Skid Resistance of Bituminous-Pavement Test Sections: Toronto By-Pass Project

J. Ryell, J. T. Corkill, and G. R. Musgrove, Ontario Ministry of Transportation and Communications, Downsview

As part of a program to determine the most suitable method of improving the driving qualities of Canada's Highway 401 Toronto By-Pass, 18 bituminous test sections were constructed in 1974 on the existing concrete pavement. The test sections include dense-graded and open-graded bituminous mixes that contain a variety of aggregate types including traprock, steel slag, and blast-furnace slag. A comprehensive test program in which the skid characteristics of various test sections were monitored by brake-force and side-force skid trailers and texture was analyzed by use of photo-interpretation techniques is described. Skid resistance was measured in weather conditions that varied from drizzle to slush from heavy snow by using a continuously recording side-force-friction trailer. Not all of the mixes have provided the required level of skid resistance, particularly in the driving lane and the center lane where large numbers of trucks travel. The most striking results of the project are (a) the excellent performance of bituminous mixes that contain crushed traprock or slag screenings as the fine aggregate and (b) the low skid resistance of many mixes in which the fine aggregate consists of natural sand blended with limestone screenings. All mixes were characterized by a general decline in skid resistance during the first four years as texture depths were reduced by compaction under traffic. The first phase of pavement improvement on the Toronto By-Pass, in which bituminous overlays were used with an open-graded surface-course mix, is described. Data on mix composition, skid resistance, and noise characteristics are also presented.

In its present form, the pavement of the Highway 401 Toronto By-Pass is the result of an extensive reconstruction program carried out between 1963 and 1973 when the original 4-lane pavement was widened to a 12-lane system of collector and express lanes. Exposed concrete pavement was chosen for this highway because it showed the best potential for providing a long service life under anticipated heavy traffic conditions. Traffic on the freeway has increased dramatically in recent years: Traffic on the central section between Dufferin Street and Keele Street increased from 111 000 vehicles/day in 1967 to 199 000 vehicles/day in 1976.

The original surface texture of the concrete pavement on the freeway provided satisfactory skid resistance in its early life. Unfortunately, the use of tungsten carbide studs on tires between 1966 and 1971 rapidly wore away the original surface texture, exposing the limestone aggregates in the concrete. Heavy traffic has since polished the surface and produced a pavement with a texture depth that is only about one-tenth of that desired.

In the summer of 1974, 18 bituminous-overlay test sections were constructed on a 2.4-km (1.5-mile) section of the westbound express lanes immediately west of the Allen Expressway. The project evaluated traditional dense-graded and open-graded mixes with varied stone contents. Coarse aggregates were selected on the basis of their anticipated high resistance to polishing; they consisted of traprock (a very hard, fine-grained basaltic quarried material), blast-furnace slag, and steel slag. Natural sand, limestone screenings, traprock screenings, and slag materials were used as the fine aggregates, and in some mixes blends of two materials were used. Other test mixes included sand asphalts that contained small fractions of coarse aggregate and a mastic type of bituminous mix. An asbestos filler was added to some mixes.

The objective of the project was to determine the most suitable bituminous surface-course mix for future short- and long-term programs to improve the driving quality, and especially the skid resistance, of the pavement. This paper describes the mix design and materials and the performance and properties of the test sections during the first four years of service. In the first phase of pavement improvement on the Toronto By-Pass in 1976, 1977, and 1978, an open-graded bituminous surface-course mix was used that contained traprock aggregates. The skid-resistance measurements and noise characteristics of this mix are reported.

BITUMINOUS TEST SECTIONS

Materials and mix proportions for the bituminous test sections were selected on the basis of the experience of the Ontario Ministry of Transportation and Communications with the skid resistance of freeway surface-course layers, a review of mixes used by other agencies, and an earlier, small pilot project to determine the practicality of using several special mixes. Seventeen mixes were evaluated in single-course thicknesses of 25 or 38 mm (1 or 1.5 in). Test section 1-19 was a repeat of section 1 but was placed over a 38-mm-thick bituminous base-course layer. Each test section was 137 m (448 ft) long and 16 m (52 ft) wide [11-m (36-ft) pavement plus 5-m (16-ft) shoulders]. A previous paper (1) has described the construction and skid-resistance performance of the test sections during the first year.

The composition and characteristics of the test mixes are given in Tables 1 and 2, and the aggregate gradations used in several sections are shown in Figures 1-3. The type of surface-course mix specified for main highways in Ontario—known as HL1—is a dense-graded mix in which crushed traprock, a very hard, fine-grained basaltic quarried material, is used as the coarse aggregate.

Test sections 1 to 6 consist of HL1 mixes in which the coarse-aggregate content is progressively increased to obtain a greater density of stone particles at the surface. The mix used in test section 1 is typical of many HL1 mixes used on main highways in Ontario. The type of fine aggregate used in these six sections was varied since the composition and percentage of such material are known to have a marked effect on the initial texture and stability of the mix. The mixes that contain traprock screenings as the fine aggregate used a lower content of asphalt cement than mixes that contain a natural sand. Short-fiber asbestos filler was added to mixes 5 and 6 to increase the flexibility of the bituminous overlay and to provide better resistance to reflective cracking from the concrete pavement base.

Test sections 7 to 10 are termed modified HL1 mixes since slag coarse aggregates were used in place of the normal traprock stone. Slag aggregates have been used with success in surface-course bituminous mixes in Europe and North America, and Fromm and Corkill (2) have reported on their performance on small test sections in Ontario. The materials used in these sections came from the steel industry in Hamilton, Ontario.

Steel-making slag is the term used to describe material that results from the production of steel from iron in open-hearth, basic-oxygen, and electric-arc furnaces. The crushed particles are hard and coarse textured and have a higher unit weight than do natural aggregates. Test section 7 used steel-slag screenings as the fine aggregate in conjunction with the slag coarse aggregate. In section 8, a blend of natural sand and limestone screenings was mixed with the slag coarse aggregate.

Blast-furnace slag describes material that results from the manufacture of iron from iron ore, limestone, and coke in blast furnaces. The product is air cooled before crushing and screening, and the surface of the particles has a rough, vesicular appearance. Test section 9 used blast-furnace slag screenings as the fine aggregate in conjunction with slag coarse aggregate, and in section 10 the fine aggregate consisted of a blend of natural sand and limestone screenings. Because of its higher absorption characteristic, blast-furnace slag requires more asphalt cement than other aggregates.

Bituminous mixes in test sections 11 and 12 can be described as sand-asphalt mixes that use traprock screenings as the fine aggregate. Both mixes contained small percentages of coarse aggregate in the form of 6-mm (0.25-in) traprock chips and asbestos-fiber filler.

Test sections 13 to 16 consist of open-graded mixes designed for high permeability to facilitate rapid drainage of surface water into, and laterally through, the surface-course layer. Open-graded mixes have been used in North America since the 1950s (3). These mixes use a combined aggregate grading with a large fraction of single-sized coarse aggregate and a relatively small amount of material passing the 2.36-mm (no. 8) sieve. The smaller-sized material plus the asphalt cement fills only a portion of the voids created by the single-sized coarse aggregate, and this results in a mix with a large volume of voids. The traprock aggregates used in the four mixes were processed to meet the special requirements of open-graded bituminous mixes (Figure 3). Traprock screenings were washed to reduce the fraction of material passing the fine sieves, and the material in the coarse aggregate retained on the 10-mm (0.375-in) sieve was screened off. Mixes 13 and 14, which contain 67 percent coarse aggregate and had 12.2 percent pavement voids after three months in service, meet the requirements for open-graded mixes established for the project.

