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Full-Depth Reclamation Method for Rehabilitation of Streets Pavement in City of Sirjan: Mix Design and Bearing Capacity

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ABSTRACT

This paper aims to evaluate the full-depth reclamation (FDR) technique for the improvement of urban streets in the city of Sirjan from a technical standpoint. Also, experimental results of soil-reclaimed asphalt pavement (RAP) blend stabilized with Portland cement has been represented. The experimental program of this research includes two phases. The first phase includes geotechnical investigation of different pavement layers for assessment of the quality of existing materials and estimation of a structural number of existing pavements, and the second phase includes determination of optimum mix design for the recycled layer (stabilized soil-RAP blend). To this end, unconfined compressive strength and density tests were conducted on several soil/RAP ratios of 100/0, 80/20, 60/40, and 40/60. For each blend, different percentages of Portland cement were mixed to soil/RAP blends and cured for 7 and 28 days. Results showed that by adding RAP to virgin soil, unconfined compression strength and optimum moisture content of stabilized samples decrease. Furthermore, the addition of Portland cement to the mixture increases compressive strength and decreases optimum moisture content. The results of this study also show the significant ability of FDR to increase the structural number of distressed pavements.

Keywords: Full-Depth Reclamation (FDR), Portland cement, Reclaimed Asphalt Pavement (RAP), USC

1. INTRODUCTION

In asphalt, pavements require rehabilitation at the end of design life. Regarding the cost of reconstruction and the cost of transporting and storing removed pavement materials, paying attention to recycling techniques for asphalt pavements has been increasingly considered by transportation agencies .Pavement recycling techniques have well-recognized financial and environmental benefits. Full-depth reclamation (FDR) is a technology used for pavement rehabilitation. In this method, the existing asphalt layer and aggregate materials below it are pulverized and treatment with an additive [1]. In the past, hot mix asphalt (HMA) overlay was usually used to improve the condition of distressed pavements, without any respect to the pavement condition and the type of distresses .Over time, due to the limitations of traditional rehabilitation methods, other methods such as cold recycling, hot recycling, and full-depth reclamation methods were proposed [2]. In the cold and hot recycling methods, only asphalt layer is reused and recycled, and then an HMA layer is placed on it as a surface layer. The method of full-depth reclamation is different from the two previous methods because in the FDR method, the whole of the HMA layer and a portion of the aggregates underneath it are recycled to form a stabilized base layer [1]. The goal of the full depth reclamation method is to create a stabilized base layer. At first, if the thickness of the asphalt is more than 10 cm, it should be grinded and removed by milling machines. Then, Wirtgen Recycler WR 2500 pulverizes asphalt pavement and the aggregate layer underneath it. After that, the suitable stabilizer is sprayed on the mixed materials (Portland cement in this study). With the second pass of the Wirtgen machine, the Portland cement is thoroughly mixed with the previously crushed material. At this stage, also with the help of a tanker attached to the Wirtgen machine, the optimum moisture content for mixing is provided. In the end, the stabilized layer is compacted by Sheepsfoot as well as steel wheel rollers. The final product of FDR is a stabilized base layer, consisting of RAP and aggregate materials, which are stabilized by Portland cement. Full-depth reclamation technology is proposed for pavements with critical distresses. Hot recycling and cold recycling are two other technologies that are used for pavements with better conditions .In other words, for distressed pavements with good bearing capacity, hot and cold recycling are more logical than FDR [3]. In cases where the structural number (SN) of the existing pavement is low, and bearing capacity has been decreased due to structural damage, a full-depth reclamation is a good option in order to increase the bearing capacity and to resolve structural damages [3]. The full-depth reclamation reduces costs between 25% and 50% compared to traditional pavement reconstruction methods [4]. FDR has been prosperously used by several transportation agencies such as Nevada [5 & 6], Utah [4] and Texas [7] and has the following benefits [4, 8-10]:

- Eliminating the deep distresses of pavement.
- In this kind of rehabilitation, existing asphalt concrete materials and underlying layers are reused and do not need to be deposited.
- FDR is an environmentally friendly method.

To increase the strength of pulverized materials in FDR method, three types of additives are used for stabilization, including mechanical additives such as virgin aggregate, chemical additives such as Portland cement and calcium chloride, and bituminous additive like emulsions [2]: Selecting proper stabilizer depends on price, availability, and effectiveness [11]. Taha et al. (2002) investigated the influence of RAP and Portland cement on the UCS of the soil/RAP blends stabilized with Portland cement. They found that decreasing the proportion of RAP or increasing the content of cement in the blend increases UCS, maximum dry density, and optimum moisture content. Also, they stated that the mixture of soil and RAP stabilized with Portland cement is able to be used as a base course [8].Yuan et al. (2011) investigated the mixture of RAP/base stabilized with cement as additive. A linear relationship between the content of Portland cement and UCS was proposed by them, and they stated that the UCS increases with increasing cement content [10].Yang and Wu found a considerable correlation between UCS, RAP, and cement. They showed that by increasing RAP content, UCS increases a little at first, and then it lessens. They found that, in high cement percentages (1.5, 2 and 2.5 Percent), UCS reduces by increasing RAP content [12].Full-depth reclamation is a cost-effective and environmentally friendly technology. This method has been used since 2014 in the Kerman state (Iran- Kerman- Sirjan) to improve the distressed pavements. The present study consists of two parts. The first part examines the appropriateness of the FDR method for rehabilitation of streets pavement in the city of Sirjan. In this part, after the geotechnical investigation of existing pavements layers, the structural number was estimated before and after FDR implementation for Sirjan streets. Then the positive effect of FDR has been investigated. The purpose of the second part is to determine the optimal percentage of Portland cement according to the percentage of RAP and aggregates.

