Ontario, Rept. EM-10, Feb. 1978.
11. T.C. Johnson. Is Graded Aggregate Base the Solution in Frost Areas? Proc., Conference on Utilization of Graded Aggregate Base Materials in Flexible Pavements, Oak Brook, IL, March 1974.

Simulating Pavement Performance Under Various Moisture Conditions

MICHAEL J. MARKOW

A computer program to simulate highway pavement performance, maintenance, and rehabilitation has recently been completed for the Federal Highway Administration. As part of this effort, closed-form pavement performance equations have been incorporated to predict the onset and propagation of various damage mechanisms as a function of layer thicknesses and material properties, traffic loadings, cumulative damage already sustained, moisture, and temperature. Both flexible and rigid pavements are considered. The simulation is carried out on a seasonal basis (up to 12 seasons per year allowed) to permit users to specify variations in climatic conditions and pavement material properties. In addition, moisture-induced decreases in layer and subgrade strengths are rendered sensitive to the amount of unsealed cracking in the pavement surface, the seasonal rainfall, and the quality of subsurface drainage. In this way the preservation of road investment, as represented by rates of future damage accumulation, is explicitly tied to both pavement drainage characteristics and the quality of subsequent surface maintenance. This paper describes the technical assumptions and relationships employed in this approach and gives examples of its application to a selected pavement design, maintenance policy, and climatic region. The case study indicates that subsurface drainage above can have a significant effect on pavement life, influencing the date of required resurfacing by up to four years.

The structural design, construction, and performance of pavements have been the subject of much theoretical and empirical research. Most efforts in this area have concentrated on the relationship of component layer thicknesses and material properties to the formation and propagation of particular types of distress. Comparatively little attention, however, has been devoted to the changes in pavement condition over time as damage begins to accumulate and the interaction between this damage and the pavement environment to influence subsequent pavement performance. The specific mechanism of interest here is the infiltration of water into cracks and joints, with resulting potential weakening of the pavement structure. This mechanism is important because a good deal of structural maintenance and rehabilitation is devoted to preserving the integrity of the pavement surface. The benefits of such work are often justified in part by the reduction in water infiltration, but typically no quantitative evidence of impacts on future pavement damage is provided.

The lack of current information on the effects of water infiltration and drainage has been cited by Cedergren (1). By using data from several road tests and test tracks, he calculated relative damage factors, which ranged from 5 or 10 to 1 to 70 000 to 1 for wet versus dry conditions, respectively. Although the trend indicating shortened pavement life with increasing traffic loads under wet conditions is clear, the wide range of these estimates precludes their applications to predicting pavement performance.

Recently modifications have been completed of the Federal Highway Administration's EAROMAR system--a simulation model of freeway performance that enables one to conduct economic analyses of different strategies for roadway and pavement reconstruction and pavement reconstruction, rehabilitation, and maintenance (2). As part of the simulation of pavement performance, we have included models of water infiltration to the pavement substructure, its effect on material properties, and resulting changes in damage accumulation. The approach followed within EAROMAR bases the amount of water entering the pavement structure on the seasonal rainfall and the extent of cracking in the pavement surface. Reduction in pavement strength is dependent on the length of time the sublayers remain saturated, which is a function of the amount of water that has entered the pavement and the drainage characteristics of the sublayers input by the user. The model considers only water entering the pavement structure through discontinuities in the surface (typically the most significant source); groundwater sources and side infiltration are not included. The technical relationships employed are based on work by Moulton (3) supplemented by data presented by Cedergren (1) and by assumptions on pavement material behavior.

GENERAL MODEL CONSIDERATIONS

In pavements subjected to rainfall, one may distinguish three periods associated with wet weather in addition to the period corresponding to dry conditions:

1. The time during which rain is falling, in which the pavement sublayers may or may not be building up to saturation;
2. If rainfall is sufficiently heavy or the sublayers are of sufficiently low permeability, the time during which the sublayers are saturated or sufficiently wet to affect material properties and structural behavior; and
3. The time during which any residual water not sufficient to affect pavement behavior is drained off.

