it was not expected to have strength values comparable with those of normal AC. Within the bounds of the experimentation and the materials used, the following conclusions are warranted for the making and testing of A-R concrete specimens:

1. Good coating of the 9.5-mm dense-graded and open-graded aggregates was obtained when the aggregate was at a temperature of 149°C (300°F) and the A-R was at 121°C. A Hobart C-10 food mixer was used with a type-D wire whip and medium speed. This type of mixer is commonly used in many laboratories.
2. Compaction of standard-sized specimens could not be effected by using the tamping-foot procedure of the California kneading compactor at a temperature of 121°C. Specimens could be formed by using static double-plunger compaction and also by using our VKC, which gave higher densities. The Marshall compaction procedure was not attempted.
3. It was necessary to leave the hot-compacted specimen in the mold for three days at ambient temperature prior to extrusion in order to eliminate swelling of the unconfined specimen that would cause cracking.
4. The air-void content for the 9.5-mm dense-graded specimens had a much higher value when the specimens were mixed with the vulcanized rubber than when they contained devulcanized rubber.
5. Specimens made by using both aggregates and the vulcanized rubber had Hveem stability values that ranged between 25 and 35 and cohesiometer values between 170 and 200 when tested at 25°C.
6. Dynamic modulus of elasticity values for both aggregates and both types of rubber were approximately 70 percent of that for regular AC. The lowest modulus at 4°C was 896 MPa (130 000 psi).
7. Due to the high void content of the 9.5-mm dense-graded specimen made with the vulcanized rubber, it will be necessary for the aggregate to be very clean in order to obtain good resistance to debonding from the action of water.

ACKNOWLEDGMENT

The initiation and support given to this study by personnel of the Arizona Department of Transportation are acknowledged. Special mention should be made of university students David Bell and Armando Murrieta, who worked so carefully in an area so new and unpredictable. I acknowledge the sponsorship of the program by the Arizona Department of Transportation and the Federal Highway Administration.

REFERENCES

1. R.A. Jimenez, G.R. Morris, and D.A. DaDeppo. Tests for a Strain-Attenuating Asphaltic Material. Proc., AAPT, Vol. 48, 1979, pp. 163-187.
2. G.R. Morris and C.H. McDonald. Asphalt-Rubber Stress-Absorbing Membranes: Field Performance and State of the Art. TRB, Transportation Research Record 595, 1976, pp. 52-58.
3. Supplemental Specifications to the Arizona Highway Department Standard Specifications for Road and Bridge Construction. Arizona Department of Transportation, Phoenix, 1978.
4. R.A. Jimenez. Testing Methods for Asphalt--Rubber. Arizona Department of Transportation, Phoenix, Rept. ADOT-RS-15(164), 1978.
5. Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II. AASHTO, Washington, DC, 1978.
6. R.A. Jimenez. Testing of Asphalt-Rubber and Aggregate Mixtures. Arizona Department of Transportation, Phoenix, Rept. FHWA/AZ-79/111, May 1979.
7. R.A. Jimenez. Fatigue Testing of Asphaltic Concrete Slabs. In Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM, Philadelphia, Special Tech. Publ. 508, 1972, pp. 3-17.
8. Materials Testing Manual. Materials Division, Arizona Department of Transportation, Phoenix, 1975.
9. R.A. Jimenez. Testing for Debonding of Asphalt from Aggregates. TRB, Transportation Research Record 515, 1974, pp. 1-17.
10. R.A. Jimenez. Structural Design of Asphalt Pavements. Arizona Department of Transportation, Phoenix, Rept. ADOT-RS-13(142), May 1975.
11. W. White. Relationship Between Values of Dynamic and Resilient Modulus for Asphaltic Concrete. Univ. of Arizona, Tucson, C.E. 200 Rept., 1978.

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.

Field Evaluation of Rubber-Modified Bituminous Concrete

JACK E. STEPHENS

The flexibility and, as a result, the durability of bituminous concrete placed as an overlay over old pavement can be increased by the addition of reclaimed rubber. The conditions under which the modified characteristics are most beneficial have not been well defined. Within the maintenance program of the Connecticut Department of Transportation, reclaimed-rubber test sections were placed at nine locations. The locations were selected to include three levels of traffic from a low of 1300 average daily traffic (ADT) to a high of 10 400 ADT and three levels of pavement condition (low, medium, and high). At each location, mixes in which the rubber content was 0, 1, and 2 percent of the mix were placed. Comparisons were made of permeability, density, skid number, and crack development over three years.

The planning for this study was formally started by a group that consisted of the Office of Research of the Connecticut Department of Transportation (ConnDOT), the Civil Engineering Department of the University of Connecticut (UConn), the Solid Waste Section of the Department of Environmental Protection, and the Reclaiming Division of Uniroyal, Inc. ConnDOT, UConn, and the Rubber Reclaimers Association had carried out a laboratory study in which reclaimed rubber was added to asphalt paving mixes (1). The results from that work indicated that reclaimed rubber added to mixes in the laboratory significantly improved the properties of pavement

Table 1. Overlay test sections.

Pavement Distress Level	Traffic Level: Low Route No.	Location	1978 ADT	Medium Route No.	Location	1978 ADT	High Route No.	Location	1978 ADT
Low	354	Colchester	1300	66	Marlborough	7600	44A	Coventry	9 500
Medium	85	Bolton	3700	2	Preston	4600	44	Barkhamsted	9 600
High	354	Salem	1300	69	Woodbridge	5000	101	Dayville	10 400

Figure 1. Temperature cracks in sections with low distress level.

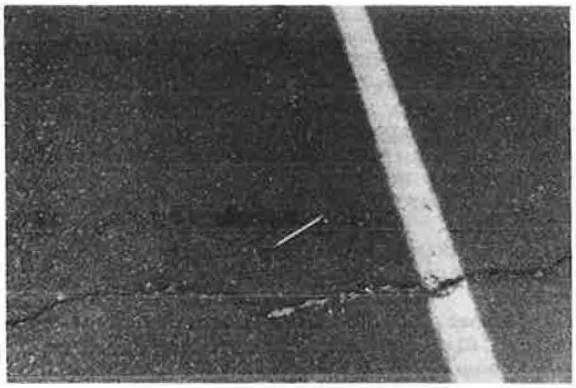


Figure 2. Temperature and age cracks.

mixes. Subsequent discussions resulted in an agreement between UConn and and ConnDOT to undertake full-scale evaluations of rubber-modified mixtures. The Civil Engineering Department and the Office of Research would develop the program and the Civil Engineering Department would carry out the evaluations. The materials would be placed within the maintenance program of the Bureau of Highways. Mix design would be carried out by the Civil Engineering Department and quality control by the ConnDOT materials laboratory. The Office of Research would obtain skid numbers. The Federal Highway Administration (FHWA) would provide partial funding to ConnDOT for the project.

A bituminous concrete overlay over a cracked pavement is subjected to high stress concentrated in the volume of material immediately over each crack. If the strength of an overlay cannot be made great enough to resist these stresses, then sufficient flexibility of the mix is critical for long life of the overlay. The extent to which the overlay can be altered by the use of a softer rubber is limited by the stability of the resulting mix at summer temperatures.

The addition of reclaimed rubber increases the flexibility of the mix through two different mechanisms. The modified asphalt is less sensitive to temperature and a softer grade can be used; equally important, however, is the increased binder-film thickness. The potential for improvement of overlays and seal coats is apparent. However, there is a limit to the crack motion that can be accommodated by even the rubber-modified asphalt. Thus, a full-scale field-test program was needed to determine the effective improvement.