2. MATERIALS AND METHODS

2.1. ASSEMNET OF EXSITING PAVEMENTS

In the present study, four streets, including Qods street, Nasiri jonobi street, Meqdad street, and Ebnesina street, were candidate for rehabilitation activities. Due to heavy traffic and severe environmental conditions, several types of pavement distresses were observed, including alligator cracking, block cracking, rutting, longitudinal joint cracks, reflective cracking, polished aggregate, and Potholes**.** Figure 1 shows some of these distresses. In most cases, the severity level of distresses was evaluated as medium to a high level.

Figure 1. Some of the pavement failures on Sirjan streets.

2.2. GEOTECHNICAL EXPLORATION

In each direction of the street, a borehole was drilled (two boreholes for each street). Boreholes showed that on all the streets, a layer of aggregate material is located between the subgrade and the asphalt concrete layer (Figure 2). The thickness of the asphalt concrete layer for each borehole is shown in Table 1. It is seen that the minimum and the maximum thickness of the asphalt layer is between 9 and 18.5cm.

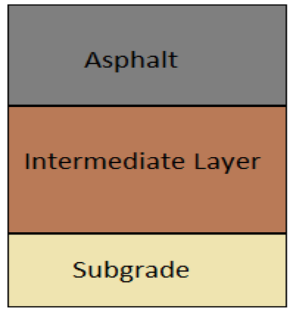

Figure 2. Cross section of streets pavement in the city of Sirjan.

In this study, routine geotechnical tests including soil classification (ASTM D-2487, AASHTO T-234), modified proctor compaction test (ASTM D-180), Atterberg limits (ASTM D-4318), sand equivalent value test (ASTM D-2419), and soaked CBR test (ASTM D-1883) were conducted to evaluate aggregate materials of the intermediate layer and subgrade soil. Table 2 shows the results of the experiments performed on the subgrade soil. As evidence, according to the classification of AASHTO, all subgrade soils are classified as A-2. In other words, the subgrade is mainly sand with clay or silt.

Table 1. Thickness of the asphalt concrete layer.

Location	number of borehole	Thickness of asphalt concrete layer (cm)
Qods Street	1	14
Qods Street	2	18.5
Nasiri jonobi Street	3	9
Nasiri jonobi Street	4	10
Meqdad Street	5	14
Meqdad Street	6	14.5
Ebnesina Street	7	11.5
Ebnesina Street	8	13.5

Table 2. Geotechnical properties of subgrade soil.

Street Name	Borehole #	ASTM classification	AASHTO classification	LL	PI	SE	Optimum Moisture (%)	Maximum Dry Density (gr/cm3)	Soakd CBR
Qods	1	SC	A-2-4	29	9	18	8.2	2	17
Qods	2	SC	A-2-6	32	11	20	9.5	2.08	17
Nasiri jonobi	3	SM	A-2-4	24	NP	17	8.8	2.13	18
Nasiri jonobi	4	SM	A-2-4	22	NP	18	10.7	2.05	18
Meqdad	5	SC	A-2-6	30	10	14	10.4	2.1	22
Meqdad	6	SC-SM	A-2-4	26	7	12	11.6	1.98	21
Ebnesina	7	SM	A-2-4	21	NP	24	11.6	1.97	19
Ebnesina	8	SC	A-2-6	29	8	20	8.9	2.07	19

NP: Non-plastic

Table 2 shows that the plasticity index (PI) is between 7 and 11 with an average of 9, except in boreholes 3, 4, and 7. Also, the liquid limit (LL) is between 21 and 32, with an average of 27. Table 2 also shows that the sand equivalent (SE) value for subgrade is between 12 and 24, with an average of 18. Modified proctor compaction test shows that the minimum optimum moisture content of subgrade soil is 8.2% for borehole #1 and the maximum optimum moisture content is 11.6% for boreholes #6 and #7. The maximum dry density (γ_d) is between 1.97 and 2.13 gr/cm^3 with an average of 2.05 gr/cm^3. Since the soaked CBR values range from 17 to 22, the soil quality as subgrade can be defined as medium to good. The intermediate layer is located between the subgrade and the asphalt concrete layer. Table 3 shows the material characteristics of the intermediate layers. As can be seen, the thickness of the intermediate layer is between 10 and 26.5cm and in terms of gradation; it can be classified as A-1, except for boreholes #1 and #8, which are classified as A-2. Table 3 also shows that the liquid limit is between 21 and 41 (except for borehole #7) with an average of 25 and sand equivalent is between 19 and 47 with an average of 27. The intermediate layer has less liquid limit and more sand equivalent value in comparison with subgrade soil.

Table 3. Experimental results for intermediate layer.

