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Research Article

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Evaluation of Sulfur Modified Emulsified Asphalt for Road Construction

Yasser M. Alghrafy[1]*, El-Sayed M. Abdellah[2]

[1]Demonstrator, Civil Engineering Department, Faculty of Engineering, Sana'a University, Sana'a, Yemen
[2]Professor of Highways and Airports Engineering, Civil Engineering Department, Faculty of Engineering, Assuit University, Assuit, Egypt
*Corresponding author. Email:alghrafy@gmail.com

Abstract The primary aim of this study is to assess the engineering properties of asphalt emulsion (EA) and 30/70 sulfur modified emulsified (ESA) asphalt treated mixtures with soils, namely marl, sabkha and dune sand, that cover an important geographical area of Arabian Peninsula and long the coastal regions of the Red sea for their potential applications in local roads. ESA and EA mixes were designed for the three soils utilizing low percentage of Portland cement (2%) and were subjected to Marshall Stability test. After that, designed mixes were evaluated for Tensile strength test, static triaxial (shear strength) and dynamic resilient modulus at 22 ºC.
Results of the laboratory tests showed that the proprieties of treated soils by ESA have improved in ITS (1% for marl and 16% for sabkha soils), resistance to water absorption (15% for marl, and 33% for sabkha), durability (1% for marl, and 8% for sabkha) and resilient modulus (15% to 20% for sabkha depending on the applied deviator stress.) as compared with those of treated soils by EA. shear strength and Marshall stability testing indicated that ESA has marginally reduced the shear strength and stability (dry and soaked) of soils compared with EA. 30/70 sulfur modified emulsified technology can be used successfully to construct road bases from available marginal soils.

Keywords Asphalt emulsion, construct road, Emulsified Sulfur Asphalt, Treated soil, Road base

Introduction

Most important parts of Egypt and Saudi Arabia are covered with the dune sand, which is characterized as poorly graded soil with high permeability. In addition to that, marl and sabkha are available in some parts in Egypt and Saudi Arabia, which have a poor strength with change their properties with water. But in some cases, it is usually required to use these materials as sub-grade layers or as a backfill in base and sub-base layers of local roads, so some kinds of stabilization are required to improve the characteristics of these materials.

The basic idea of Asphalt emulsion is a combination of asphalt binder and water that includes an emulsifying agent which affects in asphalt to become it mixed with the water [1]. In the manufacture of asphalt emulsion, a mixture of emulsifier solution ('soap') and hot asphalt are passed through a colloid mill, where the emulsification takes place. The soap solution contains water, emulsifier, acid or base. Asphalt emulsion may be either anionic with electro-negatively charged asphalt globules or cationic with electro- positively charged asphalt globules, depending upon the emulsifying agent [2]. The asphalt emulsion has many advantages compared to hot asphalt and cut back binders which related to the Lower application temperature, compatibility with other water-based binders like rubber latex, cement and low-solvent content [1]. George (1976) showed that, well-graded sands with sufficient silt-clay material respond well to emulsions [3].

Gentry and Esch (1985) concluded that, when emulsified asphalt mixed with Type III Portland cement, it could stabilize the soils enough to use for wearing course or sub-grade material for highway and airport construction

[4]. Using emulsion asphalt with dune sand, the stability, resilient modulus, fatigue, and rutting characteristics of such mixes were improved significantly [5].

The stabilizing agents have both enhanced strength and resistance of the analyzed soils to water damage [6].

Oruc, Celik, and Akpinar (2007) studied the addition of Portland cement on emulsified asphalt mixtures, emulsified asphalt mixtures with cement showed better water resistance and an increase in the resilient modulus [7]. Bunga et al. 2004 showed the physical, chemical, and mechanical characteristics of sandy clay loam are improved due to using emulsified asphalt [8].

Weber (2002) showed that, the cost of constructions reduces by as much as 21 percent and binder cost reductions as high as 32 percent are feasible when use sulfur with asphalt mixtures [9].

Al-Mehthel et al. (2010) indicated that 30% replacement of asphalt with sulfur is the optimum replacement. Sulfur asphalt outperformed conventional asphalt and polymer modified asphalt in terms of rutting resistance [10]. Cooper III, Mohammad, and Elseifi (2011) indicated that, the use of sulfur-modified WMA improved the predicted rutting and fatigue performances and the overall pavement service lives over conventional mixtures at all traffic levels [11].

Materials and Methods

Raw Materials

Three types of soils were selected for this study, non-plastic marl, dune sand and sabkha. The Sabkha was collected from Al-Aziziyah zone, which is located 10 km south of Dhahran, Saudi Arabia. Marl and dune sand were chosen due to their abundance at low cost in Saudi Arabia. It was collected from Dhahran city. Asphalt cement (60/70 penetration grade) and sulfur was collected from the Saudi-Aramco. Usually (AC 60/70) is used in all road projects in Saudi Arabia. The asphalt emulsion (EA) used in this study is the only locally available grade CSS-1h, obtained from SANDFIX© Company and the Emulsified Sulfur Asphalt (ESA) was produced using the laboratory Emulsified Asphalt plant available in KFUPM laboratory. Table 1 shows the physical properties for Emulsified Asphalt.

