



**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF GRADUATE STUDIES**

**DEPARTMENT OF ROAD AND TRANSPORTATION ENGINEERING**

**Thesis on**

**Software Development for the AASHTO and ERA  
Flexible Pavement Design Methods**

*Master Degree*

**By**

**Amare Setegn**

**Advisor Dr. Bikila Teklu**

**(September 2012)**



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## **Dedication**

This work is dedicated to all my beloved families for their affectionate and strong will for strengthening my pursuit in academic carrier, and to my remarkable late friend Dagnev Engidaw /RIP/ for his encouragement towards the success of this study and experience sharing on well-mannered administrative cleverness.

## **Abstract**

In Ethiopia the number and type of traffic increases and the change is alarming. This leads to the construction of road infrastructures which needs economical and safe design of roads. Nowadays, flexible pavement roads and surface failure before the expected design period has become a critical issue in our country.

The design in our country is based on the prevailing condition of soil and materials report using the Ethiopian Roads Authority (ERA) Pavement Design Manual where the results obtained will be compared with that of the *AASHTO* Structural Design Pavement manual. Finally, the thickness obtained using both design guides will be compared. And it is known that pavement thickness design in our country is manual based.

Manual design method has a drawback in avoiding human mistake, error and doing many alternatives for comparison as flexible pavement design involves different nomograph, charts, tables and formulas so it is cumbersome and time taking practice which may result in unsafe or uneconomical design.

The development of the software is using MATLABR2008b programming language. And the goals achieved are the thicknesses of surface, base and subbase layers of flexible pavement roads are determined and different design charts, default values and tables are digitalized.

Furthermore, comparison between AASHTO and ERA methods in terms of thickness and construction cost can be made to select the best design alternative. Besides, the designer or researcher can do as many alternatives as needed in short time.

The result obtained by the developed software (AASHERA) is verified by comparing with the manuals and examples from different books. And the analysis results turn out to be successful when it is compared with the manuals and books calculation.

*KEY WORDS: AASHTO Flexible Pavement Design, ERA Flexible Pavement Design, AASHTO Road Test, AASHERA*

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## Notations and Abrivation

<i>AASHERA</i>	is a name from AASHTO and ERA manual based design software in MATLAB
AASHO	is American Association of State Highway Officials
$\mathbf{a}_1$	is Layer coefficients representative of surface courses
$\mathbf{a}_2$	is Layer coefficients representative of base courses
$\mathbf{a}_3$	is Layer coefficients representative of subbase courses
<i>CBR</i>	is California Bearing Ratio
$D_D$	is Directional distribution factor
$D_L$	is Lane distribution factor
$D_1, D_2, D_3$	is Actual thicknesses of surface, base, and subbase courses
<i>ERA</i>	is Ethiopian Roads Authority
ESAL	is Equivalent Single Axle Loads
<i>g</i>	is yearly traffic growth rate
HMA	is Hot Mix Asphalt
<i>IRI</i>	is International Roughness Index
MATLAB	Stands for <i>matrix laboratory</i>
$m_2, m_3$	is Drainage coefficients for base and subbase layers
MDD	is maximum dry density of subgrade soil
$M_R$	is Subgrade resilient modulus
NAPA	is National Asphalt Pavement Association
PAPA	is Pennsylvania Asphalt Pavement Association
$\Delta PSI$	is difference between the initial design serviceability index, $p_o$ , and the design terminal serviceability index, $p_t$
<i>R</i>	is reliability of the pavement design process
$S_o$	is Combined standard error of the traffic prediction and performance prediction
SN	is Structural Number an index that is indicative of the total pavement thickness required
<i>t</i>	is road design period in years
TRL	is Transport Research Laboratory
WADOT	is Washington State Highway Pavements
$W_{18}$	is Predicted number of 80 KN (18,000 lb.) ESALs
$\widehat{W}_{18}$	is the cumulative two-directional 18-kip ESAL units predicted for a specific section of highway
$Z_R$	is the Standard normal deviate
$\mu_f$	is the relative damage of the subgrade soil to calculate effective roadbed resilient modulus

## 1. Introduction

These days the number and type of traffic increases from day to day throughout the world and in a country like Ethiopia the change is alarming. This leads to the construction of road infrastructures which needs economical and safe design of roads. The most common type of pavement used in Ethiopia is flexible pavements. There is still widespread use of essentially empirical design methods, ranging from “catalogues” of structural designs for various combinations of traffic loads and subgrade strength, to regression based design charts which incorporate such factors as material properties, temperature variations, equivalent single axle load (*ESAL*) applications, and bearing capacity. Complementing these structural designs is a large variety of performance prediction models (eg. International Roughness Index, *IRI*, vs age), distress prediction models (eg. fatigue damage and rutting damage vs *ESAL* accumulation, plus thermal cracking vs age) [1].

The design of flexible pavements in our country is based on the prevailing condition of soil and materials report using the Ethiopian Roads Authority (*ERA*) Pavement Design Manual, Volume 1 for Flexible Pavements and Gravel Roads, where the results obtained will be compared with that of the *AASHTO* Structural Design of Flexible Pavements manual. Finally, the thickness obtained using both design guides will be compared [2].

The *AASHTO* design method used is the one developed empirically from laboratory, field tests and measurements. The empirical design method comprises of assumptions, tables and empirically developed nomograph and charts. And it is known that the design offices in our country have no experience in using software rather it is common to use manual design method.

This application software will be used in the design of flexible pavements; in addition the program incorporates the computation of *ESAL*, reading the empirical graphs for design parameters and digitalizes all the default values and tables which would be used in the design from the manual.

It is clear that the use of software in the design will help in the development of the science and makes the cumbersome work easier. *MATLAB* has been used in the development of software like *MSLAB\_LOAD* program *AASHTO* rigid pavements design [3]. *MATLAB* will be used in the development of the software for the design of flexible pavements since it has features that are suitable in digitalizing the inputs and has an attractive and simple feature for

user interface. Then this MATLAB based program will increase the accuracy of the design and hardly comparable in time saving with that of manual design practice.

## **2. Statement of problem**

Road and surface failure is a critical issue on the flexible pavement where it involves a very high maintenance cost every year. One of the reasons causing these failures happened is improper or error of pavement thickness design.

In our country it is not common to use software based design of flexible pavements rather the design agencies practice the method by referring the hardcopy of design guideline manual and calculation. Therefore, human mistake and error cannot be fully avoided in the design which influences the quality of the design and development of the science. Manual design method has a drawback in doing many alternatives for comparison as flexible pavement design involves different nomograph, charts, tables and formulas so it is cumbersome and time taking practice which may result in unsafe or uneconomical design.

## **3. Objective**

The aim of the study is to digitalize the design inputs and develop software for the flexible pavement thickness design based on AASHTO and Ethiopian Roads Authority (ERA) manuals by using MATLABR2008b programming language. And the specific objectives are to:

- Determine the thicknesses of surface, base and subbase layers of flexible pavement roads
- Digitalize different design charts
- Digitalize default values and tables
- Compare the manual based design with the software outputs
- Comparison between AASHTO and Ethiopian Roads Authority (ERA) design methods in terms of thickness and construction cost to select the best design alternative.

#### **4. Scope of the Study**

The study focuses on developing AASHERA software for the flexible pavement thickness design by using AASHTO and Ethiopian Roads Authority (ERA) manuals. Furthermore, comparison is made between AASHTO and ERA methods in terms of thickness and construction cost to select the best design alternative. Besides, *AASHERA* will be tested and verified with manual calculations.

## **5. Thematic Literature Review**

### **5.1. Flexible Pavement**

Flexible pavement is a surface constructed by bituminous (or asphalt) materials. These can be either in the form of pavement surface treatments such as a bituminous surface treatment (*BST*) generally found on lower volume roads and *HMA* which were generally used on higher volume roads or highway network [4]. Successful HMA pavement construction requires good planning, design, construction (materials, subgrade, and workmanship) and planned future maintenance. Asphalt pavements are constructed of one or more courses of HMA placed directly on the subgrade or on an aggregate base [5].

Flexible road pavements are intended to limit the stress created at the subgrade level by the traffic traveling on the pavement surface, so that the subgrade is not subject to significant deformations. In effect, the concentrated loads of the vehicle wheels are spread over a sufficiently larger area at subgrade level. At the same time, the pavement materials themselves should not deteriorate to such an extent as to affect the riding quality and functionality of the pavement. These goals must be achieved throughout a specific design period [6].

The deterioration of paved roads caused by traffic results from both the magnitude of the individual wheel loads and the number of times these loads are applied. It is necessary to consider not only the total number of vehicles that will use the road but also the wheel loads (or, for convenience, the axle loads) of these vehicles. Equivalency factors are used to convert traffic volumes into cumulative standard axle loads. Traffic classes are defined for paved roads, for pavement design purposes, by ranges of cumulative number of equivalent standard axles (*ESAs*) [6].

In order to limit the stress created at the subgrade level by the traffic traveling on the pavement surface, material layers are usually arranged in order of descending load bearing capacity with the highest load bearing capacity material (and most expensive) on the top and the lowest load bearing capacity material (and least expensive) on the bottom.

### **5.2. Flexible Pavement Layers and Materials**

#### **Surface Course**

Obviously, surface course is the layer in contact with traffic loads and normally contains the highest quality of materials. Surface course play an important role in characteristics of friction, smoothness, noise control, rut and shoving resistance and drainage. Furthermore, surface course serves to prevent the entrance of excessive quantities of surface water into the

underlying base, subbase and subgrade. This top structural layer of material is sometimes subdivided into two layers [7]:

1. Wearing Course. This is the top layer in pavement structure and direct contact with traffic loads. A properly designed preservation program should be able to identify pavement surface distress while it is still confined to the wearing course.

2. Binder Course. The purpose of this layer is to distribute load from wearing course. This layer provides the bulk of the HMA structure.

### **Base Course**

The base course is a course of specified material and design thickness, which supports the structural course and distributes the traffic loads to the subbase or subgrade. It provides additional load distribution and contributes to drainage and frost resistance. A wide range of materials can be used as unbound road bases including crushed quarried rock, crushed and screened, mechanically stabilized, modified or naturally occurring 'as dug' gravels. Their suitability for use depends primarily on the design traffic level of the pavement and climate [6].

### **Subbase Course**

The subbase course is between the base course and the subgrade. The subbase generally consists of lower quality materials than the base course but better than the subgrade soils. The subbase consists of granular material - gravel, crushed stone, reclaimed material or a combination of these materials. It enables traffic stresses to be reduced to acceptable levels in the subgrade, it acts as a working platform for the construction of the upper pavement layers and it acts as a separation layer between subgrade and base course. Under special circumstances, it may also act as a filter or as a drainage layer. For a pavement constructed over a high quality stiff subgrade may not need the additional features offered by a subbase course [6].

### **Properties of Unbound Materials**

Table 5-1 gives guidance on the selection of unbound materials for use as base course, subbase, capping and selected subgrade layers.

**Table 5-1** Properties of Unbound Materials

Code	Description	Summary of Specification
<i>GB1</i>	Fresh, crushed rock	Dense graded, un weathered crushed stone, non-plastic parent fines
<i>GB2</i>	Crushed weathered rock, gravel or boulders	Dense grading, $PI < 6$ , soil or parent fines
<i>GB3</i>	Natural coarsely graded granular material, including processed and modified gravels	Dense grading, $PI < 6$ $CBR$ after soaking $> 80$
<i>GS</i>	Natural gravel	$CBR$ after soaking $> 30$
<i>GC</i>	Gravel or gravel-soil	Dense graded; $CBR$ after soaking $> 15$

Notes: 1. These specifications are sometimes modified according to site conditions; material type and principal use.

2. GB = Granular base course, GS = Granular sub-base, GC = Granular capping layer.

### 5.3. Advantages of HMA

There are several advantages of HMA shown as below [5]:

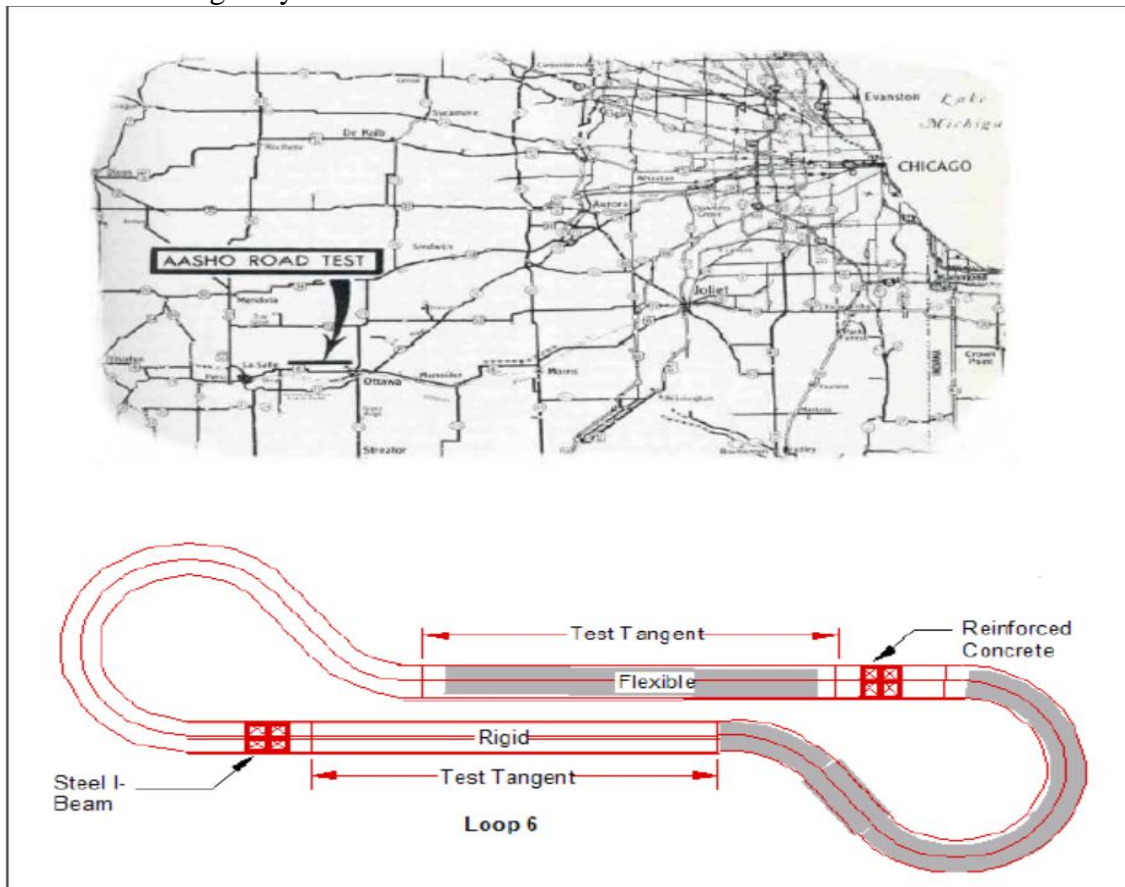
- Versatility
  - HMA pavements can be designed to handle any traffic loading, soils and materials, and can be used to salvage old pavements as well as to build new ones.
  - Phased construction can easily be incorporated.
- Economy
  - HMA pavements are economical to construct, can be constructed rapidly, immediately ready for use, can be recycled, require minimal maintenance and provide outstanding performance.
  - HMA pavements are not affected by ice control chemicals.
  - Building and site esthetics are enhanced.
  - Traffic noise is minimized when HMA pavement is used.
  - Pavement striping is highly visible on the black HMA surface.

### 5.4. Overview of AASHTO Guide for Design of Pavement Structures

In 1972, the AASHTO pavement design guide was first published as an interim guide. Updates to the guide were subsequently published in 1986 and 1993; a new mechanistic-based design guide is currently planned for completion in 2002. The AASHTO design procedure is based on the results of the AASHTO Road Test that was conducted in 1958 - 1961 in Ottawa, Illinois (Figure 5-1). Approximately 1.2 million axle load repetitions were applied to specially designed test tracks, it is the largest road test ever conducted [8].

