Performance Prediction and Cost-Effectiveness of Asphalt-Rubber Concrete in Airport Pavements

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An asphalt-rubber concrete and an asphalt concrete were tested in the laboratory and materials characterizations and properties were generated. The characterization parameters and a runway model for a municipal airport were input into the modified ILLIPAVE computer program for predictions of rutting and cracking damage and relative lives of the materials as airfield pavement surfaces in each of four climatic zones. An economic evaluation was performed comparing the expected service lives and costs of each material in each zone. An equivalent uniform annual cost per square yard over the life of the pavement for the construction cost of each pavement was determined. The material with the least equivalent uniform annual cost was selected as the most cost-effective. In every zone but the dry no-freeze zone, the asphalt-rubber concrete was calculated to be the most cost-effective material.

A research study was conducted to investigate the feasibility of using asphalt-rubber concrete, which contains ground and recycled tire rubber, as a surface material for airfield pavements at municipal airports. This research indicated that asphalt-rubber concrete, when properly designed and compacted, could provide a temperature-resistant and long-wearing pavement surface course for the large aircraft typically using a municipal airport. The asphalt-rubber concrete was predicted to be particularly advantageous over asphalt concrete in cases of wide seasonal temperature variation.

The study was performed in two parts. The first phase included development of the laboratory procedure for preparing asphalt-rubber for mix design and an evaluation and modification of the Marshall mix design procedure for designing an asphalt-rubber concrete mix (*1*, *2*). The second phase involved designing and testing an asphalt-rubber concrete mix and an asphalt concrete mix and, using a computerized pavement analysis program, evaluating and comparing the two mixes as airfield pavement surface materials (*3*). This paper describes the testing, analysis and results generated by this second phase of the study.

MATERIALS

Aggregate

The aggregate used in both mixes (asphalt concrete and asphalt-rubber concrete) was made up of crushed limestone and field sand and was blended to meet the 1977 Federal Aviation Administration (FAA) aggregate grading specification for pavements with a bituminous surface course that will accommodate aircraft with gross weights of 60,000 lb or more or with tire pressures of 100 psi or more (*4*). The maximum particle size was ½ in. (100% passing the ½-in. sieve and some retained on the ⅜-in. sieve).

Asphalt Concrete Control Mix

The asphalt concrete control mix was prepared with an AC-10 lab standard binder (American Petrofina). A Marshall mix design was performed according to the Asphalt Institute's MS-2 (*5*) with results as follows:

Property	*Design Criterion*	*% Binder*
Unit weight	maximum	5.30
Marshall stability	maximum	4.82
Air voids (%)	median of 3–5	4.41
Optimum	numerical average	4.84

For a binder content of 4.8 percent, the properties of the asphalt concrete mix as determined from the mix design curves were as follows:

Property	*Value of the Mix*	*Value Specified in Design Procedures*
Unit weight (lb/ft³)	151	—
Marshall stability (lb)	2,300	minimum = 1,500
Air voids (%)	3.0	3 to 5
Voids in mineral aggregate (%)	13	minimum = 15
Flow (0.01 in.)	8.8	8 to 16

It can be seen that the voids in mineral aggregate (VMA) of the asphalt concrete mix are below the design specification. However, the mix meets the other mix design criteria (*5*). The mix was accepted with a low VMA because the limestone aggregate had previously been used in many successful mixes.

Asphalt-Rubber Concrete

The name *asphalt rubber* has been given to a blend of asphalt paving cement and ground tire rubber which is formulated at an elevated temperature to promote chemical as well as physical bonding of the two component materials. Rubber content

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of the blend is between 18 and 25 percent by total weight of the blend (*6*).

The asphalt-rubber binder used for this study was obtained from a Texas State Department of Highways and Public Transportation road project. The binder was produced by the Arizona Refining Company and was a mixture of 77 percent AC-10 asphalt cement, 20 percent rubber, and 3 percent extender oil. The rubber was a blend of several types of ambient temperature grind, vulcanized whole tire rubber: 40 percent Baker CR40, 20 percent Baker C107, 30 percent Genstar C106, and 10 percent Genstar C112. The rubber gradation included particle sizes between the No. 16 and No. 200 sieves, with 37.5 percent of the rubber particles being retained on the No. 30 sieve. As discussed in an earlier report on this research (*1*), the aggregate blend used in the asphalt-rubber concrete mix should be adjusted to account for the rubber particles. However, in this case, the change in the aggregate blend due to this correction was smaller than the anticipated variation in the aggregate gradation itself. Therefore no adjustment was made and the same aggregate blend was used for both mixes.

