CONCLUSIONS

1. The tire-anchored timber wall concept provides a cost-effective and aesthetically pleasing alternative to conventional retaining wall construction.
2. This experimental wall demonstrated that salvaged materials--i.e., used automobile tires and railroad ties--can be satisfactorily incorporated in wall construction.
3. The wall performed according to all expectations and satisfied its design requirements. In addition, wall construction proved to be simple and rapid.
4. The wall maintained its integrity during a moderate earthquake of $M_L = 5.8$, which produced an estimated maximum bedrock acceleration at the site of 0.2-0.3 *g*.
5. Measured wall pressures for the upper two-thirds of the wall were significantly greater than estimated for design using active earth pressure theory.

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Simplified Rational Pavement Design Procedure for Low-Volume Roads

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Computerized pavement-management systems are excellent tools for designing and managing road pavements. However, in some instances, it is necessary to do pavement design analysis with a limited amount of time, resources, and input information. For this reason, a simplified pavement design procedure has been developed. This simplified procedure uses subgrade strain to predict applications to failure by using the performance concepts of the present serviceability index. For aggregate-surfaced roads, additional design criteria are rutting and aggregate loss. The designer has the capability to consider seasonal variation of pavement materials by characterizing the materials with the resilient modulus. Sample problems are given for an aggregate-surfaced and a bituminous-surfaced road. It is felt that this design method can be particularly useful to engineers in developing countries, where resource constraints and practicality may prevent the use of more complicated procedures.

During the past several years, a new pavement design procedure has been developed for the U.S. Forest Service through a cooperative agreement with the University of Texas at Austin. This new procedure is incorporated in a comprehensive and versatile computer program called the Pavement Design and Management System (PDMS) (1). This pavement-management system is an excellent tool for designing and analyzing pavement design and rehabilitation strategies. However, in some instances, it is necessary to do pavement design analysis with a limited amount of time, resources, and input information. For this reason, a simplified pavement design procedure was developed that can be used manually and does not require the use of a computer.

This simplified procedure is termed "rational" because it uses mechanistic pavement response parameters to predict pavement performance. This type of rational design algorithm is very useful when an attempt is made to use a design procedure in a variety of applications and is more quantitative than using subjective design variables, such as soil-support factors, material strength coefficients, and regional climate factors.

This paper presents the simplified rational pavement design procedure. It is felt that this method can be useful in many applications of pavement design, particularly to engineers in developing countries, where resource constraints and practicality may prevent the use of more complicated procedures. A short background of the development of the method is followed by the performance equations and instructions on using the design procedure. Sample problems are given for an aggregate-surfaced and a bituminous-surfaced road.

BACKGROUND

The basic algorithm used in the simplified design procedure was developed by correlating pavement performance with calculated values of subgrade compressive strain. This was accomplished through the use of linear elastic-layer theory and performance data from the American Association of State Highway Officials (AASHO) Road Test (2). The resulting equation predicts the number of axle applications of any load X necessary to reduce the pavement condition to a terminal level of the present serviceability index (PSI):

$$\begin{aligned}\log_{10} N_x = {} & 2.151\,22 - 597.662\,(\epsilon_{SG}) \\ & - 1.329\,67\,(\log_{10} \epsilon_{SG}) + \log_{10}\,[(PSI_i - TSI)/(4.2 - 1.5)]^{1/2}\end{aligned} \qquad (1)$$

where

$\log_{10} N_x$ = $\log_{10}$ of allowable applications of any axle load X,
ϵ_{SG} = subgrade compressive strain due to axle load X,
PSI_i = initial PSI of road, and
TSI = terminal serviceability index, or failure level of PSI.

Figure 1. Strain algorithm results for 18-kip single-axle and 48-kip tandem-axle loads.

