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Development of Computer Program for Structural analysis of Flexible Pavement

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Abstract

The main objective of this study is evaluating the distresses (rutting and fatigue) happened in the pavement and determines the effect of several parameters on pavement. This study includes two steps, First experimental work to compute stiffness, rutting parameters and fatigue parameters of three asphaltic layers. Second, was a computer program developed by visual basic languish to evaluating the sensitivity of several parameters (resilient modulus, thickness of layer) on the rutting resistance and fatigue life. Asphalt concrete mixtures, were prepared for three asphaltic layers (wearing, binder and base), mixture in this study have been subjected to the following tests: marshal test, resilient modulus test at (20°C and 45°C), permanent deformation under repeated load test at(45°C) and repeated flexural beam fatigue test at (20°C). From the result of experimental work and developed computer program it was found that 2 cm decrease of wearing course thickness cause (2.2%, 5.2%) decrease of fatigue life and rutting resistance, while 2 cm decrease of binder course thickness cause (2.868%, 2.107%) decrease of fatigue life and rutting resistance, decreasing of base course thickness 2 cm cause (3.14%, 1.53%) decrease of fatigue life and rutting resistance respectively. Also it found that decrease of wearing course resilient modulus 5000 psi decrease fatigue life and rutting resistance about (4.58% and 8.723%) respectively, decrease binder resilient modulus 5000 psi cause decrease fatigue life and rutting resistance about (5.836% and 7.159%) and decreasing of base layer resilient modulus from 5000 psi decrease fatigue life and rutting resistance about (6.766% and 3.32%) respectively.

Keywords: asphalt concrete, fatigue life, mechanistic-empirical design method, rutting resistance

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INTRODUCTION

In the recent ten years, some of the newly constructed asphalt concrete pavements in Baghdad as well as other cities across Iraq have shown premature failures with consequential negative impact on both roadway safety and economy. Frequently, load associated mode of failure (rutting and fatigue) is the main failure type found in the constructed roads. Investigations of the reasons beyond this failure showed that it can be grouped into two categories, extrinsic and intrinsic. The first category is due to the heavy axle loading. The second category is limited to the mixture itself.[1] Flexible pavement design can either be developed based on in-situ testing of pavements, which is the principle of empirical approach based on the results of experiments and which involves building pavement test sections representing a wide range of road materials and subjecting them to actual or simulated traffic loads, or can be developed by the mechanistic approach which provides a scientific basis for relating the mechanics of structural behavior to loading. In order to quantify how the load on a structure is distributed to its members, another approach for designing pavements is the mechanistic-empirical methodology which is the combination of mechanistic approach and empirical approach. The mechanistic models generate responses including stresses, strains, and deflections at critical locations of a pavement structure.[2]

Reported that since 1960, several major advances were made in design and construction technology for flexible pavements.[3] The AASHTO Road test[4] brought forth many new concepts such as the user-oriented definition of pavement failure (rather than one based on structural failure) leading to the development of the serviceability-performance methods of analysis.

A major technical advance was achieved in the early 1960 through the development of a more fundamental approach to flexible pavement design on the basis of multi-layered elastic theory. Because of the use of computer solutions, several design methods have evolved based on theoretical multi-layered stress and strain analysis.

As a result of those design techniques, a major change in design philosophy was the recognition that flexible pavements fail by different distress mode.

The pavement designer became able to analyze cracking due to repeated loads and to analyze permanent deformation due to repetitive shear deformations.

After the AASHTO road test, a number of mechanistic design methodologies have been developed. The fundamental principles underlying these models are traffic loading, material and structural system response and environmental interaction.[2]

VESYS mechanistic program relies on a full viscoelastic characterization of the HMA layers and similar in outline to both the Asphalt Institute and SHELL methods. It analyses the problem as a probabilistic rather than a deterministic hence the input data are mean values and standard deviation.

It is basically a research tool and not appropriate for practical use for pavement design. The KENLAYER was developed by Huang at the University of Kentucky in 1993. It is similar in outline to all of the mechanistic methods previously described. However the KENLAYER is significantly different as more material models are available for linear-elastic, non-linear elastic, viscoelastic and combinations thereof.