A Marshall method mix design, modified for asphalt-rubber binder as described in an earlier report on this study (*1*), was performed on the asphalt-rubber concrete. However, the air void contents in the Marshall samples of the asphalt-rubber concrete were too high to meet the Marshall design criterion for air voids. This occurrence is consistent with difficulties experienced by earlier researchers in compacting asphalt-rubber materials in the laboratory (*1*). Therefore, the air void content requirement for the asphalt-rubber concrete was relaxed to 6 to 8 percent to allow the study to continue. At this time, it is not known whether the higher air void content will adversely affect the oxidation and aging rates of an asphalt-rubber concrete as it does with asphalt concretes with high air void contents. Also, it is possible that a lower air void content can be attained during field compaction with higher laydown temperatures and/or greater compaction efforts than those used for asphalt concrete.

The optimum binder content for the asphalt-rubber concrete is:

Property	*Design Criterion*	*% Binder*
Unit weight	maximum	4.88
Marshall stability	maximum	4.05
Air voids (%)	median of 3–5	5.27
Optimum	numerical average	4.73

Thus, the binder contents for the two mixes were close enough to each other to be considered the same. This does not usually occur, and separate mix designs need to be performed for the two materials.

For a binder content of 4.7 percent, the properties of the asphalt-rubber concrete mix as determined from the mix design curves were as follows:

Property	*Value of the Mix*	*Value Specified in Design Procedures*
Unit weight (lb/ft^3)	145	—
Marshall stability (lb)	2,200	minimum = 1,500
Air voids (%)	7.5	6 to 8 (see above)
Voids in mineral aggregate (%)	16	minimum = 15
Flow (0.01 in.)	7.3	8 to 16

The density of the asphalt-rubber concrete mix is seen to be about 6 lb/ft^3 less than that of the asphalt concrete mix. This is largely due to the relaxed air void content requirement for the asphalt-rubber concrete.

LABORATORY TESTS

Laboratory tests were performed on the asphalt concrete control material at optimum binder content (AC) and on the asphalt-rubber concrete at optimum binder content and at +0.5 percent binder content (ARC-low, ARC-medium, and ARC-high).

Marshall Stability

Marshall stabilities were measured on the two materials as part of the mix design process. The maximum Marshall stabilities for both mixes were almost the same (about 2,300 lb), but the maximum for the asphalt concrete control mix occurred at a higher binder content (about 4.8 percent) than that of the asphalt-rubber concrete (about 4.1 percent). The shapes of the stability vs. binder content plots were similar, indicating that the materials were about equally sensitive in stability to changes in the binder content.

Resilient Modulus

Resilient modulus was measured on each material, and curves of resilient modulus vs. temperature were plotted. The modulus of the asphalt concrete control was slightly more sensitive to temperature change than that of the asphalt-rubber concrete.

Fatigue

To study the fatigue characteristics of the materials, a third-point bending test was used on beam specimens. Plots of strain vs. cycles to failure were generated. Regression lines were fitted and fatigue parameters were calculated according to the familiar fatigue equation:

$$N_f = K_1(1/\varepsilon_t)^{K_2} \quad (1)$$

where

N_f = number of load applications to failure,
ε_t = tensile strain induced, and
K_1, K_2 = regression constants.

Two sets of regression equations, as shown in Table 1, were generated to describe the variation of the fatigue parameters with temperature for each material. These equations predict longer laboratory fatigue lives for the asphalt-rubber concrete than for the asphalt concrete.

It has been shown that the fatigue life of a material during laboratory testing is less than that experienced by the same material in the field (*7*). The difference between laboratory and field fatigue lives can be accounted for by applying a multiplier to the laboratory value of K_1. Finn et al. (*8*) suggested a multiplier of 13 after looking at data for asphalt

TABLE 1 REGRESSION EQUATIONS TO PREDICT FATIGUE PARAMETERS FOR ANY TEMPERATURE (°F) FOR MATERIALS AT OPTIMUM BINDER CONTENTS

	$\lvert\log K_1\rvert$ vs. $\log T$ (°F)
Material	Regression Equation
AC	$\lvert\log K_1\rvert = 14.630 - 4.558 \log T$
ARC-Medium	$\lvert\log K_1\rvert = 20.483 - 7.879 \log T$
	K_2 vs. $\log K_1$
Material	Regression Equation
AC	$K_2 = 1.512 - 0.280 (\log K_1)$
ARC-Medium	$K_2 = 1.900 - 0.243 (\log K_1)$

Note: Generated from laboratory data.

TABLE 2 AVERAGE VALUE OF CRACK SPEED INDEX FOR EACH MATERIAL AT EACH TEST TEMPERATURE

Material	Temperature (°F)	Crack Speed Index
AC	34	-1.223
	77	-5.054
ARC-Low	34	2.474
	77	-4.476
ARC-Medium	34	-2.288
	77	-0.740
ARC-High	34	-1.408
	77	---

concrete from the AASHO road test. The multiplier of 13 was used to estimate field fatigue for all materials in this project, but it may not be accurate for all types of materials. A means has been developed at Texas A&M University to derive the K_1 multiplier from laboratory data (*9*), but tests on healing would have been necessary to perform this analysis on the materials in this study.

