Use of Saline Water in Compaction of Engineered Fills

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ABSTRACT

Many arid regions in the world have limited fresh water supplies but are near oceans or inland saline lakes. In these locations, it can be expensive and difficult to use fresh water for moisture conditioning during soil compaction of grading projects. However, local high salinity (ocean water or water from inland saline lakes or seas) water is often abundant and much less expensive than fresh water. Due to limited background research regarding the behavior of soils compacted using high salinity water, engineers generally prohibit its use for water conditioning required during compaction.

The limited amount of literature on the subject suggests that using high salinity water instead of freshwater during compaction increases the maximum dry unit weight and reduces the optimum moisture content. However, the data are sparse and the effects of soil plasticity on compaction when using saline water have not been thoroughly investigated. Additionally, most of the published literature deals with the use of water from inland salt lakes with very high salinity levels. This paper reviews the current literature, presents new data in which ocean water is used to condition soils during compaction, and investigates the importance of clay content when compacting soils with high salinity water. Results confirm that use of ocean water also increases optimum dry unit weight and decreases optimum water content. Ocean water appears to be as effective as highly saline water. The changes in compaction behavior are evident at clay contents as low as 10 percent.

INTRODUCTION

It is well know that plasticity of clays is affected by both soil mineralogy and the concentration and valance of ions in pore fluid (Mitchell & Soga, 2005). Published lab testing results show that use of saline water as a pore fluid reduces plasticity compared to fresh water (Azadi, 2008, Azadi et al, 2008, Campbell et al, 2009, Mahasneh, 2004). The magnitude of change in plasticity is more pronounced for higher plasticity clays. For example Heise (2011) showed significant reduction in plasticity of bentonite when using ocean water for pore fluid but no significant plasticity change in kaolinite. Because compaction behavior of soils is related to both the fines content (particle size less than .075 mm, or #200 sieve) and plasticity of fines, it is likely that using high salinity water to condition soils for compaction will affect the compaction behavior of the soils. Furthermore, the effect of the high salinity water is likely to be a function of fines content and plasticity of the fines.

PREVIOUS STUDIES

There are a few laboratory studies of the effects of saline water on compaction of clayey soils (Mahasneh, 2004; Azadi, 2008; Azadi et al, 2008; Alainachi and Alobaidy, 2010). However, these studies all used highly saline water, up to 500 g/l of dissolved solids, compared to ocean water which averages approximately 35 g/l dissolved solids. These studies show that using salt water instead of fresh water to moisture condition soils leads to an increase in the maximum dry density, decrease in the optimum water content, and increase in strength of the compacted soils.

Compaction of natural soils

Previous studies of effects of high salinity water conditioning on soil compaction have included tests on both natural soils, and soils manufactured in the lab by combining a natural clayey soil with a coarse grained sand or gravel. All previous studies performed ASTM standard D-698 Standard Proctor Maximum Density on selected samples. Alainachi and Alobaidy (2010) performed testing on five natural soil samples from test pits in Baniyas City, Abu Dhabi. These soils consisted of poorly graded sands and silty sands with fines content ranging from 7 to 11 percent. The Plasticity index of the fines ranged from 6 to 15. The samples were compacted using fresh water and Dead Sea water with a salinity of 503 g/l. Mahasneh (2004) investigated three natural soils from southern Jordan: a low plasticity clay, a sand with clay and a well graded gravel with 3 percent clay (CL). These tests were performed using Dead Sea water with a salinity of 330 g/l. Typical compaction curves comparing the use of saline lake water and fresh water are shown in Figure 1.

