RESISTANCE OF VARIOUS TYPES OF BITUMINOUS CONCRETE AND CEMENT CONCRETE TO WEAR BY STUDDED TIRES

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The objective of this investigation was to determine through field tests and literature review the resistance of different types of concrete and bituminous mixtures to wear by studded tires and to establish mix design criteria for better resistance to wear. A simple and practical apparatus was developed for measuring wear in the field. The rate of wear, calculated from traffic data and the wear profile, is defined as the average wear depth of a 6-in. wide strip of pavement caused by 100,000 passes of studded tires. The wear rate of concrete slab surfaces during a 4-year period was determined. Six concrete mixtures and six bituminous mixtures were subjected to investigation at a tollgate. Wear rate of pavement on the highway was also estimated by observing the change in color of cylinders inserted in the pavement flush with the surface.

•IN THE PAST few years, many investigations were made to evaluate the safety aspect of studded tires and their effect on the wear of road surfacing. A list of publications dealing with the subject is given elsewhere (1) and is also included in this report (11 through 33).

Almost all published data concerning the relative resistance to wear of different types of bituminous and cement concrete surfaces by studded tires are of European origin. Through special studies and literature survey, this report attempts to (a) give an indication of the rate of wear of conventional portland cement concrete and bituminous concrete mixtures used in the United States and Canada; (b) identify the relative importance of factors affecting wear; and (c) establish mix design criteria for wear-resistant mixtures.

DEFINITION OF RATE OF WEAR

In this paper the rate of wear is defined as the average wear in depth of a 6-in. wide strip of pavement in the wheelpath produced by 100,000 passes of the studded tires.

$$W_{100,000} = \frac{\delta 10^5}{(a + 2b)T\phi}$$

where

δ = maximum wear depth along the wheelpath;
T = total number of vehicles passing in a given traffic lane;
a = fraction of vehicles with rear wheels equipped with studded tires;
b = fraction of vehicles with front and rear wheels equipped with studded tires; and
ϕ = fraction of vehicles passing in the 6-in. strip of pavement (average width of tire) with maximum wear.

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The value of ϕ is derived from the shape of the wear profile as follows:

1. If the shape follows a rectangular distribution pattern, then $\phi = 6$ in./ω, where ω is the width of the wheelpath.
2. If the shape follows a normal distribution pattern, then ϕ is equal to the area under the normal curve between ±3 in. from the center.

MEASUREMENT OF WEAR

A special instrument was developed to measure the change in profile of the pavement in the wheelpath. As shown in Figure 1a, the instrument is a 12- by 36-in. rigid aluminum frame with a mobile beam to which a recording device is attached. The measuring device shown in Figure 1b can be moved freely in the channel of the frame by turning the wheel. Any change in the profile is recorded on profile paper by virtue of a device that amplifies the vertical displacement of the contact point with the pavement.

At each station, the instrument is set on three initially fixed reference points in the pavement, and the first profile is recorded. Prior to each measuring of any change in profile, the instrument is set at zero with the end points of the initial profile. Readings in time are recorded on the original profile paper for each station.

The apparatus weighs 30 lb. It can be used to record a profile of 30 in. maximum width and ¾ in. maximum depth. Only a few minutes are required for tracing the profile at a test site. The repeatability of the profile is approximately $^{1}/_{60}$ in.

GENERAL TESTING CONDITIONS

The rate of wear of a pavement by studded tires is influenced by many factors (1). The measurements were carried out under the following atmospheric conditions:

	Winter			
Condition	1966-67	1967-68	1968-69	1969-70
Snowfall, in.	73.9	52.7	90.8	77.3
Freezing index	1725	1893	1518	2064

The pavement surface condition was nearly always clean because of snow removal and salt spreading. The percentages of cars equipped with studded tires were as follows: 9 percent, 1966-67; 22 percent, 1967-68; 47 percent, 1968-69; and 38.5 percent, 1969-70. No trucks were equipped with studded tires. The number of studded tires per car was as follows: 98.9 percent had studded tires (90-120) on rear wheels, and 1.1 percent had studded tires on front and rear wheels.

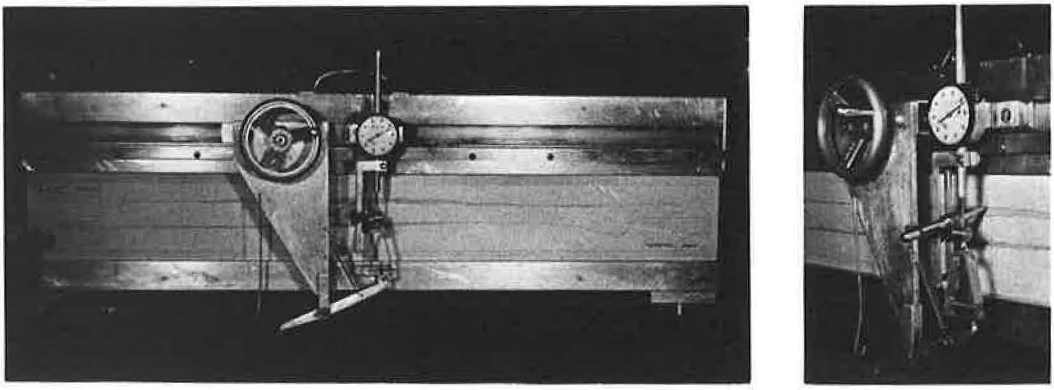

Figure 1. Profilometer used for wear measurements along wheelpath.

The nature of surfacing materials used and the traffic conditions to which the pavement was exposed during the different tests are described in the paper.

All the mixtures tested in this investigation were laid at the tollgate. The selection of a tollgate was motivated by the fact that (a) all cars are channeled in well-defined wheelpaths, (b) the number of cars passing through the lane is automatically recorded, and (c) the percentage of cars equipped with studded tires can be easily determined through periodic surveys.

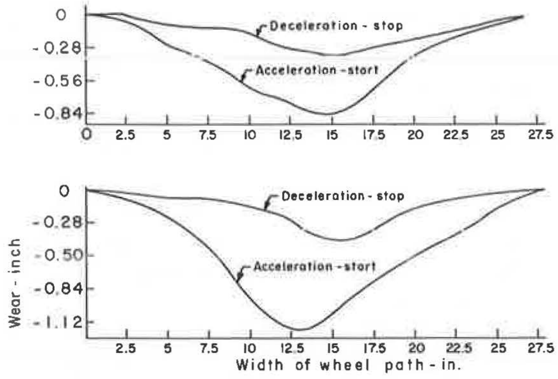

Figure 2. Typical profiles of pavement wear near Laval tollbooths.

WEAR PROFILES ACROSS WHEELPATH

The profile of wear of a pavement surface depends on the distribution of wheel loads across the wheelpath. Examination of wear profiles of numerous pavement sections investigated suggests that the shape of the wear profile along the wheelpath depends on its width, and may vary from the shape of a normal distribution for a narrow wheelpath to the shape of a more or less rectangular distribution (more exactly a flat-topped platykurtic distribution) for a wide wheelpath.

Figure 2 shows two typical profiles of pavement wear near a tollbooth where the wheel loads were channeled in a 27.5-in. wheelpath. The amount of wear decreases systematically from the point of maximum wear to the edges of the wheelpath.

Figure 3 shows a comparison of the shape of the wear profile along the wheel track and the shape of normal distribution. Each point on the graph represents the sum of 14 wear values taken from the wear profiles of the individual tollbooth lanes made with the same concrete at an equal distance from the maximum value. The wear profile follows very closely the pattern of the curve of a normal distribution.

If the traffic is not channeled, as is the case on unmarked pavement or on pavement where the white line has disappeared during the winter, the profile of wear of the pavement surface follows more or less a rectangular distribution. Many profiles measured along the wheelpath of the pavement of the Montreal Laurentian Autoroute substantiate this statement.

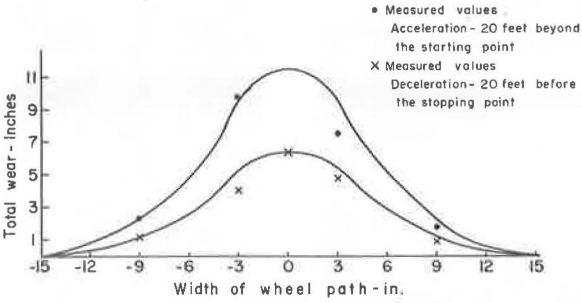

Figure 3. Wear of pavement surface near 14 tollbooths at Laval.

