The Effects of Subgrade Soil Stabilization on Pavement Structural Design

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Abstract

This research work presents the effect of subgrade soil stabilization on pavement structural design through improving the engineering properties of weak subgrade soil by using Portland cement material. Soil samples were collected from three locations. Portland Cement material is selected in this study to stabilize the subgrade soils tack in consideration soil type and plasticity index. The California Bearing Ratio (CBR) test was performed on the laboratory-moulded stabilized and un-stabilized specimens in order to evaluate and compare the bearing capacity (is the capacity of soil to support the loads that are applied to the ground above) for each sample and the value of CBR before and after being stabilized. The soil and stabilizer (cement) were mixed with different percentages of cement to determine the optimum moisture content. Total of 45 CBR tests were performed taking into consideration 1- day and 7- day curing time to stabilize soil with cement. Outperforming results were observed for the increased added percentage of cement and in term the CBR value. Five percent cement was found to be the optimal mixing ratio and it demonstrated cost effective design. The results showed that the soil CBR values increased by approximately 60-70% at day 7 for this ratio. Furthermore, pavement design was conducted for un-stabilized and stabilized soils and the cost savings achieved from the stabilization was presented. The data showed that pavement design for stabilized soils achieved approximately 20-25% cost savings when compared with un-stabilized soils.

Keywords: *California Bearing Ratio, Curing time, pavement design, subgrade soil, cement, stabilization*

1. Introduction

Soil stabilization refers to the alteration of soils to enhance their physical properties such as strength and permeability [1]. It provides an economical alternative to the removal and replacement of weak soil [4]. Soil stabilization techniques allow modification of soil characteristics to improve engineering performance. This eliminates the need to import expensive materials [5]. With technological advancements, soil stabilization has diverse applications in civil engineering projects. The process of soil stabilization involves blending stabilizers and additives with native soil [9]. Mechanical stabilization alters gradation through compaction. Chemical stabilization uses additives that alter the soil matrix [2]. Stabilized soils are used in foundations, pavements, embankments etc. Cement and lime stabilization have been used for decades in road construction [3]. Soil stabilization serves as a cost-effective ground improvement technique.

Research on stabilization involves laboratory testing to evaluate suitable stabilizer materials and their optimum dosages [7]. Extensive studies have been done on stabilization using conventional agents as well as industrial by-products. Numerical modeling and theoretical analysis have helped gain an improved understanding of the fundamental mechanisms underlying soil modification. Life cycle assessment studies have been useful in determining the environmental impacts of various stabilization alternatives.

The improved soil properties are utilized to design economical flexible pavement sections [11]. The influence of cement content on the performance along with material and construction costs is evaluated to determine the optimum level of modification. The findings provide useful insights on subgrade stabilization, pavement analysis and design. Prior research on cement stabilization has evaluated the improvements in Atterberg limits, compaction characteristics, unconfined compressive strength, durability and other engineering properties of fine-grained soils [6, 8]. Effects of cement type and content, curing conditions, additives, soil mineralogy among other factors have been investigated.

The aim of the study is to evaluate the improvement in strength characteristics of silty clay subgrade soils with cement stabilization using California Bearing Ratio (CBR) testing and to discuss the effects of subgrade soil stabilization on pavement structural designs by using cement additive with various soil types, as well as the procedures for mixing the cement with soil to determine the treatment level for soil and improve the engineering properties of the pavement soil subgrade. These requirements also apply to roads and structures with a stabilized surface layer.

2. Materials and Methods

The soils were obtained from various sources, and all of the samples utilized in this study were molded in the laboratory according to the (ASTM) and the (AASHTO) standards. For the laboratory testing program, cement (Type IP Portland-Pozzonlan Cement) was investigated as a stabilizer to treat different types of soil. This study consisted of two parts. The first part was experimental where the subgrade soil materials were stabilized at different percentages of cement (2.5%, 5% and 7.5%) to determine the optimum value for the mix designs. The second part of the study concerned the effects of soil stabilization on the pavement design. The Modified Proctor tests were performed to find the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), CBR and compaction test of the soil before and after cement stabilization were performed.

2.1 Samples collection

One type of soil was selected to be used in this study (low and high plasticity clay). The soil sample were collected from different locations in Jordan including Irbid, Ajloun, and the capital Amman. Sampling depth ranges from100-150 cm. The Collected soil samples were collected in plastic bags, then transported to the laboratory for testing according to the above mentioned standards.