**Figure 5-1** AASHTO Road Test (1958 – 1961)

Picture from: Highway Research Board



#### 5.4.1. AASHTO Road Test Limitation and Assumption

It is extremely important to know the equation's limitations and basic assumptions when using the 1993 AASHTO *Guide* empirical equation, otherwise, this can lead to invalid results at the least and incorrect results at the worst.

The empirical equations developed from AASHTO Road Test were related to loss in serviceability, traffic, and pavement thickness. Through the specific conditions of the AASHTO Road Test, these equations have some significant limitations [4]:

- The equations were developed based on the specific pavement materials and roadbed soil present at the AASHTO Road Test.
- The equations are based on an accelerated two-year testing period rather than a longer, more typical 20+ year pavement life. Therefore, environmental factors were difficult if not impossible to extrapolate out to a longer period. Thus, the equations were developed based on the environment at the AASHTO Road Test only.
- The equations were developed based on the loads of operating vehicles with identical axle loads and configurations, as opposed to mixed traffic.

Therefore, In order to apply the equations developed as a result of the AASHTO Road Test, some basic assumptions were made [4].

- Loading can be applied to mixed traffic by use of ESALs.
- The accelerated testing done at the AASHTO Road Test (2-year period) can be extended to a longer design period.
- The characterizations of material may be applied to other surface, base, and subbase by assigning appropriate layer coefficients.
- The characterization of subgrade support may be extended to other subgrade soils by an abstract soil support scale.

#### 5.4.2. Flexible Pavement Thickness Design

The American Association of State Highway Officials (*AASHTO*) has carries out a Road Test at Ottawa; Illinois provided the basis for calculating the required pavement thickness. Models (Road Test) were developed to related pavement performance, vehicle loadings, strength of roadbed soils, and the pavement structure [8].

Equation 5-1 is the AASHTO Empirical Equation used by the Department for design purposes [8]. Empirical equations are used to relate observed or measurable phenomena of pavement characteristics.

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

-----Equation 5-1

Where:  $W_{18}$  = Predicted number of 80 KN (18,000 lb.) ESALs

$Z_R$  = Standard normal deviate

$S_o$  = Combined standard error of the traffic prediction and performance prediction

SN = Structural Number

$\Delta PSI$  = difference between the initial design serviceability index,  $p_o$ , and the design terminal serviceability index,  $p_t$

$M_R$  = Subgrade resilient modulus (in psi)

The purpose of the AASHTO model is to calculate the Required Structural Number (SN) in the pavement thickness design process [8]. SN is the strength of the pavement that must be constructed to carry the mixed vehicle loads over the roadbed soil, while providing

satisfactory serviceability during the design period. Therefore, by conducting the SN, the pavement layer thickness can be calculated which is discussed briefly in the methodology.

### **Accumulated 18-kip Equivalent Single Axle Loads ESAL**

The predicted loading is simply the predicted number of 80 KN (18,000 lb.) ESALs for the pavement experience over its design lifetime. The Accumulated 18-kip Equivalent Single Axle Loads (ESAL) is the traffic load information used for pavement thickness design. The accumulation of the damage caused by mixed truck traffic during a design period is referred to the Accumulated 18-kip Equivalent Single Axle Loads ESAL.

### **Reliability**

The reliability of the pavement design process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period [8]. The use of Reliability (R %) also tailors the design to more closely match the needs of the project. It is the probability of achieving the design life that the Department desires for that facility. The standard normal deviate ( $Z_R$ ) and the standard deviation ( $S_o$ ) are used in equation 1 to account reliability.

### **Roadbed Soil Resilient Modulus (MR)**

Subgrade support is characterized by the subgrade resilient modulus ( $M_R$ ). The Resilient Modulus ( $M_R$ ) is a measurement of the stiffness of the roadbed soil [8]. A material's resilient modulus is actually an estimate of its modulus of elasticity (E). While the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads – like those experienced by pavements [4].

It is recognized that many agencies do not have equipment for performing the resilient modulus test. Therefore, suitable factors are reported which can be used to estimate MR from standard CBR, R-value, and soil index test results or values. A widely used empirical relationship developed by Heukelom and Klomp (1962) and used in the 1993 AASHTO Guide is equation 5-2: [4]

$$M_R(\text{psi}) = 1500 * CBR \text{-----Equation 5-2}$$

The resilient modulus of the hot mix asphalt is the most common method of measuring stiffness modulus. The test procedures for conducting this test are described in ASTM D4123 [5].

**Standard Normal Deviate ( $Z_R$ )** is the corresponding Reliability (R) value that has been converted into logarithmic form for calculations purposes [8].

**Standard Deviation ( $S_O$ )** takes into consideration the variability of all input data. The 1993 design guide recommends an approximate range of 0.4 to 0.5 for flexible pavements [8].

**Change in Serviceability ( $\Delta PSI$ )** is the difference between the Initial Serviceability ( $P_o$ ) and Terminal Serviceability ( $P_t$ ) [8]. Present Serviceability Index (PSI) is the ability of a roadway to serve the traffic which uses the facility. A rating of 0 to 5 is used with 5 being the best and 0 being the worst [8]. The PSI decreases as the road condition decreases due to deterioration.

**Initial Serviceability ( $P_i$ )** is the condition of a newly constructed roadway. **Terminal Serviceability ( $P_t$ )** is the condition of a road that reaches a point where some type of rehabilitation or reconstruction is warranted. The typical  $P_o$  value for a new pavement is 4.6 or 4.5. The recommended values of  $P_t$  are 3.0, 2.5 or 2.0 for major roads, intermediate roads and secondary roads, respectively.

### **5.5. Overview of Ethiopian Roads Authority (ERA) Manual**

This manual gives recommendations for the structural design of flexible pavement and gravel roads in Ethiopia. The manual is intended for engineers responsible for the design of new road pavements and is appropriate for roads which are required to carry up to 30 million cumulative equivalent standard axles in one direction. This upper limit is suitable at present for the most trafficked roads in Ethiopia [6].

ERA manual which also known as overseas road notes was developed by Transport Research Laboratory (TRL) to design flexible pavement thickness besides understanding the behaviors of road building material, also interaction in pavement structural layers design. In advance, overseas road notes is confident to be applying in tropical and sub tropical regions associated with climate and various types of material and reliable road maintenance levels [9].

To give satisfactory service, a flexible pavement must satisfy a number of structural criteria or considerations; some of these are illustrated in Figure 5-2. Some of the important considerations are:

- (1) The subgrade should be able to sustain traffic loading without excessive deformation; this is controlled by the vertical compressive stress or strain at this level,

- (2) Bituminous materials and cement-bound materials used in road base design should not crack under the influence of traffic; this is controlled by the horizontal tensile stress or strain at the bottom of the road base,
- (3) The road base is often considered the main structural layer of the pavement, required to distribute the applied traffic loading so that the underlying materials are not overstressed. It must be able to sustain the stress and strain generated within itself without excessive or rapid deterioration of any kind.
- (4) In pavements containing a considerable thickness of bituminous materials, the internal deformation of these materials must be limited; their deformation is a function of their creep characteristics,
- (5) The load spreading ability of granular subbase and capping layers must be adequate to provide a satisfactory construction platform.

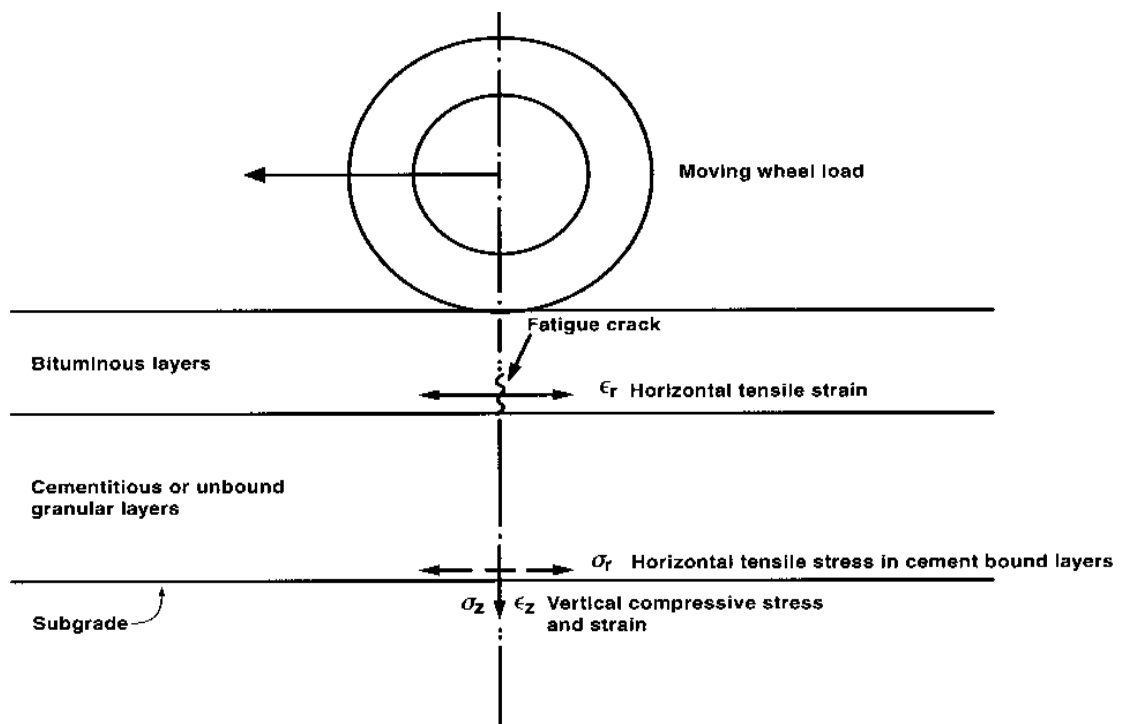


Figure 5-2 Critical Stresses and Strains in a Flexible Pavement

In practice, other factors have to be considered such as the effects of drainage. When some of the above criteria are not satisfied, distress or failure will occur. For instance, rutting may be the result of excessive internal deformation within bituminous materials, or excessive deformation at the subgrade level (or within granular layers above) [6].

### **Main Characteristics of Major Material Types: Granular Materials**

Granular materials include selected fill layer; gravel subbase, road base or wearing course; and crushed stone subbase or road base. These materials exhibit stress dependent behavior, and under repeated stresses, deformation can occur through shear and/or densification.

The selected fill, compacted at 95% MDD (AASHTO T180) exhibits a minimum soaked CBR of 10%. Its minimum characteristics are specified by a minimum grading modulus (0.75) and maximum plasticity index (20%). The gravel subbase and road base materials have minimum soaked CBRs of 30% and 80% respectively, when compacted to 95% and 98% MDD respectively [6].

Thus, ERA manual structural catalogue had been produce in order to design the flexible pavement thickness design based on the traffic and subgrade strength classes' requirement [6]. The catalogue shown in figure 5-3 is for granular road base and subbase layer materials.

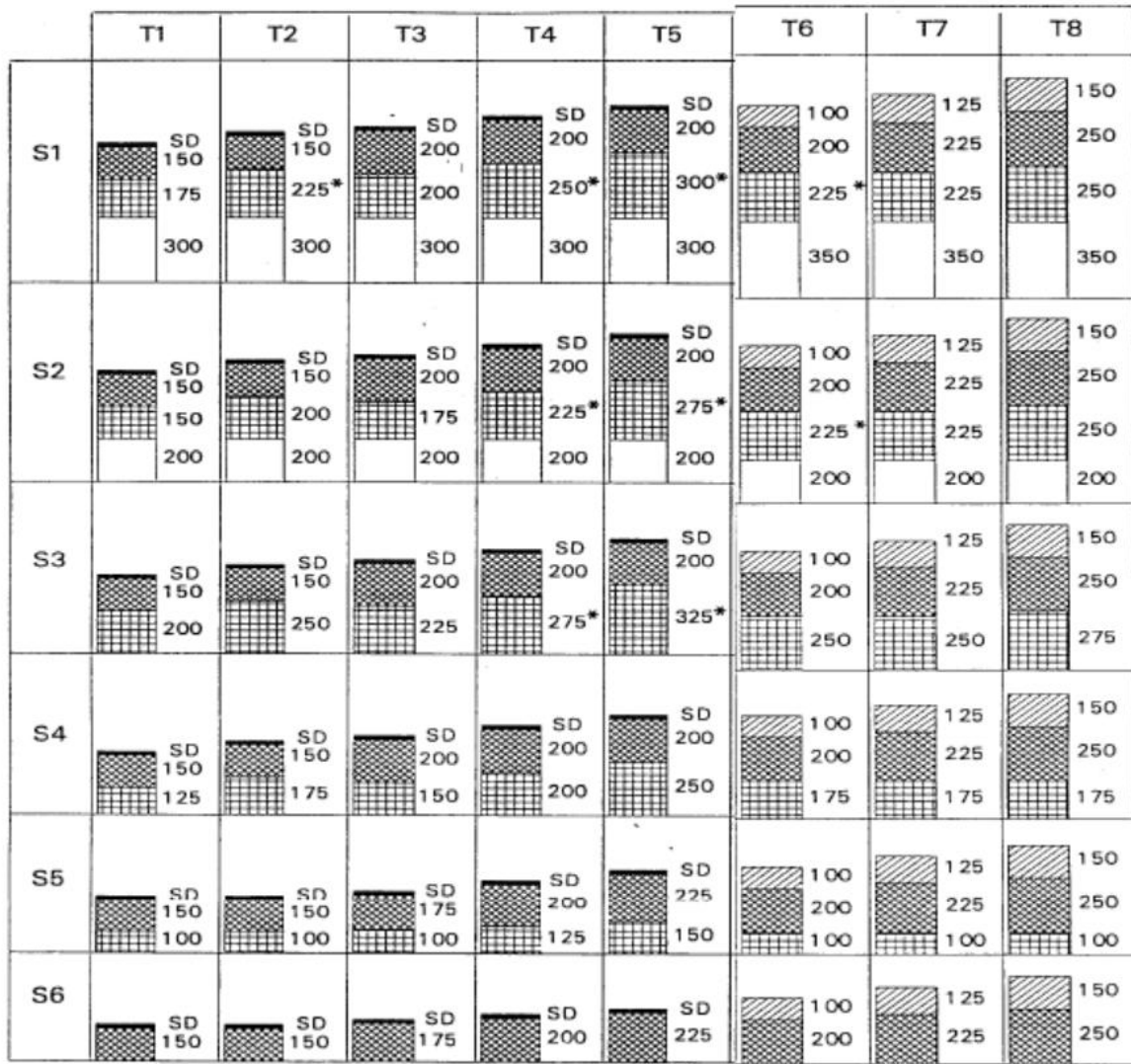


Figure 5-3 Ethiopian Roads Authority Structural Catalogue

## 5.6. MATLAB Programming

Computer software is a general term used to describe a collection of computer program, procedures and documentation that perform some tasks on a computer system. Software encompasses an extremely wide array of products and technologies developed using different techniques such as programming languages.

In computer software development, there are four steps that need to be considered to enhance the reputation of programmer and develop a successful computer software program as [10]:

**Design** is the first step; design processes include defining the data requirements, objective, scope and chosen of function or process to be used clear output to be achieved.

**Coding** is the second step; the program is written in the language chosen and ensures the language syntax rules followed precisely.

**Testing computer programs** the purpose of testing is to ensure that the program works as expected.

**Maintenance of Computer Software** is important to the changes of requirements for programs from time to time. Simple steps such as commenting code can help, as well as providing a statement of intent at the top of the code and a history of changes.

The MATLAB high-performance language for technical computing integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include

- Math and computation
- Algorithm development
- Data acquisition
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

The name MATLAB stands for *matrix laboratory*. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis.

