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Groove-Depth Requirements for Tine-Textured Pavements

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This paper discusses the depth required for grooves on new tine-textured concrete pavements in order to ensure an adequate skid resistance over their entire design life. It is based on measures of texture depth and skid resistance, with both ribbed and smooth tires, made on new to 5-year-old pavements in New York. Initial groove-depth needs of 3/16-in minimum were calculated from two values estimated from the study data: (a) minimum groove depth (0.050 in) to ensure adequate skid resistance with a minimum legal tire tread and (b) mean groove wear rate (0.013 in/million vehicle passes). Groove depth measurements on new concrete pavements and bridge decks indicated 21 and 14 percent compliance, respectively, with the proposed new standard of 3/16-in minimum, and 60 and 44 percent compliance with the current standard of 2/16-in minimum. Prospects for improving the compliance rate were judged to be most promising in two areas—increasing the awareness and motivation of construction personnel and improving the design of tining rakes over those now in use. Although the findings of this study are specific to standards and conditions in New York, the methodology should be of general interest.

Many highway agencies require a tined finish on new portland cement concrete pavements (1). The method was introduced because textures obtained by previous methods were found to wear too quickly, and pavements provided only marginal skid resistance after passage of a relatively few vehicles (2). Although assumptions of improved durability and skid resistance over other methods have been generally confirmed (3), the relative newness of tine texturing has precluded evaluation of its long-term durability and skid resistance under actual traffic. Ensurance of adequate skid resistance over a pavement's entire design life requires knowledge of minimum texture needs and the rate at which texture and skid resistance decay, so that the depth of groove required at construction can be judged. This paper describes the collection and analysis of data to address these questions. Although the findings reflect specific needs and conditions in New York State, the methodology is generally applicable.

PURPOSE AND SCOPE

The primary purpose of the study was to determine the rate at which tined textures, and the skid resistance they provide, decay under traffic, and thus to determine what initial groove depth is required to sustain adequate skid resistance over a pavement's entire design life. A related consideration was that an evaluation of the effectiveness of current design practices, including skid-resistance-decay rates, had been recommended by the Federal Highway Administration (FHWA) (4), though this policy is under review (5).

A secondary purpose was to evaluate newly constructed pavements and bridge decks for compliance with specified texture depth. New York requires a groove depth of 3/16 ± 1/16 in (6), but past experience has shown that texture depths vary significantly from job to job, and even within the same job (7). It was believed that data collected on new construction would show whether depths actually obtained are sufficient to permit adequate skid resistance over the entire design life, given the decay rate measured.

The study was based on measures of skid resistance and texture parameters collected in 1978 and 1979 on 11 in-service pavements, 9 unopened pavements, and 25 unopened bridge decks. These sites represented all of those that, by the summer of 1978, had been finished with a tined texture under new specifications implemented in 1974. In all cases, pavements were built with a New York State class C concrete mix (nominal water-cement ratio = 0.44, cement factor = 6.4), and bridge decks were built with a class E mix (nominal water-cement ratio = 0.44, cement factor = 7.0).

PROCEDURES AND RESULTS

Texture wear rates were estimated from texture depth measurements and ribbed-tire skid resistance tests on 11 pavements in service (series 1). To extend the range of corresponding traffic volumes, measurements were made in both the driving and passing lanes and for two years (1978 and 1979). Five sites were tested in each lane of each pavement, for a total of 110 sites.

The minimum mean groove depth (MGD) required to provide adequate drainage beneath a minimum legal tire tread (2/32 in deep in New York) was estimated from texture and skid resistance measurements with both ribbed and smooth tires at 30 additional sites, selected from these same 11 pavements (series 2). These additional sites were chosen to represent as wide a range in groove depth among sites as possible and also because each was relatively uniform within the distance required for a valid skid test--about 60 ft.

To judge compliance with the current specification as well as with initial texture depth needs determined from this study, depths were also measured on 9 unopened pavements and 25 unopened bridge decks (series 3). The entire testing program is outlined in the table below.

Variable	Series 1	Series 2	Series 3
Objective	Wear rates	Groove depth	Compliance
Test pavements	11	4	9, including 25 bridge decks

Table 1. Performance data for tine-textured pavements, series 1.

		1978						1979				
Sites	Lane	CVP[a] (000 000s)	SN_{40}	SN_{55}	MTD (in)	MGD (in)	BPN	CVP[a] (000 000s)	SN_{40}	SN_{55}	MTD (in)	MGD (in)
1-10	Driving	2.911	38.6	32.5	0.025	0.092	53.5	3.472	41.2	36.1	0.022	0.079
	Passing	NA	59.2	52.8	0.033	0.113	68.9	NA	56.4	49.0	0.035	0.099
11-20	Driving	2.494	39.3	30.4	0.023	0.088	66.7	3.003	39.9	33.4	0.022	0.078
	Passing	0.212	50.8	52.8	0.032	0.111	78.5	0.255	56.5	50.2	0.030	0.103
21-30	Driving	NA	41.6	36.8	0.035	0.153	72.9	NA	40.9	35.7	0.035	0.141
	Passing	0.098	61.1	54.3	0.032	0.127	74.4	0.198	59.2	52.5	0.033	0.125
31-40	Driving	0.720	39.9	36.2	0.035	0.136	70.7	1.362	34.4	30.2	0.035	0.126
	Passing	0.079	59.0	52.4	0.045	0.147	79.9	0.149	53.1	46.7	0.043	0.138
41-50	Driving	0.785	46.5	40.8	0.048	0.163	71.7	1.480	38.9	34.6	0.046	0.144
	Passing	0.070	62.0	55.2	0.067	0.191	82.7	0.131	55.1	50.3	0.059	0.174
51-60	Driving	1.920	39.5	33.3	0.030	0.128	61.5	2.758	36.2	31.8	0.028	0.121
	Passing	0.143	58.9	52.9	0.039	0.128	76.4	0.206	54.4	47.6	0.031	0.121
61-70	Driving	1.920	40.6	34.7	0.018	0.091	56.3	2.758	35.5	30.6	0.017	0.093
	Passing	0.143	58.3	53.7	0.019	0.074	70.6	0.206	54.7	47.2	0.018	0.090
71-80	Driving	1.880	43.1	35.9	0.027	0.115	60.5	2.700	35.7	30.6	0.027	0.113
	Passing	0.183	60.0	55.5	0.026	0.117	73.7	0.263	54.3	48.1	0.033	0.125
81-90	Driving	1.559	35.7	30.0	0.032	0.131	54.7	2.149	34.5	30.9	0.036	0.129
	Passing	0.123	56.5	50.1	0.036	0.124	69.1	0.169	54.9	49.2	0.035	0.126
91-96	Driving	2.946	35.4	31.1	0.014	0.051	57.4	3.982	39.3	32.0	0.011	0.036
	Passing	1.036	44.0	39.4	0.018	0.063	70.1	1.400	45.5	39.7	0.028	0.063
97-100	Driving	5.451	34.8	30.6	0.016	0.072	48.0	7.366	38.9	31.9	0.015	0.062
	Passing	1.387	44.4	40.8	0.033	0.110	65.2	1.875	47.4	41.8	0.035	0.100
101-110	Driving	2.919	37.3	34.3	0.017	0.066	59.1	3.945	41.7	35.4	0.018	0.057
	Passing	0.468	47.7	44.6	0.025	0.082	72.4	0.633	48.2	43.0	0.028	0.078