Data for several cities throughout the United States were reviewed in their months of maximum rainfall. Seldom do the total days of precipitation greater than 0.1 in (2.5 mm) exceed 10, and the number of days in which the precipitation exceeds 0.5 in (12.7 mm) is typically 7 or fewer. However, the period of saturation following a rain can last from 5 to 20 days, except in those pavements that have exceptionally good drainage qualities (1). Therefore, in our model we considered only the second period above--the period (after it stops raining) during which the pavement is significantly wet or saturated--as the time relevant to estimating changes in rate of pavement damage and neglected the time during which the rain is actually falling (period 1 above). (This assumption was made to simplify the model derivation; there is no reason why the time during rainfall could not also be included if desired.)

Drainage characteristics of pavement sublayers are specified to EAROMAR by qualitative descriptors--good, fair, or poor. For use in the drainage model these descriptions must be reduced to quantitative measures of subsurface permeability. Cedergren (1) presented coefficients of permeability for standard bases and subbases of about 0.02-20 ft/day (0.6-610 cm/day) and for open-graded bases of about 3000-250 000 ft/day (900-75 000 m/day). Based on these data we defined the following correspondence between user descriptions of drainage quality and coefficient of permeability used in model calculations:

Poor: 0.1 ft/day (0.03 m/day),
Fair: 100 ft/day (30.5 m/day), and
Good: 10 000 ft/day (3050 m/day).

Thus, typical bases and subbases used in flexible and rigid pavements today lie in the poor to fair range under this designation.

Quantifying the deleterious effects of water on pavement life requires estimates of (a) the reduction in sublayer material properties during the time the pavement is significantly wet and (b) the duration of this period of weakened strength (in terms of the three wet periods described earlier and the length of time between the starts of the second and third periods, respectively). Unfortunately, the answers to these key questions are not well supported by field documentation.

Von Quintus and others (4) presented data on seasonal changes in plate-bearing capacity for a pavement that had a granular base, frost-susceptible subgrade, and high water table. Based on the September bearing strength normalized to a value of 100, seasonal variations at this site ranged from about 20 in the spring-thaw months to more than 140 in the frozen winter months. Values of relative damage factors between wet and dry periods were discussed earlier; Cedergren (1) calculated values of about 10 to 40 to 1 for the AASHO Road Test. However, these data are not tied to detailed material properties. We have therefore assumed that, during the time of substantial pavement wetness, individual subsurface layer moduli are reduced by 50 percent.

Determining the time during which the pavement is sufficiently wet to affect performance is more difficult. Equations are available that relate degree of drainage (i.e., percentage of water removed from a saturated layer) to time, but again these data are not tied to changes in layer material properties or pavement performance. As a conservative estimate we have calculated drainage times on the basis of an assumed degree of drainage of 0.8. The implication of this and the preceding assumption is that in the time required to drain 80 percent of the water from a saturated layer, the sublayer moduli will be considered to be reduced in value by 50 percent in the EAROMAR simulation.

Based upon these general formulations, the following model relationships were derived.

ESTIMATES OF DURATION OF PAVEMENT WETNESS

The duration of pavement wetness is determined by the interaction of water inflow and outflow characteristics of the pavement structure. As explained in the preceding section, outflow characteristics dominate the particular model within EAROMAR, and it is these relationships that will be explained first. Following the description of outflow equations, we will consider the influence of inflow parameters on the model.

The time required to drain a saturated subsurface layer is captured within the relationships shown in Figure 1 (3). The normalized time factor (t/m) is dependent on the degree of drainage achieved (U), the width of road to be drained (L), the depth of the drainage layer (H_d), and the transverse slope of the drainage layer (S:1). From our earlier discussion, we have assigned a value of 0.8 to U, taken to be the point at which wetness no longer affects pavement structural behavior. Pavement cross slopes typically vary from 0.125 to 0.25 in/ft (1-2 cm/m); we have therefore taken the slope factor (S) to be a constant equal to 0.015. Also, we have taken L conservatively to be equal to the sum of the widths of all lanes plus shoulders in the roadway. Finally, we have assumed H_d typically to be about 1 ft (0.3 m). Based on these assumptions, we fit the following function to data points generated from Figure 1:

$$t/m = 2.5 \exp(-2S') \tag{1}$$

$$S' = 0.015L/H_d \tag{2}$$

$$L = (N_{lanes} \times W_{lane}) + \Sigma W_{shldr} \tag{3}$$

where

t/m = normalized time of drainage;
H_d = thickness of the drainage layer, assumed to be 1 ft;
N_{lanes}, W_{lane} = number and width in feet, respectively, of lanes in this roadway; and
W_{shldr} = widths in feet on the left and right shoulders in the roadway.

