# Economic Analysis of Rubber-Modified Asphalt Mixes

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(Reviewed by the Highway Division)

**Abstract:** The Alaska Department of Transportation and Public Facilities (ADOTPF) is presently evaluating the use of recycled rubber in hot mix pavement applications. The benefits of adding rubber to the mix include increased skid resistance under icy conditions, improved flexibility and crack resistance, elimination of a solid waste, and reduced traffic noise. The major disadvantage of these rubber-modified mixes is their high cost in relation to conventional asphaltic concrete pavements. A comparison of the economics of the rubber-modified system with that of the conventional pavement shows that the rubber-modified surfacing is cost-effective. This conclusion is based on an analysis of life-cycle costs, but does not include potential intangible benefits of the rubber-modified system, such as increased skid resistance and noise reduction.

## Introduction

The Alaska Department of Transportation and Public Facilities (ADOTPF) is currently evaluating rubber-modified hot mix pavements as an alternate to conventional asphaltic concrete. One of the systems being tested by ADOTPF replaces a portion of the aggregate in the mixture with approximately 3% by weight of granulated coarse and fine rubber particles produced by grinding up discarded tires. The benefits of using ground rubber include increased mix flexibility and durability, elimination of a solid waste material (rubber tires), and reduced traffic noise. Other reported benefits include improved deicing and skid resistance, and a reduction of sand, salting, and winter maintenance costs. The major disadvantage to the widespread use of the rubber-modified mix is its high cost as compared with conventional asphalt hot mix (*Technical data* 1981).

Because the capital cost and expected life of rubber-modified asphalt pavements are different than those of conventional systems, the final choice between the two alternatives should be based on an economic analysis that takes both variables into account. The purpose of this paper is to examine methods of equitably comparing the cost of each alternative. The procedures presented are applicable not only to this specific example, but also to pavement feasibility studies that evaluate other alternatives.

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## Use of Rubber in Asphalt Mixtures

The original development work in the area of coarse rubber-asphalt paving mixtures was performed in the late 1960s by the Swedish companies Skega AB and AB Vaegfoerbaettringar (Bjorklund 1979). The material application was patented under the trade name Rubit. This product has been patented in the United States under the trade name PlusRide™, and is marked by PlusRide™ Asphalt, Inc. of Bellevue, Washington (*Technical data* 1981).

It should be noted that considerable experimental work and field trials have been performed in the United States, particularly in Arizona, California, and Colorado, where rubber-modified asphalt has been used as binder in chip seal coats (Takallou et al. 1985). These installations have utilized finely ground (number 16 to number 25) crumb rubber, which has been reacted with asphalt at elevated temperatures to form a thick elastomeric material. This material is then diluted with an extender oil. As such, these installations differ substantially from PlusRide™.

The concept of incorporating larger rubber particles, 1/4 in. to 1/16 in. (6.4 to 1.6 mm), in pavement surfacing layers had not been used in the United States prior to 1979. Between 1979 and 1987, 12 experimental rubber-modified pavement sections totaling 34.1 mi (55 km) in length were constructed by the Alaska Department of Transportation and Public Facilities. In these projects, 3% of coarse rubber particles by weight of the total mix were incorporated into hot mixed asphalt pavements. Table 1 shows the characteristics for all rubber-modified asphalt projects placed in Alaska. The paving mixes have been successfully prepared in both batch- and drum-dryer-type plants, and placed with conventional pavers and rollers.

In Alaska, mix design experience using the Marshall method has demonstrated that the rubber gradation greatly affects mix properties, and from 2 to 3% more asphalt is normally required to achieve a 3% or lower voids content (Narusch 1982). The attainment of an average field voids level of less than 5% has been shown by field experience to be critical to pavement resistance to raveling (Narusch 1982). Therefore, high compactive efforts and asphalt contents are necessary to achieve the lower air voids. Even though high asphalt contents and soft asphalt grades (AC-2.5 and AC-5) were used in these mixes, no asphalt bleeding has been reported even though pavement temperatures as high as 38°C (100°F) have been reported.

### Laboratory Study

A laboratory study was performed at Oregon State University to evaluate the effect of mix ingredients on properties of rubber-asphalt mixes. The aggregates and asphalt cement (AC-5) used in this study were obtained from Juneau, Alaska. The recycled rubber was provided by Rubber Granulators of Everett, Washington (Takallou et al. 1985).

The two general types of tests used in this study were mix design and mix properties tests. The Marshall mix design, and diametral modulus and fatigue life test procedures were used to evaluate the optimum asphalt content and mix properties (resilient modulus and fatigue life) for the different mix combinations (Takallou et al. 1985).



**TABLE 1. Properties and Characteristics of Alaska's Rubber-Modified Asphalt Pavements (Takallou et al. 1985)**

| | Sieve Sizes | | | | | | | | | Mix Design | | | | | | Mix Properties | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project Identification (1) | 3/4 in. (2) | 5/8 in. (3) | 1/2 in. (4) | 3/8 in. (5) | 1/4 in. (6) | Number 4 (7) | Number 10 (8) | Number 30 (9) | Number 200 (10) | Asphalt content (percent of total mix) (11) | Rubber (percent specified of total mix) (12) | Asphalt type (13) | Average thickness (in.) (14) | Base (in.) (15) | Length of paving lane (ft) (16) | Marshall stability (lbs) (17) | Approximate percent asphalt (18) | Percent voids (19) | Condition, 1987 (20) |
| Carnation 1979 | 100 | --- | --- | 60–77 | --- | 45–59 | 29–41 | 12–20 | 4–10 | 7.0–8.0 | 3.0–3.5 | AC-5 | 2.25 | 2″ AC | 212 | 320 | 7.5 | 3.0 | Good |
| Seward Highway 1980 | 100 | --- | 78–94 | 43–57 | --- | 29–43 | 22–34 | 15–23 | 5–11 | 6.1–7.1 | 3.0–3.5 & 4.0 | AC-5 | 1.50 | 3″ AC | 6,792 | 440 | 7.0 | 2.3 | Overlayed 1982 |
| Peger 1981 | 100 | --- | --- | 53–67 | --- | 28–42 | 20–32 | 14–22 | 5–11 | 8.0–9.0 | 3.0 | AC-2.5 | 1.70 | Gravel | 649 | 270 | 8.5 | 1.7 | Seal coated 1986 |
| Huffman 1981 | --- | --- | --- | 100 | --- | 47–60 | 30–42 | 15–24 | 5–11 | 9.0 –10.0 | 3.0 | AC-5 | 0.75 | 1-1/2″ AC | 5,330 | 370 | 8.5 | 3.0 | Good |
| Lemon Road 1983 | --- | 100 | --- | 62–76 | 32–42 | --- | 22–32 | 20–25 | 8–12 | 8.1–9.1 | 3.0 | AC-5 | 1.50 | 7″ ATB | 5,075 | 820 | 8.6 | 1.1 | Good, minor potholes at one intersection |
| Richardson Highway 1985 | --- | 100 | --- | 64–76 | 30–44 | 49–63 | 19–32 | 13–25 | 8–12 | 7.0–8.0 | 3.0 | AC-2.5 | 2.0 | 8″ D.I. base | 5,597 | 350 | 7.5 | 2.1 | Very good |
| New Seward Highway 1985 | 100 | --- | --- | 50–62 | 34–44 | --- | 21–29 | 16–23 | 7–11 | 7.3–8.1 | 2.5 | AC-5 | 1.75 | 2″ AC | 10,243 | 800 | 7.7 | 1.8 | Very good, one thermal crack in 1/2 mile after 2 winters |
| "A" St., Anchorage 13th to Firewood Drive 1985 | 100 | --- | --- | 50–62 | 30–44 | --- | 20–32 | 12–23 | 7–11 | 7.0–8.0 | 2.5 | AC-5 | 2.0 | 3″ ATB | 12,322 | 870 | 7.5 | 1.4 | Very good |