Table 1: Emulsified Asphalt Physical Properties, ASTM D-2397

Test Properties	Min	Max
Viscosity by Sabolt Furol at 25 ºC, sec.	20	100
Settlement, 5 days, %	--	5
Sieve test, %	--	0.10
Cement mixing test	--	2
Residue %	57	--
Test on residue Penetration, 100 grms. For sec.77of	100	250
Ductility 77of cm	40	--
Solubility in trichloroethylene %	97.5	--

Experimental Design

Soil characterization

To investigate the probable treatment of these soils and their use in the construction of road projects, physical property tests were performed. These Physical tests included Liquid Limit, Plastic Limit, Specific Gravity, Relative Density tests and grain size distribution. The compaction and strength characteristics were investigated by using modified Proctor compaction and California bearing ratio tests.

Optimization of stabilized soils

The modified Marshall Mix design method was employed to prepare the test specimens.

The purpose of the mix design is to find the optimum emulsified sulfur asphalt and optimum emulsified asphalt.

The Cold Mixture Design method according to A Basic Asphalt Emulsion Manual [12] was used for mixing the EA and ESA with soil. It was used to determine the optimum EA and ESA content for dune sand, marl and Sabkha. Thus mix trials were made for different emulsion ranges (3% to 18% of dry soil's weight). Water added was varied between 1% and 5%. A 2% Portland cement was added for early curing. Mixing time was limited to (30) seconds to avoid stripping problem. The product mix was compacted using the Marshall compactor; where 75 blows applied to each side The compacted specimens, after curing for 48 h in an oven at 60 °C, were tested using Marshall stability test at 25 °C for dry samples and after soaking for 2 h at 25 °C for wet samples to determine durability.

Evaluation of Designed Mixes

The experiment was designed to portray the three soils marl, sabkha and dune sand with EA and ESA. Marshall Stability, ITS (indirect tensile strength), Resilient Modulus and Static triaxial tests were carried out at temperatures of 22°C. All tests were done following ASTM [13] and AASHTO [14] Standards. A flow chart of the experimental design and the experimental design are shown in Figure 1 and Table 2, respectively.

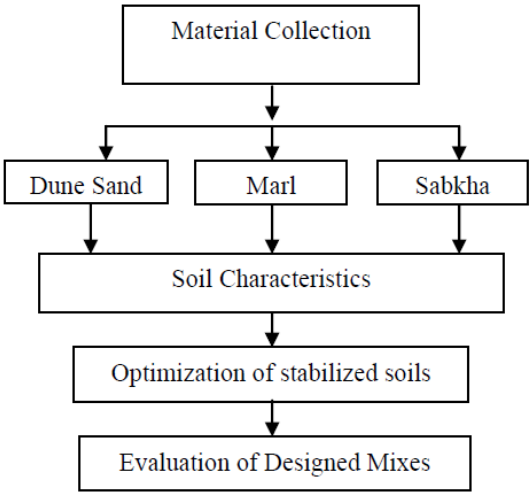

Figure 1: Flow chart of the experimental design

Table 2: Experimental Design

Test	Method	Temperature, °C	EA or ESA%
Marshal Stability	ASTM D 1559 ---	22	3 to 18
Indirect tensile strength	ASTM D 4867	22	3 to 18
Static triaxial	ASTM D 2850	22	At optimum
Resilient modulus	AASHTO T-307	22	At optimum

Statistical Analysis

The data generated from all tests were subjected to statistical scrutiny via analysis of variance (ANOVA) using Minitab (version 16) software [15]. The effect of EA and ESA as additive material in the soil mixes, were statistically analyzed using the data obtained from the different tests performed on modified mixes.

The experimental design for marshal stability and indirect tensile strength involve one factor (additive type EA or ESA). For dynamic triaxial test, the hypothesis tested using general Lanier models (a three-factor analysis of variance (ANOVA). The three factors were additive type, Deviator stress, and confining stress. All factors were statistically tested for the null hypothesis "Ho: The data obtained has equal means". Null hypothesis is rejected at 95% confidence level if P-value is less than or equal to 0.05.

Results & Discussion

Materials characterization

Asphalt properties

Standard laboratory test results for asphalt cement are shown in Table 3.