The first phase of placing test sections of rubber-modified bituminous concrete consisted of selecting test sites. Sections planned for overlays were reviewed for condition, volume of traffic, and construction problems. The plan called for selection of locations that had three levels of average daily traffic (ADT) and three levels of pavement condition (Table 1). A pavement of adequate structural strength cracks due to temperature stresses. Such cracks tend to create the effect of dividing the pavement into large blocks. Substantial movement occurs at these cracks and reflection cracks occur in the overlay. A typical pavement that exhibits a block pattern of cracks is shown in Figure 1. The width of these cracks changes sharply with temperature; the cracks expand and contract. Such pavements were used for good-condition sections. Further aging results in progressive formation of cracks, each at right angles to an existing crack or edge (Figure 2). Such cracks do not show much orientation with the wheel paths. These represented the record level of deterioration. Pavements similar to those in Figure 3 were selected as badly cracked test sections. Due to the frequency of such cracks, temperature does not cause significant changes in crack width.

Locations were selected in which conditions were constant for several hundred feet and from lane to lane. On most of the secondary roads used, the cross section had been modified repeatedly through the addition of widening strips and overlays. The support then varied across the width of the road and changes occurred within the current lanes. Where practical, the control and test sections were in the same lane. Since the precise location of test sections was not known in advance of the paver, precise crack surveys of prior condition could not be made and comparisons are therefore between the condition

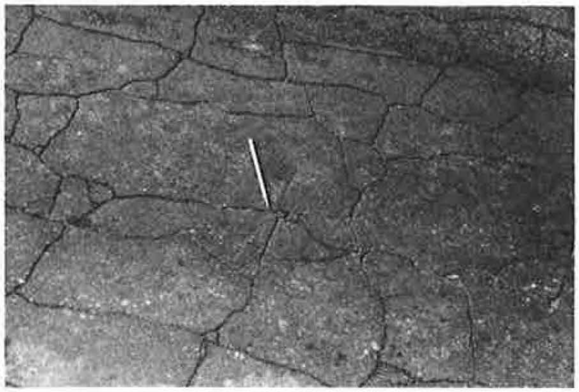


Figure 3. Sections with high distress level.

of the control and that of the test sections at the same age.

MIX DESIGN

Since the rubber-modified mix was not a bid item and required maximum cooperation from the contractor, the changes were held to a minimum. The approved mix for each contractor became the starting point for developing the rubber-modified mix. The work done several years earlier in the University laboratories had resulted in criteria for such mixes. For most local aggregates, an optimum mix used 1-2 percent rubber and 0.25 percent more binder for each 1 percent rubber. Marshall tests were run on the approved mix, 1 percent reclaimed rubber and 0.25 percent more asphalt were added, and the tests were repeated. A third trial was made with 2 percent rubber and 0.50 percent additional asphalt. For most mixes, the Marshall results were within ConnDOT specifications, and the mixes were used without further modifications.

When it was recognized that the addition of both rubber and asphalt increased the possibility of overfilling the voids, the standard Marshall computations for the voids in the mineral aggregate and the percentage of such voids filled were not considered adequate. The accepted criteria are based on experience with a normal binder. The rubber-modified mix that used reclaimed rubber is quite different. If the rubber is only partly dissolved in the asphalt, it creates a stringy web within the asphalt, which stabilizes the binder and appears to permit the use of thicker films. Past experience with limits on the voids and percentage filled may not be applicable here. For this reason, each mix was placed in a gyratory compactor and subjected to 500-600 cycles as a test for long-term stability (2). A small number of the mixes did prove unstable under this test. Since the ConnDOT master specification for binder content of class 1 mixes ranges from 5.8 to 8 percent, the addition of 1 percent rubber and 0.25 percent asphalt to a mix already at the high end was significant. This problem was overcome for those mixes by not adding more asphalt. Of course, the same possibilities existed for the 2 percent rubber mixes and the extra asphalt was reduced by increments of 0.25 percent as indicated by the gyratory test. In no instance was the asphalt reduced below the content of the ConnDOT-approved mix (3).

In general, the mixes used for any one location were the producer's ConnDOT-approved mix, this same mix with 1 percent rubber and 0.25 percent binder added, and this same mix with 2 percent rubber and 0.50 percent binder added. The characteristics of the mixes used are listed in Table 2.

MIXING

Since at least 7 of the 41 plants operating in Connecticut would be supplying material for test sections, procedures that require significant plant modification could not be used. Uniroyal had successfully placed a number of rubber-modified running tracks by using reclaimed rubber. The same procedure of adding the reclaimed rubber to the aggregate and asphalt in the pug mill was used in this program. The presoftened character of the reclaimed rubber makes possible a degree of solution in the binder during the short time in the mixer. Most plants had inspection ports through which the rubber could be introduced into the pug mill, and owners obligingly cut such openings in plants that did not have them.

The reclaimed rubber was packed in 50-lb plastic bags. Batch sizes were adjusted to use an even number of bags. The pug mill was charged with aggregate and binder, and the bags of rubber were added. The heat in the mixer completely destroyed the bags by the time the rubber was uniformly distributed through the mix. Hauling and spreading was carried out as for any other mix. When the paving machine reached the test area, the preceding standard material was used up as much as was practical before the test mix was started, thus keeping transitions short. Rolling was accomplished by using a steel breakdown roller and then a rubber-tired roller.

EVALUATIONS OF OVERLAYS

The locations of the test sections were not intended to be representative of each roadway but were selected as having consistent conditions of traffic volume and pavement distress. In an area of shallow cuts and low fills, the relative elevation of grade line and land profile can change several times in the 1500 ft required for three sections. Road widths have gradually increased and alignments improved over the years. Current pavements are not always centered over old pavements. Where widening strips have been used, support conditions can vary across the width of the pavement. Where such undesired variables became apparent, the control section was adjusted to assure maximum usefulness of the comparisons. Tables 3-5 summarize the crack data. Since the length of the different sections varied, crack frequency has been tabulated in terms of feet of crack per foot of paver pass; transverse and longitudinal values are reported separately. By August 1980, no general deterioration had occurred and so none was included in the evaluation.

Since there were no replicate sections, the number of data points for any one set of conditions (traffic volume, pavement distress, rubber level) is too small for significant statistical analysis of individual sections. After each thick overlay had been reviewed, overall comparisons were made for different rubber levels.

Route 2, Preston

At the test site, the old bituminous concrete pavement had been widened at an earlier date to provide a third (climbing) lane. The longitudinal crack developing during the three-year evaluation of the 1.5-in overlay is a reflection of the edge of the old pavement and can be expected to appear over the full length of the old test sections. The transverse cracking is also a reflection of underlying

Table 2. Preliminary laboratory tests of thick overlays.