Figure 4 shows the results of measurements taken of wheelpath widths at intersections in Montreal. These measurements were made during the fall and represent the width of the worn portion of a transverse pavement marking across the wheelpaths. The width of wheelpath is less than 2.5 ft for most streets, but in some cases it may reach 4.75 ft. It is, thus, reasonable to assume that the wear pattern may vary between the shape of a normal distribution curve and the shape of a rectangular distribution curve.

As shown earlier in this paper, to determine the rate of wear of a pavement surface, one must take into account the width of the wheelpath and the profile of the wear. Figure 5 shows the influence of the shape of the distribution and the width of the wheelpath on the calculated rate of wear. The relative wear is the ratio, expressed in percent, between the wear that would be caused with a given width of wheelpath and wear profile and the wear that would be caused if the traffic were centralized on a 6-in. band (average width of a tire). For example, if the wheelpath is 30 in. wide, the relative wear will be about 45 percent if the wear is centralized in a narrow band, which follows a normal distribution, and only 20 percent if the shape of the wear follows a rectangular distribution.

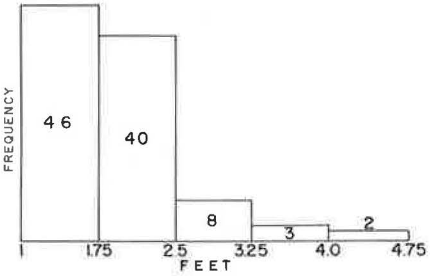

Figure 4. Width of wheelpath on pavement at 99 intersections in Montreal.

If a road is to be resurfaced whenever the wear in the wheelpath reaches a certain depth, more vehicles will have passed over a given section of road before it reaches critical depth if the pattern of wear is rectangularly distributed (125 percent more for the preceding example). Perhaps a way could be found to cause wheelpath wear to follow a more or less rectangular distribution pattern.

EFFECT OF STUDDED TIRES ON WEAR OF CONCRETE PAVEMENTS

Ordinary Concrete Pavement

The purposes of this test was to determine the rate of wear of an ordinary concrete pavement by studded tires during a 4-year period. The pavements of the lanes were built with the same 3,000-psi minimum compressive strength concrete made with coarse-crushed limestone aggregate and silica sand.

The wear measurements were made at two locations along one of the two wheelpaths of each of the 14 lanes: 20 ft from the starting point of the rear tires where the cars accelerate and 20 ft from the stopping point of the front tires where the cars decelerate. A summary of the calculated rate of wear is shown in Figure 6. Examination of the results indicates the following:

1. The average rate of wear after 100,000 passes of studded tires is 0.26 in. at the point of acceleration and 0.10 in. at the point of deceleration.
2. The average ratio between the rate of wear at the acceleration point and at the deceleration point is 2.3 in the north direction and 2.9 in the south direction. The difference between wear rates in both directions could be explained by the impatience of the drivers going to work in Montreal in the morning or driving back to Montreal after the weekend.

An evaluation was made of the rate of wear of the slabs during the 1969-70 winter season. Two lanes out of 14 were not resurfaced and were subjected to additional wear measurements. The results in-

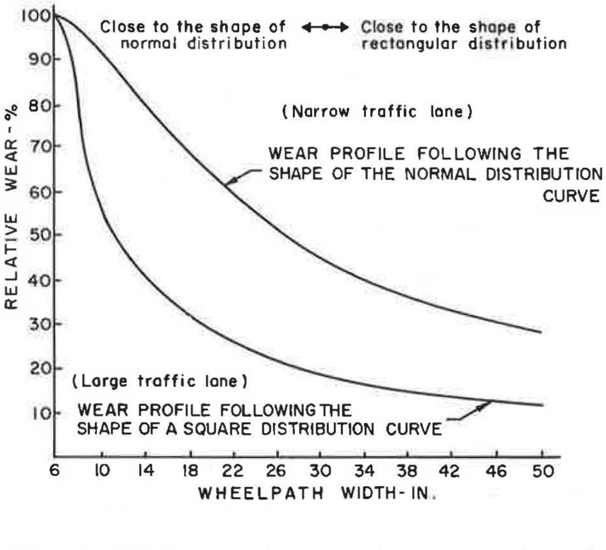

Figure 5. Relative wear of pavement in relation to shape of wear profile and width of wheelpath.

indicate that the wear rate obtained during the fifth winter (1969-70) is very close to those obtained during the four preceding years. The appearance of the wheel track after 400,000 passes of studded tires is shown in Figure 7.

Concrete Properties and Its Constituents

A testing program was prepared to determine whether the type of coarse aggregate, its nominal size, or concrete compressive strength has significant influence on the rate of wear of concrete pavement by studded tires. The characteristics of the test slabs are given in Table 1. The type of concrete and the constituents used in this study comply with the CSA and the ASTM standards for ready-mixed concrete.

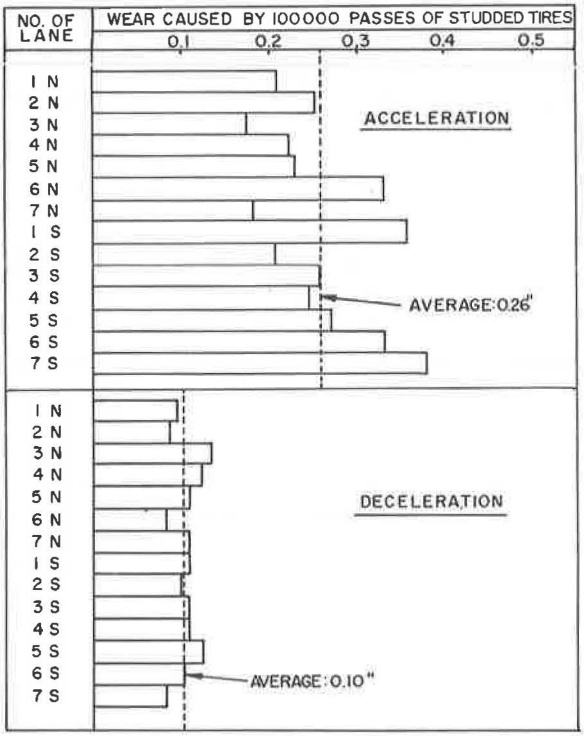

Figure 6. Average wear on concrete lanes at Laval tollbooth.

The relationship between the number of passes and the rate of wear is shown in Figure 8. The relationship is curvilinear at the beginning and linear after a number of passes. In the case of acceleration, the wear rate stabilizes at about 0.2 in. after 100,000 passes of studded tires, whereas, in the case of deceleration, the wear rate stabilizes at about 0.1 in. after 80,000 passes. For acceleration as well as for deceleration, the wear rate after 10,000 passes is about three times greater than the wear after 100,000 passes.

The effect of nominal size of aggregate, the nature of coarse aggregate, and the compressive strength on the wear rate are shown in Figure 9. For purposes of comparison, Figure 9 also shows the wear rate of the concrete slabs after 4 years of service at the Laval tollgate and the additional wear of the nonsurfaced slabs during the winter of 1969-70. These data indicate the following:

1. There is no significant difference between the wear rate of a concrete slab manufactured with a maximum size of limestone aggregate of $1\frac{1}{2}$ in. and that of one manufactured with a maximum size of limestone aggregate of $\frac{3}{4}$ in.;
2. There is a significant difference between the rate of wear of a concrete slab manufactured with an igneous hard aggregate (lamprophyre) and that of one manufactured with a limestone aggregate (Fig. 9); and
3. There is no significant difference between the rate of wear of a concrete slab having a compressive strength of 5,000 psi and that of one having a compressive strength of 8,000 psi.

Figure 7. Appearance of concrete surface after 400,000 passes.