TABLE 1. *Continued*

| Project Identification (1) | Sieve Sizes: 3/4 in. (2) | 5/8 in. (3) | 1/2 in. (4) | 3/8 in. (5) | 1/4 in. (6) | Number 4 (7) | Number 10 (8) | Number 30 (9) | Number 200 (10) | Mix Design: Asphalt content (percent of total mix) (11) | Rubber (percent specified of total mix) (12) | Asphalt type (13) | Average thickness (in.) (14) | Base (in.) (15) | Length of paving lane (ft) (16) | Mix Properties: Marshall stability (lbs) (17) | Approximate percent asphalt (18) | Percent voids (19) | Condition, 1987 (20) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| "C" St., Anchorage 15th to Firewood Drive 1985 | 100 | --- | --- | 50–62 | 30–44 | --- | 20–32 | 12–23 | 7–11 | 7.1–7.9 | 2.5 | AC-5 | 2.0 | 3" ATB | 9,610 | 870 | 7.5 | 1.4 | Very good |
| O'Malley Road, Anchorage 1986 | 100 | --- | --- | 50–62 | 30–44 | --- | 22–30 | 13–21 | 7–11 | 7.1–7.9 | 2.5 | AC-5 | 1.50 | 2" AC and 3" ATB | 5,808 | 870 | 7.5 | 1.1 | Minor intersection rutting |
| Minnesota Extension, Anchorage 1986 | 100 | --- | --- | 50–62 | 30–44 | --- | 20–30 | 13–21 | 7–11 | 7.1–7.9 | 2.5 | AC-5 | 2.0 | 2" AC and 3" ATB | 22,176 | 870 | 7.5 | 1.1 | Good |
| Airport Road, Fairbanks 1986 | --- | 100 | --- | 61–73 | 30–40 | --- | 20–26 | 13–21 | 8–11 | 7.0–8.0 | 3.0 | AC-2.5 | 1.50 | 1.5" AC | 78,144 | 330 | 7.5 | 1.8 | Slight to moderate flushing in mainline wheel |



**TABLE 2. Recommended Asphalt Content and Mix Properties, Approximately Two Percent Air Voids (Takallou et al. 1985)**

| Aggregate gradation (1) | Rubber content (2) | Rubber gradation (% coarse/% fine) (3) | Design asphalt content (%) (4) | Marshall stability (lbs) (5) | Flow (0.01 in.) (6) |
|---|---|---|---|---|---|
| Gap-graded | 2 | 0/100 | 7.0 | 920 | 15 |
| | | 60/40 | 7.2 | 690 | 21 |
| | | 80/20 | 8.0 | 665 | 23 |
| | 3 | 0/100 | 7.5 | 600 | 19 |
| | | 60/40 | 7.5 | 650 | 22 |
| | | 80/20 | 9.3 | 436 | 33 |
| Dense-graded | 0 | No rubber | 5.5 | 1,500 | 8 |
| | 3 | 80/20 | 7.5 | 550 | 22 |

Note: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

## Mix Design Results

The laboratory mix design results show that the asphalt content required to reach a certain minimum voids level for rubber-modified mixes depends on rubber and aggregate gradation and rubber content (see Table 2). The results show that the mixture with gap-graded aggregate and 3% coarse rubber requires the highest design asphalt content (9.3%), based on dry aggregate weights. [Coarse rubber is defined as rubber particles in which 80 to 90% is in a size range from number 10 to 1/4 in. (2 mm to 6 mm). The remaining rubber content is buffings, primarily in a size range from number 10 to number 40.] Reducing the rubber content to 2% resulted in a reduction in asphalt content to 8.0%. The mixture with 3% coarse rubber and dense aggregate grading required 7.5%, and the conventional asphalt mix (no rubber) had the lowest design asphalt content (5.5%). The asphalt contents reported were all for 2% air voids (Takallou et al. 1985).

## Mixture Properties

To evaluate the effect of mixture variables on the behavior of rubber-modified asphalt, 20 different mix combinations were tested for diametral modulus (ASTM D-4123) and fatigue life (Takallou et al. 1987). These variables included: (1) Two rubber contents; (2) three rubber gradations; (3) two mix and compaction temperatures; (4) two aggregate gradations; (5) two cure times; and (6) use of surcharge (Table 3). The test results, also given in Table 3, show that the modulus and fatigue life of rubber-modified asphalt mixes depend on rubber gradation, aggregate gradation, and rubber content. For example, the mixtures with the finer rubber gradations had higher resilient modulus and lower fatigue life values than mixtures with coarser rubber gradations. In addition, the aggregate gradation affects the mixture properties. The mixes with dense-graded aggregate had higher resilient modulus and lower fatigue life values than mixes with gap-graded aggregates. Reducing the rubber content to 2% also resulted in higher resilient modulus and lower fatigue life values as compared with mixes with 3% rubber content.