		Advance Laboratory Tests						Control Tests	
		Marshall			Gyratory				
						Stability Index			
Route No. and Location	Anticipated Rubber Content (%)	Asphalt (%)	Stability (lbf)	Flow (0.01 in)	Compaction Index	200 Rev.	600 Rev.	Bulk Specific Gravity	Density (lb/ft^3)
2, Preston	0	5.3	2400	8	0.983	1.67	3.1	2.410	150.4
	1	5.75	2340	9	0.986	1.91	1.9	2.409	150.3
	2	6.0	1320	9	0.989	1.76	2.2	2.374	148.1
44A, Coventry	0	5.5	3010	10.5	0.981	1.33	3.1	2.528	157.7
	1	5.75	2340	13.5	0.941	1.24	1.9	2.458	153.3
	2	6.0	2350	13.5	0.988	1.26	2.2	2.397	149.6
66, Marlborough	0	5.5	3090	10.5	0.992	1.69	1.98	2.517	157.1
	1	5.75	2340	13.5	0.979	1.24	1.5	2.430	151.6
	2	6.0	2930	13.5	0.988	1.26	1.5	2.418	150.9
85, Bolton	0	5.5	3010	10.5	0.981	1.33	3.1	2.572	152.9
	1	5.75	2340	13.5	0.941	1.24	1.9	2.427	149.9
	2	6.0	2350	13.5	0.988	1.26	2.2	2.377	152.2
44, Barkhamsted	0	6.0						2.450	152.9
	1	6.0						2.402	149.9
	2	6.0						2.439	152.2
354, Colchester	0	6.0	2330	13	0.975	1.45	1.6	2.611	162.9
	1	6.0	2390	12	0.987	1.26	2.0	2.491	155.4
	2	6.0	2040	13.5	0.989	1.33	1.4	2.334	145.6
69, Woodbridge	0	5.5	3670	13.5	0.983	1.76	2.9	2.426	151.4
	1	5.75	2790	12.0	0.986	1.70	1.5	2.463	153.7
	2	6.0	2320	12.0	0.984	1.92	1.8	2.409	150.3
101, Killingly	0	5.5	2600	8	0 948	1.86	0.24	2.375	148.2
	1	5.75	2590	10	0.949	1.45	1.8	2.378	148.4
	2	6.0	1220	12	0.986	1.97	72.5	2.355	147.0
354, Salem	0	5.5	2790	5.5	0.982	1.30	1.7	2.467	135.3
	1	5.75	2170	10.5	0.993	2.29	2.4	2.351	135.0
	2	6.0	1510	10	0.986	2.11	73.4	2.300	133.6

Table 3. Cracks in 1 percent and control sections.

		1979			1980		
			Crack Length (ft/ft of pass)			Crack Length (ft/ft of pass)	
Route No. and Location	Rubber Content (%)	Section Length (ft)	Longitudinal	Transverse	Section Length (ft)	Longitudinal	Transverse
2, Preston	1	490	0.0163	0.1469	490	0.0653	0.2796
	0	213	0.0084	0.2864	500	0.492	0.530
44, Barkhamsted	1	383	0.274	0.334	383	0.316	0.360
	0	240	0.358	0.467	435	0.524	0.423
44A, Coventry	1	607	0	0	612	0.008	0
	0	600	0	0	600	0.142	0
66, Marlborough	1	790	0.270	0.287	790	0.299	0.297
	0	0	0	0	646	0	0.272
69, Woodbridge	1	403	0.062	0.206	402	0.0597	0.2114
	0	403	0.2804	.0.3648	402	0.2761	0.3781
85, Bolton	1	436	0.0160	0.0917	436	0.0367	0.0963
	0	436	0.0711	0.0092	436	0.2294	0
101, Killingly	1	630	0.0127	0.0063	630	0.0127	0.0412
	0	663	0	0.0618	663	0	0.0769
354, Colchester	1	515	0.0447	0.2000	509	0.1984	0.2043
	0	425	0.2188	0.1247	645	0.2822	0.1225
354, Salem	1	540	0.222	0.0370	540	0.400	0.048
	0	300	0.1267	0.0433	500	0.134	0.1180

cracks. These cracks are much more frequent in that portion of the lane over the old pavement. The portion over the widening strip is nearly free of cracks. There was a distinctive difference in the performance of the sections that contained 0, 1, and 2 percent rubber during the period of observation.

At two years, the pavement with 0 percent rubber was performing as well as or better than the rubber sections. During the third year, the cracks in the section with 0 percent rubber adjacent to the section with 1 percent rubber increased sharply and by the end of the year exceeded several times the quantity in the section with 1 percent rubber (Table 3). The cracks in the section with 2 percent rubber and in the corresponding area with 0 percent rubber also increased but more erratically. Considering the 1 percent rubber, the cracks at two years are only two-thirds of those in the controls and the rate of increase during the third year is two-thirds that of the controls. During the first two years, the section with 1 percent rubber had sustained one-third less cracks than the average of the two controls. Equally significant is the fact that the rate of cracking also averaged one-third less during the third year.

Route 44, Barkhamsted

This section, 1.5 in thick, was placed on an old overlay over a two-lane concrete pavement. The resurfacing was carried out in three passes of the paver. As a result, the degree of reflection crack-

Stability (lbf)	Flow (0.01 in)	Asphalt (%)	Rubber (%)	Gradation (% passing) 3/4	1/2	3/8	No. 4	No. 8	No. 50	No. 200
2880	8.5	5.6	0	100	97.2	70.9	50.2	40.8	16.2	3.7
2480	11	6.5	1.3	100	100.0	85.8	63.1	52.2	22.2	6.4
2140	8.5	6.4	1.6	100	92.6	70.2	53.6	45.0	20.0	5.7
1575	12	5.4	0	98	93	74	57	43	16	4
2180	8	6.2	1.8	100	93.8	69.1	56.1	45.5	17.5	3.9
2330	11.5	5.7	1.7	100	90.2	65.3	51.7	42.0	17.8	4.0
3010	12.5	6.8	0	100	100.0	74.5	50.4	39.4	15.8	5.4
3120	10.5	6.7	1.8	100	98.4	75.4	63.4	51.5	19.6	4.5
3300	11.5	7.1	2.2	100	98.1	71.9	55.4	43.8	17.0	4.6
2400	12.5	5.5	0	100	95	77	56	45	18	5
1760	10.5	5.8	1.5	100	87.3	63.8	53.3	42.3	16.8	3.7
2190	10.5	6.4	1.7	100	98.9	69.2	58.4	45	17	3.8
2400	12.5	5.5	0	100	95	73	53	43	16	4.4
1760	10.5	7.2	0.9	100	95.4	71.9	52.4	44.9	19.9	4.4
2190	10.5	5.6	1.6	100	96.3	66.4	43.5	36.4	14.9	2.7
1707	11	6.0	0	100	92	74	53	43	17	4
2250	10.5	6.6	1.3	100	98.5	78.9	58	48.2	22.8	6.6
1200	15.	6.7	1.9	100	92.5	84.0	58.2	44.2	16.4	4.7
2590	9.5	6.0	0	100	100	81.9	62.9	52.5	16.9	3.7
2250	10.5	7.5	1.1	100	97	88.1	68.1	56.2	18.7	5.1
1770	11	7.8	2.0	100	98.2	87.3	64.6	52.4	18.4	4.7
2880	8.5	5.7	0	100	100	80.1	52.9	42.7	15.8	4.0
2500	12	6.9	1.2	100	97	72.6	54.7	45.3	18.3	5.9
2500	11	8.3	1.7	100	98.7	85.5	63.2	52.4	19.2	4.8
2754	10	6.8	0	100	100	74.5	50.4	39.4	15.8	5.4
2870	9.5	6.7	1.8	100	98.4	75.4	63.4	51.5	19.6	4.5
2080	11	7.1	2.2	100	98.1	71.9	55.4	43.8	17.0	4.6

Table 4. Cracks in 2 percent and control sections.