Table 3: The results of test performed on asphalt cement (AC 60/70)

Test	Method	Unit	Value
Penetration at 25 ^oC	ASTM D 5	mm	67.6
Rotational viscosity at 135 ^oC	-----	centi-poise	571.75
Softening point	ASTM D 36	^oC	52.3
Ductility at 25 ^oC	ASTM D 113	cm	150+
Flash point, Cleveland	ASTM D 92	^oC	340

Soils Properties

Marl, sabkha, and dune sand were classified as non-plastic because it was difficult to get the required number of blows for the liquid limit test, in addition, it could not be rolled to a thread of 3.18mm plastic limit test; as a result, the liquid limit and plastic limit are reported as nil. The dry and washed grain-size distribution curves are presented in Figure 2, it can be seen that dune sand can be classified as SP according to the USCS system and according to the AASHTO soil classification system, the soil can be classified as A-3 based on dry sieving. Sabkha soil are classified as SP-SM and A-3 according to the USCS and AASHTO soil classification systems based on both dry and washed sieving. Similarity, marl can be classified as SM according to the USCS system and A-1-b according to the AASHTO soil classification system based on dry sieving.

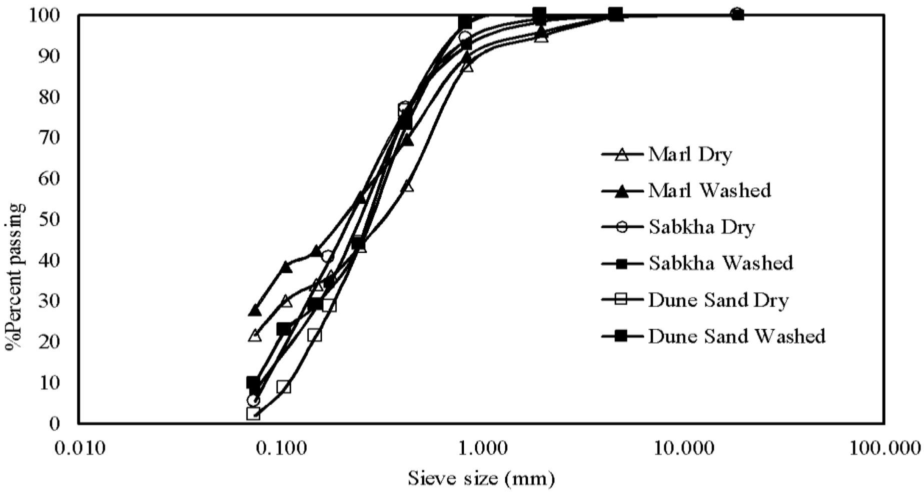

Figure 2: Soil grain size distribution

Typical plots of water content versus dry unit weight for marl and sabkha, soils are plotted in Figure 3. A study of this figure reveals that the maximum dry unit weight was 18.4 kN/m^3 when the water content was 13% whilst, the maximum dry unit weight for sabkha was 17.1 kN/m^3 at an optimum moisture content 12 %. Relative density experiment was done to get the minimum and maximum density for sand soil and they were 16.3 kN/m^3 and 18.4 kN/m^3, respectively.

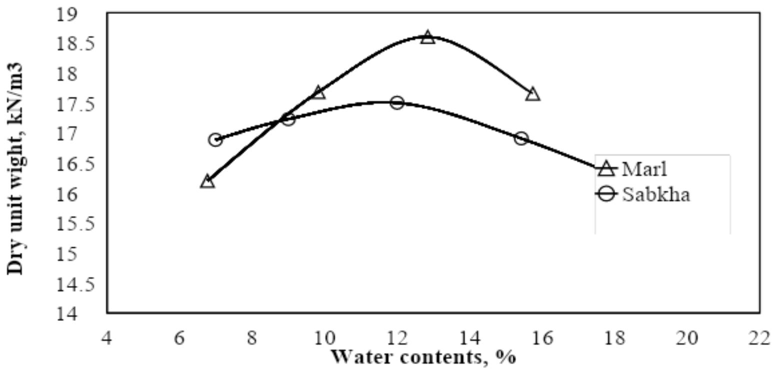

Figure 3: Moisture-Unit Weight Relationship for marl and sabkha

CBR test was used to evaluate the suitability of a soil to be used as a subgrade material in pavements. Figure 4 shows the moisture-CBR relationship for sabkha and marl, it noticed that the maximum CBR for sabkha soil was 26% at a moisture content of 10% and the maximum value of the CBR for marl was 24.7% at a moisture content of 12%. Regarding the sand, the maximum value of the CBR was 15% at a moisture content of 8% which was done on samples compacted to at least 95% of the maximum density achieved in relative density test. Table 4 shows the Physical Properties soils.