The findings of this study indicate that the rubber gradation, rubber content, and aggregate gradation have a considerable effect on the mix

TABLE 3. Specimen Identification and Summary of Resilient Modulus and Fatigue Life (Takallou et al. 1985)

| Specimen identification (1) | Asphalt content (%) (2) | Rubber content (%) (3) | Rubber blend (% fine/% coarse) (4) | Mixing/compaction temperature (°F) (5) | Aggregate gradation (6) | Cure time (hrs) (7) | Surcharge (lbs) (8) | Number of samples used in calculations (9) | Air Voids (%) $\bar{x}$ (10) | Air Voids (%) $\sigma$ (11) | Resilient Modulus (ksi) $\bar{x}$ (12) | Resilient Modulus (ksi) $\sigma$ (13) | $N_f$ $\bar{x}$ (14) | $N_f$ $\sigma$ (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A[a] | 9.3 | 3 | 80/20 | 375/265 | Gap | 0 | 0 | 4 | 1.99 | 0.11 | 411 | 22 | 27,993 | 3,728 |
| B | 9.3 | 3 | 80/20 | 375/265 | Gap | 2 | 0 | 4 | 2.09 | 0.03 | 414 | 46 | 23,800 | 3,558 |
| C[a] | 9.3 | 3 | 80/20 | 375/265 | Gap | 0 | 5 | 4 | 2.07 | 0.12 | 360 | 19 | 48,240 | 4,627 |
| D | 9.3 | 3 | 80/20 | 425/265 | Gap | 0 | 0 | 4 | 2.00 | 0.05 | 405 | 31 | 40,117 | 11,026 |
| E | 9.3 | 3 | 80/20 | 425/265 | Gap | 2 | 0 | 3 | 2.02 | 0.03 | 438 | 43 | 26,199 | 4,096 |
| F | 9.3 | 3 | 80/20 | 425/265 | Gap | 0 | 5 | 5 | 1.96 | 0.24 | 393 | 103 | 82,360 | 7,235 |
| G | 9.3 | 3 | 80/20 | 375/210 | Gap | 0 | 0 | 3 | 4.34 | 0.34 | 375 | 17 | 42,710 | 4,131 |
| H | 7.5 | 3 | 60/40 | 375/265 | Gap | 0 | 0 | 5 | 2.20 | 0.17 | 614 | 73 | 13,155 | 4,203 |
| I | 7.5 | 3 | 0/100 | 375/265 | Gap | 0 | 0 | 4 | 2.44 | 0.26 | 528 | 87 | 16,663 | 2,004 |
| J | 9.3 | 3 | 80/20 | 425/210 | Gap | 0 | 0 | 4 | 4.16 | 0.31 | 374 | 44 | 22,200 | 5,406 |
| K[a] | 8.0 | 2 | 80/20 | 375/265 | Gap | 0 | 0 | 3 | 2.26 | 0.17 | 471 | 22 | 28,858 | 4,683 |
| L | 7.2 | 2 | 60/40 | 375/265 | Gap | 0 | 0 | 3 | 2.19 | 0.30 | 720 | 38 | 13,197 | 5,474 |
| M[a] | 7.0 | 2 | 0/100 | 375/265 | Gap | 0 | 0 | 3 | 2.69 | 0.11 | 814 | 114 | 9,536 | 4,316 |
| N[a] | 7.5 | 3 | 80/20 | 375/265 | Dense | 0 | 0 | 5 | 2.94 | 0.20 | 674 | 55 | 16,506 | 6,730 |
| O | 7.5 | 3 | 80/20 | 375/265 | Dense | 2 | 0 | 4 | 2.28 | 0.13 | 858 | 68 | 11,620 | 6,268 |
| P | 7.5 | 3 | 80/20 | 375/265 | Dense | 0 | 5 | 4 | 2.01 | 0.06 | 649 | 60 | 18,311 | 7,065 |
| Q | 7.5 | 3 | 80/20 | 425/265 | Dense | 0 | 0 | 4 | 2.01 | 0.09 | 803 | 105 | 7,500 | 1,942 |
| R | 7.5 | 3 | 80/20 | 425/265 | Dense | 0 | 0 | 3 | 2.03 | 0.21 | 702 | 20 | 17,296 | 3,945 |
| S | 7.5 | 3 | 80/20 | 375/210 | Dense | 0 | 0 | 3 | 4.58 | 0.89 | 352 | 23 | 13,113 | 3,725 |
| T[a] | 5.5 | 0 | 0 | 375/265 | Dense | 0 | 0 | 5 | 2.13 | 0.25 | 1,105 | 67 | 9,323 | 2,758 |

[a]Mix combinations used to establish fatigue curves.

Note: 1 in. = 25.4 mm; 1 Kip/sq in. (ksi) = 6.894 kPa; 1 lb = 0.454 kg; $t$°C = ($t$°F − 32)/1.8; test temperature = +10°C; strain level = 100 microstrain.

design asphalt content, fatigue life, and modulus value of the mix (Takallou et al. 1985). The study also shows that the rubber-modified mixes have a greater fatigue life than conventional asphalt concrete mix.

## Analysis of Laboratory Data

One of the main benefits of rubber-modified asphalt concrete over conventional mixes is increased pavement fatigue life. To evaluate the relative superiority of fatigue life for rubberized pavement over the conventional pavement systems, elastic layered theory was used. The procedure and results of layer equivalency studies for rubber-modified asphalt are described in the following paragraphs.

### Analysis Procedure

The Elastic Layer System Computer Program (ELSYM5) was used to analyze the typical pavement structures obtained (see Fig. 1) (Hicks 1982). Output from this program includes stresses, strains, and displacements in any of the given layers.

As shown in Fig. 1, three pavement structures representative of three seasons (winter, spring, and fall) were evaluated. The layer equivalencies for each season were calculated for three different surface thicknesses: 2, 4, and 6 in. (51, 102, and 152 mm). The modulus for the surface and subgrade varied for each season. The base modulus was assumed to be 1.5 times the subgrade modulus. The values for surface resilient modulus were



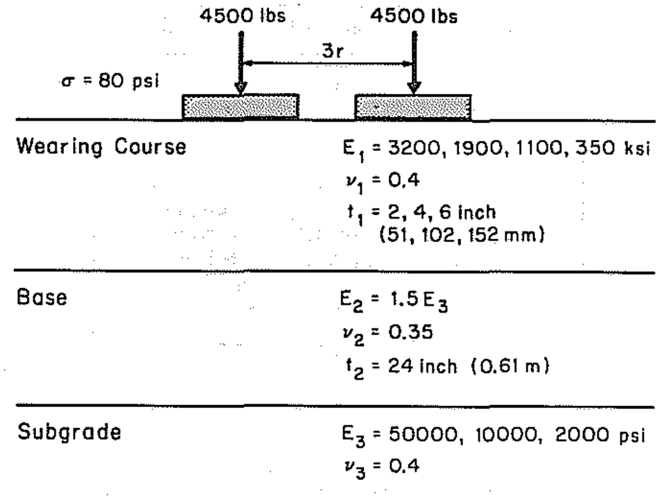


FIG. 1. Pavement Structures Used for ELSYM5 Analysis (Takallou et al. 1985) (1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 psi = 6.894 kPa; 1 ksi = 1,000 psi)

obtained from laboratory-prepared samples. The resilient modulus values for subgrade ranged from 2,000 to 50,000 psi (13,788 to 344,700 kPa). Table 4 shows the modulus data for conventional and rubberized asphalt, as well as the subgrade for each of the seasons analyzed.