Fracture

The Texas Transportation Institute overlay tester was used to investigate the fracture properties of the materials. The overlay tester opens a crack of controlled width at the bottom of a beam specimen. Repeated cycles drive the crack progressively upward through the beam. The load, P, and the length of the crack up into the beam, c, are measured.

The fracture of asphaltic concrete obeys a law of fracture mechanics known as Paris's law (*10*). Although it originally was an empirically derived relation, it has subsequently been derived from first principles of mechanics by Schapery (*11*). The fracture constants A and n, which can be calculated from the results of the overlay test, appear in Paris's law:

$$dc/dN = A(\Delta K)^n \qquad (2)$$

where

c = crack length,
N = number of load cycles,
dc/dN = crack speed, or rate of growth of the crack,
ΔK = change of stress intensity factor during load application,
A = fracture coefficient, and
n = fracture exponent.

Empirically, it has been found that the sum of $\log_{10} A$ and n, called the crack speed index, is an indicator of the relative effectiveness of materials in resisting cracking. A lower crack speed index indicates greater effectiveness at reducing cracking. The average values of crack speed index for each material are shown in Table 2. On this basis, the ranking of the materials for fracture resistance at low temperature (34°F) from best to worst is: ARC-medium, ARC-high, AC, ARC-low. At moderate temperature (77°F), one of the two high-binder-content asphalt-rubber concrete samples proved defective and therefore this material was not evaluated. Of the other materials, their order from best to worst fracture resistance was as follows: AC, ARC-low, ARC-medium. The results indicate that, with respect to the fracture resistance, the asphalt-rubber concrete with medium (optimum) binder content performed best at low temperature (34°F) but the asphalt concrete performed best at moderate temperature (77°F).

Creep

Creep tests were performed on cylindrical samples, and creep compliances were calculated. Averages of the compliances at each test temperature were fitted with a curve of the form:

$$D(t) = D_1 t^m \qquad (3)$$

The degree to which the resulting constants change with temperature is an indicator of the relative temperature susceptibility of the material. In order to numerically compare the temperature susceptibilities, a time-temperature shift property was calculated for each material. A "master" creep curve was created by shifting the average creep compliance curves horizontally parallel to the time axis until each one lined up with the curve for 70°F, the reference temperature. The amount of the time shift for each temperature was expressed as a ratio, a_T, as follows:

$$a_T = t/(t_{T0}) \qquad (4)$$

where

t_{T0} = time at which a given compliance is reached when the material is at the reference temperature, and
t = time at which the same compliance is reached when the material is at some other temperature.

TABLE 3 TIME-TEMPERATURE SHIFT CONSTANTS FOR EACH MATERIAL AT EACH TEST TEMPERATURE

Material	Temperature (°F)	$\log_{10} a_T$	Time-Temperature Shift Constants C_1	C_2
AC	40	2.25	6.75	120
	70	0.0		
	100	-1.35		
ARC-Low	40	2.65	3.76	72.6
	70	0.0		
	100	-1.10		
ARC-Medium	40	2.70	2.70	60.0
	70	0.0		
	100	-0.9		
ARC-High	40	2.4	2.40	60.0
	70	0.0		
	100	-0.80		

One commonly used function that can be fitted to the curves of $\log_{10} a_T$ vs. temperature is the "WLF equation" (*12*):

$$\log_{10} a_T = \frac{-C_1(T - T_0)}{(C_2 + T - T_0)} \tag{5}$$

where

C_1, C_2 = materials constants; the constant C_1 is the temperature susceptibility constant.
T_0 = the master curve temperature; 70°F, in this case.
T = any other temperature.

The values of the temperature shift constants for the materials in this study are shown in Table 3. On the basis of the WLF equation and the constant c_1, the materials in this study can be ranked in order of increasing temperature susceptibility in creep behavior: ARC-high, ARC-medium, ARC-low, AC. Thus, the results of the creep testing indicate that the rubber helps the material to maintain a more stable compliance (or modulus) during temperature changes.

Permanent Deformation

Repeated load tests as described in the VESYS manual (*13*) were performed on cylindrical samples in order to obtain permanent deformation parameters for the prediction of rutting behavior. A three-parameter equation was generated to describe the shape of the permanent strain vs. cycles curves:

$$\varepsilon_a = \varepsilon_o \, e^{-(\rho/N)^\beta} \tag{6}$$

where

ε_a = permanent (accumulated) strain,
N = loading cycle, and
ε_o, ρ, and β = calculated parameters.

This equation describes an S-shaped curve.