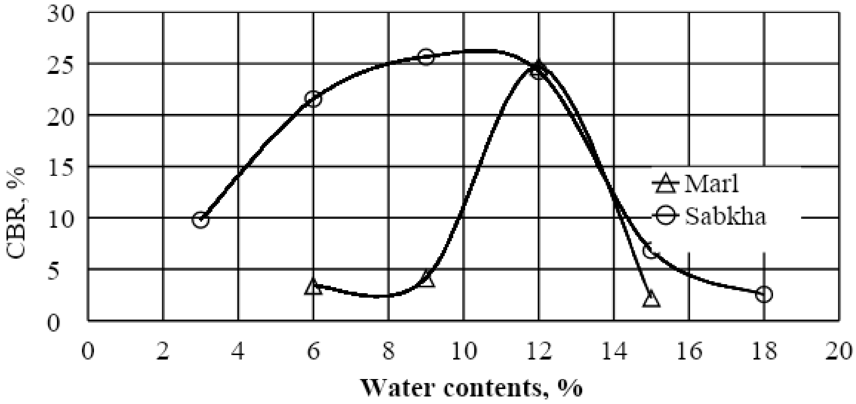

Figure 4: Moisture-CBR relationship for marl and sabkha

Table 4: Soils Physical Properties

Test	Method	Marl	Dune sand	Sabkha
Specific Gravity	ASTM D 854	2.68	2.63	2.47
Dry Density, kN/m^3	ASTM D 1557	18.4	---	17.1
Optimum Water content, %	ASTM D 1557	13	9	12
Minimum density, kN/m^3	ASTM D 4254	---	16.3	---
Maximum density, kN/m^3	ASTM D 4254	---	18.4	---
California Bearing Ratio (CBR), %	ASTM D1883	25	15	10
Soil classification	AASHTO	A-1-b	A-3	A-3
	USCS system	SM	SP	SP-SM

Mix Design

The comparison between dry and soaked stability curves for marl, sabkha, and dune sand are presented in Figures 5, 6, and 7 respectively. The results of the emulsified sulfur asphalt mix design indicated that the optimum residual emulsified sulfur asphalt content for the marl is 7.2 %, 3.6 % for sabkha and 5.4 % for the dune sand. While the results of the emulsified asphalt mix design indicated that the optimum residual emulsified asphalt content for the marl is 8 %, 4 % for sabkha and 5.4 % for the dune sand.

The results of stability show that the dry stability curves were consistently above soaked stability due to water effect. Water can cause loss of cohesion (strength) of asphalt and destroys the adhesion bond between the asphalt and the soils in the mixture.

Marl produced a higher stability (dry and soaked) relative to the soil materials and the stability of the sabkha stabilized Marshall Specimens was found to be higher than that of the dune sand. Although, all Marshall Stability results were found to exceed the minimum required Marshall Stability (6.6 kN) [12] except soaked marshal stability for dune sand. It can also be noticed that, Dry and soaked stability for EA mixes were higher than that for ESA mixes, this is due to the fact that moisture reduce stability of sulfur – asphalt mixes.

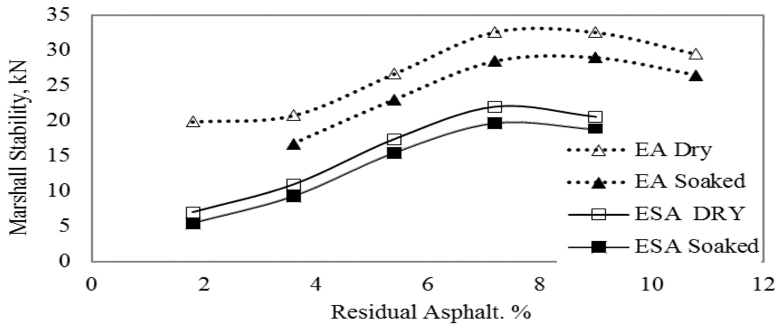

Figure 5: Dry and soaked stability for marl soil

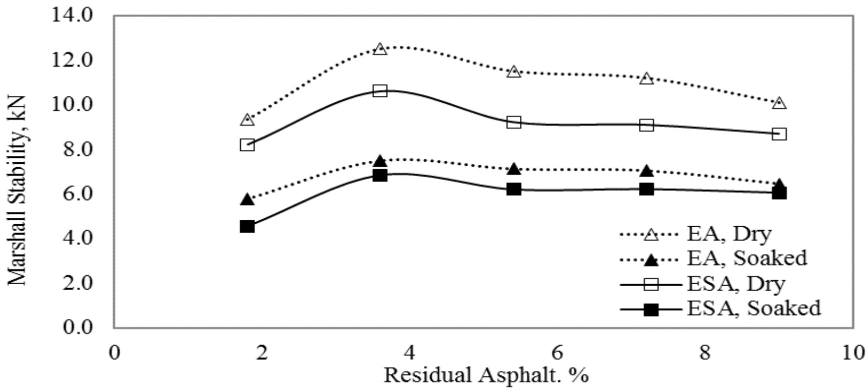

Figure 16: Dry and soaked stability for sabkha soil.