2.2 Materials Characterization

The natural untreated soil samples were tested before adding a cement stabilizer, and the results were used as a reference point to compare the results after adding the stabilizer. Basic proprieties for un-stabilized soil were tested and summarized in Table 1. The examined explanatory parameters include Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI), classification of soil, MDD, and OMC extracted from the compaction curve using the Modified Proctor Test, and California Bearing Ratio (CBR). The results of gradation test and Atterberg Limits that were performed on the soil sample are presented in Table 2.

Tab. 1. Characterization and classification of Soil Samples

Soil location/criteria	Atterberg Limits			Proctor Test		California Bearing Ratio CBR %	AASTHO Classification
	LL	PL	PI	MDD gm/cm^3	OMC %		
Ajloun	37	22	15	1.68	16.9	5.8	A-6
Irbid	45	23	22	1.51	20	4.6	A-7-6
Amman	41	23	18	1.59	18.5	5.1	A-7-6

Notes: as per ASTM D4318

Tab. 2. Result of Gradation and Atterberg Limits of Soil Samples

Soil location/Test	**Sieve analysis**	**% Passing by Weight**	**Atterberg Limits**		
Ajloun	3 inch [75.0 mm]	100	LL	PL	PI
	No.4[4.75 mm]	97	37	22	15
	No.10[2.00 mm]	94			
	No.40[0.425 mm]	82			
	No.200[0.075 mm]	56			
Irbid	3 inch [75.0 mm]	100	LL	PL	PI
	No.4[4.75 mm]	99	45	23	22
	No.10[2.00 mm]	98			
	No.40[0.425 mm]	94			
	No.200[0.075 mm]	88			
Amman	3 inch [75.0 mm]	100	LL	PL	PI
	No.4[4.75 mm]	98	41	23	18
	No.10[2.00 mm]	95			
	No.40[0.425 mm]	88			
	No.200[0.075 mm]	67			

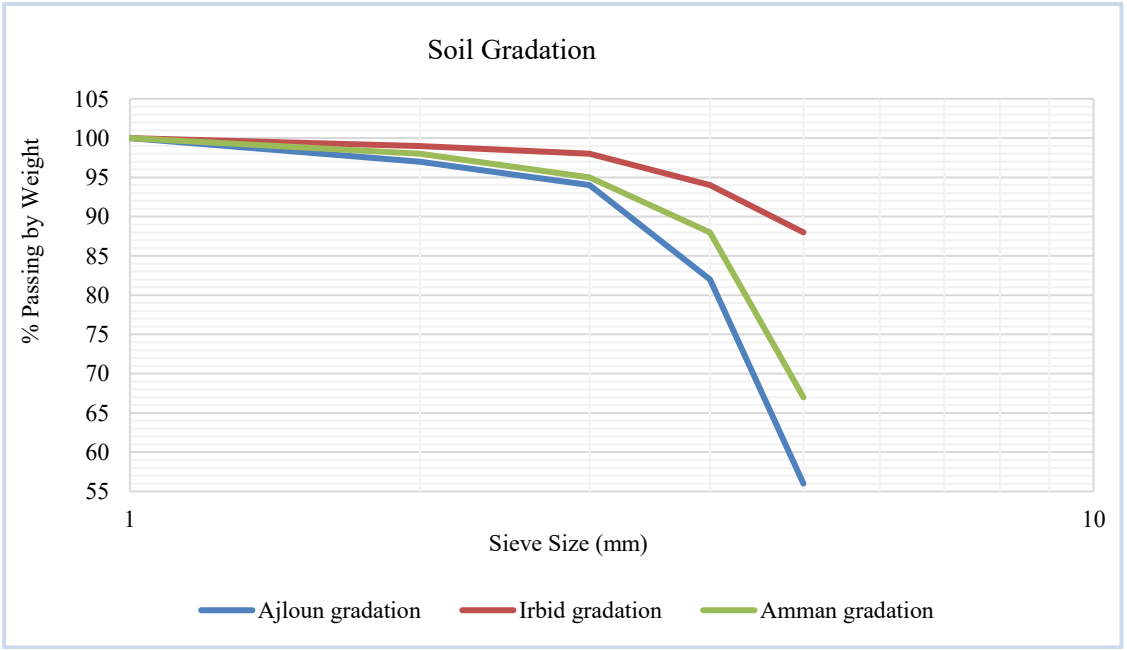

Fig. 1. Soil Gradation for three Samples

The results in table 1 and 2 were obtained by taking the average of the samples. Maximum dry density (MDD) and Optimum Moisture Content (OMC) of soils are generally an important factor in determining the soil suitability or unsuitability for stabilization by any stabilizer. The soil at the construction site must be stable enough to carry the loads from the structures through footings without undergoing undesirable settlements during the construction process and during the service period.