The procedure used to determine the layer equivalency of the rubber-modified asphalt is outlined in the flow chart in Fig. 2. The laboratory-determined fatigue curves normally indicate that expected pavement lives less than field experience would indicate. To adjust these curves, a shift factor was determined by comparing the conventional-mix laboratory fatigue life curves at +10°C to typical field fatigue curves developed by Monismith (Yoder and Witzak 1975). This comparison yielded an approximate shift factor of 90 as shown in Figs. 3(*a*–*b*). The shift factor determined

TABLE 4. Resilient Modulus for Conventional Asphalt and Rubberized Asphalt (Takallou et al. 1985)

| Pavement surface layer (1) | Pavement layer (2) | Resilient Modulus (psi) Winter (−6°C) (3) | Resilient Modulus (psi) Spring thaw (−6°C) (4) | Resilient Modulus (psi) Spring/fall (+10°C) (5) |
|---|---|---|---|---|
| Conventional | Surface | $3.2 \times 10^6$ | $3.2 \times 10^6$ | $1.1 \times 10^6$ |
| | Subgrade | 50,000 | 2,000 | 10,000 |
| Rubberized | Surface | $1.9 \times 10^6$ | $1.9 \times 10^6$ | $3.5 \times 10^5$ |
| | Subgrade | 50,000 | 2,000 | 10,000 |

Note: 1 psi = 6.894 kPa.

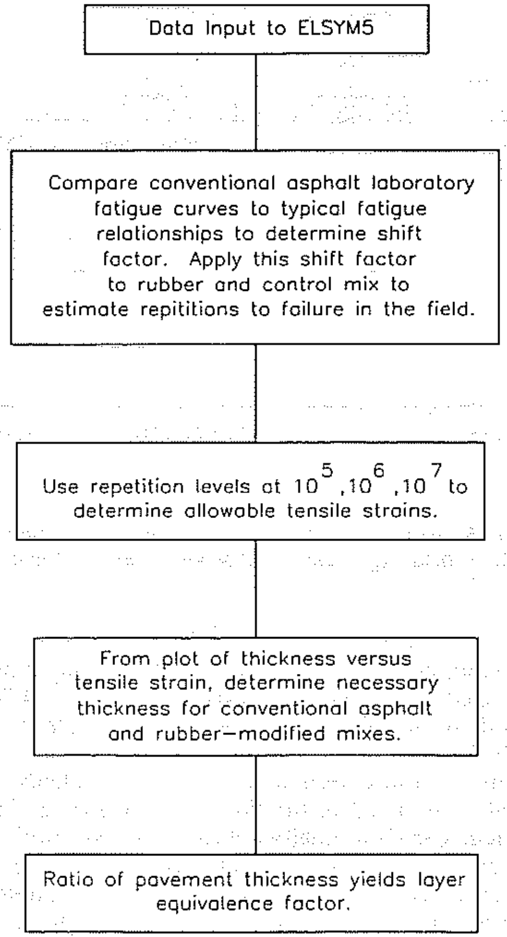


**FIG. 2. Flow Chart for Determination of Layer Equivalencies (Takallou et al. 1985)**

was also applied to the rubber-modified mix fatigue curves. The shifted fatigue curves are shown in Figs. 4(*a–b*).

**Layer Equivalency Determination**

After the laboratory fatigue curves were shifted, representative lives were selected ($10^5$, $10^6$, and $10^7$) and the allowable tensile strain in the asphalt layer determined [Figs. 4(*a–b*)]. These strain values were used to determine the required thickness of the conventional and rubber-modified mixes. The ratio of the required thicknesses (conventional/rubber) is the layer equivalency for rubberized asphalt [Figs. 5(*a–c*)].

As indicated, the layer equivalencies range from 1.2 to 1.4 depending on the season of the year. These layer equivalency ratios correspond to a 20 to 40% reduction in surface thickness for the rubber-modified mix when compared with conventional asphaltic concrete mixes.



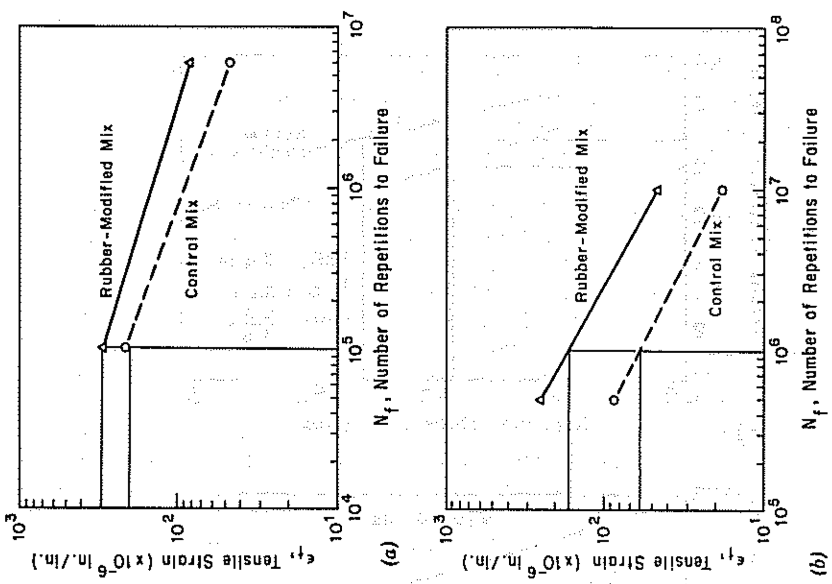


**FIG. 4. Shifted Laboratory Fatigue Curves: (*a*) Spring/Fall (+10°C); (*b*) Spring Thaw and Winter (−6°C)**

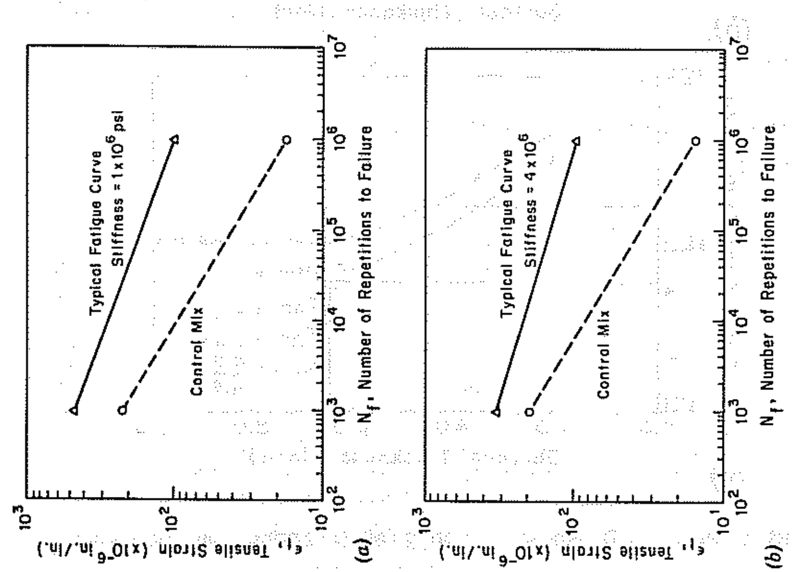


**FIG. 3. Comparison of Laboratory and Field Fatigue Curve (Takallou et al. 1985): (*a*) Fatigue Curves at +10°C; (*b*) Fatigue Curves at −6°C (1 psi = 6.894 kPa)**