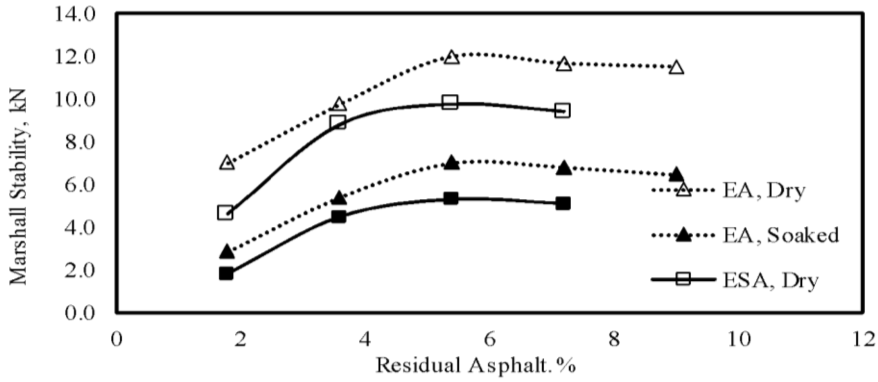

Figure 7: Dry and soaked stability for dune sand soil

The results of obtained durability are shown in Figure 8 which indicate that marl, sabkha and dune sand mixes at optimum residual emulsion sulfur asphalt and optimum residual emulsion asphalt have a more than 50% (minimum durability 50%)[12, 13]. EA blends showed lower durability compared to their ESA blends for marl and sabkha.

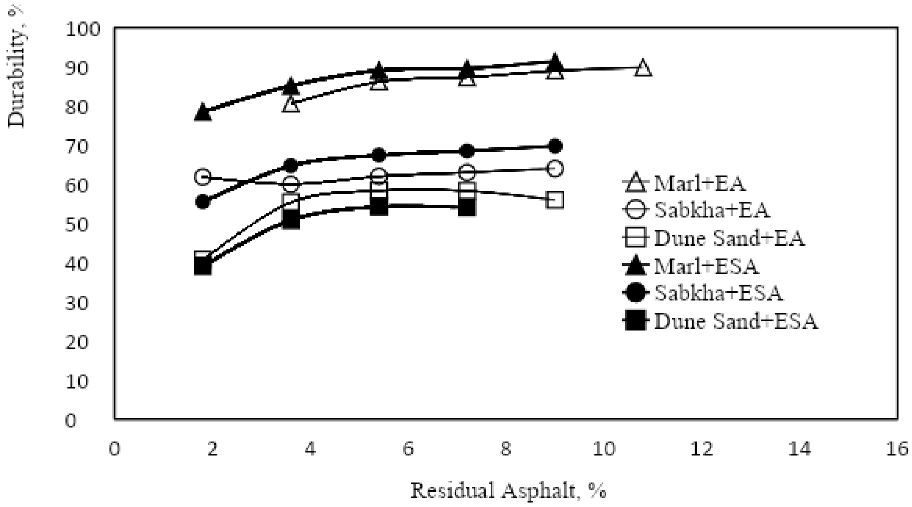

Figure 8: Durability variation versus EA and ESA contents

Inverse relationship of water absorption was found with binder content in Figure 9. As expected, when the residual asphalt content increased, the water absorption decreased. For all mixes the results of water absorption showed that at optimum residual emulsion sulfur asphalt and optimum residual emulsion asphalt have a less than 4% (maximum allowable value for the water absorption is 4 %) [12]. ESA blend shows lower water absorption from 30% to 80% compared to their EA blend.

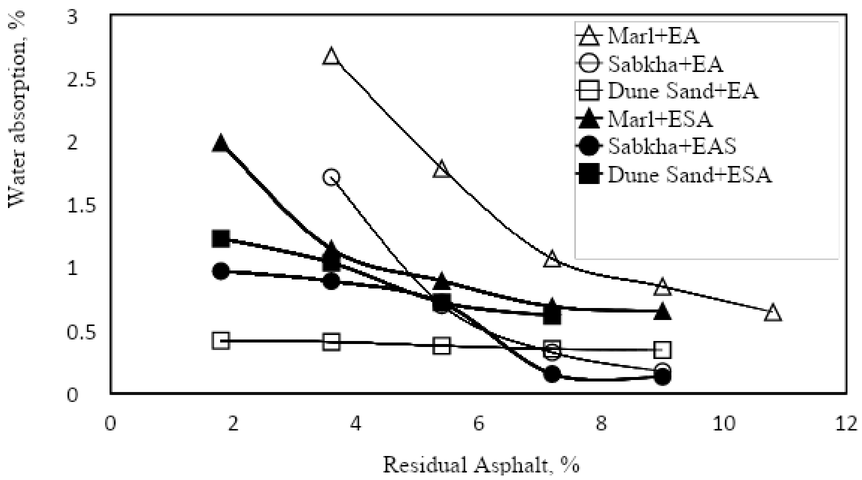

Figure 9: Water Absorption variation versus EA and ESA contents

The results of Marshall Stability loss are shown in Figure 10. The results indicate that marl, sabkha and sand mixes at optimum residual emulsion asphalt have a Stability loss less than 50 percent (maximum Stability loss 50% allowed [12]). Summary of marshal, durability, water absorption, and stability loss are shown in Table 5.