Different material parameters may be entered for each season variations; there is more detailed characterization of traffic loading with respect number and speed; up to 19 material layers can be explicitly examined; the user can specify the parameters of the critical failure criteria. The program can also be easily calibrated using the observed field failure parameter to set the platform for a given environmental condition. Considering the design parameter and composition of the pavement layers.

MATERIAL CHARACTERIZATION

The materials used in this work, asphalt cement, aggregate, and fillers were characterized using routine type of tests and results were compared with State Corporation for Roads and Bridges Specifications.[5]

Asphalt Cement

One type of asphalt cement (40–50) penetration graded was used in this study. It is obtained from Dourah Refinery, south-west of Baghdad. Physical properties of this type of asphalt cement are shown in Table 1.

Table 1. *Physical Properties of Asphalt Cement.*

Test	Test Conditions	ASTM Designation	Units	Asphalt cement 40-50
Penetration	100 gm, 25°C, 5 sec., 0.1 mm.	D5	1/10 mm	46
Specific Gravity	25°C	D70	----	1.03
Ductility	25°C, 5 cm/min.	D113	Cm	> 100
Softening Point	(4±1) ^{o}C/min.	D36	^{o}C	49

Coarse and Fine Aggregate

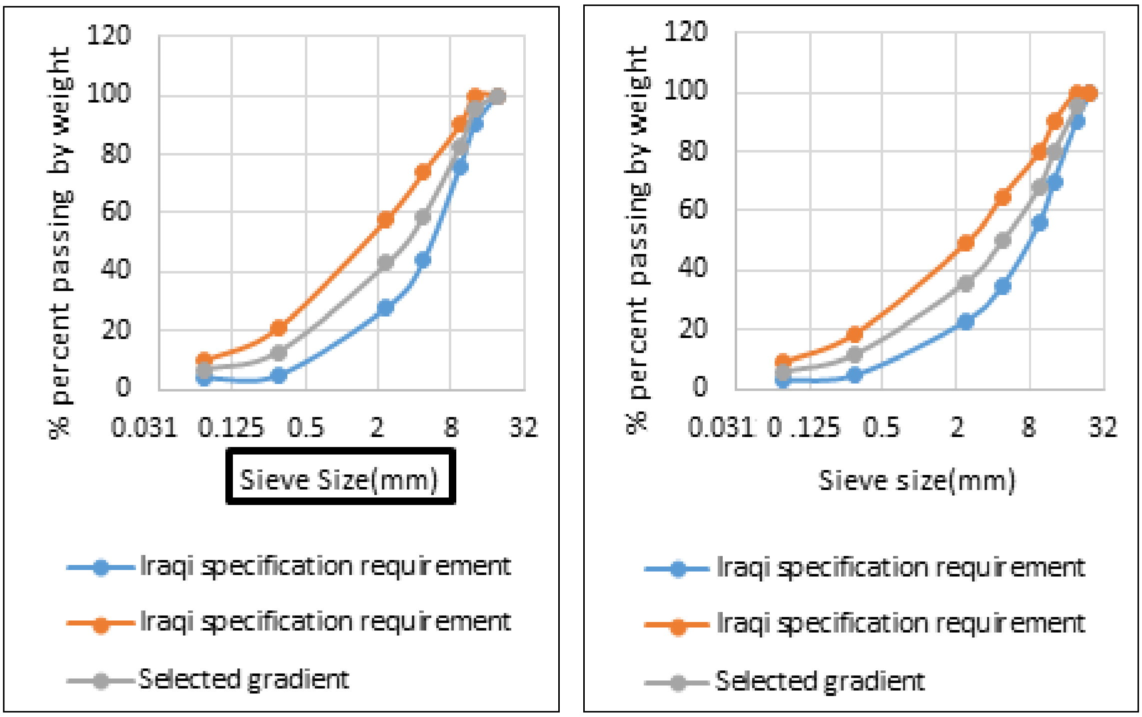
Crushed coarse aggregate (retained on sieve No. 4) was obtained from AL-Ukhaider Karbala quarry. Crushed sand and natural sand used as Fine aggregate (particle size distribution between sieve No. 4 and sieve No. 200) was brought from the same source. It consists of hard, tough grains, free from loam and other deleterious substances. The coarse and fine aggregates used in this work were sieved, and recombined in the proper proportions to meet the wearing course gradation as required by specification.[5] The physical properties and selected gradation curve for the aggregate are presented in Table 2, and Figure 1.