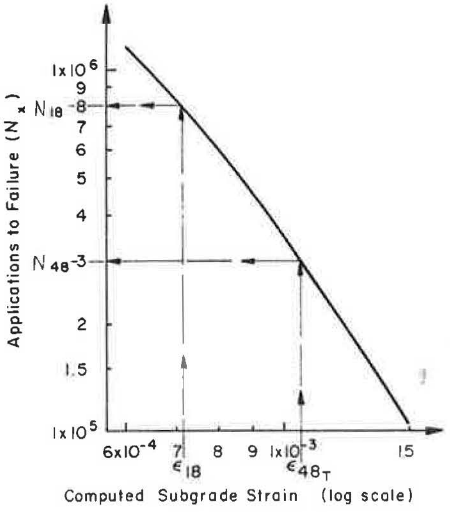
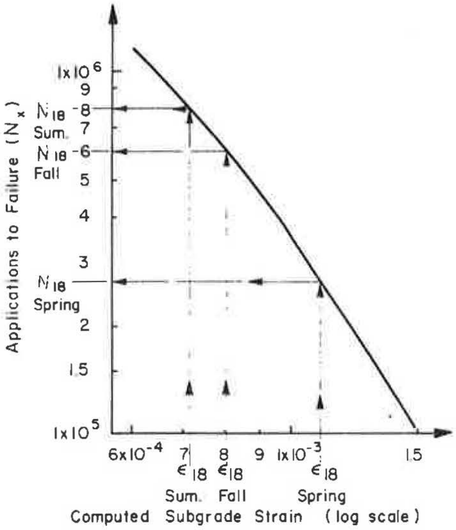


Figure 2. Strain algorithm results for seasonal variation.



The use of Equation 1 to predict performance for different axle loads is shown in Figure 1. The heavier load of a 48-kip tandem axle produces more subgrade strain than an 18-kip single axle, and fewer applications of the heavier axle are necessary before failure is predicted.

The same concept is used to consider seasonal variation in pavement strength, as shown in Figure 2. At a given time of the year for a certain pavement structure, the modulus of elasticity of each layer can be used to characterize the strength of the pavement material. The moduli of pavement layers could change due to heavy rainfall, poor drainage, frozen conditions, dry weather, or almost any environmental effect. During the summer, a certain load may produce a calculated strain (ϵ_{sum}) leading to N_{sum} applications to failure. During a spring thaw condition, the modulus of the subgrade may be very low, leading to a high strain (ϵ_{spr}) and low number of applications to failure (N_{spr}).

In this design procedure, Miner's rule of linear cumulative damage is used to evaluate pavement performance in different seasonal conditions. The number of applications to failure for each seasonal period is calculated separately by using Equation 1. This equation computes the applications to failure (N) for seasonal period i. During a given seasonal period, if n axle applications are expected to be applied, then the damage for that period will be n/N. When one year is considered and when more than one seasonal period is expected, the total damage during that year is

$$\sum_{i=1}^{j} (n_i/N_i) \qquad (A)$$

where j is the number of seasonal periods during the year. If there are three seasons, then the annual damage would be

$$(n_1/N_1) + (n_2/N_2) + (n_3/N_3) \qquad (B)$$

When this annual damage is multiplied by the number of years being analyzed and becomes greater than or equal to 1, a failure condition is predicted.

PERFORMANCE EQUATIONS

Aggregate-Surfaced Roads

Three performance equations (aggregate loss, rutting, and PSI) are used in the design of pavement structures for aggregate-surfaced roads.

Aggregate Loss

Loss of aggregate surfacing due to traffic is a natural phenomenon that occurs on roads with unbound surfaces. It is desirable to estimate aggregate loss over the design period in order to predict how much of the pavement structure will be worn or eroded away. Predicting aggregate loss is very difficult, so if the designer has some information on local conditions that can be used to make a reasonable estimate, this is recommended over using predictive equations. However, if local experience is not available, aggregate loss can be estimated by using an equation developed during a road study in Brazil (3):

$$\text{GLIN} = (\text{B}/25.4) \cdot [0.0045 \cdot \text{LADT} + (3380.6/\text{R}) + 0.467 \cdot \text{G}] \qquad (2)$$

where

GLIN = aggregate loss during period of time being considered (in),
B = number of bladings during period of time being considered,
LADT = average daily traffic (ADT) in design lane (for one-lane road use total traffic in both directions),
R = average radius of curves (ft), and
G = absolute value of grade (%).