TABLE 1

CONCRETE TEST SLABS AT STE. THERESE TOLLGATE

Section	Compared Variables	Type of Coarse Aggregate	Nominal Size of Particles (in.)	Slump (in.)	Air Content (percent)	Compressive Strength (psi)
3N	Nominal size	Limestone	¾	3.25	7.8	4,140
6N	Nominal size	Limestone	1½	3.0	6.7	4,170
4N	Type of coarse aggregate	Limestone	¾	2.0	4.8	5,320
3S	Type of coarse aggregate	Lamprophyre	¾	3.0	6.2	4,970
5N	Type of coarse aggregate	Limestone	1½	3.5	7.6	3,645
6S	Type of coarse aggregate	Lamprophyre	1½	4.5	8.2	3,840
4S	Compressive strength, psi	Lamprophyre	¾	2.5	5.4	8,135
3S	Compressive strength, psi	Lamprophyre	¾	3.0	6.2	4,970

Discussion of Concrete Wear

A literature survey reveals that three previous studies have been made on the wear of portland cement concrete by studded tires (2, 3, 4). The New Jersey study (2) and the Maryland study (3) were carried out on concrete pavements, whereas the Swedish study (4) was made on laboratory and field samples in the laboratory.

The New Jersey study was carried out on a test track. The average pavement wear was about 0.01 in. for 4,990 abrupt stops and 0.013 in. for 1,400 panic stops. Assuming that the wear is concentrated along a wheel track of 24 in. and that the initial wear is about three times higher than the stabilized wear in a long term, the calculated rate of wear for abrupt stops will be about 0.25 in. for 100,000 passes of studded tires. This value is close to the one obtained at the point of acceleration at the Laval tollbooth.

In the Maryland study on an experimental road, the average wear after 10,000 passes was found to be 0.009 and 0.030 in. respectively for a passenger vehicle test loop and a truck test loop. If the same assumptions given previously for the New Jersey study are used, the calculated rate of wear becomes 0.12 in. for a passenger car, which is close to 0.10 in. per 100,000 passes found at the point of deceleration in this study.

The study by B. Örbom of the National Swedish Road Research Institute (4) was carried out in the laboratory with a special wheel-test machine installed in a cold room. The

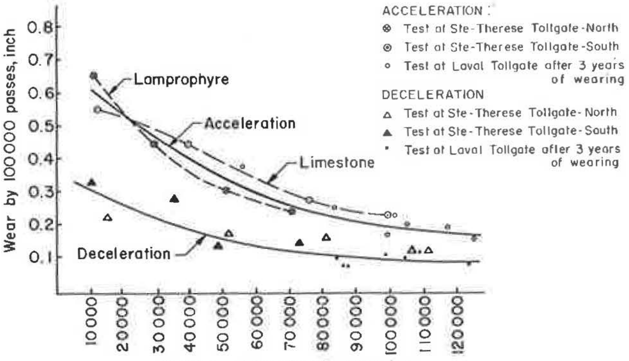

Figure 8. Relation between number of studded tires passing and wear of concrete slabs.

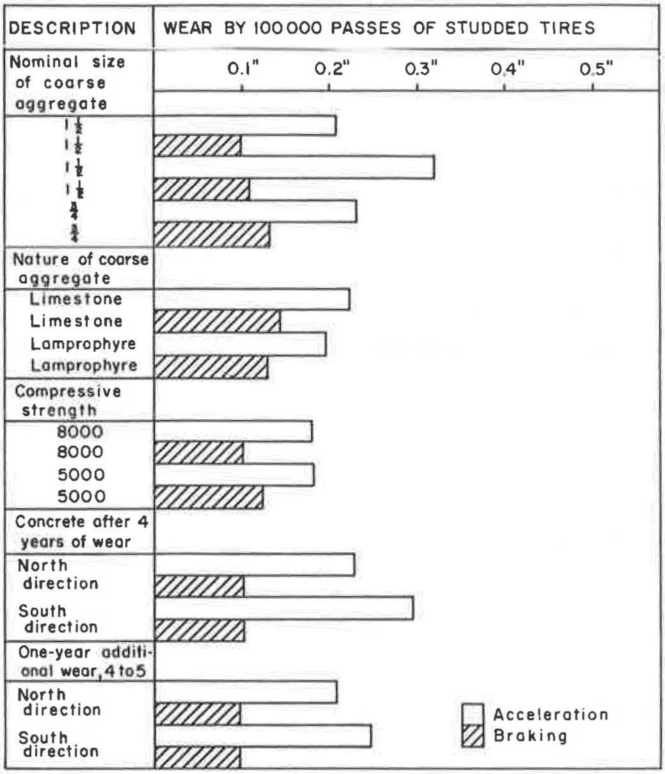

Figure 9. Resistance of various types of concrete mixtures to wear by studded tires.

principal variables studied were cement content; type, shape, and amount of coarse aggregate; and consistency of concrete.

As in the study described in this paper, Örbom shows that the wear rate of all pavements was relatively high in the prime phase of the tests but decreased later when the number of coarse aggregate pieces protruding above the abraded surface increased. Örbom's study also indicates that older cement mortar offers better resistance to wear and that resistance to wear is improved by minimizing the segregation during placement, which causes the accumulation of mortar in the surface layer.

Table 2 gives the effects of different factors on the resistance of concrete pavement to wear by studded tires. From Table 2 it is reasonable to conclude that the resistance of a portland cement concrete surface of wear by studded tires can be improved by using as great an amount as possible of sound, hard, and durable aggregate in a uniform concrete mix with very little mortar exposed on the surface.

It was also found in this study that the wear rate at places of acceleration is more than two times greater than at places of deceleration. This result is in opposition to Wehner's findings (5). This can be explained by the fact that, in the United States and in Canada, passenger cars are equipped with studded tires on rear wheels only, whereas in Germany most passenger cars are equipped with studded tires not only on the rear wheels but also on the front wheels, which bear about 70 percent of the load during braking.

EFFECT OF STUDDED TIRES ON WEAR OF ASPHALT PAVEMENTS

Various Types of Bituminous Mixtures

The purpose of this test was to determine the effects of various types of mixes, conventional and special, on the rate of wear of bituminous pavement by studded tires. The

TABLE 2

EFFECT OF FACTORS ON RESISTANCE OF CONCRETE PAVEMENT TO WEAR BY STUDDED TIRES

Factor	Influence on Wear	Ratio
Number of passes of studded tires[a]		
10,000 vs 100,000 passes	Very significant	3:1
Cement content[b]		
325, 350, and 400 kg/m^3	Not significant	–
Amount of coarse aggregate[b]		
55, 61.5, and 73.5 percent	Significant	1.6:1.1:1
Size of coarse aggregate[a]		
¾ vs 1½ in.	Not significant	–
Type of coarse aggregate		
Granite, gneiss, diabases, quartzite, and sandstone[b]	Not significant	–
Limestone vs lamprophyre[a]	Significant	1.3:1
Shape of coarse aggregate[b]	Not significant	–
Age of mortar[b]		
2 months vs 11 years	Very significant	2:1
Compressive strength of concrete		
502 vs 645 kg/cm^2[b]	Not significant	–
4,970 vs 8,135 psi[a]	Not significant	–

[a] Data taken from Keyser's work (1). [b] Data taken from Örbom's work (4).

properties of the bituminous mixtures used are given in Table 3. Twelve types of mixes were compared as follows:

1. Three conventional mixes—sheet, stone-filled, and bituminous concrete made with limestone aggregate and silica sand;
2. Three special gap-graded mixes composed of sheet containing respectively 30, 40, and 50 percent one-size coarse limestone aggregates passing the ¾-in. sieve and retained on the ⅜-in. sieve; and
3. Three conventional mixes and three gap-graded mixes that were the same as in 1 and 2 except made with lamprophyre of igneous origin instead of limestone.

The criteria on which the design of special mixes are based are given in the discussion of this section. All bituminous mixes were of good quality and complied with the

TABLE 3

ASPHALT CONCRETE MIXTURES USED IN STUDY OF RESISTANCE TO WEAR BY STUDDED TIRES

Section	Type of Grading	Type of Mixture	Type of Coarse Aggregate	Bitumen Content (percent)	Gradation (percent passing)			Stability	Voids in Mixture (percent)
					Retained No. 4 Sieve	No. 4 to No. 200 Sieve	Passing No. 200 Sieve		
N1	Discontinued	AE[a], 50 percent	Limestone	6.0	31	61	8	2,240	3.9
N2	Discontinued	AE[a], 40 percent	Limestone	5.3	37	57	6	2,450	4.7
N3	Discontinued	AE[a], 30 percent	Limestone	5.9	30	63	7	2,200	3.6
N4	Fine	Sheet	Limestone	7.6	0	90	10	1,665	5.1
N5	Stone sheet	Stone-filled	Limestone	5.8	20	70	10	2,245	3.2
N6	Dense	Bituminous concrete	Limestone	5.8	40	53	7	2,515	1.5
S6	Discontinued	Bituminous concrete	Lamprophyre	5.2	27	70	3	2,180	4.7
S5	Stone sheet	Stone-filled	Lamprophyre	5.9	11	79	10	2,100	3.8
S4	Fine	Sheet	Lamprophyre	8.2	0	87	13	1,300	4.0
S3	Discontinued	AE[a], 30 percent	Lamprophyre	6.2	26	66	8	1,870	4.5
S2	Discontinued	AE[a], 40 percent	Lamprophyre	4.8	45	47	8	2,120	4.1
S1	Discontinued	AE[a], 50 percent	Lamprophyre	4.6	50	44	6	2,810	2.8

[a] Elementary aggregate ½ in.