MATLAB also provides many interesting sets of tools to make our life far easier in building exciting applications because all the real hard code is already written for us. MATLAB is not only a programming language but also a true graphical development environment. MATLAB also has the ability to develop programs that can be used as a front-end application to a database system, serving as the user interface which collects user input and displays formatted output in a more appealing and useful form [11].

## 6. Methodology

### 6.1. Introduction

The main requirement is to determine the thicknesses of various pavement layers to satisfy the design objectives and comparison between AASHTO and Ethiopian Roads Authority (ERA) design methods in terms of thickness and construction cost to select the best design alternative.

This section will review the design stages of flexible pavement by AASHTO, 1993 and Ethiopian Roads Authority, 2001 and describes the framework of the AASHERA software development.

### 6.2. Framework for the Development of AASHERA

The development of AASHERA software for the design of flexible pavement for the two design methods is 8 stages which are illustrated in Chart 6-1.

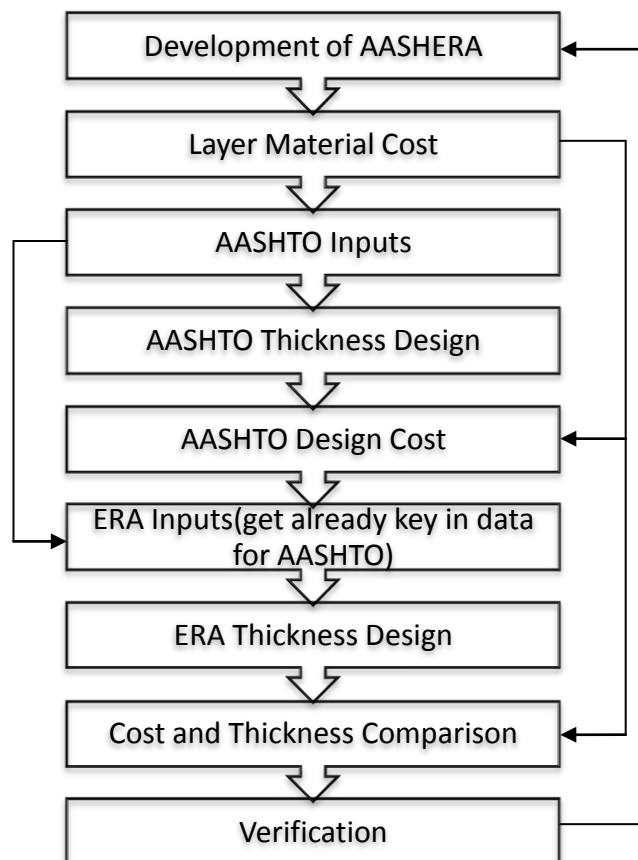


Chart 6-1 Frameworks for the Development of AASHERA

### 6.3. AASHTO Guide for Design of Pavement Structures

#### 6.3.1. Predicted Number of 18-kip ESAL, $W_{18}$

Normally, the design procedure for traffic volume is based on cumulative expected 18-kip ESAL during the analysis period,  $W_{18}$  [8].  $W_{18}$  is known as Predicted number of ESALs over the pavement's life. Thus, the traffic during the first year in the design lane ( $w_{18}$ ) 18-kip ESAL application can be determined by equation 6-1.

$$w_{18(\text{traffic during first year})} = D_D * D_L * \widehat{w}_{18} \text{ -----Equation 6-1}$$

Where:

$w_{18}$  = Cumulative one direction 18-kip ESAL units predicted for a specific section of highway during the analysis period.

$D_D$  = Directional distribution factor, express as a ratio that accounts for the distribution of ESAL unit by direction. ( $D_D = 0.3$  to  $0.7$ )

$D_L$  = Lane distribution factor, express as a ratio that accounts for distribution of traffic when two or more lanes are available in one direction (Table 6-1).

$\widehat{w}_{18}$  = the cumulative two-directional 18-kip ESAL units predicted for a specific section of highway during the analysis period (from the planning group).

Table 6-1 Lane distribution factor (DL) (AASHTO Guide 1993)

Number of lanes in each direction	Percent of 18-kip ESAL in design lane
1	100
2	80-100
3	60-80

Therefore, the cumulative 18-kip ESAL traffic for the design period can be determined by using equation 6-2 [8]:

$$\text{Cumulative 18 - kip ESAL, } W_{18} = w_{18(\text{traffic during first year})} \left[ \frac{(1+g)^t - 1}{g} \right] \text{ -----Equation 6-2}$$

Where  $g$  = growth rate in percent and  $t$  = design period in years

### 6.3.2. Subgrade Soil Resilient Modulus ( $M_R$ )

Resilient modulus ( $M_R$ ) values for pavement structure design should normally be based on the properties of the compact layer of roadbed soil. In the flexible pavement design requirements, it may necessary to convert CBR value or R-value information to resilient modulus,  $M_R$ . Typically  $M_R$  for flexible pavement is from 3,000 to 30,000 psi [8]. The procedures of determination of Effective Subgrade Resilient Modulus ( $M_{R,eff}$ ) are shown as the steps below:

1. Obtain  $M_R$  values (Separate year into time intervals)
2. Compute the relative damage ( $\mu_f$ ), by using Chart 6-3 or using equation 6-3:

$$\mu_f = 1.18 * 10^8 * M_R^{-2.32} \text{ -----Equation 6-3}$$

3. Compute average  $\mu_f$  for entire year using equation 6-4:

$$\frac{\sum \mu_f}{n} \text{ -----Equation 6-4}$$

Where n = the total number of interval time.

4. Determine effective  $M_R$  using average  $\mu_f$  by using Chart 6-3 or Equation 6-3.

Alternatively we can calculate the effective resilient modulus of the subgrade by multiplying the CBR value of the subgrade by 1500.

### 6.3.3. Design Serviceability Loss, $\Delta PSI$

The serviceability of a pavement is defined as its ability to serve the type of traffic (automobiles and trucks) which use the facility. The primary measure of serviceability is the Present Serviceability Index (PSI), which ranges from 0 (impossible road) to 5 (perfect road) [8]. The serviceability loss is the difference between the initial serviceability index and the terminal serviceability index:

$$\Delta PSI = P_o - P_t \text{ -----Equation 6-5}$$

Where:  $P_o$  = Original or initial serviceability

$P_t$  = Terminal serviceability index

According to AASHTO Road Test, the recognized original or initial serviceability ( $P_o$ ) value was 4.7 for flexible pavement. Meanwhile the terminal serviceability index ( $P_t$ ) of 2.5 or higher is suggested for design of major highway and 2.0 for low traffic volume [8].

Month	Roadbed Soil Modulus, $M_R$ (psi)	Relative Damage $u_f$
Jan	20,000	0.01
Feb	20,000	0.01
Mar	2,500	1.51
Apr	4,000	0.51
May	4,000	0.51
June	7,000	0.13
July	7,000	0.13
Aug	7,000	0.13
Sept	7,000	0.13
Oct	7,000	0.13
Nov	4,000	0.51
Dec	20,000	0.01
Summation:	$\Sigma u_f =$	3.72

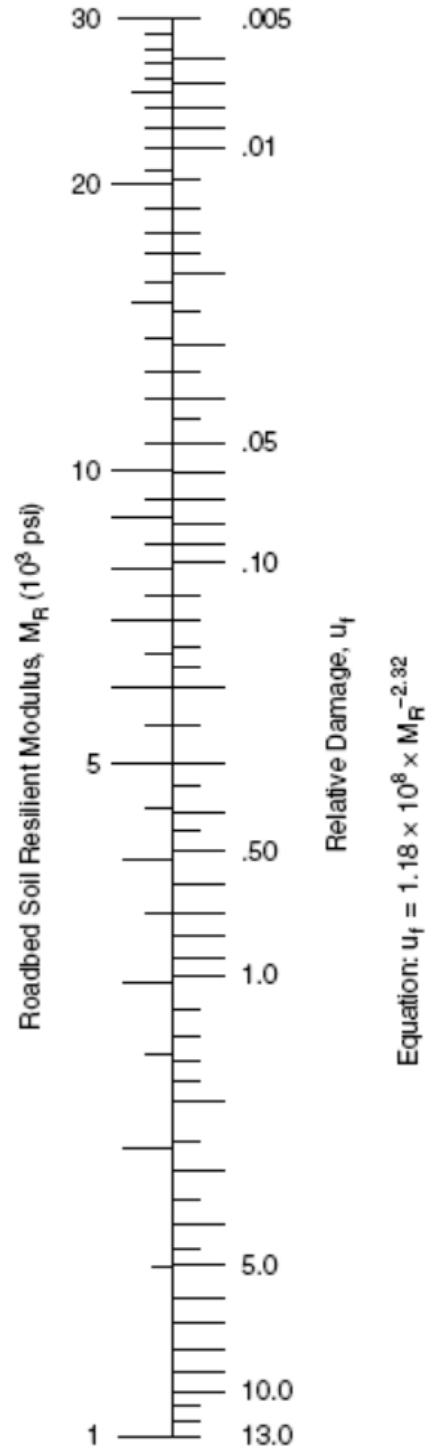


Chart 6-2 Estimation of effective roadbed soil resilient modulus

### 6.3.4. Reliability, R

Basically, it is a means of incorporating some degree of certainty into the design process to ensure that the various design alternatives will last the analysis period. The reliability design factor accounts for chance variations in both traffic prediction ( $W_{18}$ ) and the performance prediction ( $W_{t18}$ ), and therefore provides a predetermined level of assurance (R) that pavement sections will survive the period for which they were designed. Note that the higher levels correspond to the facilities which receive the most use, while the lowest level, 50 percent, corresponds to local roads [8].

The performance equation 6-6 gives the allowable number of 18-kip (80-KN) single axle load applications  $W_{t18}$  to cause the reduction of PSI to  $P_t$ . If the predicted number of applications  $W_{18}$  is equal  $W_{t18}$ , the reliability of the design is 50%, because all variables in equation 6.6 are based on mean values. To achieve a higher level of reliability  $W_{18}$  must be smaller than  $W_{t18}$  by a normal deviate  $Z_R$  [12].

$$\log W_{t18} = 9.36 \log(SN + 1) - 0.2 + \frac{\log \left[ \frac{\Delta PSI}{4.2 - 1.5} \right]}{0.4 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \log(M_R) + 8.07$$

-----Equation 6-6

$$\log W_{18} = Z_R * S_o + \log W_{t18}$$

-----Equation 6-7

$$Z_R = \frac{\log W_{18} - \log W_{t18}}{S_o}$$

-----Equation 6-8

In this study, the recommended reliability level for different types of road is shown in table 6-2 .These values have corresponding standard normal deviates ( $Z_R$ ). Therefore, in AASHERA when the engineer chooses a certain degree of reliability from the dropdown menu, the corresponding  $Z_R$  will automatically be incorporated in the design equation. Table 6-3 shows the corresponding  $Z_R$  values for the different reliability values [8].

Table 6-2 Suggested level of Reliabilities for various functional classifications

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 6-3 Standard Normal Deviates for various levels of reliability

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

### 6.3.5. Overall Standard Deviation, $S_o$

The overall standard deviation ( $S_o$ ) takes into consideration the variability of all input data. According to AASHTO Guide 1993, the recommended performances predict error developed at the Road Test was 0.35 for flexible pavement. However, the AASHTO 1993 design guide recommends an approximate range of 0.4 to 0.5 for flexile pavements and the standard deviation must be selected according to the local conditions with 0.35 for no traffic variation and 0.45 with traffic variation.

### 6.3.6. Pavement Layer Material Characteristic

#### Layer Coefficient, $a_i$

According to AASHTO 1993, there are 3 common types of pavement material constituted the individual layers of the structure known as Asphalt concrete surface course ( $E_{AC}$ ,  $a_1$ ), granular base layers ( $E_{BS}$ ,  $a_2$ ), and granular subbase layers ( $E_{SB}$ ,  $a_3$ ).

The layer coefficient  $a_i$  is a measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement. Layer coefficients can be determined from roads test as was done in the AASHO Road Test or from correlations with material properties. The elastic (resilient) modulus has been adopted as the standard material quality measure, so the layer coefficient in AASHERA is based on the resilient modulus of the material.

Though there are correlations available to determine the modulus from tests such as the R-value, the procedure recommended is direct measurement using AASHTO Method T-274 (subbase and unbound granular materials) and ASTM D-4123 for asphalt concrete and other stabilized materials [8].

Therefore, the layer coefficients for  $a_1$ ,  $a_2$  and  $a_3$  can be determined from Chart 6-3, Chart 6-4 and Chart 6-5 respectively by applying the elastic modulus of asphalt concret ( $E_{AC}$ ), base layer ( $E_{BS}$ ) and subbase layer ( $E_{SB}$ ) into the charts or using equation 6-9, 6-10 and 6-11 respectively:

$$a_1 = 0.169(\ln E_{AC}) - 1.76 \text{ -----Equation 6-9}$$

$$a_2 = 0.249(\log_{10} E_{BS}) - 0.977 \text{ -----Equation 6-10}$$

$$a_3 = 0.277(\log_{10} E_{SB}) - 0.839 \text{ -----Equation 6-11}$$

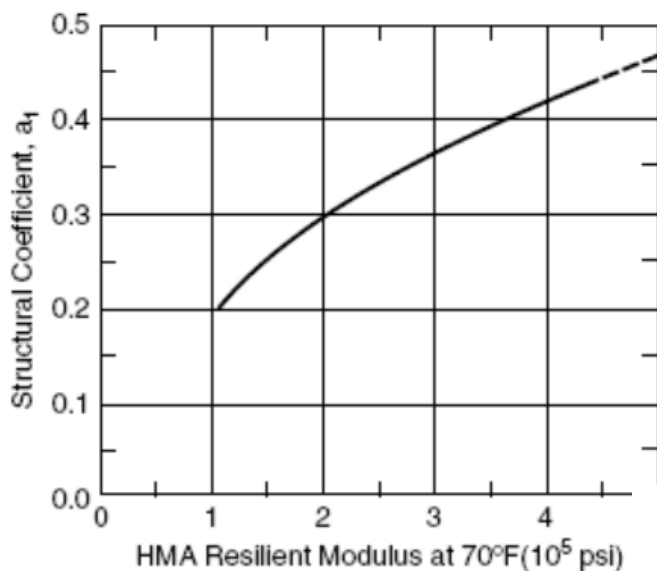
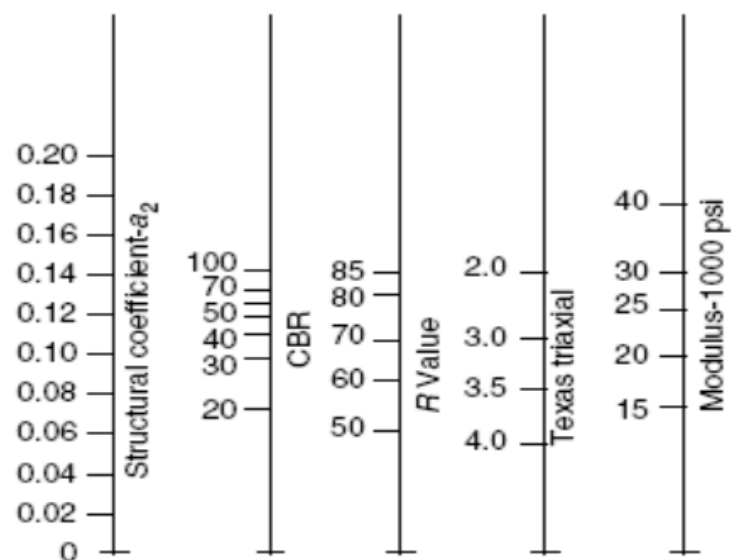


Chart 6-3 Chart for estimating structural layer coefficient of dense-graded asphalt concrete ( $a_1$ ) based on the elastic (resilient) modulus.

Chart 6-4 Variation in granular base layer coefficient ( $a_2$ ) with various base strength parameters.