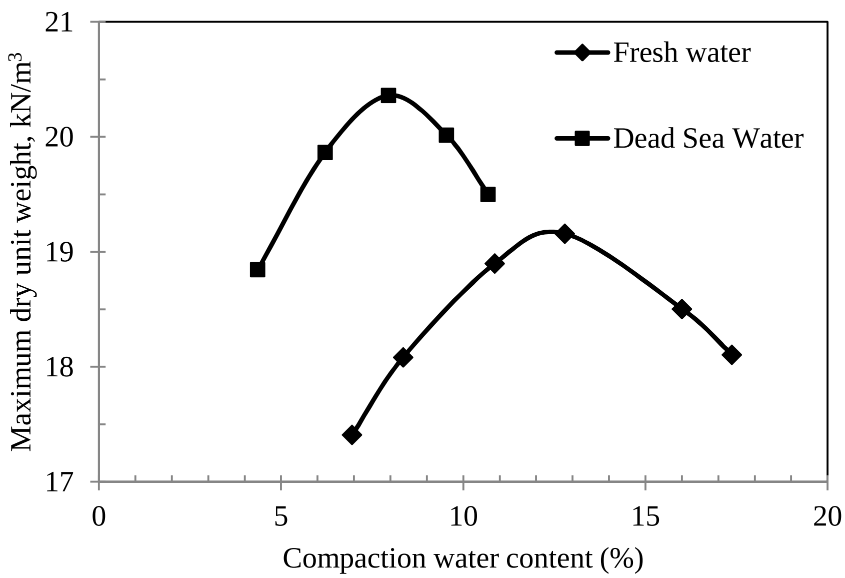

Figure 1. Typical Modified Proctor compaction curves for soil using both fresh water and saline water (data from Mahasneh, 2004)

As shown in Figure 1, the use of high salinity water generally increases the maximum unit weight and decreases the optimum water content. The data for these tests on natural soils is presented in Table 1. As shown in Table 1, with one exception, the use of high salinity water increases dry unit weight and decreases optimum water content. The one test where unit weight was decreased by the use of high salinity water appears to be an anomaly. Disregarding the anomalous data point, the use of saline lake water increases dry unit weight by 0.84 kN/m^3 (5.4 lb/ft^3) and decreases optimum water content by 4.0 percent.

Table 1. Effects of high salinity water on compaction of natural soils

Reference	Soil classification	Percent fines	PI of fines	Salinity of water, g/l	Average increase in $\gamma_{d\text{-}max}$, kN/m^3 (lb/ft^3)	Average decrease in w_{opt} (%)
Alainachi and Alobaidy (2010)	SP-SM	7	6-15	503	0.39 (2.5)	2.0
	SP-SM	8	6-15	503	1.8 (11.5)	4.2
	SP-SM	10	6-15	503	0.20 (1.3)	3.0
	SP-SM	11	6-15	503	0.20 (1.3)	3.0
	SP-SM	11	6-15	503	1.59 (10.1)	4.0
Mahasneh (2004)	GW	3	10.0	330	0.30 (1.9)	5.0
	SC	25	10.0	330	1.15 (7.3)	5.0
	CL	62	18.0	330	-3.50 (-22.3)	11.0
				Average	0.36 (2.3)	4.7
				Average ignoring one negative change in optimum unit weight	0.84 (5.4)	4.0

Compaction of manufactured soils

Two papers reporting studies of manufactured soils were found in the literature. Azadi (2008) reports on a series of tests with a sand-gravel base soil which was mixed with a bentonitic clay from Azerbaijan near Urmieh Lake. The sand-gravel/clay mixtures were varied from 17 to 33 percent clay. These soils were compacted with fresh water and with Urmieh lake water which has a saline content of 346 g/l. Azadi et al (2008) reports on compaction tests of two manufactured soils. Two separate series of tests are reported in this paper. In both cases, a sand-gravel mixture was used as the base soil. In one series, the sand-gravel was mixed with a low plasticity clay, PI = 14.5. In the second series the sand-gravel was mixed with a high plasticity bentonite, PI = 145. These tests also used Urmieh Lake water for conditioning the soils. Both series varied the clay percent from 11 to 33 percent. As with the tests on natural soils, these tests generally showed an increase in dry unit weight and a decrease in optimum water content when soils were compacted using high salinity water, rather than fresh water. The results of these tests are presented in Table 2. Again, there is one anomalous point where use of high salinity water decreased the maximum dry unit weight. Ignoring the one anomalous point, the use of high salinity water rather than fresh water generated an average increase in dry unit weight of 0.93 kN/m^3 (2.5 lb/ft^3) and decrease in optimum water content of 2.3 percent.