Note: Each value is the mean of five individual test results, each from a different test site.
[a]CVP = cumulative vehicle passes.

Variable	Series 1	Series 2	Series 3
Measurement sites	110	30	115
Texture measurements			
Sand patch	1978-1979		
Gage depth	1978-1979	1979	1978-1979
Skid measurements			
Ribbed tire	1978-1979	1979	
Smooth tire		1979	

All skid tests were made at 40 and 55 mph, according to ASTM E 274-77, at fixed distances from the pavement edge in the left wheelpath of both driving and passing lanes. The tests employed a ribbed tire that meets the requirements of ASTM E 501-76, and a smooth tire that meets those of ASTM E 524-76. Results of the series 1 and 2 skid tests are given in Tables 1 and 2.

Pavement macrotexture was measured by using both the sand-patch method (7,8) and a dial depth gage. The latter had been used previously in New York to measure flailed grooves (9) and is similar to gages used in Louisiana (10). In series 1, 10 individual sand-patch tests were made in both 1978 and 1979 at randomly selected locations at each 60-ft measurement site (7), and mean texture depths (MTDs) were calculated. Also, during both years, dial-gage measurements were made at close intervals along the entire length of each 60-ft site, and MGDs were calculated. Because these two measures were found to correlate well, only the dial gage was used for series 2 and 3 tests. Mean values for series 1 and 2 texture measurements are given in Tables 1 and 2, and series 3 values are plotted as histograms in Figure 1.

Traffic volumes, without regard to vehicle classification, were estimated at the time of skid testing, from available annual average daily traffic (AADT) (11) plus individual traffic counts to determine distributions between driving and passing lanes. They are expressed in Table 1 in millions of vehicle passes.

Table 2. Skid resistance with ribbed and smooth tires, series 2.

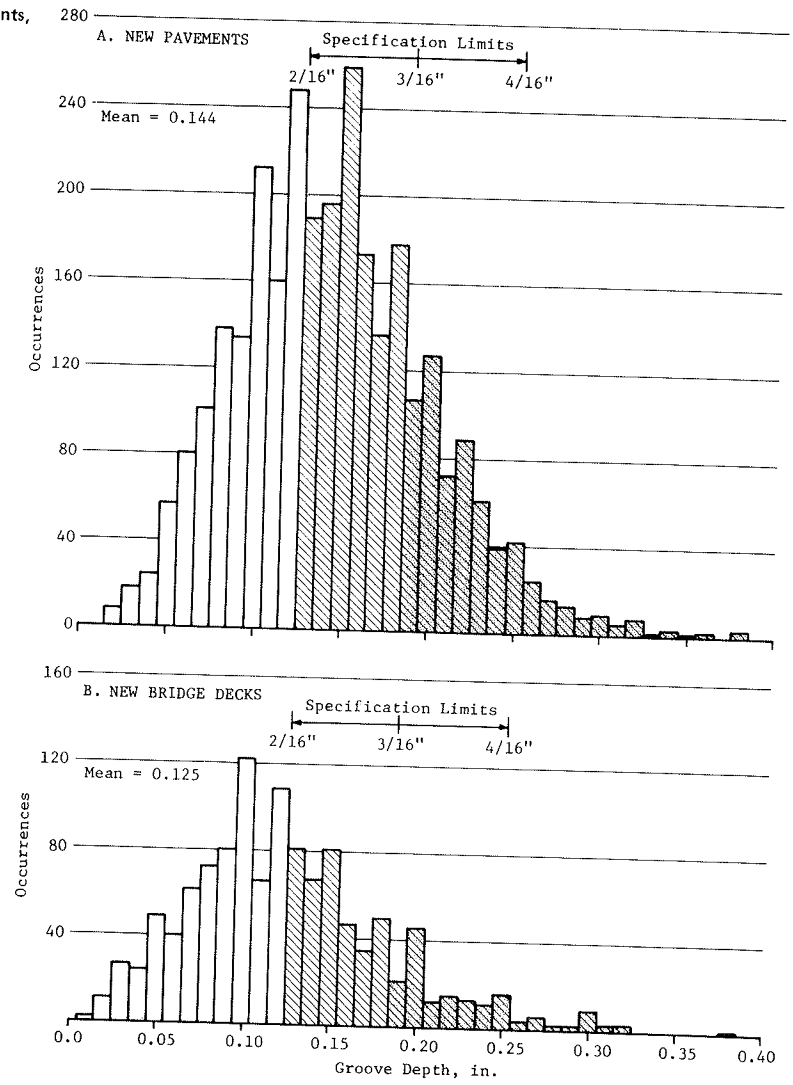
			SN_{40}		SN_{55}	
Route	Site	MGD (in)	Ribbed	Smooth	Ribbed	Smooth
I-88 Oneonta to Otego	111	0.0788	45.4	37.9	38.9	31.6
	112	0.0815	42.7	36.3	37.0	28.7
	113	0.0385	43.3	27.3	36.8	21.5
	114	0.1056	49.4	44.5	42.3	36.7
I-88 Franklin to Unadilla	115	0.0608	37.9	30.0	31.7	25.8
	116	0.0856	37.9	31.4	31.7	28.5
	117	0.0489	34.8	26.7	30.1	23.0
	118	0.1174	41.7	38.6	35.7	34.0
	119	0.1223	43.2	40.3	37.0	34.1
	120	0.1225	41.2	38.3	34.9	32.6
	121	0.1261	40.9	37.1	34.8	33.9
	122	0.1342	38.5	35.5	33.0	32.5
	123	0.0191	41.6	19.8	33.2	19.2
	124	0.0181	35.7	14.7	30.2	12.6
	125	0.0847	31.9	30.2	29.6	27.2
	126	0.1184	32.6	32.4	30.5	30.0
I-88 Sidney to Bainbridge	127	0.1486	37.0	35.6	32.6	31.5
	128	0.1376	39.1	36.6	33.5	31.7
	129	0.0766	37.4	35.4	31.4	27.6
	130	0.1357	40.2	38.7	34.1	29.9
	131	0.1151	38.1	34.5	32.5	28.1
	132	0.0886	40.8	37.6	34.7	28.5
	133	0.0924	37.6	35.9	33.5	29.2
	134	0.0239	37.6	22.5	29.4	16.1
	135	0.0123	36.0	17.8	28.5	11.9
	136	0.0229	41.2	21.3	32.2	16.0
	137	0.0509	44.1	30.5	37.7	27.6
I-88 Oneonta bypass[a]	138	0.0190	45.4	23.9	39.9	16.5
	139	0.0115	54.9	29.3	41.7	21.4
	140	0.0150	53.4	27.0	43.1	18.3

