ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

CE 461

Implementation of AASHTO Flexible Pavement Design into MATLAB GUI

Ugurcan Ozdemir

METU ID: 1737691

Contents

INTRODUCTION

This paper covers the pavement analysis and design procedure according to AASHTO regulation published by 1993 at last and also the design is applied by the MATLAB Graphical User Interface.

AASHTO flexible pavement design procedure stands on empirical which based on experiment and experience equations which were conducted from 1956 to 1960 at Ottowa, IL. Due to the empirical methods, there are some deficiencies and restrictions during the analysis and design. Therefore, there are only set of conditions and material types exists as input variables. After the last version (1993) of AASHTO Guide for Design of Pavement Structures which is basis for developing other modules, there are many other approaches developed in order to analyze and design both flexible and rigid pavements such as mechanistical – empirical approach.

The main objective of this work is to develop a MATLAB Graphical User Interface which takes necessary inputs such as material types, traffic volume data and gives the structural number and according layer thicknesses respectively for flexible pavement. The program developed by the MATLAB GUI is also calculated Equivalent Single Axle Load (18 kip) by taking traffic volume measuring parameters such as average daily traffic, class type and load with respect to axle configuration and load as inputs and gives the total ESAL result which is one of the parameter being used during the calculation of the thickness of the separate layers.

Due to the restrictions of the AASHTO regulation for flexible pavement design, the thicknesses of three layers which are asphalt cement surface, base course and sub base course are calculated for each set of design requirements.

Before the implementation of AASHTO flexible pavement design into MATLAB Graphical User Interface, the design procedure of the flexible pavement according to AASHTO is described and therefore, the theory under lying the MATLAB GUI program is clearly identified.

AASHTO FLEXIBLE PAVEMENT DESIGN

The aim of the structural design of the flexible pavement is determined the layer thicknesses given all the design requirements.

A flexible pavement is mainly formed of sub grade layer, sub base layer, base layer and surface layer respectively from down to up. The sub base layer is not must to be exist under the base layer. In other words, the base course may be constructed on the top of the roadbed soil if there is not a problematic issue with respect to design requirements. The base course can include either aggregates such as crushed stone and gravel or bituminous material. The surface layer above the base course is typically formed as a mixture of asphalt concrete binder. The design is conducted step wise by a method called Layered Design Analysis since flexible pavement is also a layered system.

After the program which gives the layer thicknesses rounded to nearest ½ inch according to AASHTO design recommendations is developed, the user has to be aware of all design requirements and input instead of using the series of nomographs and iterating design equation.

The flexible pavement design according to AASHTO is based on the empirical equation after the result of the AASHTO Road Test. This equation includes a term which is Structural Number (SN) defined as "an abstract number expressing the structural strength of a pavement structure required for a given combination of soil support (M_R), traffic expressed in equivalent single 18 kips axle (ESAL), final serviceability and environment " (AASHTO,1993)

After the AASHTO road test, this equation is derived and used for designing flexible pavement design:

$$log_{10}(W_{18}) = Z_R.S_0 + 9.36\log(SN+1) - 0.2 + \frac{log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + 2.32log_{10}(M_R) - 8.07 \quad (1)$$

W_{18} : predicted number of 18 kip traffic load application (ESAL)

Z_R : standard normal deviate

S_0 : combined standard error of traffic prediction

SN : structural number

ΔPSI : serviceability change during the design period

M_R : resilient modulus (psi)

The thicknesses of the each layer is calculated by the Layered Design Analysis and therefore, the structural number is calculated first before the thicknesses.

Layered Design Analysis

The AASHTO regulation for flexible pavement design is based on the step by step method which calculates the layer thicknesses by first iterating the structural number which is surface course. The structural number of the each layer is affected by the thicknesses of the layer, layer coefficients relating to resilient modulus of each layer and drainage coefficients. The sum of the each layer structural number gives the total structural number.

$$SN = a_1.D_1 + a_2.D_2.m_2 + a_3.D_3.m_3 \quad (2)$$

a_1, a_2, a_3 : layer coefficients for surface layer, base and sub base course layer, respectively

D_1, D_2, D_3 : layer thicknesses for surface layer, base and sub base course layer, respectively

m_1, m_2, m_3 : layer drainage coefficients for surface layer, base and sub base course layer, respectively

Note that since there are many combinations of values of thicknesses that comply with this equation, there is not a unique solution for this equation. In addition, the procedure is limited with a modulus of up to 40000 psi for base and sub base layer.