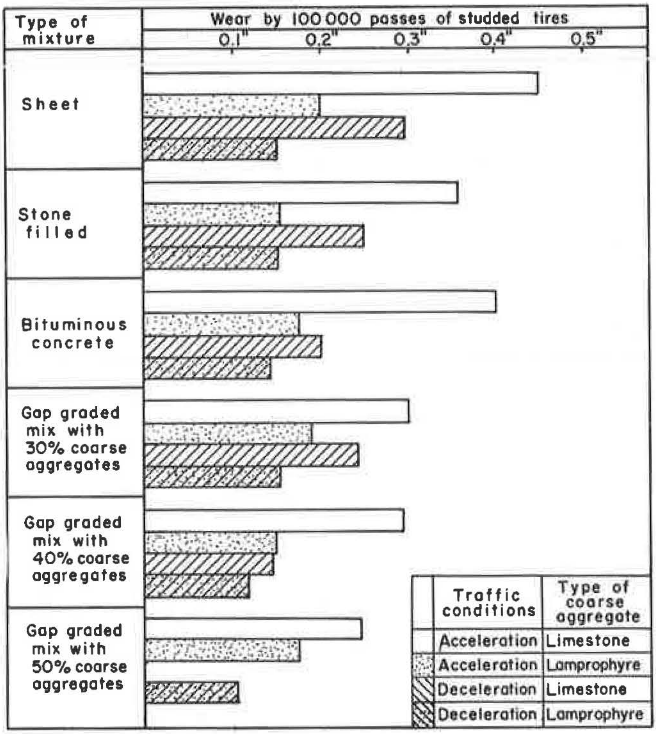

Figure 10. Resistance of various types of bituminous mixtures to wear by studded tires.

physical requirements of standard specifications for surface mixes. Figure 10 shows the results obtained with different mixes at places of acceleration and deceleration. The wear measurements were made at two locations along one of the two wheelpaths of each of the 12 lanes: 17 ft from the starting point of the rear tires where the cars accelerate and 15 ft from the stopping position of the front tire where the cars decelerate. In the calculation of the wear caused by 100,000 passes of studded tires, it was assumed that the wear profile follows the shape of a normal distribution curve. The following observations are made based on data shown in Figure 10:

1. The mixes can be classified in the order of a decreasing rate of wear: sheet, stone-filled sheet, bituminous concrete, and gap-graded mixes with 30, 40, and 50 percent coarse aggregate. By considering the results obtained at the point of acceleration, we note that the wear caused by studded tires can be reduced from 150 to 200 percent through the use of special mixes.
2. Figure 11 shows the influence of the type of coarse aggregate on the resistance to wear and the variation of wear with the type of mix. There is a relationship between the type of coarse aggregate and the rate of wear. For example, lamprophyre, an igneous hard rock, offers a better resistance to wear than limestone, a sedimentary rock. In fact, the average ratio of the rate of wear of limestone mixes to that of lamprophyre mixes is 1.65 at the point of acceleration and 1.15 at the point of deceleration.
3. For special gap-graded mixes, there is a relationship between the coarse aggregate content and the wear resistance. The mixes containing the most coarse aggregates offer a better resistance to wear.

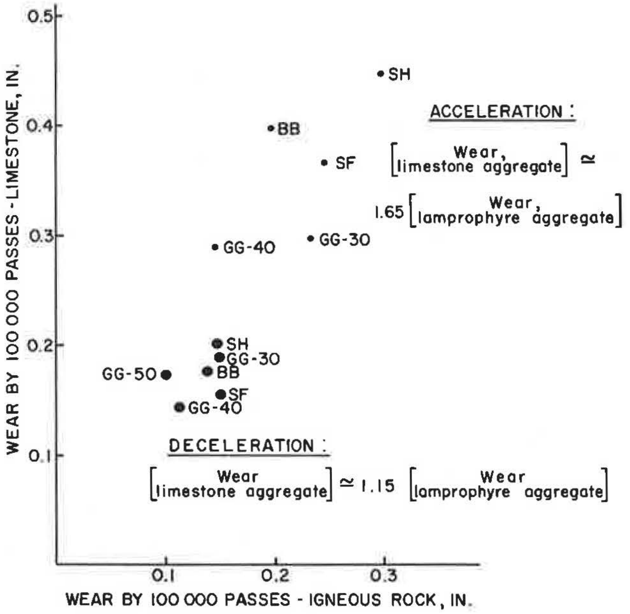

Figure 11. Effect of type of coarse aggregate on resistance to wear by studded tires.

Experimental Overlay

The purpose of this test was to determine the rate of wear of four types of conventional bituminous overlays under normal traffic conditions. Mix types tested were (a) stone-filled sheet with coarse limestone aggregate, (b) stone-filled sheet with coarse lamprophyre aggregate, (c) bituminous concrete with coarse limestone aggregate, and (d) bituminous concrete with coarse lamprophyre aggregate.

The characteristics of the stone-filled sheet mixes and the bituminous concrete mixes are given in Table 4. The characteristics of the stone-filled sheet comply with The Asphalt Institute Vb mix, and those of the bituminous concrete comply with The

TABLE 4

SUMMARY OF TESTS ON BITUMINOUS OVERLAYS

Designation	Lamprophyre		Limestone	
	Stone-Filled	Bituminous Concrete	Stone-Filled	Bituminous Concrete
Gradation, percent passing				
$^3/_4$ in. sieve	100	100	100	100
$^1/_2$ in. sieve	97	93	95	96
$^3/_8$ in. sieve	80	75	83	79
No. 4 sieve	72	54	75	60
No. 8 sieve	69	51	69	54
No. 16 sieve	52	37	55	41
No. 30 sieve	40	26	42	32
No. 50 sieve	30	19	31	24
No. 100 sieve	13	9	15	11
No. 200 sieve	4	4	6	4
Bitumen content, percent	5.8	5.3	5.9	5.0
Voids in mixture, percent	3.2	0.9	2.7	2.0
Voids between aggregate, percent	17.2	14.3	17.0	14.3
Degree of compaction	96.8	99.0	97.3	98.0

Asphalt Institute IVb mix. The degree of compaction of the overlay was higher than 95 percent in all cases.

Stations for measurement were installed along the Montreal Laurentian Autoroute: 11 on the curves, and 12 on the straight sections. Reference marks were set to measure the wear of pavement with the profilometer. Cylinders made of bituminous mixes consisting of three layers of a different color, each layer with a known thickness, were driven into the pavement 1 ft in front of each measurement station (Fig. 12). To ensure that at least one cylinder was in the wheelpath, three cylinders were obliquely placed at each measurement station along the wheel track: 1 ft, center to center, in the transverse direction; and 6 in., center to center, in the longitudinal direction.

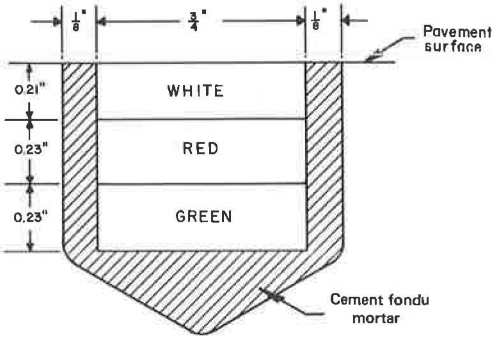

Figure 12. Cylinders of colored bituminous mixes used in overlay tests.

After 1 year of wear, cross sections were taken at measurement stations. It was noted that, in most cases, the wear was spread over a much larger surface than the one predicted by the width of the profilometer (30 in.) because of the fact that traffic was not directed between the white traffic lines during the winter. This fact altered our measurements. On the other hand, it was noted that many cylinders inserted in the pavement were worn down to the next color (Table 5), indicating that the wear of the surfacing had exceeded 0.21 in. in certain spots.