This function of soil is tested through the site investigation process. The construction site is hence treated and compacted based on the site investigation report. The amount of compaction required for the soil in the respective area varies from site to site.

2.3 Soils Samples Classification

According to the results of Gradation and Atterberg Limits of Soil Samples (see Table 2) the results of soil classification for three samples are showed in Table 1. According to AASTHO classification. Ajloun soil was classified A-6 with low plasticity clay, Irbid soil was classified A-7-6 with high plasticity clay and Amman soil was classified A-7-6 with high plasticity clay.

The soils utilized in the study were classified using the AASHTO soil classification and the Unified Soil Classification System (USCS). The consistency limit is used to determine these classes. The liquid limit and plastic limit tests of soil are performed using the Casagrande equipment in line with the ASTMD 4318 standard protocol. Depending on the USCS classification, Ajloun soil was classified **CL** (clay with low plasticity), Amman and Irbid soil were classified **CH** (clay with high plasticity).

2.4 California Bearing Ratio (CBR)

The CBR test is probably the most popular method for constructing pavement structures. This method was developed in 1930 by the California Division of Highways and has subsequently been adopted and modified by other states, the United States Army Corps of Engineers (USACE), and many countries worldwide. The American Society for Testing and Materials (ASTM) approved the ASTM D 1883 CBR of Laboratory-Compacted Soils method. The CBR is a measure of the strength of the subgrade of a road, as well as the materials used in its construction. It is the ratio of the bearing load that reaches a material to a certain depth compared to the force that gives the same penetration into crushed stone. CBR measured subgrade and material strength. It uses a 150mm diameter mould with a loading frame and gauges for monitoring. The specimen was submerged in water for four days, and expansion characteristics were recorded.

2.5 CBR Test Procedure

The CBR test procedure was performed in accordance with ASTM D1557 standard procedure to evaluate the value of CBR for soil samples (treated and untreated). CBR value was Calculated by the given formula:

$$\text{CBR}\ (\%) = \frac{\text{Pt}}{\text{Ps}} * 100 \qquad \text{Eq.(1)}$$

Where,

Pt = corrected unit (or total) test load corresponding to the chosen penetration from the load penetration curve.

Ps = unit (or total) standard load for the same depth of penetration as for Pt (Table 4). The relative rating strength as a function of CBR values is explained in Table 5.

The higher the CBR value of a particular soil, the more strength it has to support the pavement. This means that a thinner pavement structure could be used on soil with a higher CBR value than on soil with a low CBR value. Generally, clays have a CBR value of 6 or less. Silty and sandy soils are next, with CBR values of 6 to 8. The best soils for road-building purposes are the sands and gravels whose CBR values normally exceed 10. Three soil locations (Ajloun, Amman and Irbid) were tested to find the CBR value before and after stabilization with cement.

Tab. 3. The difference between the standard proctor test and modified proctor test

Test Details	Standard proctor (Light compaction)	Modified Proctor (Heavy compaction)
The weight of Rammer	2.6 kg	4.89 kg
The height of free fall of the Rammer	310 mm	450 mm
No. of Layers	3 layer	5 layer
No. of Blows	25 blow each layer	56 blow each layer
The compactive effort	592 kg/m^3	2700 m^3

Tab. 4. Unit or Total standard loads for CBR

Penetration Depth	Unit standard load	Total standard load
2.54 mm (0.1 inch)	70 kg/cm2 (995.63 psi)	1370 kgf (19,486.33 psi)
5 mm (0.2 inch)	105 kg/cm2 (1493.45 psi)	2055 kgf (29,228.97 psi)

Tab. 5. Relative ratings of supporting strengths as a function of CBR values [10]

CBR (%)	**Material**	**Rating**
> 80	Subbase	Excellent
50 to 80	Subbase	Very Good
30 to 50	Subbase	Good
20 to 30	Subgrade	Very good
10 to 20	Subgrade	Fair-good
5 to 10	Subgrade	Poor-fair
< 5	Subgrade	Very poor

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3. Results and Discussion

3.1 California Bearing Ratio (CBR)

The CBR test results were analyzed separately for each sample based on the location from where the soil sample was collected, taking into consideration the curing time of mixing soil with cement.