[a]Broom-textured section used to simulate totally worn tine texture.

Decay of Skid Resistance (Series 1)

Values of mean skid resistance at both 40 mph (SN_{40}) and 55 mph (SN_{55}) are plotted in Figure 2 against values of cumulative vehicle passes (CVPs). Separate plots and their regression lines are given on both linear (Figures 2a and b) and logarithmic (Figures 2c and d) rectangular coordinate grids. Previous skid-resistance-decay studies in New York,

Figure 1. Distribution of groove-depth compliance measurements, series 3.



primarily those that involve asphalt pavements (2,12-14), used semi-log regressions of skid-number (SN) versus CVP. However, these data were found to be better represented by log-log regressions. The least-squares lines and their regression equations are based on all of the skid data; however, for simplicity, the figures show only the mean values given in Table 1. (Also, the variance within these groups of five was small and corresponded to a standard deviation of 2.64.)

In Figures 2c and d, the rate of skid resistance decay appears to stabilize at about 2 million vehicle passes. This pattern is interpreted to mean that the tined grooves, though wearing, are providing adequate drainage, that the observed decay in skid resistance primarily reflects the polishing of microtexture (i.e., that small-scale roughness on the horizontal surfaces between grooves), and that a level of polishing equilibrium has been reached. Skid resistance from this point on can be expected to remain stable until the grooves become too shallow to provide adequate drainage, at which point skid resistance will again begin to decay as hydroplaning effects appear.

From a design point of view, it is important to consider what measures can be taken to increase the skid-resistance level at which equilibrium occurs and to ensure that grooves are deep enough in the first instance to give adequate drainage for the design life. The former concern is usually addressed by such practices as selecting hard, angular fine aggregate (15) or by the application of sprinkle treatments (16). Use of burlap-drag or broom texturing between tined grooves, now recommended by FHWA (17), may enhance initial skid resistance but is not likely to affect the level at which equilibrium occurs. The latter concern (adequate groove depth) will be considered later.

A useful concept in judging the adequacy of design and construction practices, from the standpoint of skid resistance durability, has been the 90th percentile critical traffic volume (90 percent CTV), defined as the cumulative traffic volume beyond which less than 90 percent of measured SNs are expected to equal or exceed 32 (2,12). The value of 32 corresponds to the American Association of State Highway and Transportation Officials (AASHTO) minimum stopping sight distance at 40 mph (18) and is used in New York as a design guide for minimum acceptable SN. The 90 percent CTV for tine-textured pavements in New York, calculated from the standard error of estimate for the regression in Figure 2a, was found to be 7.83 million vehicle passes at 40 mph. Any increase that may occur in the equilibrium skid resistance while groove depth is still adequate would be reflected in an increase in this value.

Decay of Texture Depth (Series 1)

To assess from experience what minimum nominal groove depth may be required during construction to ensure an acceptable level of skid resistance at the end of design life, three pieces of information are needed:

1. Minimum groove depth capable of sustaining adequate skid resistance,
2. Groove wear rate, and
3. Design life.

Average groove wear rate is estimated in this section.

Figure 3 shows the decay of texture with traffic as measured by the sand-patch method and dial-depth gage. Results by the two methods were found to be highly correlated (r = 0.92), as shown in Figure 4. Because dial-gage measurements related more directly to provisions of New York's specifications, they were used alone in estimating texture wear rate, and

Figure 2. Decay of skid resistance with traffic, series 1.