The permanent deformation parameters were sensitive to several factors, including stress level and temperature, during testing. Therefore, an adjustment had to be applied to the permanent deformation parameters from the laboratory results before they were used to predict field behavior. The adjustment procedure is described in an earlier project report (*3*). The adjusted values of permanent deformation parameters were plotted vs. temperature.

The permanent deformation parameters calculated from the laboratory tests for the mixes at optimum binder contents are shown in Table 4. If the values generated from the laboratory results are used in Equation 6, then the equation predicts that at low temperature (40°F) and at high temperature (100°F) the asphalt-rubber concrete would experience less strain under a given number of loadings than would the asphalt concrete. Thus, it appears as though the addition of rubber causes the material to become more resistant to permanent deformation at low and at high temperatures. At moderate temperature (70°F), however, the asphalt concrete is predicted to be less susceptible to permanent deformation at high numbers of cycles.

TABLE 4 PERMANENT DEFORMATION PARAMETERS FROM LABORATORY TESTS FOR MATERIALS AT OPTIMUM BINDER CONTENTS

Material	T(°F)	ϵ_o	ρ	β	ϵ_o/ϵ_r	Regression
AC	40	0.0187E+0	1.1539E16	0.0637	1,662	Nonlinear
	70	0.8232E-3	0.9817E04	0.2070	27.44	Linear
	100	0.9355E+0	6.3750E16	0.0591	31,509	Nonlinear
ARC-Medium	40	0.0181E+0	3.4514E16	0.0645	1,445	Nonlinear
	70	0.0238E+0	2.8904E16	0.0524	544	Nonlinear
	100	0.0588E+0	2.5023E16	0.0560	1,680	Nonlinear

DESIGN DATA

A comparative analysis of the materials was performed by selecting a structural model and environmental and loading conditions and by putting this information along with material parameters obtained from the laboratory tests into the modified ILLIPAVE pavement analysis program (*14*).

Airport Type and Traffic

Asphaltic materials are typically used as surface layer materials at medium to small civil airports. Therefore, the Robert Mueller Municipal Airport in Austin, Texas, was selected as an appropriate airport model for this study.

Total numbers of aircraft using the Austin airport between 1969 and 1981 were known, and projections were available for 1985 and 1990 (*15*). Five air carriers were included in the traffic: DC-9, DC-10, B-727, B-737, and B-757. The total yearly traffic for each aircraft, as summarized in Table 5, was divided by 365 to obtain an estimate of daily traffic. This was then multiplied by a wander factor to account for lateral wander of the aircraft. The wander factors used in this study were computed by Brent Rauhut Engineering, Inc. (*15*), generally following a procedure by Ho-Sang (*16*) which assumes that the lateral movement of each aircraft type over the width of the runway is normally distributed. The wander factors are shown in Table 6.

Previous research has shown that the contact pressures against a pavement can be much higher than the tire inflation pressure (*14*). This can greatly increase the pavement damage caused by heavy vehicles, thus greatly reducing pavement life. Therefore, an attempt was made to estimate the contact pressures of the aircraft. A previously calculated pressure distribution (*17*) for a 32 × 8.8 Type VII aircraft tire was used as a model, and similar pressure distributions along the width centerline of the tire were calculated for each aircraft in the traffic pattern.

Pavement Structure

A typical pavement section was chosen from the main runway at the Austin municipal airport, and material properties were

TABLE 5 SUMMARY OF AIRCRAFT TRAFFIC DATA FROM THE AVIATION DEPARTMENT, AUSTIN, TEXAS

	Aircraft Type				
Year	DC-9	DC-10	B-727	B-737	B-757
1969	32,660				
1971	17,410		2,176	2,176	
1974	2,570		15,430	7,710	
1976	1,870		11,230	5,610	
1981	5,200		31,200	15,600	
1985	2,910	580	36,670	17,460	580
1990	3,100	3,100	37,200	15,500	3,100

TABLE 6 SUMMARY OF AIRCRAFT TRAFFIC WANDER FACTORS FOR EACH AIRCRAFT CONSIDERED IN PAVEMENT EVALUATION

Aircraft	Wander Factor[a]
B-727	0.77
B-737	0.57
B-757	0.61
DC-9	0.68
DC-10	0.72

[a] Wander Factor is the inverse of the Pass-to-Coverage Ratio

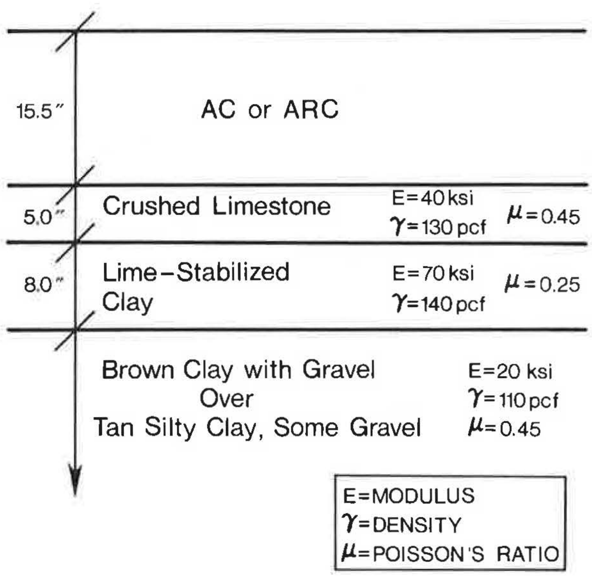

FIGURE 1 Schematic of pavement structure used for the modified ILLIPAVE performance analysis.