The denominator of the normalized time is a function of the yield capacity of the drainage layer:

$$m = nL^2/k_d H_d \tag{4}$$

where

m = normalizing factor;
n = yield capacity (effective porosity) of drainage layer;
L = width of roadway drained, defined by Equation 3; and
k_d = coefficient of permeability of pavement drainage layer.

Values of n can be estimated from Figure 2 (3) by using the coefficients of permeability assigned earlier to users' qualitative descriptions of drainage, as shown below (1 ft/day = 0.3 m/day):

Drainage Quality Input	Coefficient of Permeability k_d (ft/day)	Yield Capacity n
Good	10^4	0.23
Fair	10^2	0.08
Poor	10^{-1}	0.055

With these values one can solve Equation 4 for m and determine t/m from Equation 1. The time of drainage corresponding to the period in which we have assumed that pavement structural behavior is affected is then given by the following:

$$t_{drain} = m(t/m) \tag{5}$$

Figure 1. Time-dependent drainage of saturated layer.

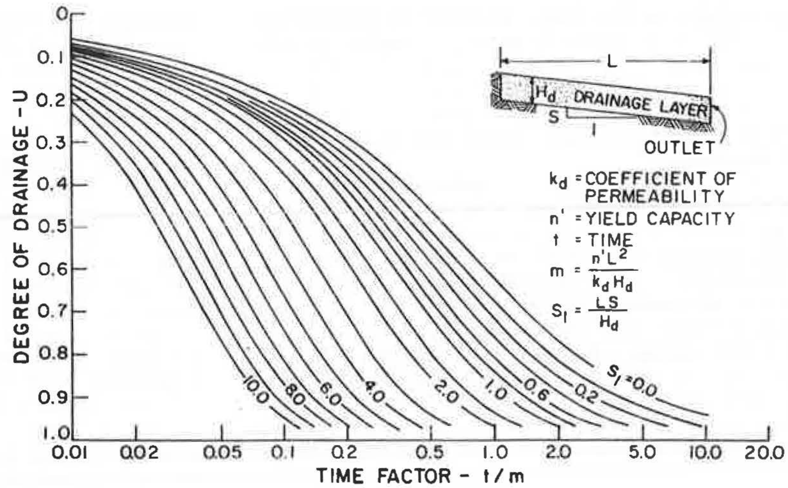
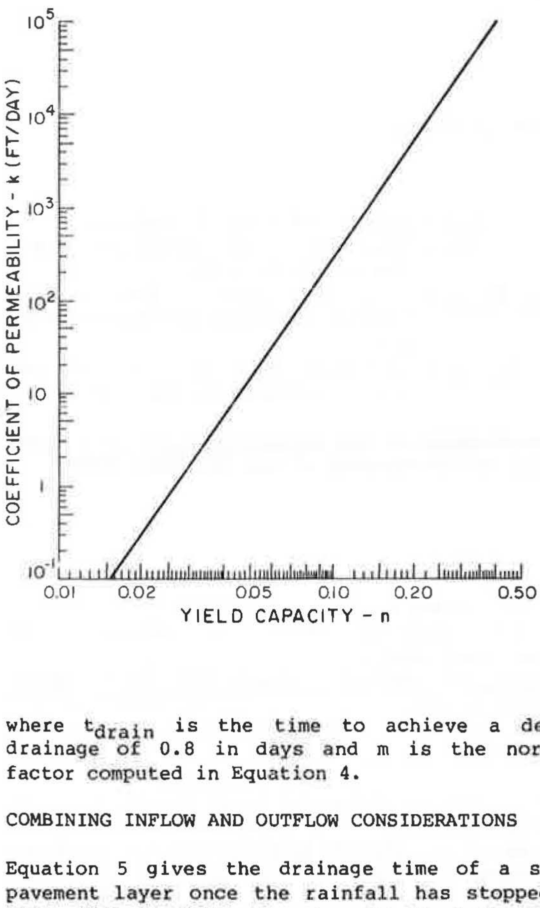


Figure 2. Chart for determining yield capacity (effective porosity).



where t_{drain} is the time to achieve a degree of drainage of 0.8 in days and m is the normalizing factor computed in Equation 4.