Mineral Filler

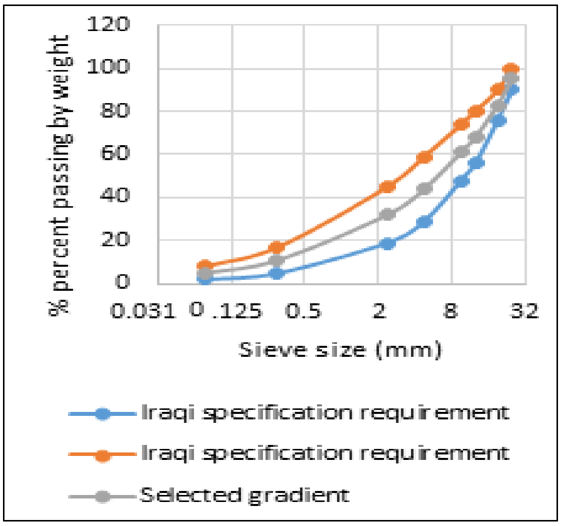
Limestone dust was used as a filler material. It is non plastic filler produced in the lime factory in Karbala governorate. The physical properties of limestone dust are presented in Table 3.

Table 2. *Physical Properties of Aggregate.*

Property	Coarse Aggregate		Fine Aggregate	
	Test Result	ASTM Designation No.	Test Result	ASTM Designation No.
Bulk Specific Gravity	2.542	ASTM C 127	2.558	ASTM C 128
Apparent Specific Gravity	2.554	ASTM C 127	2.563	ASTM C 128
Percent Water Absorption	1.076	ASTM C 127	1.83	ASTM C 128
Percent Wear (Loss Angeles Abrasion)	17.92	ASTM C 131		



a- Wearing Course Gradation   b- Binder Course Gradation



c- Base Course Gradation

Fig.1 *Mixtures Gradation According to SCRB Limit*

Table 3. *Physical Properties of Mineral Filler.*

Property	Physical Properties
Passing Sieve No. 200 (0.075 mm)	94
Specific Gravity	2.617

Preparation of Asphalt Mixture

The aggregate was first sieved, washed, and dried to a constant weight at 110ºC. Coarse and fine aggregates were combined with mineral filler to meet the specified gradation of SCRB then heated to a temperature of (160ºC). The asphalt cement was heated to a temperature of (150ºC) to produce a kinematic viscosity of (170±20) centistokes. Then, asphalt cement was added to the heated aggregate to achieve the desired amount, and mixed by hand using a spatula for two minutes until all aggregate particles were coated with asphalt cement.

Experimental Work

The experimental work was started by determining the optimum asphalt content for all the asphalt concrete mixes using the Marshall Mix design method.

Marshall Test Method

This method covers the measurement of the resistance to plastic flow of cylindrical specimen of asphalt paving mixture loaded on the lateral surface by mean of the Marshall apparatus according to ASTM D 1559.

The cylindrical specimen was conditioned by placing in water bath at 60ºC for (30) minute, then inserted into the testing device, and compressed on the lateral surface with a constant load of 20 KN until the device reached the maximum load resistance which is recorded as stability, and the corresponding flow value at that point was also recorded. The bulk specific gravity and density ASTM (D 2726), theoretical (maximum) specific gravity of void-less mixture were determined in accordance with ASTM (D 2041). The percent of air voids was then calculated.

Indirect Tension Repeated Load Test

The indirect tension repeated load test specified by (ASTM D4123) "Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures" was conducted using the pneumatic repeated load system (PRLS). In these tests, repetitive loading is applied to the diametral specimen and the resilient vertical strain is measured under the load repetitions. Diametral loading is applied with a constant loading frequency of 60 cycles per minute and loading sequence for each cycle is 0.1 sec load duration and 0.9 sec rest period to simulate the testing condition explained by Shell Nomograph that is addressed in.[3] Marshall Specimen were used to measure the resilient modulus for each layer at (20ºC and 45ºC). The applied stress level was 20 psi, and three asphalt content were used (4.6, 4.2, 3.8) for wearing, leveling and base courses at (20ºC and 45ºC). The resilient strain (εr) and resilient modulus (Mr) are calculated as follows:

$\varepsilon_r = rd/h$ Eq. (1)

$Mr = \sigma/\varepsilon_r$ Eq. (2)

where

εr= axial resilient microstrain
rd= axial resilient deflection
h= specimen height
σ = repeated axial stress

Permanent Deformation Test

The Indirect Tension repeated loading tests were conducted for cylindrical specimens, 102 mm in diameter and 203 mm in height, using the pneumatic repeated load. In these tests, repetitive compressive loading with a stress level of 20 psi was applied in the form of rectangular wave with a constant loading frequency of 1 Hz (0.1 sec. load duration and 0.9 sec. rest period) and the axial permanent deformation was measured under the different loading repetitions. All the uniaxial repeated loading tests were conducted at 40°C. The specimen preparation method for this test can be found elsewhere,[1] The permanent strain (εp) is calculated by applying the following equation:

$$\varepsilon p= (pd \times 10^6)/h \qquad \text{Eq. (3)}$$

where
εp= axial permanent micro strain
pd= axial permanent deformation
h= specimen height

The permanent deformation test results for this study are represented by the linear log-log relationship between the number of load repetitions and the permanent micro-strain with the form shown in Eq.6 below which is originally suggested by[6, 7]

$$\varepsilon p=a N^b \qquad \text{Eq. (4)}$$

where
εp= permanent strain
N=number of stress applications
a= intercept coefficient
b= slope coefficient

Flexural Fatigue Test

This test was conducted with a slabs sample of (400×300×50) mm each slab was compacting with a vertical load of (5) kN and vibration at air supply of 10 bar. Beams were obtained using diamond cutting device the dimension of beams specimen were (50±6 mm high, 63±6 mm width and 400 mm long according to AASHTO T321. The standard beam fatigue test procedure as per AASHTO T 321 was adopted. This test is used to determine fatigue life of HMA mixture until fatigue failure occurs. The failure criteria is that initial stiffness is reduced to 50 %. Tests can be run at a constant strain level or at a constant stress level, in this work, the constant strain level is selected because it is a thin layer. In this study, flexural beam testing was performed at a strain level of 250, 450 and 750 micro strain, loading frequency (5 Hz) and at 20°C.

DEVELOPMENT OF PROGRAM

Empirical-Mechanistic method of design is based on the mechanics of materials that relates input, such as wheel load, to an output or pavement response. In pavement design, the responses are the stresses, strains, and deflections within a pavement structure and the physical causes are the loads and material properties of the pavement structure. The relationship between these phenomena and their physical causes are typically described using some mathematical models [8].

Along with this mechanistic approach, empirical elements are used when defining what value of the calculated stresses, strains, and deflections result in pavement failure. The relationship between physical phenomena and pavement failure is described by empirically derived equations that compute the number of loading cycles to failure.

In this study a computer program developed to carry out flexible pavement design using the mechanistic–empirical design method. This program is written in Visual Basic Language (vp.net 2012) which operates under Windows environment.

Input of the Program

The input data are Layers properties such as Resilient Modulus of the layers (surface course, binder course, base course, sub base course and subgrade course), Poisson ratio for all layers and thickness of (surface, binder, base and sub base course). Figure 2 shows the input sheet.

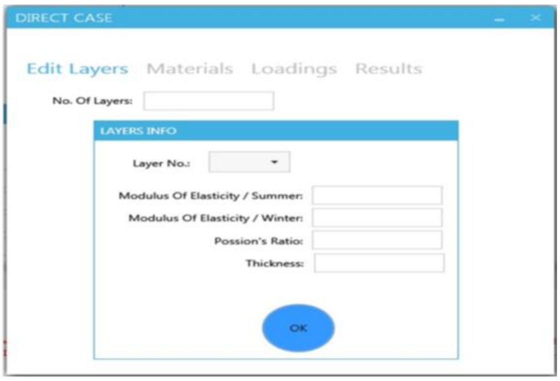


Fig.2. *Input Data of Developed Program.*

Design Traffic

Design traffic is computed for each load group separately from the following equation

$$N_j = ADT * \frac{1}{Np} * \frac{P_j}{100} * D_D * D_L * G_f * 365 \qquad \text{Eq. (5)}$$

Where

Ni=the number of repetition for i type of vehicle.