The following observations are based on a comparison of the ratios of the number of stations where cylinders had worn from white to red (the wear of surfacing exceeding 0.21 in.) to the total number of stations:

1. Overlays with limestone aggregate on straight sections and those on curved sections were practically worn out at the same rate.

	Ratio of Red to Total	
Section	Stone-Filled	Bituminous Concrete
Straight	3:3	1:2
Curve	2:2	1:2

2. The bituminous concrete mix provided a better resistance to wear than the stone-filled sheet mix.

	Ratio of Red to Total	
Mix	Limestone	Lamprophyre
Bituminous concrete	2:4	0:2
Stone-filled sheet	5:5	1:2

3. Mixes made with lamprophyre aggregates provided a better resistance to wear than those produced with limestone.

	Ratio of Red to Total	
Aggregate	Stone-Filled	Bituminous Concrete
Coarse lamprophyre	1:2	0:2
Coarse limestone	5:5	2:4

TABLE 5

RELATIVE WEAR OF BITUMINOUS OVERLAYS AFTER ONE YEAR OF SERVICE

Mix	Aggregate	Straight Section			Curved Section		
		Ratio of Red to Total	Station	Color	Ratio of Red to Total	Station	Color
Stone-filled	Limestone	7:9	2	RRR	6:6	4	RRR
			3	RWW		14	RRR
			13	RRR			
	Lamprophyre	2:6	10	WRR			
				WWW			
Bituminous concrete	Limestone	3:6	6	RRR	3:6	5	WWW
			17	WWW		15	RRR
	Lamprophyre	0:9	8	WWW			
			9	WWW			

Table 6 gives an estimate of the average wear of the bituminous overlays in inches per 100,000 passes under normal traffic conditions. It shows that, assuming a minimum total wear of 0.21 in., the minimum wear rate is equal to approximately 0.11 in. per 100,000 passes.

Based on the comparison of results given in Table 6, the estimated value might be too low for stone-filled sheet with limestone aggregate and too high for bituminous concrete made with lamprophyre. It is likely to be realistic for stone-filled sheet with lamprophyre and bituminous concrete made with limestone aggregate. The wear rate for bituminous overlays of 0.11 in. per 100,000 studded tire passes is about 40 percent lower than the wear rate found for bituminous concrete and stone-filled sheet at the Laval tollgate at the point of deceleration.

Wear per 100,000 Passes, in.

	Tollbooth Deceleration		Experimental Resurfacing	
Type of Mix	Limestone	Lamprophyre	Limestone	Lamprophyre
Stone-filled sheet	0.16	0.15	>0.11	0.11
Bituminous	0.18	0.14	0.11	0.11

Discussion of Asphalt Wear

A literature survey reveals that several studies have been made on the rate of wear of bituminous concrete overlays by studded tires. An attempt will be made in the following discussion to (a) compare the rates of wear reported in the literature to those

TABLE 6

AVERAGE WEAR OF BITUMINOUS OVERLAYS UNDER NORMAL TRAFFIC CONDITIONS

Item	Northbound	Southbound
Number of vehicles equipped with studded tires (3 lanes)	3,297,019	3,533,300
Number of vehicles in the central lane (0.4 x total)	1,318,807	1,413,320
Number of studded tire passes		
36-in. wheelpath	217,603	233,198
48-in. wheelpath	171,445	183,732
Pavement wear, in. per 100,000 studded tire passes		
36-in. wheelpath	0.10	0.09
48-in. wheelpath	0.12	0.11

found in our study, (b) give relative wear of different types of bituminous mixes, (c) outline the factors influencing the resistance of bituminous mixes to wear, and (d) establish mix design criteria for wear-resistant bituminous mixtures.

In a report published by the National Road Research Institute (6), Rosengren states that "the maximum wear depth in the wheel-tracks in Finland and Norway has been computed at 20 mm per one million passes, in each direction, by stud-equipped vehicles.... In Germany, wear amounted to 28-35 mm per one million passes at constant speed on the straight-ahead section."

If we assume that the shape of wear follows a normal distribution curve along a wheelpath of 24 in. and that the cars are equipped with four studded tires 6 in. wide, the computed wear per 100,000 passes of studded tires is equal to about 0.07 in. for Finland and Norway and between 0.10 and 0.12 in. for Germany. These values are similar to the mean value of 0.11, with a possible range of ±0.03 in.

The studies made by Wehner in Germany (5) also give the ratios of wear for straight driving to wear for curves, acceleration point, and deceleration point. They are 1:1.1, 1:1.3, and 1:2.6 respectively. These figures are not in complete agreement with the results of our study. The corresponding figures in our investigation are approximately 1:1.1, 1:2.8, and 1:1.4.

The higher rate of wear at deceleration than at acceleration found in Europe and the reverse figures found in our study are attributable to the fact that in Europe nearly all passenger cars are equipped with four studded tires, whereas in America nearly all cars are equipped with studded tires on the rear wheels only.

Table 7 gives the relative resistance to wear of different types of bituminous mixes. Examination of the data allows the following observations:

1. The standard mixes conforming to The Asphalt Institute or the ASTM mixes are less resistant to wear than the mixes commonly used in Europe known under the name of mastic, gussasphalt, rolled asphalt, or Topeka;
2. As indicated by our study, it is possible to design bituminous mixes that will have considerably higher resistance to wear than conventional mixes.

Table 8 gives the effect of different factors contributing to the resistance to wear of asphalt pavement by studded tires. From Table 8, it is reasonable to conclude that the resistance of bituminous surfacing to wear can be improved by designing a mix with an optimum stone-to-mortar ratio. This will ensure that (a) the surface of the bituminous

TABLE 7

RELATIVE WEAR OF BITUMINOUS MIXTURES

Source	Asphalt Institute Formulas	Aggregate		Filler	Bitumen	Relative Wear	Notes
		Coarse	Fine				
Anderson et al. (7)	—	38	40	22	9.1	1	Mastic asphalt
	—	35	47	18	7.1	1.1	Topeka
	IVb	60	30	10	6.8	1.3	Asphaltic concrete
Huhtala (8)	VIa	38	50	12	7.6	1	Topeka
	IVb	64	28	8	5.4	1.2	Asphaltic concrete-gravel
	VIa	54	38	8	5.4	1.3	Asphaltic concrete
Keyser (1)	—	54	40	6	4.7	1	Skip-special
	—	47	46	7	5.0	1.2	Skip-special
	—	42	51	7	5.7	1.2	Skip-special
	IVa	50	47	3	5.2	1.6	Asphalt concrete $^{0}/_{12}$
	VIa	28	63	9	6.0	1.5	Stone filled
	VIIa	5	85	10	8.0	1.8	Sheet asphalt
Thurmann-Moe (9)	—	38	32	30	9	1	Gussasphalt
	IVa	57	35	8	6	1.5	Asphaltic concrete
	—	47	37	16	5.8	1.5	Rolled asphalt
Peffekoven (10)	—	49	43	8	7.2	1	Rolled asphalt
	—	46	32	22	7.4	1.1	Gussasphalt
	IVa	60	33	7	7.5	1.2	AC-$^{0}/_{12}$
	Va	51	39	10	6.6	1.4	AC-$^{0}/_{8}$
	Va	52	39	9	6.6	1.5	AC-$^{0}/_{8}$

TABLE 8

EFFECT OF FACTORS ON RESISTANCE OF ASPHALT PAVEMENT TO WEAR BY STUDDED TIRES

Factors	Influence on Wear	Wear Ratio
Penetration of bitumen[a] 60 vs 300	Significant	1:1.3
Bitumen content[a] 5 vs 7 percent (opt. at 7 percent)	Very significant	1:1.8
Type of aggregate[b] Lamprophyre vs limestone	Very significant	1:1.6
Mix type[b] Special mix vs sheet	Very significant	1:1.8
Voids in mix[a] 3 vs 7 percent	Significant	1:1.4
Uniformity[a] Asphalt concrete variation	Variation	X ± 42 percent
Vehicle speed[a] 60 to 80 km/hr	Not significant	—
Vehicle weight[a] Car vs truck	Very significant	1:1.9
Tire pressure[a]	Not significant	—
Temperature[c] 37 ± vs 50 F	Very significant	1:1.5

[a] Data taken from Thurmann-Moe's work (9).
[b] Data taken from Keyser's work (1).
[c] Data taken from Huhtala's work (8).

layer is as rich as possible in durable stone (which can be achieved by proper gradation of the mix and the type of aggregate used); (b) the aggregate is solidly held in place by the mortar (which can be further improved by using a harder bitumen, an optimum asphalt content, and proper grading of fines); and (c) the mix can be uniformly laid and properly compacted.