The CBR value of the three types of soils investigated increased with increasing cement percentage as well as increasing the curing time, as shown in Table 6 and Figure 2.

Tab. 6. The CBR value for all type of soils

Treatments	**Ajloun soil**		**Amman soil**		**Irbid soil**	
Curing time	1 Day	7 Days	1 Day	7 Days	1 Day	7 Days
CBR value with zero% cement (un-stabilized sample)	5.8	5.8	5.1	5.1	4.6	4.6
CBR value with 2.5% cement	9.5	10.4	8.9	9.5	6.1	7.2
CBR value with 5% cement	12.1	15.8	11.4	13.1	8.1	9.8
CBR value with 7.5% cement	18.1	19.5	15.4	16.4	12.4	12.5

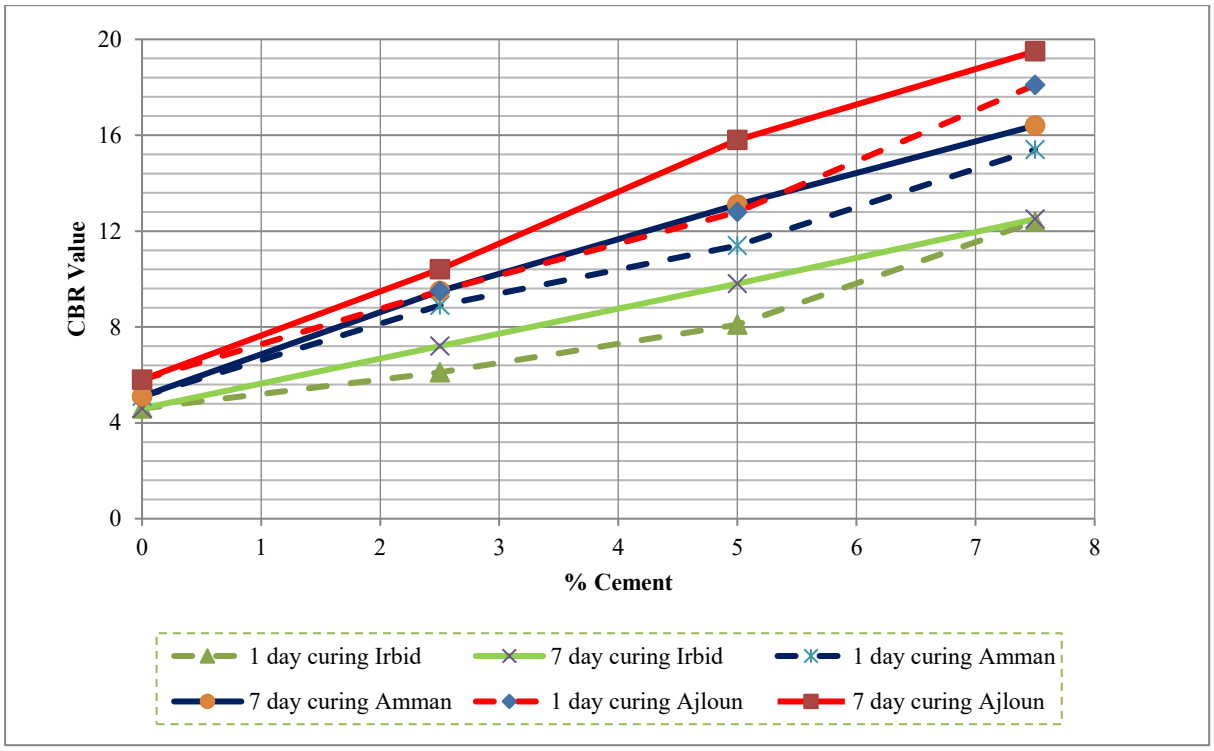

Fig. 2. CBR vs % cement for various type of soil

3.2 Cost Analysis for Soil Stabilization

The amount and cost of cement required for stabilizing 1 m^2 of soil at different cement percentages 2.5%, 5% and 7.5% by weight of soil are presented in Table 7. The cement requirement and stabilization cost increase proportionately as the cement percentage rises from 2.5% to 5% to 7.5%. The non-linear rise in cost is due to the discrete nature of Portland Cement. Overall, the table provides a quantitative estimate of the material requirements and costs for stabilizing soil at different cement dosages.