COMBINING INFLOW AND OUTFLOW CONSIDERATIONS

Equation 5 gives the drainage time of a saturated pavement layer once the rainfall has stopped. However, the quantity of water to be drained depends not only on the seasonal rainfall but also on the condition of the pavement surface (the number of open cracks and joints). We have treated both these contributing factors to inflow as multipliers of the time computed in Equation 5. Thus, if either the seasonal rainfall (for a fixed amount of cracking) or the amount of cracking or open joints (for a fixed seasonal rainfall) increases, the time during which pavement structural response is affected will also increase. If either the seasonal rainfall or the open cracks and joints in the pavement are negligible, the time the pavement is affected will also be negligible.

Table 1. Rainfall data for selected cities in peak month of 1978.

City	Total Precipitation (in)	Days of Precipitation	Avg Daily Precipitation (in)
Boston	8.12	15	0.54
San Francisco	6.20	16	0.39
Seattle	6.05	16	0.38
Los Angeles	7.70	10	0.77
Miami	2.57	11	0.23
Chicago	6.38	12	0.53
New Orleans	12.53	17	0.74

Consider first the effects of seasonal rainfall. To convert total precipitation to an equivalent time or duration comparable with the duration predicted in Equation 5, we require an assumed rainfall intensity. Data in Table 1 and reported by Cedergren (1) and Moulton (3) suggest that a daily intensity of 0.5 in/day (12.7 mm/day) is reasonable as a composite national figure.

Findings reported by Cedergren (1) showed that substantial quantities of water can enter even very narrow cracks in a pavement under field test conditions. [Cracks 0.125 in (3 mm) wide admit more than 95 percent of water falling at an intensity of 2 in/h (50 mm/h), even with steep pavement transverse slopes. Cracks as narrow as 0.035 in (0.89 mm) can absorb 70 percent or more of runoff at the same intensity.] In practice these rates may be reduced somewhat, due to debris at the bottom of the crack or to buildup of water in the crack. Nevertheless, infiltration rates become quite high at low levels of cracking or open joints in the pavement surface.

To model this relationship we have assumed the fraction of water inflow to be a negative exponential function of cracking and open joints subject to assumed boundary conditions. Specifically, if there are no open cracks or joints in the pavement surface, water infiltration is reduced to zero. At cracking (or open joints) covering 50 percent of the pavement surface (a highly cracked pavement), infiltration is assumed to equal 99 percent of all water falling on the pavement area.

By combining the above assumptions and incorporating a definition of the total area of discontinuities in the pavement surface, we obtain the following relationships:

$$t_{wet} = (r_{season}/i_{avg})\,[1 - \exp(-9C)]\,t_{drain} \qquad (6)$$

$$C = (1/5280) \{[(LCRACKS + ACRACKS)/W_{lane}] + [(SHOULDER \times W_{wet})/2W_{lane} N_{lane}] + (JOINTS \times W_{wet})\} \quad (7)$$

where

t_{wet} = duration of pavement wetness in days during which structural response is assumed to be affected;
r_{season} = seasonal rainfall in inches input by the user;
i_{avg} = daily rainfall intensity, assumed to equal 0.5 in (12.7 mm);
C = fraction of pavement area having cracks or open (unsealed) joints;
t_{drain} = time in days to drain the saturated pavement sublayers;
LCRACKS, ACRACKS, SHOULDER, JOINTS = quantities of damage components per lane mile computed by pavement simulation models within EAROMAR;
W_{lane}, N_{lane} = width of lane in feet and number of lanes in roadway, respectively, as input by user; and
W_{wet} = width of subsurface zone wetted by open joint, assumed to be 6 ft (1.8 m).

REDUCTIONS IN PAVEMENT STRENGTH

Pavement characteristics simulated within EAROMAR are affected by water infiltration in two ways. First, the strengths of granular bases and subgrades are reduced by 50 percent, as described in the general model formulation. Second, the American Association of State Highway and Transportation Officials (AASHTO) regional factor is adjusted to reflect saturated conditions above and beyond those assumed by the user in initial program input. Resulting model relationships are as follows:

$$F_{red} = (t_{season} - 0.5t_{wet})/t_{season} \quad (8)$$

$$R' = [5t_{wet} + R(t_{season} - t_{wet})]/t_{season} \quad (9)$$

where

F_{red} = reduction factor applied to moduli of granular pavement layers and to California bearing ratio (CBR) and moduli of subgrade,
t_{season} = length of season in days determined from season information input by user,
t_{wet} = duration of pavement wetness in days computed from Equation 6,
R' = AASHTO regional factor corrected for additional wetness due to cracked pavement surface, and
R = regional factor input by user.

Note that Equations 8 and 9 apply a time-average correction (under wet versus dry conditions) to the pavement material properties and regional factor. Multiplication by 0.5 in Equation 8 reflects the assumed loss in material strengths under wet conditions; the coefficient 5 in Equation 9 reflects the value of the regional factor associated with saturated conditions.

The effects of water infiltration on pavement performance are therefore modeled within EAROMAR through the material-related and environmental adjustments indicated above. This makes it possible to consider interactions between load-related and environmental influences on pavement damage and to see what effects unsealed cracks and joints have on the rate of future pavement damage. The latter relationship in turn allows one also to investigate the benefits achieved through the routine maintenance actions of sealing joints and cracks. Predictions of these models applied to a case study are described below.

CASE STUDY

To investigate the trends predicted by Equations 1 through 9, we applied the EAROMAR system to simulate pavement performance and costs on three roadways, each 10 miles (17 km) long, all having identical pavement, traffic, and maintenance policies but differing in drainage characteristics. The deterioration of the pavements was estimated by using damage models described by Markow and Brademeyer (2). Maintenance was applied, depending on the amount of damage accumulated and the time interval since that activity had last been performed. Overlays were scheduled when the pavement present serviceability index (PSI) fell below 2.5 or when rutting exceeded 1.0 in (2.5 cm).

The roadways tested all had flexible pavements with a structural number of 4.7. This structure was designed according to AASHTO recommendations (5) for simulated traffic of 9300 vehicles per day, imposing an average of 770 equivalent 18-kip axle loads per day. No traffic growth was assumed. Environmental factors specified were typical of northeastern United States: an average rainfall of 10 in (25 cm) per three-month season, a freezing index of 800, and an AASHTO regional factor of 2.5. The asphalt concrete moduli of the pavement surface were varied seasonally as a function of the average seasonal temperature.

Results of the simulations indicated that pavement performance under good and fair drainage conditions was virtually identical. Under poor drainage conditions, however, the rate of pavement damage increased, resulting in worse pavement surface conditions over time and increased pavement-related costs to both the highway agency and road users. If this finding were generally true, it would mean that a minimally acceptable value of subbase permeability lies between the poor and fair values [0.1-100 ft/day (0.03-30.5 m/day)].

Figure 3 illustrates trends in PSI over a 20-year analysis period. The pavements subject to good and fair drainage are overlaid after 13 years in service, their PSI having dropped to 2.5 in that time. The pavement having poor drainage, however, fails after only 9 years' service. The four years' difference in pavement life is due solely to the effects of water infiltration in weakening the sublayers of the pavement with poor drainage, which leads to more rapid damage accumulation.

The trends in pavement damage are indicated in Figures 4 through 6, which show patterns similar to that noted for PSI above. Both roughness and rutting are accelerated in the pavement with poor drainage and are correctable only through overlays. The levels of cracking, however, show no real variation among the three pavements. The reason is that, for this particular simulation, most of the cracking is due to cold-weather shrinkage, which is independent of traffic loads. (Had the cracking been dominated by fatigue mechanisms, the trends likely would have been different between the poor drainage and the other pavements.)

Cracking is reduced to zero in those years in which pavements are overlaid. In other years cracking is allowed to accumulate until it is repaired by routine maintenance on a three-year cycle. (Figure

Figure 3. Serviceability over time.

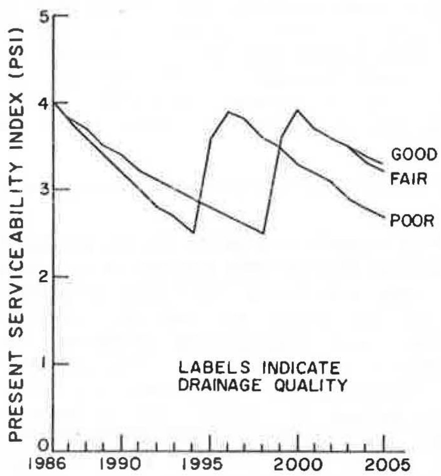
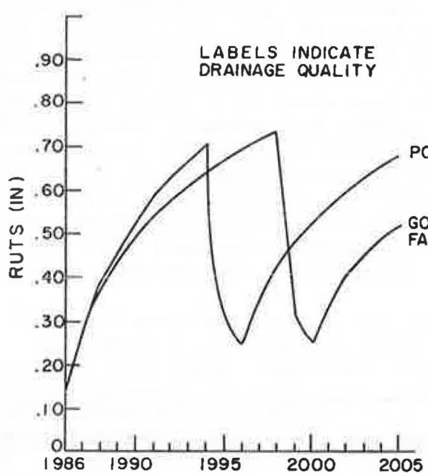


Figure 4. Rutting over time.