Table 1. Composition of test mixes.

Test Section	Type of Mix	Coarse Aggregate Retained on 4.75-mm Sieve		Fine Aggregate Passing 4.75-mm Sieve		Filler Material		Percent Retained on 4.75-mm Sieve[a]	Asphalt (percent by weight of mix)
		Type	Percent	Type	Percent	Type	Percent		
1	HL1								
	L	TR	45	41	41			43.8	5.4
	F			LS	14				5.4
2	HL1								
	L	TR	45	NS	41			48.2	5.4
	F			TRS	14				5.3
3	HL1								
	L	TR	45	TRS	55			47.5	4.1
	F								4.0
4	HL1								
	L	TR	55	NS	34			54.1	4.8
	F			LS	11				4.8
5	HL1								
	L	TR	60	NS	28	ASB	2	58.1	5.6
	F			LS	10				5.7
6	HL1								
	L	TR	60	TRS	38	ASB	2	62.3	5.3
	F								5.4
7	Modified HL1								
	L	SL	45	SLS	55			46.8	5.3
	F								5.2
8	Modified HL1								
	L	SL	50	NS	38			47.1	5.7
	F			LS	12				5.7
9	Modified HL1								
	L	BF	45	BFS	55			43.2	8.0
	F								7.8
10	Modified HL1								
	L	BF	40	NS	45			40.5	6.8
	F			LS	15				6.5
11	Sand								
	L	TR	14	TRS	84	ASB	2	5.4	7.1
	F								7.0
12	Sand								
	L	TR	9	TRS	89	ASB	2	6.9	7.0
	F								7.2
13	Open-graded,								
	F	TR	67	TRS	33			60.5	5.9
14	Open-graded,								
	F	TR	67	TRS	31	ASB	2	71.7	5.8
15	Open-graded,								
	F	TR	30	TRS	70			29.3	5.6
16	Open-graded,								
	F	TR	30	TRS	68	ASB	2	31.4	6.6
17	Mastic, F	TR	70	TRS	19	MF	9	75.2	7.5
1-19[b]	HL1								
	L	TR	45	NS	41	ASB	2	47.4	5.4
	F			LS	14				5.4

Notes: 1 mm = 0.039 in.
L = laboratory mix designs, F = field-laboratory tests, TR = traprock, LS = limestone screenings, NS = natural sand (glacial deposit), TRS = traprock screenings, ASB = short-fiber asbestos, SL = steel slag, SLS = steel-slag screenings, BF = blast-furnace slag, BFS = blast-furnace-slag screenings, and MF = mineral filler (finely crushed limestone).

[a] Based on field-laboratory extraction tests.

[b] Same as section 1 but constructed over a 38-mm-thick bituminous base course.

Mixes 15 and 16, which contain 30 percent coarse aggregate, cannot be categorized as open-graded mixes since the pavement void contents—6.7 and 7.2 percent, respectively—are much lower than those generally specified for such mixes.

Test section 17 consists of a mastic type of mix based on the German Gussasphalt technology (4) and modified so that the material could be mixed and placed by conventional hot-mix plant and paving equipment. Machine-laid Gussasphalt has been widely used on the German Autobahn system since 1954. The demonstrated long life and durability of Gussasphalt is the most important reason for its widespread use in Germany. The mastic mix used in test section 17 was based on work carried out by the Michigan Department of State Highways and Transportation (5).

The asphalt cement used in the test sections was 85-100 penetration grade except for the mastic mix in section 17, which used a harder 60-70 grade.

TRAFFIC

A permanent counting station is situated immediately east of the project. Average daily traffic volumes for twenty-eight 24-h periods in 1975 are given below:

	Vehicles per Day	
Lane	Total	Commercial
Driving	12 900	3740
Center	17 300	1900
Passing	14 600	150

Volumes of commercial vehicles were manually recorde during a 24-h period in midsummer.

SKID-RESISTANCE STANDARDS

Skidding is a major factor in a large proportion of high-

Table 2. Characteristics of test mixes.

Test Section	Type of Mix	Marshall Stability (kN)	Marshall Flow (mm)	Voids in Mineral Aggregate (percent by volume)	Voids (percent by volume)
1	HL1				
	L	7.22	2.64	16.9	2.8
	F	11.62	2.97	17.5	3.7
2	HL1				
	L	7.22	2.64	17.2	3.0
	F	12.75	3.43	15.0	0.8
3	HL1				
	L	14.15	4.23	12.9	1.2
	F	15.14	3.92	13.5	2.0
4	HL1				
	L	7.69	2.61	16.0	2.7
	F	13.45	3.15	14.2	1.2
5	HL1				
	L	8	3.84	14.2	1.0
	F	8.46	5.77	16.0	0.9
6	HL1				
	L	9.73	5.82	15.2	1.0
	F	11.42	4.79	18.6	3.4
7	Modified HL1				
	L	15.64	4.10	18.5	2.7
	F	16.18	3.38	18.7	3.3
8	Modified HL1				
	L	9.6	3.31	17.3	2.3
	F	13.29	3.51	17.7	1.9
9	Modified HL1				
	L	12.58	3.28	24.0	6.9
	F	14.78	3.82	23.1	6.1
10	Modified HL1				
	L	8.78	2.66	17.9	2.9
	F	14.02	2.50	17.0	2.2
11	Sand				
	L	9.26	6.97	17.7	0
	F	9.66	10.30	19.5	0.2
12	Sand				
	L	11.78	4.92	16.8	0
	F	8.38	11.56	20.7	1.1
13	Open-graded,				
	F	6.48	3.25	20.6	4.7
14	Open-graded,				
	F	7.51	3.05	19.6	4.0
15	Open-graded,				
	F	11.9	4.92	16.3	0.7
16	Open-graded,				
	F	9.4	7.82	18.6	0.2
17	Mastic, F	8.38	14.54	21.0	1.0
1-19[a]	HL1				
	L	7.22	2.64	16.9	2.8
	F	12.55	3.72	14.6	0.4

Notes: 1 kN = 225 lbf; 1 mm = 0.039 in.
L = laboratory mix designs; F = field-laboratory tests.

[a]Same as section 1 but constructed over a 38-mm-thick bituminous base course.

Figure 1. Aggregate gradations for test section 1.

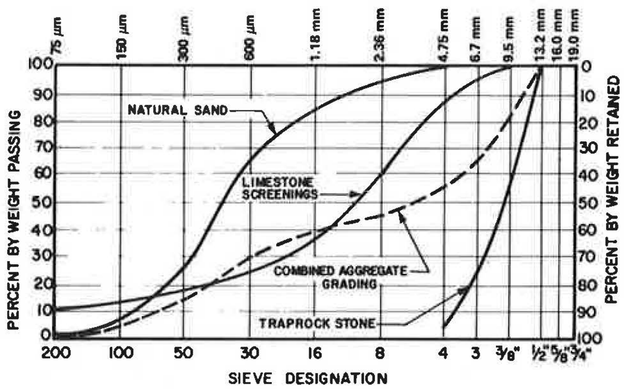


Figure 2. Aggregate gradations for test section 7.