estimated for the underlying layers. Material characterizations obtained from the laboratory testing were used for the top bituminous layer. Figure 1 shows the typical section.

Seasonal Temperatures

Because asphaltic materials are temperature sensitive, the analysis was performed using four climatic zones of four seasons each. Seasonal average temperatures were used and are shown in Table 7.

COMPUTER ANALYSIS

Modified ILLIPAVE Computer Program

The computer program used in this analysis was the third in a series of programs developed to analyze the stresses, strains, and displacements in a pavement under repeated loads. The original program was developed by Duncan et al. (*18*). The program was revised at the University of Illinois (19) and was renamed ILLIPAVE. The program was then obtained and revised by Texas A&M University (*14*) and provides for multiple tires on one or two axles, nonuniform vertical and horizontal contact pressure distributions on circular loaded areas, and all of the nonlinear stress-strain curve capabilities available in the two previous programs. This program predicts rut depth and fatigue cracking.

TABLE 7 AVERAGE SEASONAL TEMPERATURE FOR EACH OF FOUR SEASONS FOR EACH CLIMATIC ZONE

	Temperature, °F			
Zone	Winter	Spring	Summer	Fall
Wet-Freeze	35	65	95	60
Wet-No Freeze	75	95	105	95
Dry-Freeze	35	60	90	50
Dry-No Freeze	55	75	95	75

Mixed-Traffic Damage Evaluation: Comparison of Mixes

Computer runs were made for every combination of aircraft, climatic zone, and material using the modified ILLIPAVE computer program. For any particular computer run, one aircraft was considered as making up the entire traffic count. Then calculations were performed on the totals for each of the damage criteria (cracking and rutting) to produce damage totals for the mixed-traffic condition (*3*). A 20-year period was analyzed.

Rutting was chosen as the critical failure mode because the cracking indices that predict field cracking behavior never got very large. A rut depth of 0.7 in. was chosen as the comparative level. This is a large rut depth for an airport runway, but it allowed a better comparison between materials in the climates with large temperature ranges than a smaller rut depth would have.

A cracking index of 0.2 (adjusted to the field fatigue condition) was chosen as a comparison level, but not as a failure index. A pavement with this level of cracking index would exhibit low-severity fatigue cracking with few of the cracks being interconnected and none of them being spalled.

In every combination of type of damage and climatic zone, the modified ILLIPAVE program predicted that the asphalt-rubber concrete would experience less damage and therefore would perform better than the asphalt concrete control material.

Predicted Cracking

For all four climatic zones, the predicted field cracking index was highest for the asphalt concrete control and lowest for the asphalt-rubber concrete with medium (optimum) binder content. This means that the asphalt concrete pavement would be expected to crack earlier than the asphalt-rubber concrete pavement. Of the four environmental zones, the wet non-freeze zone displayed the greatest difference between the predicted cracking performances of the control vs. the rubberized materials. Also, the predicted field cracking indices for all materials were the highest in this zone, which had three hot seasons (> 90°F). This indicates that the predicted cracking behavior of all four mixes was most susceptible to hot temperatures, with the asphalt concrete mix being the worst case. Table 8 is a tabulation of the calculated 20-year field damage indices that illustrate these observations. Figure 2 shows plots of calculated field cracking index vs. time (years) for all four materials in two of the climatic zones.

Predicted Rutting

The modified ILLIPAVE program predicted that all four of the materials considered would reach a rut depth of at least 0.5 in. during the 20-year analysis period. The years in which each material reached 0.5-in. predicted rut depth and the comparison level of 0.7-in. predicted rut depth are shown in Table 9. Figure 3 shows plots of calculated rut depth vs. time (years) for all four materials in two of the climatic zones.