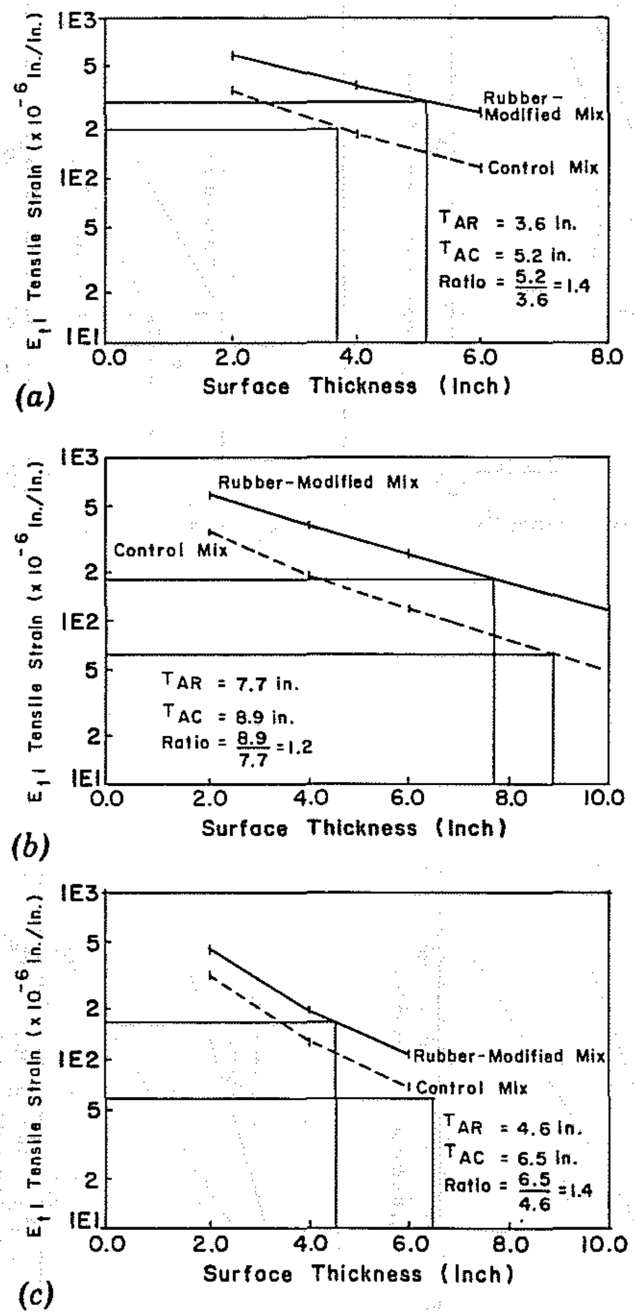


**FIG. 5. Required Thickness: (*a*) Spring/Fall; (*b*) Spring Thaw; (*c*) Winter**



## MATERIAL COSTS

The total mix price and the price for the asphalt binder material shown in Table 5 was supplied by ADOTPF personnel from an actual contract unit price on a project in the Anchorage area (Takallou et al. 1985). The binder cost already includes a general contractor's markup for overhead and profit.

The price of the 80/20 blend (coarse/fine) of rubber material, which was used on all the projects, was supplied by Rubber Granulators of Everett, Washington (Takallou et al. 1985). The prices for engineering services and the royalty quotes of $4.50/ton were obtained from PaveTech Corporation of Bellevue, Washington (*Technical data* 1981).

Table 5 also shows the relative component percentages of the total mix cost. The values shown for the conventional asphalt cement (col. 2) were estimated from given values for the binder, total mix cost, and typical component percentages supplied by a Corvallis, Oregon, paving contractor (Takallou et al. 1985). The component percentages for the PlusRide™ material were estimated by using the given cost information for binder, rubber, royalty, and total mix, and by transferring the remaining component costs from the respective conventional mix to the rubber-modified cost column (col. 4). This table allows one to focus attention on the components of the rubber-modified process, which, if improved, might produce the greatest cost savings to placement of a rubber-modified pavement.

The cost increase shown for a component is due to the extra work or increased material costs required in mix production. For example, increasing the asphalt content from 6.5 to 8.5% naturally raises the mix binder cost. The aggregate cost has been inflated because of the gap-grading

**TABLE 5. Economic Comparison of Asphalt Cement and Rubber-Modified Binders, Anchorage Area**

| | Conventional asphalt cement binder | | PlusRide™ rubber-modified binder | |
|---|---|---|---|---|
| Component (1) | Cost ($/ton) (2) | Cost (%) (3) | Cost ($/ton) (4) | Cost (%) (5) |
| Binder | 12.00 | 30.8 | 15.73 | 28.3 |
| Rubber | — | — | 7.20 | 12.9 |
| Aggregate | 8.00 | 20.5 | 8.25 | 14.8 |
| Energy costs | 1.50 | 3.8 | 1.75 | 3.1 |
| Mixing | 7.00 | 17.9 | 7.25 | 13.0 |
| Haul | 2.25 | 5.8 | 2.25 | 4.0 |
| Placement | 4.25 | 10.9 | 4.35 | 7.8 |
| Engineering services and royalties | — | — | 4.50 | 8.1 |
| Markup | 4.00 | 10.3 | 4.40 | 7.9 |
| Total | 39.00 | 100.0 | 55.68 | 100.0 |

Note: Costs are in dollars/ton of mix. Costs are generally based on material for approximately 16,500 sq yd (13,635 m$^2$) placed at 1-1/2-in. (43-mm) depth, 15 miles (24.1 km) from the plant. Rubber costs include shipment from Seattle, Washington, to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 8.5% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