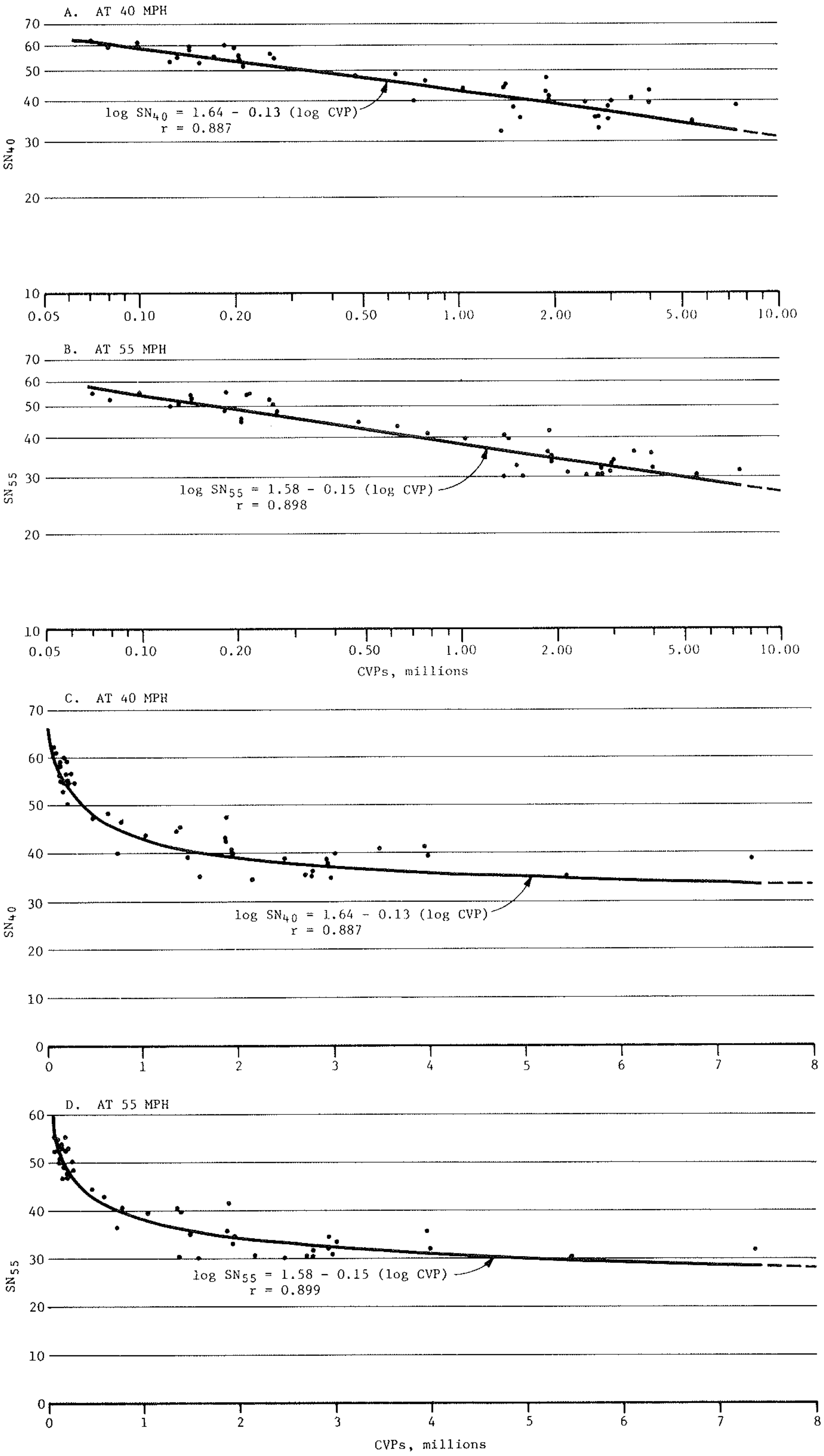


Figure 3. Decay of surface texture with traffic, series 1.

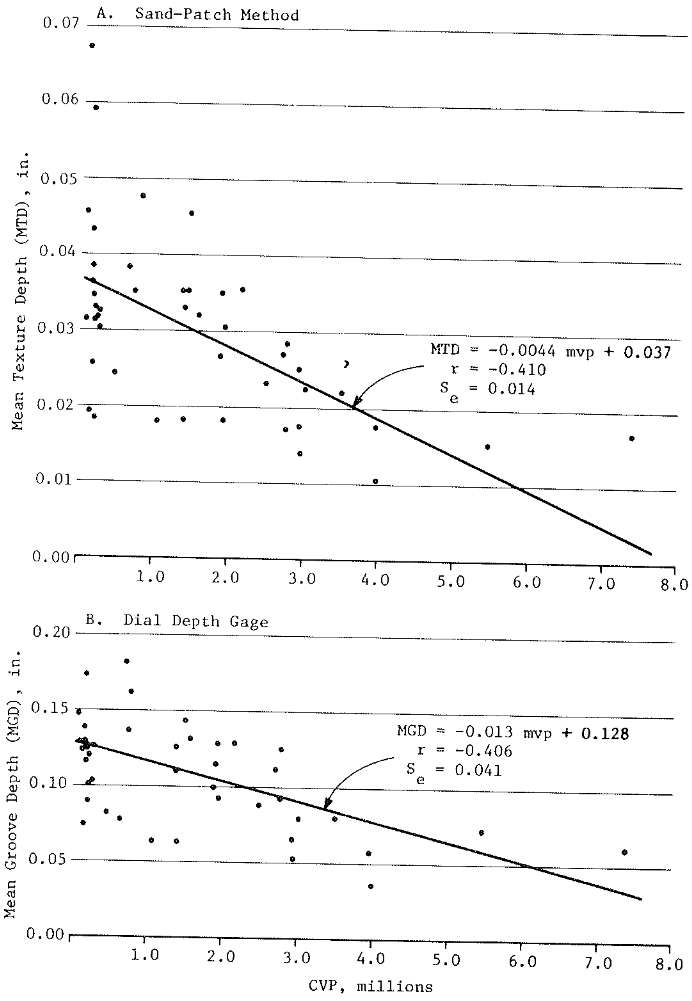
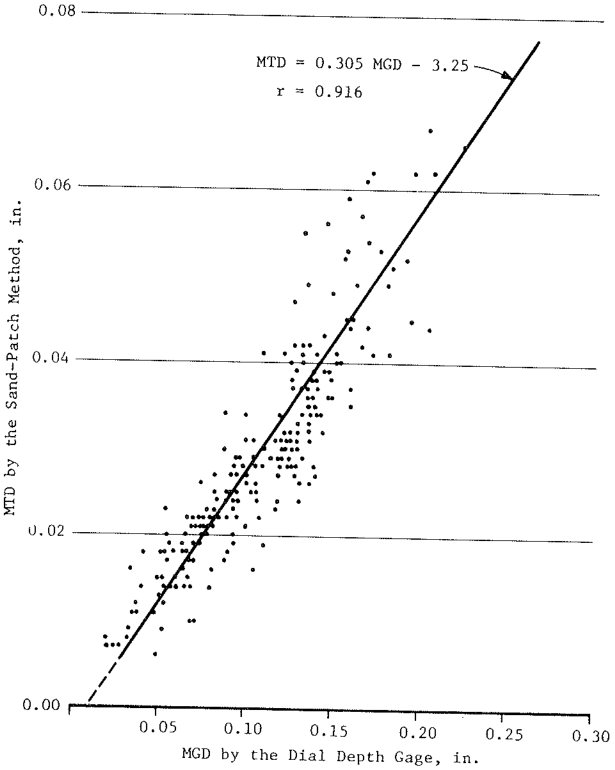