Expected aggregate loss is used in the simplified design procedure to reduce the thickness of the surface layer to an average expected thickness over the design life. For example, if 1 in of aggregate loss is expected every year, a total of 10 in would be lost over a 10-year design period. If the surface is to be constructed with a thickness of 12 in, the average thickness over the 10-year period would be [12 in - (10 in/2)] or 7 in. Therefore, 7 in is used as the surfacing thickness in the simplified design procedure, even though the initial construction is 12 in.

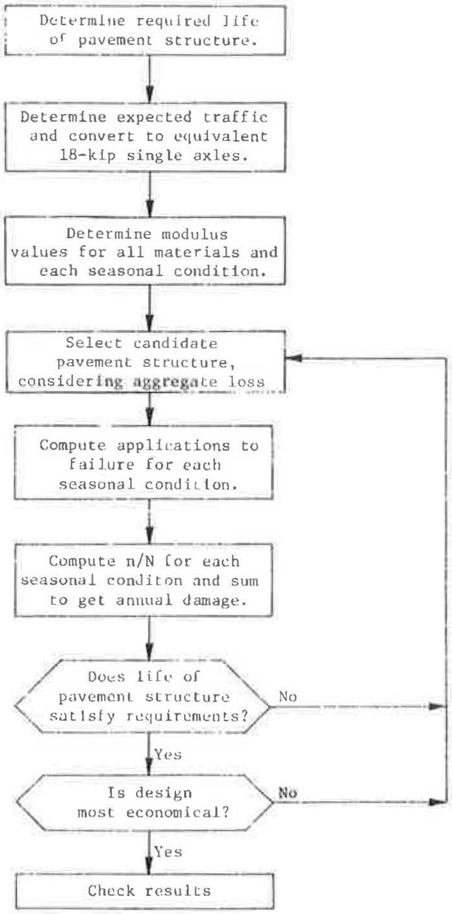
Rutting

Rutting is a separate failure criterion for aggre-

Table 1. Variables used in subgrade strain equation.

Pavement Structure	Term in Equation	Variable or Value
Three-layer asphalt	E_{AC}, D_{AC}	E and D of asphalt layer
	E_{BS}, D_{BS}	E and D of base layer
	E_{SB}, D_{SB}	E and D of subbase layer
Two-layer asphalt	E_{AC}, D_{AC}	E and D of asphalt layer
	E_{BS}, D_{BS}	E and D of base layer
	E_{SB}, D_{SB}	Zero
One-layer asphalt	E_{AC}, D_{AC}	E and D of asphalt layer
	E_{BS}, D_{BS}	Zero
	E_{SB}, D_{SB}	Zero
Two-layer aggregate	E_{AC}, D_{AC}	Zero
	E_{BS}, D_{BS}	E and D of aggregate surfacing
	E_{SB}, D_{SB}	E and D of aggregate base layer
One-layer aggregate	E_{AC}, D_{AC}	Zero
	E_{BS}, D_{BS}	E and D of aggregate surfacing
	E_{SB}, D_{SB}	Zero

Figure 3. Flowchart for simplified design procedure.



gate-surfaced roads. The equation used to predict the number of 18-kip axle applications necessary to produce a critical rut depth is

$$N_{RUT} = 0.1044 \cdot RUT^{2.575} \cdot (\log_{10} THICK)^{5.155} \cdot (E_{AGG}/1800)^{3.434} \cdot (E_{RBD}/1800)^{1.048} \quad (3)$$

where

N_{RUT} = number of 18-kip equivalent single-axle loads to reach the critical, or failure, rut depth;
RUT = critical, or failure, rut depth (in);
THICK = thickness of aggregate (in);
E_{AGG} = elastic modulus of aggregate (psi); and
E_{RBD} = elastic modulus of roadbed (psi).

The above relationship was developed by modifying an equation that was published by the U.S. Army Corps of Engineers (4). The thickness of aggregate term (THICK) in Equation 3 refers to the total depth of aggregate above the subgrade. In the case of an aggregate surface over a base layer, this term would be the total thickness of the surface and the base. The elastic modulus of the aggregate (E_{AGG}) refers to the modulus of the material above the subgrade. If two layers occur above the subgrade (i.e., surface and base), the weighted average of the modulus of the surface and the modulus of the base should be used for E_{AGG}. The weighted average is calculated by multiplying the thickness of each layer times the modulus of each layer, summing up these products for all layers, and dividing the sum by the total thickness (THICK). For example, the weighted average modulus of a 4-in surface with a modulus of 20 000 psi and an 8-in base with a modulus of 10 000 psi would be (4 • 20 000 + 8 • 10 000) ÷ 12 = 13 300 psi.