In our study a successful trial was made to determine the optimum ratio between one size of stone and a high-quality sheet asphalt mortar. One size of stone was used to ensure a surface that was rich in coarse particles and solidly held into the matrix.

As shown by the values of the relative rate of wear given in the references, the resistance to wear of an asphalt wearing course can be very significantly improved by rolling coarse precoated chips into the surface. However, this practice may not be the best or the most economical solution for the following reasons:

1. Precoated chips will not provide a surface rich in coarse aggregates during the lifetime of the overlay. As Thurmann-Moe stated in his study (9), satisfactory results can be obtained with precoated chips if the stone content of the paving mixture does not exceed 35 percent. This means that poor performance of the overlay can be expected when the chips are worn out.
2. Treatment of pavement surface with precoated chips (which is practiced neither in the United States nor in Canada) will significantly increase the cost of the overlay pavement.

FURTHER STUDY

A laboratory test apparatus has been designed to measure the relative wear resistance of bituminous and concrete mixes. Preliminary tests on field samples show a good correlation between the relative wear obtained in the field and that obtained in the laboratory. A comprehensive study based on a statistical experimental design has been planned and is being carried out to evaluate the relative resistance to wear of different types of portland cement concrete and bituminous mixtures to wear by studded tires, all of which are designed according to the established criteria.

CONCLUSIONS

1. Rate of wear has been defined as the average depth of wear of a pavement caused by 100,000 studded-tire applications (in a 6-in. wide strip).
2. A simple and practical apparatus has been developed for measuring wear across the wheelpath.
3. The progress of pavement wear can be followed by inserting specially made colored cylinders into the pavement.
4. The wear profile of a narrow wheelpath follows the shape of a normal distribution pattern, whereas the wear pattern of a large wheelpath follows the shape of a platykurtic or a rectangular distribution.
5. The rate of wear of a new concrete pavement decreases with the number of passes of studded tires. The rate of wear after 10,000 passes is three times higher than the rate of wear after 100,000 passes.
6. The mean rate of wear of a concrete pavement stabilizes at the following values after 100,000 passes of a studded tire: acceleration, 0.26 in. per 100,000 passes; deceleration, 0.10 in. per 100,000 passes.
7. The resistance of a concrete pavement surface can be significantly improved by using the maximum possible amount of durable aggregate in a uniform concrete mix with a strong mortar matrix. As small an amount of mortar as possible should be exposed at the surface.
8. Bituminous mixes can be classified in the following order of decreasing rates of wear: sheet, stone-filled sheet, bituminous concrete, and gap-graded mixes with 30, 40, and 50 percent coarse aggregate.
9. The mean rate of wear of commonly used bituminous surfacings made with limestone aggregates expressed in inches of wear per 100,000 passes of a studded tire are as follows: acceleration, 0.36 to 0.44; deceleration, 0.18 to 0.20; and normal, 0.11.
10. The rate of wear can be reduced from 150 to 200 percent through the use of mixes made with hard and durable aggregates or by using special gradings.
11. In designing wear-resistant bituminous mixes, one must consider the following criteria: (a) the surface should be as rich in stone as possible; (b) the coarse aggregate should be durable and solidly held in place by the mortar; and (c) the produced mix should be uniformly laid and properly compacted. This can be achieved by ensuring a good balance between the quantity of sound, coarse aggregate of one size and the quantity of improved mortar in the mix.

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DISCUSSION

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Although Hode Keyser refers to laboratory studies in his paper, his study is essentially a field investigation, even though related laboratory studies are under way. It is particularly interesting for us in Minnesota to note that the results of our laboratory and field studies generally agree very well with his findings, even though there may be a few differences. There are several significant points covered in his paper that I would like to discuss in the following:

1. Rates of pavement wear—The initial rate of pavement wear is the most rapid, being about three times as rapid as the so-called terminal wear rate. The wear rate seems to stabilize at a depth of about 0.2 in. Our Minnesota tests agree remarkably well with these figures.
2. Concrete strength effect—It is stated that wear resistance of portland cement concrete pavement can be improved by using a strong mortar matrix along with the maximum possible amount of durable aggregate. However, it is also pointed out that there is no significant difference between the wear rate of one slab with a compressive strength of 5,000 psi and another with a strength of 8,000 psi. The Minnesota tests indicate that a stronger matrix (containing an additional 15 percent of cement) did not show much wear advantage. This also appears to be the case in our field tests, although this has not yet been fully established over an extended period of time. Although higher mortar strength may result in some slight wear improvement, the added cost is not yet fully justified.
3. Effect of kind of aggregate in concrete—The report indicates that there is less wear for concrete containing hard aggregate, such as igneous particles, than for concrete containing limestone aggregate. This is in agreement with the Minnesota findings that a gravel aggregate with a high proportion of igneous particles performs better with respect to wear than a limestone aggregate. The pavement containing limestone, which in our case had a Los Angeles rattler loss of 32, wore generally about 1.5 times as fast as the pavement containing gravel aggregate.
4. Effect of mortar at surface of portland cement concrete—Hode Keyser indicates that the amount of mortar at the surface of concrete should be as low as possible but should include an abundance of coarse aggregates. This is particularly pertinent to the initial wear rate on a new pavement, which is higher than the terminal rate that prevails as the wear progresses deeper. Again the Minnesota results confirm this finding. (Concrete of low slump design and placed with controlled vibration would probably help to prevent aggregate from settling excessively below the surface and thereby developing a thick layer of the less resistant mortar at the surface.)
5. Surface composition of asphaltic concrete—The results of this study indicate that in asphalt mixtures the surface layer should be as rich as possible in durable coarse aggregate particles with the least possible amount of mortar at the top. This is consistent with the Minnesota observations on asphaltic concrete having the lowest wear rate. In such a mixture the studs impinge more directly on the hard aggregate particles, which resist the abrasion more effectively than the mortar.
6. Effect of kind of aggregate in asphalt mixtures—The asphalt mixes containing the harder traprock wear less than mixes with the softer dolomitic limestone. The Minnesota tests agree with this finding. The average terminal rate for dolomite was 0.57 in. per million studded-tire passes. For traprock, the average terminal wear rate was 0.41 in. per million studded-tire passes.
7. Influence of aggregate size—according to Hode Keyser, the larger maximum aggregate size of 1½ in. was no better than the ¾-in. size. In Minnesota we have no direct comparison with this, but fine-grained mixes (No. 4 maximum size) in the final laboratory test series were less wear resistant than the coarser asphaltic concrete.
8. In his conclusion Hode Keyser indicates that a good correlation was obtained between relative wear in the laboratory and in the field. The Minnesota results also substantiate this finding, notwithstanding the fact that other investigators previously reported that it was not possible to establish a good correlation between field and laboratory results.

Having compared the results of Hode Keyser's study with our results in Minnesota, I should like to present some information concerning Minnesota's recent research activities on the problem of studded-tire use in our state.

By way of background, the use of studded tires has been legal in Minnesota since the fall of 1965. We have, therefore, completed the sixth winter of exposure of pavements to studded tires. The percentage of automobiles equipped with studded tires during this time is shown in Figure 13. The decrease in 1970-71 may have been influenced by the possibility of a ban on studded tires. The 1965 legislature authorized a 2-year trial

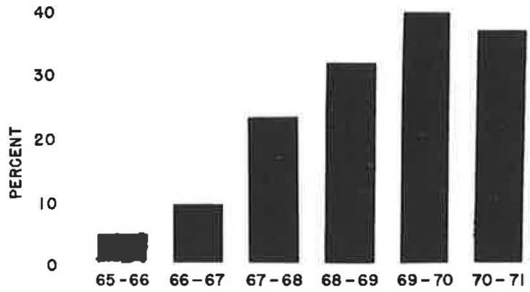


Figure 13. Automobiles in Minnesota equipped with studded tires.

period for the studs. Limited field tests were undertaken by the highway department, starting in the fall of 1964 with a car equipped with four studded tires, to observe particularly the effects of abrupt starting and stopping on both portland cement concrete and asphalt surfaces. Results of the field tests that had been continued in 1965 and 1966 demonstrated the potential for causing surface damage in areas of concentrated braking or acceleration, but it was thought that such wear, if localized, could be tolerated and could be repaired by special maintenance efforts. These tests did not, however, indicate strongly the type of extensive high-speed traffic wear that has been evident more recently.

