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Design and Performance of Bituminous Friction-Course Mixes

NABIL KAMEL, G.R. MUSGROVE, AND A. RUTKA

Performance data from two major experimental field projects carried out in Ontario to develop bituminous friction-course mixes with improved texture and friction characteristics are presented. The new mixes maintain excellent surface texture and provide longer-lasting skid-resistance characteristics. Design principles, construction, and subsequent performance characteristics of these skid-resistant pavement surfaces are discussed. Aggregate properties, gradations, and mixture characteristics that produce and maintain optimum texture levels with Ontario materials are identified. Mixes within such gradation boundaries were found not only to maintain superior texture qualities and friction levels but also to require less asphalt cement when compared with conventional asphalt surfaces. The new friction-course mixes use normal paving-grade asphalts and require no special additives or fillers. Use of the new friction-course mixes for rehabilitation of pavements that have low friction levels and experience a high rate of wet-weather collisions has produced an average reduction of 54 percent in wet-pavement collisions and a 29 percent reduction in total collisions at eight black-spot freeway locations. Treatment at five black-spot signalized highway intersections produced an average reduction of 71 percent in wet-pavement collisions and 46 percent reduction in total accidents. The Ontario Ministry of Transportation and Communications has implemented a policy that specifies the use of the new friction-course mixes for new construction and resurfacing projects for all main highways. The new surface mixes are also used for rehabilitation at locations other than main highways at which excessive wet-pavement collisions occur.

Pavement skid-resistance research in Ontario started in 1962 by using the British portable skid tester. Early efforts were primarily directed toward developing high-speed friction measuring capabilities and developing techniques to evaluate pavement textures. In 1967, organized high-speed skid testing started with a Ministry-built brake-force trailer that met the requirements of the American Society for Testing and Materials (ASTM 274). In 1970, Schonfeld's photointerpretation technique for pavement-texture classification (1,2) was introduced.

In the mid-1970s, considerable attention was given to the construction and maintenance of skid-resistant pavements so that wet-weather accidents would be reduced. An extensive program of transverse grooving on slippery concrete pavements was introduced (3) as were procedures for the posting of Slippery When Wet signs and wet-pavement advisory speed limits at highway locations at which more than one-third of the accidents were occurring under wet conditions. In addition, two major experimental projects were carried out to develop alternative bituminous surface-course mixes with improved texture and friction characteristics for new construction. In 1974, 17 test mixes were constructed on a section of Canada's Highway 401 (Toronto By-Pass) to evaluate improved surface mixes for heavily trafficked freeways and main highways (4). In 1978, 17 other test mixes were constructed on Highway 7 near Lindsay to develop improved surface mixes for highways that had a lower traffic volume (5). Each experimental project included both types of dense and open-graded mixes and evaluated a variety of aggregate types. Results from the test roads provided an excellent data base for examining the effects of traffic, mix properties, aggregates, etc., on skid resistance.

It is the purpose of this report to review Ontario's experience with the design, construction, and performance of these skid-resistance mixes over the past seven years and to present data on their effectiveness in terms of accident reductions observed after resurfacing at highway locations that had experienced excessive rates of wet-pavement accidents.

SKID-RESISTANT MIXES

A skid-resistant surface must have sufficient microtexture (harshness) and sufficient macrotexture (stone projections). Figure 1 shows a pavement surface profile and texture parameters as defined by Schonfeld (1,2). Pavement surface microtexture is a function of the harshness of the microprojections on matrix surfaces as well as the harshness of the macroprojection surfaces. Macrotexture is a function of such physical properties as height, width, and angularity as well as density of the macroprojections on the pavement surface.

The role of the macrotexture is to break up the water film and to provide drainage channels so that most of the water can be drained from the contact area between the rolling tire and the pavement surface. The microtexture allows penetration of the remaining thin film of water on the roadway surface. Good friction levels can only be obtained with adequate harshness or microtexture on the pavement surface. This is a desired property at all speeds. Adequate macrotexture will limit the drop in friction levels as vehicle speed and/or water thickness on the pavement surface increases.

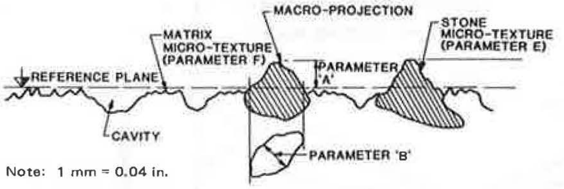
Microtexture may be obtained by using aggregates with high polish resistance, which show differential polishing and/or microtexture regeneration characteristics (6,7). Attainment and maintenance of macrotexture stone projections on the pavement surface are influenced by aggregate size, shape, gradation, type and composition, hardness, and resistance to wear (4-7).

SELECTION OF COARSE AGGREGATE IN FRICTION-COURSE MIXES

Both macrotexture and microtexture qualities required for good wet-surface friction characteristics are influenced by the quality, quantity, and gradation of the coarse aggregate in the mix. To ensure attainment of adequate texture and friction levels, many European countries and Japan use quality specifications or guidelines related to polished-stone value (PSV), aggregate-abrasion value (AAV), texture depth, and minimum skid-resistance levels (_8_).

In Ontario, results from both the Highway 401 and the Highway 7 test sections confirm that coarse aggregates with higher PSVs produce mixes that maintain higher friction levels. This is demonstrated in Figure 2 for both heavy and moderate traffic. The two mixes from Highway 401 shown in Figure 2 have been exposed to extremely heavy traffic. Over a five-year testing period, accumulated total traffic amounted to approximately 24 million vehicles of which 7 million were commercial trucks. The Highway 7 test at Lindsay has an annual average daily traffic (AADT) of 5500, of which 12 percent are heavy commercial vehicles.

Figure 1. Pavement surface profile.



Note: 1 mm = 0.04 in.