ADT=initial average daily traffic.

P_j=percentage of J type of vehicle.

Gj=growth factor for J type of vehicle.

D_L=lane distribution factor.

D_D=directional distribution factor.

Np=number of periods in the year.

Coefficients of Fatigue and Rutting

Failure criterion for fatigue cracking is expressed as:

$$N_f = f_1(\epsilon_t)^{-f_2} \times (E)^{-f3} \qquad \text{Eq. (6)}$$

In which

Nf = allowable number of load repetitions to prevent fatigue cracking,

Єt = tensile strain at the bottom of asphalt layer,

E1 = elastic modulus of asphalt layer, and

f1, f2, f3 = coefficient of fatigue.

Failure criterion for permanent deformation is expressed as;

$$N_d = f_4(\epsilon_c)^{-f_5} \qquad \text{Eq. (7)}$$

Where

Nd = allowable number of load repetitions to limit permanent deformation, Єc = compressive strain on the top of subgrade, and

f4, f5 = coefficient of permanent deformation.

Figure 3 shows Fatigue and Rutting Parameters sheet.

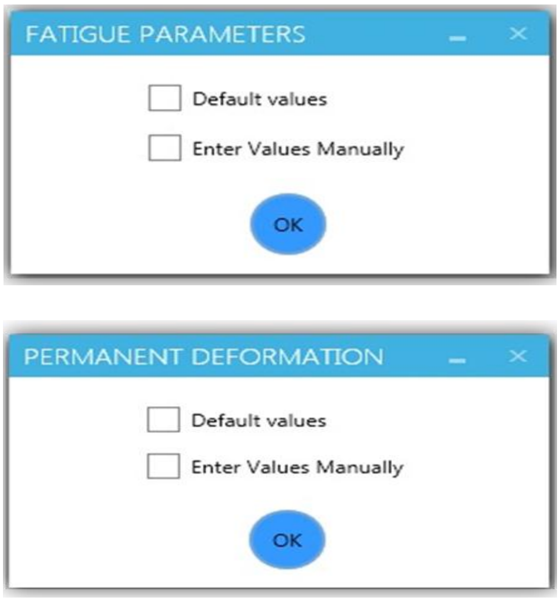


Fig.3. *Fatigue and Rutting Parameters.*

Output of the Program

The program is developed to determine the fatigue life and rutting resistance of pavement for a specified layer thickness.

$$Dr = \frac{Actual\ number\ of\ repitition s}{Allowable\ number\ of\ repititions} \quad \text{Eq. (8)}$$

$$Design\ life = \frac{1}{Dr} \quad \text{Eq. (9)}$$

Figure 4 shows load group data sheet.

Fig.4. *load Group Data Sheet.*

Sensitivity Analysis on Effect of Thickness

Sensitivity analysis was carried on the failure parameters with respect to changes in the tensile and compressive strains at the bottom of the Asphaltic Concrete and at the top of the subgrade respectively.

This was done by increasing and decreasing the thicknesses of the pavement layers.

For the 3 layers under consideration, two of the pavement layers thicknesses were kept fixed at each time and the layer of interest varied. The results were shown in Table 4 and Table 5.

SENSITIVITY ANALYSIS

Table 4. *Effect of Layer Thickness on Rutting Resistance.*

Thickness(cm)			Rutting Life (Years)	Subgrade Top Compressive Strain
Surface	Binder	Base		
6	7	10	16.8	1.950E-02
5	7	10	16.6	1.956E-02
4	7	10	15.92	1.958E-02
3	7	10	15.85	1.959E-02
5	6	10	15.79	1.958E-02
5	5	10	15.64	1.961E-02
5	4	10	15.51	1.967E-02
5	7	9	15.64	1.959E-02
5	7	8	15.4	1.962E-02
5	7	7	14.81	1.964E-02
5	7	6	14.48	1.967E-02