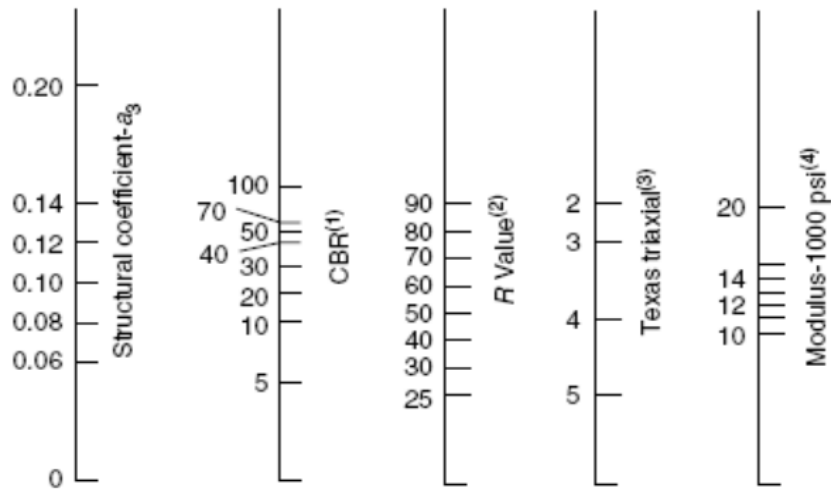


Chart 6-5 Variation in granular subbase layer coefficient ( $a_3$ ) with various subbase strength parameters (AASHTO Guide 1993)

### Drainage Coefficient ( $m_i$ )

The factor used for modifying the layer coefficients for drainage is called drainage coefficient,  $m_i$ . Drainage coefficients are measures of the quality of drainage and the availability of moistures in the granular base and subbase. Generally, quick draining layers that almost never saturate can have drainage coefficients as high as 1.4, while slow-draining layers that often saturate can have drainage coefficients as low as 0.40.

Two equal drainage coefficients ( $m_2$  and  $m_3$ ) are needed for the base and subbase layers, respectively. It is up to the design engineer to identify what level of drainage is achieved under a certain set of drainage conditions. AASHERA takes the average drainage coefficient values for each range to avoid manual reading of the table developed by AASHTO as shown in table 6-4.

Table 6-4 Recommended drainage coefficient for untreated base and subbase layers in flexible pavements

Quality of Drainage		% of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Rating	Water Removed within	<1%	1-5%	5-25%	>25%
Excellent	2 h	1.40-1.35	1.35-1.30	1.30-1.20	1.20
Good	1 day	1.35-1.25	1.25-1.15	1.15-1.00	1.00
Fair	1 week	1.25-1.15	1.15-1.05	1.00-0.80	0.80
Poor	1 month	1.15-1.05	1.05-0.80	0.80-0.60	0.60
Very Poor	Never drain	1.05-0.95	0.95-0.75	0.75-0.40	0.40

### 6.3.7. Determination of Structural Number (SN) and Layer Thickness

Structural Number (SN) is an index that is indicative of the total pavement thickness required. It is also known as abstract number expressing structural strength. Once the design structural number (SN) for the pavement structure is determined from the nomograph, a set of pavement layer thickness, when combined will provide the load-carrying capacity corresponding to the design. The following equation 6-12 provides the basis for converting the SN into actual thickness of surface, base and subbase courses [8]:

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + \dots a_n D_n m_n \text{-----Equation 6-12}$$

Where:

$a_1$  = Layer coefficients representative of surface courses (Chart 6-3)

$a_2$  = Layer coefficients representative of, base courses (Chart 6-4)

$a_3$  = Layer coefficients representative of subbase courses (Chart 6-5)

$D_1, D_2, D_3$  = Actual thicknesses (in inches) of surface, base, and subbase courses

$m_2, m_3$  = Drainage coefficients for base and subbase layers (Table 6-4)

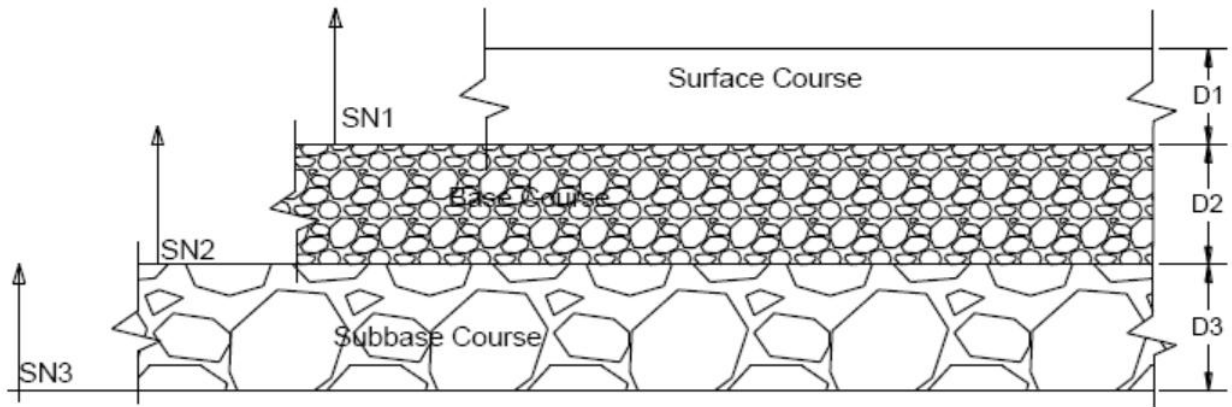


Figure 6-1 Structural number and thickness of pavement structure to be calculated

The general Equation 5-1 was derived from empirical information obtained from AASTHO Road Test. The design nomograph (Chart 6-6) can solve this equation to determine the structural number (SN) for flexible pavement design [8] .

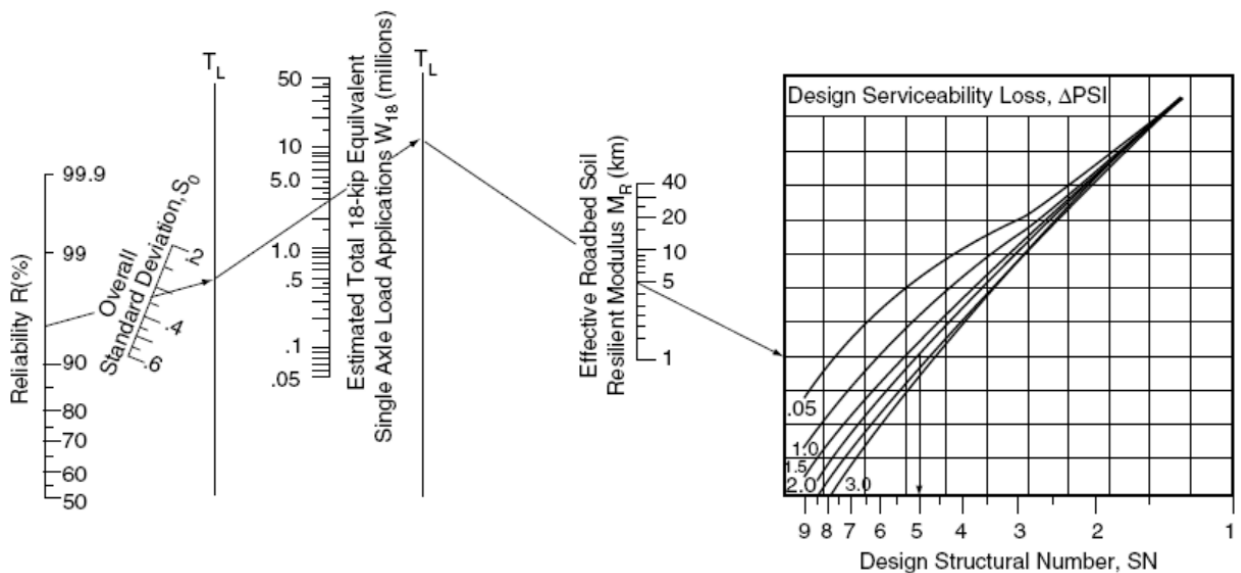


Chart 6-6 Design chart for flexible pavements based on using mean values for each input

The general procedures to determine the thickness of pavement corresponding to the design SN are as shown below:

1. Using  $E_{AC}$  as the  $M_R$  value, determine from Chart 6-6 the structural number  $SN_1$  required to protect the base and compute the thickness of layer 1 by using equation 6-13 below:

$$D_1^* \geq \frac{SN_1}{a_1} \text{-----Equation 6-13}$$

Check  $SN_1^* = a_1 D_1^* \geq SN_1$  OK!

- Using  $E_{BS}$  as the  $M_R$  value, determine from Chart 6-5 the structural number  $SN_2$  required to protect the subbase and compute the thickness of layer 2 by using equation 6-14 below:

$$D_2^* \geq \frac{SN_2 - SN_1^*}{a_2 m_2} \text{-----Equation 6-14}$$

$$SN_2^* = a_2 m_2 D_2^*$$

Check  $SN_1^* + SN_2^* \geq SN_2$  OK!

- Based on the roadbed soil resilient modulus  $M_{R,eff}$ , determine from Chart 6-5 the total structure number  $SN_3$  require and compute the thickness of layer 3 by using equation 6-15 below:

$$D_3^* \geq \frac{SN_3 - (SN_1^* + SN_2^*)}{a_3 m_3} \text{-----Equation 6-15}$$

$$SN_3^* = a_3 m_3 D_3^*$$

Check  $SN_1^* + SN_2^* + SN_3^* \geq SN_3$  OK!

- Therefore, the total thickness for pavement structure =  $D_1^* + D_2^* + D_3^*$

**Minimum Thickness:** it is generally impractical and uneconomical to use layers of material that are less than some minimum thickness. Furthermore, traffic considerations may dictate the use of a certain minimum thickness for stability. Table 6-5 shows the minimum thickness of asphalt surface and aggregate base. Because such minimum depend somewhat on local practices and conditions, they may be changed if needed [8].

Table 6-5 Minimum Thickness (inch)

Traffic, ESAL's	Asphalt Concrete	Aggregate Base
Less than 50,000	1	4
50,001–150,000	2	4
150,001–500,000	2.5	4
500,001–2,000,000	3	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4	6

#### 6.4. Design Stages for Ethiopian Roads Authority (ERA) method

The design stage of Ethiopian Roads Authority (ERA) was divided in to 3 main parts as shown below:

1. Estimate the amounts of traffic and cumulative number of equivalent standard axles over the design life of the road. The ESA obtained will be used to identify the traffic classes (Table 6-6)
2. Determine the subgrade strength classes based on CBR value (Table 6-7)
3. Select the combination of pavement material and thickness from the structural catalogue (Chart 6-7) that will meet the satisfactory of pavement service and design life based on T and S values.

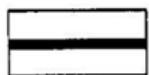
Table 6-6 Traffic class

<b>Traffic Classes (10<sup>6</sup>esa)</b>
T1 = < 0.3
T2 = 0.3-0.7
T3 = 0.7-1.5
T4 = 1.5-3.0
T5 = 3.0-6.0
T6 = 6.0-10
T7 = 10-17
T8 = 17-30

Table 6-7 Subgrade Strength class

<b>Subgrade strength classes (CBR %)</b>
S1 = 2
S2 = 3-4
S3 = 5-7
S4 = 8-14
S5 = 15-29
S6 = 30+

#### Material Definitions



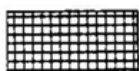
**Double surface dressing**



**Bituminous surface**  
(Usually a wearing course, WC, and a basecourse, BC)



**Granular roadbase, GB1 - GB3**



**Granular sub-base, GS**

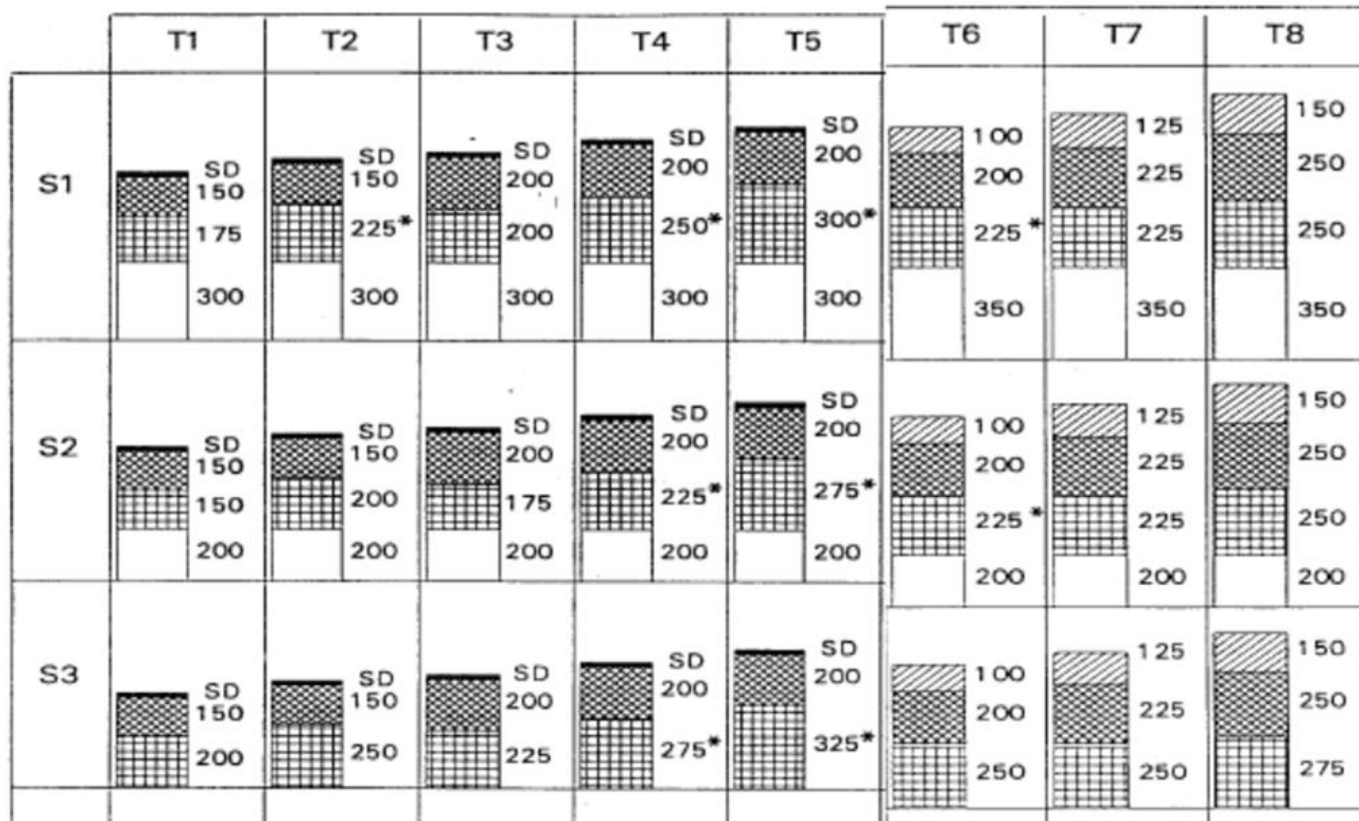


Chart 6-7 Ethiopian Roads Authority (ERA) structural catalogue sample

In AASHERA software, the inputs required in the design are called from AASHTO design process that the user key in previously. Therefore, the Ethiopian Roads Authority method is sharing the same input with AASHTO method but provided different design results.

## 7. Result Analysis and Discussion

### 7.1. Introduction

The development of flexible pavement thickness design software was done by using *MATLAB R2008b* programming language. AASHTO, 1993 and Ethiopian Road Authority (ERA) design methods are incorporated in the development of the software. This section describes how the user input the required variables and analyse for all pavement thickness design methods.