Street Name	Borehole #	thickness (cm)	Classification Unified	Classification AASHTO	LL	PI	SE	Optimum Moisture (%)	γd (gr/cm3)	Sc1
Qods	1	17	GP-GC	A-2-4	29	8	35	6.2	2.22	65
Qods	2	20	GW-GM	A-1-b	24	NP2	28	5.8	2.22	64
Nasiri jonobi	3	21	SM	A-1-b	21	NP	24	6.3	2.22	47
Nasiri jonobi	4	10	GP-GM	A-1-b	22	NP	27	6.1	2.2	72
Meqdad	5	16	SM	A-1-b	24	NP	20	6.8	2.17	58
Meqdad	6	16.5	GM	A-1-b	26	NP	21	5.6	2.27	61
Ebnesina	7	12.5	SP-SM	A-1-b	NI3	NP	47	4.3	2.23	56
Ebnesina	8	26.5	GP-GC	A-2-7	41	19	19	5.9	2.23	68

1-Soaked CBR, 2-Non-Plastic, 3-Non-Limit

Modified proctor compaction test shows that the optimum moisture content for the intermediate layer is between 4.3 and 6.8%, and also the maximum dry density is between 2.17 and 2.27 gr/cm^3. The lowest soaked CBR for the intermediate layer is 47%, and its maximum value is 72%. Generally, the CBR value for the intermediate layer is greater than the subgrade.

2.2.1. Specifications of Intermediate layers as aggregates subbase

According to Iran highway asphalt paving code, for construction of the subbase layer, aggregate materials should be in accordance with one of the gradients of type I to IV. Also, other characteristics of subbase materials must be following Table 4. Table 5 presents the results of a comparison of the intermediate layer characteristics and subbase in accordance with Iran Highway Asphaltic Pavements (IHAP). As can be seen, most aggregates which taken from the intermediate layer of Sirjan streets, do not match completely with the gradation limits provided by IHAP for the subbase. In the case of specifications, the sand equivalent is less than the standard, so the materials of the intermediate layer are near to aggregate subbase with little disagreements in SE value and gradation.

Table 4. Specifications of aggregate subbase

	Standard value	AASHTO	ASTM
Plasticity Index (PL)	Maximum 6	T 90	D 4318
Liquid Limit (LL)	Maximum 25	T 89	D 4318
Sand Equivalent	Minimum 30	T 176	D 2419
Soaked CBR	Minimum 30	T 193	D 1883

In general, it can be concluded that the aggregate base has not been constructed, and just a layer with specifications close to the aggregate subbase is built up directly under the HMA layer.

Table 5. Comparison of intermediate layer materials with standard aggregate subbase according to IHAP.

number of borehole	Compare with subbase grading	Compare with standard subbase values
1	Close to grading type III	near to subbase value with little disagreements in LL and PI
2	Close to grading type III	near to subbase value with little disagreements in sand equivalent value
3	Close to grading type III with slight differences in # 40 and # 10 sieves	near to subbase value with little disagreements in sand equivalent value
4	Close to grading type II	near to subbase value with little disagreements in sand equivalent value
5	Close to grading type III with slight differences in # 40 and # 10 sieves	near to subbase value with little disagreements in sand equivalent value
6	Close to grading type III with slight differences in # 40 and # 10 sieves	near to subbase value with little disagreements in sand equivalent value
7	Close to grading type III with slight differences in # 40 sieve	Matches with the subbase
8	Close to grading type III	Matches with the subbase

2.2.2. Drainage Coefficient for Intermediate Layer

In order to determine the drainage quality of the intermediate layer, the drainage time (t_{50}) should be calculated. t_{50} is equal to the time required to drainage 50% of the water enter into the layer, which is in terms of the day. This parameter can be computed using the following equations:

$$t_{50} = \frac{n_0 \times L^2}{2K(H + LS)} \qquad (1)$$

$$n = 1 - \frac{\gamma_d}{G_s \times \gamma_w} \qquad (2)$$

where n_0 is the effective porosity and its value is equivalent to 80% of the porosity of the soil (n); L is drainage path length (cm), H is the thickness of the layer (cm), K is coefficient of permeability of soil (cm/day), and S is the lateral slope of the layer. In this study, L and S were measured as 7m, and 3%, respectively. To calculate the coefficient of permeability, Chapuis (2004) proposed an empirical relationship for K as follows [13]:

$$K(cm/s) = 2.4622(D_{10}^2 \times \frac{e^3}{1+e})^{0.7825} \qquad (3)$$

where D_{10} is the effective size (mm), and e is the void ratio. This equation is valid for sand and gravel. After determining t_{50} , Table 6 is determined the drainage quality for the intermediate layer of each street according to IHAP.

Table 6. Drainage quality for the intermediate layer

t50	drainage quality
2 hours	excellent
1 day	good
1 week	fair
1 month	poor
Non-drainage	very poor

Table 7 shows the drainage coefficients for the intermediate layer. As can be seen, drainage quality is poor in most cases. The drainage coefficient is determined according to the drainage quality and climate conditions of the area. According to IHAP, if the annual precipitation is less than 250 mm, the area is considered arid. The maximum annual precipitation in Sirjan was 179.1 mm between 2011 and 2014. IHAP states that the drainage coefficient in the arid area is 1.15, 0.975 and 0.95 according to drainage quality of fair, poor and very poor, respectively.