**TABLE 6. Economic Comparison of Estimated Asphalt Cement and Asphalt-Rubber Binders, Anchorage Area**

| Component (1) | Conventional asphalt cement binder Cost ($/ton) (2) | Cost (%) (3) | Rubber-modified with 9.3% asphalt rubber and 3% 80/20 blend rubber Cost ($/ton) (4) | Cost (%) (5) | Rubber-modified with 8.0% asphalt rubber and 2% 80/20 blend rubber Cost ($/ton) (6) | Cost (%) (7) | Rubber-modified with 7.0% asphalt rubber and 2% 60/40 blend rubber Cost ($/ton) (8) | Cost (%) (9) | Rubber-modified with 7.5% asphalt binder, 3% 80/20 blend rubber, dense aggregate Cost ($/ton) (10) | Cost (%) (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| Binder | 12.00 | 30.8 | 17.21 | 30.1 | 14.80 | 28.3 | 12.95 | 25.1 | 13.88 | 25.8 |
| Rubber | — | — | 7.20 | 12.6 | 4.80 | 9.2 | 5.20 | 10.2 | 7.20 | 13.5 |
| Aggregate | 8.00 | 20.5 | 8.25 | 14.4 | 8.25 | 15.8 | 8.25 | 16.2 | 8.00 | 15.0 |
| Energy costs | 1.50 | 3.8 | 1.75 | 3.1 | 1.75 | 3.3 | 1.75 | 3.4 | 1.75 | 3.3 |
| Mixing | 7.00 | 17.9 | 7.25 | 12.7 | 7.25 | 13.8 | 7.25 | 14.2 | 7.25 | 13.5 |
| Haul | 2.25 | 5.8 | 2.25 | 3.9 | 2.25 | 4.3 | 2.25 | 4.4 | 2.25 | 4.2 |
| Placement | 4.25 | 10.9 | 4.35 | 7.6 | 4.35 | 8.3 | 4.35 | 8.6 | 4.35 | 8.1 |
| Royalties | — | — | 4.50 | 7.9 | 4.50 | 8.6 | 4.50 | 8.8 | 4.50 | 8.4 |
| Markup | 4.00 | 10.3 | 4.40 | 7.7 | 4.40 | 8.4 | 4.40 | 8.7 | 4.40 | 8.2 |
| Total | 39.00 | 100.0 | 57.16 | 100.0 | 52.35 | 100.0 | 50.90 | 100.0 | 53.50 | 100.0 |

Note: Costs are in dollars per ton of mix. Costs are generally based on material for approximately 6,500 sq yd (13,635 $m^2$) placed at 1-1/2-in. (43-mm) depth, 15 miles (24.1 km) from the plant. Rubber costs include shipment from Seattle, Washington, to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 9.3% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

requirement. The energy cost is slightly higher to compensate for the added mixing time and higher temperatures recommended for rubber-modified production. Mixing expenses are higher in rubber-modified production due to the additional manpower and equipment required for introducing the rubber into the batch. Reducing the additional price for these components in rubber-modified pavements would require modification to the materials and/or production processes.

The increase in placement expense and contractor's markup is attributed to the fact that the contractor perceives a higher risk involved with production and placement of rubber-modified pavements versus the conventional pavement. Perceived risk values will either increase or decrease depending on the ease or difficulty of construction of rubber-modified projects.

Table 6 contrasts conventional asphalt mix prices to prices for the four rubber-modified mixes evaluated in the Oregon State University laboratory. The rubber-modified component costs for energy, mixing, hauling, placement, engineering services and royalties, and markup are identical to the costs stated in Table 5 for the Anchorage area.

## Life-Cycle Cost Analysis

This section presents three different methods of comparing the costs of rubber-modified mixes to a conventional mix. The first analysis uses an assumed maintenance scenario and equal surfacing thicknesses to calculate the life required for equivalent annual costs. The second uses equal surfacing thicknesses of rubber-modified and conventional asphalt pavements and only the capital cost to determine the required life for equivalent annual costs. The last method utilizes the layer equivalency ratios shown



in Figs. 5(*a–c*) to compare the capital costs of rubber-modified and conventional asphalts based on unequal thicknesses.

### Equal Annual Capital and Maintenance Cost

Table 7 presents a life-cycle cost analysis to determine the required life for equivalent annual costs of rubber-modified mixes to a conventional mix with a life of 15 years. The analysis utilizes Anchorage area costs per square yard and estimated maintenance prices for crack and chip sealing. The following assumptions were made:

1. Discount rate = 4.0%.
2. Crack seal maintenance cost = $0.10/sq yd.
3. Chip seal maintenance cost = $0.40/sq yd.
4. Conventional mix cost without binder = $27.00/ton.
5. Binder cost = $185/ton.
6. Rubber cost = $240/ton.
7. A-R mix without binder and rubber cost = $33.00/ton.
8. Salvage value = $0.00 at the end of pavement life (Hicks 1982).
9. Unit weight (A-R mix) = 140 pcf.
10. Unit weight (conventional mix) = 149 pcf.

The results indicate that the pavement lives for the rubber-modified mixes must be in the range of 20 to 23 years when compared with 15 years for a conventional mix in order to institute the additional costs. Table 7 includes one maintenance for illustrative purposes. The chip and crack seal intervals were assumed to be at one-quarter, one-half, and three-quarter points in the estimated pavement life. This assumption means that maintenance intervals would increase with the increase in fatigue life.

The objective of illustrating life-cycle costs in this manner is to show how typical pavement maintenance costs correlate to the *relative* pavement condition throughout pavement life. It assumes that a pavement with a fatigue life of 20 years will deteriorate at a slower rate than a pavement with a life of 15 years. Fig. 6 shows the relationship between the level of service of a pavement and time used in the development of the life-cycle cost comparisons shown in Table 7. The conservative straight-line deterio-