A - Height of macro-projections (mm)

B - Width of macro-projections (mm)

C - Angularity of macro-projections (scale 0.0-3.0)

D - Density of distribution of macro-projections (%)

E - Harshness of macro-projection surfaces (scale 0.0-6.0)

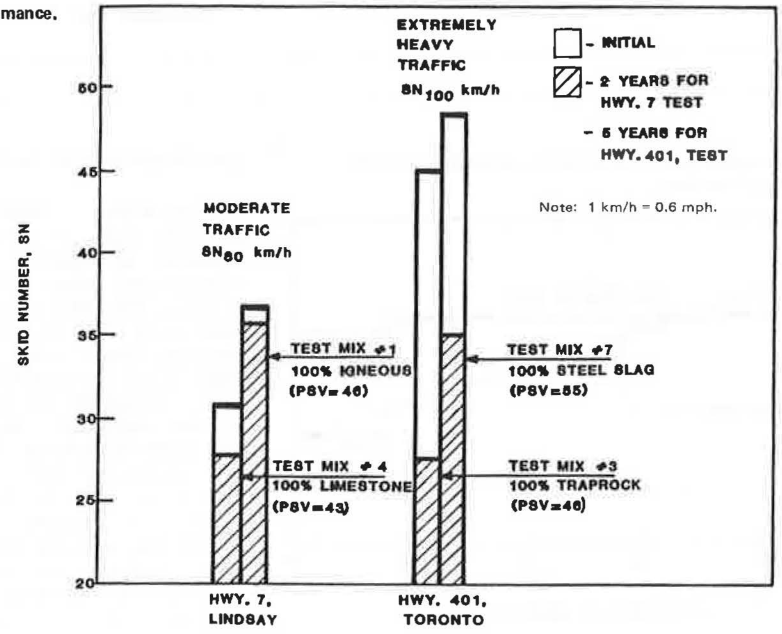
F - Harshness of micro-projections on matrix surfaces (scale 0.0-6.0)

Of particular interest is the low PSV of the traprock aggregate (PSV = 46). This value indicates that the material will ultimately polish to a degree equivalent to, or only slightly better than, some limestone aggregates. The traprock aggregate is very hard, fine-grained, dark in color, and 100 percent crushed material. Mixes that have 100 percent traprock materials (such as that illustrated in Figure 2) have been used satisfactorily for a number of years in Ontario on highways that experience very heavy traffic. The satisfactory skid performance of the traprock mixes may be attributed to the excellent abrasion resistance of the traprock material (AAV ≈ 2). The traprock aggregates tend to maintain angularity under severe traffic conditions and in turn provide and maintain sharp, angular macrotexture projections on the pavement surface and acceptable overall skid-resistance levels.

It is important that PSV be considered along with aggregate ability to withstand abrasion and maintain angularity. Maintenance of angular macrotexture stone projections on the pavement surface is essential in providing good friction levels for high-speed traffic. Stones with moderate PSV but high abrasion resistance such as the traprock materials appear to provide satisfactory skid-resistance performance under extremely heavy traffic.

Blending of a better friction-quality coarse aggregate, i.e., one that has a higher PSV, in a mix can yield significant improvement in skid resistance. Figure 3 provides a comparison between the skid-resistance performance of four mixes from the Highway 7 test. In the dense-graded friction-course (DFC) mix, the coarse aggregate is a 1:1 blend of local limestone and imported igneous materials. This mix provides superior skid-resistance levels in comparison with the two mixes that contain 100 percent limestone coarse aggregate. Its skid resistance is as good as the standard heavy-duty HL1 mix, which incorporates 100 percent traprock coarse aggregate and local fines. This DFC mix with the coarse-aggregate blend is of particular interest because of its apparent economic advantages in comparison with the standard HL1 mix; the DFC mix uses a higher percentage of local materials and requires less asphalt cement.

Figure 2. Effect of PSV on skid-resistance performance.



Note: 1 km/h = 0.6 mph.

Figure 3. Skid-resistance performance of four mixes with and without coarse-aggregate blend.

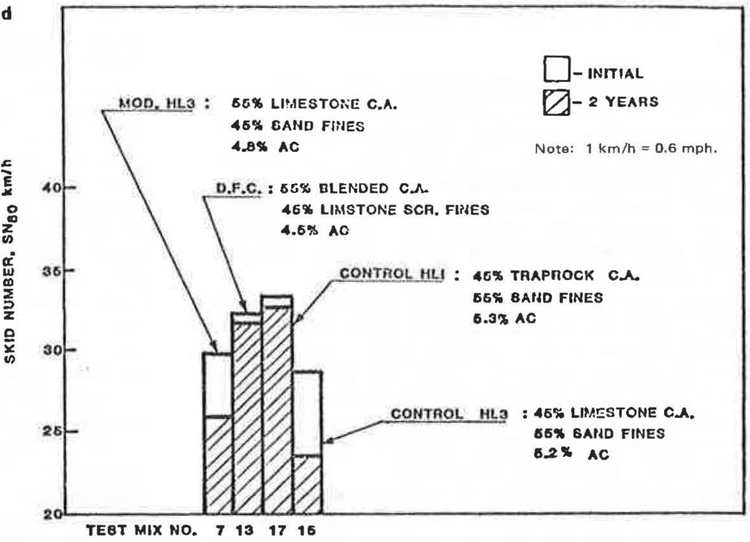


Figure 4. Change in height and density of macroprojections for two HL1 mixes with different coarse-aggregate content.

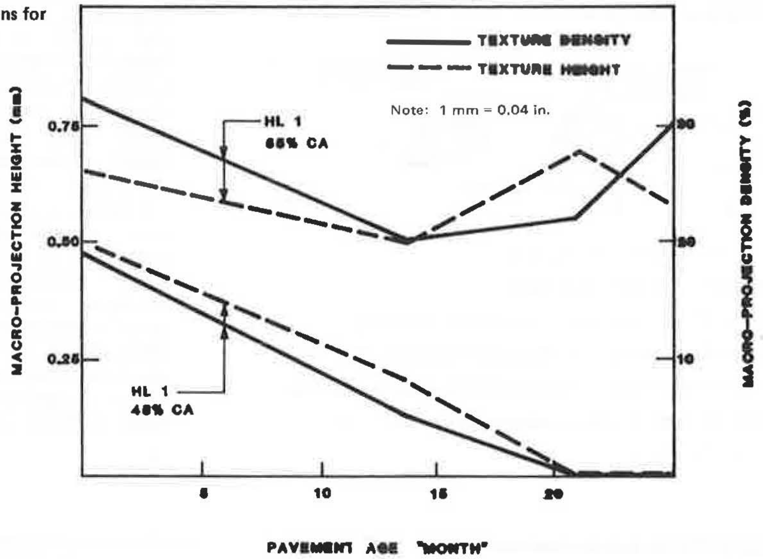
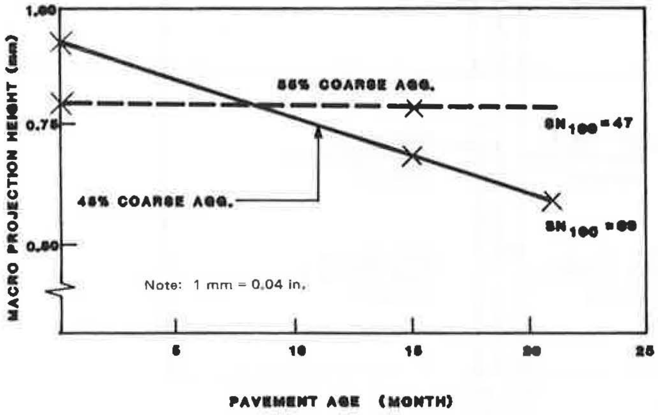


Figure 5. Change in macroprojection height for two steel-slag mixes with different coarse-aggregate content.