2.3. STRUCTURAL NUMBER OF PAVEMENT SECTIONS BEFORE FDR

Equation (4) was employed to calculate the structural number of the pavement sections [14].

$$SN = \frac{1}{2.5}(a_1 D_1 + a_2 m_2 D_2 + a_3 m_3 D_3) \quad (4)$$

where a_1, a_2, and a_3 denotes layer coefficients for asphalt concrete layer, base layer and subbase layer, respectively; m_2 and m_3 denotes drainage coefficients for base and subbase layers, respectively, and D_1, D_2, D_3 denotes the thickness of asphalt concrete layer, base layer and subbase layer in cm, respectively.

Table 7. The drainage coefficients for the intermediate layer.

Borehole #	t50 (days)	drainage quality	drainage coefficient
1	23	poor	0.975
2	13	fair	1.15
3	25	poor	0.975
4	25	poor	0.975
5	26	poor	0.975
6	46	poor	0.975
7	46	poor	0.975
8	7	very poor	0.95

As stated, the intermediate layer has characteristics close to the subbase materials. With respect to the absence of the base layer, D_2 was assumed zero. The value of a_1 was determined according to the severity of the HMA layer damages .Due to the high severity of HMA layer damages, the value of a_1 was considered as 0.1. Also, a_3 was calculated according to the CBR of the intermediate layer. Table 8 shows the calculation of the structure number (SN) for each borehole. According to Table 8, the average structural number is 1.44. The low structural number along with the low quality of drainage indicates that the bearing capacity of the existing pavements is low, and they require structural improvement.

Table 8. Structure number of existing pavements.

number of borehole	a1	a3	m3	D1	D3	SN
1	0.1	0.129	0.975	14	17	1.42
2	0.1	0.128	1.15	18.5	20	1.92
3	0.1	0.124	0.975	9	21	1.38
4	0.1	0.132	0.975	10	10	0.91
5	0.1	0.126	0.975	14	16	1.34
6	0.1	0.128	0.975	14.5	16.5	1.4
7	0.1	0.126	0.975	11.5	12.5	1.07
8	0.1	0.1278	1.15	13.5	26.5	2.097

2.4. TECHNICAL COMPARISON OF VARIOUS REHABILITATION OPTIONS

Three common methods for rehabilitation of pavements with structural deficiencies are reconstruction, HMA overlay, and recycling. The pavement recycling method includes cold recycling, hot recycling, and full-depth reclamation. According to hot mix asphalt recycling general technical specifications of Iran, for the use of hot recycling, the pavement must have sufficient bearing capacity. Also, hot recycling may not be used in urban area because of environmental issues. In addition, for hot recycling, the thickness of the HMA layer should not show high variability along with the project, which is not consistent with streets condition in Sirjan. According to cold mix asphalt recycling general technical specifications of Iran, application of cold recycling method for Sirjan streets is not possible due to the following reasons:

- High severity of rutting and patching
- High severity of alligator and block cracking
- Deficiencies of pavement drainage

Full-depth reclamation is able to solve the structural problems of pavement and is environmentally friendly. Therefore, it is more suitable than other recycling methods for the rehabilitation of Sirjan streets. In addition to the different recycling methods, an alternative solution is HMA overlay. This option is not effective where the pavement has not a sufficient bearing capacity. As mentioned before, Sirjan streets do not have enough bearing capacity, and the HMA overlay is not a suitable choice. On the other hand, FDR technology reuses RAP materials and is very suitable for the urban area because it does not increase the total thickness of the pavement, which can be a problem in urban areas.

2.5. MIX DESIGN FOR FDR MATERIALS

2.5.1. Materials

The aggregate material was obtained from the intermediate layer. The aggregate material was classified as SP-SC and non-plastic with the sand equivalent of 28. According to the IHAP, the gradation of this soil was very close to subbase materials except for percent passing from #40 and #10 sieves. Reclaimed asphalt pavement was collected from a street using Wirtgen recycler WR 2500. The RAP classification was SP category and non-plastic. Water absorption (ASTM C127) and percentage of bitumen (ASTM D- 2172) was determined as 4.5% and 2.34%, respectively. Figure 3 illustrates the gradation curve for RAP and SP-SC soil. Portland cement type II was used in this study.

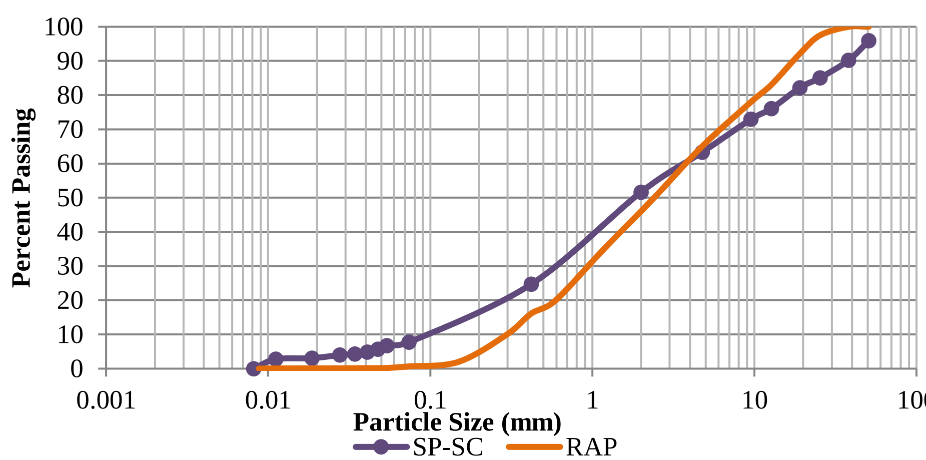

Figure 3. Particle size distribution for SP-SC and RAP.