Table 2. Effects of high salinity water on compaction of manufactured soils

Reference	Soil classification	Percent fines	PI of fines	Salinity of water (g/l)	Average increase in $\gamma_{d\text{-}max}$, kN/m^3 (lb/ft^3)	Average decrease in w_{opt} (%)
Azadi (2008)	SC	17	26.0	346	0.91 (5.8)	2.5
	SC	20	26.0	346	0.03 (0.2)	2.0
	SC	25	26.0	346	0.23 (1.5)	4.4
	SC	33	26.0	346	-1.02 (-6.5)	2.5
Azadi et al (2008)	SP-SC	11	145	346	0.08 (0.5)	2.5
	SC	14	145	346	0.20 (1.3)	2.5
	SC	20	145	346	0.52 (3.3)	2.5
	SC	33	145	346	0.71 (4.5)	2.5
	SP-SC	11	14.5	346	0.91 (5.8)	2.5
	SC	14	14.5	346	0.27 (1.7)	2.5
	SC	20	14.5	346	0.30 (1.9)	2.5
	SC	33	14.5	346	0.30 (1.9)	2.5
				Average	0.30 (1.9)	2.3
		Average ignoring one negative change in optimum unit weight			0.39 (2.5)	2.3

Salt water effects on strength of compacted soils

A small amount of laboratory test data is available concerning the strength of soils compacted using high salinity water versus fresh water. Azadi et al (2008) performed California Bearing Ratio (CBR) tests on the same manufactured sand-clay mixtures used in compaction testing. The CBR test results are shown in Table 3. The data show a significant increase in CBR values for samples compacted with the highly saline Urmieh Lake water. The data are not sufficient to identify any trend with clay content or plasticity of clay.

Table 3. Comparison of CBR values for samples clayey sand compacted using fresh water and saline lake water

Reference	Soil classification	Percent fines	PI of fines	CBR value: Fresh water	CBR value: Saline Lake water	Percent increase
Azadi et al (2008)	SP-SC	11	145	34.8	60.8	74.4
	SC	14	145	29.8	45.3	52.1
	SC	20	145	11.4	19.0	66.8
	SC	33	145	14.8	16.6	12.4
	SP-SC	11	14.5	85.7	95.3	11.2
	SC	14	14.5	26.8	68.9	157.1
	SC	20	14.5	27.9	40.8	43.6
	SC	33	14.5	28.4	61.2	115.3

Mahasneh (2004) performed unconfined compression testing on three natural soil samples and the results are presented in Table 4. These data show a significant increase in unconfined compressive strength when saline lake water is used in compaction. There does not seem to be any trend with fines content. In the case of the gravel and sand samples tested by Mahasneh (2008), the increase in strength should be, in part, due to the increase in dry unit weight of the samples as shown in Table 1. However, for the clay sample, the compaction test showed a significant decrease in dry unit weight (Table 1) but a significant increase in strength. This implies that the strength increase must be due to a decrease in the plasticity of the clay or some cementation action of the salts in the water. The data from Azadi et al (2008) and Mahasneh (2008) clearly show a consistent increase in the undrained strength of compacted soils when using high salinity water versus fresh water. The data are insufficient to identify the source of the strength increase. It appears that the increased strength is due to both an increase in dry unit weight and chemical reactions with the high salinity water, reduced plasticity and/or some sort of cementation.