COARSE AGGREGATE IN MIX

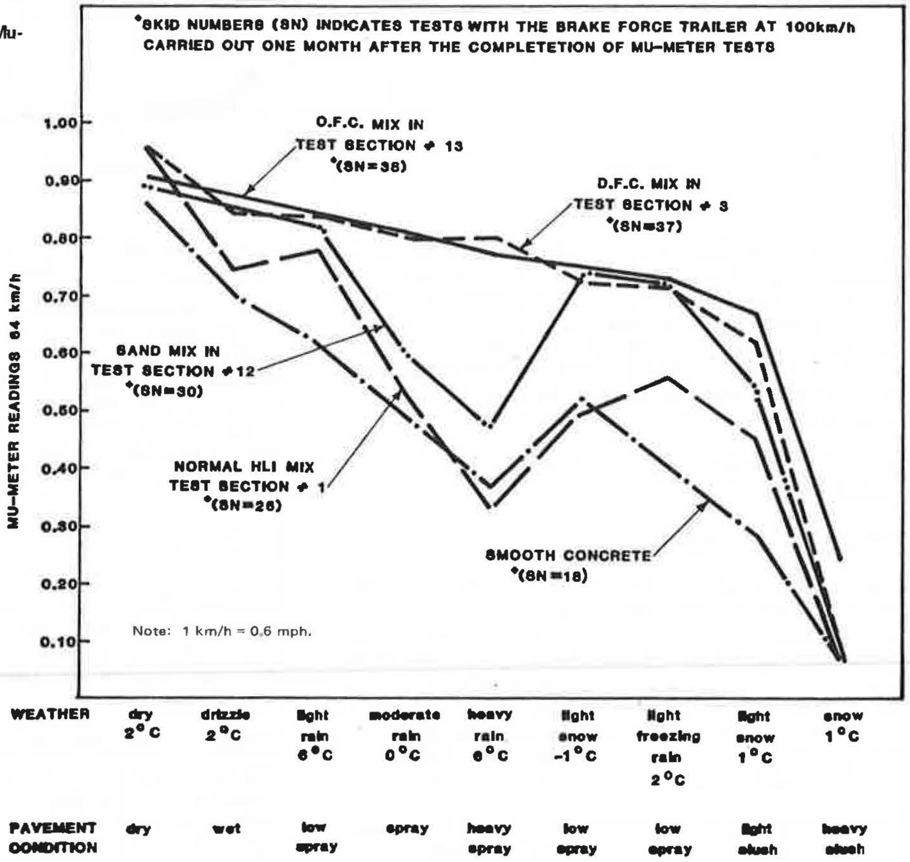
An important finding of the Highway 401 Toronto By-Pass test is that mixes that had a higher stone content maintained better surface textures than traditional mixes that had 45 percent stone. Figure 4 shows the change in macrotexture depth and density (measured by the photointerpretation method in the driving lane; AADT was 12 900 of which 3740 were commercial vehicles) with pavement age for two mixes that contained 45 percent and 55 percent traprock coarse aggregate (i.e., retained by No. 4 sieve). The fine aggregate in both mixes is a blend of sand and limestone screenings. The superiority of the mix that has 55 percent stone content is quite clear. It provided and maintained a better texture depth and density of stone projections on the pavement surface, whereas the macrotexture on the mix that had 45 percent coarse aggregate virtually disappeared after less than two years in service.

Table 1. Mix composition and asphalt content for conventional and stonier mixes.

Type of Mix	Aggregate Retained on 4.75-mm Sieve		Aggregate Passing 4.75-mm Sieve		Asphalt (percent by weight of mix)	Test Mix No.	Test Date[a]
	Type	Percent	Type	Percent			
HL1	Traprock	45	Sand and limestone screenings	55	5.4	1	1974
	Traprock	55	Sand and limestone screenings	45	4.8	4	1974
DFC	Steel slag	45	Steel slag screenings	55	5.3	7	1974
	Steel slag	55	Steel slag screenings	45	4.8	2	1978

[a] All tests were done on Highway 401.

Figure 6. Skid-resistance measurements in different weather conditions by using the Mu-meter (driving lane).


*SKID NUMBERS (SN) INDICATES TESTS WITH THE BRAKE FORCE TRAILER AT 100km/h CARRIED OUT ONE MONTH AFTER THE COMPLETETION OF MU-METER TESTS

Note: 1 km/h = 0.6 mph.

Overall, the mix that had 55 percent coarse aggregate provided skid numbers (SNs) approximately 4 points higher than traditional HL1 mix that had 45 percent stone when tested under standard test conditions at 100 km/h.

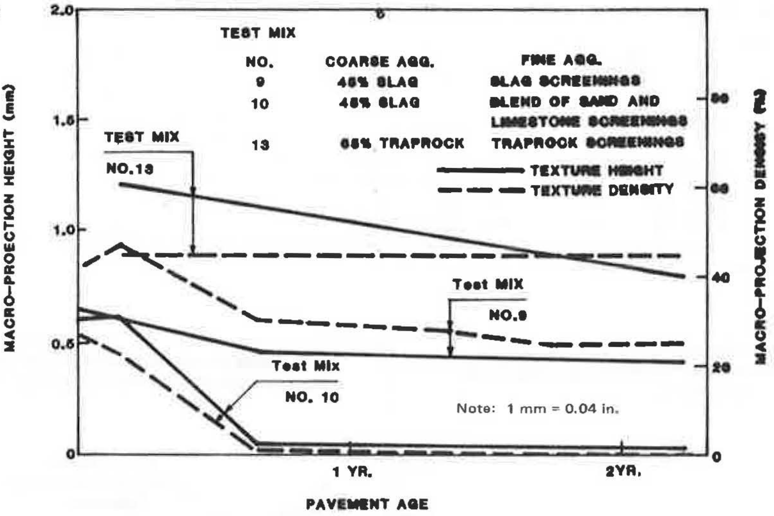
Similar observations may also be made for two steel-slag test mixes that contained 45 percent and 55 percent coarse aggregate (Figure 5). The skid resistance of the mix that had 45 percent stone (retained by No. 4 sieve) declined from SN_{100} of 48 to 39 after 21 months in service. The skid resistance of the mix that contained 55 percent coarse aggregate has shown no significant decline in its 21 months of service.