The elastic-modulus values used in this design procedure can be determined by using resilient-modulus testing. However, this type of testing may not be available for use with the simplified procedure. If this is the case, the elastic modulus can be estimated from the California bearing ratio (CBR) test by using the following relationship:

$$E = 1800 (CBR^{0.7}) \quad (4)$$

where E is the estimated elastic modulus in pounds per square inch. Equation 4 was developed by observing other published relationships relating modulus to CBR (5).

If CBR tests cannot be run on the roadbed material, its modulus may be estimated from the following equation for fine-grained materials developed by Visser (6):

$$\log_{10}E_{RBD} = 4.2106 + LL(0.0164) - W(0.0433) - PL(0.0097) \quad (5)$$

where

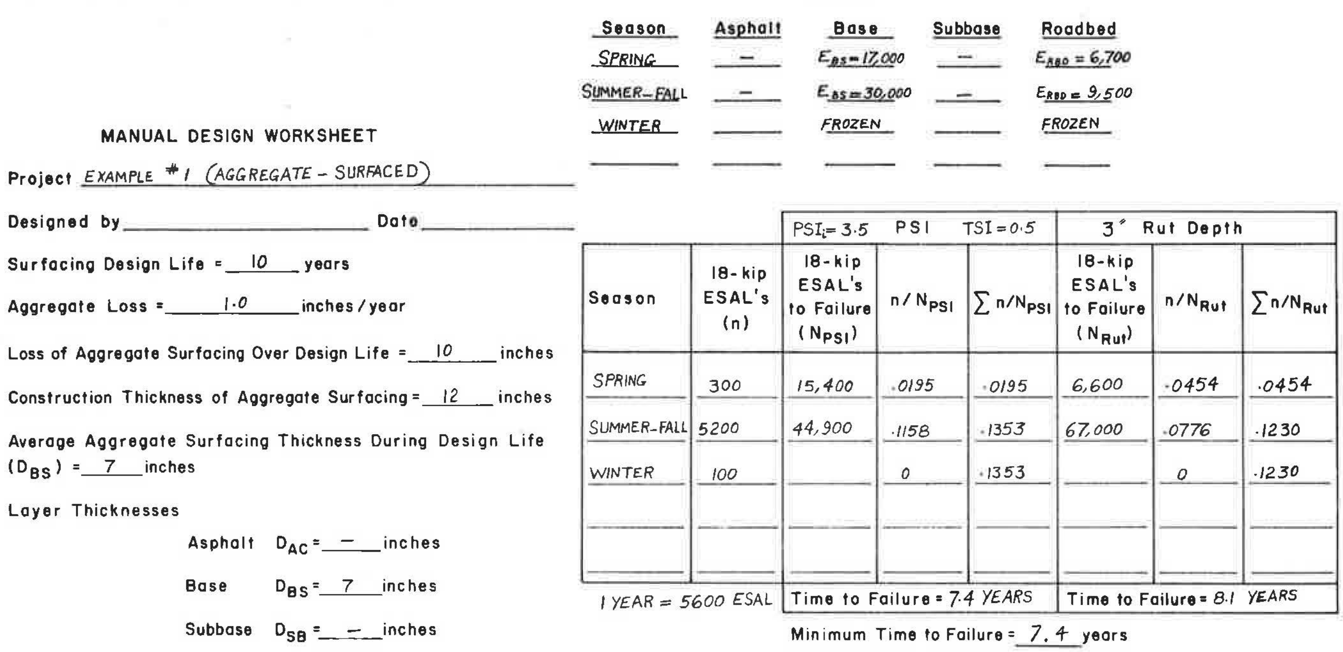
$\log_{10}E_{RBD}$ = $\log_{10}$ elastic modulus of roadbed (psi),
LL = liquid limit of soil (%),
W = water content of soil (%), and
PL = plastic limit of soil (%).

