THE STRUCTURAL COEFFICIENT OF FULL-DEPTH RECLAMATION LAYER

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الملخص

يتم إستخدام الرصف الإسفلتي القديم والمتهالك كركام في خلطات إعادة تدوير الرصف على البارد. والطريقة الأكثر شيوعا في هذا الشأن تشتمل على عملية يتم فيها إعادة تدوير الرصف القديم في الموقع على البارد، حيث يتم خلط كامل طبقات الرصف الإسفلتي القديم وجزء من طبقة الأساس الحبيبي مع البيتيومين الرغوي والإسمنت بدون تسخين لإنتاج خلطة باردة جديدة تستخدم كطبقة أساس.

لا يوجد دوليا قيم معتمدة للمعامل الإنشائي لخلطات الرصف المعاد تدويرها على البارد وبالرغم من أن القدرة الإنشائية لخلطات الرصف المعاد تدويرها على البارد تعتبر مكافئة للقدرة الإنشائية للخلطات الإسفلتية التقليدية الباردة فإنها إنشائيا لا تكافئ الخلطات الإسفلتية الساخنة ولكنها متفوقة إنشائيا على الأساس الحبيبي التقليدي، ويستخدم المعامل الإنشائي لحساب الرقم الإنشائي للرصف والمطلوب لتصميم سمك طبقات الرصف.

أستخدم في هذه الدراسة معيار انفعال الضغط الرأسي في طبقة التأسيس الترابي لحساب المعامل المكافئ والمعامل الإنشائي باستخدام برنامج حاسوب الكنلير (KENLAYER). حيث تم حساب انفعال الضغط في طبقة التأسيس الترابي لقطاع رصف نموذجي قريب جدا من القطاع المستخدم بالطرق الرئيسية في ليبيا لإيجاد طبقة إسفلتية ساخنة سمكها 6 بوصة (150 ملم). المعامل المكافئ هو النسبة بين سمك طبقة إعادة التدوير وسمك الخلطة الإسفلتية الساخنة. تم إجراء هذا العمل لمختلف قيم معامل المرونة لطبقة إعادة التدوير ولمختلفٍ درجات الحرارة والتي تعنى مختلف قيم معامل المرونة للطبقة الإسفلتية الساخنة، كما تم أيضا مقارنة العلاقة الناتجة من هذه الحسابات بين معامل المرونة لطبقة إعادة التدوير والمعامل الإنشائي بالعلاقة الإمبريقية المحافظة جداً والمبنية على العامل الإنشائي (0.14) ومعامل المرونة 207 ميجابسكال (30000 باوند/البوصة المربعة) لطبقة الأساس الحبيبي.

$M_R = 30{,}000(a_i/0.14)^3$

وجد أنه لا يمكن التنبؤ بقيمة محددة للمعامل الإنشائي ولكن يمكن تحديد مجال ضيق له قيمته القصوى تحدد عن طريق معيار انفعال الضغط و قيمته الدنيا تحدد عن طريق المعادلة الإمبريقية السابقة الذكر كما يمكن تحديد قيمة وحيدة معقولة للمعمل الإنشائي داخل هذا الإطار الضيق عن طريق الخبرة الهندسية ومن خلال معرفة مستويات خبرة المنفذ ومستويات مراقبة الجودة. الطريقة التي استخدمت لإيجاد المعامل الإنشائي أثبتت جدواها من خلال تطبيقها على حالة دراسية.

ABSTRACT

Reclaimed asphalt pavement is used as an aggregate in the cold recycling of asphalt paving mixtures. The more common method involves a process in which the asphalt pavement is recycled in-place (cold in-place recycling), CIPR. Where the reclaimed asphalt pavement is combined without heat with foamed bitumen and cement and mixed at the pavement site, at full- depth to produce a new cold mix end product.