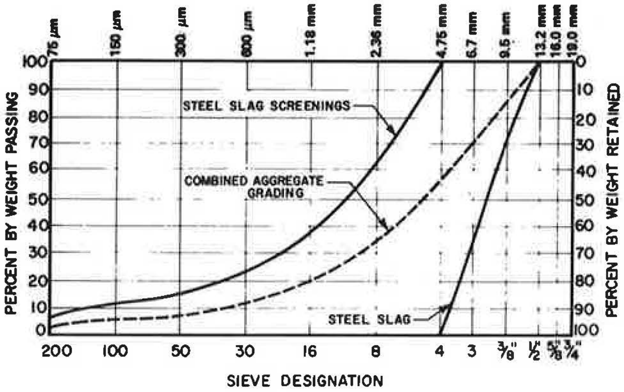
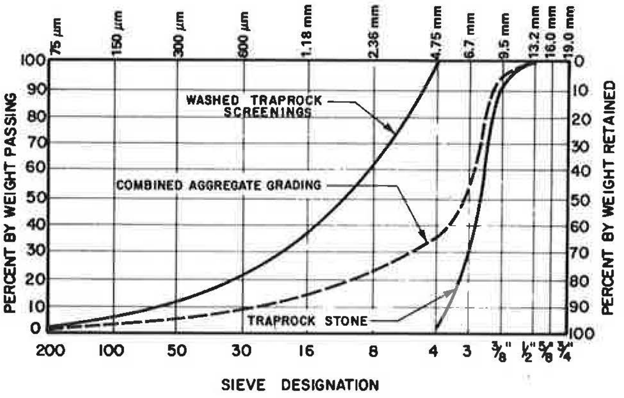


Figure 3. Aggregate gradations for test section 13.



way accidents, especially at high traffic speeds and volumes and in wet conditions. The goal for highway engineers must be to construct and maintain roadway surfaces at an optimal level of skid resistance so that skidding accidents are kept at the minimal practicable level.

National Cooperative Highway Research Program (NCHRP) Report 37 (6) discusses minimum skid-resistance values and recommends tentative requirements for main highways based on an analysis of skid values and accident data. Based on that report and in view of the absence of intersections, sharp bends, and steep gradients on Highway 401, a skid number of 31 measured by the ASTM brake-force trailer at 100 km/h (60 mph) is taken as the desired or target level for purposes of comparison between the pavement surfaces evaluated.

TEST METHODS

Pavement skid resistance and the physical parameters of the surface texture were measured by using four methods: the American Society of Testing and Materials (ASTM) brake-force trailer, the Mu-meter trailer, the British sideways-force-coefficient routine investigation machine (SCRIM) (10), and photo-interpretation.

Brake-Force Trailer

In North America, the most commonly accepted technique for measuring the skid resistance of pavements is based on the use of a skid trailer that conforms to ASTM Standard E274. The test unit consists of a towing vehicle and a brake-force trailer. The test measures the steady friction force generated when the standard tire of the locked left test wheel slides over wet pavement at a constant traveling speed. During the test, a specified quantity of water from the supply system in the tow truck is discharged through a nozzle in front of the test tire to produce a water-film thickness of 0.5 mm (0.02 in). The tread of the standard tire on the brake-force trailer has seven plain ribs. The measured friction force is described as the skid number (SN).

Each test section on the project was tested 10 times during the first four years of service. Initial measurements were completed immediately after construction and subsequently in the spring and fall of each year. Tests were carried out in the wheel paths of each lane at speeds of 50 and 100 km/h (30 and 60 mph). Results of the tests are summarized in Table 3 and Figure 4.

Mu-Meter

The Mu-meter is a continuously recording friction-measuring trailer that measures the side-force friction generated between the test surface and two pneumatic tires. The tires are mounted on free-running wheels set at a fixed toe-out angle of 7.5° to the line of drag. Vehicle test speed was 64 km/h (40 mph). In February and March 1975, when the test sections were approximately 18 months old, tests were performed to determine skid resistance on the driving lanes in a variety of weather conditions that ranged from drizzle to slush from heavy snow. Test results for four selected bituminous test sections and the adjacent smooth, polished concrete are shown in Figure 5. The skid values shown represent the average number of continuous passes over the pavement sections. Because of the variations in precipitation and pavement conditions that can sometimes occur in a short period of time, the weather and pavement conditions indicated may vary slightly between different pavement sections. The significance of the test data lies in the indicated change in pavement friction that occurs as pavement conditions become more adverse (as conditions change from drizzle to heavy rain to slush).

SCRIM

The SCRIM device (10) is a continuous testing instrument that measures the coefficient of sideway force of the pavement surface (similar to the Mu-meter). The test wheel is inclined at 20° to the line of travel and rolls free over pavement that has been wet by a watering truck. The smooth test tire is inflated to a pressure of 345 kPa (50 lbf/in^2). Since SCRIM has its own deadweight and suspension system, there is a known static reaction between tire and pavement. A signal from an electric load cell provides the sideway-force input into the recording system. The recorded data are then processed by computer, and a printout is produced that summarizes coefficients of side-force friction for each test section.

The SCRIM testing was carried out in August 1978 in conjunction with brake-force-trailer tests. Both vehicles traveled at 60 km/h (37 mph) and tested each section five times so that a comparison could be made between the friction values measured by the two devices.

SCRIM is the standard skid-measuring trailer used in Great Britain. The Transport and Road Research

Table 3. Skid numbers measured by ASTM brake-force trailer.

	Driving Lane				Center Lane				Passing Lane			
	50 km/h		100 km/h		50 km/h		100 km/h		50 km/h		100 km/h	
Test Section	Initial	Four Years	Initial	Four Years	Initial	Four Years	Initial	Four Years	Initial	Four Years	Initial	Four Years
1	51	29	32	21	49	31	36	22	49	34	36	26
2	50	31	34	21	50	33	35	24	51	35	36	28
3	60	34	45	27	62	34	47	28	63	40	47	33
4	54	31	37	25	55	32	39	25	57	36	40	30
5	48	33	31	24	47	32	31	24	50	35	40	29
6	48	34	37	29	48	33	38	28	50	37	37	31
7	62	41	48	33	61	40	46	31	63	44	49	35
8	61	34	38	27	57	33	33	27	60	35	36	23
9	50	40	37	33	52	40	38	34	57	42	40	35
10	48	33	37	25	48	33	38	27	50	38	37	31
11	50	36	38	28	50	37	41	29	54	41	40	31
12	45	35	29	27	49	38	38	28	51	41	30	30
13	43	33	42	29	45	33	43	29	51	37	41	32
14	41	33	37	30	44	33	40	29	45	36	36	31
15	51	34	40	26	44	34	43	27	58	40	44	31
16	47	35	37	27	50	36	41	28	54	41	41	29
17	41	31	28	27	40	32	30	26	37	34	28	25
18	43	29	33	20	41	30	33	21	46	33	30	25

Note: 1 km = 0.62 mile.