Table 4. Comparison of unconfined compression strength for three natural soils compacted using fresh and high salinity water

				Unconfined Compression Strength, kPa (lb/ft^2)		
Reference	Soil classification	Percent fines	PI of fines	Fresh water	Saline Lake water	Percent increase
Mahasneh (2004)	GW	3	10.0	92 (1920)	132 (2750)	43.5
	SC	25	10.0	57 (1190)	63 (1310)	10.5
	CL	62	18.0	35 (730)	57 (1190)	62.9

CURRENT WORK

Ocean water effects on compaction of manufactured soils

The existing data on the effects of high salinity water on compacted soil properties brings up a number of questions. Two questions are addressed by this study. First, are soil compaction characteristics altered by ocean water with a saline content of approximately 35 g/l? Second, what is the effect of clay content on the changes in maximum dry unit weight and optimum water content for soils compacted with ocean water versus fresh water?

To address the questions, this study used a manufactured soil so that the clay content could be controlled. Sodium bentonite was selected as the clay mineral because of its high plasticity and the significant difference in plasticity when hydrated with high salinity water versus fresh water. It was postulated that the significant decrease in plasticity of the clay under these two conditions would significantly affect the compaction characteristic. The base sand used was washed concrete sand. The grain size distribution for this sand is shown in Figure 2. The ocean water used was obtained from Long Beach, California and had a salinity of 32 g/l. The Atterberg limits of the sodium bentonite were measured using both fresh water and ocean water. Using fresh water the measured liquid limit was 687 and the plasticity index was 606. Using ocean water, the liquid limit was 209 and the plasticity index was 140.

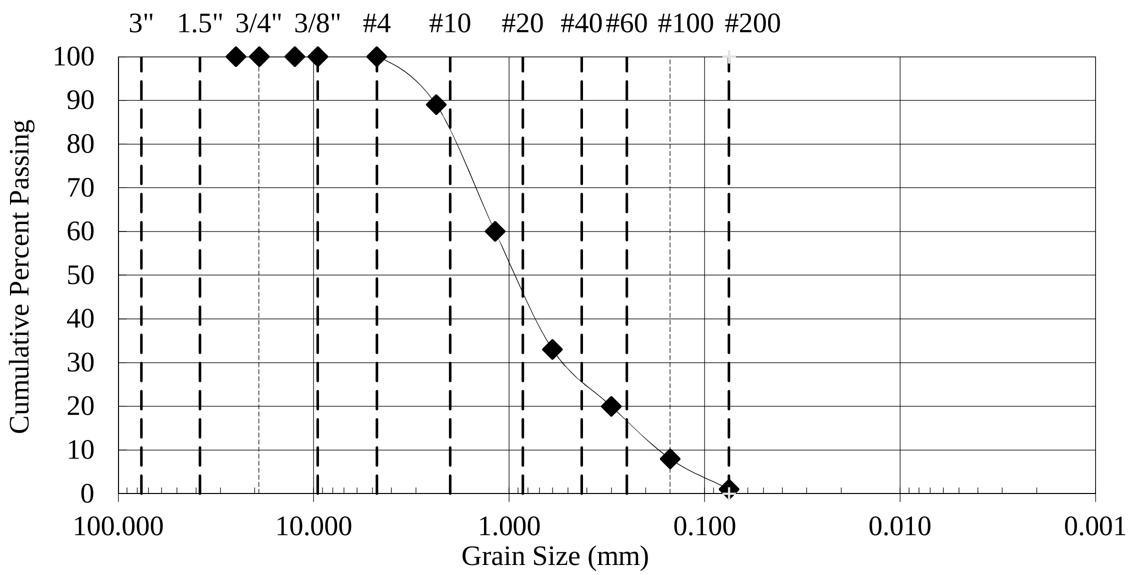

Figure 2. Grain size distribution of washed concrete sand used in study

Four different soils were tested at clay contents of 10, 20, 30 and 40 percent. Data for the compaction tests is shown in Table 5. Results from this test confirm data from other tests reported above. Namely, the use of saline water versus fresh water increased the maximum dry unit weight and decreased the optimum water content. The effects were seen even though the salinity of the water used in this study was an order of magnitude less that that used in previous studies discussed above (32 g/l versus 300 to 500 g/l). Concerning the effects of fines content, there does not appear to be any discernible trend between either maximum dry unit weight or optimum water content and percent fines. Figures 3 and 4 show data for all the manufactured soils discussed in the paper in which the fines content was varied. Figure 3 presents change in maximum dry unit weight and Figure 4 presents change in optimum water content. No patterns are apparent in these data.