Figure 4. Correlation of sand-patch and dial-gage measurements, series 1.



for the series 2 and series 3 tests as well. The wear rate estimated from the slope of the regression in Figure 3b is equivalent to an average loss of 0.013 in in MGD for each 1 million vehicle passes.

Tine texturing was originally chosen by New York because of its presumed longer life. The greatest threat in recent years to the durability of any textured surface on portland cement concrete pavement has been the use of tungsten-carbide-studded snowtires. Thus, one consideration in extrapolating texture-wear studies is the anticipated change in studded-tire use from the time or location of the study. Their use has declined in New York from a statewide average of 28 percent of vehicles in 1969-1970 to 19 percent in 1974-1975, and to less than 10 percent in 1978-1979 (2,19). Considering dates of pavement opening and the relative density of studded tire use in particular parts of the state (19), studded-tire use on the 11 tested pavements was estimated to be in the 6-14 percent range during the study period.

Minimum Required Groove Depth (Series 2)

In an attempt to determine the minimum groove depth required for tined textures to sustain adequate skid resistance, skid resistance was measured with both ribbed and smooth tires. Although a ribbed tire can drain much of the water beneath it through its grooves even on nearly smooth surfaces, a smooth tire relies on the pavement's macrotexture for nearly all drainage and thus is more sensitive to differences in macrotexture (20).

Thirty sections of pavement were tested that had relatively uniform within-section groove depth, but varied in MGD among sections from very deep to nearly smooth. Data from these tests are given in Table 2 and plotted in Figures 5 and 6. The curves that represent the ribbed tire show a slight decline in SN with increasing groove depth. This is probably due to a slight increase in tire-pavement contact as the new surface begins to wear, in a situation where the water drainage qualities of the surface are more than adequate. Curves that represent the smooth tire, on the other hand, show SN increasing markedly with increasing groove depth, as pavement contact increases with improved drainage. The MGD at which curves for ribbed and smooth tires converge is taken to represent the minimum value that will permit full drainage beneath a smooth tire--that is, about 0.015 in at 40 mph.

Also of interest in these figures are the curves that represent the difference in SNs between the two tires for the same groove depth. Much of the scatter in the individual sets of data is thereby removed. Common variables are eliminated by subtraction, and good correlations for both 40- and 55-mph tests remain. Note that, although skid resistance with either the ribbed or smooth tire is significantly lower at 55 than at 40 mph at all texture depths, the difference in skid resistance between the two tires is virtually the same at both speeds.

These graphs were used to estimate the minimum MGD that would provide sufficient drainage beneath a minimally legal treaded tire (2/32 in in New York State) to maintain adequate skid resistance, defined for design purposes in New York as SN=32. The approach taken was to construct an SN-MGD curve on Figure 5 to represent test tire grooves of 2/32 in and to identify the MGD at which the ordinate of that curve equalled an SN of 32. The 2/32-in curve was constructed by linear interpolation between the existing curves for ribbed and smooth tires (broken line in Figure 5). Since the ribbed tire was new (0.385 in or about 13/32 in) and all of the 30 experimental sites were tested within about two days, an average tread depth of 12/32 in during this period was assumed. By using this approach, a minimum acceptable groove depth of 0.050 in for a 2/32-in tire was determined. As an aside, the difference in skid resistance between that estimated for a 2/32-in treaded tire and that found by testing with a smooth tire was in the range of 1.5 to 2 SNs at relatively low levels of texture (MGD = 0.040 to 0.070 in). This value compares favorably with research in Virginia (21), in which it was estimated that a loss of 2/32 in in tire tread depth corresponded to a loss of about 1.25 SNs.

By using an estimate for minimum acceptable groove depth of 0.050 in and by applying the mean groove-wear rate established earlier (0.013 in/million vehicle passes), initial groove depths required at construction to ensure a terminal groove depth ≥ 0.050 at the end of design life were calculated for pavements that have different AADTs. These calculations were based on a distribution of single-lane, one-way AADTs for concrete pavements in service in 1977 and are given in Table 3.

Table 3 shows that, had those concrete pavements in service in 1977 been built in compliance with the current New York groove-depth requirement of 3/16 ± 1/16 in (minimum 0.125 in), a minimum of only 43 percent of them would have had textures adequate to provide acceptable skid resistance for their design life. Similarly, if the mean groove depth then specified (3/16 in or 0.1875 in) had been attained, a minimum of 71 percent would have had a sufficient groove depth. An extension of this logic results in Table 4, which shows the diminishing return of each incremental increase in MGD. For instance, an increase from 2/16 to 3/16 in is associated with a 66.0 percent increase in benefit, from 3/16 to 4/16 in with 19.0 percent, and from 4/16 to 5/16 in with 10.8 percent. Although the data probably argue for increasing the minimum in New York from 2/16 in, it is difficult to argue for more than 4/16 in on the basis of Table 4. Even 4/16 in may be impractical because of the difficulty of its attainment in practice and undesirable because of the level of noise that it may generate.