Route No. and Location	Rubber Content (%)	1979 Section Length (ft)	1979 Crack Length (ft/ft of pass) Longitudinal	1979 Crack Length (ft/ft of pass) Transverse	1980 Section Length (ft)	1980 Crack Length (ft/ft of pass) Longitudinal	1980 Crack Length (ft/ft of pass) Transverse
2, Preston	2	500	0.134	0.1148	506	0.2253	0.3559
	0	500	0	0.186	427	0.1710	0.2579
44, Barkhamsted	2	456	0.508	0.314	456	0.492	0.314
	0	400	0.800	0.335	500	0.855	0.356
44A, Coventry	2	680	0.153	0.044	680	0.168	0.075
	0	680	0.003	0.022	680	0.010	0.063
66, Marlborough	2	616	0	0.203	616	0	0.0235
	0	297	0	0.23	646	0	0.272
69, Woodbridge	2	412	0.0121	0.2233	412	0.051	0.2937
	0	412	0.0510	0.2573	412	0.1141	0.4126
85, Bolton	2	586	0.3038	0.1348	595	0.3899	0.0924
	0	586	0.3127	0.1999	595	0.4370	0.2017
101, Killingly	2	690	0	0	690	0.0406	0.0145
	0	300	0	0.027	300	0	0.033
354, Colchester	2	578	0.2247	0.3685	578	0.2820	0.3927
	0	350	0	0.2029	658	0.0182	0.2342
354, Salem	2	528	0.4527	0.0322	528	0.6572	0.1212
	0	300	0.1267	0.0433	500	0.134	0.1180

ing must be compared within one pass. The center pass, in which the rubber was used, contains the center-joint reflection crack. Compared with cracking in overlays on bituminous concrete pavements, the cracking occurred early and there was little increase from 1979 to 1980. The maximum reflection cracks expected are 1 ft/ft of lane along the center line and 15 ft transversely at 40-ft intervals. This is 1.0 ft longitudinally and 0.337 ft transversely per foot of lane. For the control, 70 percent of the center joint and 100 percent of the transverse cracks have reflected through. For the section with 1 percent rubber, the amounts are 32 percent longitudinally and 100 percent transversely and for the section with 2 percent rubber, 49 percent longitudinally and 100 percent transversely. Both are better than the control sections. Due to terrain variations, control sections have been included before and after the rubber sections.

Route 44A, Coventry

The existing pavement consisted of several inches of bituminous concrete. The predominant distress was an occasional temperature crack. Both the mixtures that contained rubber were mixed late in the afternoon and stored overnight in heated bins. Cracking since the application of the 1.5-in overlay has been slow to develop, which makes this one of the most successful of the test sections. Cracking amounts to only a foot or so per 100 ft of lane, and any differences are probably due to local differences independent of rubber level. Both sections reach from curb to center line of the westbound lane.

Table 5. Total cracks, 1980.

	1 Percent Rubber			2 Percent Rubber		
Route No. and Location	Rubber Content (%)	Total Cracks (ft/ft of pass)	Change from 0 Percent (ft/ft of pass)	Rubber Content (%)	Total Cracks (ft/ft of pass)	Change from 1 Percent (ft/ft of pass)
2, Preston			0.667 1			−0.157 3
	1	0.344 9		2	0.581 2	
	0	1.022		0	0.423 9	
44, Barkhamsted			0.277			0.405
	1	0.670		2	0.806	
	0	0.947		0	1.211	
44A, Coventry			0.134			−0.17
	1	0.008		2	0.243	
	0	0.142		0	0.073	
66, Marlborough			−0.324			0.248 5
	1	0 596		2	0.023 5	
	0	0.272		0	0.272	
69, Woodbridge			0.383 1			0.182
	1	0.271 1		2	0.344 7	
	0	0.654 2		0	0.526 7	
85, Bolton			0 096 4			0.156 4
	1	0.133 0		2	0.482 3	
	0	0.229 4		0	0.638 7	
101, Killingly			0.023			−0.022 1
	1	0.053 9		2	0.055 1	
	0	0.076 9		0	0.033	
354, Colchester			0.002			−0.422 3
	1	0.402 7		2	0.674 7	
	0	0.404 7		0	0.252 4	
354, Salem			−0.196			−0.526 4
	1	0.448		2	0.778 4	
	0	0.252		0	0.252	

Note: The minus signs indicate more cracking in the rubber section than in the control.

Most of the longitudinal cracking occurs near the outer edge, which suggests lack of lateral support.

Route 66, Marlborough

Like the Barkhamsted section, the 12-ft sections of 1.5-in overlay are in the center pass over an old overlay on concrete. In contrast to Route 44, Barkhamsted, the roadway here is not an embankment through the sections that contain 2 and 0 percent rubber, and the center-line joint has not opened. The section with 1 percent rubber includes a small fill and the center line has reflected through for a portion of the length. Comparison of longitudinal cracking is not realistic under these conditions. The transverse crack frequency is lower in the section that contains 2 percent rubber. More interestingly, 75 percent of the 1980 transverse feet of crack in 2 percent rubber consists of full-width cracks. Only 55 percent of the transverse feet of crack in the sections with 0 percent rubber are part of full-width cracks. That is, the cracks in the section with 2 percent rubber are longer but occur less frequently than those in the section with 0 percent rubber. No explanation of this difference has developed.

Route 69, Woodbridge

This 1.5-in overlay covers an older bituminous concrete pavement. Frequent well-defined cracks were present, but no rutting or surface degrading had occurred. The condition of the old pavement was in all probability due to age-hardening of the mix. To avoid placing spreader joints in the new layers above those in the existing pavement, the overlay was placed in four passes. It was anticipated that the two outer or the two inner passes would be generally comparable. Since a large portion of the outer passes was over areas originally constructed as shoulders, the two inner passes were selected as test and control sections. Both the section with 1 percent rubber and that with 2 percent rubber performed sharply better than the material with 0 percent rubber did. At two years, the section with 2 percent rubber had one-fifth as much longitudinal cracking as the section with 1 percent rubber but 10 percent more transverse cracking.

At three years, the cracking in the section with 2 percent rubber had increased to five-sixths of the longitudinal cracking of the section with 1 percent rubber and 39 percent more transverse cracking. Considering the two types of cracking together, the section that contained 2 percent rubber had 20 percent more cracking than the section with 1 percent rubber. Projecting the changes ahead would indicate that after another year, the section with 1 percent rubber would be slightly superior to that with 2 percent rubber for both types of cracks and that both rubberized sections would be 50 percent better than the untreated sections.

Route 85, Bolton

During the three years of observation, the sections on this roadway have shown more deterioration than did most of the thick-overlay test sections. Traffic does not include heavy wheel loads. Conditions vary locally along the road and so comparisons must be made between lanes. Several areas of insufficient strength have resulted in alligator cracking. Since these areas are not evenly distributed between the sections, they cannot be included effectively in comparisons between the sections. The fact that all occur on this one route indicates a roadway that has inadequate section design for current traffic. At two and three years, the sections with 1 percent rubber and that with 2 percent rubber showed less longitudinal cracking than the section with 0 percent rubber did. The section with 2 percent rubber also had less transverse cracking. Due to the local variations in conditions along this route, comparisons for the section with 1 percent rubber are not so clear. The total length of transverse cracks is

low in the section with 1 percent rubber but even lower in the adjacent area with 0 percent rubber. If a larger sample of lane with 0 percent rubber is considered (that opposite both the section with 1 percent rubber and that with 2 percent rubber), the section with 1 percent rubber is superior. Overall, at this test site the rubberized material is superior.