The predicted time to rutting failure is also computed by using the cumulative-damage concept explained earlier. Different times to rutting failures are calculated for each season; the traffic determines the fractional damage for each season. An illustration of this will be given later in a sample problem.

PSI

The relationship between PSI and road roughness for aggregate-surfaced roads has been found to be similar to that for bituminous-surfaced roads (7). For this reason, PSI is also a failure criterion for the design of aggregate-surfaced roads. In an effort to reduce computations in the simplified procedure, only 18-kip single axles are used with Equation 1. Since Equation 1 requires the subgrade strain as an input, the following equation was developed to predict subgrade strain, given the modulus and thickness of the pavement layers:

Figure 4. Sample worksheet for aggregate-surfaced road.



MANUAL DESIGN WORKSHEET

Project EXAMPLE #1 (AGGREGATE - SURFACED)

Designed by ____________ Date ________

Surfacing Design Life = 10 years

Aggregate Loss = 1.0 inches/year

Loss of Aggregate Surfacing Over Design Life = 10 inches

Construction Thickness of Aggregate Surfacing = 12 inches

Average Aggregate Surfacing Thickness During Design Life (D_{BS}) = 7 inches

Layer Thicknesses

Asphalt D_{AC} = — inches

Base D_{BS} = 7 inches

Subbase D_{SB} = — inches

Modulus

Season	Asphalt	Base	Subbase	Roadbed
SPRING	—	E_{BS} = 17,000	—	E_{RBD} = 6,700
SUMMER-FALL	—	E_{BS} = 30,000	—	E_{RBD} = 9,500
WINTER		FROZEN		FROZEN

		PSI$_i$ = 3.5 PSI TSI = 0.5			3" Rut Depth		
Season	18-kip ESAL's (n)	18-kip ESAL's to Failure (N_{PSI})	n/N_{PSI}	$\sum n/N_{PSI}$	18-kip ESAL's to Failure (N_{Rut})	n/N_{Rut}	$\sum n/N_{Rut}$
SPRING	300	15,400	.0195	.0195	6,600	.0454	.0454
SUMMER-FALL	5200	44,900	.1158	.1353	67,000	.0776	.1230
WINTER	100		0	.1353		0	.1230
1 YEAR = 5600 ESAL		Time to Failure = 7.4 YEARS			Time to Failure = 8.1 YEARS		

Minimum Time to Failure = 7.4 years

$$\begin{aligned}\log_{10}\epsilon_{SG} = & -2.240\,02 - (2.914\,40 \times 10^{-5} \cdot E_{RBD}) \\ & - (5.085\,14 \times 10^{-2} \cdot D_{AC}) - (2.029\,47 \\ & \times 10^{-2} \cdot D_{BS}) - (5.372\,88 \times 10^{-8} \cdot E_{AC} \cdot D_{AC}) \\ & - (9.378\,88 \times 10^{-4} \cdot D_{BS} \cdot D_{SB}) - (2.910\,66 \\ & \times 10^{-7} \cdot E_{BS} \cdot D_{BS}) - (8.602\,53 \times 10^{-7} \cdot E_{SB} \cdot D_{SB}) \qquad (6)\end{aligned}$$

where

ϵ_{SG} = compressive subgrade strain due to 18-kip axle load,
E_{AC} = elastic modulus of asphalt layer,
E_{BS} = elastic modulus of base layer,
E_{SB} = elastic modulus of subbase layer,
E_{RBD} = elastic modulus of roadbed material,
D_{AC} = thickness of asphalt layer,
D_{BS} = thickness of base layer, and
D_{SB} = thickness of subbase layer.

All E-terms are in pounds per square inch and all D-terms are in inches. If a pavement structure being considered does not have a certain layer, values of zero are used for the modulus and thickness of that layer. For example, if a one-layer aggregate-surfaced road is being analyzed, there is no asphalt layer or subbase layer, so zero is used in the equation for E_{AC}, D_{AC}, E_{SB}, and D_{SB}. The modulus and thickness of the aggregate surfacing are input as E_{BS} and D_{BS}. Table 1 indicates what variables should be used in the subgrade strain equation for different pavement structures. Equations 4 and 5 can be used to estimate modulus values for the roadbed, base, and subbase materials.