Specifications Compliance (Series 3)

As noted, New York specifications require a minimum texture groove depth of 2/16 in (0.125 in) on both new pavements and bridge decks. The preceding analysis suggests that a minimum depth of 3/16 in (0.1875 in) or greater would be more consistent with expectations for acceptable design-life skid resistance. To determine what levels of texture depth are actually being obtained, 9 new pavements and 25 new bridge decks were evaluated by dial depth gage. These results are given for individual paving contracts and bridge decks in Table 5 and represented graphically without regard to source in Figure 1.

The mean of all groove-depth measurements was found to be 0.144 in for pavements and 0.125 in for bridges. Forty percent of all measurements on pavements and 56 percent on bridge decks were less than 2/16 in, the specified minimum value. If 3/16 in were to become the required minimum, then 79 percent of pavement measurements and 86 percent of bridge deck measurements would be deficient. Obviously, greater groove-depth requirements would result in an even higher proportion of deficiencies. It is clear then that, though deeper groove standards are needed, it would be impractical to impose them without also acting to improve construction compliance. Experience in this study suggests that the best hopes in this regard are (a) increasing awareness of construction personnel as to the importance of the

Figure 5. Relation between skid number and mean groove depth at 40 mph, series 2.

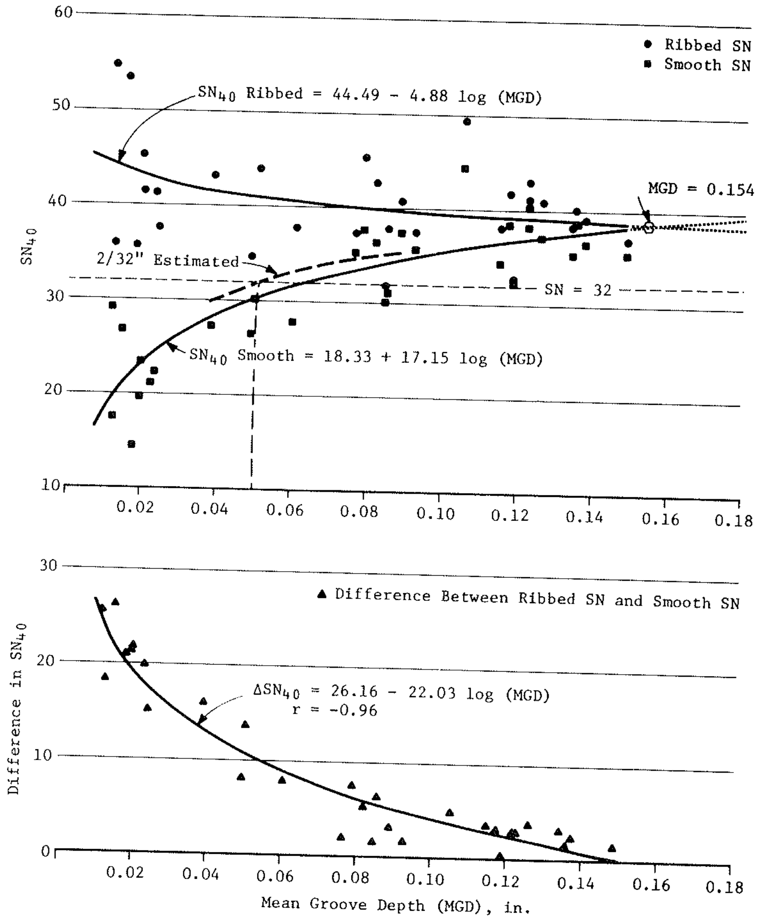


Figure 6. Relation between skid number and mean groove depth at 55 mph, series 2.

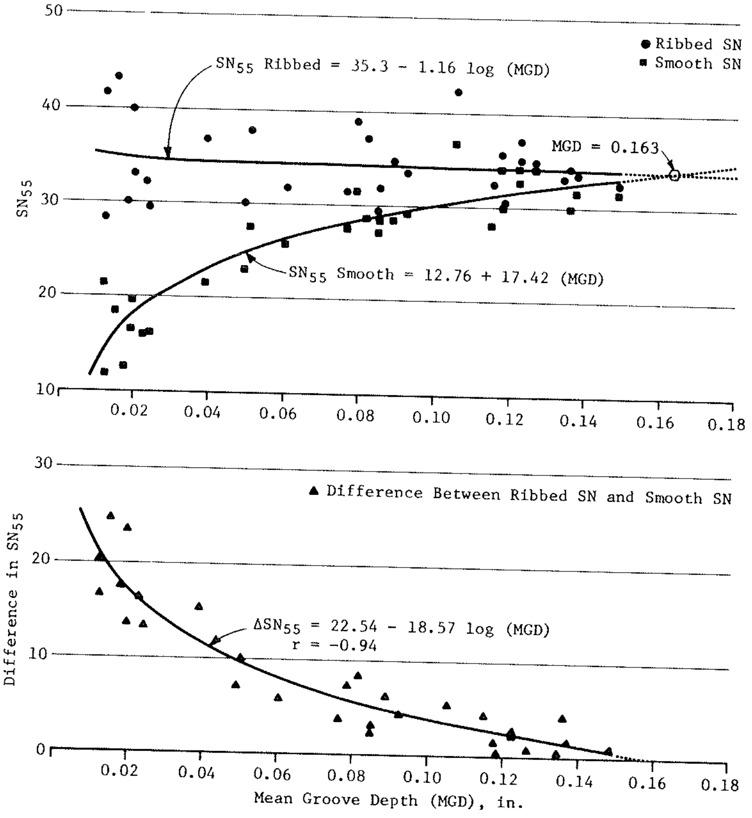


Table 3. Analysis of groove depth needs for New York pavements.