For all four climatic zones, the modified ILLIPAVE program predicted that the asphalt concrete would experience the largest rut depths and the asphalt-rubber concrete, optimum (medium) binder content, would experience the smallest rut depths. The difference between the predicted rut depths of the control and the rubber material was greatest in the wet

TABLE 8 FIELD CRACKING INDICES FOR COMBINED TRAFFIC AT 20 YEARS

Zone (Temperatures, °F)	Material	Cracking Index (Field, 20 Years)
Wet-Freeze	AC	0.21
(35-65-95-60)	ARC-Low	0.07
	ARC-Medium	0.04
	ARC-High	0.05
Dry-Freeze	AC	0.16
(35-60-90-50)	ARC-Low	0.06
	ARC-Medium	0.03
	ARC-High	0.04
Wet-No Freeze	AC	0.83
(75-95-105-95)	ARC-Low	0.15
	ARC-Medium	0.10
	ARC-High	0.11
Dry-No Freeze	AC	0.35
(55-75-95-75)	ARC-Low	0.13
	ARC-Medium	0.06
	ARC-High	0.07

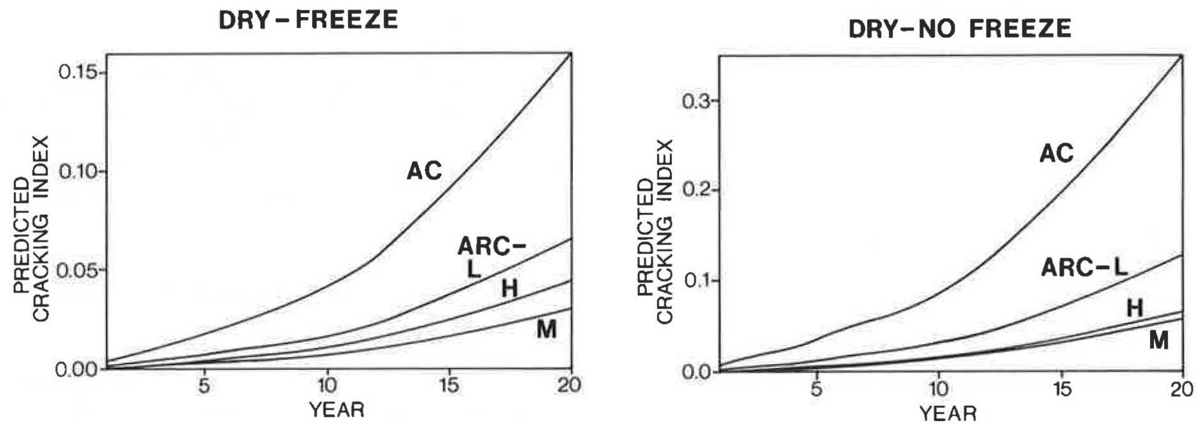

FIGURE 2 Plots of predicted field cracking index for combined traffic vs. year, for all four mixes, in two climatic zones.

nonfreeze zone, and the difference was very small and probably would be considered insignificant for the dry nontreeze zone. Therefore, it could be concluded that the asphalt concrete or the asphalt-rubber concrete would perform equally well as pavement materials in moderate temperatures, but that at hot or cold temperatures the asphalt-rubber concrete would be considerably more resistant to permanent deformation than the asphalt concrete.

TABLE 9 TIMES TO RUT DEPTHS OF 0.5 IN. AND 0.7 IN. FOR COMBINED TRAFFIC AND FOR VARIOUS MATERIALS AND CLIMATIC ZONES

ZONE (Seasonal Temperatures, °F)	MATERIAL	YEAR (First Rut Depth ≥ 0.50 in.)	FIELD CRACKING INDEX	YEAR (First Rut Depth ≥ 0.70 in.)	FIELD CRACKING INDEX
Wet/Freeze	AC	01	0.006	04	0.020
(35-65-95-60)	ARC-Low	12	0.024	17	0.050
	ARC-Med.	13	0.016	17	0.027
	ARC-High	12	0.018	17	0.038
Dry/Freeze	AC	01	0.004	05	0.017
(35-60-90-50)	ARC-Low	13	0.028	18	0.054
	ARC-Med.	13	0.013	18	0.025
	ARC-High	12	0.016	17	0.033
Wet/No Freeze	AC	01	0.019	01	0.019
(75-95-105-95)	ARC-Low	09	0.031	13	0.062
	ARC-Med.	11	0.031	15	0.060
	ARC-High	08	0.020	13	0.045
Dry/No Freeze	AC	10	0.086	15	0.201
(55-75-95-75)	ARC-Low	11	0.034	16	0.083
	ARC-Med.	12	0.020	16	0.038
	ARC-High	11	0.020	15	0.038

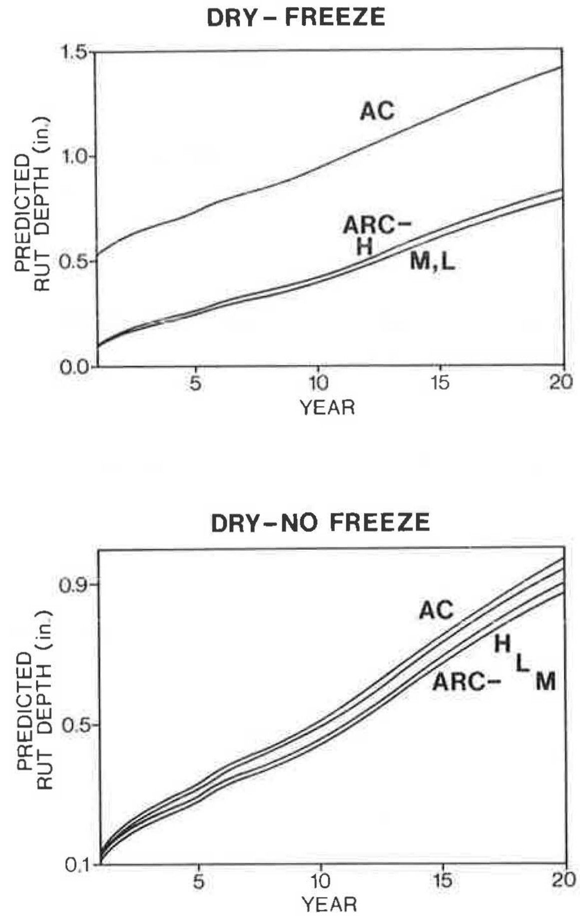

FIGURE 3 Plots of predicted rut depth for combined traffic vs. year, for all four mixes, in two climatic zones.

COST-EFFECTIVENESS COMPARISON

Approximate costs for asphalt concrete and for asphalt-rubber concrete were estimated for the materials compacted in place. A cost-effectiveness analysis was then performed for each of the mixes. Because the material used in the surface layer was the only difference between the pavements analyzed, the cost-effectiveness of that layer was analyzed.

Cost Data

Cost estimates for asphalt-rubber concrete were based on (1) the cost of producing the asphalt-rubber binder and (2) substitution of the cost of the asphalt-rubber binder for the cost of the asphalt cement in asphalt concrete unit prices. An additional 10 percent was added to the cost of haul, laydown, and compaction for the asphalt-rubber concrete over that cost for the asphalt concrete to account for higher temperatures or greater compactive effort possibly required for compaction of the asphalt-rubber concrete. An industry-supplied price of $100 per ton, delivered to the batch plant, was used for the asphalt cement. A price of $370 per ton was used for the asphalt-rubber binder; this was based on a binder containing 18 percent rubber, 82 percent asphalt cement, and no cutback, for a job using 1,000 tons or more of the binder material.

Approximate in-place component costs for hot mixes made with asphalt cement binder and asphalt-rubber binder are given in Table 10. Using an asphalt-rubber binder increased the cost of the concrete by 50 percent. Most of this cost increase was related to production of the asphalt-rubber binder.

Cost-Effectiveness Analysis Based on Projected Lives of Pavements

Rutting was chosen as the type of pavement distress that controls the useful lives of the pavement surface layers. As discussed above, a limiting rut depth of 0.7 in. was set, and predicted pavement lives were determined.

The steps in the cost comparison were as follows:

1. Determine the construction cost of each paving material in place per square yard.
2. Determine the equivalent uniform annual cost per square yard of each pavement over its predicted life.
3. Select the most cost-effective material in each climatic zone as the one that provides the least equivalent uniform annual cost per square yard for the life of the pavement.

The equivalent uniform annual cost per square yard is the annual cost per square yard that, if paid annually over the life of the pavement, has a present value equal to the in-place cost per square yard of construction of the asphaltic surface layer. It includes only the cost of construction distributed uniformly over the expected life of the pavement. It does not include the cost of maintenance or rehabilitation of the pavement or the costs to the user while these activities are being carried out. Because these are largely unknown for asphalt-rubber concrete pavements, it was assumed for the purposes of this cost-effectiveness analysis that they are roughly proportional to the equivalent uniform annual cost of construction and that a comparison of these would provide a rational means of selecting the preferable material in each climatic zone.

The interest rate that was used in calculating the equivalent uniform annual cost was 4.0 percent. This was considered to be a reasonable estimate of the difference between actual interest and actual inflation rates as applied to construction.

Construction Cost per Square Yard

The following steps were followed for the determination of the in-place construction cost per square yard for the asphaltic surface layer:

1. Using the compaction curves from the Marshall mix designs, determine the in-place density of each of the four materials.
2. Determine the tons per square yard of each material.
3. Determine the cost per square yard of each material in place.

The results of these determinations are shown in Table 11.