Bituminous-Surfaced Roads

Bituminous-surfaced roads use only the PSI (Equation 1) as a failure criterion. For aggregate-surfaced roads, Equations 4 and 5 are used to estimate modulus values, and Equation 6 and Table 1 are used to predict subgrade strain.

DESIGN PROCEDURE

For the simplified design method, the designer selects a candidate pavement structure and manually computes the number of allowable 18-kip equivalent single-axle load applications to a given level of PSI and rut depth. The minimum allowable number of 18-kip applications from these two equations is compared with the expected number of applications for that roadway. If the expected applications exceed the allowable, the pavement structure thickness must be increased by the designer and the calculations repeated until a satisfactory number of allowable 18-kip single-axle applications is reached.

A flowchart for using the manual design method is shown in Figure 3:

Step 1: Determine the number of years the surfacing must perform before a rehabilitation will be allowed. This will be the length of time for which the surfacing will be designed.

Step 2: Convert mixed traffic into an equivalent number of 18-kip single-axle applications.

Step 3: Determine seasonal modulus values for the materials in the pavement structure.

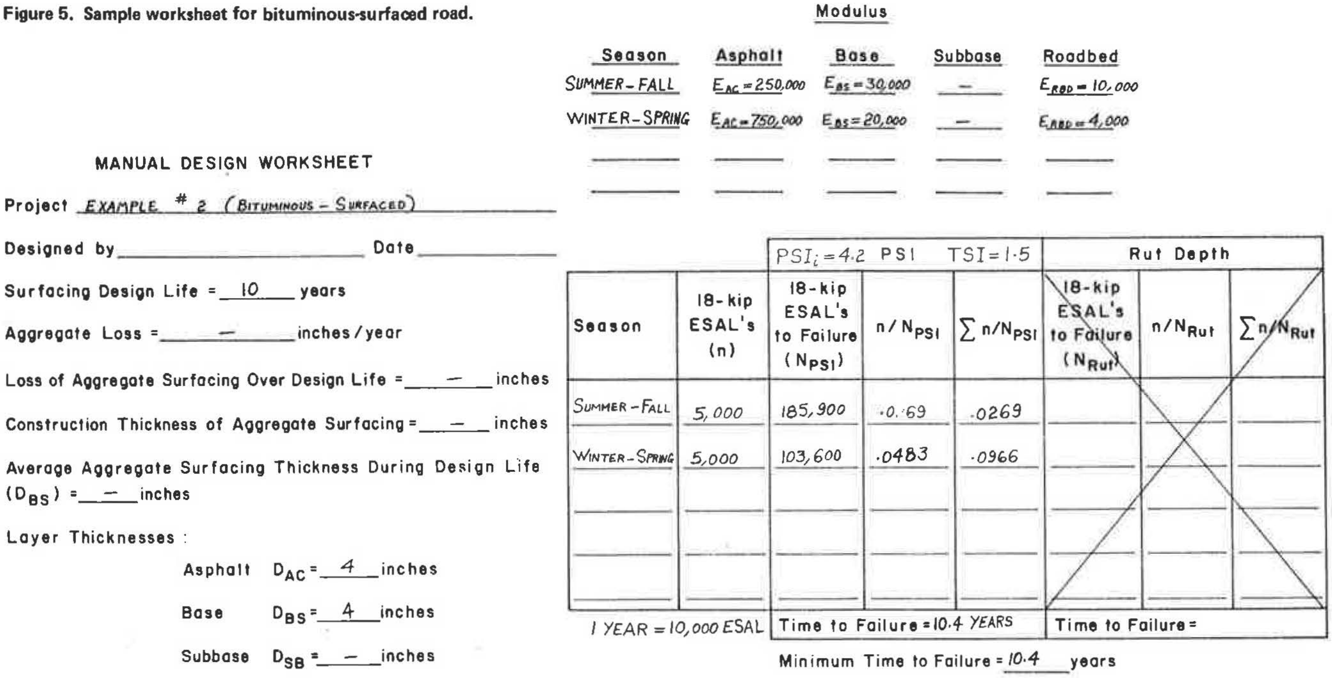
Step 4: Select a candidate pavement structure to determine whether it will satisfy the performance requirements. For aggregate-surfaced roads, the surface thickness must be reduced to represent the average surface thickness over the design period when aggregate loss is taken into consideration.