2.5.2. Fabrication and curing of samples

In order to remove the moisture, RAP materials and SP-SC soil were dried at room temperature 72 hours before the test. According to previous studies and thickness of asphalt on Sirjan streets, different RAP/soil ratios (0/100, 20/80, 40/60, and 60/40) were stabilized with 3, 4, 5, and 6 percent of portland cement. In the primary step, OMC[1] and MDD[2] were determined according to ASTM D-180-C. The diameter and height of the mould were 101.16 and 116.43 mm, respectively. The mixture of soil and RAP was compacted in 5 layers, and each layer was compacted by 56 blows. In order to cure, the specimens were placed in plastic bags after 24 hours (Figure 4). According to ASTM D1633, the UCS tests were carried out on specimens a loading rate of 1 mm/min after 7 and 28 days of curing. To increase the accuracy of measurement, two samples were made for each curing time (7 and 28 days). In other words, UCS has been the average of two values at any curing time.

Figure 4. Sample cure in plastic bag.

3. RESULTS AND DISCUSSION

3.1. MODIFIED PROCTOR TEST

Figures 5 and 6 demonstrate OMC and MDD variations versus Portland cement for various percentages of RAP, espectively.

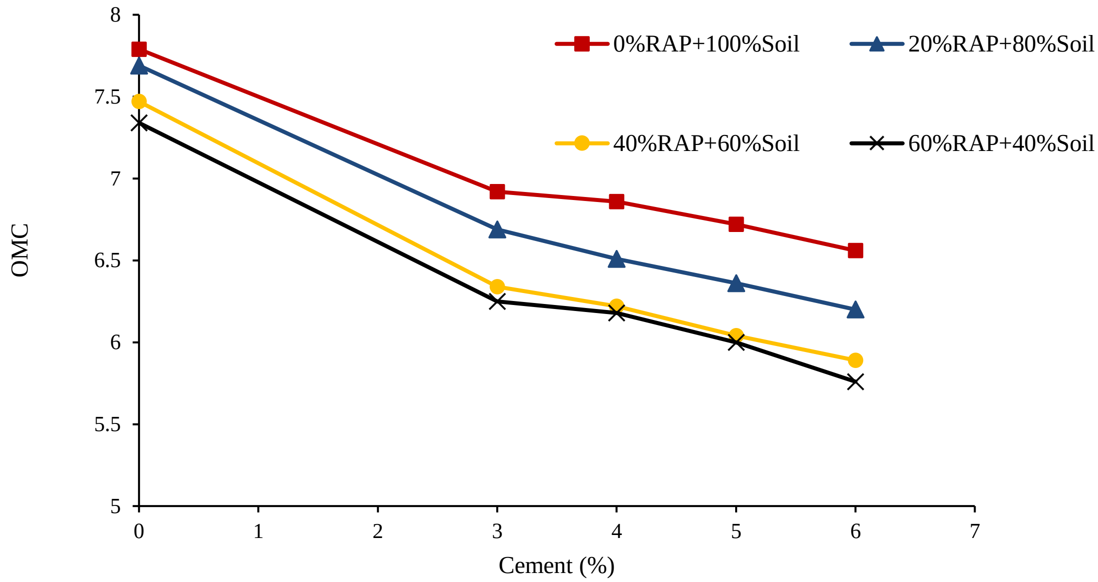

Figure 5. OMC for different blends of RAP/soil treated with cement.

[1] optimum moisture content

[2] maximum dry density

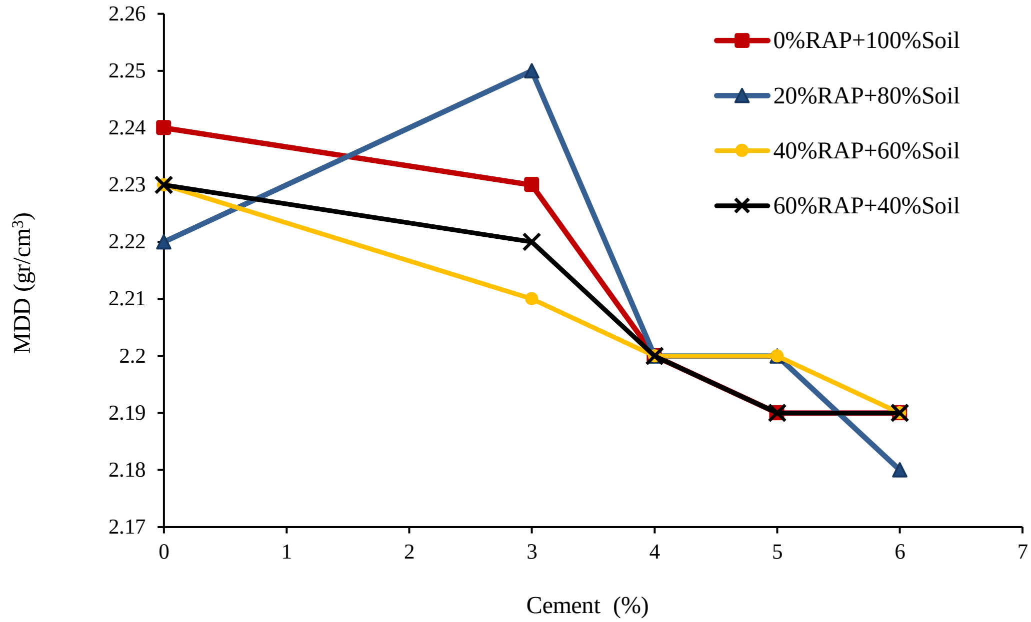

Figure 6. MDD for different blends of RAP/soil treated with cement.