It appears that mixes that have 55 percent coarse aggregate provide higher resistance to the immersion of stone projections into the matrix under heavy truck traffic; they maintain better and longer-lasting surface macrotexture. The use of mixes that have such a high stone content also has economic advantages, mainly due to the reduced asphalt content required. As shown in Table 1, the stonier mixes use approximately 10 percent less asphalt cement than is used in traditional mixes that contain 45 percent stone content.

Results of laboratory testing on mixes that have varying coarse-aggregate content in the United Kingdom appear to confirm our findings with the stonier mixes. Fabb and Heyes (9) found the optimum stone content for deformation resistance to be approximately 55 percent of the total mix when crushed coarse aggregate is used. In Japan (10), the use of such stonier asphalt mixes is prompted due to its excellent skid-resistance characteristics and the higher resistance to rutting, particularly on heavily trafficked routes.

One last observation concerns sand mixes that contain little or no coarse aggregate. The Highway 401 mixes included four sand mixes that had coarse aggregate percentages between 9 and 30. All the mixers contained traprock coarse aggregate and traprock screening fines. Such mixes produce good microtexture but little macrotexture on the pavement surface. They provide reasonably good levels of skid resistance when tested under standard conditions with the brake-force trailer, but tests with the Mu-meter showed these mixes to exhibit a significant decline in skid resistance under conditions of moderate or heavy rain [Figure 6 (4)]. Such mixes

Figure 7. Change in height and density of macroprojections for test sections 9, 10, and 13.



would provide a satisfactory surface texture only for low-speed traffic. In contrast, as indicated in Figure 6, mixes that have a high stone content, such as the open-graded friction-course (OFC) mix and the DFC mix, which also contain 100 percent traprock, retain a high level of skid resistance during particularly adverse conditions such as heavy rain and light snow or slush on the pavement surface.

SELECTION OF FINE AGGREGATE IN FRICTION-COURSE MIXES

Heavily Traveled Pavements

Maintenance of adequate texture levels and skid resistance on heavily traveled highways depends not only on the quality of the coarse aggregate in the asphalt mixture but also on the quality of the fine aggregate in the mix. Under heavy traffic, as on the Highway 401 Toronto By-Pass, the fine aggregate plays as important a role as coarse aggregate in achieving and maintaining skid resistance. This has been clearly demonstrated by the Highway 401 test mixes.

All test mixes in the Highway 401 test that contained a blend of sand and limestone screening fine aggregate showed a sharp decline in skid resistance in their early service life. In contrast, all successful mixes contained premium-quality crushed fine aggregate such as traprock and steel-slag screenings.

Figure 7 (4) presents texture measurements for three test mixes. Macrotexture depth for test mix 10, which contains a blend of sand and limestone-screening fine aggregate, declined rapidly and almost ceased to exist during the first year in service. This is mainly due to compaction of the bituminous mix under traffic, which resulted in the impression of the coarse aggregate particles into the matrix of the mix. Under the same testing conditions, mixes 9 and 13, which contained slag and traprock screening fine aggregate, provided and maintained reasonable macrotexture depth, macrotexture density, and good overall levels of skid resistance.

In 1976, the above finding triggered a skid-resistance survey for HL1 mixes in service. More than 50 contract locations were tested on highways where AADT was 5000 vehicles or more per lane per day. It was found that the fine aggregate in 93 percent of the deficient pavements was predominantly sand and in 90 percent of the satisfactory pavements was predominantly crushed screenings.

The use of hard, harsh, and angular fine aggregate appears to provide a number of advantages:

1. Increased aggregate interlock, which causes a significant increase in Marshall stability for such mixtures; this provides high resistance to the impression of coarse aggregate, under heavy truck traffic, into the matrix of the mix;
2. Increased harshness of the pavement surface due to an angular and harsh pavement matrix; and
3. Increased macrotexture depth and density of stone projections on the pavement surface by the protrusion of the coarse aggregate particles from the matrix.

In summary, for heavily trafficked freeways and main highways that have a high volume of truck traffic, it is essential that surface-course mixes contain prime-quality (hard, harsh, and angular) coarse and fine aggregates so that adequate texture and skid-resistance levels can be maintained.

Pavements That Had Moderate and Low Traffic Volume

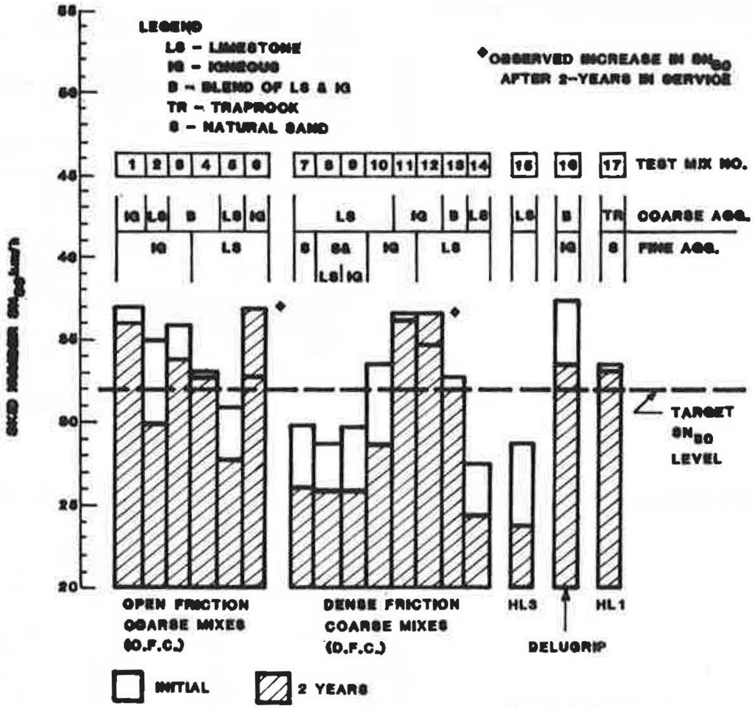
For highways that have a moderate volume of traffic, surface texture and skid resistance of asphalt mixes depend primarily on the quality of the coarse aggregate in the mix. Results from the Highway 7 test indicate that mixes that have similar coarse aggregate (i.e., similar in type and in percentage in the mix) provide essentially similar skid-resistance levels regardless of the type of fine aggregate in the mix. For example, the highest skid-resistance values were obtained with four test mixes that contained igneous coarse aggregate. Two of these mixes contained local limestone screenings and two contained igneous-screening fines (mixes 1 and 6 and 11 and 12 in Figure 8). The Lindsay mixes also indicated that replacing the sand fines with a blend of sand and limestone or sand and igneous screenings or with 100 percent limestone screenings failed to provide significant improvement in skid resistance (mixes 7, 8, 9, 14, and 15).