Tab. 7. Cost implementation of soil stabilization

Percentage of cement	Amount of cement kg/m^3	Number of bags/m^3 (1bag=50 kg)	Cost of soil stabilization USD/m^3	Cost of soil stabilization USD/m^2
2.5%	12.8	0.26	1.84	0.65
5%	25.6	0.51	3.60	1.29
7.5%	38.4	0.77	5.44	1.94

3.3 Design of Pavement Layers Thickness with constant value for base and subbase

The objective of structural design is to determine the number and thickness of the different layers within a pavement structure required to accommodate a given traffic loading. This includes the surface course as well as any underlying base or subbase layers. The design was done according to the AASHTO 1993 method used for the structural design of flexible pavements.

The resilient modulus was determined as follows:

$$MR = 1500 * (CBR) \quad \text{Eq.(2)}$$

Where "MR" is the resilient modulus in "psi", and CBR is the California Bearing Ratio. Available data indicated that Equation 2 provided better results at values of CBR less than 20 in the 1993 AASHTO design guide. Table 8 shows the values of MR, Structural Number (SN) and pavement thickness for various types of soil.

Tab. 8. Pavement Layers Thickness for several soil with constant base and subbase thickness

Soil sample	**Cement (%)**	**CBR % value**	**MR value (ksi)**	**Structural Number (SN)**				**Pavement thickness (D in inch)**				**Total thickness (inch)**
				SN1	**SN2**	**SN3**	**SN4**	**D1**	**D2**	**D3**	***D4**	**D total**
Ajloun soil	0%	5.8	8.7	3.08	3.75	4.46	-	6	6	8	-	20
	2.5%	10.4	15.6	2.42	3.09	3.80	4.19	5.5	6	8	14	19.5
	5%	15.8	23.7	1.98	2.65	3.36	3.59	4.5	6	8	14	18.5
	7.5%	19.5	29.25	1.76	2.43	3.14	3.31	4	6	8	14	18
Amman soil	0%	5.1	7.65	3.30	3.97	4.68	-	7.5	6	8	-	21.5
	2.5%	9.5	14.25	2.64	3.31	4.02	4.33	6	6	8	14	20
	5%	13.1	19.65	2.20	2.87	3.58	3.85	5	6	8	14	19
	7.5%	16.4	24.6	1.76	2.43	3.14	3.54	4	6	8	14	18
Irbid soil	0%	4.6	6.9	3.74	4.41	5.12	-	8.5	6	8	-	22.5
	2.5%	7.2	10.8	2.86	3.53	4.24	4.76	6.5	6	8	14	20.5
	5%	9.8	14.7	2.42	3.09	3.80	4.28	5.5	6	8	14	19.5
	7.5%	12.5	18.75	2.20	2.87	3.58	3.92	5	6	8	14	19

*: D4 is the depth of the subgrade top layer that has been stabilized with cement.

3.4 Cost for pavement layers and stabilization with constant base and subbase thickness

The new design with constant base and subbase thickness is more economical and has high percentages of cost reduction. According to Table 9, the percent of cost reduction has increased as the cement content was increased, which resulted in a higher CBR values of the stabilized layers. This was the case for the three types of soils used in this study.

Tab. 9. Cost analysis for pavement design and soil stabilization with constant base and subbase thickness