It is observed that MDD and OMC values decrease with increasing cement in a constant RAP to soil ratio. Only in 20% of RAP, MDD increases by increasing cement content from 0 to 3%. Several prior types of research have been concluded that in a constant RAP/soil ratio, by increasing the Portland cement, OMC, and MDD increases (8, 10). On the other hand, researchers in some other studies did not get an indication tendency for MDD and OMC by increasing cement content [15, 16]. OMC was reduced by increasing cement in mixtures. This was due to an increase in the specific surface of soil due to the greater degree of flocculated soil structure by increasing cement. Fig 8 illustrates that in constant cement content, the OMC was decreased by increasing RAP content. In fact, lower water absorption occurs with increasing bitumen-coated particles. This is consistent with a number of past studies [8, 10, 17]. As shown in Figure 5, the OMC reduction rate in a constant RAP/soil ratio is approximately equal for different RAP values with increasing cement.

3.2. UNCONFINED COMPRESSIVE STRENGTHS

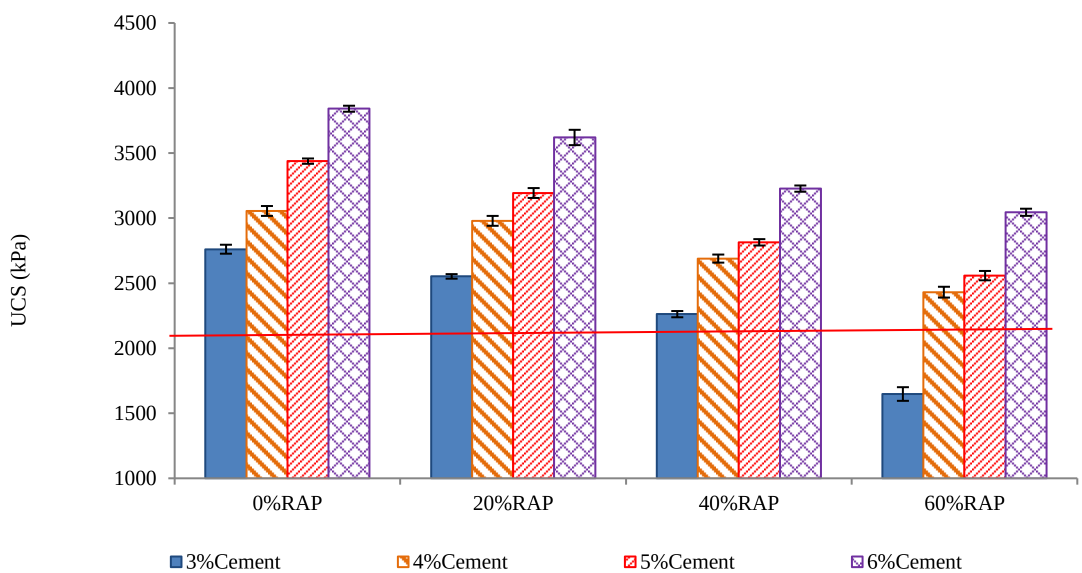

Figure 7. UCS for different blends of RAP/soil treated with cement (7-days).

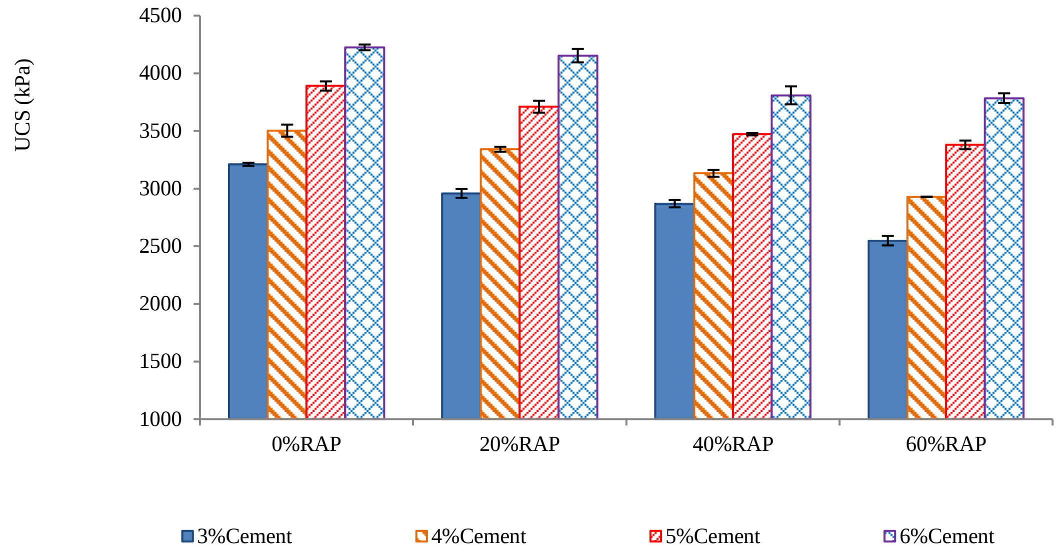

Figure 8. UCS for different blends of RAP/soil treated with cement (28-days).