It appears that for moderate and low traffic conditions, skid-resistance levels (SN_{80}) of bituminous concrete mixes are predominantly influenced by the type of coarse aggregate in the mix. The role of fine aggregate is significantly less apparent than it is in the case of heavily traveled highways.

AGGREGATE GRADATIONS FOR FRICTION-COURSE MIXES

The gradation requirements of the Ontario Ministry

Figure 8. Initial and two-year skid-resistance measurements, westbound.



Note: 1 km/h 0.6 mph.

Table 2. MTC gradation requirements for coarse aggregates.

MTC Sieve Designation	Percentage Passing by Weight		
	HL1 and HL3	DFC	OFC
13.2 mm	100	100	100
9.5 mm	50-73	50-73	95-100
6.7 mm	-	-	20-45
4.75 mm	0-10	0-10	0-10
75 µm	0-2	0-2	0-2

Note: 1 mm = 0.04 in.

Table 3. MTC gradation requirements for fine aggregates.

MTC Sieve Designation	Percentage Passing by Weight		
	HL1 and HL3	PFC	OFC
9.5 mm		100	100
4.75 mm	100	85-100	85-100
2.36 mm	80-100	50-70	50-70
1.18 mm	55-90	25-50	25-45
600 µm	35-70	15-40	10-30
300 µm	15-40	10-30	0-20
150 µm	5-10	5-25	0-10
75 µm	0-5	0-17	0-3

Note: 1 mm = 0.04 in.

of Transportation and Communications (MTC) for coarse aggregate used in conventional surface mixes (HL1 and HL3), DFC mixes, and OFC mixes are shown in Table 2. The nominal size for coarse aggregate is 13.2 mm (1/2 in) for conventional and DFC mixes and 9.5 mm (3/8 in) for OFC mixes. Only crushed-screening fine aggregate is acceptable for friction-course mixes. Screenings are washed for use in the OFC mixes and used unwashed for the DFC mixes. Gradation requirements for fine aggregate in conventional, DFC, and OFC mixes are shown in Table 3.

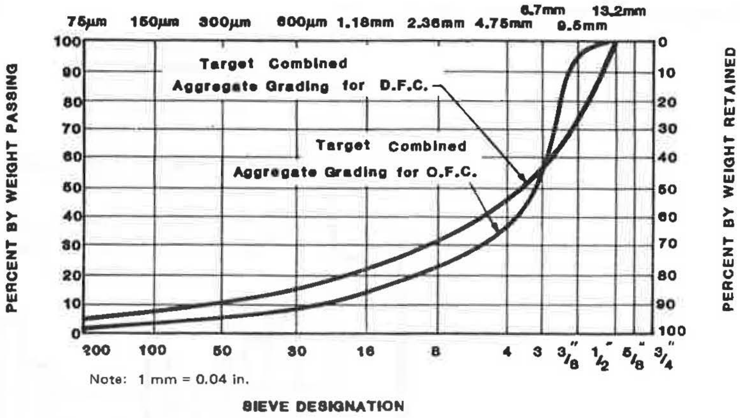
Based on the performance of the various friction-course mixes on Highway 401 and Highway 7, recommended target gradations for total aggregates in OFC and DFC mixes have been developed as shown in Figure 9. From 1978 to 1980, MTC constructed many pavement friction-course sections that met the above target gradations with excellent results. Mixes were placed on highways that had extremely heavy traffic volumes, e.g., the Highway 401 Toronto By-Pass and Highway 417 in Ottawa, as well as on highways that had moderate traffic, e.g., Highway 401 in Kingston and Highway 7 in Lindsay. Such mixes produce excellent surface textures and maintain superior overall friction levels. As previously shown, these stonier mixes demand less asphalt cement and thus have additional economic advantages over normal mixes. They also maintain high levels of skid resistance during adverse weather conditions such as heavy rain and light snow or slush on the pavement surface.

MIX DESIGN

The DFC mixes are designed in almost the same manner as conventional mixes. The MTC mix design method uses the Marshall equipment (11). The briquettes are compacted mechanically by using 60 blows of a Marshall hammer per side. The most significant difference is that particular emphasis is placed on visual evaluations of loose and compacted mix samples. The results of both the visual assessments and the Marshall mix properties determine the designed asphalt content in the mix.

DFC mixes that contain 100 percent crushed-screening fine aggregate are characterized by high Marshall stability values, usually a minimum of 9000-10 000 N (2000-2250 lbf). They are also characterized by relatively higher voids in the pavement that result from difficulties in compacting these dense, high-stone-content mixes in the field (5). With maximum effort, it is normal to obtain only 90 percent compaction in the field with these high-stability, high-stone-content mixes. For this reason, and to ensure durability, DFC mixes must be designed to have well-coated aggregate particles. MTC practice is to design these mixes with a rich to very rich asphalt appearance. In many instances

Figure 9. Target aggregate gradations for OFC and DFC mixes.



Note: 1 mm = 0.04 in.

Table 4. Marshall design values for DFC and OFC mixes.

Aggregate Type in Mix	Percent Retained by 4.75-mm Sieve	Asphalt (%)	Voids (%)	Flow (0.25 mm)	Voids in Mineral Aggregate (%)	Stability (N)
DFC Mixes						
Steel slag	55	4.8	3.7	15.1	17.4	13 608
Igneous	55	5.0	3.0	16.2	13.7	10 564
Traprock	45	4.5	1.2	21.5	12.7	13 900
Sandy dolostone	60	4.8	2.0	15.1	11.9	10 453
Limestone	55	4.5	1.7	20.3	11.9	9 341
OFC Mixes						
Steel slag	65	5.2	5.6	17.9	16.0	8 227
Igneous	65	5.3	6.5	13.6	17.7	6 049
Traprock	65	5.0	8.4	11.7	20.1	8 139
Sandy dolostone	65	4.6	9.0	11.1	18.0	7 784
Limestone	65	4.1	5.5	13.5	13.7	7 784

Note: 1 mm = 0.04 in; 1 N = 0.04 in.

visual assessment of loose and compacted mix samples becomes the decisive factor in selecting the designed asphalt level. Examples of Marshall design values for DFC mixes are shown in Table 4. For purposes of comparison, design specifications for traditional HL1 and HL3 surface-course mixes call for an asphalt content of 5-7 percent and design voids of 2-4 percent.