Soil sample	Percentage of cement %	Pavement Layers thickness (D in inch)				Cost of soil stabilization USD/m2	Cost of pavement layers USD/m2	Total cost USD/m2	Reduction percent in cost %
		D1	D2	D3	D4				
Ajloun soil	Zero %	6	6	8	-	-	25.14	25.14	-
	2.5%	5.5	6	8	14	0.64	22.15	22.79	9.34%
	5%	4.5	6	8	14	1.29	20.73	22.02	12.41%
	7.5%	4	6	8	14	1.93	15.88	21.82	13.21%
Amman soil	Zero %	7.5	6	8	-	-	30.65	30.65	-
	2.5%	6	6	8	14	0.64	26.71	27.35	10.76
	5%	5	6	8	14	1.29	25.39	26.68	12.95
	7.5%	4	6	8	14	1.93	24.57	26.5	13.53
Irbid soil	Zero %	8.5	6	8	-	-	34.46	34.46	-
	2.5%	6.5	6	8	14	0.64	30.76	31.4	8.87
	5%	5.5	6	8	14	1.29	29.37	30.66	11.0
	7.5%	5	6	8	14	1.93	28.27	30.2	12.36

3.5 Use of RAP

Furthermore, the study also considered using RAP to further reduce the cost of pavement using recycled asphalt pavements of percentages 15, 25 and 50%.

It was found that combining RAP with soil stabilization was cost-effective, with reduction rates ranging from 9.3 % to 33.7 % as shown in Table 10 and Figures 3 - 5. Also, when the RAP and stabilization percentages increase, the cost reduction increases directly. The highest cost reduction was in Ajloun soil (Figure 3) by using 50% RAP with 7.5% cement stabilization.

Generally, the higher the RAP content, the lower the production cost, and the higher the cement percentage, the higher the

resilience modulus, which reduces the required thickness, resulting in the cost reduction.

Tab. 10. Cost Reduction due to the combined effect of soil stabilization and RAP

RAP%	0%	15%	25%	50%
Un-stabilized 0%Ajloun	0.00	11.5	16.0	25.1
Stabilized 2.5% Ajloun	9.3	16.3	21.3	30.3
Stabilized 5% Ajloun	12.4	19.5	**24.3**	33.2
Stabilized 7.5% Ajloun	13.2	20.0	24.7	33.7
Un-stabilized 0%Amman	0.00	6.8	16.2	25.1
Stabilized 2.5% Amman	10.7	17.4	22.1	30.9
Stabilized 5% Amman	12.9	19.4	**24.3**	33.1
Stabilized 7.5% Amman	13.5	20.2	24.9	33.6
Un-stabilized 0%Irbid	0.00	7.7	13.1	24.8
Stabilized 2.5% Irbid	8.8	15.3	20.2	29.0
Stabilized 5% Irbid	11.0	17.7	**22.1**	31.0
Stabilized 7.5% Irbid	12.3	18.8	23.6	32.2