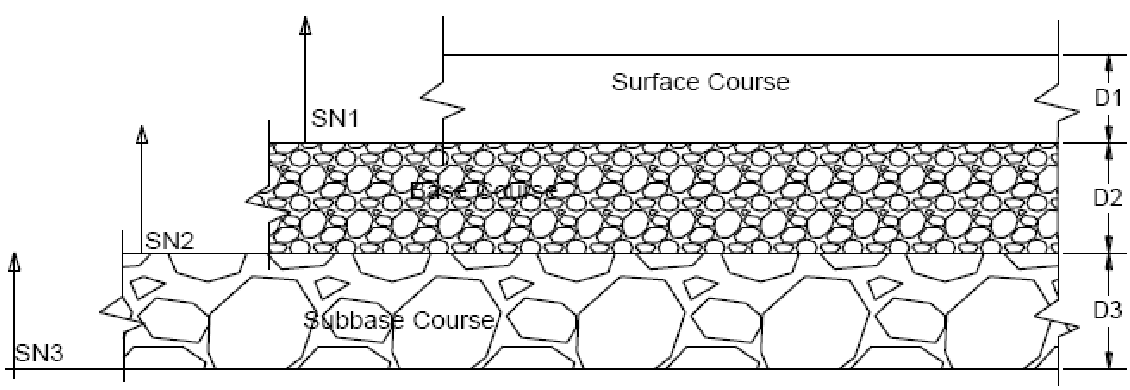

Figure 1: Thickness of Layers using Layered Analysis Approach

$$D_1^* \geq \frac{SN_1}{a_1} \qquad (3)$$

$$SN_1^* = a_1.D_1^* \geq SN_1 \qquad (4)$$

$$D_2^* \geq \frac{SN_2 - SN_1^*}{a_2.m_2} \qquad (5)$$

$$SN_1^* + SN_2^* \geq SN_2 \qquad (6)$$

$$D_3^* \geq \frac{SN_3 - (SN_1^* + SN_2^*)}{a_3.m_3} \qquad (7)$$

The Layered Design Analysis is calculated as shown above equations. First, the structural number of the surface course is calculated from the equation 1 and the thickness of the surface course is calculated by equation 3 and rounded to the nearest ½ inch. The thickness obtained from the calculation surface course is used for calculating the base course thickness by equation 5. The same procedure is conducted for calculation of the sub base layer thickness.

Design Input Parameters

- Traffic Load

The traffic volume is calculated as the number of single axle 18 kip load expected during the design period according to AASHTO design procedure.

Total number of equivalent single axle load (18 kip) is calculated as below equation:

$$ESAL(w_{18}) = ADT.TKS.DD.LD.TF.365.G \qquad (8) \qquad or$$

$$ESAL(w_{18}) = W_{80}.DD.LD.365.G$$

ADT : Average daily traffic

TKS : Percentage of truck traffic

DD : Directional distribution of truck traffic

LD : Lane distribution of truck traffic

TF : Average truck factor

G : Annual traffic growth factor

W_{80} : Total ESAL of traffic

Where the annual growth rate is calculated as below:

$$G = \frac{(1+g)^n - 1}{g} \; where\; g = Annual\; traffic\; growth\; rate(\%) and\; n = design\; period$$

During the calculation of ESAL, in order to calculate truck factor of vehicles with respect to ESAL, load equivalency factor is used according to the vehicles that have axle configuration and axle load distribution. The load equivalency factor (LEF) is obtained from these equations:

$$LEF_{L1} = \left[\frac{(L_1 + L_2)^{4.62}}{(18+1)^{4.62}}\right] \cdot \left[\frac{10^{G_t/\beta_{18}}}{\left(10^{G_t/\beta_{L_1}}\right)^{\cdot {L_2}^{3.82}}}\right] \qquad (9)$$

L_1 : load on single, tandem or tridem axle

L_2 : axle type code (1 for single axle, 2 for tandem axle, 3 for tridem axle)

G_t : a function (the logarithm) of the ratio of loss in serviceability at time t to the potential loss taken to a point where p_t=1.5

$$G_t = \log_{10}\left(\frac{4.2 - p_t}{4.2 - 1.5}\right) \; where \; p_t \; is \; serviceability \; at \; the \; end \; of \; time \; t, equal \; to \; 2, 2.5, 3 \qquad (10)$$

β : a function of design and load variables that influence the shape of the p vs. W serviceability curve

$$\beta = 0.40 + \frac{0.081x(L_1 + L_2)^{3.23}}{(SN+1)^{5.19} x {L_2}^{3.23}} \; where \; SN(structural \; number \; for \; flexible \; pavements \qquad (11)$$

- Reliability

The reliability of the road enables the designer to give the level of certainty in the design. The reliability is based on both traffic volume and the importance of the design. The more important the design and the larger traffic volume, the more reliability it is needed.