Route 101, Killingly

This test section is the main street of the village of Dayville. The 1.5-in test sections were placed in the center pass of a three-pass resurfacing. More recently, a utility trench has been dug longitudinally in the center of one outer pass. Slumping of the trench sides has caused some longitudinal cracking in the center test pass. Allowing for this source of damage, the Route 101 test has essentially no longitudinal cracks. Of the few transverse cracks that have appeared, approximately twice as many occur in the nonrubberized material.

Route 354, Colchester

The pavement under the sections 1.5 in thick is a bituminous concrete section with an occasional full-width, full-depth crack. The pavement had much the appearance of an overlay over a jointed-concrete pavement. Due to the large crack width, nearly all the cracks have reflected through in the test sections. There are large differences in the crack frequency between the test sections. Three factors contribute to this problem. The tests with 0 and 1 percent rubber are in shallow cuts. The section with 2 percent rubber is in a zone of transition from cut to fill. The section with 0 percent rubber is level. The grade increases through the section with 1 percent rubber to a maximum in the section with 2 percent rubber. In addition, heavy woods shade the sections with 0 and 1 percent rubber during most of the day. The resulting differences in daily temperature cycles may affect the spacing of cracks. The frequencies of transverse cracks in the rubber sections were greater than those in the controls in both 1979 and 1980. However, the reverse is true for the longitudinal cracks. The numerical differences are large enough to be impressive, but the reversal of effect between transverse and longitudinal cracking is not readily explained by the rubber level.

Route 354, Salem

Traffic for the two locations on Route 354 is similar since there are no major intersections between. However, the pavement conditions prior to overlaying were noticeably different. Cracking was much more extensive in the Salem area. The old pavement was a penetration treatment, and the cracks were smaller but occurred much more frequently. Only a small number of the cracks have reflected through the test overlay. At the end of two and three years, more cracks have appeared in the rubber sections and longitudinal cracks predominate. The comparison is complicated by a very different frequency of cracks in the two lanes. The road has been widened in the past, and the pavement conditions under the overlay vary from side to side. The comparison with a control section in the same lane reduces the difference, but the level of performance of the rubber sections appears lower.

ALL RUBBER-MODIFIED SECTIONS VERSUS CONTROLS

There are enough sections to justify statistical comparisons of rubber levels. Since overlays should last several years, statistical comparisons have been made that use the three-year (1980) data. In anticipation of the possibility that performance measured by longitudinal crack frequency might be different from that found by using transverse cracks, probabilities were computed first for each crack type separately. In recognition of the differences between locations, the data were paired by putting the proper control with each test section and by grouping pairs for common rubber level. By using the Student's t-test, there is then a 90 percent probability that the sections that contain 1 percent rubber have fewer longitudinal cracks and a 35 percent probability that they have fewer transverse cracks. There is an 86 percent probability that the sections with 2 percent rubber contain more longitudinal cracks than the controls do and 70 percent probability that the sections with 2 percent rubber have more than the sections with 1 percent rubber do. The transverse cracking shows the same trend. There is a 90 percent probability of more cracks than in the controls and a 98 percent probability of more cracks than in the sections with 1 percent rubber.

Failure stresses in a pavement are the sum of flexure and temperature stresses. Cracks result when the tensile stress exceeds the strength of the mix. Under a wheel load, the radius of curvature is smallest at right angles to the direction of traffic. Since stress level is inversely proportional to the radius of curvature, the highest flexural tensile stress would be perpendicular to the wheel paths and would result in longitudinal cracks.

If base deflections are small, large tensile stress will not occur from flexural stress and the effect of temperature becomes more important. The proximity of free edges limits the magnitude of transverse temperature stresses. On the other hand, the continuity of the pavement in the direction of traffic induces high-temperature stresses that result in transverse cracks.

Thus, the demands on the overlay material over a crack are different, depending on the direction of the crack. The material with 1 percent rubber is more effective at resisting load-induced flexure tensile stresses than direct tension. This difference may be due to the magnitude of the strain. For flexure, the tensile strain is limited by the curvature. The strain due to temperature is limited only by the coefficient of expansion of the material. If cracks are far apart, the temperature strain can be large. The addition of rubber to the mix makes the material plastic enough to accommodate the strain associated with flexing but not that of shrinkage. The transverse cracks would then reflect through more quickly than the longitudinal cracks.

Although the longitudinal and the transverse cracking had different frequencies, considering them together gives further insight into the relative performance. Considering all cracking, there is a 96 percent probability that the sections with 1 percent rubber have less cracking than the control sections do but only a 30 percent probability that the sections with 2 percent rubber have less than the controls do.

Two sections were underlaid by concrete pavement. Both had high traffic levels. On Route 44, Barkhamsted, both the section with 1 percent and that with 2 percent rubber performed better than the control did; the section with 1 percent rubber was superior. On Route 66, Marlborough, the comparison reverses and the controls are better than the rubber-modified sections. Thus, no conclusions are possible about the effect over concrete.

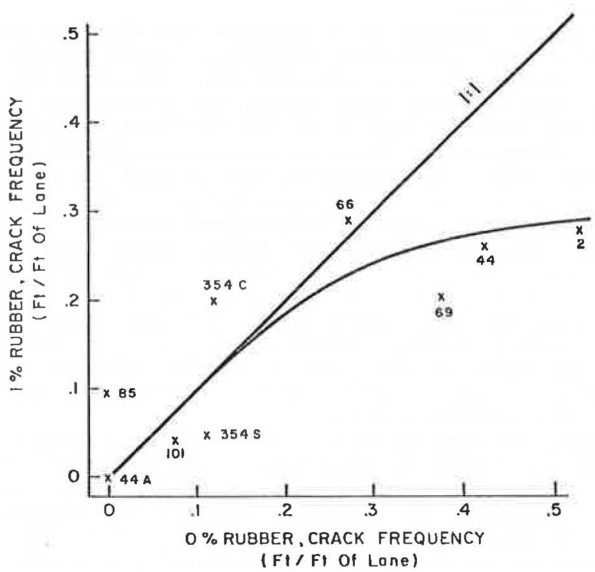
The relative crack frequency does correlate with

Table 6. Effect of 1 percent and 2 percent rubber.

Level of Distress	Level of Traffic: Low	Medium	High	All Levels of Traffic (avg)
Sections with 1 Percent Rubber				
Low	+0.0027	-0.324	0.134	-0.0624
Medium	0.0964	0.6771	0.271	0.3482
High	-0.196	0.3831	0.0230	0.0700
All levels of distress (avg)	-0.0356	0.2454	0.1427	
Sections with 2 Percent Rubber				
Low	-0.4223	-0.2485	-0.170	-0.0813
Medium	0.1564	-0.1573	0.405	0.1347
High	-0.5264	0.182	-0.0221	-0.1222
All levels of distress (avg)	-0.2643	0.0911	0.0710	

Note: Values are decrease in feet of crack per foot of paver pass compared with 0 percent controls.

Figure 4. Transverse cracking in sections with 0-1 percent rubber.



traffic and distress. Table 6 shows the differences in feet of crack per foot of lane for the rubberized test sections and the controls. The data have been arranged in the same relative position of traffic and distress levels as the original selections of test sections. That is, in Table 6 the entry corresponding to low traffic and low deterioration was the section on Route 354, Colchester, for which the feet of crack (transverse and longitudinal totaled) per foot of paving pass for material with 1 percent rubber is 0.0027 greater than that for the material with 0 percent rubber or the control. Throughout Table 6, positive values denote improvement of the section with 1 percent rubber compared with the section that had 0 percent rubber. Negative values indicate comparisons in which the section with 0 percent rubber has less cracks. Pavements originally classified as of medium distress benefited most from the addition of 1 percent rubber. Roadways with medium traffic levels demonstrated more benefits than did low-volume locations. The effect of traffic was great enough that when both low- and high-level distressed pavements were combined with high traffic, they showed a benefit from the addition of rubber.