Figures 7 and 8 show UCS (7 and 28 days) for the blend of RAP/SP-SC soil treated with several percentages of cement. UCS was captured from the apex of the stress-strain curve and is the average of two tests. As you can be seen, in a constant RAP to soil ratio, by increasing the cement content, the UCS increases for treated materials. In other words, increasing RAP leads to reducing UCS, while cement is fixed. The cause for this decrease is that the friction among the aggregates is reduced by the bitumen. This is consistent with many of the past researches [8, 10, 12, 18, 19] .Figure 8 shows that the rate of increase of UCS versus cement is approximately equal for all different RAP values .Also, the UCS reduction rate is approximately equal for different cement values with increasing RAP .The results also show that by increasing one percent of Portland cement, the strength of the mixture increases by about 10 percent.

3.3. THE OPTIMUM VALUE OF PORTLAND CEMENT

The mixture of RAP and intermediate layer soil is used after stabilization as the base course in Sirjan streets. The UCS (7 days) for the stabilized base course is regarded by many transportation agencies and the Portland cement association to be 2100 kPa [1, 20]. The horizontal line in Fig. 9 shows the UCS of 2100 kPa.

Table 9. Optimum content of Portland cement with respect to RAP to soil ratio.

RAP (%)	Optimum cement content	UCS (kPa)	allowable 7 days UCS (kPa)
0	3	2762	2100
20	3	2551	2100
40	3	2262	2100
60	4	2431	2100

Table 9 shows optimum cement values for the stabilization of various RAP-soil blends. Cement less than 3% is not suitable for treatment soil and RAP. Less than 3% of cement causes inappropriate mixing of aggregate and RAP .The Iranian standard for treatment and manufacturing of Embankment does not recommend less than 3% of Portland cement for stabilization. Therefore, in this research, the minimum amount of cement for stabilization is considered 3%. Table 9 shows the optimum cement value for various RAP-soil percentages.

3.4. BEARING CAPACITY AFTER FULL DEPTH RECLAMATION

In order to determine the effect of FDR method on the bearing capacity of pavement, the allowable number of 18-kip (80-kN) single-axle load applications was determined using the following equation [14]:

$$\log W_{8.2} = Z_R S_0 + 9.36\log(SN+1) - 0.2 + \frac{\log(\frac{\Delta PSI_{TR}}{4.2-1.5})}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log\frac{M_R}{0.07} - 8.07 \quad (5)$$

$W_{8.2}$: Number of 18-kip (80-kN) single-axle load applications

M_R: Resilient modulus (kg/cm^2).

Z_R: Normal deviate for a given reliability R, (-1.282 for R=90%).

S_0: Standard deviation (0.35).

ΔPSI_{TR}: allowable serviceability loose due to traffic loading over the pavement life (1.7).

SN: Structural number.

The California bearing ratio (CBR) for the explored Subgrade soils in the city of Sirjan ranged from 17 to 22%, hence the CBR design value was set to the minimum value of 17%. The equation (6) was used to calculate the structure number after implementing Full Depth Reclamation.

$$SN = \frac{1}{2.5}(a_1 D_1 + a_{FDR} D_{FDR}) \quad (6)$$

Where a_1 and D_1 are Layer coefficient and thickness for asphalt surface layer, respectively. According to IHAP, the layer coefficient of the asphalt surface layer was assumed as 0.44. In addition, the thickness of the asphalt on the stabilized base course was considered 6, 8, 10, and 12 cm. a_{FDR} is the layer coefficient for the stabilized layer. The layer coefficient for the cement stabilized base course in full depth reclamation varies according to the amount of RAP and cement in the stabilized layer. The American Concrete Institute (ACI) suggested the values of layer coefficient for the cement stabilized course between 0.12 and 0.28, with a majority of 0.17 to 0.23 [21]. Diefenderfer and Apeagyei (2011), calculated the layer coefficient for the FDR-stabilized layer, using the FWD. They showed that the layer coefficient changes between 0.18 and 0.33 [22]. In another study, Nantung and Shields (2011), calculated the amount of layer coefficient for the FDR-stabilized course based on the FWD measurements. They stated that the layer coefficient varies from 0.05 to 0.45, and most of the observed values range between 0.15 and 0.3 [23]. Therefore, in the present study, a_{FDR} was considered 0.2, which is the average value obtained by the previous researchers. Also, the thickness of the FDR stabilized base was considered as 15, 20, 25, and 30cm. Table 10 shows the structure number after implementing of full-depth reclamation. As mentioned in Table 8, the average SN for Sirjan streets before the full depth reclamation was 1.44. The SN values in Table (10) confirm the significant improvement of the structural number after rehabilitation using the FDR method. Figure 9 shows the allowable number of 18-kip (80-kN) single-axle load applications based on subgrade CBR and thickness of FDR stabilized base layer. It is observed that by increasing the CBR of the subgrade or increasing the thickness of the stabilized base course, the allowable number of 18-kip (80-kN) single-axle load applications increases.

Table 10. SN after implementing of full depth reclamation.