Table 5. Effects of ocean water on compaction of sand-bentonite mixtures

	Maximum dry unit weight, kN/m^3 (lb/ft^3)			Optimum water content, percent		
Percent clay	Fresh water	Ocean water	Increase	Fresh water	Ocean water	Decrease
10	19.41 (123.5)	19.89 (126.5)	0.48 (3.0)	10.5	9.0	1.5
20	19.18 (122.0)	19.42 (123.5)	0.24 (1.5)	10.5	8.5	2.0
30	18.47 (117.5)	18.79 (119.5)	0.32 (2.0)	13.0	11.5	1.5
40	18.63 (118.5)	18.94 (120.5)	0.31 (1.5)	13.0	12.0	1.0

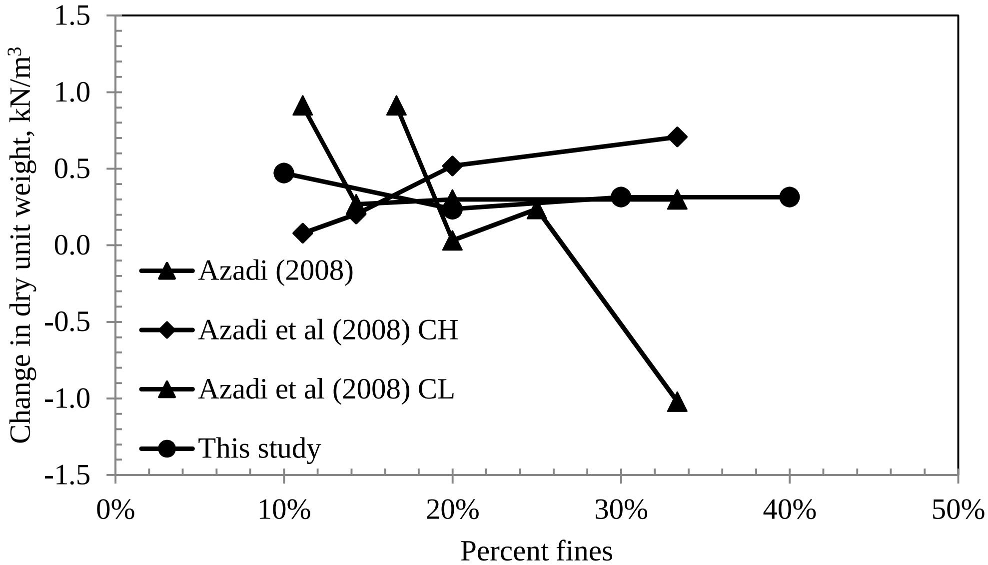

Figure 3. Change in maximum dry unit weight for compaction with high salinity water versus fresh water as a function of percent fines