### 7.2. Result analysis and discussion

#### 1. Starting AASHERA

The main graphical user interface is the first screen that the user sees when AASHERA opens for the first time, as shown in Figure 7-1. It gives access to the file, inputs, output, comparison and help menu bars. Meanwhile, when the main graphical user interface begins the first show is Tips dialogue box to provide introduction, direction and improve users understanding about AASHERA software. After reading the Tips click > **Ok** to exit the dialogue box.

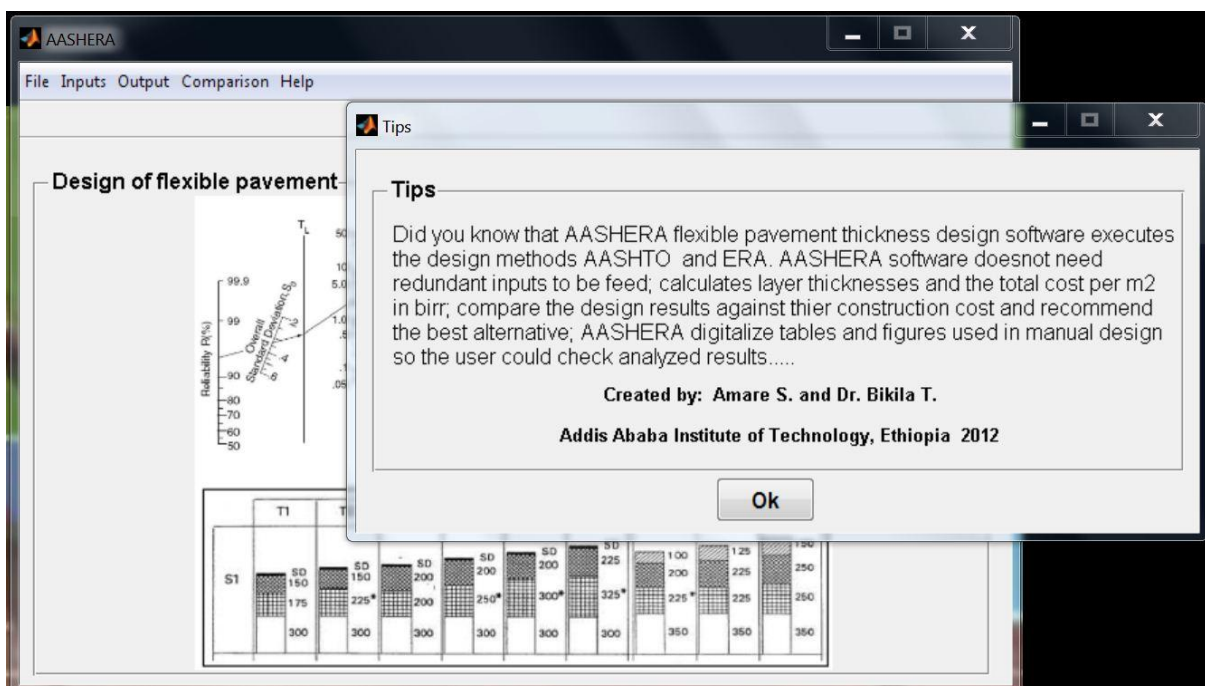


Figure 7-1 Main graphical user interface and tips dialogue box

After exiting the tips dialogue box the main graphical user interface appears (Figure 7-1) which contains the menu bar. In addition, AASHTO nomograph and ERA charts are shown

in the panel to introduce the designer as the software will design both the above mentioned methods.

To begin a new project, select **inputs** which gives dropdown list of different input submenus > click **Material Price** > start feeding the prices and go to the other inputs required. Feeding all the inputs required, select **Output** > click **AASHTO Thickness Design** > click the **analyse button** and get the thicknesses calculated for surface, base and subbase layers > click **Back** button in the dialogue box to return to the main user interface. And similar procedures will be followed to the other submenus (AASHTO Design Cost and ERA Thickness Design) in the Output menu bar. To see the comparison of the two methods results against construction cost, thickness and to get help from AASHERA follow similar procedures as clarified above.

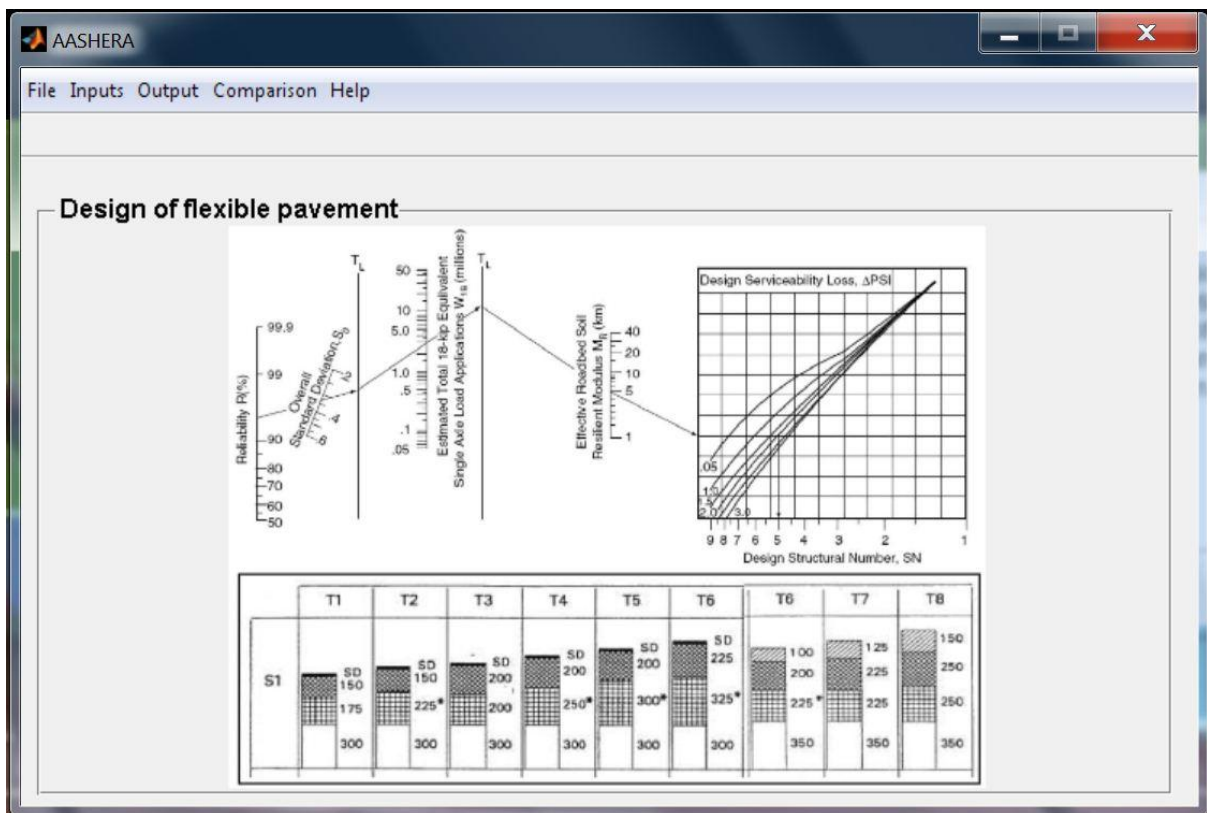


Figure 7-2 Main graphical user interface dialogue box

## 2. Material Price

The Material Price dialogue box (Figure 7-3) will appear when the user select **inputs** from the main user interface and > click **Material Price**.

The name of the project and its description are filled in this dialogue box then this information will be incorporated in the design report. The current material price should be keyed in Ethiopian birr for 50mm thick and one m<sup>2</sup> layer to make easier and uniform input for the user. The material price will be used in the calculation of construction cost for the two design methods. Click > **Done** button in the dialogue box to return to the main user interface.

Project	
Name :	Lot-1
Description :	Piazza to 5-killo Road

Material Price per Layer in Birr	
AC with 50mm Thickness =	424 per Sq.meter
Base with 50mm Thickness =	110 per Sq.meter
Subbase with 50mm Thickness =	63 per Sq.meter
Subgrade with 50mm Thickness =	32 per Sq.meter

Done

Figure 7-3 Material Price dialogue box

### 3. AASHTO Input Data

The AASHTO input data will be keyed in the input menu bar dropdown submenu bar dialogue boxes. The parameters that the designer will feed are traffic data, reliability, serviceability index, resilient modulus of pavement layers, roadbed resilient modulus and drainage properties of layers.

#### 3.1. Traffic Data, Reliability and Serviceability Loss

AASHTO input dialogue box (Figure 7-4) will appear when the user select **inputs** from the main user interface and > click **AASHTO Input**.

Traffic Input Data	
Cumulative 2 direction ESALs(18Kip), w18 :	2.5 x10 <sup>6</sup>
Design Period :	15
Growth Rate(%) :	3
Directional Distribution, Dd(%) :	50
Lane Distribution Factor, DL(%) :	80

Reliability	
Reliability, R(%) :	95
Standard Deviation, So :	0.35
Standard Normal Deviate, ZR :	-1.645

Serviceability Loss	
Initial Serviceability Index, Po :	4.6
Terminal Serviceability Index, Pt :	2.5
Design Serviceability Loss, Po-Pt :	2.1

Traffic Data Result	
ESAL During 1st yr (1 Direction), w18 :	1e+006
Cumulative ESAL for Design Period W18:	1.85989e+007

Figure 7-4 Traffic data, reliability and serviceability inputs dialogue box

These inputs are important in order to determine one direction ESAL during first year, cumulative 18-KIP ESAL, serviceability loss and standard normal deviate. The designer will key in the required variables and select the parameters that are presented in a dropdown list like directional distribution, lane distribution and reliability.

Furthermore, the lane distribution factor table (Figure 7-5) can be referred by clicking > **Refer** button; the standard normal deviate will be changed automatically for your selection of reliability. Then click > **Done** button to analyse the inputs which gives the traffic data result and the loss in serviceability loss. Click > **Back** button to get back to the main menu interface.

No. of Lanes in Each Direction	% of 18-kip ESAL in the Design Lane
1	100
2	80–100
3	60–80
4	50–70

Figure 7-5 Lane Distribution Factor Table [8]

### 3.2. Elastic Modulus of Pavement Layers $E_{AC}$ , $E_{BS}$ and $E_{SB}$

Elastic modulus of pavement layers dialogue box (Figure 7-6) will appear when the user select **inputs** from the main user interface and click > **Moduli of Pavement Layers**.

**Resilient Moduli of Pavement Layer, MR**

MR of Asphalt Concrete(psi) :

MR of Base Layer(psi) :

MR of Subbase Layer(psi) :

**Structural Layer Coefficient**

Asphalt Concrete, a1 =

Base Layer, a2 =

Subbase Layer, a3 =

Figure 7-6 Pavement layers elastic modulus dialogue box

Elastic Modulus of asphalt concrete ( $E_{AC}$ ), base course ( $E_{BS}$ ) and subbase course ( $E_{SB}$ ) are used to determine the structural layer coefficients  $a_1$ ,  $a_2$  and  $a_3$  respectively. The designer will key in the three variables. Then click > **Done** button to analyse the inputs and click > **Back** button to get back to the main menu interface. Furthermore, structural layer coefficient charts can be referred by clicking > **Refer** button from figure 7-7, figure 7-8 and figure 7-9.

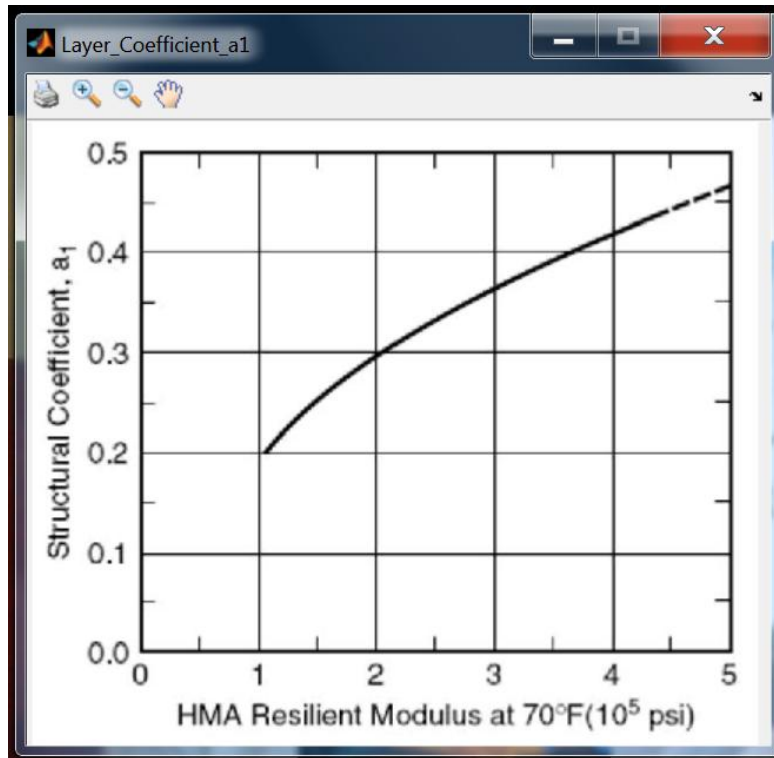


Figure 7-7 Layer coefficient a1 chart [8]

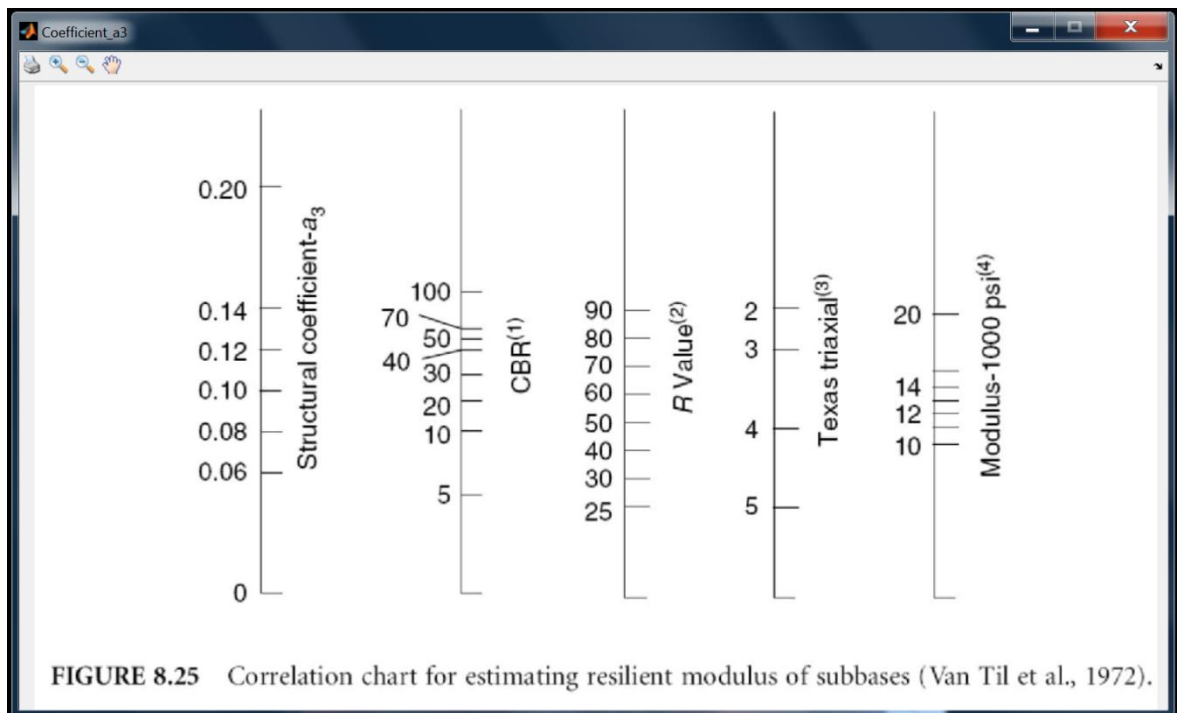


Figure 7-8 Layer coefficient a3 nomograph [8]