According to AASHTO (1993), the reliability is incorporated with the standard normal deviates (Z_R). Table 1 indicates the recommended reliability values for different road types according AASHTO manual (1993) and table 2 shows the corresponding Z_R values for different reliability levels.

Functional Classification	**Recommended Level of Reliability**	
	Urban	**Rural**
Interstate and Other Freeways	85 – 99.9	80 – 99.9
Principal Arterials	80 – 99	75 – 95
Collectors	80 – 95	75 – 95
Local	50 – 80	50 – 80

Table 1: Reliabilities for Various Functional Classifications (AASHTO, 1993)

Reliability (%)	Standard Normal Deviate (Z_R)	Reliability (%)	Standard Normal Deviate (Z_R)
50	0	**93**	-1.476
60	-0.253	**94**	-1.555
70	-0.524	**95**	-1.645
75	-0.674	**96**	-1.751
80	-0.841	**97**	-1.881
85	-1.037	**98**	-2.054
90	-1.282	**99**	-2.327
91	-1.340	**99.9**	-3.090
92	-1.405	**99.99**	-3.750

Table 2: Standard Normal Deviates for Various Levels of Reliability

- The Standard Normal Deviate and Overall Standard Deviation

Due to the uncertainties leading to probabilistic approach, all the input parameters are assumed to be their corresponding mean values. There is also uncertainties existing in the traffic prediction and therefore, Standard Deviation (S_0) with standard normal deviate (Z_R) is becoming more significant in the design. To conclude, the reliability factor (FR) is defined as below.

$$FR = 10^{Z_R.S_0} \qquad (12)$$

The value of the S_0 which can be selected from local condition is 0.45 for flexible pavement with respect to AASHTO.

$$W_{18} = w_{18}\,.FR \qquad (13)$$

The traffic volume is directly taken into consideration during the calculation, the reliability factor must equal to 1; therefore, the reliability will then be 50 percent which means there is a 50 – 50 chance that the designed section survive along the design period with a specified serviceability change.

- Terminal Serviceability and Serviceability Change

The serviceability change is the difference between initial serviceability (P_0) and terminal serviceability (P_t). The AASHTO road test indicates that the initial serviceability is equal to 4.2. Terminal serviceability is the indicator of minimum index level that can be tolerated before the rehabilitation. AASHTO design manual recommends terminal serviceability as 2.5 for higher traffic volumes and 2 for minor road ways.

- Layer Material Properties

  - *Resilient Modulus (M_R)*

The flexible pavement consists of different layers which are asphalt concrete (AC), base course (BC) and sub base course (SBC) and all of these layers has different resilient modulus which are taken as the input in to the program. Since the effect of the seasonal variation to resilient modulus of the sub grade cannot be negligible, effective resilient modulus for subgrade is calculated with the light of the AASHTO design procedure. 4 seasons having different number of days which form the year is taken into account during the calculation the effective modulus of the sub grade as below:

$$U_f = 1.18\,x\,10^8\,x\,{M_R}^{-2.32} \qquad (14)$$

U_f : relative damage M_R: resilient modulus of a specific season

The weighted damage is calculated from the number of days for each season, then effective resilient modulus is back calculated.

  - *Layer Coefficients*

A layer coefficient a_i of a unit thickness of material is a measure of its relative ability to function as a structural component of the pavement (Bekele, 2011). There are two way for obtaining layer coefficients: field test which is road test and equation that correlation with resilient modulus of the material.

$$a_1 = 0.169\ln(E_1) - 1.76 \qquad (15)$$

$$a_{2,granular} = 0.249\log(E_2) - 0.977 \qquad (16)$$

$$a_3 = 0.227\log(E_3) - 0.839 \qquad (17)$$

a_1 : layer coefficient for the AC layer

$a_{2,\ granular}$: layer coefficient for a granular base layer

a_3 : layer coefficient for the sub base layer

E_i : resilient modulus of the corresponding layer

- *Drainage Coefficient*

Drainage is one of the most important factor in the both structural design and service life of the pavement. During the design of the flexible pavement, drainage coefficient, m is used for different layers.