For design of OFC mixes, Marshall testing is carried out, but once again visual evaluations of loose and compacted mix samples would greatly influence the selection of the designed level of the asphalt binder. OFC mixes are also designed to have well-coated aggregates and a rich to very rich asphalt appearance. Examples of Marshall design values for various OFC mixes are given in Table 4.

CONSTRUCTION OF FRICTION-COURSE MIXES

Details on construction of DFC and OFC mixes have been given by Kamel, Corkill, and Musgrove (5). Mixing temperatures for OFC mixes range between 121 and 135°C (approximately 250-275°F). It is MTC practice to maintain the mixing temperature for OFC mixes below 149°C (300°F) to prevent asphalt runoff. Mixing temperatures for DFC mixes range from 150°C to 165°C (approximately 300-325°F).

Placing the OFC and the DFC mixes is carried out by using conventional equipment, i.e., a paver equipped with a vibratory screed. Compaction is carried out immediately after the mix has been placed by using only a 10-ton steel drum roller on the OFC mixes and both the steel and rubber-tired rollers on the DFC mixes. The OFC mixes are constructed to be 25 mm (1 in) thick and the DFC mixes are placed 38 mm (1.5 in) thick.

PERFORMANCE OF FRICTION-COURSE MIXES

This section provides additional information on field performance of both OFC and DFC mixes. Testing results on pavement core samples, pavement permeability, skid resistance, and noise characteristics as well as winter maintenance and performance are discussed.

Pavement Core Samples

Pavement core samples taken from the wheel tracks in the driving lane from both the Highway 401 and the Highway 7 tests showed initial pavement voids for OFC mixes that ranged between 10 and 20 percent (4,5). Initial pavement voids of 15 percent in these open-graded mixes are desired.

On the Highway 401 Toronto By-Pass, further coring after approximately four years indicated that pavement voids declined on the average by 3.7 percent. There was no significant difference in results from cores taken from the wheel paths and from the center of the lane. The Highway 7 tests on the OFC mixes indicated that the voids in the pavement decreased by an average of 1.3 percent during the first 13 months in service.

For the DFC mixes, initial pavement voids were found to range between 9 and 15 percent. The high number of voids in the pavement illustrates the problem of compacting these high-stone-content/high-stability mixes in the field. Subsequent testing,

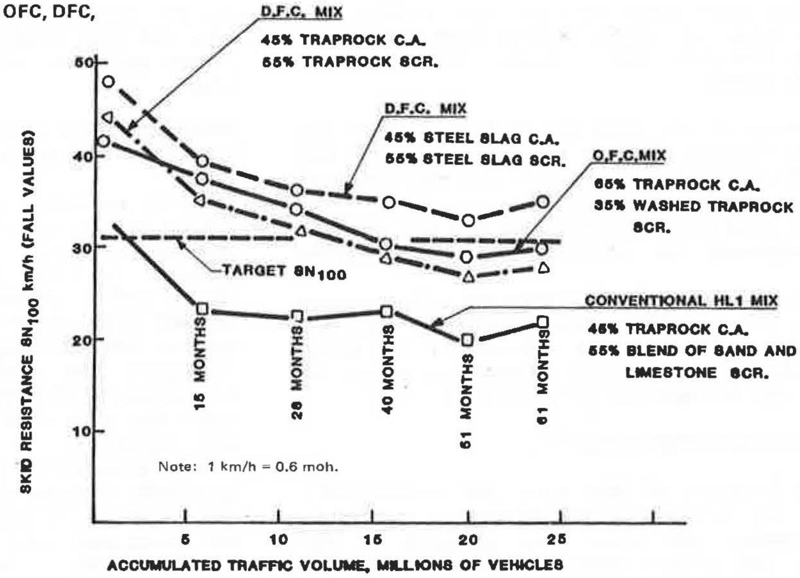


Figure 10. Five-year skid performance history of OFC, DFC, and HL1 mixes.

however, showed a reduction in the pavement voids in cases of both heavy and moderate traffic. On the Highway 401 Toronto By-Pass, the DFC mixes experienced an average reduction of 3.65 percent in the pavement voids during the first 18 months after construction. On Highway 7 the reduction in pavement voids averaged 0.9 percent during the first 13 months of service. It should be noted that initial pavement voids in conventional dense-graded surface mixes (HL1 and HL3) would normally range between 7 and 8 percent.

Pavement Permeability Tests

In situ permeability tests have also been carried out on the OFC and the DFC mixes on Highway 401 in Toronto and Highway 7 in Lindsay (4,5). Test results indicated high initial permeability obtained in all cases, but subsequent measurements after one, two, and four years showed substantial permeability reductions.

Under the heavy truck traffic on Highway 401 in Toronto, the OFC mixes showed high permeability in the first two years after construction. During the next two years the mixes became considerably less permeable; three of nine locations showed permeability readings in the impermeable range. The testing also showed a trend for the passing lane, in which a limited number of trucks travel, to retain its initial high permeability characteristics better than the center and driving lanes do. Under the moderate traffic conditions on Highway 7 at Lindsay, testing conducted one year after construction indicated that the OFC mixes maintained their original high permeability properties.

Test results on the various DFC test mixes on Highways 401 and 7 also indicated considerable reductions in pavement permeability within the first two years of service. All DFC mixes on the Highway 401 test provided four-year permeability readings in the impermeable range.

Pavement Skid Resistance and Noise Characteristics

Figure 10 shows the high-speed skid resistance (SN_{100}) versus accumulated traffic volumes for some selected mixes from the Highway 401 Toronto By-Pass test: two DFC mixes that contained traprock and steel-slag coarse and fine aggregates, one OFC mix that contained traprock coarse aggregate and washed traprock screening fines, and a standard HL1 (control) mix that contained traprock coarse aggregates and a blend of sand and limestone screening fines. As can be seen, the initial SN_{100} values obtained on the DFC and the OFC mixes have SNs 9 to 15 points higher than that observed on the standard HL1 mix. Over the five years in service, the OFC and the DFC mixes maintained significantly higher friction levels in comparison with the HL1 mix. With a total of approximately 24 million vehicle passes, 7 million of which were heavy commercial trucks, the skid resistance of the OFC and the DFC mixes was close to or above the identified target friction level, whereas the skid resistance of the standard mix declined sharply below target values during the first year in service.