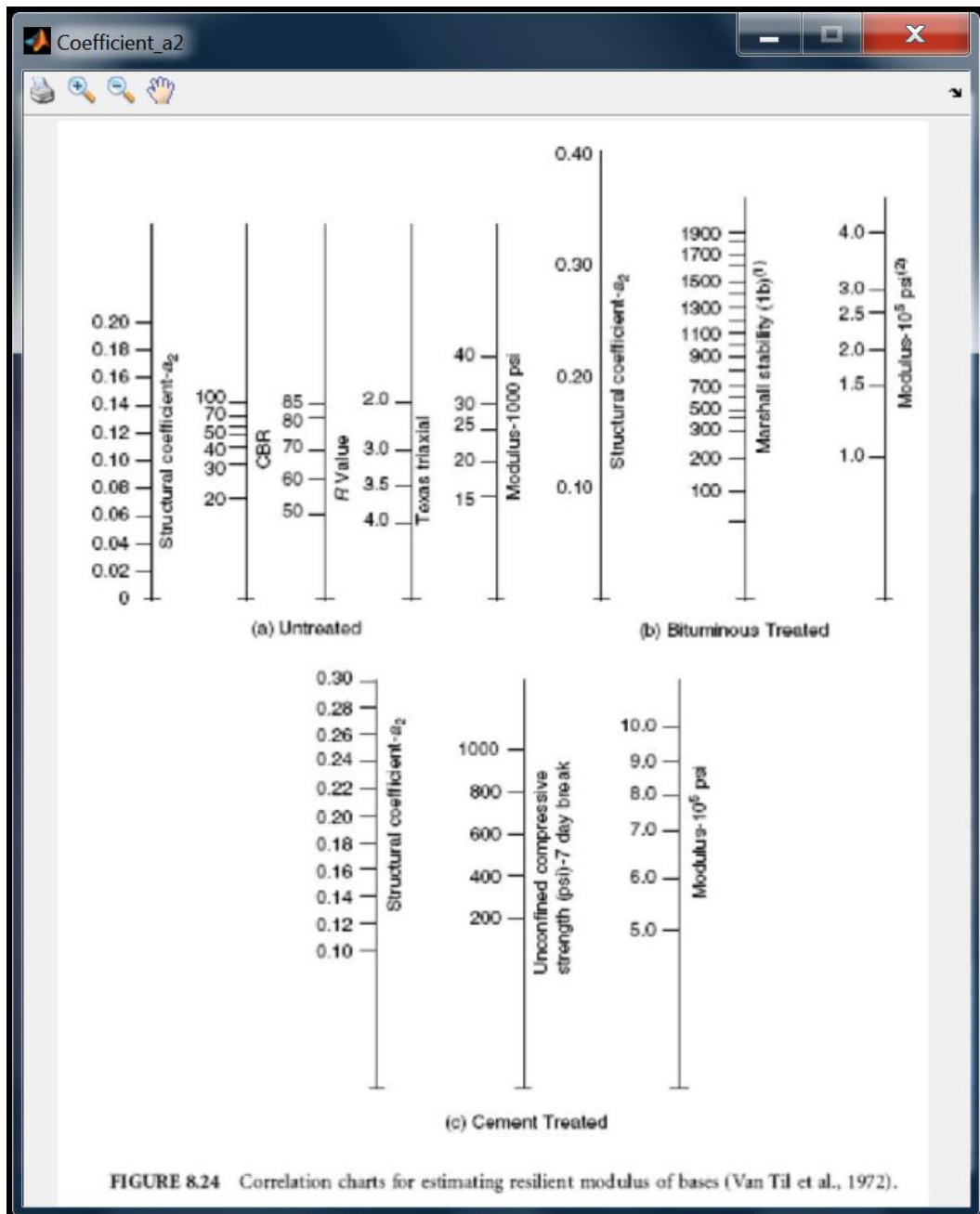


Figure 7-9 Layer coefficient a2 nomograph [8]

### 3.3. Effective Roadbed Soil Resilient Modulus

Effective roadbed resilient modulus of the subgrade dialogue box (Figure 7-10) will appear when the user select **inputs** from the main user interface and > click **Moduli of Roadbed**. This is to determine the effective roadbed soil resilient modulus,  $M_R$ .

Month	Roadbed Modulus(psi)	Relative Damage, u	Month	Roadbed Modulus(psi)	Relative Damage, u
JAN			JUL		
FEB			AUG		
MAR			SEP		
APR			OCT		
MAY			NOV		
JUN			DEC		

Average u  
 OR
  CBR

**Computed MR**  
 Effective Roadbed Soil Resilient =

Figure 7-10 Effective roadbed soil resilient modulus dialogue box

Either the user key in roadbed resilient modulus for each month maximum and minimum values to consider the variability of the property due season and select Average u radio button or select CBR radio button to key in CBR value and the AASHERA software calculates the effective roadbed resilient modulus when the designer click > **Done** button.

Furthermore, relative damage and roadbed soil resilient modulus correlation chart can be referred by clicking > **Refer** button from figure 7-10. Click > **Back** button to get back to the main menu interface.

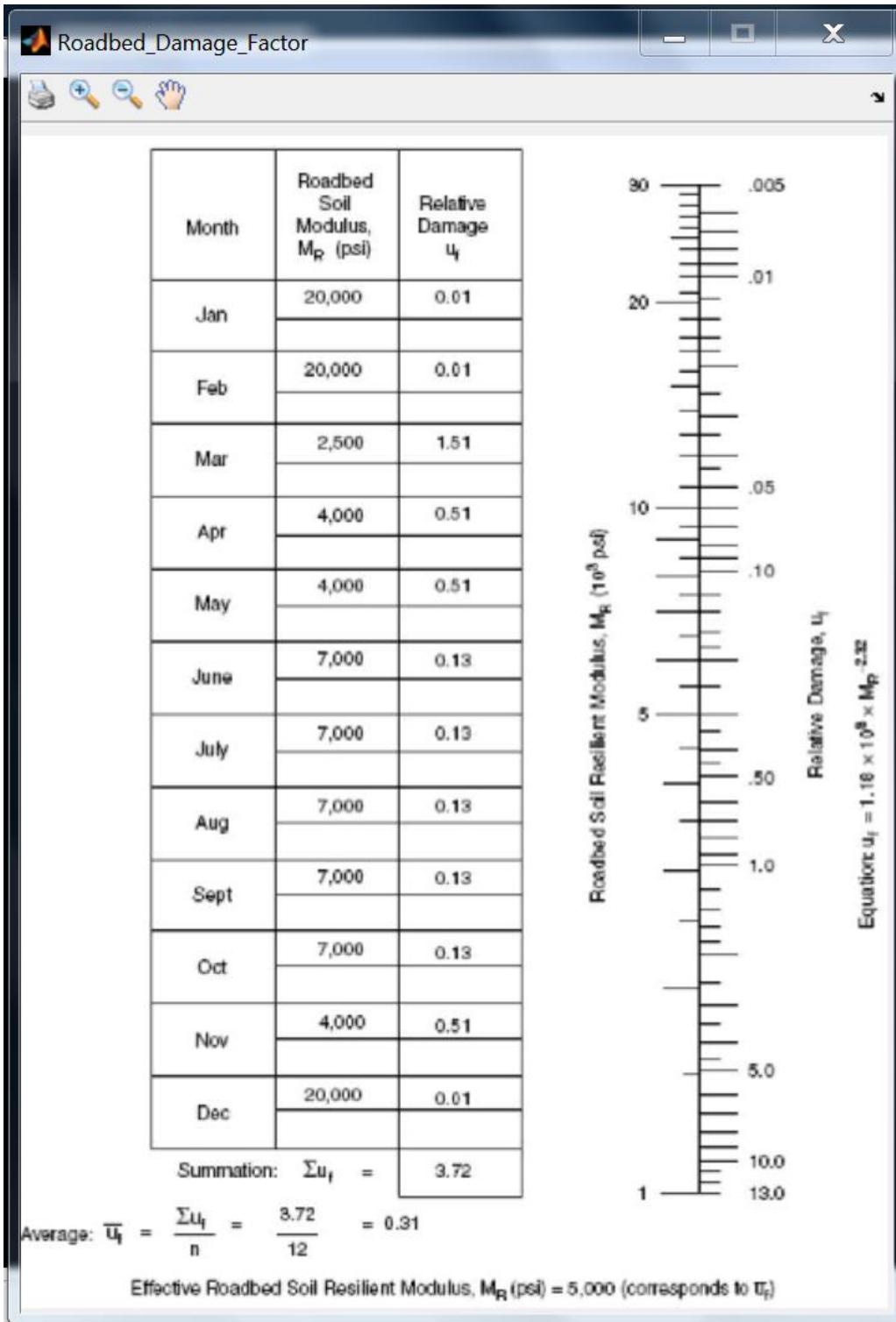


Figure 7-11 Relative damage and roadbed soil resilient modulus correlation chart [8]

### 3.4.Drainage Coefficient, $m_i$

Drainage coefficient dialogue box (Figure 7-12) will appear when the user select **inputs** from the main user interface and > click **Drainage Coefficient**. From the site condition as quality of drainage and percentage of pavement exposed to moisture level are needed to determine the drainage coefficient,  $m_i$ . AASHERA calculates the average value of drainage coefficient when the designer selects the quality of drainage and % of time exposed to moisture level approaching saturation from the dropdown menu and click > **Done** button.

Furthermore, Drainage coefficient table can be referred by clicking > **Refer** button from figure 7-12. Click > **Back** button to get back to the main menu interface.

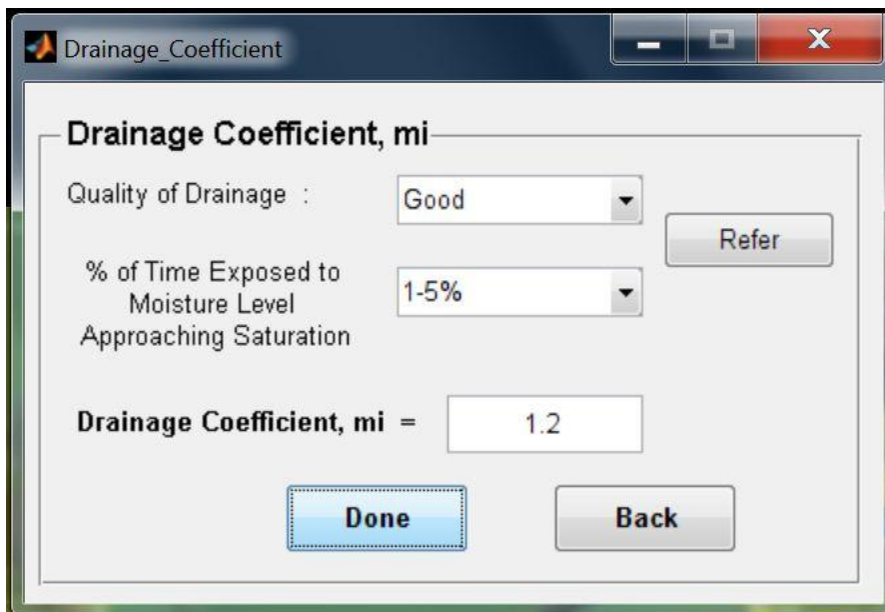


Figure 7-12 Drainage Coefficient dialogue box

Quality of Drainage		% of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Rating	Water Removed Within	<1%	1-5%	5-25%	>25%
Excellent	2 h	1.40-1.35	1.35-1.30	1.30-1.20	1.20
Good	1 day	1.35-1.25	1.25-1.15	1.15-1.00	1.00
Fair	1 week	1.25-1.15	1.15-1.05	1.00-0.80	0.80
Poor	1 month	1.15-1.05	1.05-0.80	0.80-0.60	0.60
Very Poor	Never drain	1.05-0.95	0.95-0.75	0.75-0.40	0.40

Figure 7-13 Recommended Drainage Coefficients for Untreated Base and Subbase in Flexible Pavements [8]

#### 4. AASHTO and ERA design methods analysis results

##### 4.1.AASHTO Thickness Design

AASHTO Thickness Design dialogue box (Figure 7-14) will appear when the user select **Output** from the main user interface and > click **AASHTO Thickness Design**. In the AASHTO Thickness Design dialogue box, the design thickness which fulfill the minimum thickness requirement can be calculated automatically as the designer click > **Analyse** button. Besides, all the important inputs from previous process called automatically into the form for calculation and showing the engineer the inputs of the design.

The screenshot shows a software window titled "Pavement\_Thickness\_Design" with a standard Windows-style title bar (minimize, maximize, close buttons). The main content area is titled "Pavement Thickness Design" and is divided into several sections:

- Design Inputs:** A table of input fields with the following values:

Standard Normal Deviate(ZR) :	-1.645
Standard Deviation(So) :	0.35
Serviceability Loss :	2.1
Effective Roadbed Resilient Modulus(MR) :	5700
Cumulative 18kip ESAL(W18) :	1.85989e+007
- Structural Layer Coefficients:** A table of coefficient input fields with the following values:

a1 =	0.419968
a2 =	0.137803
a3 =	0.0783961
- Structural Number, SN:** Three input fields for SN1, SN2, and SN3 with values 3.2, 4.51, and 5.55 respectively. Below these is a "Refer" button.
- Thickness Of Layers, inch:** Three input fields for D1, D2, and D3 with values 8, 7, and 11 respectively. Below these is a "Total Thickness =" field with the value 26.

At the bottom of the window, there are two buttons: "Analyse" (highlighted with a blue border) and "Back".

Figure 7-14 AASHTO Thickness Design dialogue box

Furthermore, the Nomograph chart for AASHTO flexible pavement design can be referred by clicking > **Refer** button (figure 7-15) in order to compare the structural number (SN) calculated by AASHERA. Click > **Back** button to get back to the main menu interface.

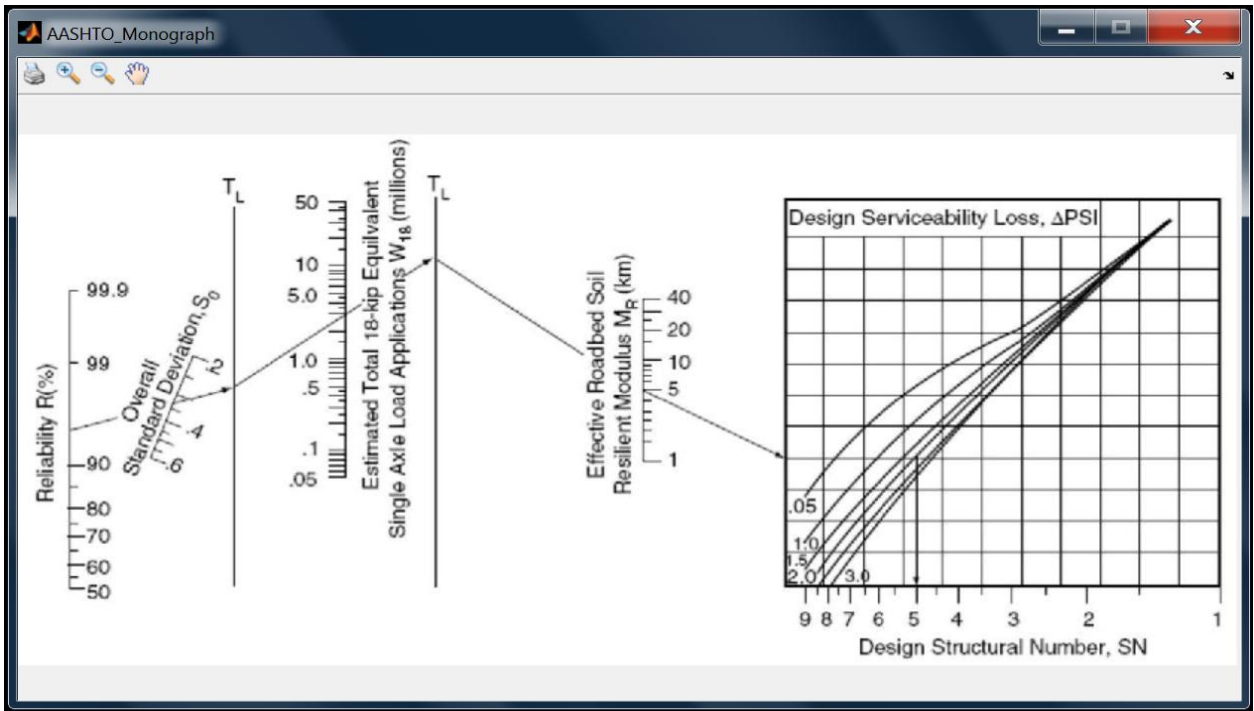


Figure 7-15 Nomograph chart for AASHTO flexible pavements design

#### 4.2.AASHTO Result Construction Cost

AASHTO result construction cost dialogue box (Figure 7-16) will appear when the user select **Output** from the main user interface and > click **AASHTO Design Cost**. Here the engineer selects the type of carriageway in the dropdown menu. The construction cost is calculated as the designer click > **Analyse** button. Click > **Back** button to get back to the main menu interface.