DFDR(cm) / D1(cm)	15	20	25	30
6	2.30	2.66	3.00	3.50
8	2.60	3.00	3.40	3.80
10	2.96	3.36	3.76	4.20
12	3.30	3.70	4.10	4.50

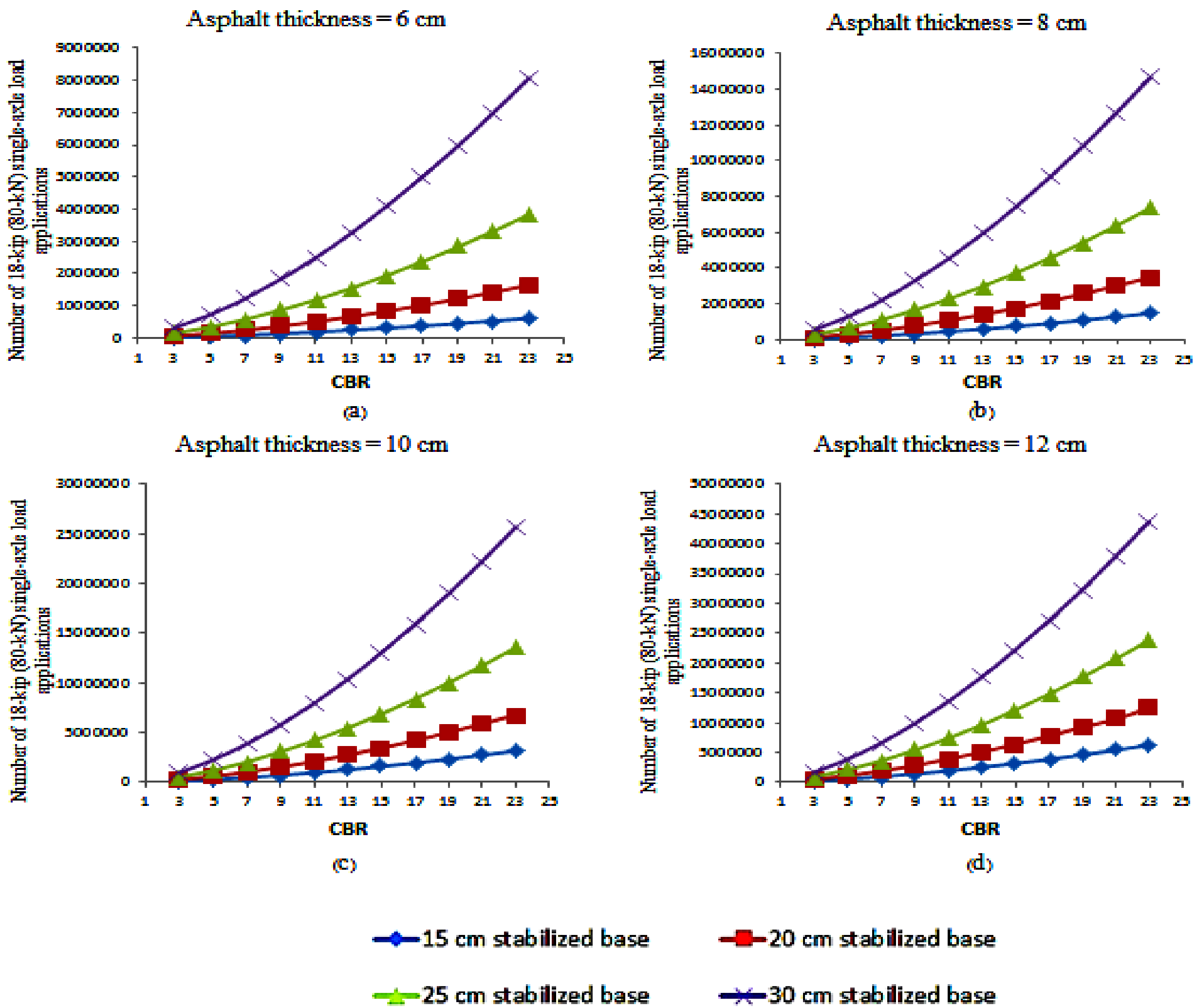

Figure 9. Allowable Number of 18-kip (80-kN) single-axle load applications after rehabilitation using FDR method.

4. CONCLUSION

The results of this research can be summarized as follows:

1. For the evaluated pavements in the city of Sirjan, there was a layer with characteristics close to the aggregate subbase under the asphalt concrete layer. Field and geotechnical investigations showed that pavements in the city of Sirjan have low bearing capacity, poor drainage, and high surface distressed.

2. Among several in-place recycling methods (cold and hot in-place recycling), only FDR can solve the pavement problems deeply, and also, it is environmentally friendly.

In the FDR method, by increasing the cement in the stabilized base course, the amount of optimum moisture content and the maximum dry density were decreased, except for the 20% RAP. In fact, for the 20% RAP, by increasing the cement from 0 to 3%, the maximum dry density increased. Increasing RAP also reduces the optimum moisture content.

In a constant RAP to soil ratio, increasing cement content in the stabilized base course increases the unconfined compressive strength (UCS). Increasing RAP also reduces UCS.

With respect to the minimum allowable unconfined compressive strength (2100 kPa), the optimum Portland cement content for the stabilization of the FDR layer was determined as 3 to 4 percent.

The average structural number of existing pavements was estimated about 1.44, which shows the low bearing capacity of existing pavements. The structural number ofter application of FDR was determined between 2.3 to 4.5, depending on the thickness of asphalt concrete and FDR layers.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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