Both the DFC and the OFC mixes that had high stone content are characterized by well-developed macrotexture of the surface. The texture and appearance of such mixes can be described as coarse, rugged, and open in comparison with the fine, level, and tight surface of conventional mixes.

As indicated previously, the OFC and the DFC mixes also retain a high level of skid resistance during particularly adverse conditions such as heavy rain and light snow or slush on the surface (Figure 6). The performance of two OFC and four DFC test mixes in the Highway 401 experimental sections has been excellent. During their seven years in service, these mixes have maintained high skid-resistance levels and excellent overall performance.

The OFC surfaces also provide reduced tire-pavement noise levels. An earlier study (12) found the OFC mixes 3 dB(A) quieter than adjacent smooth concrete and 4-5 dB(A) quieter than a typical conventional HL1 mix. This study measured near-tire noise levels by using a microphone mounted 152 mm from the road surface on a 1974 Ford LTD sedan equipped with summer radial tires and operated at 100 km/h.

Winter Performance and Maintenance

MTC also carried out a study of the OFC and DFC mixes on the Highway 401 Toronto By-Pass to observe pavement performance during various winter storms and to determine whether more deicing materials were required to clear these coarse open-textured mixes (13). Adjacent normal dense-graded asphalt surfaces and concrete pavements were included as control sections.

The observations extended over two winters and covered all types of winter storms with particular emphasis on freezing rain storms. The following results were found:

1. Spinning of the sand and salt in such a way to cover all traffic lanes is the most effective way to clear OFC pavements. More salt was not required to clear OFC and DFC pavements.
2. Under most storm conditions, the OFC and DFC pavements appeared to provide the best friction levels.
3. The timing of salt applications with respect to freezing rain storms appeared critical for all pavement surface types. With spinning of the deicing materials, freezing rain storms presented no problems on the OFC and the DFC pavements.

BITUMINOUS-SURFACE-COURSE POLICY

In 1978, as a result of this work, MTC introduced a new policy for bituminous-surface-course construction on freeways and other main highways in Ontario. The new policy specifies the use of OFC mixes for all urban freeway surfacing and the use of DFC mixes on other freeways and main highways that carry a traffic volume in excess of 5000 vehicles/lane/day. HL1 mixes are used on facilities that have an AADT range between 2500-5000 vehicles/lane/day.

Since the introduction of the new surface policy in 1978, a total of approximately 400 lane-km (250 lane miles) of pavement has been constructed by using OFC and DFC mixes in the MTC system. For freeways and main highways only traprock and steel-slag coarse and fine aggregates are acceptable for DFC mixes.

Table 5. Tentative guidelines for friction-classification system.

Facility Type	Speed Limit (km/h)	Friction Level (SN) at Speed Limit		
		Good	Borderline	Low
Freeway and main highway	100	>30	25-30	<25
Two-lane and four-lane road	80	>31	27-31	<27
Intersection	80	>39	31-39	<31
	60	>44	36-44	<36

Note: 1 km = 0.6 mile.

FRICTION-COURSE MIXES FOR REHABILITATION AT BLACK-SPOT HIGHWAY LOCATIONS

In 1978, procedures were also introduced that identified highway locations that had high rates of wet-pavement accidents (black spots). It was found that although the total length of identified black spots on the system represented only a fraction of a percentage point (0.29 percent), they exhibited 26 percent of the total wet-pavement accidents on the system (14). The study also found that wet-pavement collisions on freeway and four-lane black spots account for more than 75 percent of the total black-spot accidents.

The black-spot improvement program provided an excellent opportunity to test the effectiveness of the new friction-course mixes. Both the OFC and the DFC mixes were used for rehabilitation at such highway locations. The tentative friction guidelines shown in Table 5 have been used in establishing priorities for treatment. Rehabilitation at some black spots included geometrics and/or other improvements as well as resurfacing as noted in the following sections.

Number of Accidents Before and After Treatments at Freeway Black Spots

Table 6 shows the number of wet-pavement and total accidents before and after resurfacing at eight freeway locations treated during the period 1976-1978. Six locations are on the Highway 401 Toronto By-Pass, one on Highway 401 near London, and one on Highway 417 (Ottawa Queensway). Two years' accidents were considered before resurfacing, and one, two, and three years' accidents were considered after treatment for work done in 1978, 1977, and 1976.

Reductions in wet-pavement accidents after resurfacing ranged between 17 and 73 percent. For all eight locations combined, an average of 54 percent reduction in wet-pavement accidents was obtained.

Table 6. Change in accidents before and after resurfacing at black-spot freeway locations.

Location	Year of Treatment	Wet-Pavement Accidents		Total Accidents		Remarks
		No.	Change (%)	No.	Change (%)	
Highway 401, Toronto: Interchanges 51A to 53, express lanes	1976	B 64 A 30	-53	B 220 A 173	-21	Eastbound and westbound, three lanes each direction
Collector lanes	1977	B 40 A 23	-40	B 155 A 118	-24	Eastbound and westbound, three to four lanes each direction
Interchanges 58 to 57, collector lanes	1978	B 7 A 2	-71	B 16 A 5	-69	Westbound, three lanes before and four lanes after treatment
Interchange 56 to 55, collector lanes	1978	B 22 A 10	-55	B 46 A 35	-24	Westbound, four lanes
Transfer lanes at Interchange 56	1978	B 15 A 6	-60	B 26 A 15	-42	Westbound, two lanes; AADT, 17 000
Interchanges 51A to 50, collector lanes	1978	B 30 A 25	-17	B 98 A 92	-6	Westbound, three to four lanes
Highway 401, London: Interchange 19 to 1.1 km west	1978	B 6 A 2	-67	B 13 A 7	-46	Only two westbound lanes treated; WB AADT, 9000
Highway 417, Ottawa: St. Laurent Boulevard to Hurdmans Bridge	1977	B 73 A 20	-73	B 168 A 79	-53	Eastbound and westbound, two lanes before and three lanes after treatment; AADT, 61 000 in both directions
Total		B 257 A 118	-54	B 742 A 542	-29	

Note: B and A designate number of accidents before and after resurfacing, respectively.

Table 7. Change in accidents before and after treatment at black-spot intersections.