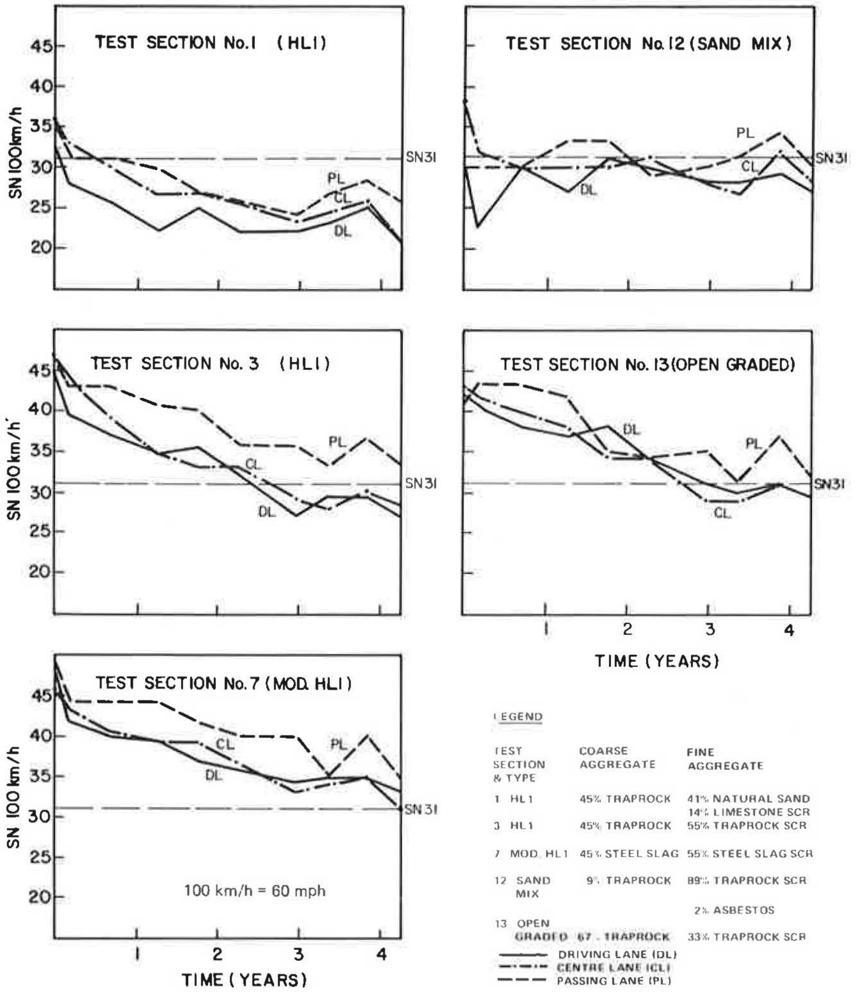


Figure 4. Skid resistance versus time for selected test sections.

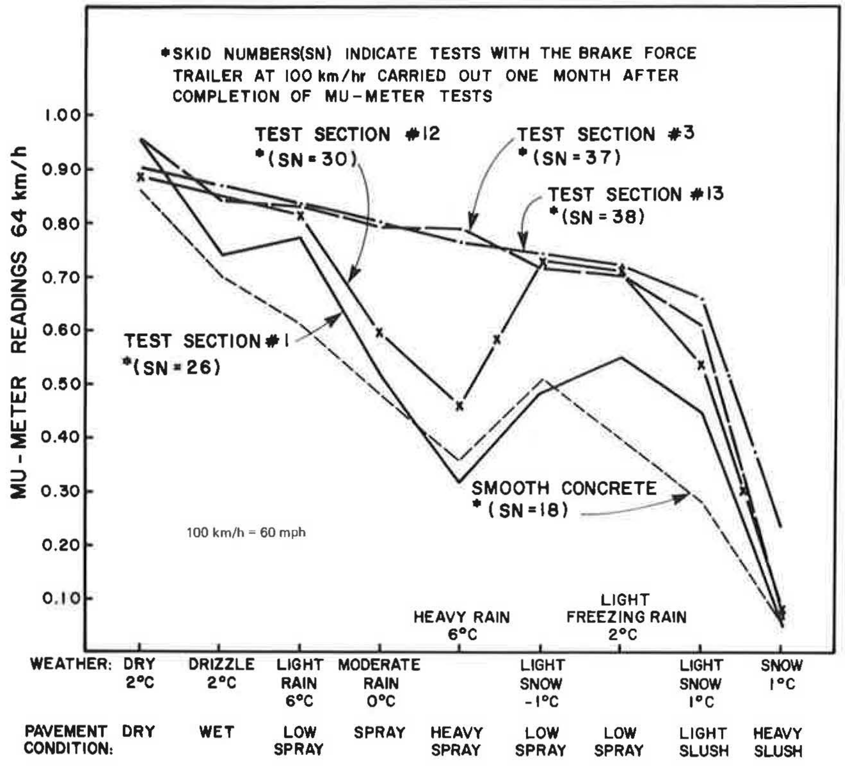


Figure 5. Mu-meter measurements of skid resistance in the driving lane in various weather conditions.

Laboratory has developed proposals for minimum standards of skid resistance that take into account the degree of difficulty at a site and include a risk rating to be determined by the accident potential of the site (11). These minimum coefficient values of side-force friction, measured at 50 km/h (30 mph), range from 0.30 for easy sites to 0.75 for very difficult sites. For alignment and traffic volumes similar to those of the Toronto By-Pass, values between 0.45 and 0.55 are specified.

Photo-Interpretation

The photo-interpretation method (7) is based on the interpretation of stereo pairs of color photographs of the pavement texture taken by using a specially designed camera box and light source. The color slides are examined by a skilled photo-interpreter to determine various texture parameters such as height and width of macroprojections, angularity of stone particles, and harshness of microtexture (see Figure 6). The textures are then classified in accordance with ASTM Standard E 559—Tentative Recommended Practice for Classifying Pavement Surface Textures Suitable for Skid-Resistance Photo-Interpretation.

In this research, photographs were taken in the wheel paths of each test section immediately after construction and subsequently twice each year. The photo-interpretation test was used to study the parameters of the pavement textures achieved immediately after construction and as changes occurred under traffic. A summary of the initial and 21-month macrotexture parameters for the driving, center, and passing lanes on the project is given in Table 4. These parameters indicate the significant changes in pavement texture that have occurred in some test sections during the early life of the pavement.

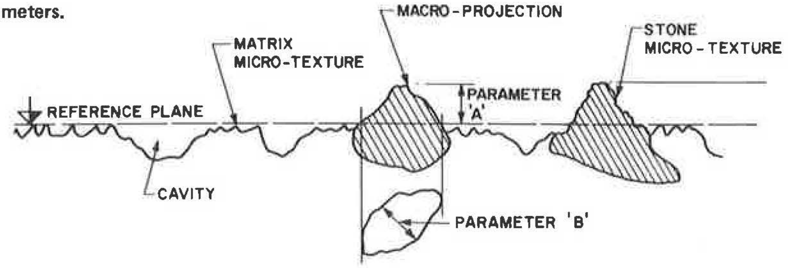
SKID-RESISTANCE CHARACTERISTICS

A bituminous surface-course mix must first provide an adequate level of skid resistance and then ensure that the required skid-resistance properties are retained for the design life of the pavement.