Some rationalization of these trends is possible. A new overlay over low-distress pavement can be expected to perform adequately, and in the short period of three years, large differences might not be apparent. A new overlay over a high-distress pavement may also show little improvement. Frequently, the new overlay placed is not adequate for long life under the poor foundation and/or high loading conditions that had caused the original distress. The substitution of a better material, which is still less than adequate, would delay cracking, but by the end of three years it also would have cracked. Since the rubber-modified mix retains a greater degree of plasticity at all ages, increased traffic kneads the material and impedes the formation of reflection cracks.

By using the differences between the section with 2 percent rubber and the control sections, similar trends were found, except that at high distress levels the differences indicate better performance for the controls. This is caused by the poor performance of the section on Route 354 in Salem.

Figures 4-7 were prepared to provide a basis for

Figure 5. Longitudinal cracking in sections with 0-1 percent rubber.

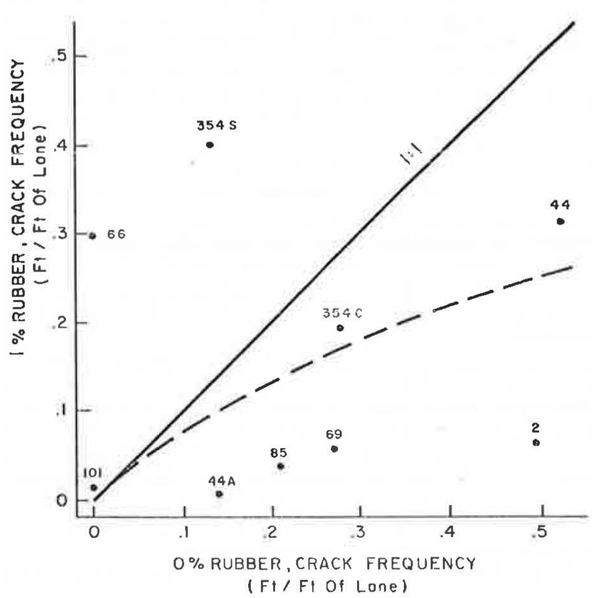
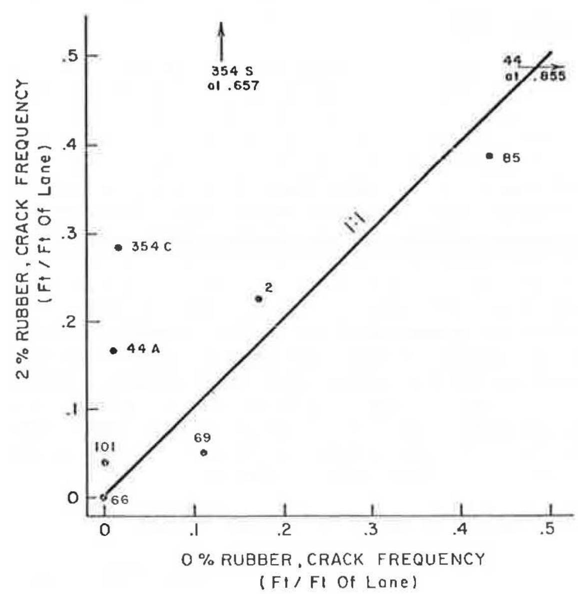
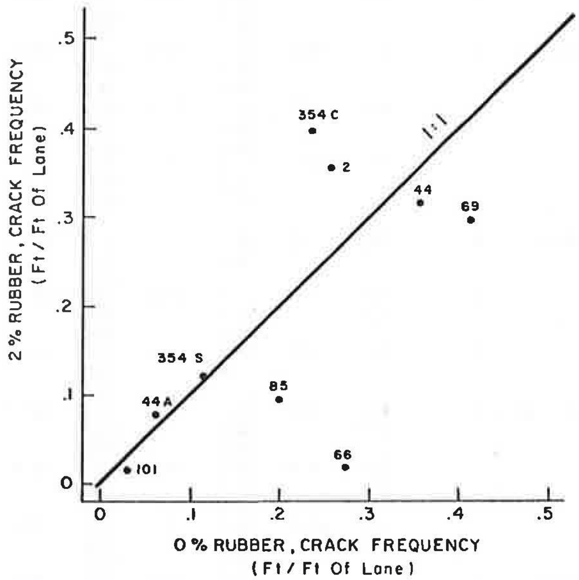


Figure 6. Longitudinal cracking in sections with 0-2 percent rubber.



further comparison of the performance of the different levels of rubber. In both Figures 4 and 5, the points tend to fall below a 1:1 correlation, which indicates that the material with 1 percent rubber performed better than the control did. In Figures 6 and 7 the points are along or above the 1:1 correlation line. The latter condition indicates no improvement by using 2 percent rubber.

Figure 7. Transverse cracking in sections with 0-2 percent rubber.



Figures 4 and 5 may give an indication of the degree of distress for which 1 percent rubber would be effective.

An approximate curve through the limited data (line A in Figure 4) could be useful for estimating the benefit to be obtained by adding 1 percent rubber to the mix. For example, a 1.5-in overlay is to be placed over a pavement with 0.9 ft of transverse and 0.6 ft of longitudinal crack per lane foot. Assuming that one-third of the cracks present at the time of placing an overlay 1.5 in thick reflect through a 0 percent overlay in three years, what reduction in cracks can be brought about by adding 1 percent rubber? Entering Figure 4 with one-third of 0.9 ft/ft of lane for 0 percent rubber gives 0.23 ft of transverse crack per foot of lane for 1 percent rubber or a reduction of 23 percent at three years compared with 0 percent rubber. To estimate longitudinal cracks, enter Figure 5 with one-third of 0.6 or 0.2 ft/ft of lane and read 0.13 or a 35 percent reduction. Since this use of the data was not anticipated, the assumption of one-third reflection cracks in three years must be refined with experience.

Permeability is one of the properties that has been useful in predicting the rate of aging of pavements. It has been postulated that air circulation through the pavement voids hastens hardening. Recognizing that three years of observation might not adequately show the differences in performance of the rubberized class 1 pavement, permeability tests were carried out. To a degree, density measurements serve the same purpose. Values for air permeability and nuclear density were determined in the wheel paths when the pavements were one year old (Table 7).

Table 7. Permeability and nuclear density of overlays.