6 shows annual averages of surface cracking. Since some cracks existed at the beginning of those years in which crack filling was performed, the annual average does not reduce to zero in these years, even after maintenance.) Because the cracking in all roadways falls within the same range of values, observed differences in pavement performance are due only to the length of time the pavement sublayers are saturated and not to differences in water inflow.

The ride quality of the pavement surface has effects on road users through influences on speed, travel-time costs, and vehicle-operating costs. Differences in these user costs among pavement policies can in turn be applied to justify, on an economic basis, specific pavement maintenance, rehabilitation, or reconstruction actions. Figure 7 shows the trends in annual user costs for the three pavements tested. As expected, user costs increase more rapidly on the pavement with poor drainage, demonstrating the effects on the motoring public of the damage accumulation.

The fact that the curves for fair and good drainage generally coincide in Figures 3-7 indicates that subbase permeabilities of the order of 100 ft/day (30.5 m/day) already provide adequate drainage for the rainfall amounts and intensities tested. Results for these drainage levels would be expected to diverge as either rainfall amount or daily intensity

Figure 5. Roughness over time.

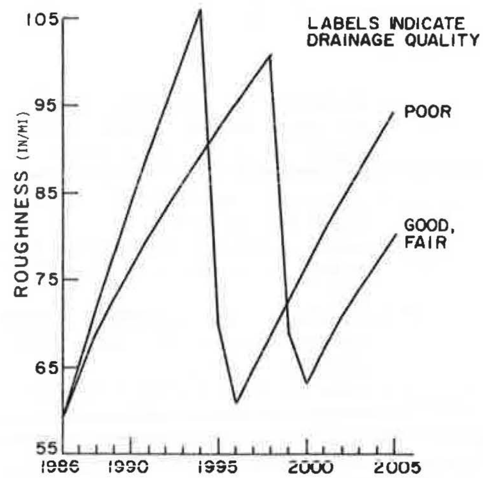
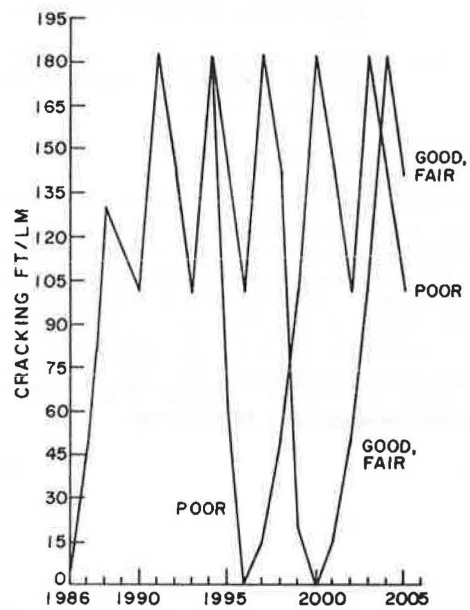


Figure 6. Cracking over time.



increased. In fact, we have observed differences in pavement performance and costs for good versus fair drainage in a separate set of simulations that used annual rainfall of 80 in (200 cm) per year, twice those assumed in Figures 3-7. However, the relative benefits for good versus fair drainage are much less than those for fair versus poor drainage, supporting our statement earlier that an acceptable minimum value of coefficient of permeability for the pavement drainage layer lies within the poor to fair range.

The stream of user costs (Figure 7) can be considered with agency expenditures and both streams discounted through the analysis period to conduct an economic analysis based on total costs. Table 2 presents results for the three roadways analyzed by the EAROMAR simulation (exclusive of salvage value). At a 4 percent discount rate (appropriate for constant-dollar analyses), the pavement with fair drainage provides a net benefit of $184 000 and that with good drainage a net benefit of $191 000 through the analysis period. On an economic basis, this is the amount one should be willing to pay to

Figure 7. User costs over time.

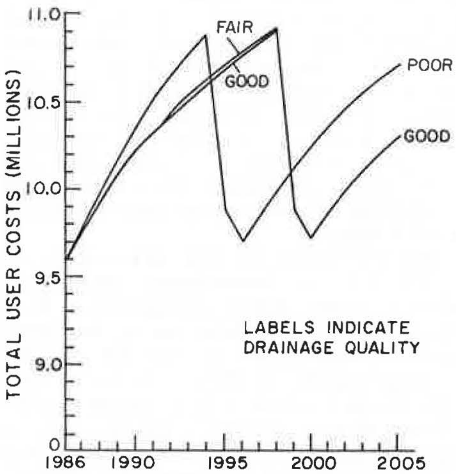


Table 2. Economic analysis of roadways with different drainage characteristics.

Quality of Drainage	Millions of Dollars: Overlay Expenditures	Maintenance Expenditures	User Costs	Total Costs	Cost Difference in Relation to Poor Drainage
Good	0.576	0.004	138.838	139.418	0.191
Fair	0.576	0.004	138.845	139.425	0.184
Poor	0.674	0.003	138.933	139.609	-

improve the drainage conditions or maintenance on the poor roadway. Stated another way, if the 10-mile roadway that has poor drainage could be rehabilitated to provide fair to good drainage or could be maintained each year to prevent water infiltration at a cost whose value discounted at 4 percent did not exceed $184 000 to $191 000, this improvement would be economically justified.

CONCLUSIONS

We have presented here an approach to assess the effects of drainage quality on pavement performance and costs. Although the procedure has been applied to date only within a simulation model and must yet be verified in the field, it provides a sound rational basis for organizing information on pavement structure, traffic and environmental loads, and damage accumulation with respect to water infiltration.

The results of our simulations indicate that, for flexible pavements in regions subject to annual rainfall of about 40 in (100 cm), the inclusion of good drainage characteristics within the pavement structure may increase acceptable performance life by about four years. On the other hand, poor drainage characteristics increase rates of rutting and roughness accumulation, decreasing overall pavement condition and increasing user costs for vehicle operation and travel time.

Further research is now under way to test this model for different pavements in different environmental regions and to assess the implications of maintenance policy on rates of damage influenced by water infiltration.

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REFERENCES

1. H.R. Cedergren. Drainage of Highway and Airfield Pavements. Wiley, New York, 1974.
2. M.J. Markow and B.D. Brademeyer. Modification of System EAROMAR: Final Technical Report. FHWA, June 1981.
3. L.K. Moulton. Highway Subdrainage Design. FHWA, Rept. FHWA-TS-80-224, Aug. 1980.
4. H.L. Von Quintus, F.N. Finn, W.R. Hudson, and F.L. Roberts. Flexible and Composite Structures for Premium Pavements, Volume 1: Development of Design Procedure. FHWA, Rept. FHWA-RD-80, Nov. 1980.
5. AASHTO Interim Guide for Design of Pavement Structures. American Association of State Highway and Transportation Officials, Washington, DC, 1972.

Pumping Mechanisms of Foundation Soils Under Rigid Pavements

LUTFI RAAD

Pumping of foundation soils under rigid pavements is a soil structure interaction problem in which the interaction among traffic loads, concrete slab, pavement materials, and water should be considered. Repeated stress induced by moving wheel loads could result in pore-water pressures that reduce the strength and stiffness of underlying soil layers and lead to pumping and loss of foundation support. Pumping mechanisms of granular bases in rigid pavements are investigated in terms of dynamic pore-pressure generation and dissipation. Analyses are performed to study the significance of permeability and compressibility of base materials, loading conditions, and drainage conditions on pumping. Higher pore-pressure values are obtained as a result of decrease in base permeability or increase in its compressibility. The inclusion of lateral drains increases the rate of dynamic pore-pressure dissipation and therefore reduces the pumping potential of the granular base. The efficiency of lateral drains, however, is a function of loading frequency. Higher frequency of loading may not allow enough time for pore-pressure dissipation, which may lead to pumping of the base material. The significance of loss of foundation support on the structural response of the pavement is also studied. Results indicate that loss of foundation support leads to increased stresses and deflections in the concrete slab and therefore hastens its rate of deterioration.