Figure 7-16 AASHTO construction cost result dialogue box

### 4.3.Ethiopian Roads Authority (ERA) Thickness Design and Cost

Ethiopian Roads Authority Design dialogue box (Figure 7-17) will appear when the user select **Output** from the main user interface and > click **ERA Thickness Design**. The design thickness can be calculated automatically as the designer click > **Analyze** button. Besides, all the important inputs from previous process called automatically into the form for calculation and showing the engineer the inputs of the design. Click > **Back** button to get back to the main menu interface.

The screenshot shows a software window titled "ERA\_Design\_Catalogue". It is divided into two main sections: "ERA Design Input" and "ERA Design Result".

**ERA Design Input:**

- Cumulative ESAL, W18 : 1.85989e+007
- Traffic Class : T8
- CBR (%) : 3.8
- Subgrade Strength Class : S2

**ERA Design Result:**

**Layer Materials and Thickness, mm**

Layer	Material	Thickness (mm)
Surface Layer	Flexible Bituminous surface	150
Base Layer	Granular road base(GB1-GB2)	250
Subbase Layer	Granular subbase(GS)	250
Subgrade Layer	Selected subgrade layer	200

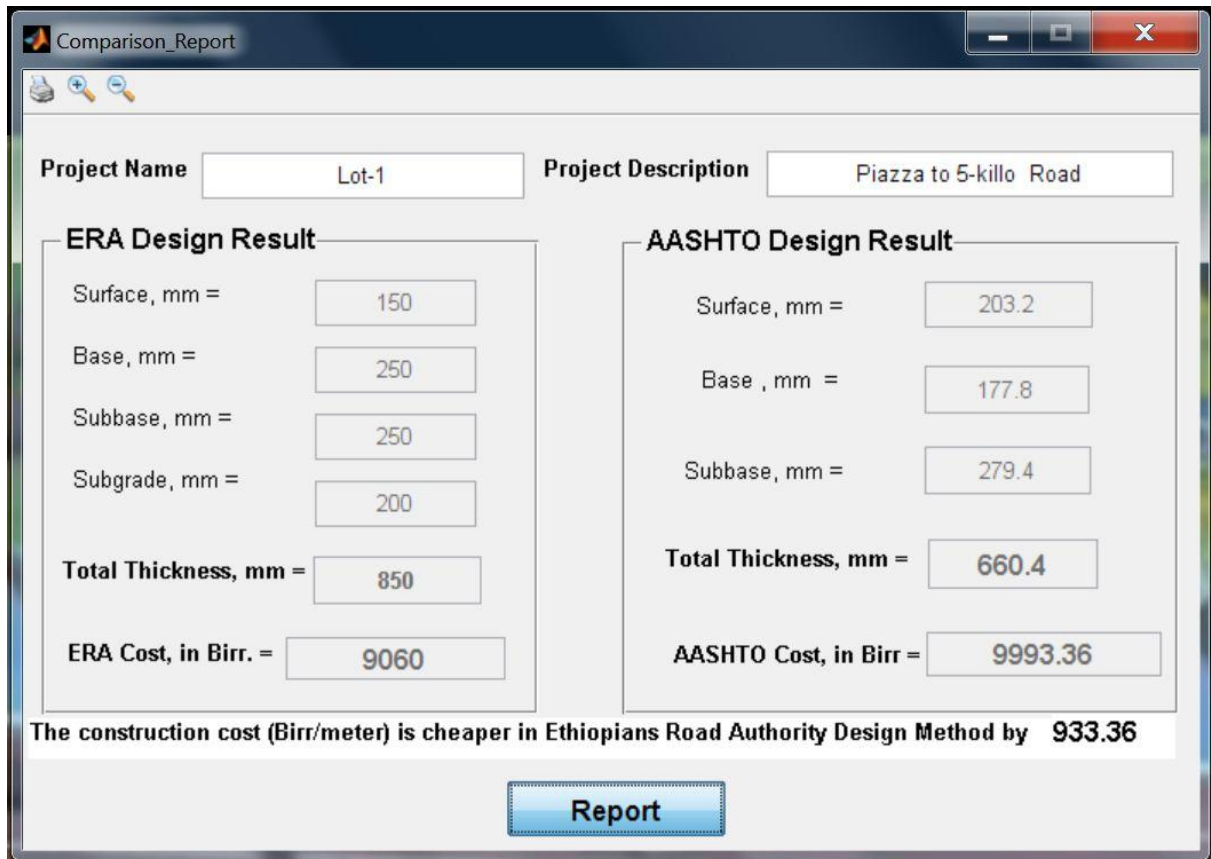
ERA Cost, in Birr. : 9060      Total Thickness, mm : 850

Buttons: **Analyze** (highlighted in blue), **Back**

Figure 7-17 Ethiopian Roads Authority Design dialogue box

#### 4.4. Construction Cost and Total thickness Comparison

Construction cost comparison dialogue box (Figure 7-18) will appear when the user click > **Comparison** from the main user interface and > click **Cost and Thickness**. The comparison report is generated as the designer click > **Report** button. Click > **Print** button to print out the comparison result.



The screenshot shows a software window titled "Comparison\_Report" with a standard Windows-style title bar. The window contains two columns of data for comparison. The left column is for the ERA Design Result and the right column is for the AASHTO Design Result. At the top, there are input fields for "Project Name" (Lot-1) and "Project Description" (Piazza to 5-killo Road). Below these are two main sections: "ERA Design Result" and "AASHTO Design Result". Each section lists "Surface, mm =", "Base, mm =", "Subbase, mm =", and "Subgrade, mm =" with corresponding input boxes. Below these are "Total Thickness, mm =" and "Cost, in Birr. =". At the bottom of the window, a summary line states: "The construction cost (Birr/meter) is cheaper in Ethiopians Road Authority Design Method by 933.36". A blue "Report" button is centered at the bottom.

Parameter	ERA Design Result	AASHTO Design Result
Surface, mm =	150	203.2
Base, mm =	250	177.8
Subbase, mm =	250	279.4
Subgrade, mm =	200	
Total Thickness, mm =	850	660.4
Cost, in Birr. =	9060	9993.36

The construction cost (Birr/meter) is cheaper in Ethiopians Road Authority Design Method by 933.36

Figure 7-18 Comparison dialogue box

#### 4.5. Help on AASHERA

The designer can also get pdf format of the thesis as helping tool for design or any further study by clicking > **Help** from the main user interface and > click **About AASHERA**.

## 8. Validation of AASHERA for Flexible Pavement Design

Validation of new design software is compulsory in order to ensure the software output accuracy compare with manual design. The outputs of AASHERA have been validated against manual calculations based on the design examples from AASHTO guide for design of pavement structures 1993 appendix H, Pavement Analysis and Design page 520 by Yang H. Huang (some call this book *'The bible of road pavement design'*) and The Handbook of Highway Engineering page 8-25 by Michael S. Mamlouk as shown in table 7-1. The results obtained as shown in table 7-1 meet the accuracy of requirement. Therefore, AASHERA achieve high confident of validation. The difference between manual and AASHERA result is because of decimal place rounding and human error due manual reading. The validation for Ethiopian Roads Authority is checked by referring the chart of Pavement Design manual.

Table 8-1 Validation against manuals and books

Input and output variables	AASHTO guide	Yang H. Huang	Michael S. Mamlouk
Cumulative two direction 18-kip ESAL ( $10^6$ )	2.5	2.5**	1.2**
Design Period (year)	15	15**	15**
Growth rate (%)	3	3**	3.61**
Directional distribution factor, $D_D$	50	50**	50**
Lane distribution factor, $D_L$	80	80**	60**
Cumulative ESAL 18-kip ( $10^6$ )	18.6	18.6	7
Reliability (%)	95	95	95
Standard Deviation ( $S_o$ )	0.35	0.35	0.45
Loss in PSI ( $\Delta PSI$ )	4.6 – 2.5 = 2.1	2.1	4.6 - 3.0=1.6
Elastic Modulus of Asphalt Concrete, $E_{AC}$ (psi)	400,000	400,000	450,000
Elastic Modulus of Base Course, $E_{BS}$ (psi)	30,000	30,000	40,000
Elastic Modulus of Subbase Course, $E_{SB}$ (psi)	11,000	11,000	20,000
Effective Roadbed Resilient Modulus, $M_R$ (psi)	5,700	5,700	7,000
Layer Coefficient of Asphalt Concrete, $a_1$	0.42 ( <b>0.4199</b> )*	0.42( <b>0.4199</b> )*	0.44 ( <b>0.4398</b> )*
Layer Coefficient of Base Course, $a_2$	0.14 ( <b>0.1378</b> )*	0.14( <b>0.1378</b> )*	0.17 ( <b>0.1689</b> )*
Layer Coefficient of Subbase Course, $a_3$	0.08 ( <b>0.0783</b> )*	0.08( <b>0.0783</b> )*	0.14 ( <b>0.1373</b> )*
Drainage Coefficient of Base, $m_2$	Good and 1-5% → 1.2	1.2	1.1
Drainage Coefficient of Subbase, $m_3$	Good and 1-5% → 1.2	1.2	1.1
$SN_1$ by manual calculation	3.2	3.2	2.7
<b><math>SN_1</math> by AASHERA</b>	<b>3.2</b>	<b>3.2</b>	<b>2.7</b>
$SN_2$ by manual calculation	4.5	4.5	3.5
<b><math>SN_2</math> by AASHERA</b>	<b>4.51</b>	<b>4.51</b>	<b>3.55</b>
$SN_3$ by manual calculation	5.6	5.6	5.2
<b><math>SN_3</math> by AASHERA</b>	<b>5.55</b>	<b>5.55</b>	<b>5.18</b>
$D_1$ (in) by manual calculation	8	8	6.5
<b><math>D_1</math>(in) by AASHERA</b>	<b>8</b>	<b>8</b>	<b>6.5</b>
$D_2$ (in) by manual calculation	7	7	6
<b><math>D_2</math>(in) by AASHERA</b>	<b>7</b>	<b>7</b>	<b>6</b>
$D_3$ (in) by manual calculation	11	11.5	8
<b><math>D_3</math>(in) by AASHERA</b>	<b>11</b>	<b>11</b>	<b>8</b>

\*values obtained by AASHERA and \*\* values generated by AASHERA to match the given Cum. ESAL

## **9. Conclusion and Recommendation**

### **9.1. Conclusion**

From this work, it can be concluded that, digitalizing the input parameters needed and the result obtained by developing AASHERA flexible pavement thickness design software is successful. The software can determine the thickness of asphalt concrete, base and subbase courses based on AASHTO guide 1993 and Ethiopian Roads Authority 2001 manual. The result obtained by AASHERA is accurate, as the software is verified using the sample examples analysed in different manual and well done books which are in appendix A. The minute difference between manual and AASHERA result is because of decimal place rounding and human error due manual reading.

In AASHERA software the designer can easily analyse and compare the results obtained to select the best design alternative between AASHTO guide and Ethiopian Roads Authority manual based on construction cost and thickness.

Therefore, development of software to design the pavement thickness is very important to save cost, time, energy and decrease error. Thus, the design can be made in a very short time period of design process and help to minimize the error compared to manual calculation by using AASHERA. And the software gives gap for the designer or researcher to design many alternatives in short period of time compared to that of manual methods.

### **9.2. Recommendation**

This study was conducted in short time and limited budget, thus, there are still several improvements that can be made. In order to have complete software for flexible pavement thickness design, extensive study and time frame is required.

#### **Limitations and recommendations**

- The application of AASHERA can be used only where computer is provided in contrast to manual design. So the designer should equip himself with all the necessary hard copy materials if the condition doesn't allow him to use AASHERA.
- AASHERA executes AASHTO and ERA design manuals only so it limits the range of comparison for better design or research. Further study can be done to incorporate other design methods.
- Even though there is printing toolbar to print the analysis result from the graphics; database system is not developed for AASHERA to generate printable design report in pdf or word formats. So further study can incorporate database to make it better tool.
- Further study is needed to incorporate rehabilitation design /asphalt overlay design/ in addition to new road design in AASHERA to upgrade the tool for further use.

## 10. Reference

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## APPENDIX-A Design Examples for validation

### Example-1

## APPENDIX H FLEXIBLE PAVEMENT DESIGN EXAMPLE

The following example is provided to illustrate the flexible pavement design procedure presented in Section 3.1 of Part II. The design requirements for this example are described here in the same order as they are in Part II, Chapter 2.

### H.1 DESIGN REQUIREMENTS

#### Time Constraints

The analysis period selected for this design example is 20 years. The maximum performance period (or service life) selected for the initial flexible pavement structure in this example is 15 years. Thus, it will be necessary to consider stage construction (i.e., planned rehabilitation) alternatives to develop design strategies which will last the analysis period.

#### Traffic

Based on average daily traffic and axle weight data from the planning group, the estimated two-way 18-kip equivalent single axle load (ESAL) applications during the first year of the pavement's life is  $2.5 \times 10^6$  and the projected (compound) growth rate is 3 percent per year. The directional distribution factor ( $D_D$ ) is assumed to be 50 percent and the lane distribution factor ( $D_L$ ) for the facility (assume three lanes in one direction) is 80 percent. Thus, the traffic, during the first year (in the design lane) is  $2.5 \times 10^6 \times 0.80 \times 0.50$  or  $1.0 \times 10^6$  18-kip ESAL applications. Figure H.1 provides a plot of the cumulative 18-kip ESAL traffic over the 20-year analysis period. The curve and equation for future traffic ( $w_{18}$ ) are reflective of the assumed exponential growth rate ( $g$ ) of 3 percent.

#### Reliability

Although the facility will be a heavily trafficked state highway, it is in a rural situation where daily traffic volumes should never exceed half of its capac-

ity. Thus, a 90-percent overall reliability level was selected for design. This means that for a two-stage strategy (initial pavement plus one overlay), the design reliability for each stage must be  $0.90^{1/2}$  or 95 percent. Similarly, for a three-stage strategy (initial pavement plus two overlays), the design reliability for all three stages must be  $0.90^{1/3}$  or 96.5 percent.

Another criteria required for the consideration of reliability is the overall standard deviation ( $S_o$ ). Although it is possible to estimate this parameter through an analysis of variance of all the design factors (see Volume 2, Appendix EE), an approximate value of 0.35 will be used for the purposes of this example problem.

#### Environmental Impacts

Eighty bore holes were obtained along the 16-mile length of the project (approximately one every thousand feet). Based on an examination of the borehole samples and subsequent soil classifications, it was determined that the soil at the first twelve bore hole sites (approximately 12,000 feet) was basically of the same composition and texture. Significantly different results were obtained from examinations at the other bore hole sites. Based on this type of unit delineation, this 12,000-foot section of the project will be designed separately from all the rest.