During the design, identifying what level of drainage is achieved under set of the drainage conditions for each layer is based on engineering judgment by the designer. Table 3 indicates the drainage coefficients according to AASHTO recommendations for different drainage levels. The higher value of drainage coefficient, the more improved drainage condition is. Also note that the base and sub base layer is not treated so that these drainage coefficients can be used and drainage coefficient for AC layer is 1.

Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation				
Quality of Drainage	**Less than 1%**	**1 – 5 %**	**5 – 25 %**	**Greater than 25 %**
Excellent	1.40 – 1.35	1.35 – 1.30	1.30 – 1.20	1.20
Good	1.35 – 1.25	1.25 – 1.15	1.15 – 1.00	1.00
Fair	1.25 – 1.15	1.15 – 1.05	1.00 – 0.80	0.80
Poor	1.15 – 1.05	1.05 – 0.80	0.80 – 0.60	0.60
Very Poor	1.05 – 0.95	0.95 – 0.75	0.75 – 0.40	0.40

Table 3: Recommended Values for Modifying Layer Coefficients of Untreated Base and Sub base Materials in Flexible Pavement

IMPLEMENTATION OF AASHTO FLEXIBLE PAVEMENT DESIGN INTO MATLAB GRAPHICAL USER INTERFACE

AASHTO flexible pavement analysis and design procedure is implemented into MATLAB Graphical User Interface. This MATLAB GUI takes the material properties, design parameters and specific parameters as inputs and gives layer thicknesses for sub base, base and surface course layer and related Structural Number and calculated layer coefficients. The program also gives the layer thickness configuration.