The 1967 legislature consequently extended the use of studded tires for another 2-year period. Further field tests and observations again were considered to be insufficiently conclusive to justify the prohibiting of studs because, it was contended, any disadvantages or objections to studs were more than offset by the high safety benefits that were attributed to them. As a result, the 1969 legislature again authorized an additional 2-year extension and at the same time directed the department of highways to conduct an in-depth study of studded-tire effects.

Three specific objectives were outlined in the statute: (a) to determine the relative damage, if any, caused to Minnesota highways by metal studs, sand, and salt; (b) to determine if pavement surfaces could be made more resistant to stud damage by changing the aggregates or binder composing the pavements; and (c) to determine the effect on highway safety in Minnesota if studs were eliminated.

To pursue the first two objectives, the highway department expanded its field studies and initiated a laboratory pavement-wear study under a contract with the American Oil Company Research and Development Laboratory in Whiting, Indiana. The third objective was attained by contracting with Cornell Aeronautical Laboratory to conduct a study of the safety effectiveness of studded tires.

Notwithstanding the high estimated cost, approximately $300,000, the highway department, because of the urgency, undertook the projects independently to ensure obtaining the desired information in time to report to the 1971 legislature. Subsequently, we informed a number of other northern states of our program and invited their participation. In response, eight states joined with us, providing financial support in amounts ranging from $12,500 to $26,000 for a total of $161,000. The states are Illinois, Iowa, Michigan, New York, North Dakota, Pennsylvania, Utah, and Wisconsin.

The laboratory study at the American Oil Company was designed essentially to answer the four following questions:

1. How do the wear rates compare for various pavement types used in Minnesota?
2. What are the relative contributions to pavement wear of studs, salt, and sand?
3. Can surfacing courses be designed that economically will be capable of resisting stud-induced abrasion?
4. Can data obtained be used to estimate long-range wear rates caused by the use of studded tires?

The American Oil Company traffic simulator is a 14-ft diameter turntable type of machine with the capability of accommodating 12 pavement test slabs trapezoidal in shape and 2 ft wide (Fig. 14). The two cross-arm beams are each fitted with a regular size automobile wheel and tire at each end and are rotated by a central supporting drive post. In the test the wheels are loaded to 1,000 lb each, and the assembly is rotated with the wheels rolling freely at 35 mph while temperature is maintained at 25 F ±5 F. Special mechanisms permitted the application of sand or salt or both on the pavement surfaces in front of the rotating wheels to simulate conditions typical of those existing on Minnesota highways during the winter.

Figure 14. Test simulator test track of American Oil Company.

The tests were arranged in four series, three of which were made on both asphalt and portland cement concrete pavement types representative of those commonly used in Minnesota, and the fourth on a variety of specially designed surfacing courses to evaluate their relative capability of reducing the wear effects of studs. Each of the first three series was divided into two subseries: one in which studded tires were run over the test pavements, and one in which snow tires were run over the same slabs.

In the first three series, different deicing surface treatments were used: series 1 with sand and salt surface applications, series 2 with only salt applied, and series 3 with neither sand nor salt. From comparison of results of these three series, it was expected to be able to establish the relative wear contribution of each factor—studs, salt, or sand. For series 4, studs, sand, and salt were used and no tests were run without them, because the purpose was only to compare wear resistance under the most abrasive condition. The studded tires each contained 90 studs, with 15 in each of six circumferential rows. The protrusion of the studs beyond the surface of the tires was limited to between a minimum of 0.020 in. and a maximum of about 0.070 in. The studs used throughout the tests were all produced by one manufacturer. To obtain a uniform application of stud contacts on the test zone of the pavement surface, the machine had been modified so that each wheel was slowly moved radially a distance of 1.78 in. from its innermost to its outermost position. The full motion was very gradual, requiring 11 complete revolutions of the turntable. The overall stud contact width on the test slabs was 7.7 in. The resultant effect on the test slabs resembled the central portion of the approximately 36-in. width wheelpath on a typical roadway traffic lane.

Pavement mixtures used in the tests were composed of materials furnished by the Minnesota Department of Highways. The mixtures were designed, based on trial mixes made in the highway department laboratory. All materials were packaged in the Minnesota Department of Highways laboratory in exact proportions for each mix. The materials were then shipped to the American Oil Company where the mixtures and test slabs were produced under observation and with control tests by Minnesota personnel.

There were three asphalt test mixes, including the following:

1. Asphaltic concrete composed of dolomitic limestone coarse aggregate plus natural sand plus filler, with 85 to 100 penetration asphalt.
2. Modified asphaltic concrete consisting of crushed gravel coarse aggregate plus sand without filler and with 85 to 100 penetration asphalt.
3. An asphaltic mixture of intermediate type consisting of graded gravel and sand aggregate without filler and with 85 to 100 penetration asphalt.

Two of the mixes were replicated, making a total of five asphalt slabs. There were 5 portland cement concrete mixes:

1. Three gravel and sand mixes—two were with different gravels, one with 15 percent added cement;
2. One limestone with natural sand; and
3. One traprock with traprock sand.

A fourth test series was run, including a number of new and untried materials or mixtures that, based on a laboratory sandblast abrasion test, gave indications of possibly having improved wear resistance. These included eight bituminous mixes, three portland cement concrete mixes, and one epoxy and sand mix.

Each test was run up to a total of four million studded-tire passes or until the depth of the worn channel reached approximately 1.5 in. (Fig. 15). This maximum was fixed because of the mechanical limitation of the machine to operate to any greater depth. Operation of the test was continued around the clock with automatic controls to shut down operation in the event of any mechanical failure.

Figure 15. Four-inch portland cement concrete slab after test of 4 million tire passes (studded tires on right, tires without studs left of center, and original surface extreme left).

Most of the test runs were completed, although the series 3 tests of tires without studs were deleted from the schedule because the amount of wear produced by the tires without studs, even when salt was applied, was so insignificant as to not warrant running another test of tires without studs. Interpretation of the significance of the tests cannot be made until full analysis of the data and comparison of results of the several series are completed. A major consideration is the fact that the amount of wear is affected significantly by the length of protrusion of the studs beyond the tire surface. Therefore, wear rates must be adjusted to a common denominator of constant stud protrusion.

Test series 1 (conducted with sand and salt on road surface)—Test 1A used tires with studs. There were five specimens of asphalt with wear-rate depths that ranged from 0.54 to 0.75 in. per million studded-tire passes. There were also eight specimens of portland cement concrete with wear-rate depths ranging from 0.25 to 0.43 in. per million studded-tire passes. Test 1B used tires without studs. The average wear for all pavements was 0.0027 in. per million wheel passes. The studs produced more than 100 times as much wear as regular tires when sand and salt were applied.

Test series 2 (conducted with only salt on road)—Test 2A used tires with studs and with salt and no sand on road surface. This series generally corroborated the results of test 1A. Unexpectedly, the mixes containing 15 percent addition of cement with both

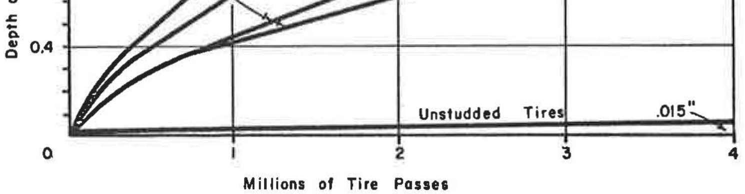


Figure 16. Wear rates of pavement specimens at test track.