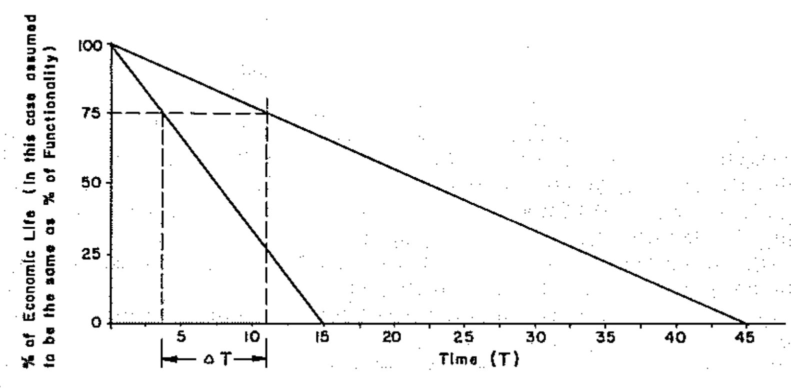


**FIG. 6. Straight Line Deterioration with Time (Yoder and Witzak 1975)**

**TABLE 7. Life-Cycle Cost Comparisons with Equivalent Annual Costs**

| Year (1) | $ Cost/sq yd (2) | Description (3) |
|---|---|---|
| *(a)* Alternative Number 1: Conventional Asphaltic Concrete[a] | | |
| 0 | 6.54 | 3 in. surfacing—6.5% AC |
| 4 | 0.10 | Crack seal |
| 8 | 0.40 | Chip seal |
| 12 | 0.10 | Crack seal |
| 15 | — | End of economic life |
| *(b)* Alternative Number 2: 9.3% Asphalt Binder and 3% 80/20 Blend Rubber[b] | | |
| 0 | 9.00 | 3 in. surfacing |
| 6 | 0.10 | Crack seal |
| 12 | 0.40 | Chip seal |
| 18 | 0.10 | Crack seal |
| 23 | — | End of economic life |
| *(c)* Alternative Numbers 3 and 4: 8% Asphalt Binder and 2% 80/20 Blend Rubber and 7% Asphalt Binder and 2% 60/40 Blend Rubber[c] | | |
| 0 | 8.13 | 3 in. surfacing |
| 5 | 0.10 | Crack seal |
| 10 | 0.40 | Chip seal |
| 15 | 0.10 | Crack seal |
| 20 | — | End of economic life |
| *(d)* Alternative Number 5: 7.5% Asphalt Binder, 3% 80/20 Blend Rubber, Dense-Graded Aggregate[d] | | |
| 0 | 8.43 | 3 in. surfacing |
| 5 | 0.10 | Crack seal |
| 10 | 0.40 | Chip seal |
| 15 | 0.10 | Crack seal |
| 21 | — | End of economic life |

[a] $AE_1(4)$ = 6.54 (A/P,4,15) + 0.10 (P/F,4,4)(A/P,4,15) + 0.40 (P/F,4,8)(A/P,4,15) + 0.10 (P/F,4,12)(A/P,4,15); $AE_1(4)$ = $0.63/sq yd

[b] $AE_2(4)$ = 9.00 (A/P,4,23) + 0.10 (P/F,4,6)(A/P,4,23) + 0.40 (P/F,4,12)(A/P,4,23) + 0.10 (P/F,4,18)(A/P,4,23); $AE_2(4)$ = $0.63/sq yd

[c] $AE_{3,4}(4)$ = 8.13 (A/P,4,20) + 0.10 (P/F,4,5)(A/P,4,20) + 0.40 (P/F,4,10)(A/P,4,20) + 0.10 (P/F,4,15)(A/P,4,20); $AE_{3,4}(4)$ = $0.63/sq yd

[d] $AE_5(4)$ = 8.43 (A/P,4,21) + 0.10 (P/F,4,5)(A/P,4,21) + 0.40 (P/F,4,10)(A/P,4,21) + 0.10 (P/F,4,15)(A/P,4,21); $AE_5(4)$ = $0.63/sq yd



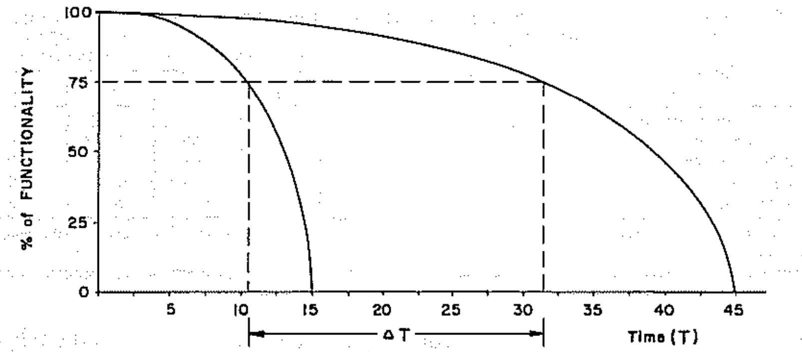


**FIG. 7. Typical Shapes for Pavement Deterioration Curves (Yoder and Witzak 1975)**

ration rates used in the figure are not intended to follow typical pavement deterioration curves like those shown in Fig. 7. Since deterioration curves vary from area to area, no attempt was made to estimate their shape for this cost example. The maintenance interval multipliers may stay the same (in this case, 3), but the difference in time ($\Delta T$) increases with the use of a typical deterioration curve. As $\Delta T$ increases, the equivalent annual costs for the rubber-modified mixtures will decrease.

Table 7 shows the necessity for an evaluation based on the expected life of the structure. Any costs (such as those for typical maintenance) that can be deferred to a later date will make pavements with a higher capital cost appear more economically attractive as future dollars are returned to the present.

The approach presented in Table 7 could also be useful for showing the value of user cost benefits as valued over the life of the project. For instance, the rubber-modified surface has been found to reduce stopping distances by 25% under icy road conditions in studies in Fairbanks, Alaska (Esch 1984). If this could be quantified in terms of added safety benefits, the annual equivalent values of rubber-modified asphalt might be more favorable.

## Equal Annual Capital Cost

There is a more conservative approach to evaluating life costs for conventional and asphalt rubber-modified pavements. The method is conservative because it does not take into account the possibility of reduced long-term maintenance and user costs. It only considers the capital cost of the pavement system. With the capital costs of both pavement systems known and the life of the conventional system assumed, the life of the rubber-modified system to provide equivalent costs is determined by using the following:

$$X(\text{CRF}, n) = Y(\text{CRF}, n') \quad (1)$$

where $X$ = cost of conventional pavement in $/ton or $/sq yd; $Y$ = cost of rubber-modified pavement in $/ton or $/sq yd; $n$ = life of the conventional

**TABLE 8. Comparison of Pavement Life for Equivalent Annual Capital Costs**

| Surfacing alternative (1) | Discount rate (%) (2) | Life required for equivalent annual capital cost (yrs) (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|
| Conventional asphaltic concrete (assumed life) | --- | 2.0 | 5.0 | 10.0 | 15.0 | 20.0 |
| Rubber-modified asphaltic concrete | 3.5 | 2.9 | 7.4 | 15.6 | 24.9 | 36.0 |
| Rubber-modified asphaltic concrete | 4.0 | 2.9 | 7.5 | 15.9 | 25.7 | 38.2 |
| Rubber-modified asphaltic concrete | 4.5 | 2.9 | 7.5 | 16.1 | 26.6 | 41.0 |

Note: Cost per ton of conventional asphaltic concrete = $39.00 (Table 5). Cost per ton of rubber-modified asphaltic concrete = $55.68 (Table 5).