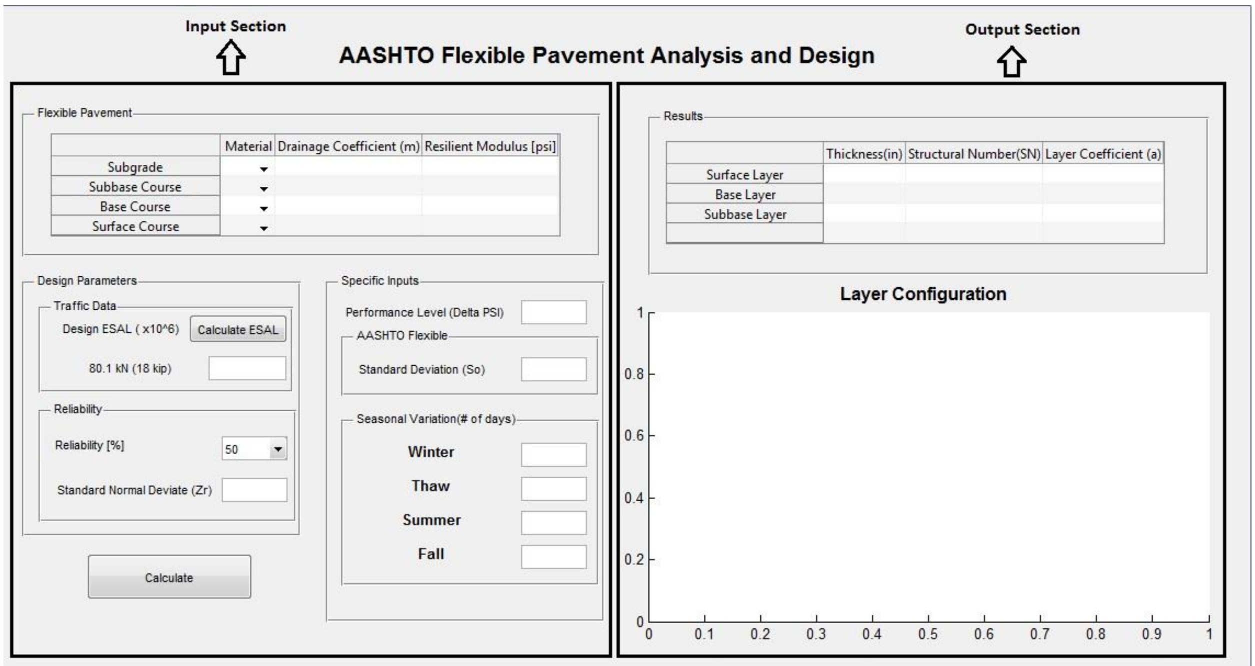

Figure 2: MATLAB GUI for Flexible Pavement Design

Material Properties

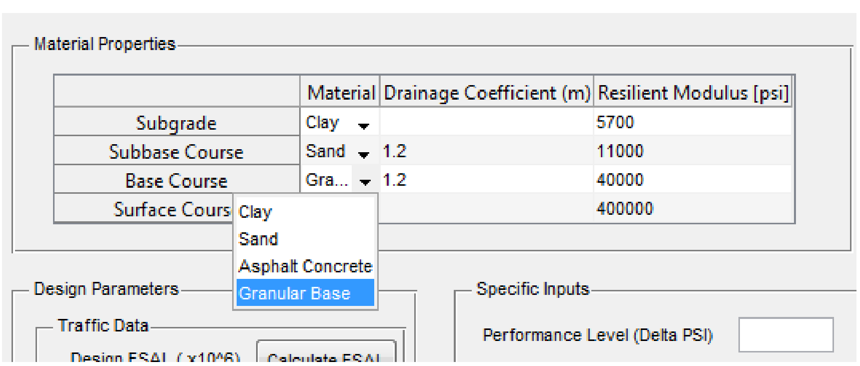

Figure 3: Material Properties of the Pavement

The user enters the material type, drainage coefficient and resilient modulus of the layers.

Selecting material type is just for showing layer configuration.

Note that drainage coefficient of the surface course is equal to 1, and drainage coefficient of the subgrade does not affect the calculation and so the design.

For resilient modulus, sub base and base materials is calibrated with a modulus up to 40000 psi. However, there is no restriction for surface layer.

Design Parameters

- Traffic Data

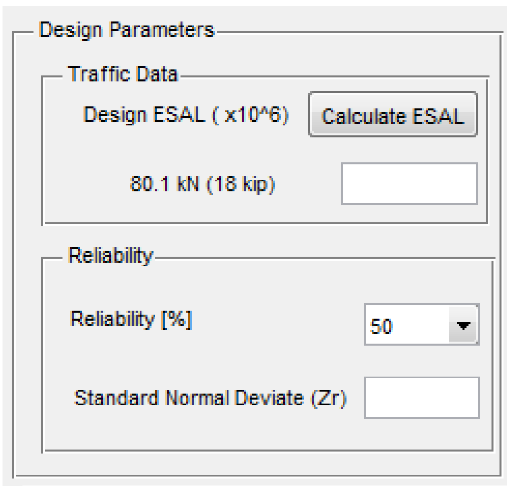

Figure 4: Design Parameters

The program allows the user either enter the Equivalent Single Axle Load by hand or calculate the ESAL by entering traffic volume data with another MATLAB GUI. If the user calculate ESAL by clicking the "Calculate ESAL" button, different MATLAB GUI is opened.

The new opened MATLAB GUI takes terminal serviceability, structural number, lane distribution, directional distribution, design period and annual growth rate as input. After the counting the traffic data with respect to vehicle class and axle configuration, the data can be entered at the Calculation of ESAL panel.