There are no universally accepted structural coefficient values for cold in-place recycled mixes (CIPR). Even though, the structural capacity of CIPR mixes considered equal to that of conventional cold mix paving material, it is not the structural is equivalent to hot mix asphalt (HMA), but is superior to gravel or crushed stone base course. The structural layer coefficient is used to calculate the structure number (SN) needed for the design of layer thicknesses. In this study, the maximum vertical compressive strain on the top of the subgrade layer was used to calculate the equivalency factor and the structural coefficient. By using the KENLAYER; the elastic layered program, the subgrade compressive strains were calculated for the typical pavement system commonly used for the major highways in Libya to get the thickness of FDR layer that would give the same compressive strain as six inches (150 mm) HMA. The thickness equivalency was taken as the ratio of the thickness of the FDR layer to that of the HMA layer of six-inch (150 mm). This was done for different FDR modulus values and different mean annual air temperatures (MAATs) which imply different resilient modulus values of HMA. As a result a relationship was developed between FDR modulus and FDR structural coefficient for various MAATs which are considered as the upper bound structural coefficient values. The conservative equation: $M_R = 30{,}000(a_i/0.14)^3$ is considered as the lower bound values of structural coefficient. A reasonable single structural coefficient value could be specified within the specified range based on the levels of experience and quality control. A case study is used to verify the developed procedure for the design of pavement structural systems with FDR layers.

KEYWORDS: Cold In-place Recycling; Full-depth Reclamation; Foamed Bitumen; Structural Coefficient; Structural Equivalency Factor.

INTRODUCTION

The full-depth reclamation (FDR), or deep in-sites recycling (DISR), of damaged hot-mix asphalt pavement with foamed bitumen and an active filler (e.g., Portland cement or lime) to provide a stabilized base for a new hot-mix asphalt (HMA) wearing course [1].

The full-depth reclamation (FDR) is defined by the asphalt recycling and reclaiming association (ARRA)as: A pavement rehabilitation techniques in which the full flexible pavement section and a predetermined portion of the underlying material are uniformly crushed, pulverized, adding a stabilizing agent; compacting the mixture, and surfacing with a new bound material layers usually HMA [2].

The depth of FDR layer must be selected as part of the total pavement structural design to support the anticipated traffic loading during the intended design period. To accomplish this, the FDR material must be appropriately characterized. Therefore, an interactive design process is necessary between the structural design of the pavement and the mix design process.

The AASHTO Guide for the design of pavement structures [3] among other Guides across the world uses the structural number (SN) approach for pavement design this approach has a number of advantages, namely design and ability to incorporate local knowledge into designs regarding climate, material behaviors and performance. In addition, new materials can be readily incorporated in the SN approach. For these reasons, the SN approach has been extended to include foamed bitumen stabilize layers. The SN design procedure requires material type and quality to be known for inclusion in a pavement structure. Provided the quality of the material and thickness of each individual layer can be calculated using " structural layer coefficients" assigned to each material type. The overall pavement structure's capacity is calculated as the sum of the products of structural layer coefficients and thickness of the individual layers [4].

Recycling can save energy, pavement materials, reduce greatly emission of greenhouse gas, and reduce costs by more than 30 % [5].The strength of the pavement layers is usually taken into consideration in the design of a pavement by the AASHTO structural coefficient or an equivalency factor. The selection of the correct structural coefficient for each layer will lead to the effective use of the highway funds.

A large amount of research has been conducted to determine the properties of various recycled mixtures, but on the other hand, little research has been directed to the establishment of reliable structural coefficients for those mixtures. Layer coefficients vary considerably with material, binder, and mixing process [6]. A binder that showed promise for use in cold recycling is foamed bitumen. A study of recycling has shown that there is a strong correlation between the structural equivalency of recycled layer and a conventional mixture with the same binder [7] Several studies investigated the mechanical properties of cold recycled mixtures and found out that the modulus of the mixtures after 28 day of cure ranges from 100,000 Psi to slightly above 200,000 Psi (690 MPa To 138 MPa), and suggested structural layer coefficients for cold recycled mixtures ranges from 0.23 to 0.38 [8-13]. A very conservative empirical equation was developed between the modulus of the recycled layer and its structural coefficient [14] based on modulus and structural coefficient of conventional granular base course material:

$$MR = 30{,}000(a_i/0.14)^3 \quad (1)$$

Where: MR = modulus of the recycled layer, in psi

a_i = structural coefficient of the recycled layer

Alternative empirical equation was developed to estimate layer coefficient for cold in-place recycled base course from the resilient modulus [15]:

$$a_i = 0.249(\log MR) -0.977 \quad (2)$$

Equation (2) estimate higher values than equation (1) for the same modulus. Both equations were used to estimate the structural coefficient of full-depth reclamation using fly-ash.

The structural layer coefficients and the structural layer equivalencies are essentially the same. Both relate the strength or performance capability of the pavement material (according to a specific criteria e.g. fatigue or permanent deformation) with that of a material with known performance characteristics usually the HMA for surface mixture used in the AASHTO Road test. The coefficient is given as a proportion of the coefficient determined during the AASHTO Road test. To give the same structural number (SN), the thickness of the layer has to be increased in the same ratio as the coefficient of the layer and the AASHTO hot mix. The structural layer equivalency is given as the thickness of the layer to give the same performance as another layer, usually the AASHTO HMA surface layer.

The coefficient can be defined as:

$$a_{fdr} = \text{coefficient} = (H_{hma}/ H_{fdr})\, a_{hma} \quad (3)$$

$$\text{and the equivalency factor} = (H_{hma}/H_{fdr}) \quad (4)$$

Where H_{hma} = thickness of the standard HMA

H_{fdr} = thickness of the full-depth reclamation material
a_{hma} = structural coefficient of the standard HMA
Structural coefficients or equivalency factors (E.F.) are mostly function of materials modulus and strength.

OBJECTIVES

The main objective of this study was to determine the structural layer coefficient of full-depth reclamation (FDR) layer mixture with foamed bitumen and cement using the permanent deformation criteria and to compare it with that estimated by equations (1) and (2).

The maximum vertical compressive strain on top of subgrade was used to calculate structural coefficients, by using the KENLAYER-layered elastic program. The subgrade strains were calculated for the pavement system commonly used for major highways in Libya to get a thickness of FDR layer that would give the same compressive strain as a six inch (150 mm) HMA. The thickness equivalency was taken as the ratio of the thickness of FDR layer to that of the HMA layer of six inches (150 mm). This was done for different FDR modulus and different mean annual air temperatures which imply different resilient modulus values of HMA. The FDR modulus maybe determined from laboratory tests, or from the AASHTO Design Guide, 1993 empirical equation:

$$M_R = 740 \text{ CBR} \tag{5}$$

ASSUMPTIONS

- ❖ The standard structural pavement system was as shown in Figure(1a) which is composed of 2 inch (50 mm) HMA wearing course, 6 inch(150 mm) HMA binder course, 10 inch (250 mm) granular base course over a subgrade has an effective modulus of resilient of 10,000 Psi (690 MPa).
- ❖ The FDR pavement structural system was as shown in Figure (1b) which is composed of 2 inch (50 mm) HMA wearing course (overlay), FDR layer with variable thickness, 10 inch (250 mm) granular base course over subgrade has an effective modulus of resilient of 10,000 Psi (690 MPa).