pavement in years; $n'$ = asphalt rubber pavement life in years; and CRF = capital recovery factor = $i(1 + i)^n/(1 + i)^n - 1$. By substitution:

$$X\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = Y\left[\frac{i(1+i)^{n'}}{(1+i)^{n'} - 1}\right] \quad (2)$$

where $i$ = discount rate in decimal form. If we define $D$ as follows:

$$D = \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]\frac{X}{Y} \quad (3)$$

and then by solving for $n'$, we obtain the relation for asphalt-rubber life

$$n' = \frac{\ln\left(\frac{D}{D-i}\right)}{\ln(1+i)} \quad (4)$$

Table 8 summarizes the pavement life needed from the rubber-modified asphalt to offset the increased capital costs. Assumed lives for the conventional asphaltic pavement ranged from 2 to 20 years. This means that the needed life for the rubber-modified mix would have to range from 3 to 40+ years. The table also shows the effect of using a discount rate of 3.5%, 4.0%, and 4.5%. These values were based on the real cost of capital as used in constant dollar studies. The real cost of capital essentially reflects the difference between the market rate of return and inflation, and this difference has historically been between 3.7% and 4.4% (Epps and Wootan 1981).

Table 8 can become considerably more useful as information concerning pavement life becomes more readily available. In its present form, the table can be used as a simple tool for determining the equivalent life of rubber modified mixes versus conventional mixes.

**Capital Cost Comparison Considering Layer Equivalencies**

The required thickness of a rubber-modified mix can be reduced by 1.2 to 1.4 times compared with the conventional mix if the equivalency factors developed earlier are used. This implies that a rubber-modified mixture could be placed with a thickness ranging from approximately 2 to 2-1/2 in. (51 to 64 mm) and the expected fatigue life would be the same as a 3-in. (76-mm) conventional surfacing.

Table 9 presents the capital cost per square yard based on varying



**TABLE 9. Capital Cost Comparison Considering Layer Equivalencies**

| Surfacing alternative (1) | Capital Cost for Given Thickness ($/sq yd) 3 in. (76 mm) (2) | 2-1/2 in.[a] (64 mm) (3) | 2-1/4 in.[b] (57 mm) (4) | 2 in.[c] (51 mm) (5) |
|---|---|---|---|---|
| Conventional asphaltic concrete | 6.54 | N/A | N/A | N/A |
| 9.3% asphalt and 3% of 80/20 rubber blend | 9.00 | 7.50 | 6.77 | 6.00 |
| 8.0% asphalt and 2% of 80/20 rubber blend | 8.13 | 6.77 | 6.11 | 5.42 |
| 7.0% asphalt and 2% fine rubber | 8.13 | 6.77 | 6.11 | 5.42 |
| 7.5% asphalt, 3% of 80/20 rubber blend, and dense-graded aggregate | 8.43 | 7.03 | 6.33 | 5.62 |

[a]Equivalency of 1.2:1.
[b]Equivalency of 1.33:1.
[c]Equivalency of 1.5:1.

thickness for each of the alternatives discussed in the previous section. Note that the capital cost of a rubber-modified surfacing becomes advantageous only when the layer equivalency is at least in the range of 1.2 to 1.3. Therefore, the rubber-modified mixes would be economically acceptable since the laboratory results showed a layer equivalency range of only 1.2 to 1.4. Like the life-cycle cost analysis presented in the previous section, this capital cost comparison does not take into account reported benefits of the rubber-modified mix that have not been verified or quantified to date.

**Overview**

The information presented in this section indicates that rubber-modified asphalt mixes would need to have a life span of approximately 20 to 23 years to provide the same life cost as an equivalent thickness of conventional asphalt concrete surface, which lasts 15 years. In a comparison of capital costs, thickness of the rubber-modified mix must be reduced by a factor of at least 1.2 to 1.3 for the cost to be equivalent to a conventional asphalt surface.

The rubber-modified mixes could become more economically feasible by reducing life-cycle and/or capital costs. The life-cycle costs could be reduced by including intangibles, such as those discussed in the introduction. Capital costs could also be reduced in many ways. For example, Table 6 shows the relationship between the total mix cost and the cost for each of the mix components. Cost reductions in the mix are most sensitive to items that have the highest component percentage of cost as compared with the total mix. As an example, if the rubber components were obtained locally, up to an 8.0% savings to the total cost of the mix could result. However, if the mixing time for the rubber-modified material was made equivalent to the mixing time for a conventional mix, the cost of the mix would only be reduced by 0.4%. The effort spent in changing these factors may be the same, but the payoffs favor one cost-cutting effort more than the other. By evaluating the sensitivity of the mix price in relation to the component prices, areas that will produce the greatest cost savings to the total mix are readily identified.

## Conclusions and Recommendations

The economic analysis presented in this paper shows the rubber-modified asphalt mix to be more cost effective than a conventional mix. This is based on annual equivalent costs, capital costs, and layer equivalencies, which were used to objectively show the economic consequences of using either the conventional asphaltic concrete surfacing or the rubber-modified asphaltic concrete. The following recommendations provide guidelines for preparing an economic analysis similar to the specific example previously presented:

1. Break down total costs into component costs so efforts at cost reduction can best be directed to areas that have the greatest potential for savings.
2. Capital cost comparisons are most useful when evaluating immediate cash flow projections. However, comparing only capital costs can be misleading when evaluating the total cost of an alternative over the life of the investment. When a choice must be made from options that have unequal lives, the decision should be made by using an annual equivalent cost comparison (another method that is equally acceptable would be net present worth). The interest rate used in this type of analysis should be the difference between the current or forecasted market rate of return and the current or forecasted inflation rate.
3. If the equivalent cost between alternatives is relatively equal, evaluate the intangible benefits of each system to help determine a clear first choice. If there is any way in which these intangibles can be rationally quantified, their value can be included in the economic analysis to make the final selection between alternatives easier.
4. It may be easier to compare system costs if layer equivalency information is readily obtainable. However, for layer equivalencies to work, all other factors between the systems, such as pavement deterioration, noise reduction, reduced winter maintenance costs, etc., must be assumed equal.

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## Appendix II. Notation

*The following symbols are used in this paper:*

$A$ = single payment in a series of payments;
$AE$ = annual equivalent costs;
$C$ = temperature, centigrade Units;
$E$ = modulus of elasticity;
$E_t$ = tensile strain;
$F$ = future value;
$M_R$ = resilient modulus;
$N_f$ = number of repetitions to fatigue failure;
$P$ = present value;
$T$ = time;
$t$ = thickness;
$t_{AC}$ = thickness, conventional asphaltic concrete;
$t_{AR}$ = thickness, asphalt rubber;
$\nu$ = Poisson's Ratio; and
$\sigma$ = vertical Stress.