The initial skid resistance of all test sections in the Toronto By-Pass project was high (Table 2) and in general met or exceeded the target value of 31 at 100 km/h (60 mph). Most sections exhibited a significant decline in skid resistance during the first four years of service, particularly in the driving and center lanes where the heavy truck volumes are concentrated. This decline in skid resistance is attributed to compaction of the bituminous mixes under traffic, which resulted in impressment of the coarse-aggregate particles into the matrix of the mix. Macrotexture depths (parameter A in Figure 6 and Table 3) declined rapidly in many test sections and in some cases were virtually nonexistent after less than two years of service.

The rate of compaction depends on volume and type of traffic and the mix composition of the pavement layer. Once maximum compaction has been achieved, the density of the macroprojections on the surface will change little. Changes in pavement skid resistance after this

Figure 6. Texture parameters.



'A' – Height of macro-projections (mm)
'B' – Width of macro-projections (mm)
'D' – Density of distribution of macro-projections (%)

Table 4. Initial and 21-month surface macrotexture parameters.

	Driving Lane								Passing Lane							
	Initial				21 Months				Initial				21 Months			
Test Section	SN_{100}	A (mm)	B (mm)	D (%)	SN_{100}	A (mm)	B (mm)	D (%)	SN_{100}	A (mm)	B (mm)	D (%)	SN_{100}	A (mm)	B (mm)	D (%)
1	32	0.43	3.0	20	25	0	0	0	36	0.38	4.0	32	27	0.43	3.8	23
2	34	0.38	4.8	30	27	0	0	0	36	0.45	4.0	28	32	0.45	4.0	30
3	45	1.00	4.4	72	36	0.80	3.8	37	47	1.00	4.4	78	40	0.80	4.0	75
4	37	0.65	4.8	32	25	0.70	3.8	22	40	0.75	4.4	50	32	0.50	3.8	30
5	31	0.65	6.0	25	25	0.40	4.0	15	40	0.60	6.8	35	30	0.60	7.2	27
6	37	1.00	4.8	42	35	0.75	4.0	32	37	0.95	4.8	50	37	0.70	5.6	57
7	48	0.95	3.8	52	37	0.60	4.0	24	49	0.95	3.4	58	42	0.75	3.2	45
8	38	0.80	4.0	27	28	0.45	3.6	15	36	0.55	4.0	30	30	0.45	4.0	23
9	37	0.60	4.0	42	37	0.43	4.8	25	40	0.70	3.8	45	40	0.48	3.2	45
10	37	0.65	4.8	27	25	0	0	0	37	0.65	4.8	30	34	0.48	4.0	30
11	38	0.60	2.8	24	28	0	0	0	40	0.45	3.6	35	32	0	0	0
12	29		0	0	31	0	0	0	30	0	0	0	33	0	0	0
13	42	N/A	N/A	N/A	38	0.90	6.0	45	41	1.30	6.0	45	35	1.00	5.6	45
14	37	0.80	2.8	40	35	0.65	3.8	35	36	0.75	3.6	45	37	0.75	3.6	45
15	40	0	0	0	29	0	0	0	44	0	0	0	36	0	0	0
16	37	0.48	3.0	25	32	0.45	3.2	15	41	0	0	0	38	0	0	0
17	28	0.90	5.2	70	30	1.00	5.2	65	28	0.70	6.0	75	26	0.65	6.0	72
1-19	33	0.60	2.4	18	22	0	0	0	30	0.60	3.2	12	26	0.33	3.4	15

Note: 1 mm = 0.039 in.

time can take the form of a loss in friction values as the angularity of the stone projections is reduced and the microtexture is lost because of polishing of the aggregate particles. This appears to be a relatively slow process and is most noticeable in the course, open-graded mixes. An increase in skid resistance can result from differential wear between the stone particles and the matrix; that is, parameters A, B, and D increase. This phenomenon appears to be continuing in some of the project HL1 and modified HL1 mixes where low-abrasion, hard, coarse-aggregate particles and somewhat softer, fine-aggregate materials are blended together. Aggregate polishing and differential wear continue simultaneously and, for a given traffic condition, the properties of the aggregate largely control whether the net change in skid resistance is positive or negative.

HL1 and Modified HL1 Mixes

The most striking feature of skid-resistance characteristics in the Toronto By-Pass project is the excellent performance of the bituminous mixes that contain crushed traprock or slag screenings as the fine aggregate and the poor performance of the mixes in which the fine aggregate consists of natural sand or limestone screenings. The traprock and slag screenings initially produced higher skid numbers and deeper textures, and the sections have maintained adequate friction characteristics during the first four years of service.

Under the standard test conditions for the ASTM trailer, test section 7 (steel-slag coarse and fine aggregates) and test section 9 (blast-furnace-slag coarse and fine aggregates) in each of the three pavement lanes have maintained skid values in excess of the target value of 31. Macroprojection height exceeds 0.4 mm (0.016 in) in the driving lane (Table 3), and the matrix and stone microtexture have not polished to a significant extent.

In comparison, mix 8 (steel-slag coarse aggregate and a blend of natural sand and limestone screenings as the fine aggregate) and mix 10 (similar fine aggregate and blast-furnace-slag coarse aggregate) exhibit significantly lower skid resistance. Except for the passing lane of section 10, the mixes have not maintained the desired level of skid resistance. The effect on skid resistance of the fine-aggregate component is strikingly illustrated in Table 3 for sections 9 and 10, the two test sections that contain blast-furnace slag. In less than a year, the macroprojection height (parameter A) and the density of stone projections (parameter D) for mix 10 declined to zero, whereas mix 9, the mix that contains the blast-furnace-slag screenings, has maintained a well-developed macrotexture. The skid resistance of section 9 increased during the first few months, and in the passing lane a significant improvement in friction properties has occurred during the past two winters.

In comparing the performance of the two slag aggregates, it is evident that the vesicular nature of the blast-furnace-slag coarse aggregate provides the harshest microtexture to the stone projections and that this roughness is maintained, or regenerated, under heavy traffic. The steel slag produces better microtexture in the matrix. A combination of steel-slag fine aggregate and blast-furance-slag coarse aggregate might therefore represent the best use of the slag materials provided the blast-furnace-slag coarse particles do not exhibit undue wear under traffic.