Table 5. *Effect of Layer Thickness on Fatigue Life*

Thickness (cm)			Fatigue Life	Bottom HMA Tensile Strain
Surface	Binder	Base		
6	7	10	24.757	1.762E-03
5	7	10	24.5	1.764E-03
4	7	10	24.213	1.795E-03
3	7	10	23.905	1.836E-03
5	6	10	25.170	1.615E-03
5	5	10	24.840	1.620E-03
5	4	10	24.443	1.631E-03
5	7	9	24	1.699E-03
5	7	8	23.578	1.705E-03
5	7	7	23.463	1.704E-03
5	7	6	23.245	10708E-03

Sensitivity Analysis on Effect of Layers Modulus

This was done by increasing and decreasing the modulus of the pavement layers. For the 3 layers under consideration, two of the pavement layers modulus was kept fixed at each time and the layer of interest varied. The result was shown in Table 6 and Table 7.

Table 6. *Effect of Resilient Modulus on Rutting Resistance.*

Resilient Modulus (psi)			Rutting Resistance	Top Subgrade Compressive Strain
Surface	**binder**	**Base**		
33867	27836	25086	18	1.83E-02
30000	27836	25086	17.77	1.86 E-02
25000	27836	25086	16.22	1.885 E-02
33867	20000	25086	17.32	1.78 E-02
33867	15000	25086	16.08	1.82 E-02
33867	10000	25086	15.36	1.79 E-02
33867	27836	20000	17.05	1.547 E-02
33867	27836	15000	16.56	1.579 E-02
33867	27836	10000	16.01	1.62 E-02

Limitation of the Program

The developed program was running under these limitations:

1. Maximum size of aggregate used in this study was (12.5 mm) for wearing course, (19mm) for binder course and (25 mm) for base course.
2. Asphalt cement (40-50) penetration grade was used in this study.
3. The optimum asphalt content that have been adopted in this study was (4.6%, 4.2% and 3.8%) from weight of mixture for wearing, binder and base course.
4. The temperature that has been adopted in this study was 20°C for winter and 45°C for summer.
5. The failure criteria of fatigue test is that initial stiffness is reduced to 50% while rutting test was conducted under 10000 repetitions of load.

Table 7. *Effect of Resilient Modulus on Fatigue Life.*

Resilient Modulus (psi)			Fatigue Life (Years)	Bottom HMA Tensile Strain
Surface	**binder**	**Base**		
65617	45714.85	40656	24.823	1.634E-03
60000	45714.85	40656	24.325	1.689E-03
55000	45714.85	40656	23.206	1.773E-03
33867	45714.85	40656	25	1.601E-03
33867	40000	40656	23.541	1.752E-03
33867	35000	40656	23.044	1.83 E-03
33867	45714.85	40656	22.11	2.32 E-03
33867	45714.85	35000	20.376	3.44 E-03
33867	45714.85	30000	19	3.77 E-03

CONCLUSIONS

1. Decreasing of surface thickness from 6–4 cm causes increase of tensile strain at bottom of asphalt layer and compressive strain at top of subgrade about (2% and 0.41%), and decrease of fatigue life and rutting resistance about (2.2% and 5.2%).
2. Decreasing of binder layer thickness from 6 cm to 4 cm causes increase of critical strain about (2.99% and 0.459 %) for tensile strain and compressive strain respectively, and decrease of fatigue life and rutting resistance about (2.868%,2.107%) respectively.
3. Variation of base layer thickness from 9 cm to 7 cm cause increase of tensile strain at bottom of asphalt layer and compressive strain at top of subgrade about (3.27% and 0.455%)

respectively, and decrease fatigue life about (3.14%) and rutting resistance about (1.53%).

4. Reducing of surface layer resilient modulus about (5000 psi) cause increase of critical strain about (4.97% and 1.344%) for tensile strain and compressive strain. And decrease of fatigue life and rutting resistance about (4.58% and 8.723%).
5. Fatigue life and rutting resistance decrease (5.836% ,7.159%)when binder resilient modulus decrease 5000 psi and both critical strain increase about (9.43% and 2.24%) for tensile strain and compressive strain.
6. Decreasing of base layer resilient modulus 5000 psi increase the critical strain about (9.6% and 2.59%) for tensile strain and compressive strain respectively and decrease of fatigue life and rutting resistance about (6.799% and 3.32%).

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