The site of this highway construction project is in a location that can be environmentally classified as U.S. Climatic Region II, i.e., wet with freeze-thaw cycling. The soil is considered to be a highly active swelling clay. Because of this and the availability of moisture from high levels of precipitation, a drainage system will be constructed which is capable of removing excess moisture in less than 1 day. The duration of below-freezing temperatures in this environment, however, is not sufficient to result in any problems with frost heaving.

Table H.1 summarizes the data used to consider the effects of roadbed swelling on future loss of serviceability. Columns 1 and 2 indicate the bore hole number and length of the corresponding section (or

segment) of the project. The depth to any rigid foundation at the site is, for all practical purposes, semi-infinite. (Roadbed soil thicknesses greater than 30 feet are considered to be semi-infinite.)

Column 4 shows the average plasticity index (PI) of the soil at each bore hole location. PI values above 40 are indicative of potential high volume change of the material.

Column 5 represents the estimated moisture condition of the roadbed material after pavement construction. Because of the plan to construct a "good" drainage system, the future moisture conditions are considered to be "optimum" throughout the project length.

Column 6 presents the results of applying the chart in Figure G.3 of Appendix G to estimate the potential vertical rise ( $V_R$ ) at each bore hole location.

Column 7 represents a qualitative estimate of the fabric of the soil or the rate at which it can take on moisture. The natural impermeability of clay materials means that the soil at this site tends towards "tight." This, combined with the relatively low moisture supply (due to the installation of a drainage system), means that the swell rate constant at each location having a "tight" fabric (i.e., plasticity index (PI) greater than about 20) can be estimated at 0.07 (see Figure G.2 in Appendix G). For the occasions where PI was less than 20, a value of 0.10 was used because of the likelihood of greater permeability.

Based on the data in Table H.1, the overall swell rate constant and potential vertical rise are determined by calculating a weighted average; thus,

$$\text{Swell Rate Constant} = 0.075$$

$$\text{Potential Vertical Rise } (V_R) = 1.2 \text{ inches}$$

The swelling probability is simply the percent of the length of the project which has a potential vertical rise greater than 0.2 inches. 10,100 feet out of the total 12,000 have a  $V_R$  greater than 0.2 inches, thus the swelling probability is 84 percent.

These factors were then used to generate the serviceability loss versus time curve presented in Figure H.2. The curve shown was generated using the equation presented in Figure G.4 of Appendix G. This represents a graph of the estimated total environmental serviceability loss versus time, since frost heave is not a consideration.

### Serviceability

Based on the traffic volume and functional classification of the facility (6-lane state highway), a terminal serviceability ( $p_t$ ) of 2.5 was selected. Past experience indicates (for the purposes of this hypothetical example) that the initial serviceability ( $p_o$ ) normally achieved for flexible pavements in the state is significantly higher than that at the AASHTO Road Test (4.6 compared to 4.2). Thus, the overall design serviceability loss for this problem is:

$$\Delta \text{PSI} = p_o - p_t = 4.6 - 2.5 = 2.1$$

### Effective Roadbed Soil Resilient Modulus

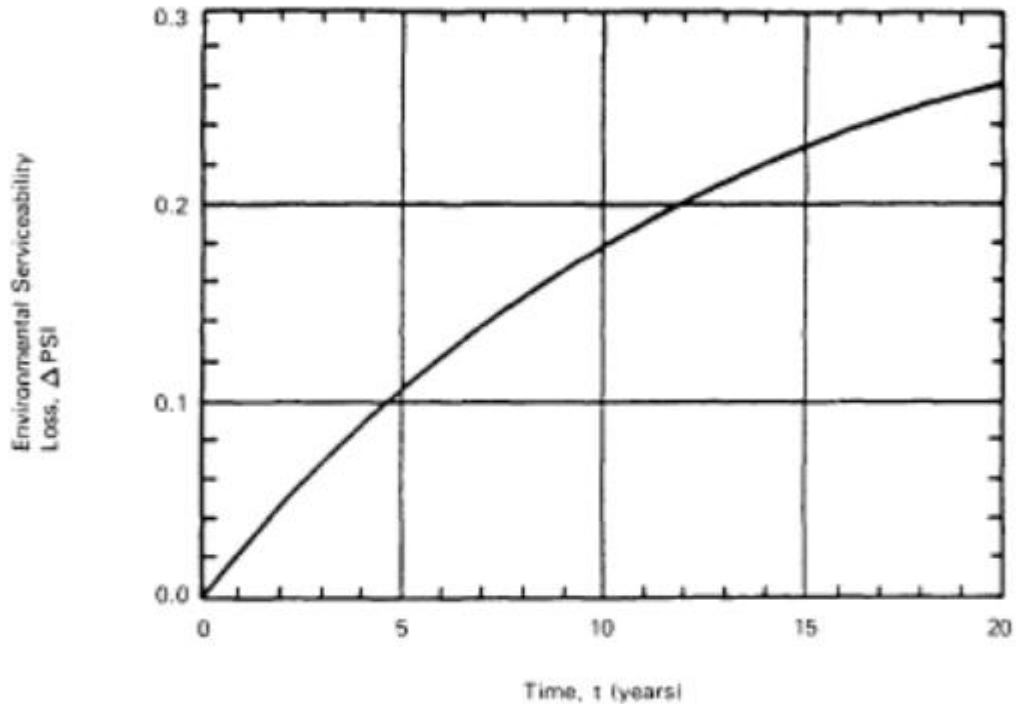
Figure H.3 summarizes the data used to characterize the effective resilient modulus of the roadbed soil. Individual moduli are specified for 24 half-month intervals to define the seasonal effects. These values are also reflective of the roadbed support that would be expected under the improved moisture conditions provided by the "good" drainage system:

Roadbed Moisture Condition	Roadbed Soil Resilient Modulus (psi)
Wet	5,000
Dry	6,500
Spring-Thaw	4,000
Frozen	20,000

The frozen season (from mid-January to mid-February) is 1 month long, the spring-thaw season (mid-February to March) is 0.5 months long, the wet periods (March through May and mid-September through mid-November) total 5 months, and the dry periods (June through mid-September and mid-November through mid-January) total 5.5 months. Application of the effective roadbed soil  $M_R$  estimation procedure results in a value of 5,700 psi.

### Pavement Layer Materials Characterization

Three types of pavement materials will constitute the individual layers of the structure. The moduli for



**Figure H.2. Graph of Environmental Serviceability Loss Versus Time for Swelling Conditions Considered**

each, determined using the recommended laboratory test procedures, are as follows:

Asphalt Concrete:  $E_{AC} = 400,000$  psi

Granular Base:  $E_{BS} = 30,000$  psi

Granular Subbase:  $E_{SR} = 11,000$  psi

These values correspond to the average year-round moisture conditions that would be expected without any type of pavement drainage system. (The effects of positive drainage on material requirements are considered in a later section.)

### Layer Coefficients

The structural layer coefficients ( $a_i$ -values) corresponding to the moduli defined in the previous section are as follows:

Asphalt Concrete:  $a_1 = 0.42$  (Figure 2.5, Part II)

Granular Base:  $a_2 = 0.14$  (Figure 2.6, Part II)

Granular Subbase:  $a_3 = 0.08$  (Figure 2.7, Part II)

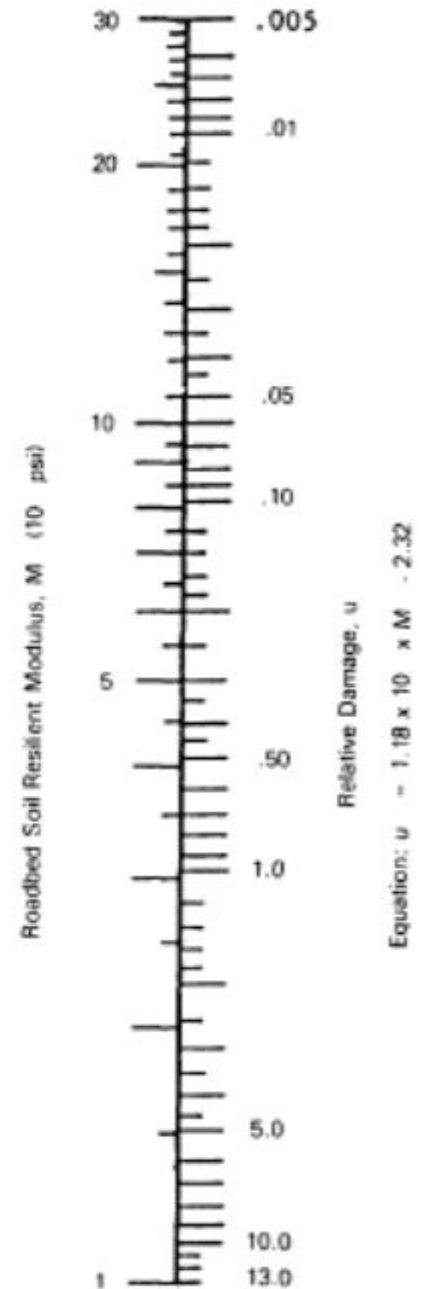
### Drainage Coefficient

The only item that is considered under the heading "Pavement Structural Characteristics" (Part II, Section 2.4) in the design of a flexible pavement is the method of drainage. The drainage coefficient ( $m$ -value) corresponding to the granular base and subbase materials for a "good" drainage system (i.e., water removed within 1 day) and the balanced wet-dry climate of U.S. Climatic Region II is 1.20. (The range in Part II, Table 2.4, for 1 to 5 percent moisture exposure time is 1.15 to 1.25.)

## H.2 DEVELOPMENT OF INITIAL STAGE OF A DESIGN ALTERNATIVE

Since the estimated maximum performance period (15 years) is less than the design analysis period (20 years), any initial structure selected will require an overlay to last the analysis period. The thickest recommended initial structure (evaluated here) is that corresponding to the maximum 15-year performance period. Thinner initial structures, selected for the purpose of life-cycle cost analyses, will require thicker

Month	Roadbed Soil Modulus, M (psi)	Relative Damage, u
Jan.	6,500	0.167
	20,000	0.012
Feb.	20,000	0.012
	4,000	0.515
Mar.	5,000	0.307
	5,000	0.307
Apr.	5,000	0.307
	5,000	0.307
May	5,000	0.307
	5,000	0.307
June	6,500	0.167
	6,500	0.167
July	6,500	0.167
	6,500	0.167
Aug.	6,500	0.167
	6,500	0.167
Sept.	6,500	0.167
	5,000	0.307
Oct.	5,000	0.307
	5,000	0.307
Nov.	5,000	0.307
	6,500	0.167
Dec.	6,500	0.167
	6,500	0.167
Summation: u =		5.446



Average:  $\bar{u} = \frac{5.46}{24} = 0.227$

Effective Roadbed Soil Resilient Modulus,  $M_R$  (psi) 5,700  
(corresponds to  $u_1$ )

Figure H.3. Estimation of Effective Roadbed Soil Resilient Modulus



as the costs of initial construction, maintenance, rehabilitation, and the salvage value of the pavement section at the end of the analysis period. The users cost may also be considered.

### 8.5.4 Sample Problem

Design the pavement for an expressway consisting of an asphalt concrete surface, a crushed-stone base, and a granular subbase using the 1993 AASHTO design chart (Figure 8.22). The cumulative ESAL in the design lane for a design period of 15 years is  $7 \times 10^6$ . The area has good quality drainage with 10% of the time the moisture level is approaching saturation. The effective roadbed soil resilient modulus is 7 ksi, the subbase has a CBR value of 80, the resilient modulus of the base is 40 lb, and the resilient modulus of asphalt concrete is  $4.5 \times 10^5$  psi. Assume a reliability level of 95% and  $S_o$  of 0.45.

Solution

Step 1

Reliability ( $R$ ) = 95% (Given)

Step 2

overall standard deviation ( $S_o$ ) = 0.45 (Given)

Step 3

$W_{18} = 7 \times 10^6$  (Given)

Step 4

Effective road-bed soil resilient modulus = 7 ksi (Given)

Step 5

Resilient modulus of subbase = 20 ksi (Figure 8.25)

Resilient modulus of base = 40 ksi (Given)

Resilient modulus of asphalt concrete surface = 450 ksi (Given)

Step 6

Assume initial serviceability index ( $p_o$ ) = 4.6

Assume terminal serviceability index ( $p_t$ ) = 3.0

$\Delta PSI = 4.6 - 3.0 = 1.6$

Step 7

$SN_3 = 5.2$  (Using Figure 8.22 and subgrade  $M_R$  of 7 ksi)

$SN_2 = 3.5$  (Using Figure 8.22 and subbase  $M_R$  of 20 ksi)

$SN_1 = 2.7$  (Using Figure 8.22 and base  $M_R$  of 40 ksi)

Step 8

$a_3 = 0.14$  (Figure 8.25)

$a_2 = 0.17$  (Figure 8.24)

$a_1 = 0.44$  (Figure 8.23)

Step 9

Drainage coefficients =  $m_2 = m_3 = 1.1$  (Table 8.4)

Step 10

Equation 8.11:  $2.7 \leq 0.44 D_1$

$D_1 = 6.1$  in. (Round to 6.5 in.)

Equation 8.12:  $3.5 \leq 0.44 \times 6.5 + 0.17 \times D_2 \times 1.1$

$D_2 = 3.4$  in. (Use a minimum value of 6 in.) (Table 8.7)

Equation 8.13:  $5.2 \leq 0.44 \times 6.5 + 0.17 \times 6 \times 1.1 + 0.14 \times D_3 \times 1.1$

$D_3 = 7.9$  in. (Round to 8 in.)

Step 11

No information given on Freeze-thaw or swelling

Step 12

No information given on costs

**Example-3**

**Example 11.12:**

Figure 11.29 is a pavement system with the resilient moduli, layer coefficients, and drainage coefficients as shown. If predicted ESAL =  $18.6 \times 10^6$ ,  $R = 95\%$ ,  $S_0 = 0.35$ , and  $\Delta\text{PSI} = 2.1$ , select thicknesses  $D_1$ ,  $D_2$ , and  $D_3$ .

$E_1 = 400,000 \text{ psi}$	$a_1 = 0.42$		$\updownarrow$ $D_1$
$E_2 = 30,000 \text{ psi}$	$a_2 = 0.14$	$m_2 = 1.2$	$\updownarrow$ $D_2$
$E_3 = 11,000 \text{ psi}$	$a_3 = 0.08$	$m_3 = 1.2$	$\updownarrow$ $D_3$

$M_R = 5,700 \text{ psi}$

FIGURE 11.29

Example 11.12 (1 psi = 6.9 kPa).

**Solution:** With  $M_R = E_2 = 30,000 \text{ psi}$  (207 MPa), from Figure 11.25,  $\text{SN}_1 = 3.2$ ; from Eq. 11.47,  $D_1 \geq 3.2/0.42 = 7.6 \text{ in.}$  (193 mm); use  $D_1 = 8 \text{ in.}$  (203 mm).

With  $M_R = E_3 = 11,000 \text{ psi}$  (76 MPa), from Figure 11.25,  $\text{SN}_2 = 4.5$ ; from Eq. 11.48,  $D_2 \geq (4.5 - 0.42 \times 8)/(0.14 \times 1.2) = 6.8 \text{ in.}$  (173 mm); use  $D_2 = 7 \text{ in.}$  (178 mm). Note that a surface thickness of 8 in. (203 mm) and a base thickness of 7 in. (178 mm) meet the minimum thicknesses shown in Table 11.21.

With  $M_R = 5700 \text{ psi}$  (39.3 MPa), from Figure 11.25,  $\text{SN}_3 = 5.6$ ; from Eq. 11.49,  $D_3 \geq (5.6 - 0.42 \times 8 - 0.14 \times 7 \times 1.2)/(0.08 \times 1.2) = 11.1 \text{ in.}$  (282 mm); use  $D_3 = 11.5 \text{ in.}$  (292 mm).