HMA Wearing Coarse		**2" (50mm)**
Hot Mix Asphalt Concrete (HMA) Binder Course E=Variable $\mu = 0.40$		**6" (150mm)**
Granular base coarse E=30,000Psi $\mu = 0.35$		**10" (250mm)**
Subgrade E=10,000Psi $\mu = 0.35$		

(a) Standard Structural System

Hot Mix Asphalt Concrete (HMA) E=Variable $\mu = 0.40$		**2" (50 mm)**
Full-Depth Reclamation FDR.Layer E=Variable $\mu = 0.35$		**Variable**
Granular base coarse E=30,000Psi $\mu = 0.35$		**10" (250 mm)**
Subgrade E=10,000Psi $\mu = 0.35$		

(b) FDR Structural System

Figure 1: Pavement Structural System

- ❖ The elastic modulus of the HMA layers was taken as an average value of the following two equations [12]:

E_1= 80,700 $T^{(-1.284)}$ (6)

E_1= 322,000 $T^{(-1.591)}$ (7)

Where: T= mean annual air temperature (MAAT) in (°F). The estimated elastic modulus values and the corresponding structural coefficients for different MAATs are presented in Table (1).

Table 1: Elastic modulus and structural coefficient of the HMA layer for various MAATS

MAAT		E_i		a_i
°F	°C	Psi	MPa	
65	18	400,000	2758	0.4200
70	21	360,000	2482	0.3960
75	24	325,000	2241	0.3750
80	27	295,000	2034	0.3570
86	30	267,000	1841	0.3402

- ❖ The granular base course has fixed elastic modulus value of 30,000 Psi (207 MPa) and a structural coefficient of 0.14, but the FDR layer has variable elastic modulus from 50,000 Psi to 250,000 Psi (345 to 1725 MPa).
- ❖ The Poisson ratio was assumed equals to 0.40 for the HMA layers and equals to 0.35 for the rest of the layers.

PRESENTATION OF RESULTS

Figure (2) shows a sample of the relationships between the FDR thickness and the vertical compressive strain on the top of subgrade layer for HMA modulus of 400,000 Psi (2760MPa) and for FDR layer modulus of 100,000 Psi (690MPa).

From Figure (2), the equivalency factor and the structural coefficient were calculated using equations (3) and (4).The equivalency factors and the structural coefficients for various values of FDR layer modulus are presented in Table (2).

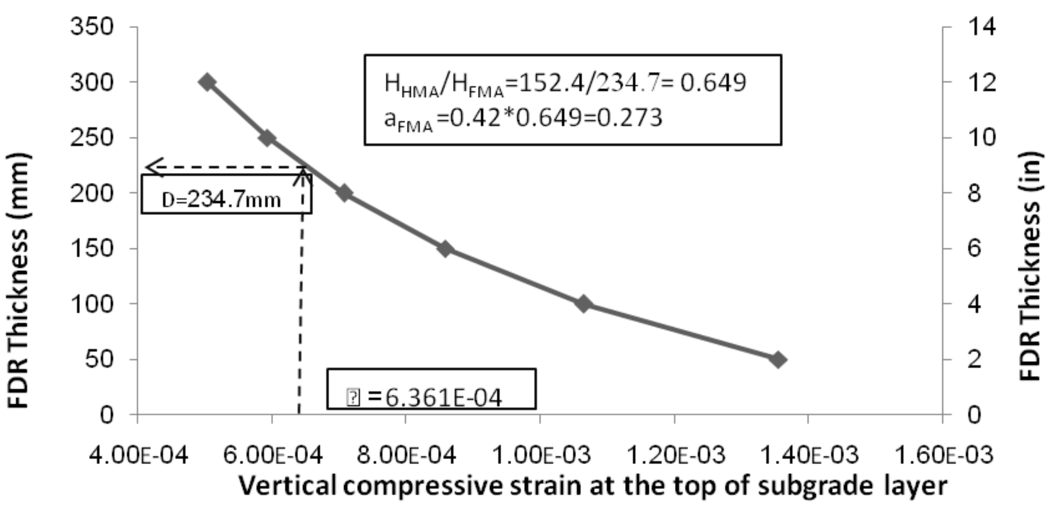


Figure 2: The relationships between the FDR thickness and the vertical compressive strain

Table 2: The equivalency factors and the structural coefficients for various values of FDR layer modulus

Elastic modules (FDR)		a_i	E.F.=H_{HMA}/H_{FDR}
Psi	MPa		
50,000	345	0.215	0.513
100,000	690	0.271	0.646
150,000	1035	0.313	0.745
180,000	1241	0.329	0.783
200,000	1379	0.339	0.806
250,000	1724	0.361	0.859

The equivalency factors and the structural coefficients for various MAATs (different HMA layer elastic modulus values) and for various FDR modulus valuesare presented in Table (3).

Table 3: The equivalency factors and the structural coefficients for various MAATs (different HMA layer elastic modulus values) and for various FDR modulus

Elastic modules (FDR)		T18ºC (65ºF)		T21ºC (70ºF)		T24ºC (75ºF)		T27ºC (80ºF)		T30ºC (86ºF)	
MPa	Psi	a_i	$E.F.$	a_i	$E.F.$	a_i	$E.F.$	a_i	$E.F.$	a_i	$E.F.$
345	50,000	0.215	0.513	0.212	0.534	0.209	0.556	0.207	0.579	0.205	0.602
690	100,000	0.271	0.646	0.266	0.672	0.262	0.698	0.259	0.725	0.256	0.752
1035	150,000	0.313	0.745	0.304	0.768	0.297	0.792	0.291	0.816	0.286	0.841
1241	180,000	0.329	0.783	0.320	0.808	0.313	0.834	0.307	0.859	0.301	0.886
1379	200,000	0.339	0.806	0.330	0.833	0.322	0.859	0.316	0.885	0.311	0.913
1724	250,000	0.361	0.859	0.352	0.888	0.344	0.917	0.338	0.946	0.332	0.977

The relationship between the FDR modulus and the FDR layer structural coefficient for different MAATs is illustrated in Figure (3), and Figure (4) shows the result of drawing equations (1) and (2) on the relationship in Figure (3).

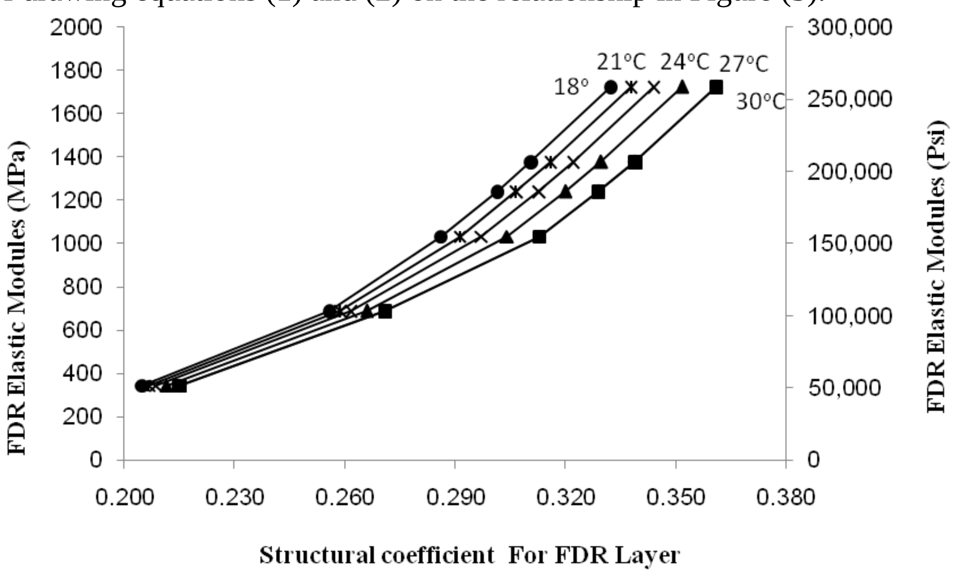


Figure 3: the relationship between the FDR modulus and the FDR layer structural coefficient for different MAATs

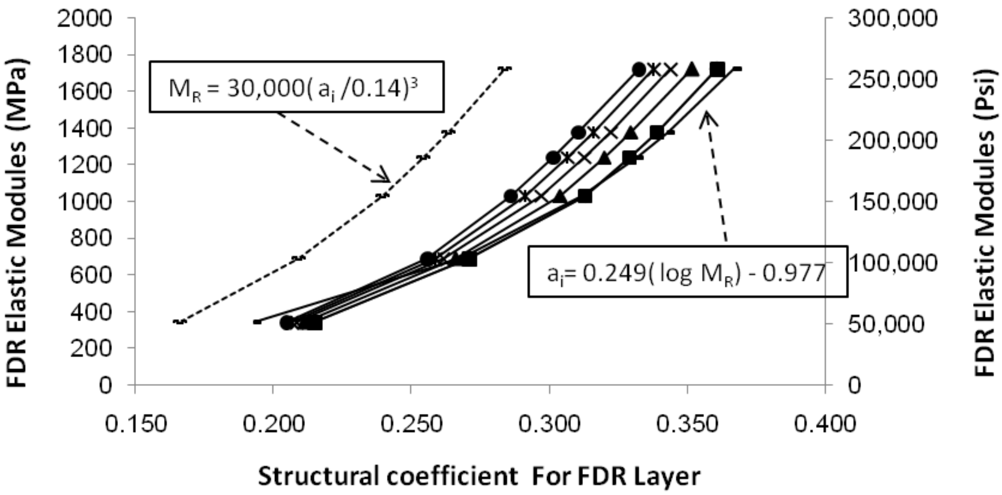


Figure 4: the relationship between the FDR modulus and the FDR layer structural coefficient for different MAATs, with equations (1) and (2)

DISCUSSION

From the data presented in Table (3) and Figures (3 and 4) and provided that the practical and the reasonable range for the FDR modulus as mentioned previously is from 100,000 Psi to 200,000 Psi (690 to 1380MPa), the following remarks could be drawn:

- As the FDR modulus increase which implies that the increase of the strength, the structural coefficient values increase for various MAATs.
- The FDR structural coefficient values decrease with the increase of MAAT.
- Equation (1) values are the most conservative values and this equation represents the lower bound values for the structural coefficient range.
- Equation (2) values within the practical range of the FDR modulus are almost coincide with the 65°F (18^{o}C) MAAT curve values and this equation represent the upper bound values of the structural coefficient range.
- The structural coefficient values for the MAATs from 65°F (18^{o}C) to 86°F (30^{o}C) lies within the upper and lower boundary values of the structural coefficient specified by the equations(1and 2) which means that the structural coefficient values determined by the vertical compressive strain criteria are reasonable values.
- The structural coefficient range for any geographic location is bounded by the equation (1) as the lower bound values and the MAAT curve of the location as the upper bound values.
- A reasonable single structural coefficient value could be determined within the specified range by the engineering judgment based on the contractor level of experience and the level of quality control available.

CASE STUDY

KASER BENGESHER-SWANI ROAD: The road was constructed in the late 70´s of the last century, it is located south of Tripoli connecting the city of Kaserbengesher with the city of Swani, and it also connects two major arterials; the airport road and Tripoli-Garian road. The road is 4-lane divided highway and about 10 km long. The present average daily traffic (ADT) is 35,000 vehicles with 12% heavy trucks. The existing pavement structure as shown in Figure (5) consisting of 2 inch (50mm) wearing course, 4 inch(100mm) binder course, 12 inch (300 mm) granular base course over subgrade layer has effective resilient modulus of 12,000 Psi (828 MPa).

Wearing coarse				**2" (50mm)**
Binder coarse				**4" (100mm)**
Granular base Coarse				**12" (300mm)**
Subgrade Fine silty sand		**CBR=8% Mr=12,000 Psi**		

Figure 5: Existing Pavement

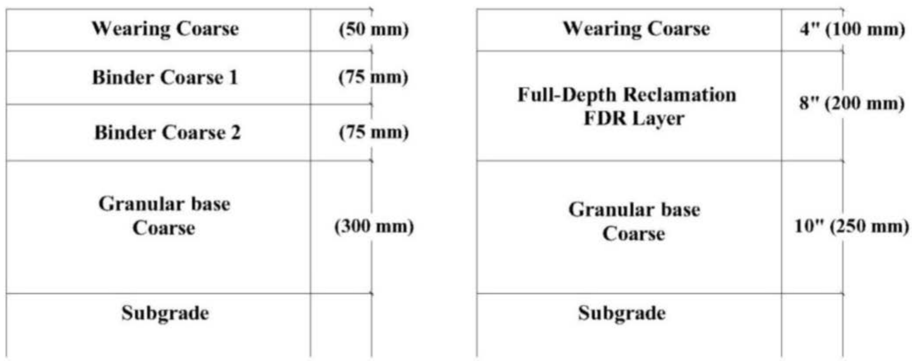
The pavement condition is very poor; sever transverse and block cracks are distributed all over the pavement surface, and these cracks were developed to sever alligator cracking due to the lack of regular maintenance and heavy truck traffic. The calculated design equivalent single axle load (ESAL) for the next 20-years is 50 million. And the required structural number (SN) according to the AASHTO design method is 5.0. The roads department in Libya decided to rehabilitate the road with either one of the following two alternatives:

ALTERNATIVE ONE: **The conventional method**

Removal of the existing asphaltic layers and reconstruct 8 inch (200 mm) HMA layers as shown in Figure (6a) which resulted in structural number of 5.04 greater than the required structural number (5.0).

ALTERNATIVE TWO: **The FDR method**

The existing asphaltic layers are reclaimed as well as part of the underlying granular base material and then combined without heat with foamed bitumen and cement and mixed at the pavement site. The end result is a mixture of reclaimed asphalt pavement and new binder. Depth of recycling typically ranges from 6 inch (150 mm) to 10 inch (250 mm). The work is carried out with a multi-functional recycling train. Due to the type of equipment available, the thickness of the FDR layer is fixed 8 inches (200 mm), and the overlay thickness will be the thickness required to satisfy the structural number of (5.0). Even though the laboratory tests of FDR mixture from another road in the same area gave the modulus value of 180,000 Psi (1242MPa), the modulus value used in determination of the structural coefficient range is 150,000 Psi (1035MPa) (the mid value of the practical range of the FDR modulus). The MAAT of Tripoli area is about 75°F (24°C). From Table (3) and Figure (4), the structural coefficient range (0.24 to 0.30). Since the contractor has no experience in construction of FDR layer, but has technical assistance from the equipment manufacture, and the supervision staff has limited experience, the structural coefficient single value for this road is 0.25 close to the lower bound value. Then the overlay thickness is 4 inch (100mm). Figure (6b) shows the FDR structure. Based on the official typical prices of road works in Libya, the cost per square meter of alt. one is 54.8 Libyandinars, and the cost of alt. two is 42.6 Libyan dinars.



(a) Alt. One Conventional Method Design. (b) Alt. Two FDR Design

Figure 6: Alternative Design

CONCLUSIONS

Based on the literature review and the results of this study, the following conclusions could be drawn:

- The FDR technology produces new material which is not structurally equivalent to HMA, but is superior to gravel or crushed stone base course.
- Equal failure criteria (fatigue and/or permanent deformation) are the rational procedure to estimate the upper bound structural layer coefficient values for FDR.
- The practical thickness for FDR ranges from 6 inch to 10 inches (150 mm to 250mm), and variation of the structural coefficient within this range is minimal.
- The structural coefficient of FDR layer is largely dependent upon the elastic modulus of the FDR. The influences of the characteristics of the surrounding layers were very small.
- It is not possible to determine a single structural coefficient value for the FDR. Engineering judgment is required to determine the reasonable single structural coefficient value within the specified range from Figure 4 based on levels of experience and quality control.

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