Traffic		Groove Depth		Distribution of Lane Miles	
One-Lane, One-Way AADT	Cumulative Passes After 15 Years (000 000s)[a]	Cumulative Loss After 15 Years (in)[b]	Initial Required (in)[c]	Percent[d]	Cumulative Percent
0-500	1.369	0.018	0.068	12.2	12.2
500-1000	4.106	0.053	0.103	20.4	32.6
1053[e]	5.769[e]	0.075[e]	0.125[e,f]	–[e]	43.0[e]
1000-1500	6.844	0.089	0.139	17.1	49.7
1500-2000	9.581	0.124	0.174	17.8	67.5
1932[e]	10.577[e]	0.1375[e]	0.1875[e,g]	–[e]	71.4[e]
2000-2500	12.319	0.160	0.210	10.8	78.3
2500-3000	15.056	0.196	0.246	6.3	84.6
3000-3500	17.794	0.231	0.281	3.4	88.0
3500-4000	20.531	0.267	0.317	3.7	91.7
4000-4500	23.269	0.302	0.352	1.8	93.5
4500-5000	26.006	0.338	0.388	2.5	96.0
5000-5500	28.744	0.374	0.424	0.8	96.8
5500-6000	31.481	0.409	0.459	0.4	97.2
6000-6500	34.219	0.445	0.495	0.1	97.3
6500-7000	36.956	0.480	0.530	0.2	97.5
7000-7500	39.694	0.515	0.565	0.2	97.7
7500-8000	42.431	0.552	0.602	0.0	97.7
8000-8500	45.169	0.587	0.637	0.3	98.0
8500-9000	47.906	0.623	0.673	0.2	98.2
9000-9500	50.644	0.658	0.708	0.3	98.5
>9500	53.381	0.694	0.744	1.5	100.0

[a] Based on assumed 15-year design life and calculated from AADT class mean.
[b] Calculated from mean annual rate of 0.013 in/million vehicle passes.
[c] Calculated from minimum acceptable of 0.050 in.
[d] From New York State data.
[e] Value that corresponds to initial minimum and mean specified groove depth.
[f] Minimum specified in New York State.
[g] Mean specified in New York State.

Table 4. Satisfaction of pavement groove depth needs.

Minimum Groove Depth (in)		Pavement Percentage of Lane Miles	Percentage Increase Between Increments
Fraction	Decimal		
2/16	0.125	43.0	
3/16	0.1875	71.4	66.0
4/16	0.250	85.0	19.0
5/16	0.3125	94.2	10.8
6/16	0.375	96.8	2.76
7/16	0.4375	97.3	0.05
8/16	0.500	97.6	0.03
9/16	0.5625	97.8	0.02
10/16	0.625	98.2	0.04
11/16	0.6875	98.9	0.07
12/16	0.750	100.0	1.01

Note: Based on an assumed design life of 15 years, 1977 traffic volume distribution, and groove wear rate of 0.013 in/million vehicle passes.

Table 5. Groove depth measurements on new pavements and bridge decks, series 3.

Surface	Pavement Contract	Deck	Groove Depth		Compliance (percentage >2/16 in)
			n	$\bar{x}$ (in)	
Pavement	C		254	0.182	81
	E		232	0.168	75
	A		436	0.165	72
	I		450	0.157	71
	B		250	0.138	57
	H		442	0.137	57
	F		246	0.129	50
	D		343	0.126	36
	G		288	0.113	36
Bridge deck	E	7	19	0.230	95
	I	19	96	0.195	91
	B	16	50	0.162	76
	D	6	117	0.141	60
	F	10	126	0.141	60
	F	13	39	0.137	51
	A	18	43	0.123	49
	A	17	59	0.123	42
	B	3	20	0.128	40
	A	2	25	0.113	36
	F	15	48	0.121	35
	F	8	24	0.108	33
	A	1	39	0.116	31
	F	11	114	0.102	30
	D	5	54	0.106	26
	F	14	46	0.117	24
	F	12	41	0.094	24
	D	4	60	0.100	22
	F	9	42	0.089	21
	I	20	128	0.089	20

texture depth requirement and then motivating and supporting them to strive for it and (b) improving the actual texturing equipment.

The most critical aspect of attaining deeper grooves may be to place the same priority on meeting groove-depth specifications as is placed on meeting other requirements, regardless of the type of rake used. Experience shows that the depth currently specified in New York (2/16-in minimum) is attainable if appropriate attention is given by construction personnel to timing, technique, and equipment used in the texturing process.

Improvements in Texturing Equipment

Most tine rakes now in use (at least in New York) have been shop-fabricated from available materials and designed so that the tines contact the concrete surface at a relatively steep angle (i.e., ±45°). Such devices tend to scratch the surface, which often results in nonuniform depth and frequent aggregate displacement. A typical example is a comb made from the tines of a common leaf rake mounted between blocks of wood. Compliance with texture depth requirements by using these devices has generally been unsatisfactory. The example cited is not unique.

One commercial rake, the Flexi-Glide tine manufactured by the A.R.M. Corporation of Anderson, Indiana, has recently come on the market and appears to offer some improvement. This rake (Figure 7) employs an uncommonly low angle of attack that seems to impress the texture into the concrete rather than scratching it in. Based on limited trial use in New York, results are encouraging. Versions mountable on pavement finishing machines are also available.

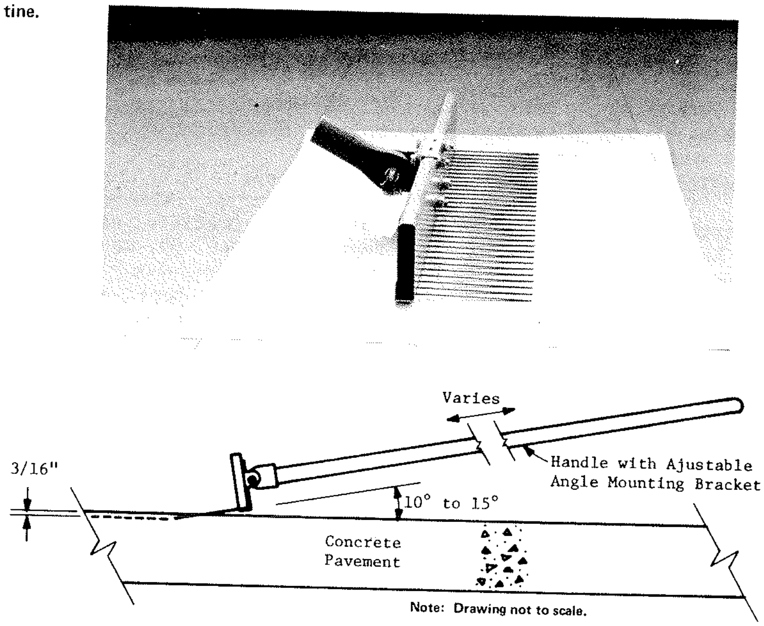
Another approach has incorporated two sets of tines of different lengths (and therefore different stiffnesses) mounted on opposite sides of the same unit. This allows the rake to be reversed when stiffer concrete is encountered, which brings the shorter and more rigid tines into use.