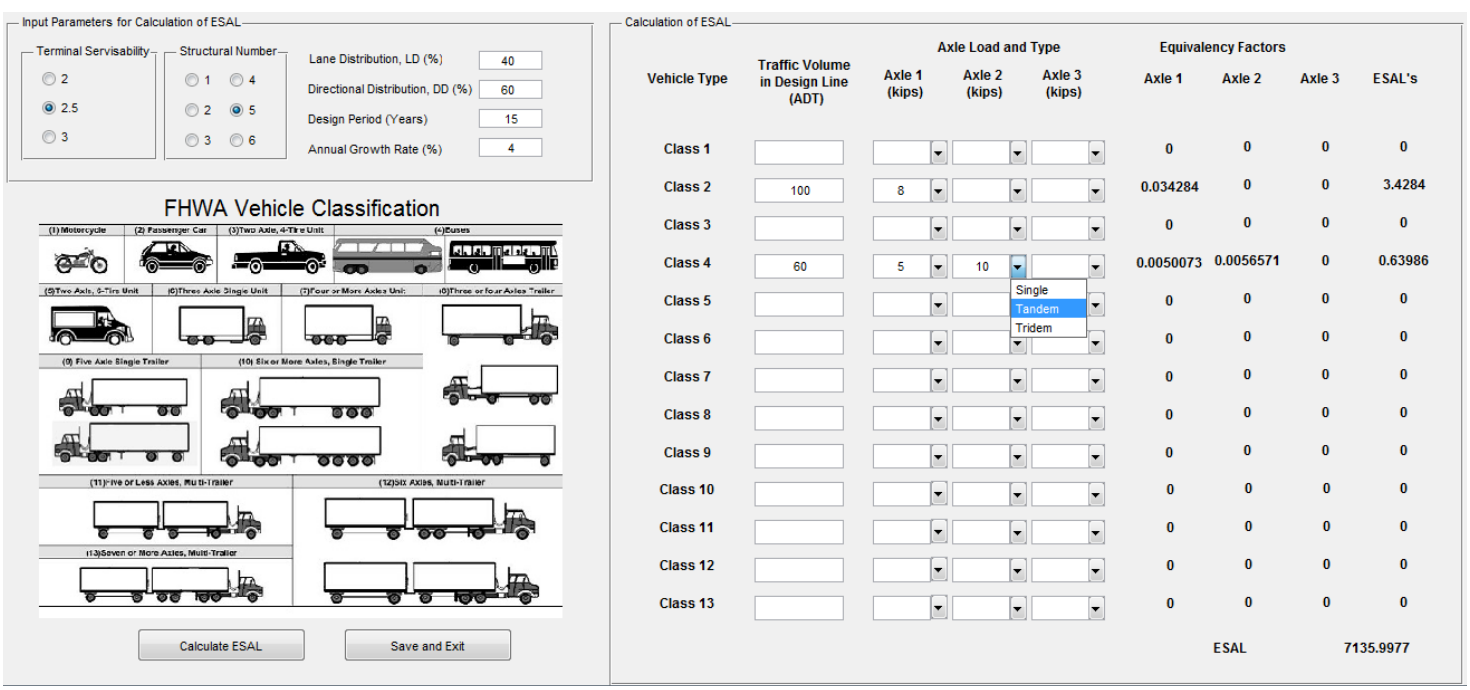

Figure 6: Calculation of ESAL

The theory lying under the calculation of ESAL is described at Traffic Load section under the title of design input parameters.

- Reliability

Reliability changing between 50 and 99.99 with different interval can be chosen and since the standard normal deviate is related with reliability, the normal deviate is printed automatically when choosing the reliability.

Specific Parameters

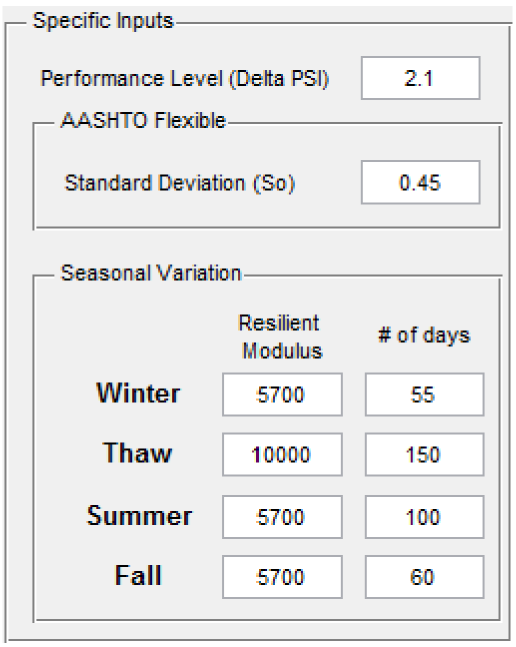

Figure 7: Specific Parameters

- Performance Level (Delta PSI)

Performance level is the measure of serviceability which means the ability of the pavement to serve the specific traffic volume. The lowest PSI is defined the moment at the pavement just before the rehabilitation. The PSI is defined as the difference between initial serviceability p_t (4.2 for flexible pavements and 45. For rigid pavements) and terminal serviceability (2.5 for major highways and 2.0 for highways with lesser traffic volumes.)

- Standard Deviation (S_0)

Due to the uncertainties during the traffic volume data, standard deviation with standard normal deviate is getting more important and therefore, reliability factor is calculated.