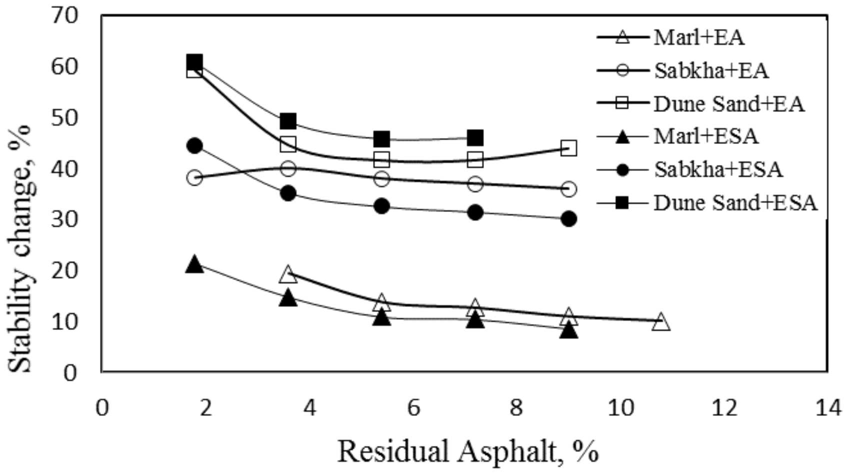

Figure 10: Stability loss variation versus EA and ESA contents

Table 5: Summary of results for marshal stability

Soil type	Type of additive	Optimum residual asphalt%	Dry Stability (kN)	Soaked Stability (kN)	Water absorption %	Durability %
Marl	EA	8.0	33.0	29.4	0.80	90
	ESA	7.2	22.4	19.8	0.68	91
Sabkha	EA	4.0	12.5	7.50	1.30	60
	ESA	3.6	10.6	6.80	0.88	65
Dune	EA	5.4	12.0	7.00	0.37	85
sand	ESA	5.4	9.80	5.30	0.71	54

The Analysis of variance (ANOVA) analysis of Marshall dry stability test shows that additive type has a significant effect on stability for all types of soil (i.e., the P-value, was less than of 0.05) as can be seen from Table 6. This means that the usage of EA or ESA causes a different and considerable change in the soil stability. For soaked stability, the behavior was different. As it can be observed from Table 6, the effect of additive type on the soaked stability was insignificant (i.e., the F-value was more than 0.05) for sabkha and dune sand, whereas for marl, the treatment type showed significant effect on the soaked stability.

Table 6: Result of Marshal Stability ANOVA at 5% significance level

Test condition	Soil type	Factors	Calculated F_{value}	P-value	Comment
Dry	Marl	Type of additives	372.23	0.000	Significant
	Sabkha		19.74	0.011	Significant
	Dune sand		14.2	0.020	Significant
Soaked	Marl		136.11	0.000	Significant
	Sabkha		0.180	0.694	Insignificant
	Dune sand		4.400	0.104	Insignificant

Evaluation of Designed Mixes

Indirect tensile strength

The relationship between ITS and percent residual asphalt content for the stabilized marl, dune sand and sabkha with EA and ESA, is presented in Figure 11. It is clear from the results that the ITS values have increased with an increase in the percent residual asphalt content until it reached at the maximum ITS value. After that, further increase in the percent residual asphalt content resulted in a reduction in the ITS value. Also, the marl mixes produced a higher ITS value relative to the other soil whereas, the ITS value of sabkha mixes were found to be higher than that of dune sand mixes. Although ITS results for marl and sabkha with EA and ESA at ORAC satisfied the recommended requirements of 200 kPs [12], but the ITS for dune sand mixes did not satisfy. Statistical analysis of ITS values reveals that the hypothesis that "additive has equal means" can be rejected with a probability of 95%. This means that the treatment type plays a very important role in the ITS values of treated mixes. The results of statistical analysis for Indirect Tensile Strength are shown in Table 7 for marl, sabkha, and dune sand mixes with EA and ESA.

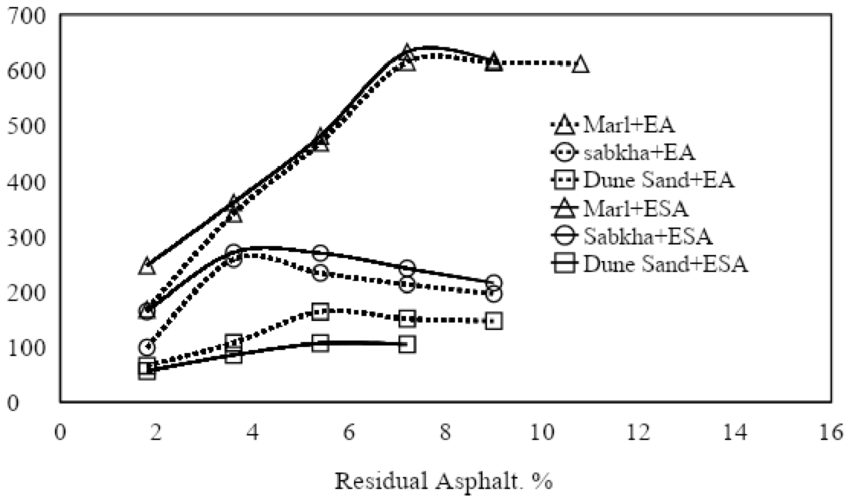

Figure 11: ITS variation versus EA and ESA contents

Table 7: Result of ITS ANOVA at 5% significance level

Test condition	Soil type	Factors	Calculated F_{value}	P-value	Comment
Dry	Marl	Type of additives	14.01	0.013	Significant
	Sabkha		38.57	0.003	Significant
	Dune sand		52.19	0.002	Significant