Consideration has also been given to using narrower tines. However, reducing tine width without also reducing tine spacing would theoretically provide less drainage area. Use of 1/8-in tines on 1/2-in centers, rather than 3/4-in centers, has been considered (in New York) and would provide both the same drainage and land area (riding surface) as before but with a narrower tine that might penetrate more easily.

CONCLUSIONS

The following conclusions have been drawn from the results of this study of the performance of tine-textured pavements in New York State. They are influenced by the concrete materials, finishing practices, pavement design assumptions, and traffic conditions found on the specific pavements studied, but they are probably applicable in much of New York. We believe, however, that the methodology employed in the analysis is generally applicable

Figure 7. Flexi-Glide tine.



Note: Drawing not to scale.

beyond New York, and in that sense the paper may be looked on as a case study.

1. Skid resistance of concrete pavements textured to produce 3/16-in wide grooves on 3/4-in centers begins to decay from an initial value when opened to traffic but appears to stabilize after passage of about 2 million vehicles. This stability is believed to correspond to equilibrium polishing of the microtexture at a time when the grooves are still sufficiently deep to provide complete drainage. Thus, attempts to improve skid resistance should be directed toward practices that will enhance the equilibrium microtexture or ensure that grooves are sufficiently deep to provide complete drainage for the pavement's entire design life, thereby fully mobilizing the equilibrium microtexture.
2. Decay of skid resistance on tine-textured pavements appears to be best represented on $\log_{10}$-$\log_{10}$ plots.
3. The 90th percentile critical traffic volume for tine-textured pavements in New York, defined as the CTV beyond which less than 90 percent of measured SNs at 40 mph are expected to equal or exceed 32, is estimated to be 7.83 million vehicle passes.
4. Pavement grooves 3/16 in wide on 3/4-in centers were found to wear at a mean rate of 0.013 in/million vehicle passes, as measured by dial-depth gage.
5. Measurements of MGD with a dial-depth gage correlated significantly with measurements of mean texture depth by the sand-patch method ($r = 0.92$).
6. A MGD of 0.050 in was found necessary to ensure an acceptable level of pavement skid resistance of at least SN = 32 for legally treaded tires. It is estimated that a minimum depth of 3/16 in would ensure that at least 71 percent of the concrete pavement placed in New York retains grooves for 15 years that are at least 0.050 in deep (based on 1977 data). The corresponding value for 4/16 in is 85 percent.
7. Present tine-texturing practice with conventional concrete in New York is resulting in 60 percent compliance on pavements and 44 percent on bridge decks with the current 2/16-in minimum groove depth standard. If the current standard had been 3/16-in minimum, compliance would be 21 and 14 percent, respectively.
8. Experience indicates that MGDs of 2/16 and 3/16 in are attainable with proper attention to equipment, technique, and particularly timing of the texturing process. Redesign of the texturing rake to result in tines of greater stiffness that intersect the pavement surface at a lower angle appears to offer possibilities for better penetration without otherwise tearing the surface.

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Short-Term, Weather-Related Skid Resistance Variations

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A three-year research program was initiated in 1978 at the Pennsylvania Transportation Institute by the U.S. Department of Transportation to investigate possible causes for seasonal and short-term skid resistance variations. The primary objective is to determine the parameters that can be used to predict the influence of seasonal and short-term effects. Results concerning short-term, weather-related skid resistance variations are presented and discussed. Twenty-one test surfaces in State College, Pennsylvania, were selected for testing. The testing program includes daily skid measurements according to ASTM test method E274 and the collection of daily weather data. After the data are adjusted for long-term variations, the short-term residuals are regressed against rainfall and temperature parameters. The number of days since the last significant rainfall and the test pavement temperature are both found to be significant causes of short-term skid resistance variations. Further unexplained variations are attributable to measurement errors, particularly the lateral placement of the skid test trailer. The Pennsylvania results are supported by data collected in a similar study of 10 sites located in North Carolina and Tennessee (Federal Highway Administration Region 15).

Skid resistance measurements made according to ASTM test method E274 (1) exhibit both long-term seasonal and short-term variations on public highways in Pennsylvania and other states (2,3). These variations make the establishment of a maintenance program in which skid resistance is one of the important factors a difficult task. Variations from day to day, seemingly due to rainfall pattern and local weather conditions, are superimposed on an annual cycle. At least in the northern states, this annual cycle tends to be higher in winter through spring than summer through fall. Frequent tests during the summer period indicate that pavement skid resistance may vary by as much as 25 percent during a single week. In analyzing these large changes, which occur rather systematically, Hegmon (4) concluded that they are real skid resistance changes related to changing conditions.

During the past two decades, several state highway departments and other agencies in the United States have conducted extensive skid resistance surveys, but until the past few years little attention was paid to seasonal and short-term variations. Until recently, the most comprehensive documented studies involving seasonal and short-term skid resistance variations were the ones undertaken by the Pennsylvania Department of Transportation (2,5). In the course of evaluating skid resistance measurements, some cyclic patterns were observed. Measurements showed that, once a pavement surface had stabilized after being exposed to traffic and weather for one to two years, the surface had cyclic skid resistance variations. The skid number gen-