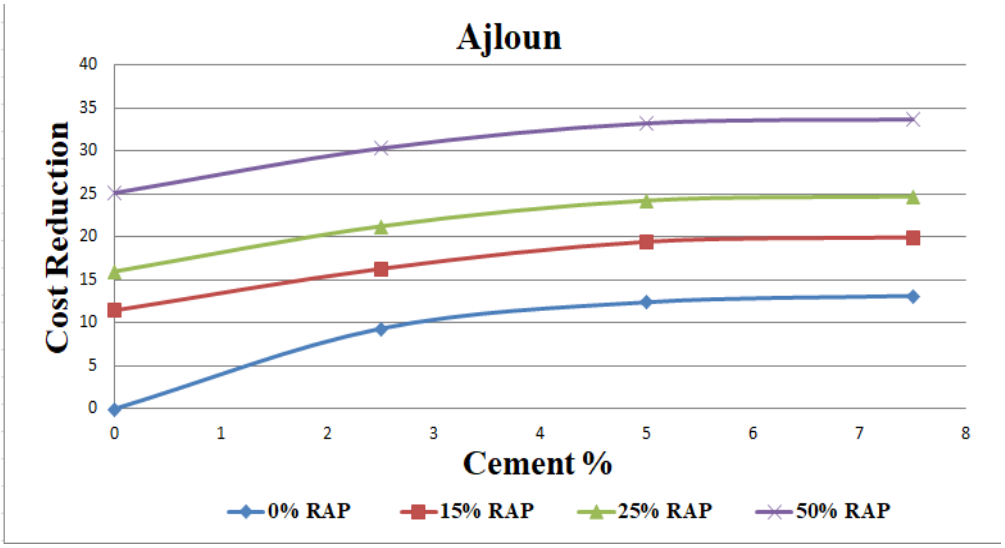

Fig. 3. Cost reduction vs. cement % for Ajloun soil with each RAP%

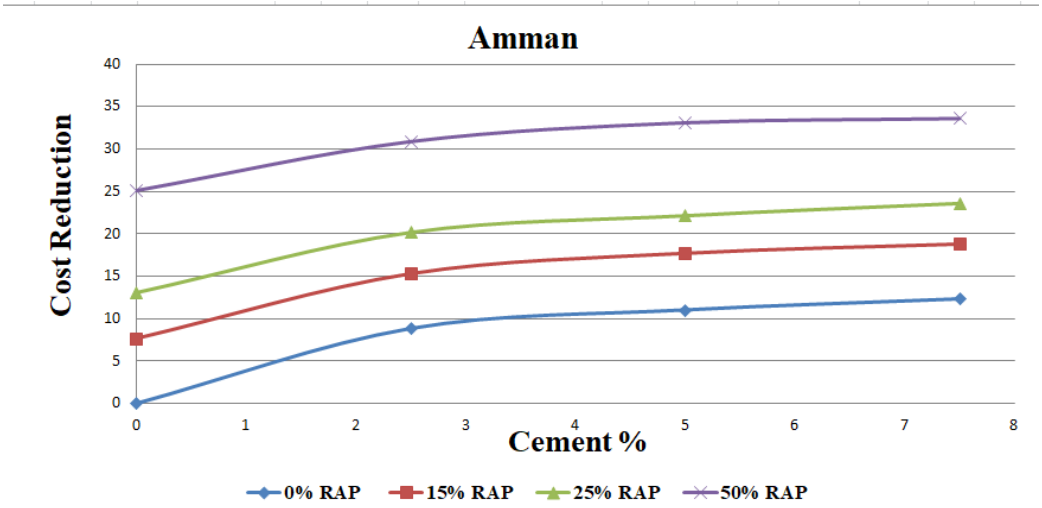

Fig. 4. Cost reduction vs. cement % for Amman soil with each RAP%

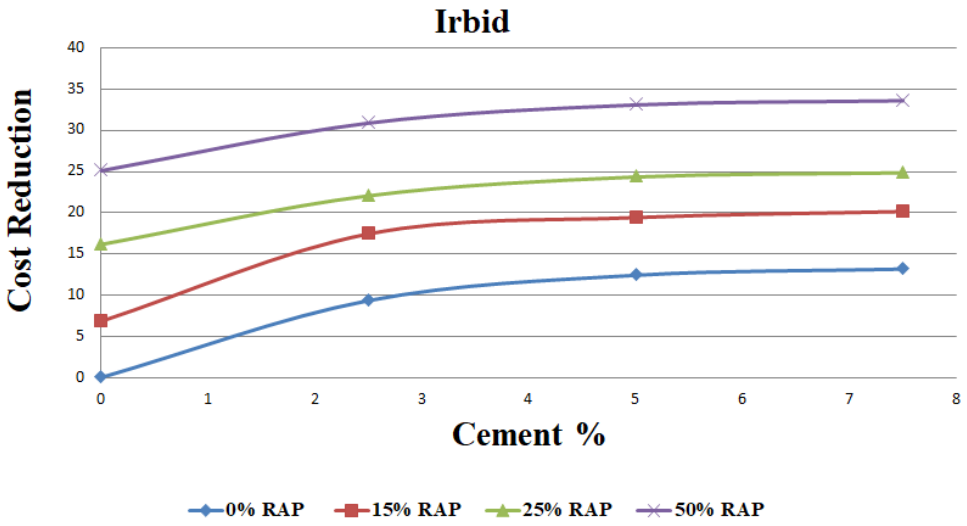

Fig. 5. Cost reduction vs. cement % for Irbid soil with each RAP%

4. Conclusion

This study investigated the effect of subgrade soil stabilization along with the inclusion of recycled asphalt pavement (RAP) on the construction cost of flexible pavements. The effect of soil stabilization was measured through enhancing the CBR values of the stabilized soils, which manifest itself in reduction of the required pavement layers as per the AASHO pavement design.

The results showed that the soil CBR values increased as the cement content increased in the range of 3-7 % cement content. The results also showed that higher RAP content results in higher cost reductions.

However, since the mix performance was not investigated, a RAP content of 25% is recommended as an optimum. Besides, the cost reduction did not increase significantly between 5% and 7%, hence, the results suggest a recommended optimum values of 5% cement content along with 25% RAP content.

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