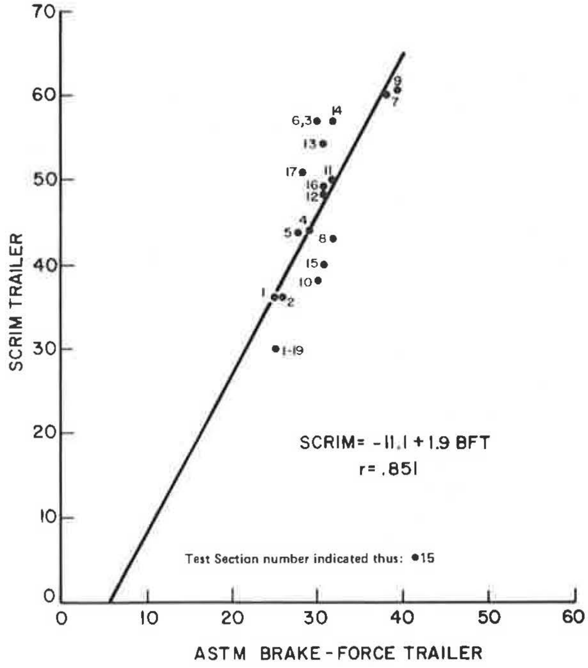
The type of fine aggregate has a similar influence on the skid resistance of the HL1 mixes that contain traprock coarse aggregate (mixes 1 to 6), particularly in the driving lane. Mixes 1, 2, 4, and 5, in which a large proportion of the fine aggregate is natural sand, have skid numbers between 6 and 10 points below the desired level at 100 km/h (60 mph), and the macrotexture parameters have significantly declined. Although the performance of these mixes is better in the passing lane, they do not provide satisfactory levels of skid resistance under heavy truck volumes in the driving and center lanes. Test sections 3 and 6, which used traprock screenings as the fine aggregate, have maintained satisfactory macrotexture (Table 3), but polishing of the fine-grained traprock particles in the driving and passing lanes has reduced the skid numbers measured by the brake-force trailer to slightly below the desired levels (Figure 4).

The addition of asbestos filler to mixes 5 and 6 reduced initial high-speed skid resistance somewhat, but little difference is apparent after four years.

The Mu-meter tests (Figure 5), which measured friction properties of the pavement sections under a variety of weather conditions, provide impressive additional evidence of the benefits of using crushed traprock or slag screenings in the bituminous mixes. Whereas mix 3 (traprock fine aggregate) maintained high skid resistance for all conditions up to heavy slush, mix 1 showed a significant decline in friction under conditions of moderate and heavy rain and light snow. In fact, in the driving lane the HL1 mix of test section 1 is little better in terms of skid resistance than the existing smooth, polished concrete of the Toronto By-Pass although the SNs measured by the ASTM brake-force trailer are significantly greater. These data clearly indicate the need for well-developed macrotextures for surfaces that carry traffic traveling at normal freeway speeds, a characteristic not necessarily measured by the standard brake-force skid trailer.

Side-force coefficients measured by SCRIM (see Figure 7) confirm the better skid resistance of the higher-stability mixes—i.e., those that contain traprock or slag screenings as the fine aggregate. Mixes 1, 2, 4, 5, 8, and 10, which contain a large proportion of natural sand, are characterized by skid coefficients between 36 and 44, which are below the levels proposed in Britain. In contrast, sections 3 and 6, which use traprock screenings as the fine aggregate and have skid coefficients in the

Figure 7. Comparison of test results for SCRIM and brake-force trailer at 60 km/h.



high 50s, and the all-slag mixes 7 and 9, which have coefficients of 60 and 61, respectively, are substantially in excess of the minimum skid-resistance values.

Open-Graded Mixes

Based on tests with the brake-force trailer, test sections 13 and 14, which consist of open-graded mixes that contain traprock coarse and fine aggregate, have maintained adequate levels of skid resistance. The visual appearance of such mixes is impressive because of their high stone content and the well-developed macrotexture of the surface. Even though the skid numbers measured for these mixes by the standard trailer are slightly lower than those of the slag mixes (test sections 7 and 9), Mu-meter measurements indicate that these mixes maintain a high level of skid resistance in conditions of moderate or heavy rain and light snow.

The SCRIM tests on sections 13 and 14 indicate friction levels in the same high range as those for sections 3 and 6, which contain similar types of material—i.e., traprock coarse and fine aggregate.

In comparison with the dense-graded mixes, the open-graded mixes appear to have some additional advantages that are not measured by standard test methods. In wet conditions, the pavement surface is comparatively dry and there is noticeably less splash and spray than there is on the other test sections. After the cessation of rain, the pavement surface dries out somewhat more rapidly.

Test sections 15 and 16, which contain a reduced fraction of coarse aggregate, initially had satisfactory skid resistance at high vehicle speeds, but in the driving and center lanes skid resistance has declined to less-than-desirable levels. As the data in Table 3 indicate, the mixes for these sections have a low proportion of stone projections (parameter D), which results in little macrotexture.

The performance of the open-graded mixes—particularly sections 13 and 14—is impressive. The interconnected voids in the mix are clearly very efficient in moving bulk water away from the tire-pavement interface. The excellent durability of the pavement during the first four years of service has overcome some of the initial skepticism about the performance of these high-void-content mixes.

Other Mixes

The two sand mixes (sections 11 and 12) that contain traprock screenings plus small amounts of 6-mm (0.25-in) traprock chips have relatively good skid resistance as measured by the brake-force trailer and SCRIM. After the first six months of service, little change in skid resistance has occurred. The matrix has excellent microtexture characteristics but, because of the lack of coarse aggregate in the bituminous mix, macrotexture is nonexistent. As the Mu-meter tests (Figure 5) indicate, this lack of coarse texture results in a significant reduction in skid resistance as rainfall intensity increases. Such mixes are not considered suitable for high-speed freeway traffic.

The mastic mix (section 17) had the lowest initial skid resistance of all the test sections, and after four years the values are somewhat less than desired. The high stone content has resulted in good surface macrotexture, but most stone projections are covered with a film of asphalt cement and mineral filler.

Comparison of Testing Devices

Since the Mu-meter was not used to test the pavement sections under the standard conditions imposed by a truck watering system, correlation with the brake-force trailer is poor. The best correlation was obtained when the Mu-meter was operated under conditions of light rain. Good correlation was obtained between measurements taken by SCRIM and the brake-force trailer (Figure 6).

In general terms, SCRIM and Mu-meter measurements correlate well with macrotexture measurements determined by photo-interpretation, i.e., parameters A, B, and D. In contrast, the brake-force-trailer tests carried out at the same time as the SCRIM tests correlated well with the microtexture of the surface, i.e., parameters D, E, and F. It appears, then, that the coefficients of side-force friction are more influenced by the harshness of the macrotexture (capability for drainage of bulk water) and that brake-force-trailer values are more dependent on the harshness of the microtexture (abrasive qualities of the pavement surface).

In considering these and previous observations, it becomes apparent that one must be cautious about using either brake-force-trailer or side-force measurements without considering other parameters to determine the adequacy of pavement skid resistance. The brake-force trailer does not provide a totally satisfactory measurement of pavement skid resistance; to ensure adequate friction at higher speeds and in adverse weather conditions such as heavy rain, sufficient texture depth (defined by stone projections above the matrix) must be achieved. Similarly, side-force friction is not by itself a totally satisfactory measurement of pavement skid resistance; to ensure adequate friction in areas of heavy traffic demand, aggregates with harsh, durable microtexture must be used.