Route No. and Location	Rubber Content (%)	Date Performed	Permeability (L/S, wheel path)						Nuclear Density (lb/ft^3, wheel path)					
			Test 1	Test 2	Test 3	Avg	SD	ADT	Test 1	Test 2	Test 3	Avg	SD	ADT
2, Preston		6/14/78						4 600						4 600
	0		0.028 7	0.031 1	0.029 9	0.029 9	0.001 200		138.6	138.7	141.2	139.5	1.473	
	1		0.006 22	0.007 56	0.007 78	0.007 19	0.000 844 4		143.6	141.5	138.7	141.3	2.458	
	2		0.016 6	0.014 4	0.013 6	0.014 8	0.001 553		138.5	136.8	136.6	137.3	1.044	
44, Barkhamsted		7/5/78						9 600						9 600
	0		0.010 0	0.009 07		0.009 54	0.005 146		151.4	151.4	151.7	151.5	0.173	
	1		0.008 83	0.007 96		0.008 39	0.000 615		151.8	152.0	151.4	151.7	0.308	
	2		0.007 41	0.007 71		0.007 56	0.000 212 1		150.6	149.8	147.8	149.4	0.964	
44A, Coventry		5/31/78						9 500						9 500
	0		0.005 04	0.004 98		0.005 01	0.000 042		142.7	142.6	142.0	142.4	0.379	
	1		0.006 16	0.006 27		0.006 21	0.000 078		145.8	146.8	142.7	145.1	2.139	
	2		0.012 4	0.013 5		0.012 95	0.000 778		143.7	143.6	143.0	143.5	0.379	
66, Marlborough		6/6/78						7 600						7 600
	0		0.012 1	0.012 6		0.012 4	0.000 354		146.1	149.6	144.32	146.7	2.689	
	1		0.006 53	0.007 90		0.007 21	0.000 969		143.2	143.7	144.4	143.8	0.603	
	2		0.010 4	0.015 2	0.013 9	0.013 2	0.002 48		148.5	144.1	146.3	146.3	2.200	
69, Woodbridge		6/20/78						5 000						5 000
	0		0.013 5	0.009 95	0.013 49	0.012 31	0.002 046 7		142.7	140.2	140.4	141:1	1.389	
	1		0.002 29	0.005 10	0.004 30	0.003 90	0.001 448		144.7	146.2	145.1	145.4	0.789	
	2		0.003 47	0.003 57	0.004 50	0.003 84	0.000 568		141.5	141.8	139.0	140.8	2.175	
85, Bolton		6/1/78						3 700						3 700
	0		0.017 4	0.012 69		0.015 03	0.003 33		142.7	142.6	142.0	142.4	0.379	
	1		0.006 37	0.005 86		0.006 12	0.000 361		144.2	142.0	142.6	142.9	1.137	
	2		0.025 7	0.020 2		0.022 92	0.003 89		140.2	139.3	138.5	139.3	0.850	
101, Killingly		7/5/78						10 400						10 400
	0		0.011 5	0.018 0		0.014 7	0.004 596		139.7	138.0	135.7	137.8	1.622	
	1		0.009 99	0.009 46		0.009 73	0.000 375		138.4	139.1	138.0	138.5	0.556	
	2		0.008 30	0.001 54		0.004 92	0.004 78		138.1	138.1	140.1	138.8	1.197	
354, Colchester		6/15/78						1 300						1 300
	0		0.003 59	0.003 53		0.003 56	0.000 042 4		139.0	139.1	140.3	139.5	0.723	
	1		0.014 1	0.008 67	0.008 78	0.010 52	0.003 104		138.4	139.6	136.9	138.3	1.353	
	2		0.034 7	0.033 0	0.034 7	0.034 1	0.000 982		132.4	128.5	133.6	131.5	2.666	
354, Salem		6/14/78						1 300						1 300
	0		0.040 1	0.022 1	0.023 9	0.028 7	0.009 91		135.6	137.6	139.1	137.4	1.756	
	1		0.007 81	0.007 42	0.006 13	0.007 12	0.000 879		131.5	134.3	133.5	133.1	1.442	
	2		0.067 4	0.052 5	0.049 8	0.056 5	0.009 4		134.3	131.0	129.3	131.6	2.542	
Avg, class 1	0					0.014 57	0.009 23					142.03	4.543	
	1					0.007 38	0.002 08					142.23	5.286	
	2					0.018 98	0.010 62					139.83	6.072	

The average air permeability for the class 1 mix with no rubber was 0.014 57 L/s. Sections with 1 percent rubber averaged one-half as much, 0.007 38 L/s. However, 2 percent rubber increased the average permeability to 0.018 98. The relationship between permeability and traffic volume is shown in Figure 8. The air permeability decreases with in-

Figure 8. Overlay permeability versus traffic volume.

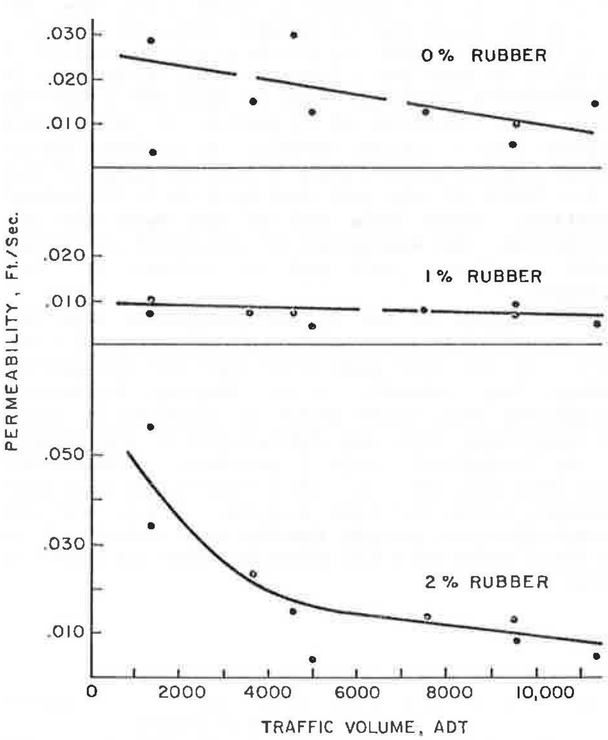


Figure 9. Overlay density.

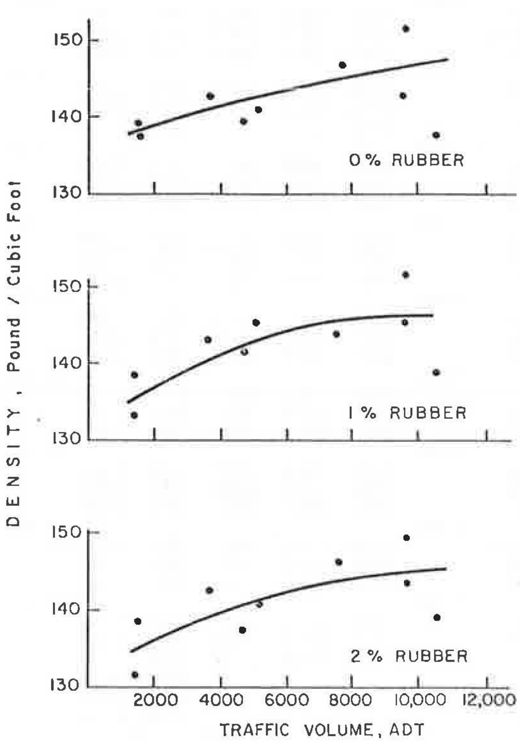


Table 8. Skid numbers, class 1 thick overlays.