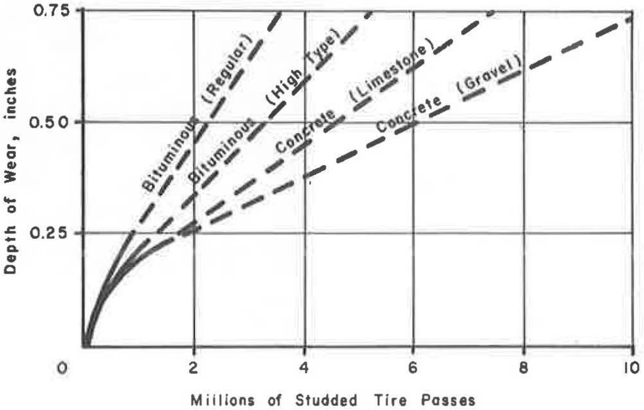


Figure 17. Wear rates of pavements of typical Minnesota highways.

types of aggregate—gravel and traprock—proved to be no better than the regular gravel mix. However, as mentioned previously, these results have not yet been adjusted for differences in stud protrusion. Test 2B, which used tires without studs on a road with salt, was postponed.

Test series 3 (conducted with no foreign material applied to road)—Test 3A used tires with studs. The results of this series were similar to test 2A that showed no significant effect of salt on the road. Test 3B used tires without studs. This series was deleted because plain tires show negligible wear on roads.

Test series 4—Of the three concretes, one with an application of a surface hardener and two with latex admixture showed no increase in wear resistance. One epoxy and sand mix was the most wear-resistant mixture, but the surface was extremely smooth and was so slippery as to be impractical for a road surface. Of the eight bituminous mixtures, four were the fine-graded type for thin overlays. Traprock and granite both performed quite well. Two were rubber and asbestos admixtures and showed a slight improvement. One with traprock instead of dolomite was somewhat improved. Traprock with rubber and asbestos reduced the wear by about 20 percent.

The wear rates of pavement at the test track and on typical Minnesota highways are shown in Figures 16 and 17. The relationships between test track wear and highway wear is shown in Figure 18.

Figures 19 through 22 show the pavement wear that has been experienced on Minnesota highways during the winters since the fall of 1965 when studded tires were first legalized in Minnesota. The photographs demonstrate the type of surface wear that has occurred on both asphaltic concrete and portland cement concrete pavements containing different aggregates, including gravel and crushed limestones.

The pavement wear developing on our high-traffic roads foretells the problems we may be expected to face in the future. Hazardous con-

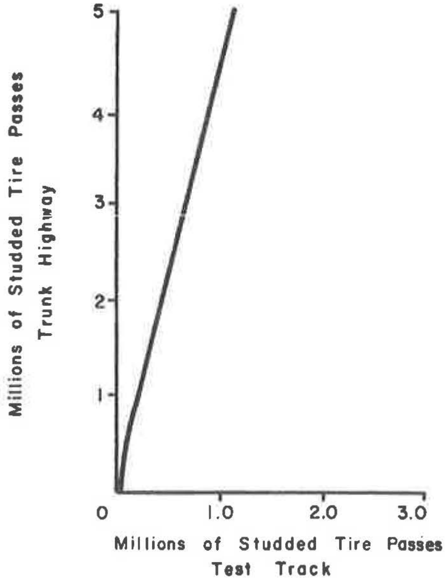
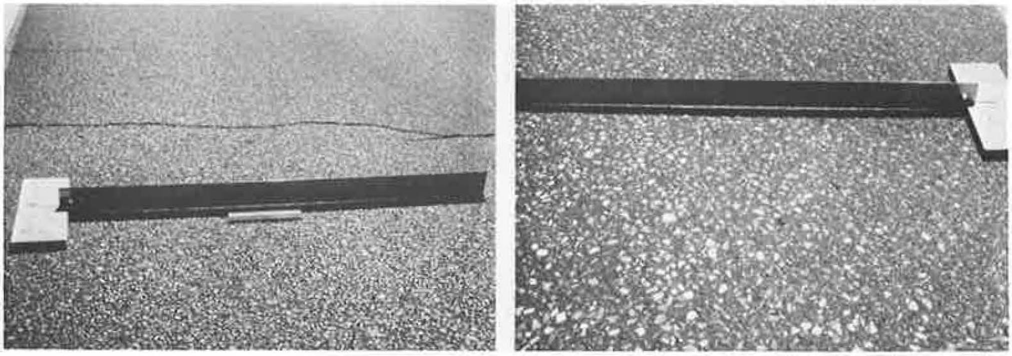


Figure 18. Relationship of wear between test track and highway surfaces.



after 215,000 studded tire passes during 1 winter

after 550,000 studded tire passes during 3 winters

Figure 19. Asphalt concrete surface with gravel aggregate.

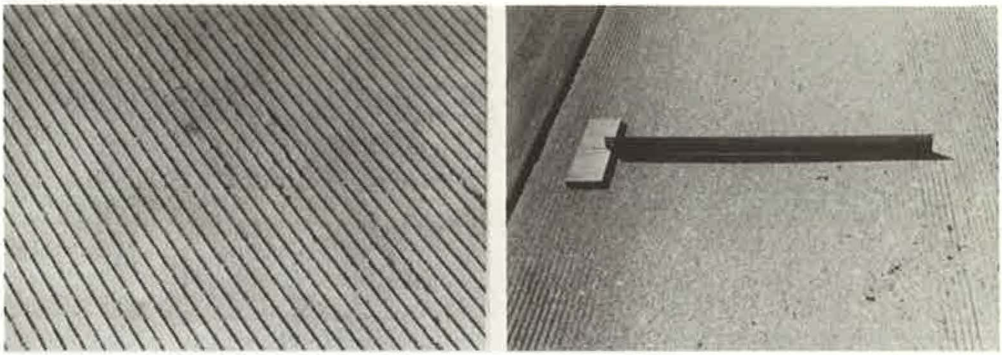
after 1,094,000 studded tire passes during 4 winters

after 1,700,000 studded tire passes during 5 winters

Figure 20. Portland cement concrete surface with hard gravel aggregate that wears less than mortar to produce rough, knobby texture.

after 213,000 studded tire passes during 3 winters

Figure 21. Portland cement concrete surface with limestone aggregate that wears same as mortar to produce smooth texture.



after 1 year and no traffic with studded tires after 169,000 studded tire passes during 2 winters

Figure 22. Portland cement concrete surface with $\frac{1}{8}$ by $\frac{1}{8}$ in. safety groove on 1-in. centers.

ditions are being created that, we feel, will more than offset any advantages that could be ascribed to studded tires. Tremendous costs will be involved in repairing damage caused by the increasing use of studded tires. It would be far better for funds needed for repairing roads damaged by studded tires to be used instead for building new and safer roads and for making safety improvements on older existing roads.

AUTHOR'S CLOSURE

It is indeed interesting to note that our special field test results generally agree with those of the Minnesota laboratory and field studies. Based on the limited number of mixes tested (8 portland cement concrete mixes and 12 bituminous concrete mixtures) and the great number of factors affecting wear, it is not surprising to note a few differences between our two studies.

Preus indicates that higher mortar strength may result in some slight wear improvement. Studies made by the Swedish Road Research Institute have indeed indicated that old concrete pavement is, in fact, more resistant to wear than new pavement.

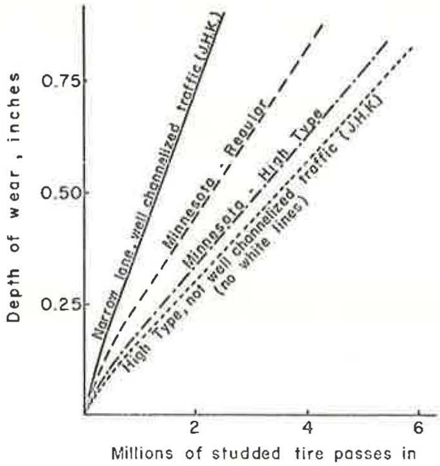


Figure 23. Estimated average wear rate of bituminous concrete pavement by studded tires.

As to the influence of aggregate size with portland cement concrete mixes, no difference was found between the $1\frac{1}{2}$ and $\frac{3}{4}$ in. sizes. However, our laboratory test clearly shows, as the Minnesota study does, that with bituminous concrete mixture the resistance to wear is significantly influenced by the nominal size of coarse aggregate.

Figure 23 shows a comparison of the rate of wear obtained on typical bituminous pavements in Minnesota and the rate of wear obtained in our study. The curves were calculated for a 36-in. wide wheelpath. The steepest curve is calculated for a well-channeled traffic condition where the wear profile follows the pattern of a reversed bell-shaped curve of a normal distribution. The flattest curve is calculated for traffic that is uniformly distributed across the wheelpath. The 2 curves represent the extreme conditions that can prevail on a pavement.