PAVEMENT CORE SAMPLES

Core samples were taken from the wheel paths of the driving lane of each test section at 3 months and 21 months after construction. The samples were subjected to the usual control tests and, in addition, the pavement voids were determined. These results were compared with the voids in the recompacted mix, and the percentage of compaction was determined. Since each test section was represented by samples taken at only one location and since many variables affect the determination of compaction, the data are useful only as a general comparison of how the various materials and mix proportions affect the degree of achieved compaction and the increase of pavement density under heavy traffic in the driving lane.

The standard requirement of the Ontario Ministry of Transportation and Communications for the field compaction of bituminous mixes other than sand mixes—i.e., not less than 97 percent of the density of the laboratory compaction for layers 38 mm (1.5 in) thick and 93.5 percent for layers 25 mm (1 in) thick—was not achieved in almost all of the test sections. The lowest densities occurred on sections 3, 6, 7, 9, and 13-16, which represent (a) normal or modified HL1 mixes that contain crushed rock or slag material as both the coarse and fine aggregates and (b) open-graded mixes. In these mixes, between 89 and 94 percent compaction was achieved. It appears that the field packing properties of a bituminous mix that contains all crushed aggregates, in either the continuously graded or the gap-graded mode, make it more difficult to attain the traditional required density.

Of the four open-graded test sections, mixes 15 and 16, with 30 percent coarse aggregate, had initial void contents of 7 percent, which is far lower than the generally specified void content for such mixes. Increasing the stone content to 67 percent in test sections 13 and 14 resulted in a pavement void content of 12.2 percent. The HL1 and modified HL1 mixes that contain crushed traprock, blast-furnace slag, or steel slag as both the fine and coarse aggregates had initial pavement void contents that ranged from 11.3 to 15.2 percent, i.e., similar to those desired for the open-graded mixes. The particle shape of the fine aggregate as well as the combined aggregate grading has a marked influence on the void content in the compacted pavement.

As anticipated, all mixes exhibited reduced voids and increased compaction between 3 and 21 months of service; some HL1 and modified HL1 mixes that contain natural sand and limestone screenings approached 100 percent of laboratory compaction. Mixes with initial void contents in excess of 10 percent showed a reduction during this 18-month period of about 1.5 to 4.5 percent; the exception was mix 13, which declined from 12.2 to 4.9 percent. The large decrease in void content in the open-graded mix is attributable in part to sand and dirt that infiltrated the matrix of the pavement layer from the roadway surface.

A further coring program carried out in the summer of 1978 produced significantly different data for the open-graded mix in section 13. The pavement void content of 15 cores varied between 7.1 and 9.5 percent and averaged 8.5 percent (this does not include the one sample taken from a flushed area of the roadway). There was no significant difference in results for cores taken from the wheel paths and the center of the lane. The mean compaction of the same core samples was 94.4 percent; compaction was 2 percent higher in the driving-lane than in the passing-lane wheel paths. Most core specimens were contaminated with fine material near the surface.

PERMEABILITY TESTS

Permeability tests were conducted after two and four years of service in the driving-lane wheel path of each test section. The test method, which is based on equipment developed by the Johns-Manville Company, requires the use of a head of water contained in a vessel that has a sealed perimeter joint with the pavement surface. Permeability is defined as the change in the head of water with time as the water is permitted to drain into the pavement layer. The method is not entirely satisfactory for measuring permeability in the upper range since such mixes exhibit little resistance to the passage of water.

After two years of service, open-graded test sections 13 and 14 showed high permeability. During the next two years, the mixes became much less permeable: Three of nine locations were defined as impermeable. Tests on section 13 after four years showed that the passing lane tended to retain the characteristics of high permeability better than the center and driving lanes. The HL1 and modified HL1 mixes, with initial void contents in excess of 10 percent, were permeable after two years but to a somewhat lesser degree than the open-graded mixes. After four years, these mixes were impermeable.

All other bituminous mixes in the project were impermeable to the penetration of water after two years.

TEXTURE DEPTH

Satisfactory skid resistance at high vehicle speeds requires adequate macrotexture or drainage of bulk water. Based on skid measurements of the 18 test sections with the brake-force trailer and the Mu-meter and the measurement of the texture parameters by photo-interpretation, desirable textures to achieve adequate surface drainage for conditions more adverse than light rain are defined as follows (1 mm = 0.039 in):

Parameter	Measurement	Minimum Amount
A	Height of macroprojections (mm)	0.5
B	Width of macroprojections (mm)	2.0
D	Density of distribution of macroprojections (%)	25

CONSTRUCTION PROGRAM

As part of the first phase of the pavement improvement program on the Toronto By-Pass, 58 lane-km (36 lane miles) in the center section were rehabilitated with bituminous overlays in 1976, 1977, and 1978. The surface course was a 25-mm (1-in) thick open-graded mix in which traprock aggregates and a mix composition similar to that of section 13 of the 1974 experimental test sections were used. A binder course 38 or 51 mm (1.5 or 2 in) in thickness was placed on the concrete.

Mean test results for the open-graded mix were as follows (1 mm = 0.039 in):

Item	1976	1977	1978
Asphalt cement content (%)	4.9	5.1	4.6
Material retained on 4.75-mm sieve (%)	60	65	62
Voids in pavement samples (%)	10.9	7.8	10.0

Skid Resistance

Average skid numbers [SN_{100} km/h (60 mph)] for the 1976 resurfacing program were initially 39 and, after two years of traffic, 34. These values are slightly less than the equivalent figures for section 13.

Noise

Changes in community noise levels attributable to resurfacing the existing concrete pavement with the open-graded bituminous mixes are difficult to determine with precision because of variations in total traffic flow. In addition, the "staged" nature of the overlay construction program resulted in not all of the 12 pavement lanes being treated in one year.

May and Osman (8) have described a near-tire procedure of noise measurement and a test program on various freeway pavement surfaces in southern Ontario, including the Toronto By-Pass. This technique uses a microphone mounted near the tire of an automobile 152 mm (6 in) from the road surface. A 1974 Ford LTD sedan equipped with summer radial tires was operated at 100 km/h (60 mph). The open-graded mix (1976 construction program) was 3 dB(A) quieter than adjacent smooth concrete and 4-5 dB(A) quieter than a typical HL1 bituminous mix.

Favorable community reaction to the open-graded mix appears to confirm the low-noise properties of the new pavement.

Summary of Results

The general effect of the use of an open-graded-mix bituminous overlay on the driving quality of the Toronto By-Pass pavement has been to double skid resistance and decrease tire-pavement noise.

CONCLUSIONS

To provide acceptable levels of skid resistance at high vehicle speeds so as to minimize the number of wet-pavement skidding accidents, a pavement surface must have sufficient roughness or macrotexture to provide for the drainage of bulk water from the contact area between the tire and the road surface and sufficient harshness or microtexture to facilitate the breakup of the remaining thin water film on the roadway surface. These characteristics can be provided by selecting aggregates that do not wear and polish rapidly and thus retain angularity and microtexture and by using fine aggregate and a mix composition that produce a stable matrix microtexture and a well-defined surface macrotexture. The choice of materials and mix types must reflect the speed and volume of traffic and the number of commercial vehicles.