Route No. and Location	Rubber Content (%)	Nov. 1977 SN	Nov. 1977 Avg SN	Nov. 1978 SN	Nov. 1978 Avg SN	Nov. 1980 SN	Nov. 1980 Avg SN
2, Preston	0	41.8	46.0	48.9	48.7	50.4	51.03
		50.2		45.8		50.9	
				51.5		51.8	
	1	46.6	46.6	44.2	47.7	50.6	51.57
				49.8		52.3	
				49.1		55.3	
	2	50.2	50.2	50.3	49.8	53.9	54.5
				49.9		54.3	
				49.2		55.2	
44, Barkhamsted	0	48.3	48.3	39.3	38.9	39.8	42.3
				39.5		46.1	
				37.9		41.1	
	1	43.4	43.4	38.1	39.3	41.3	41.8
				40.1		40.2	
				39.6		44.0	
	2	44.6	44.6	41.7	39.7	41.6	41.7
				38.8		41.8	
				38.7		43.7	
						39.8	
44A, Coventry	0	33.2	33.2	35.3	35.8	38.9	40.2
				36.3		38.1	
						43.6	
	1	33.2	34.9	42.7	42.4	42.4	41.97
		36.6		41.9		39.0	
				42.6		44.5	
	2	39.8	39.8	38.4	40.5	43.1	43.17
				42.5		42.7	
						43.7	
66, Marlborough	0	36.6	38.2	46.3	43.5	38.6	42.67
		39.8		44.0		42.0	
				40.0		47.4	
	1	36.3	38.85	44.4	44.9	41.3	45.47
		41.4		47.3		47.7	
				43.1		47.4	
	2	39.9	39.9	36.4	38.5	34.9	39.6
		39.9		41.8		42.8	
				37.4		41.1	
69, Woodbridge	0	38.2	38.2	46.8	46.0	45.4	46.3
				44.9		44.3	
				46.2		49.2	
	1	33.2	33.2	46.1	42.0	45.2	44.8
				42.2		44.9	
				40.5		44.3	
				39.3			
	2	38.9	38.9			43.8	46.1
						46.1	
						48.3	
85, Bolton	0	43.0	43.0	43.4	43.7	43.8	46.0
				43.9		47.2	
				43.7		47.0	
	1	39.9	39.9	48.1	46.8	46.4	46.57
				45.4		47.4	
				46.8		45.9	
	2	39.9	39.9	50.7	49.5	46.0	46.23
				50.1		45.4	
				49.0		47.3	
				48.3			
101, Killingly	0	38.2	36.5	48.1	46.4	46.8	44.9
		34.8		45.0		44.5	
				46.1		43.4	
	1	34.8	36.5	41.5	38.1	40.8	40.6
		38.2		36.3		39.2	
				36.6		41.8	
	2	34.8	35.6	37.9	36.7	36.7	38.4
		36.3		34.3		40.5	
				37.8		38.0	
354, Colchester	0	43.4	47.6	51.4	52.9	53.0	53.33
		51.8		52.7		54.5	
				54.7		52.5	
	1	56.7	56.7	52.0	53.1	54.4	55.43
				54.4		55.6	
				53.0		56.3	
	2	53.4	53.4	56.6	56.6	56.8	52.57
				56.6		53.6	
						47.3	
354, Salem	0	54.4	54.4	48.8	47.9	54.1	54.3
				49.1		54.0	
				45.8		54.8	
	1	50.2	50.2	46.3	47.4	54.0	54.47
				49.3		54.5	
				46.6		54.9	
	2	55.0	55.0	49.5	49.4	55.8	55.4
				50.5		53.9	
				48.1		56.5	

Note: SN = skid number.

creasing traffic. At low traffic levels, the mixture with 2 percent rubber has significantly higher permeability but is similar to the mixture with 0 percent rubber at higher volumes. The air permeability of the mixture with 1 percent rubber is low and nearly constant regardless of traffic. This implies that the mixture with 1 percent rubber compacts more completely under the roller and that no further compaction occurs under traffic.

The average densities of the pavement with 0 percent and that with 1 percent rubber were the same at 142 lb/ft^3. Since the voidless unit weight of the mix with 1 percent rubber is lower, this indicates a greater degree of compaction. The material with 2 percent rubber averaged 1.5 percent less at 139.8 lb/ft^3. The relationship between density and traffic volume (Figure 9) is that of increasing density with increasing traffic level. The two locations where the original pavements were portland cement concrete recorded the highest nuclear densities. Either the gauge is influenced by the concrete or the more rigid base aids in compaction. Both had been overlaid previously by using bituminous concrete.

A comparison of the average nuclear density at one year with the average Marshall density at the time of construction provides an insight into the characteristics of the materials. At one year, the average wheel-track nuclear density for the sections with 0 percent rubber was 92 percent of the original Marshall density. For the material with 1 percent rubber this comparison was 95 percent and for that with 2 percent rubber, 94.6 percent.

Based on the average nuclear densities, the void content of the three types of pavement at one year would be 10.4 percent for the material with 0 percent rubber, 9.2 percent for that with 1 percent rubber, and 8.1 percent for that with 2 percent rubber.

Changes in paving materials always raise concerns about skid resistance. Skid-resistance numbers determined by using equipment that meets current federal highway standards provide realistic comparisons between surfaces. Those for the rubber-modified overlays are listed in Table 8. Extensive statistical computations by using the Student's t-test show few significant differences. The only comparisons that resulted in confidence levels about 95 percent were those in 1977 when, at the 95 percent level, it could be said that those mixes that contained rubber were superior to those without and that 2 percent rubber mixes were better than mixes with either 0 or 1 percent rubber. At an 85 percent level, the mixes that had 2 percent rubber were higher than the mixes with 1 percent rubber in 1978. There is a weak trend for all materials to improve with age. For all test sections, the skid numbers compare well with the nonrubber control, and skid resistance should not be a problem.

CONCLUSIONS

The rubber-modified mixes are performing as a class better than the nonrubberized mixes do. Cracking has been reduced and there has been no reduction in skid resistance. The lower permeability and higher density of the rubber-modified mixture imply a probability of longer life.

ACKNOWLEDGMENT

The views expressed are mine and may not represent the official position of the University of Connecticut or the supporting agencies, ConnDOT and the Federal Highway Administration.

REFERENCES

1. J.E. Stephens and S. Mokrzewski. The Effect of Reclaimed Rubber on Bituminous Paving Mixtures. Univ. of Connecticut, Storrs, Civil Engineering Department Rept. CE 74-75, Feb. 1974.
2. J.L. McRae and B.D. Lagrone. Effect of Modified Reclaimed Rubber and Ground Vulcanized Rubber on the Physical Properties of Bituminous Pavements as Evaluated by the Gyratory Testing Machines. HRB, Highway Research Record 361, 1971, pp. 14-19.
3. Standard Specifications for Roads, Bridges, and Incidental Construction--Form 811. Connecticut Department of Transportation, Wethersfield, 1974.

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.

Methods of Increasing Fracture Toughness of Asphalt Concrete

R.T. WOODHAMS

Experience with rubber-modified asphalt concrete in the Canadian environment during the past seven years has yielded only marginal improvement with respect to cracking. The most effective rubbers for reducing the brittle temperature of asphalt concrete are those that have low glass transition temperatures, although reclaim tire rubber is preferred since it costs the least. Chopped nylon or polyester tire cord or integrated rovings can impart large increases in fracture toughness at temperatures below freezing. For maximum efficiency, the chopped cord should be near its critical pullout length. Calculations indicate that fracture toughness can be increased 20-fold under ideal conditions with the addition of only 1 percent fiber. Moisture damage can be minimized by the addition of a minor proportion of ferric oxide or iron naphthenate as an adhesion promoter. The combined use of rubber, chopped fibers, and an adhesion promoter should help to improve the durability of most asphalt concretes in cold climates. Paving trials are needed to indicate the long-term economic benefit of these modifications.

Despite several serious deficiencies, bitumen continues to be favored as a low-cost binder in road paving formulations. The temperature susceptibility of bitumen is so pronounced that at elevated temperatures, creep and distortion of asphalt pavements