TABLE 10 UNIT COST PER TON OF MATERIAL IN PLACE FOR ASPHALT CONCRETE AND ASPHALT-RUBBER CONCRETE

	Asphalt Cement		Asphalt-Rubber Cement Binder					
	Binder		Low Binder		Medium Binder		High Binder	
Component	$/Ton	%	$/Ton	%	$/Ton	%	$/Ton	%
Binder[a]	4.80	16.3	15.65	36.5	17.50	38.8	19.35	41.0
Aggregate	8.85	30.1	8.85	20.6	8.85	19.7	8.85	18.7
Energy Costs	1.28	4.4	1.28	3.0	1.28	2.8	1.28	2.7
Mixing	3.51	11.9	3.51	8.2	3.51	7.8	3.51	7.4
Haul, Laydown and Compaction[b]	5.92	20.1	6.51	15.2	6.51	14.4	6.51	13.8
Miscellaneous	0.66	2.2	0.66	1.5	0.66	1.5	0.66	1.4
Mark-Up (15%)	4.42	15.0	6.43	15.0	6.76	15.0	7.09	15.0
TOTALS	29.44	100.0	42.89	100.0	45.07	100.0	47.25	100.0

[a] 4.8% - Asphalt Cement Binder; 4.23% - Low Asphalt-Rubber Cement Binder; 4.73% - Medium Asphalt-Rubber Cement Binder; 5.23% - High Asphalt-Rubber Cement Binder. Asphalt Cement at $100 per ton, and Asphalt-Rubber Cement at $370 per ton, at the batch plant.

[b] 10% added to cost for compaction of Asphalt-Rubber Concrete due to anticipated increase in compaction temperature and/or compactive effort over that required for Asphalt Concrete.

TABLE 11 IN-PLACE COSTS FOR ASPHALT CONCRETE AND ASPHALT-RUBBER CONCRETE

	Percent Binder	In-Place Costs per ton, $/Ton	Density, lb/ft	Tons per Square Yard, T/S.Y.	In-Place Costs per Square Yd., $/S.Y.
Asphalt Concrete	4.80	29.44	151.2	0.851	25.04
Asphalt-Rubber Concrete					
Low Binder	4.23	42.89	144.8	0.815	34.93
Medium Binder	4.73	45.07	145.3	0.817	36.84
High Binder	5.23	47.25	144.9	0.815	38.51

TABLE 12 EQUIVALENT UNIFORM ANNUAL CONSTRUCTION COSTS FOR ASPHALT CONCRETE AND ASPHALT-RUBBER CONCRETE

		0.5 in. Rutting		0.7 in. Rutting	
Material	Climatic Zone (Temperature, °F)	Age, Years	Cost[a] per Square Yard per Year	Age, Years	Cost[a] per Square Yard per Year
AC	Wet-Freeze	1	25.04	4	6.63
ARC-Low	(35-65-95-60)	12	3.58	17	<u>2.76</u>
ARC-Medium		13	<u>3.55</u>	17	2.91
ARC-High		12	3.95	17	3.04
AC	Dry-Freeze	1	25.04	5	5.41
ARC-Low	(35-60-90-50)	13	<u>3.36</u>	18	2.65
ARC-Medium		13	3.55	18	2.80
ARC-High		12	3.95	17	3.04
AC	Wet-No Freeze	1	25.04	1	25.04
ARC-Low	(75-95-105-95)	9	4.52	13	3.36
ARC-Medium		11	<u>4.04</u>	15	<u>3.19</u>
ARC-High		8	5.50	13	3.71
AC	Dry-No Freeze	10	<u>2.97</u>	15	<u>2.17</u>
ARC-Low	(55-75-95-75)	11	3.83	16	2.88
ARC-Medium		12	3.77	16	3.04
ARC-High		11	4.23	15	3.33

[a] Most cost effective choices in each climatic zone are underlined.

Equivalent Uniform Annual Cost per Square Yard of Materials in Place

The formula for the equivalent uniform annual cost per square yard is

$$\frac{EUAC}{SY} = \frac{(PV/SY)(i)}{(1 + i)\,[1 - (1 + i)^{-n}]} \qquad (7)$$

where

EUAC/SY = equivalent uniform annual cost per square yard;
PV/SY = the "present value" or construction cost per square yard;
i = effective interest rate, which is assumed to be the difference between the actual interest and the actual inflation rates, in percent divided by 100; and
n = useful pavement life in years.

Two comparisons are shown in Table 12, one for a critical rut depth of 0.5 in. and one for a critical rut depth of 0.7 in. The most cost-effective material to use depends, not surprisingly, on the climatic zone and the level of the critical rut depth. The low or medium (optimum) binder content asphalt-rubber concretes are predicted to be more cost-effective than the asphalt concrete in every climatic zone except the dry nonfreeze zone.

CONCLUSION

The use of asphalt-rubber concrete for municipal airport pavements appears to be justified on the basis of its expected cost-effectiveness in three of the four unique climatic zones in the United States that were included in this study, excluding only the dry-no freeze zone. Production and construction practices may need to be altered to account for higher temperatures or increased compaction effort which may be required to properly mix and place ARC.

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