Static triaxial (Shear strength)

The relationship between shear strength and normal stress for marl, sabkha and dune sand with EA and ESA is presented in Figure 12. Analysis of this figure reveals that marl produced a higher shear strength (φ =27^o and C=292.5 kPa with EA, and φ =33^o and C=134 kPa with ESA) relative to the other treated soils and the shear strength of sabkha (φ =33^o and C=14.8 kPa with EA, and φ =31^o and C=14.4 kPa with ESA) which was higher than that of the dune sand (φ =30^o and C=25 kPa with EA, and φ =30^o and C=11.3 kPa with ESA).ESA mixes have slightly less shear strengths values than that for the EA mixes. The shear strength and related parameters for local soils treated with EA and ESA mixes are shown in Table 8. The results indicate that in general the maximum shear strength for mixes made with EA is higher than mixes made with ESA. The addition of ESA to the soil improves the angle of internal friction significantly compared to EA. While, the addition of ESA to the marl reduces values of cohesion significantly as compared to EA.

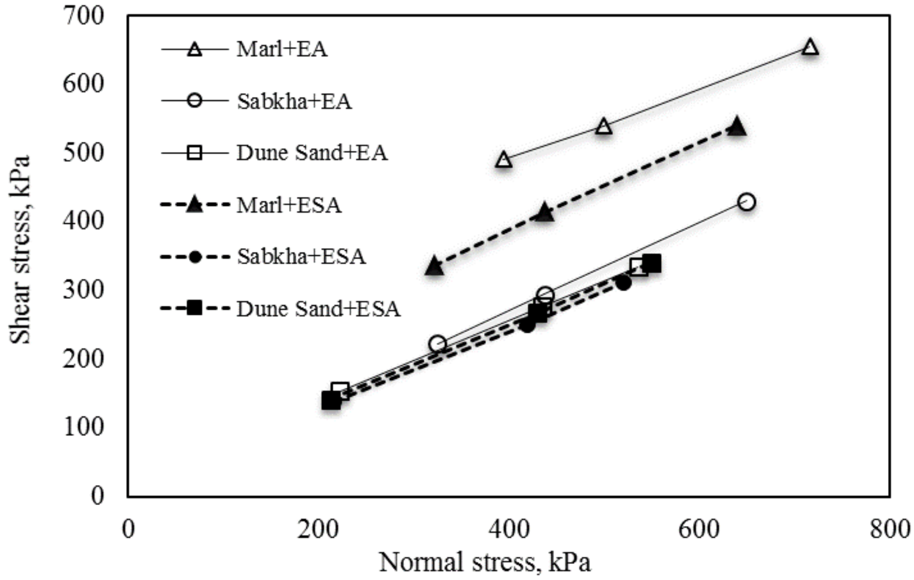

Figure 12: Mohr–Coulomb failure envelope for soils with EA/ESA.

Table 8: Shear parameter for Mohr-Coulomb failure envelope of treated soils.

Treatment type	Soil Type	Angle of Internal Friction	Cohesion (KPa)
Emulsified Asphalt	Marl	27	292.5
	Sabkha	33	14.8
	Dune sand	30	25
Emulsified Sulfur Asphalt	Marl	33	134
	Sabkha	30	15
	Dune sand	31	11.4

The regression analysis for the shear strength was developed using Minitab software version (16) software which shows that there is a relationship between shear stress (τ) and normal stress, type of soil and type of additives (EA/ESA) with a high correlation ($R^2 = 90\%$) as shown below:

$$\tau = 303 + 0.624\,\sigma - 1414\,A - 5.18\,S \qquad (1)$$

Where:

τ = shear stress, (kPa),

S= Type of soil (S = 1 (marl), S = 2 (Sabkha) and S = 3 (Dune sand)),

A= Type of additive (A =1(EA), A =2(ESA)), and

σ = normal stress, (kPa)

Dynamic resilient modulus

Dynamic resilient modulus for the three soils, namely, marl, sabkha, and sand mixed with EA and ESA was measured using the dynamic triaxial test at 22°C according to the AASHTO T-307 procedure. Three specimens were tested for each soil mixes under different combinations of confined pressure, 21–138 kPa and deviator stress, 34–276 kPa at repeated load duration of 0.1 sec to simulate a typical highway loading with a simulated speed of 65 kph.

The general variation of the resilient modulus with different stress conditions for all soils with EA and ESA at 22°C temperature are presented in Figure 13. The results show that marl soil mixed with EA or ESA produced a higher M_R relative to the other soil whereas the M_R of sabkha was higher than that of dune sand. Furthermore, the addition of ESA to marl and sabkha increases the M_R significantly as compared to EA. The incursion for marl was about 20% and 15% for sabkha depending on the applied deviator stress. On the other hand, for dune sand, ESA have slightly less resilient modulus values for than that for the EA mixes.

Table 9 presents the results of ANOVA analysis for resilient modulus (M_R). Analysis of M_R data using General Linear Model (analysis ANOVA) technique shows that confining stress and deviator stress have a significant effect on M_R for all soils with EA/ESA.

The regression analysis for marl, sabkha and dune sand shows that there is a relationship between resilient modulus (M_R) and deviator stress, confining pressure, type of soil and type of additives with a high correlation (R2 = 98%) as shown below:.

$$M_R = 166.6 - 35.8\ S + 9.7\ A - 0.25\ \sigma_c + 4.2\ \sigma_d \qquad (2)$$

Where:

M_R = Resilient modulus, (MPa),

S= Type of soil (S = 1 (marl), S = 2 (Sabkha) and S = 3 (Dune sand)),

A= Type of additive (A =1 (EA), A =2 (ESA)),

σ_c = Confining Pressure, (kPa), and

σ_d = Deviator stress, , (kPa)

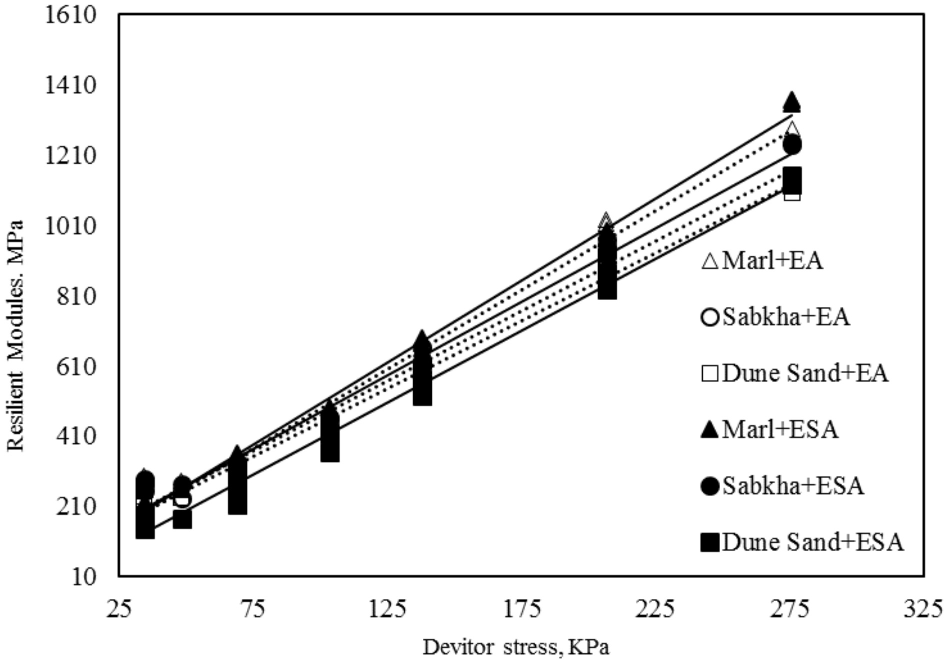

Figure 13: Variation of M_R with deviator stress for soils with EA and ESA

Table 9: Results of Resilient Modulus ANOVA at 5% significance level

Test condition	Soil type	Factors/Additives	Calculated F-value	P-value	Comment
Dry	Marl	Type of additives	0.54	0.467	Insignificant
		Confining stress	36.30	0.000	Significant
		Deviator stress	167.04	0.000	Significant
	Sabkha	Type of additives	1.27	0.264	Insignificant
		Confining stress	38.94	0.000	Significant
		Deviator stress	179.51	0.000	Significant
	Dune sand	Type of additives	0.14	0.713	Insignificant
		Confining stress	38.65	0.000	Significant
		Deviator stress	157.88	0.000	Significant

Conclusion

Summary of the general findings from the results analysis were presented in the subsequent sub-heading, test-wise. Based on the graphical and statistical interpretation of the data obtained from the various test conducted, the trend and manner in which the different additives (EA and ESE) affect each property were highlighted.

1. The resilient moduli of ESA with marl and sabkha are slightly more than EA mixes while, for dune sand, ESA have slightly less resilient modulus values for than that for the EA mixes.
2. Results of ITS, and marshal stability for EA and ESA mixes, except dune sand mixes, satisfied the limits assigned BAEM, 19.
3. ESA blend shows lower water absorption compared to their EA blend; durability increased when ESA was used as compared to EA.
4. Dune sand did not satisfy the minimum ITS requirements and therefore, it should not use as base for road construction.
5. Marl and sabkha with EA or ESA can be used for local road bases/subbases construction.
6. Modified emulsion asphalt by sulfur (ESA) can be used successfully to construct road bases with local soils.

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