- Seasonal Variation

Resilient modulus of the subgrade layer is affected from the seasonal variation and therefore, for calculating resilient modulus of subgrade, relative effective damage is calculated and resilient modulus of the sub grade layer is then back calculated:

$$U_f = 1.18\, x\, 10^8\, x\left(n_s x {M_{R(s)}}^{-2.32} + n_w x {M_{R(w)}}^{-2.32} + n_f x {M_{R(f)}}^{-2.32} + n_t x {M_{R(t)}}^{-2.32}\right)/365 \qquad (18)$$

$$M_R = \left[\frac{U_f}{(1.18x10^8)}\right]^{(-1/2.32)} \qquad (19)$$

U_f : relative damage

n_i : number of days for summer, winter, fall and thaw

$M_{R(i)}$: effective resilient modulus for summer, winter, fall and thaw

Output Section

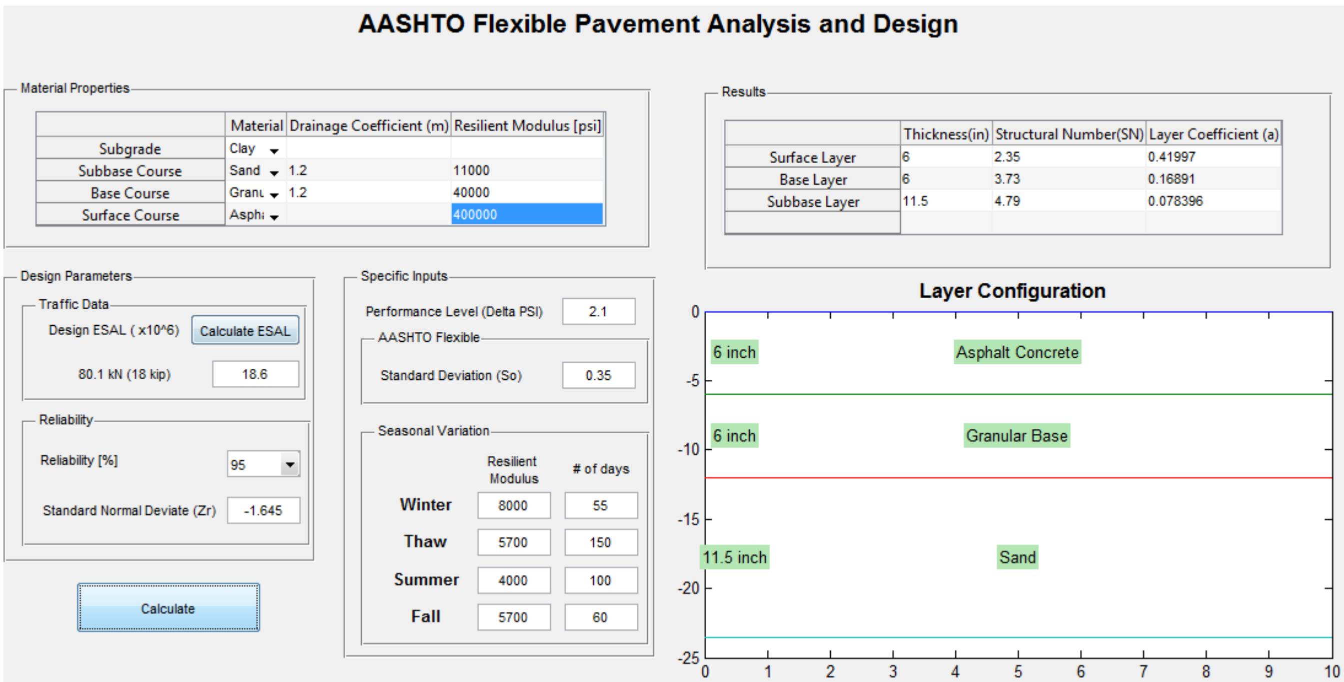

Figure 8: MATLAB GUI for Designing Flexible Pavement According to AASHTO

CONCLUSION

This report focuses on Flexible Pavement Design according to AASHTO design criteria and its implementation of MATLAB Graphical User Interface program. The flowchart of the program may be obtained like:

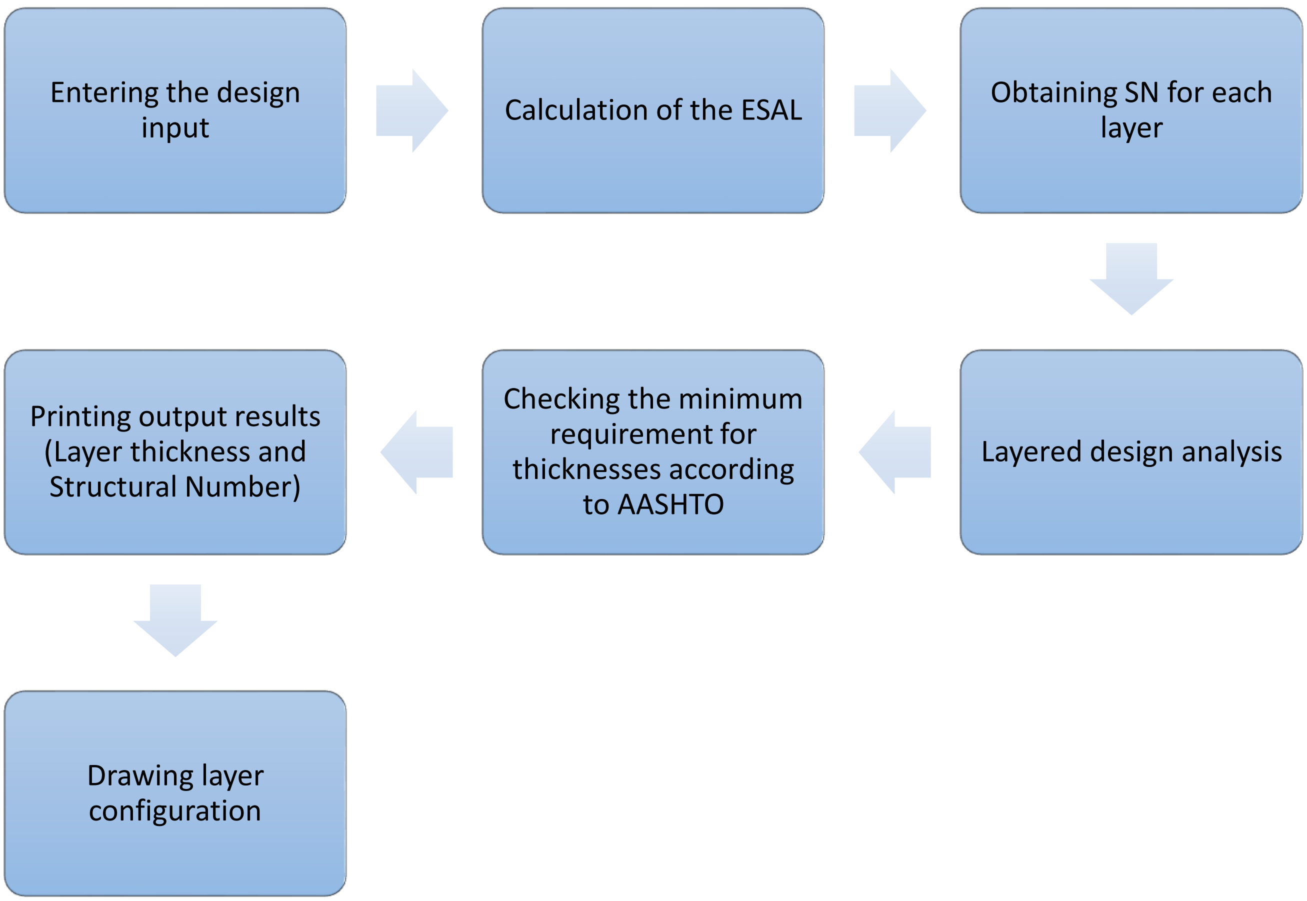

Figure 9: Flowchart of the MATLAB GUI

References

AASHTO Guide for Design of Pavement Structures. (1993). Washinton D.C.: Amerikan Assaciation of State Highway and Transportation Officials.

Bekele, A. (2011). Implementation of the AASHTO Pavement Design Procedures into MULTI-PAVE.

Izydor Kawa, Zhanmin Zhang, W. Ronald Hudson. (1998). EVALUATION OF THE AASHTO 18-KIP LOAD EQUIVALENCY CONCEPT. 4-6.

Nahusenay K. Gebrehiwot. (2011). *Implementation of Multiple Design Procedures into MULTI-PAVE*, 10-13.