Step 5: The thickness and moduli of the candidate pavement structure layers are used to calculate subgrade strain for each season. Then the number of allowable 18-kip applications (N_{PSI}) to the TSI is computed.

Step 6: The actual 18-kip applications in each season (n) are divided by the applications to failure (N). This quotient is the fractional damage caused to the pavement in one season. The fractional damage caused in one year is the sum of the fractional damage caused in each season. Calculating the inverse of the fractional damage caused in one year will determine the number of years to failure. For example, if the fractional damage caused in one year is 0.15, the inverse of this (1/0.15) is 6.7, so failure is expected to occur in 6.7 years.

At this point, the time to PSI failure has been

Figure 5. Sample worksheet for bituminous-surfaced road.



MANUAL DESIGN WORKSHEET

Project EXAMPLE # 2 (BITUMINOUS – SURFACED)

Designed by ________ Date ________

Surfacing Design Life = 10 years

Aggregate Loss = — inches/year

Loss of Aggregate Surfacing Over Design Life = — inches

Construction Thickness of Aggregate Surfacing = — inches

Average Aggregate Surfacing Thickness During Design Life (D_{BS}) = — inches

Layer Thicknesses:

Asphalt D_{AC} = 4 inches

Base D_{BS} = 4 inches

Subbase D_{SB} = — inches

Modulus

Season	Asphalt	Base	Subbase	Roadbed
SUMMER – FALL	$E_{AC}=250{,}000$	$E_{BS}=30{,}000$	—	$E_{RBD}=10{,}000$
WINTER – SPRING	$E_{AC}=750{,}000$	$E_{BS}=20{,}000$	—	$E_{RBD}=4{,}000$

		$PSI_i=4.2$ PSI $TSI=1.5$			Rut Depth		
Season	18-kip ESAL's (n)	18-kip ESAL's to Failure (N_{PSI})	n/N_{PSI}	$\sum n/N_{PSI}$	18-kip ESAL's to Failure (N_{Rut})	n/N_{Rut}	$\sum n/N_{Rut}$
SUMMER – FALL	5,000	185,900	.0269	.0269			
WINTER – SPRING	5,000	103,600	.0483	.0966			
1 YEAR = 10,000 ESAL		Time to Failure = 10.4 YEARS			Time to Failure =		

Minimum Time to Failure = 10.4 years

determined. If an aggregate-surfaced road is being considered, time to rutting failure is calculated by repeating steps 5 and 6, except that the rutting equation (Equation 3) is used instead of the PSI equation. This will result in the predicted number of 18-kip applications to rutting failure (N_{RUT}).

SAMPLE SOLUTIONS

Two sample problems are provided on completed worksheets of the type used with the simplified rational procedure. Sample 1 (Figure 4) is for an aggregate-surfaced road with a design life of 10 years. The candidate pavement structure has a construction thickness of 12 in, but because of aggregate loss the average thickness over the design life is 7 in. The minimum time to failure is 7.4 years for the PSI equation versus a slightly longer time to a 3-in rut of 8.1 years. To achieve a 10-year design life, the designer would have to increase the surfacing thickness or improve the modulus of the surfacing material.

Sample 2 (Figure 5) is also for a 10-year design life and shows an example of a satisfactory design from a design-life standpoint. No rut-depth calculations are made for bituminous-surfaced roads.

CONCLUSIONS

A simplified rational pavement design procedure for low-volume roads has been developed and is being used by the U.S. Forest Service. This procedure is very useful when constraints make the use of more complicated procedures infeasible or impractical. The procedure is rationally based, which provides a sounder basis for extrapolation of the procedure to many types of applications. Seasonal variation of materials can be considered by estimating the change in the modulus of elasticity, and Miner's rule is used to determine cumulative damage. Relatively simple equations have been developed to simplify the inputs required in the performance equations.

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