly (2013) reported a significant increase in the cohesive intercept and stiffness of the cohesionless soil stabilized with biopolymers. Chang comprehensively investigated the effect of different types of biopolymers on cohesive and cohesionless soils (Chang *et al.* 2016a, b). Saliu and Kutelu (2014) found a substantial increase in the shear and compressive strength of the base sand stabilized with saw dust and coal dust additives. Xiao *et al.* (2015) observed a 5 to 7 percent increase in peak shear strength of the well graded gravels stabilized with polyurethane adhesive foams. Nimbalkar and Indraratna (2016) presented a decent control in the stress of ballasted rail track strengthened with geosynthetics and rubber mats. The effect of chick feather and plant fibres has also been investigated by many researchers (Adili *et al.* 2012, Manoj *et al.* 2017), but they ignored biodegradation properties of these fibres. Many researchers also investigated California Bearing Ratio (CBR) characteristics of different soils combinedly treated with crushed plastic and some cementitious binders (Onyelowe *et al.* 2019, Dutta and Sarda 2006). They achieved a considerable improvement in the resilient modulus, resistance value and lateral deformation of the tested soils. Klumba and Chebet (2013) studied increase in shear strength of flat sand with solid and perforated high density plastic strips. They obtained an encouraging increase in shear strength. However, this still needs a further and through study for different types, environment and soil conditions.

This article presents an improvement in strength and durability properties of the salt bearing desert sand (Sabkha) by the addition of shredded plastic waste, a low cost and locally available additive. In the Kingdom of Saudi Arabia, polyethylene pastic bags are most abundently used for containing and transporting goods. Saudi Arabia's per capita plastic bag consumption is the highest in the Middle East, double the rate for other countries in the GCC and almost twenty times the global average measured by the European Union (Saudi Gazette 2016). There is neither any culture of separataing plastic and non-palastic wastes, nor any effective recycling system in place. Saleem *et al.* (2018) highlighted that no policy for solid waste reduction, reuse and diversion from the landfill exists in the eastern province of Saudi Arabia. This approach of strengthening the soil with shredded plastic bags will have double benefit of increaseing the strength of the soil as well as reducing the environmental pollutants. Although the study area is limited to the Eastern Province of Saudi Arabia, outcomes of this research could be equally useful for other Gulf regions owing to the fact that they have similar soil composition and behaviour.

2. Study area and methodology

The area selected for this study was the Eastern Province of Saudi Arabia. The area is located on the eastern border of Saudi Arabia where most of the new construction projects are clustered in the reclaimed coastal land. The shallower part of the study area's crust is composed of loose sand with considerable amount of dissolved and crystalized salt traces, generally termed as Sabkha soil. The study area could be considered a representative of whole Gulf region by the virtue of its geography, soil type and construction methods. Soil samples were collected from three (03) different types of construction sites (Fig. 2), covering a variety of construction project. Sample-1 and Sample-2 were collected from the heavy-duty parking and a multi-story building facility being constructed in Imam Abdulrahman Bin Faisal University, respectively, while

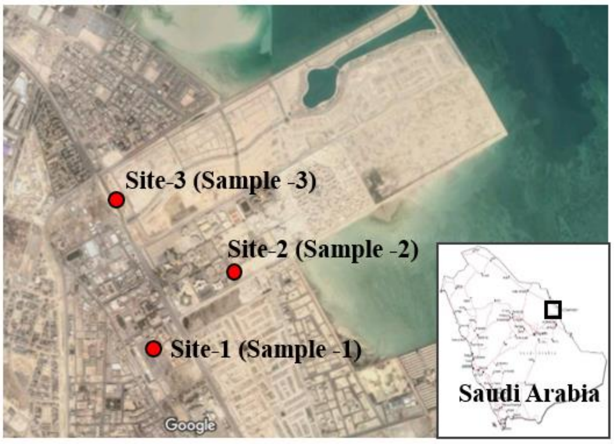

Fig. 2 Study area along with location of sampling sites

Sample-3 was collected from major highway of the province, connecting Khobar and Dammam cities. From visual observation, samples collected from all three sites appear to be poorly graded sand with negligible percentage of gravel and fines.

The standard equipment manufactured by ELE International Inc. UK was employed to perform sieve analysis, standard proctor compaction, and direct shear tests in order to determine grading, compaction and strength characteristics of the collected soil samples. All the experiments were performed in accordance with ASTM standards.

3. Results and discussion

3.1 Geotechnical characteristics of natural soil

This section briefly describes important geotechnical characteristics of the collected soil samples in their natural condition.

3.1.1 Grain size distribution

The sieve analysis tests were performed on the collected samples in accordance with ASTM D6913 to obtain soil gradation. Fig. 3 shows comparison of gradation curves for all three collected samples. It is evident from the results that the soil at all three sites is mainly sand with negligible percentage of gravel and fines which confirms its poor grading. Table 1 shows summary of grain size distribution and soil classification. Generally, the soil collected from all three sites is classified as fine sand (A-3(0)) according to AASHTO classification system and poorly graded sand (SP) according to Unified Soil Classification System (USCS). Since there is a negligible percentage of fines in all three samples (Table 1), hydrometer analysis and Atterberg limits are not determined in this study.

3.1.2 Compaction characteristics

In accordance with ASTM D558, Standard Proctor Compaction Tests were performed on soil samples collected from all three sites to obtain maximum dry density and optimum moisture content. The test was performed initially by adding 5% of water to the oven dried soil samples, followed by an addition of 4% each time until we get at least two (02) points to ensure decline of compaction curve. Table 2 and Fig. 4 show compaction test results for all three

Table 1 Summary of grain size distribution and soil classification

Sample #	Gravel (%)	Sand (%)	Fines (%)	C_u	C_c	Soil Classification	
						AASHTO	USCS
Sample -1	19.6	79.1	0.9	5.38	0.53	A-3 (0)	SP (Poorly graded sand with gravel)
Sample -2	3.6	95.6	0.8	2.21	0.92	A-3 (0)	SP (Poorly graded sand)
Sample -3	6.4	91.1	2.5	3.00	0.93	A-3 (0)	SP (Poorly graded sand)

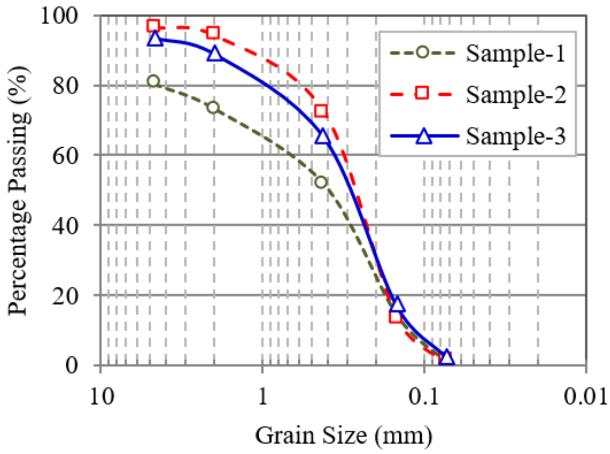

Fig. 3 Comparison of grain size distribution of the soil samples collected from all three sites

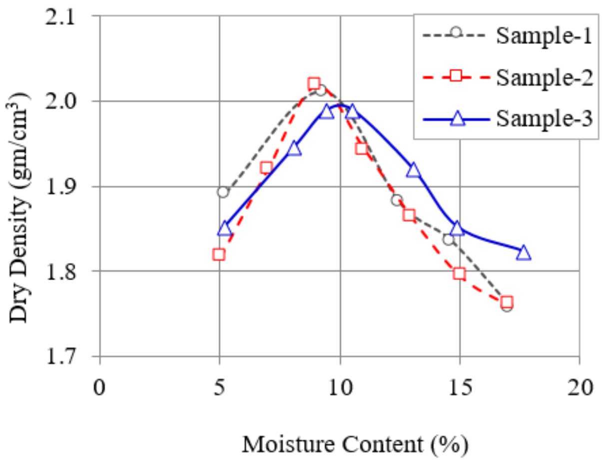

Fig. 4 Compaction characteristics of the soil samples collected from all three sites

Table 2 Maximum dry density and optimum moisture content for soil samples

Sample #	$(\gamma_d)_{max}$ (g/cm³)	OMC (%)
Sample-1	2.012	9.30
Sample-2	2.019	9.00
Sample-3	1.990	9.95

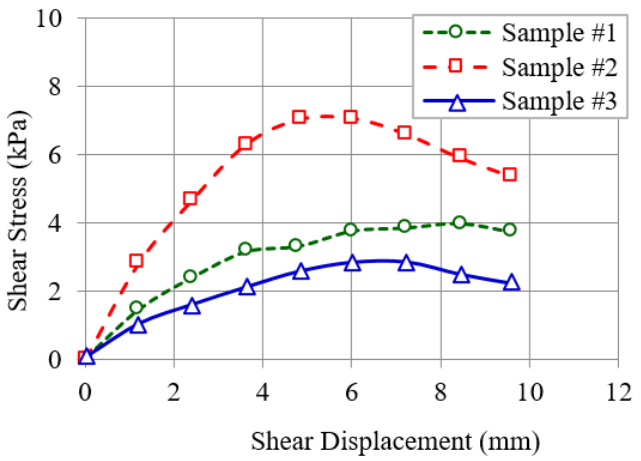

Fig. 5 Shear displacement versus shear stress for all three samples in their natural condition (no addition of shredded plastic strips) at normal load of 5 kg

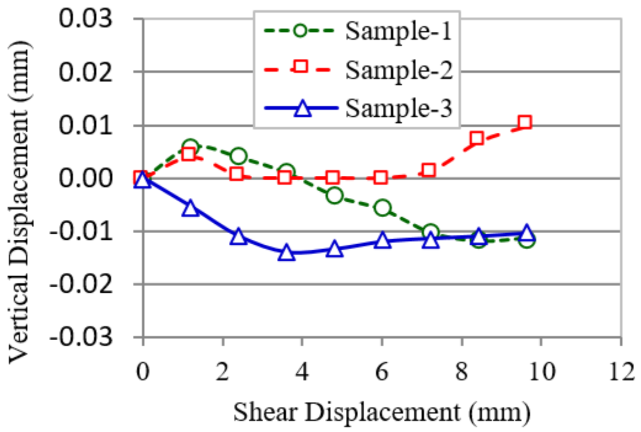

Fig. 6 Shear displacement versus normal displacement for all three samples in their natural condition (no addition of shredded plastic strips) at normal load of 5 kg

Fig. 7 Shredded plastic thoroughly mixed in the soil to improve its shear strength

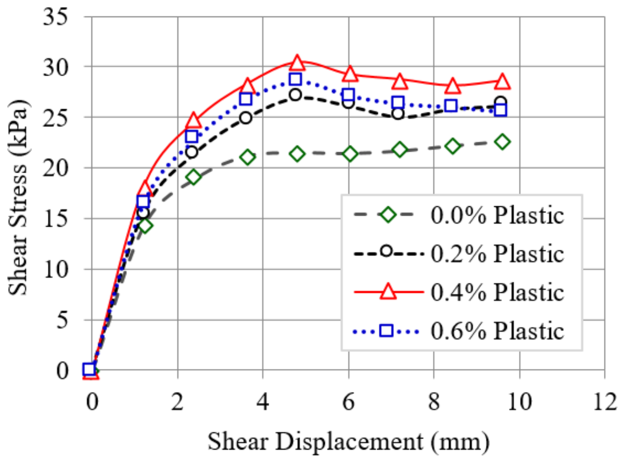

Fig. 8 Shear displacement versus shear stress for the soil in its natural and improved condition for different concentrations of shredded plastic additives. The size of plastic strips is 5 mm x 20 mm and normal load is 10 kg

tested samples in terms of maximum dry density and optimum moisture content (OMC). The maximum dry density for Sample-1 and Sample-2 are found as 2.01 gm/cm^3 and 2.02 gm/cm^3 and optimum moisture content as 9.3% and 9.0%, respectively. Since Sample-3 has slightly higher percentage of fines (2.5%, as shown in Fig. 3), maximum dry density (1.99 gm/cm^3) and optimum moisture content (9.95%) are slightly different from the other two sites. A marginal decrease of maximum dry density and increase in optimum moisture content agrees with literature studies that a soil with more fines will have higher optimum moisture content (Shooshpasha and Shirvani 2014). Overall, maximum dry density and optimum moisture content fall in the rage of case studies for sandy soils.

3.1.2 Shear strength

Direct shear tests were performed on the soil samples collected from all three sites with different normal loads according to ASTM D3080. The samples were compacted to an average density of 1600 kg/m^3 in the shear box and shear loading was applied at a rate of 1.2 mm/min. Fig. 5 and 6 show comparison of shear strength and vertical deformation of all three samples for a normal load of 5 kg. Peak shear strengths of Sample-1, Sample-2 and Sample-3 are found to be 3.97 kPa, 7.08 kPa, and 2.86 kPa, respectively. Sample-2 showed highest peak shear strength, shear modulus, and minimum vertical deformation. Sample 1 and 3 showed a typical contracting behavior of loose sand in vertical displacement while Sample-2 showed slight expansion. Since there is no significant difference in gradation, soil from Site-2 (Sample-2) is supposed to have a higher granular interlocking and, therefore, presents the behavior of dense sand. Therefore, all further experiments are performed on Sample-2.

3.2 Improvement in shear strength

Geotechnical investigation of all the collected samples revealed that the soil at all construction sites has poor gradation having strength characteristics equivalent to that of loose sand. Thus, there is an immense need for the improvement in geotechnical properties of the soil to achieve its satisfactory performance under different loading and environmental conditions. To triumph the said purpose, shredded low to medium density plastic bags are used as an

Table 3 Comparison of the mechanical characteristics of desert sand stabilized by different methods

	Soil Properties	This Study Sand + SPW (0-0.6%)	Kalumba and Chebet (2013) Sand +SPW (0 -0.3%)	Al-Aghbari *et al.* (2009) Sand + Cement (0 -12%)	Mohamedzein *et al.* (2006) Sand +solid waste incinerator ash (0 -12%)	Liu *et al.* (2017) Sand + Polymer (1 -4%) + Fiber (0 -0.4%)
Natural	Specific Gravity	2.60	2.66	2.6	2.6	2.65
	Coefficient of Uniformity, C_u	2.21	3.0	--	--	2.77
	Coefficient of Curvature, C_c	0.92	0.85	--	--	1.13
	Fines (%)	0.8	--	--	--	--
	Angle of Friction (°)	37.08	38.5	36.5	36.0	30
Improved	Increase in angle of Friction, φ (%)	20.74	10.13	15.07	42.5	20.0 (Fiber = 0.2%)
	Increase in Cohesion, C (%)	--	--	1300	508	775 (Poylemer = 4%)
	Optimum quantity of the Stabilizer (%)	0.4	0.1	8	10	0.2
	Optimum Size of the Stabilizer (mm)	5 x 20	6 x 30	--	--	--

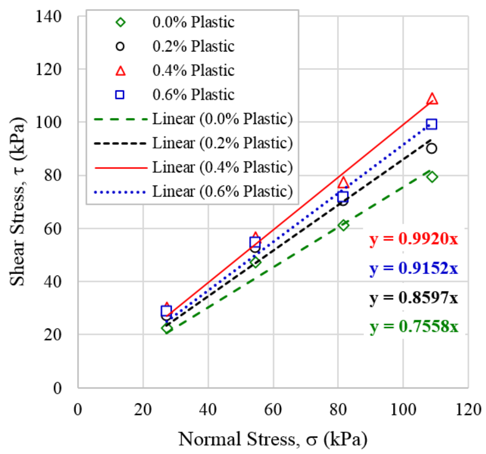

Fig. 9 Normal stress versus shear stress plot for the soil in its natural condition and improved with different concentrations of shredded plastic. The size of plastic strips is 5 mm × 20 mm

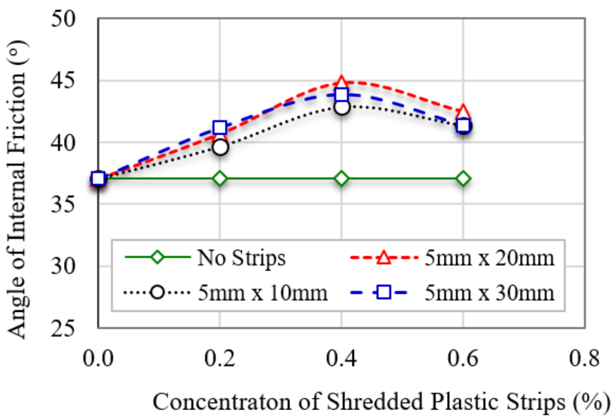

Fig. 10 Effect of different concentrations and sizes of shredded plastic strips on angle of internal friction of desert sand. The concentrations are taken by the weight of soil sample

additive for mechanical stabilization. The plastic bags are shredded into 5 mm by 10 mm, 5 mm by 20 mm, and 5 mm by 30 mm strips and thoroughly mixed in the soil (Fig. 7). For all the sizes, plastic strips are added to the soil at concentrations of 0.2%, 0.4% and 0.6% by weight and the composite material is tested in direct shear testing machine. The soil is oven dried to eliminate any effect of moisture content.

Fig. 8 shows improvement in the shear strength of the soil stabilized with different concentrations of 5 mm by 20mm plastic strips while keeping the normal load as 10 kg. The results showed a valuable increase in peak shear strength and reduction in normal displacement.

Fig. 9 is a scatter diagram between shear stress and normal stress along with the linear fit to the plotted points for different concentrations of 5mm by 20mm plastic strips. Since cohesion is zero for sandy soil, the trendlines are forced to intercept vertical axis at zero. The slopes of the lines represent angles of internal friction which are presented in Fig. 9. Fig. 10 comprehensively presents the effect of different concentrations and sizes of shredded plastic strips on angle of internal friction. The optimum concentration and size of the shredded plastic strips, to achieve maximum improvement in shear strength of the soil, are found to be 0.4% and 5 mm x 20 mm, respectively. A decrease in angle of internal friction at higher proportion and sizes of the plastic strips could be attributed to the minimization in contact between soil particles, which consequently reduces the frictional resistance to the shearing force.

Table 3 shows a comparison between the findings of this study and other works to improve strength characteristics of desert sand using different stabilizers. It can be clearly observed that the improvement in angle of internal friction achieved in the current study is one of the highest compared to other stabilizers. Furthermore, it is achieved at the lowest cost and reduction of environmental pollutants as compared to other stabilizers. However, the effect of shredded plastic reinforcement for different soil grading and environments still needs to be investigated. Furthermore, through mixing of the optimum quantity will also be a challenge in practical application.

4. Conclusions

In the Kingdom of Saudi Arabia, the shallower earth's crust is composed of poorly graded loose sand with soluble salts. This soil has low strength and durability characteristics which are adversely extrapolated in the coastal region due to the poor quality of material and earthwork used in reclamation. The infrastructure built on such poor ground conditions have faced excessive ground settlement and other safety and serviceability concerns. The geotechnical investigation of the samples collected from three representative sites has shown poor gradation of the soil which is mainly sand with negligible percentage of gravel and fines. The compaction and direct shear test on untreated samples have yilded low values of maximum dry density and peak sehar strength.

By adding low cost and locally available shredded plastic waste, a remarkable improvement in poor strength charateristics of the soil have been achieved in this study. By investigating the effect of different proportions and sizes of the shredded plastic waste, the optimum concentration and size of the plastic strips are found to be 0.4% and 5 mm x 20 mm, respectively. The angle of internal friction has been increased by seven (07) degrees which is considered a significant improvement. Other than the increase in strength and performance of the desert sand, use of this additive will reduce environmental pollutants.

The findings of this study could be applied to enhance strength and deformability of the soil in desert regions, which will consequently improve safety and serviceability of the infrastructures. Although the study area was limited to the Eastern Province of Saudi Arabia, outcomes of this research could be equally useful for other desert regions owing to the fact that they have similar soil composition and behaviour.

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