		Wet-Pavement Accidents		Total Accidents			
Location	Year of Treatment	No.	Change (%)	No.	Change (%)	Rehabilitation Type	Remarks
Highway 7 at Islington Avenue	1978	B 17 A 4	-76	B 35 A 11	-69	DFC mix with 100 percent traprock aggregate plus warning traffic sign	Four-lane undivided, 6 percent grade; AADT, 27 000; only westbound lanes (downgrade) treated
Highway 2, Counter St., Kingston	1978	B 6 A 4	-33	B 13 A 13	None	DFC mix with 100 percent traprock aggregate	Four-lane divided, 5 percent grade, sharp curve; AADT, 17 000
Highway 40 at Plank Rd., Sarnia	1978	B 5 A 1	-80	B 7 A 3	-57	DFC mix with 100 percent steel-slag aggregate	Four-lane undivided; AADT, 7500; slight grade
Highways 2 and 4 at Wonderland Road, London	1978	B 4 A 1	-75	B 12 A 9	-25	DFC mix with 100 percent steel-slag aggregate	Four-lane undivided; AADT, 8750; slight grade
Highway 3 at Ridge Road	1977	B 3 A -	-100	B 4 A 2	-50	Retexturing by cold planing	Four-lane undivided; 4 percent grade; AADT, 6000; only two westbound lanes downgrade treated
Total		B 35 A 10	-71	B 71 A 38	-46		

Note: B and A designate number of accidents before and after treatment, respectively.

Overall reduction in total accidents (i.e., wet, dry, snow, and ice) was 29 percent.

An OFC mix was used on all the Highway 401 Toronto locations and a DFC mix was used at London and on Highway 417. In all projects the surface-course mix included traprock coarse aggregate and traprock screening fines, except on Highway 401 at London where steel-slag coarse and fine aggregates were used. At Highway 417, rehabilitation included widening the pavement from two to three lanes in each direction. In all cases the old pavement was concrete. Resurfacing with the OFC and DFC mixes has approximately doubled the skid-resistance levels.

It is interesting to compare the number of accidents on the treated portions of the Highway 401 Toronto By-Pass with the accidents on the total length of the by-pass [30 km (19 miles)]. During the period of observation, traffic volumes increased by approximately 25 percent, a number of geometric improvements were made, and in 1976 the speed limit was reduced from 112 km/h (70 mph) to 100 km/h (60 mph). In the five-year period between 1975 and 1979, the total number of accidents on the 30-km section remained at relatively constant annual levels. The wet-pavement accidents as a percentage of total accidents varied between 31 and 33 percent for the period between 1975 and 1977 and 24-26 percent for 1978 and 1979. It would appear that as more rehabilitation work is carried out at black-spot locations on the by-pass, further reductions in the number and the percentage of wet-pavement to total accidents may be achieved.

Number of Accidents Before and After Treatment at Signalized Intersections

Table 7 gives the number of wet-pavement and total accidents before and after rehabilitation at five black-spot signalized intersections treated in 1977 and 1978. An average of two years' accidents before and one year after treatment was considered.

The reductions in wet-pavement collisions after treatment ranged between 33 and 100 percent. Overall, for the five intersections combined, an average of 71 percent reduction in wet-pavement accidents and 46 percent in total accidents was obtained. Pavement skid-resistance levels observed before and after treatment at various sites showed improvements between 13 and 20 SNs as measured by the ASTM skid trailer.

With one notable exception, treatment at all sites included resurfacing with a DFC mix. Traprock coarse and fine aggregates were used on Highway 7 and on Highway 2 and steel-slag coarse and fine aggregates were used on Highway 40 and on Highways 2 and 4. For Highway 3, treatment included retexturing of the pavement surface by cold planing by using a CMI rotomill (3).

The old pavement in all cases was bituminous concrete. Major deficiencies included excessive polishing of coarse aggregates on the surface, wheel-track rutting, and surface contaminations by oil deposits at the intersections.

Treatment of black-spot intersections appears most effective at the intersection of Highway 7 and Islington Avenue in Woodbridge. At this location, rehabilitation included resurfacing with a DFC mix plus installation of an electronic overhead warning traffic signal with flashing lights at the top of the grade approaching the intersection. The sign operates in conjunction with the traffic lights at the intersection and reads Be Prepared to Stop when the amber or red lights are on. During the time prior to rehabilitation, this location had consistently shown a high incidence of wet-pavement accidents. During the first year after treatment, rehabilitation resulted in a 76 percent reduction in wet-pavement accidents and a 69 percent reduction in the total accidents at the intersection.

CONCLUSIONS

1. Both macrotexture and microtexture qualities required for good wet-pavement friction characteristics are influenced by the quality and gradation of the aggregate in the asphalt mix. Mixes that contain aggregates with higher PSVs produce higher friction levels.
2. PSV should be considered along with aggregate abrasion characteristics, particularly for high-speed traffic in which maintenance of angular macrotexture stone projections on the pavement surface is essential in providing good friction levels. Stones that have moderate PSVs but high abrasion resistance, such as the traprock materials in southern Ontario, provide satisfactory skid-resistance performance under extremely heavy traffic.
3. Blending a higher PSV coarse aggregate in a mix can yield significant skid-resistance improvements.
4. The use of a high percentage of crushed coarse aggregate in bituminous mixes appears to

produce better and longer-lasting surface textures and skid-resistance levels. Such stonier mixes also have economic advantages, mainly because of less requirement for asphalt cement. Sand mixes containing traprock screenings that produce good microtexture but little macrotexture provide a reasonable level of skid resistance when tested under standard conditions with the brake-force trailer but exhibit 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.

5. For very heavily trafficked pavements with large numbers of trucks, use of prime-quality (hard, harsh, and angular) crushed coarse and fine aggregates is essential so that adequate texture and skid-resistance levels can be maintained under such severe traffic conditions. For moderate traffic volumes, skid-resistance levels of bituminous mixes are predominantly influenced by the type of coarse aggregate in the mix. The role of the fine aggregate is significantly less apparent than that in the case of heavily trafficked highways.

6. Performance analysis of various test mixes on Highway 401 in Toronto and Highway 7 in Lindsay identified target total aggregate gradation limits for DFC and OFC mixes. Mixes within such gradations produce excellent surface textures and maintain superior overall friction levels. They also maintain high levels of skid resistance during adverse weather conditions such as heavy rain or light snow and slush on the pavement surface. The OFC mixes provide reduced noise levels.

7. Use of the new friction-course mixes at highway locations that have low friction levels and experience a high rate of wet-pavement collisions appears to produce substantial reduction in wet-pavement and total accidents.

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