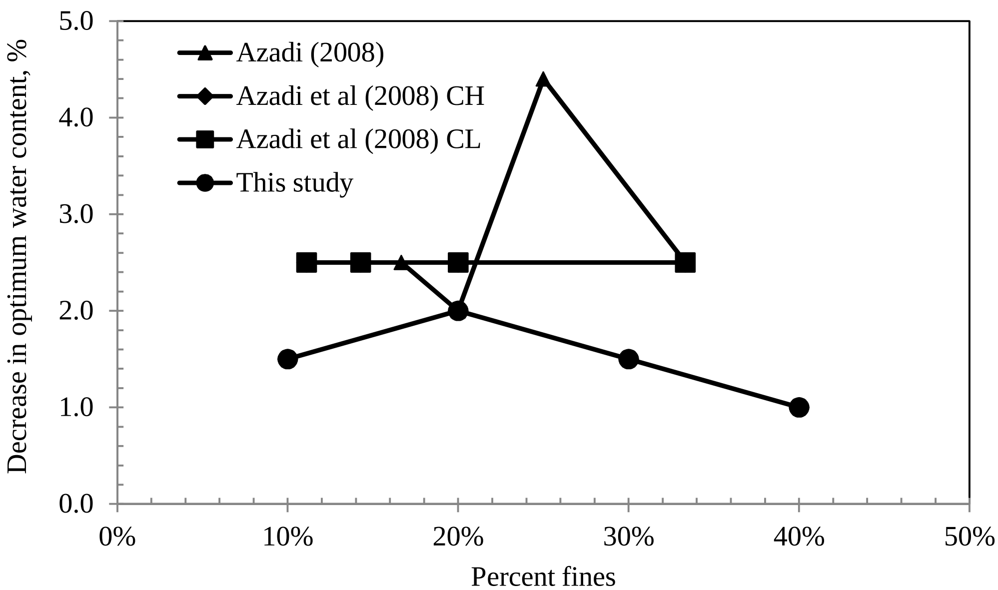

Figure 4. Change in optimum water content for compaction with high salinity water versus fresh water as a function of percent fines

Corrosiveness of soils compacted with ocean water

A major drawback of using high salinity water in compaction of soils is the increased corrosiveness of soil due to the ions present in the water. For the soils used in this study the resistivity and pH were measured using California Test Method 643, sulfate content measured using California Test Method 417, and chloride content measured using California Test Method 422. The results are shown in Table 6. All the soils tested would be classified as extremely corrosive to buried metals according to Roberge (2006). Concerning sulfate attack of Portland cement concrete, the sample with 10 percent bentonite would be considered not susceptible to sulfate attack and the other samples would be considered be moderately susceptible according to ACI 318-11 (Table 4.2.1)

Table 6. Effects of ocean water on corrosion characteristics of sand-bentonite mixtures

Percent clay	Minimum Resistivity (ohm-cm)	pH	Sulfate Content (ppm)	Chloride Content (ppm)
10	317	7.5	12	15
20	261	7.6	321	251
30	213	7.1	549	386
40	189	6.9	591	377

CONCLUSIONS

Based on the published results and the results of this study, the use of saline water during compaction has a significant effect on several soil characteristics. The use of high saline water versus fresh water causes an increase in dry unit weight and a decrease in the optimum water content. The increase in dry unit weight generally ranged from 0.3 to 1.5 kN/m^3 (2 to 10 lb/ft^3). In two cases, a decrease in maximum dry unit weight were observed, however, these cases appear to be anomalies as they did not follow the trend of the researched test results, or the results of the testing performed for this study. . The decrease in optimum water content generally ranged from 2 to 5 percent.

A review of data from this study, which compared ocean water with previously published data using highly saline water, indicates that the effects of increased dry unit weight and reduced optimum water content are achieved using ocean water. High salinity water found in inland saline lakes such as the Dead Sea and Urmieh Lake did not appear to increase the effects achieved using normal ocean water.

Neither the maximum dry unit weight nor the optimum water content appeared to show any discernible trend with percent of fines in the compacted soil. However, no tests were performed on soils with fines content less than 10 percent. Additional testing is needed to determine if there is an effect for low fines content.

While little data is available on effects of saline water on strength of compacted soil, the existing data show significant increases in measures of undrained strength when using highly saline water for compaction versus fresh water. Further research is needed to determine the magnitude and source of these strength increases.

Corrosivity and sulfate content tests performed on soils compacted with ocean water indicate that they would all be considered highly corrosive to buried metals, but only generate a moderate susceptibility to sulfate attack of Portland cement concrete. No data was available on the corrosiveness of soils compacted with highly saline water; however, it would be prudent to assume that they will create a significantly more severe environment.

Based on the published literature and the results of this study, it appears that using saline water during soil compaction may be beneficial in some projects, however, further studies of actual field observations should be performed. Using saline water can improve the sustainability of earthwork projects by reducing the consumption of scarce and expensive fresh water in arid regions. The chief drawback to the use of saline water in the increased potential for corrosivity, particularly as it relates to buried metal.

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