The performance of 18 pavement test sections on the Toronto By-Pass portion of Highway 401 during the first four years of service has provided useful data on the skid resistance of bituminous mixes under very heavy traffic volumes. The testing and evaluation reported in this paper have led to the following conclusions:

1. Almost all of the bituminous mixes tested provide substantially better skid resistance than the existing smooth, polished concrete.
2. Most bituminous mixes provided adequate skid resistance immediately after construction, but all mixes were characterized by a decline in skid resistance during the first four years of service. Initial target skid numbers must therefore be substantially higher than the required minimum level.
3. The early decline in skid resistance was caused by a reduction in the depth of the macrotexture as the coarse-aggregate particles were pressed into the matrix under wheel loads. This decline in skid resistance was most pronounced in the driving lane, where the majority of commercial vehicles travel, and least pronounced in the passing lane, which carries few trucks. There is an indication that some of the third- and fourth-year decline is attributable to wear and polishing of the coarse-aggregate particles.
4. In the driving lane, which carries 3700 commercial vehicles/day, the bituminous mixes that provide skid values close to or above the recommended minimum figures are (a) dense-graded mixes with both coarse and fine aggregates that consist of traprock, steel slag, or blast-furnace slag and (b) open-graded mixes that contain traprock coarse and fine aggregates with high stone contents. These mixes have also retained a high level of skid resistance during particularly adverse pavement conditions, such as heavy rain and slush from light snow.
5. In the passing lane, which carries few commercial vehicles, most bituminous mixes provide adequate skid resistance. The least skid resistance is provided by those that contain fine aggregates that consist of natural sand blended with limestone screenings.
6. Sand mixes that contain traprock screenings that produce good microtexture but little macrotexture have provided a reasonably good level of skid resistance when they were tested under standard conditions with the brake-force trailer but have shown a significant decline in skid resistance under conditions of moderate or heavy rain. Such mixes would provide a satisfactory surface texture only for low-speed traffic.
7. The characteristics of the fine aggregate in dense-graded bituminous mixes affect the depth of the macrotexture (the protrusion of coarse-aggregate particles from the matrix). Mixes that contain traprock or slag screenings have much better macrotexture than mixes that contain sand. This mechanism is not completely understood, and additional research is necessary to develop mix design methods and procedures of aggregate selection that will ensure adequate macrotexture in dense-graded bituminous mixes.
8. The ASTM brake-force trailer widely used in North America to measure skid resistance is useful in assessing friction values under standard conditions that approximate the thin water film that occurs in light rain on a typical pavement. Whether a pavement texture provides adequate skid resistance for high-speed traffic under a variety of adverse conditions depends on the attainment of both microtexture and macrotexture. The photo-interpretation test is a satisfactory method for the study of these two important parameters. For high-speed freeway traffic, adequate pavement macrotexture is achieved when the average projection of stone particles above the matrix is not less than 0.5 mm (0.02 in).
9. Blast-furnace-slag and steel-slag aggregates appear to provide somewhat better skid resistance in dense-graded bituminous mixes than the traprock aggregate widely used in the past on main highways in Ontario.
10. The new open-graded surface-course-mix pavement on the Toronto By-Pass is noticeably quieter under traffic than adjacent sections of smooth, polished concrete.
11. The main thrust of the project is to develop bituminous surface-course mixes that will provide adequate, long-lasting skid resistance for the heavy traffic volumes encountered on the Toronto By-Pass portion of Highway 401. Some of the conclusions on the unsatisfactory performance of bituminous mixes will obviously not apply to highways that carry less traffic or have a lower maximum speed limit.

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Synthetic Aggregates for Skid-Resistant Surface Courses

D.A. Anderson and J.J. Henry, Pennsylvania State University, University Park

Synthetic aggregates are produced by the thermal or chemical processing of natural or manmade materials. The physical properties of these aggregates vary considerably, depending on raw material and method of processing, and their properties are often considerably different from those of the natural aggregates on which current test methods and specifications are based. Skid resistance is primarily a function of the microtexture and macrotexture of the pavement surface. The physical properties of the individual aggregate particles determine level of microtexture and resistance to wear and polishing, which are important properties in the retention of skid resistance. Various methods of producing synthetic aggregates for skid-resistant surfaces are reviewed. Emphasis is placed on processing methods, available raw materials, and properties of the processed aggregate. The mechanisms by which different classes of aggregates develop microtexture and resistance to wear and polishing are discussed. It is concluded that each of these materials develops skid resistance and resistance to wear and polishing in a different way and that this should be reflected in designs and specifications. Many potentially acceptable synthetic aggregates are energy and capital intensive.

Synthetic aggregates are produced by the thermal or chemical processing of either natural or manmade raw materials and include waste materials as well as aggregates that are produced specifically for construction applications. The physical characteristics of synthetic aggregates vary depending on the raw material and the method of processing. In many cases, the physical characteristics and engineering behavior of synthetic aggregates are considerably different from those of the natural aggregates on which current specifications and test methods are based.

As supplies of readily available natural aggregate become depleted and the demand for skid-resistant pavements increases, synthetic aggregates will of necessity become more important as an aggregate source. In this paper, potential sources of synthetic aggregates are reviewed with respect to existing technology, and the aggregates are differentiated as to aggregates that are "tailor-made" as skid-resistant aggregates and those that are "non-tailor-made", such as lightweight aggregates, slags, and industrial byproducts.

SKID-RESISTANCE REQUIREMENTS

The skid resistance of a pavement is primarily a function of its surface texture. It is convenient to divide texture into two components: microtexture with asperities smaller than 0.5 mm (0.02 in) and macrotexture with asperities larger than 0.5 mm. Microtexture is generated by the surface texture of the individual aggregate particles, whereas macrotexture is generated by the gradation and maximum size of the coarse aggregate. Low-speed skid resistance is developed from microtexture. Both macrotexture and microtexture are required for high-speed skid resistance (1).

A relation between pavement texture and skid number at any speed V was developed by Leu and Henry (2):

$$SN_v = ae^{-bv} \qquad (1)$$

In this relation, coefficient a can be predicted from microtexture data (BPN or profile data) and becomes smaller as the aggregate is polished. The parameter b becomes larger as aggregate particles wear away and can be predicted from macrotexture data (i.e., sand-patch texture depth or profile analysis). It should be noted in Equation 1 that a particular skid number can be produced by different combinations of macrotexture and microtexture.

Although initial as-constructed skid resistance is an important requirement, it is also important that adequate skid resistance be maintained under the action of traffic. A loss in skid resistance can be produced by polishing (loss of microtexture) or by wear and abrasion (loss of macrotexture). Many aggregates, such as some sandstones, renew their microtexture as they wear away by exposing new, unpolished grains. Resistance to polishing is thus often gained at the expense of wear or abrasion.

To perform satisfactorily as a surface aggregate, an aggregate must

1. Be graded so that it can provide adequate initial macrotexture;
2. Provide adequate resistance to environmental exposure, abrasion, and impact (retain its macrotexture);
3. Provide adequate initial microtexture; and
4. Provide adequate resistance to polishing (retain its microtexture).

TYPES OF AGGREGATE

Different aggregates achieve microtexture and resistance to polishing through different mechanisms. James (3) has developed the following aggregate groups for purposes of classification: