A Skid Resistance Study in Four Western States

JOHN A. MILLS, III, Federal Highway Administration, Bureau of Public Roads, Richmond, Virginia

With the increasing emphasis on safety in highway engineering, the Bureau of Public Roads, together with the state highway departments of Colorado, Wyoming, Utah, and New Mexico, conducted a skid resistance study of pavement surfaces in the four states

All testing was conducted with the Bureau of Public Roads skid trailer following ASTM criteria and procedures. A total of 979 tests were conducted on a variety of surface types and highway systems.

Due to its open-textured surface, the bituminous plant-mix seal gave the highest skid-resistance coefficients; followed by chip seals, asphalt concrete and concrete. With chip seals, as with all other surfaces, ADT and age proved to be the most influential factors governing the skid resistance of pavements. A big difference in skid resistance between the inside and outside lanes on four-lane roads was frequently noticed throughout the four states.

It was concluded that the use of bituminous plant-mix seals is the best means now available for insuring a high-quality skid-resistant surface, not only as an overlay on existing surfaces, but also in the construction of new pavements. This study proved beneficial to the Bureau of Public Roads and to the participating four states. A working knowledge of the skid resistance of existing roads is, and will continue to be, extremely helpful to highway engineers.

•THERE has been an increasing awarness of the problem of pavement slipperiness. Together with strength and durability, a good skid-resistant pavement surface has become an integral part of a safe and effective highway system. With the increase in highway traffic speeds and the increase in traffic densities, roads built today must have initial and continuous high skid-resistance qualities.

It is a known fact that skid resistance of pavements is reduced primarily through wear and polish by traffic; however, to what extent the friction characteristics are lessened and the other causes and effects of this reduction are problems the research and highway engineers must face.

Although the automotive and tire industries have contributed a great deal to the research and development of skid-resistant pavements, it is quite obvious that the bulk of improvement will fall upon the highway agencies.

PURPOSE

The purpose of this study was to compare the skid-resistance values of plant-mix seals with those obtained from other conventional surface types, and to show comparisons and trends of skid resistance based on such variables as ADT, age, asphalt content, and type and grade of aggregate used on roads throughout Colorado, Wyoming, Utah and New Mexico.

This study also presents the results of those roadway sections exposed to research construction or maintenance, and of bridge deck testing in the four states.

DESIGN OF STUDY

During the four-week period in June and July 1967, the Bureau of Public Roads' skid trailer measured the skid resistance of roadways preselected by the state highway departments of Colorado, Wyoming, Utah and New Mexico in cooperation with the Bureau of Public Roads' Division offices. The test sites were arranged geographically, with the exception of Colorado, to cover as many different surface types and highway systems as possible. The bulk of testing in Colorado was centered in and around the city of Denver.

The testing equipment consisted of a ¾-ton pickup tow vehicle and a 2-wheeled trailer. The tow vehicle contained a Brush oscillograph for recording the coefficient of friction, a water supply tank and pump, and the brake actuation controls. The trailer included a brush applicator for applying water in front of the test wheel, and instrumented braking system with SR-4 strain gages for the skid resistance measurement, and a standard pavement test tire, E-17.

As outlined in ASTM the trailer was brought to a test speed of 40 mph before the operator actuated the electrical timing equipment. Operating on a 7-sec automatic cycle, a film of water was delivered to the pavement ahead of the test tire and the braking wheel was locked for two seconds (sliding distance of 118 ft). The resulting coefficient of friction based on wheel torque was recorded on a 2-channel oscillograph.

RESULTS

General

During the four weeks of testing, the skid tow vehicle and trailer traveled approximately 4,800 miles throughout the four-state area. A total of 979 tests were taken, but only 800 were used in the correlation of data included in this report. To facilitate the correlation of data, certain assumptions were made.

1. The construction stage of the pavements tested was not considered in the correlation of data.
2. The composition of the previous pavement surface overlaid by a chip seal or plant-mix seal was not considered, as the coefficient of friction measured was only on the existing surface course.
3. The primary objective of this study was to compare the skid resistance of various pavement surfaces and not to study the effect of speed, therefore, all data used in the correlation and comparisons were taken from the standard test established by ASTM (40-mph speed of trailer).
4. The tests run on paint stripes, between wheel tracks and on shoulders are not included in the correlation of the 800 tests.
5. Those tests run on slick spots or other sections that are not truly characteristic of the entire roadway were not included in the correlation.

Table 1 gives a summary of coefficients by lanes by states; see also Figures 1 through 5.

Wyoming

Plant-Mix Seals—The Wyoming plant-mix seals gave the highest friction values recorded in the four states A close analysis of the materials and quality control used on the plant-mix seals indicates that, due to the many variables involved in and on the pavement, only the following general trends can be concluded:

1. Bank gravel gave higher results than limestone, but this was expected as the limestones generally tend to polish more readily with age and wear.
2. The greater the percentage of fractured faces in the material retained on the No. 4 screen, the higher the coefficient of friction. (The author feels 100 percent fractured faces is most desirable for a high-quality, skid-resistant plant-mix seal).
3. The percent of asphalt varied from 5. 2 to 7.4 with the majority of test sections containing between 6 and 7 percent. The trend in plant-mix seals is that the coefficient of friction increases as the percent of asphalt content decreases; however, it should be

TABLE 1

SUMMARY OF COEFFICIENTS BY LANES BY STATES

State	2 Lanes—1 Direction[a] Driving	2 Lanes—1 Direction[a] Passing	1 Lane—1 Direction[b]
	Colorado[c]		
Plant-mix seals	7 02/15 = 0 47	0 57/1 = 0 57	2 86/7 = 0 41
Concrete	9 62/26 = 0 37	0 90/2 = 0 45	None Tested
Asphaltic concrete	20 40/63 = 0 32	0 84/2 = 0 42	5 89/14 = 0 42
Chip seals	None Tested	None Tested	None Tested
	Utah		
Plant-mix seals	12 00/25 = 0 48	9 04/17 = 0 53	22 64/43 = 0 53
Concrete	3 43/8 = 0 43	4 92/11 = 0 45	None Tested
Asphaltic concrete	9 45/22 = 0 43	5 07/12 = 0 42	2. 55/5 = 0 51
Chip seals	6 06/12 = 0 51	4 57/8 = 0 57	6 07/11 = 0 55
Road mix	None Tested	None Tested	2 21/8 = 0 28
	Wyoming		
Plant-mix seals	6 63/12 = 0 55	2 97/5 = 0 59	16 57/31 = 0 53
Concrete	3 63/9 = 0 40	1 59/3 = 0 53	None Tested
Asphaltic concrete	9 78/21 = 0 47	6 78/12 = 0 57	4 37/9 = 0 49
Chip seals	7 26/17 = 0 43	4 27/7 = 0 61	6 90/14 = 0 49
	New Mexico		
Plant-mix seals	16 86/34 = 0 50	12 75/23 = 0 55	None Tested
Concrete	11 83/26 = 0 46	14 01/29 = 0 48	None Tested
Asphaltic concrete	29 21/62 = 0 47	27 26/50 = 0 55	26 16/54 = 0 48
Chip seals	None Tested	None Tested	8 13/18 = 0 45

[a] In the case of 3 lanes in 1 direction, the middle and inside lanes are in the passing lane category for 2 lanes—1 direction, and the right lane is in the driving lane category for 2 lanes—1 direction

[b] In the case of a roadway having 1 lane in 1 direction with a climbing lane, the test results for each lane are shown as 1 lane—1 direction Ramps and deceleration lanes are classified with 1 lane—1 direction

[c] The tests on plant-mix sand seals in Colorado were included in the category of asphaltic concrete

noted that all sections tested gave high values. Further, while this trend is noted from a skid resistance standpoint, other factors should be considered before attempting to significantly reduce the percent of asphalt.

Portland Cement Concrete—Due to the small number of rigid pavement sections, only 12 tests were conducted with an average friction coefficient of 0.44. This value is only 0.03 less than the maximum value attained on rigid pavements in the four states, and no significant characteristic was outstanding. As in flexible pavements, bank gravel aggregates gave higher values than did limestone. One test was taken on the tunnel floor paving along I-80. The Class B concrete surface yielded a value of 0.35, which is 0.09 lower than the rigid pavement average for Wyoming and 0.06 lower than the average for concrete structures in the four states.

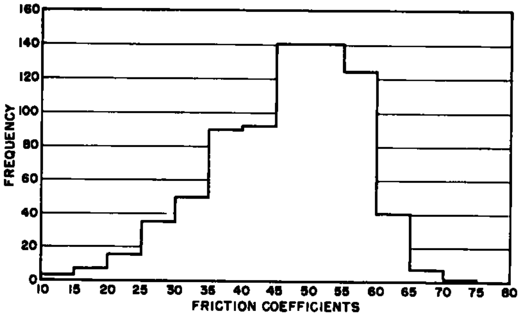

Figure 1. All surface types.

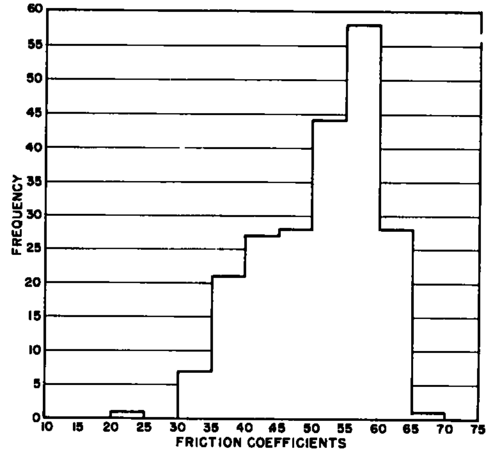

Figure 2. Plant-mix seal.

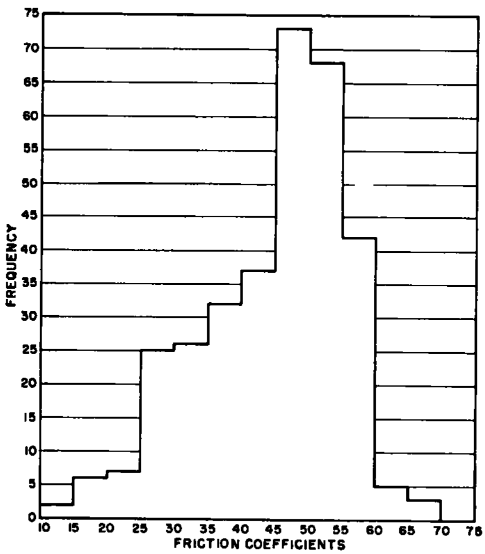

Figure 3. Asphalt concrete.

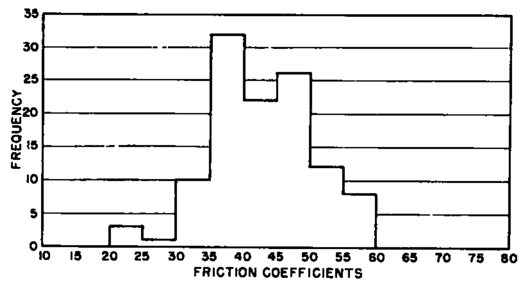

Figure 4. Concrete.

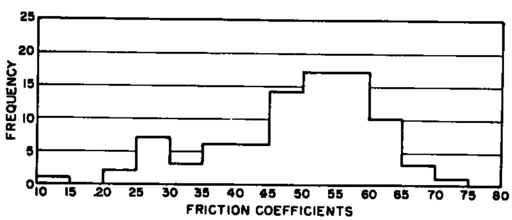

Figure 5. Bituminous-chip seal.

Asphaltic Concrete—All tests on plant-mix asphaltic-concrete sections in Wyoming were along Interstate routes, and a comparison of the average values indicates a definite trend in the coefficient of friction obtained in the outside or traveled lane and the inside or passing lane. The outside lane constantly indicated a lower coefficient than the inside lane. This is not surprising as the outside lane is exposed to a much higher traffic density than the inside lane. This trend points out a need for anticipating this decrease in skid resistance and compensating for it either during initial construction or through maintenance operations.

Chip Seals—To substantiate further the above statement regarding lane differences, the average values for chip seals by lanes show a difference of 0.18. This difference between lanes is the largest in comparison with any pavement type in all four states. The sections tested were composed of limestone, quartzite and granite, and scoria (burned shale), with the majority of surfaces having limestone chips. A comparison

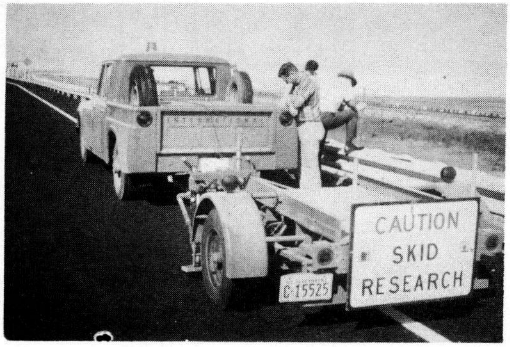

Figure 6. Tow vehicle and skid trailer.

of the native material shows granite and quartzite having a skid resistance value of 0.45, limestone having a value of 0.50 and scoria chips having a coefficient of 0.63.

One section of highway in northwest Wyoming was tested where "deslicking operations" of an old limestone chip seal were in progress. An average of the 15 tests on the old surface gave a coefficient of friction of 0.16. ["The coefficient of friction at incipient skid on untreated ice varied from 0.08 to 0.20 (1)."] An average of the tests run on the deslicked area gave a coefficient of 0.60. This increase from 0.16 to 0.60 is on a section one month old, and the answer to how long the deslicked surface will maintain this high coefficient remains to be determined. To accomplish the deslicking a repaver heated the old surface, and sand and gravel were spread and rolled on the roadway.

Colorado

The majority of tests representing Colorado data were run in or near the city of Denver. Table 2 indicates that the values obtained are lower on an average than values for similar pavement types tested in the other states. It is possible that the heavy ADT in and near Denver could be a factor contributing to the lower values.

Plant-Mix Seals—All plant-mix seal sections tested were composed of granite; consequently, a comparison of aggregate type relative to friction coefficients is impossible.

The composition of the plant-mix seals tested can be separated into two groups—a clear crack granite aggregate with 100 percent fractured faces on the plus 4 material, and an asphalt content of 7 percent; and a clear crack granite aggregate 85 percent with fractured faces and an asphalt content of 8 percent. A comparison of the average values obtained on the two compositions shows a difference of better than 0.10, with the 7 percent asphalt and 100 percent fractured faces composition being higher. All sections tested were within several months of being the same age, and it is believed that the ADT difference on the two compositions is the primary reason for the difference in friction coefficient. With only one test run in the inside lane, a valid comparison of lanes for this pavement is impossible.

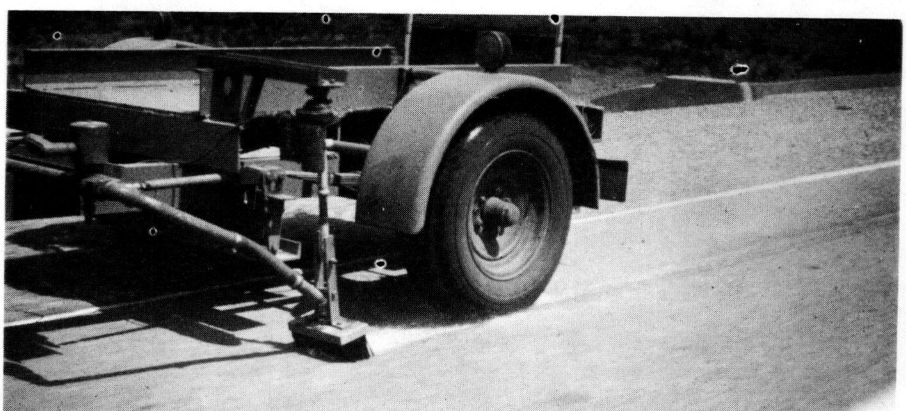

Figure 7. Skid trailer in braking cycle.

TABLE 2

SUMMARY OF PAVEMENT COEFFICIENTS BY STATE

Pavement Type	Colorado	Utah	Wyoming	New Mexico	4-State Average
Plant-mix seals	$\frac{10.45}{23} = 0.45$	$\frac{43.68}{85} = 0.51$	$\frac{26.17}{48} = 0.55$	$\frac{29.61}{57} = 0.52$	$\frac{108.92}{211} = 0.52$
Concrete	$\frac{10.52}{28} = 0.38$	$\frac{8.34}{19} = 0.44$	$\frac{5.22}{12} = 0.44$	$\frac{25.84}{55} = 0.47$	$\frac{49.93}{11} = 0.44$
Asphaltic concrete	$\frac{27.13}{79} = 0.34$	$\frac{17.07}{39} = 0.44$	$\frac{20.93}{42} = 0.50$	$\frac{82.63}{166} = 0.50$	$\frac{147.76}{326} = 0.45$
Bit-chip seals	None Tested	$\frac{16.70}{31} = 0.54$	$\frac{18.43}{38} = 0.49$	$\frac{8.13}{18} = 0.45$	$\frac{43.26}{87} = 0.50$
Road mix		$\frac{2.21}{8} = 0.28$	None Tested	None Tested	$\frac{2.21}{8} = 0.28$

In the above table the figures in the denominators denote the number of tests on the respective pavements.

Portland Cement Concrete—The discussion of the rigid pavement results is restricted, since only limited information on pavement compositions was available. An analysis of the test data does not show any definite trends. In some cases, the values obtained on sections 12 and 15 years old were higher than those only 2 or 3 years old. As with other pavements, there is an indication that friction values decrease faster on those sections exposed to higher ADT.

A section of longitudinally grooved rigid pavement was tested near Peckham. The section was subjected to intermittent grooving to decrease surface roughness, and the results show an increase in friction coefficient from 0.35 on the ungrooved section to 0.40 on the grooved section. These tests were run in the outside lane, with the inside lane yielding a value of 0.48. Further tests were run on the same pavement six miles from the grooved area, and the results show a coefficient of 0.40 (ungrooved). The data, coupled with the information in the discussion of Utah's results on grooved pavements, lead to the conclusion that grooving, although highly effective in reducing "hydroplaning," does little to increase skid resistance.

Asphaltic Concrete—Seventy-nine tests were averaged in determining the skid resistance value for Colorado. The value of 0.34 is the lowest for any surface type in any state, and this low value is believed to be due to the wide use in the Denver area

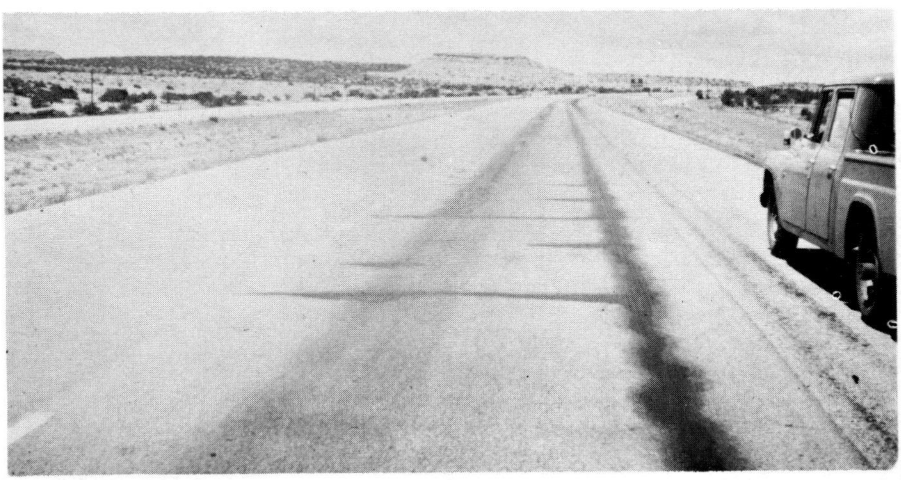

Figure 8. A plant-mix seal surface with flushing in the outside lane, outside lane coefficient = 0.38 and inside lane coefficient = 0.58, age = $1\frac{1}{2}$ yr, ADT = 6590, limestone, 75 percent fractured faces, 6.5 percent asphalt content.

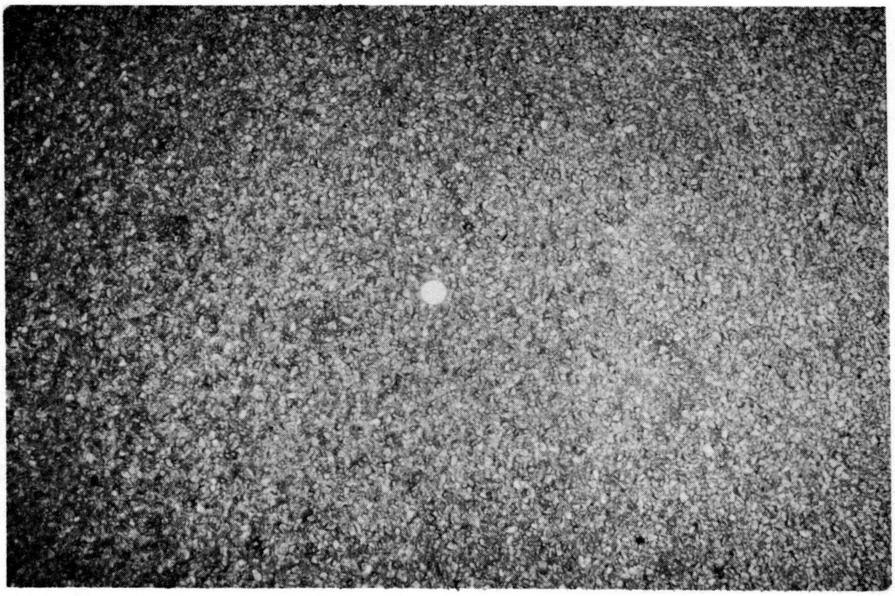

Figure 9. A close-up of the inside lane in Figure 8, where coefficient = 0.58.

of different asphaltic seals and overlays. Coated aggregate on fog-sealed mat, flushed surfaces, fine-grain sealed mats, and dense-graded plant-mix were the three more prominent surfaces tested. Since only two tests were run on the inside lane of a 2-lane, 1-direction highway, a lane comparison for this surface type was not considered. There were no chip-sealed surfaces tested in Colorado for use in this study.

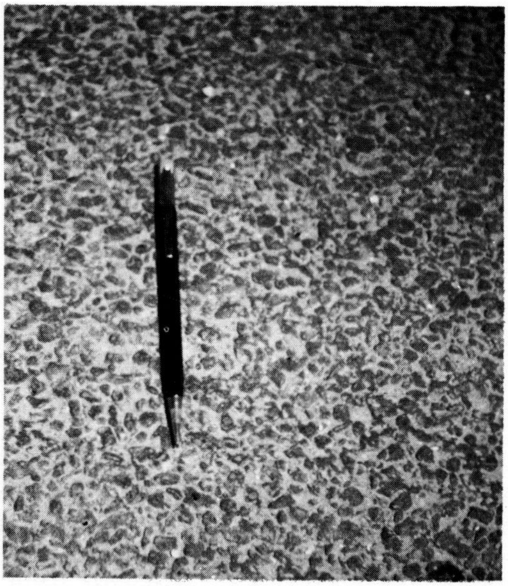

Figure 10. A plant-mix seal surface with coefficient = 0.62, age = 2 yr, ADT = 95, bank gravel, 95 percent fractured faces, 6.5 percent asphalt content.

New Mexico

Plant-Mix Seals—Fifty-seven tests were conducted on plant-mix sealed projects with an average value of 0.52 (the average for all the plant-mix seals tested in the four states). The testing is more evenly divided between the inside and outside lanes than in the other States, making the comparisons between lanes more substantial.

Of the nine projects with plant-mix seals, eight were tested in both the inside and the outside lanes with an average difference of only 0.05. This small difference could result from the greater percentage of vehicles driving in the inside lane than in other states, or perhaps the plant-mix seals in the outside lane are holding up extremely well under traffic. The aggregate compositions used in the plant-mix seals were sand and gravel, limestone, and gravel. A comparison of the friction coefficients by aggregate type shows that both sand and gravel, and gravel yielded a value of 0.56; limestone is 0.09 lower with a value of 0.47. This difference is believed to be caused by polishing of the limestone.

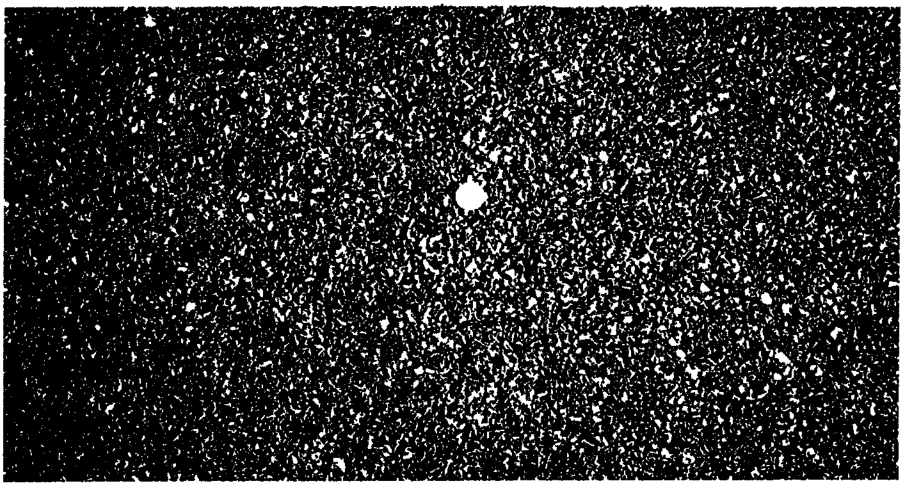

Figure 11. A plant-mix seal surface with coefficient = 0.38, age = 2 yr, ADT = 2880, limestone, 75 percent fractured faces, 6.5 percent asphalt content.

Since all plant-mix sections tested had 75 percent fractured faces on the plus 4 material, a comparison of this property is omitted. The percent of asphalt content ranged from 6 to 7 percent, with no definite trend as to the asphalt content influencing the coefficient of friction. A research project consisting of a plant-mix seal with a rubber additive was tested on a Federal-aid primary route in Santa Fe. The additive, Goodyear Plyopave LO-170, was 3 percent by weight of the mix and yielded coefficients of approximately 0.02 below the state average for the driving and passing lanes. Even though the coefficient of friction was not appreciably affected by this additive, it may extend the service life of the mix through increased flexibility and decreased hardening of the asphalt.

Portland Cement Concrete—All concrete sections tested were on Interstate routes, with an ADT range from 2,000 to 5,000. A graphical study of the data based on age with the previously mentioned ADT range disclosed a very gradual decrease in the friction coefficient after the second year. For the first two years the pavement surface seemed to experience fluctuations, which could have been caused by different types of surface finishes or the wearing down of the mortar. New Mexico had the highest average for rigid pavements in the four states (Table 2). The aggregates used were gravel, limestone, basalt, and sand and gravel, with limestone being the most predominantly used and yielding the highest coefficient average. A comparison showed the following averages: limestone 0.51, basalt 0.47, gravel 0.41 and sand and grave 0.39. The aggregates other than limestone received only limited testing. The limestone sections tested ranged in age from 1½ to 7 years and the percent of wear by the abrasion tests ranged from 19.6 to 30 percent.

Figure 12. Good surface drainage from a plant-mix seal.

Asphaltic Concrete—Due to limited information, a comparison of the percent of

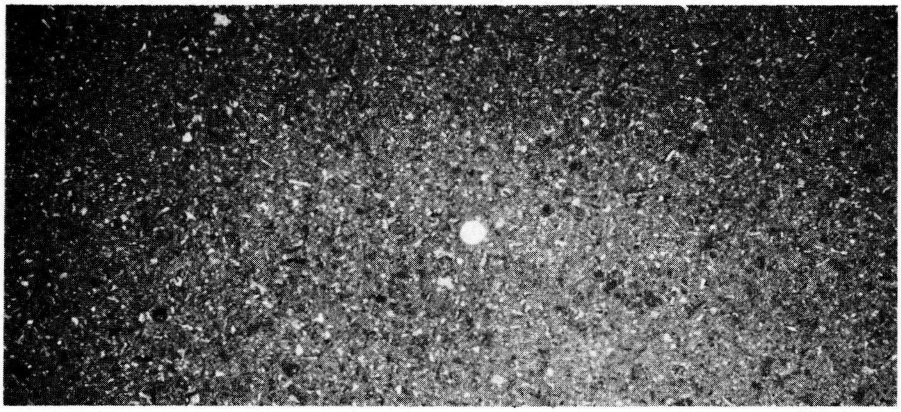

Figure 13. An asphaltic-concrete surface, coefficient = 0.53, age = 1½ yr, ADT = 945, limestone, 60 percent fractured faces, 6.0 percent asphalt content.

Figure 14. An asphaltic-concrete surface with flushing in the outside lane, outside lane coefficient = 0.39 and inside lane coefficient = 0.55, age = 3 yr, ADT = 6210, basalt, 60 percent fractured faces, 5.75 percent asphalt content.

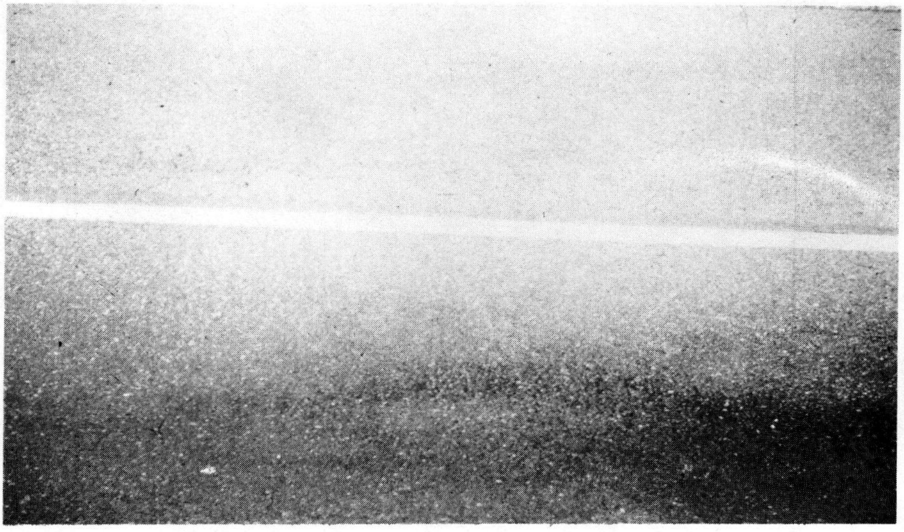

Figure 15. Close-up of Figure 14.

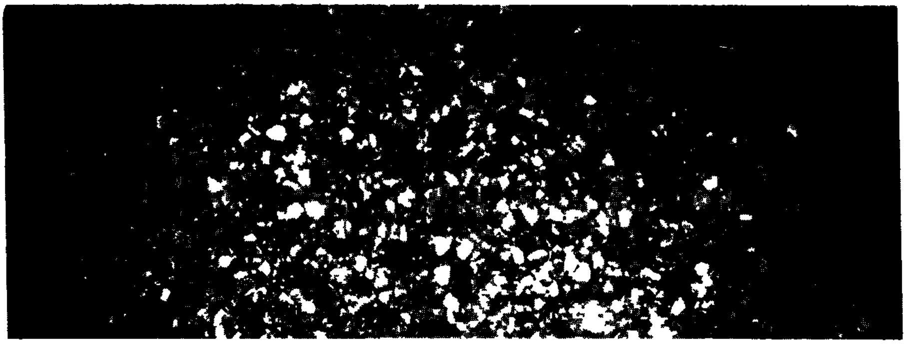

Figure 16. A chip seal surface with coefficient = 0.63, age = 3 yr, ADT = 73, quartzite and sandstone.

fractured faces of the plus 4 material in the asphaltic-concrete sections was not made. Of the 166 test results used in the analysis of asphaltic concrete, there were four different aggregate types tested and a comparison of the four showed a difference of only 0.04 between the lowest, basalt, and the highest, gravel (gravel 0.51, sand and gravel 0.50, limestone 0.49, and basalt 0.47). Even though the majority of tests were run on Interstate routes, the one-way ADT ranged from 125 to 5,465 with the average for the state approximately 1,500. A research project was conducted on an asphaltic-concrete surface treated with different types of fog seals. The following averages are based on three to eight tests on each section: Reclamite 0.49, Gilsonite 0.43, MC70 0.35, SC70 0.52, SSKH 0.40. These fog seals are being studied for surface rejuvenation.

Chip Seals—Only 18 tests were used for an average on chip seals, and due to the limited information available, very little could be gained from the sections tested. The only aggregate used was gravel and the test sections, which ranged from one to six years, showed no significant trends.

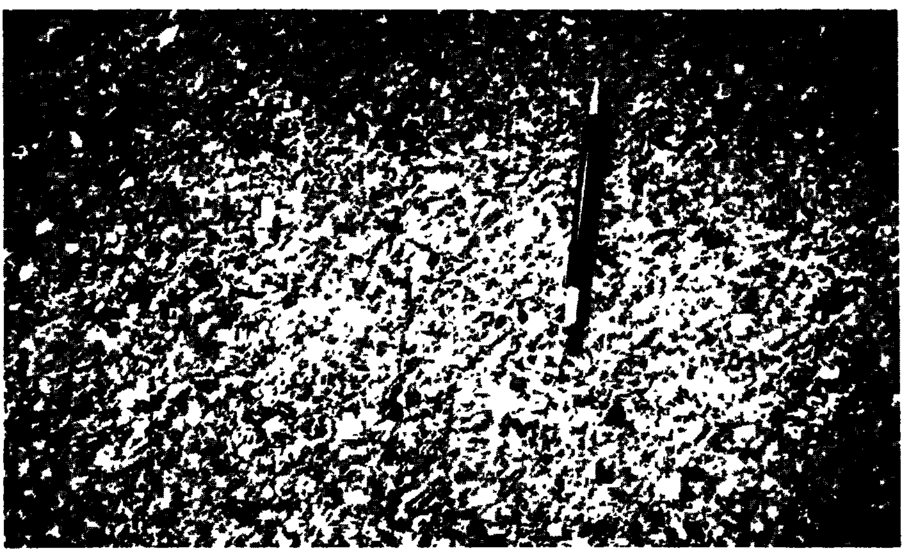

Figure 17. A chip seal with a coefficient = 0.60, age = 4 yr, ADT = 965, scoria (burned shale).

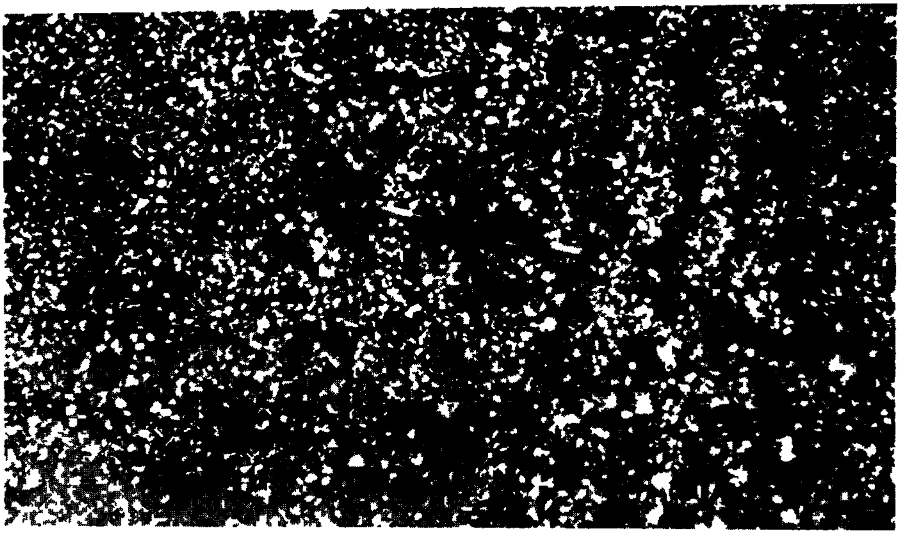

Figure 18. A chip seal surface before "deslicking operations" where coefficient = 0.16, ADT = 355 (other information not available).

Utah

Plant-Mix Seals—More plant-mix seals were tested in Utah than in any of the other states with an average value of 0.51. Over half of the tests were conducted on 1-lane, 1-direction roads, and these tests had the same average as the passing lane of the 2-lane, 1-direction roads. The only obvious reason for this similarity is that a great majority of the testing on 1-lane, 1-direction routes was on Federal-aid primary routes with reduced ADT.

The aggregate combinations used in the plant-mix seals were limestone, quartzite, sandstone, and basalt. One section contained open hearth slag. Due to the limited information available, a valid comparison as to percent of fractured faces, aggregate

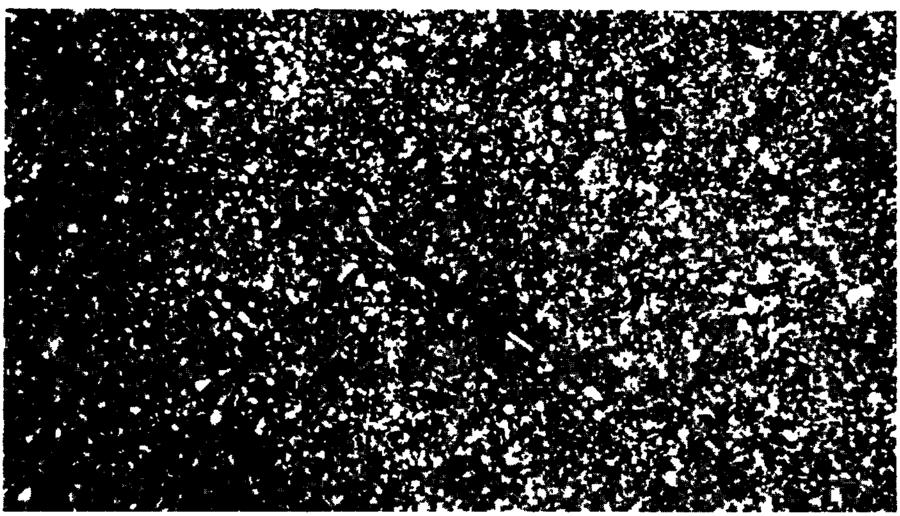

Figure 19. The same chip seal surface shown in Figure 18 after "deslicking operations" where coefficient = 0.60.

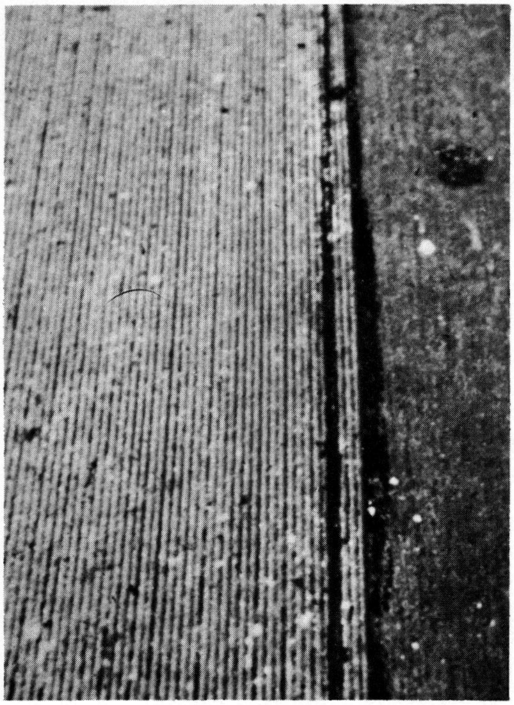

Figure 20. A concrete surface with longitudinal grooving on the left and the original surface on the right; coefficient on grooved section (left) = 0.40 and coefficient on ungrooved section (right) = 0.35, age = 15 yr, ADT = 2850 (other information not available).

used, and percent of asphalt was not made. The data available indicated a desirable minimum of 74 percent fractured faces with an asphalt content range between 6 and 7 percent.

One section was tested, which had been exposed to deslicking operations. The operation consisted of heating the pavement surface without applying any cover material. Six tests were run on this section, and no conclusions were made. Two tests on sections adjacent to the deslicked area gave an average of 0.56. Two tests on bleeding sections adjacent to the deslicked area gave an average of 0.42, and the two tests on deslicked sections gave values of 0.33 and 0.59.

Portland Cement Concrete—All testing of concrete was on Interstate routes with only 19 tests used for averaging. A comparison of values obtained on the driving and passing lanes showed a difference of only 0.02. This small difference between lanes is believed to be due to uniform wear of the concrete surface. There is a definite trend for the friction coefficient to decrease with age, which has been the case for most of the other surface types. Aggregate type was not available on concrete so a discussion of this property will be omitted. The test results of a concrete bridge deck exposed to grooving will be discussed in the section on bridges.

Asphaltic Concrete—The most widely used aggregates in asphaltic concrete were limestone, sandstone and quartzite, and limestone and quartzite. A comparison of the aggregate types showed quartzite and limestone having the highest value, 0.46, with sandstone and quartzite having 0.44, and limestone having the lowest, 0.35.

An irregularity was noticed in the lane comparison of asphaltic concrete between the driving and the passing lanes. It is believed that this decrease in the passing lane value is due to unbalanced field testing.

Chip Seals—The chip seals in Utah yielded the highest friction coefficient of all the states. The aggregate chips tested were combinations of limestone, sandstone, and quartzite. One section of Interstate tested had a blended aggregate composition of 60 percent mineral aggregate and 40 percent slag. In comparing the results of the different aggregate compositions, the reader should bear in mind that in several cases the averages are based on results obtained on only one project. Combinations of both sandstone and quartzite, and blended mineral aggregate and slag gave the highest coefficient of 0.62; quartzite and limestone had 0.57; quartzite, 0.51; and limestone, sandstone, and quartzite had the lowest, 0. 47. Correlation of the chip seals data indicated more of a coefficient decrease with ADT than with age.

Road Mix—The only road mix section tested was in Utah. Several tests were conducted on the shoulder, between the wheelpaths, and on the centerline of the roadway, and those tests averaged together were only 0.03 higher than the average of tests conducted in the wheelpath. This is an indication of the small effect the ADT of 330 vehicles over a 2-year period had on this road-mix surface. The road mix was composed of a limestone aggregate with 90 percent fractured faces and a ± 4.3 percent asphalt content.

TABLE 3

SUMMARY OF BRIDGE DECK COEFFICIENTS OF THE FOUR-STATE AREA

Pavement Type	2 Lanes—1 Direction Driving	2 Lanes—1 Direction Passing	4-State Average
Concrete	$\frac{10.45}{25} = 0.42$	$\frac{2.79}{7} = 0.40$	$\frac{13.24}{32} = 0.41$
Plant-mix seals	$\frac{1.03}{4} = 0.52$	None Tested	$\frac{1.03}{2} = 0.52$
Bituminous Miscellaneous seals[a]	$\frac{4.55}{12} = 0.38$	None Tested	$\frac{4.55}{12} = 0.38$

[a]Includes 10 tests on a sand seal overlay, 1 plant-mix overlay, and 1 Jennite sealer

Bridges

Forty-six tests were run on bridge decks in the four state area and, with only one exception, the testing was done at random. That one exception was a concrete structure in Salt Lake City, where the state highway department and an equipment manufacturer were engaged in a research project (Table 3).

Most of the testing was conducted in Colorado, since structures comprised much of the Interstate routes tested. The concrete and bituminous miscellaneous seals in Colorado yielded slightly higher values on bridge decks than they did in the driving lane. It is believed that the differences of 0.05 and 0.06 are primarily due to the workmanship of the surfaces during construction. In Wyoming, two plant-mix seal decks were tested, and the results differed by only 0.03.

A comparison between the driving and passing lanes for concrete shows the passing lane value 0.02 lower than the driving lane. This irregularity is due to the test results on the previously mentioned research project in Utah, where three low values were taken on grooved sections. Reducing the possibility of hydroplaning and reducing the roughness were the primary reasons for the grooving. At the present time equipment manufacturers are preparing equipment which will increase the friction coefficient as well as reduce hydroplaning and roughness. The testing of the different surface types was not balanced for a conclusive comparison.

CONCLUSIONS

This study indicates the increased attention to the subject of skid resistance and the concern of the Bureau of Public Roads in (a) development and use of equipment for measuring skid-resistant qualities of pavement surfaces, (b) development of materials and construction techniques for providing high skid-resistant qualities on new pavements and maintaining them after the pavement is exposed to traffic, and (c) establishment of programs for measuring and analyzing the skid-resistant qualities obtained on conventional types of surfaces now being constructed.

The rugged trip covering approximately 5,000 miles demonstrated the mobility, dependability, and expeditious manner of testing with the locked-wheel skid trailer.

With the many variables present for each pavement, it was extremely difficult to pinpoint an exact cause or reason for a pavement's behavior. Only through comparison of pavements exposed to similar conditions over a period of time can any trends or results be obtained. It was for this reason that ADT, age, aggregate type, percent of fractured faces, and asphalt content were the main properties selected for consideration and comparison.

Table 2 shows the friction coefficients by state and the four state average. A comparison shows plant-mix seals have a coefficient of friction higher than the other conventional surface types. The main reason for this is its open-textured surface, which provides for better drainage of water. A trend observed on plant-mix seals during the skid study was an increase in skid resistance with aging of the pavement. This increase is due to traffic "wearing off" the asphalt coating of the aggregates. However, the oldest plant-mix seal tested was five years old, and further study is needed on this pavement type. Eager (2) states that typical specifications for plant-mix seals include the following requirements:

Gradation of aggregate:

Pass $\frac{1}{2}$-in sieve	100%
Pass $\frac{3}{8}$-in sieve	95-100
Pass No. 4 sieve	30-50
Pass No. 8 sieve	15-30
Pass No. 40 sieve	0-10
Pass No. 200 sieve	0-5

* * *

Los Angeles abrasion	40 max.
Fractured faces	75% plus on +No. 4 size
Soundness	12% max.
Retained coating	75%+ (by AASHO T182 or other suitable stripping resistance test. May be necessary to use an additive to obtain adequate stripping resistance. Hydrated lime or chemical additives are frequently used)
Mixing temperature	275 F max (less if possible)
Placing temperature	225 F min
Grade of asphalt	60-70 or 85-100
Percentage of asphalt	6-8 (use as high as possible)
Rate of placing	$\frac{5}{8}$ in - $\frac{3}{8}$ in compacted
Tack coat	Not always used but if so at 0.05-0.10 gal per sq yd using a light RC or emulsion.

The percentages of fractured faces on the No. 4 material were investigated quite extensively in the preparation of this paper, and it is recommended that 100 percent fractured faces be included in design criteria.

The cost of plant-mix seals was not discussed; however, based on figures from the Bureau of Public Roads, "the cost of a chip seal would probably be less than one-half the cost of a plant mix seal on a square yard basis. However, the thickness would only be about one-third so that the cost per inch of depth is actually less for the plant mix seal (2)."

The friction coefficients for concrete and asphaltic concrete are practically the same for the four state averages and are closely related within each state. A great deal of aggregate polishing was experienced in both pavement surface types; however, it is believed that aggregate polishing was much more prevalent in the asphaltic concrete than in the concrete. An overall comparison of the aggregate types used showed limestone polishing more readily and giving lower values. Gravel and granite, and quartzite gave consistently higher results than did other aggregates.

Concerning concrete surfaces, even though they rank next to last in average friction coefficient, the decrease rate of skid resistance with age is less for this type of pavement than any other type tested.

The use of sand seal overlays indicated a decrease in the skid resistance in cases where high ADT was experienced. Those asphaltic surfaces where chips and other fine aggregates were removed due to wear and age retained the surface water and gave low skid values. Other fog and flush seals used for map protection and rejuvenation gave both high and low values.

The chip seal surfaces gave the second highest average skid value; however, the reader should keep the following in mind when analyzing this study: (a) there were fewer tests run on this surface type than on plant-mix seals, asphaltic concrete, or concrete; (b) the test sections consisted primarily of primary and secondary projects; and (c) the ADT in most cases was relatively low.

Chip sealed surfaces showed the effects of traffic more than the other surfaces as there was a more pronounced decrease in skid resistance with the increases in ADT. There were no definite conclusions as to aggregate preference for chip seals, as all types gave favorable results. Open hearth slag and scoria chips yielded extremely high skid values.

With chip seals, as with all other surfaces, ADT and age proved to be the most influential factors governing the skid resistance of pavements. Good workmanship and other construction procedures are most important in the preparation of a good skid-resistant surface.

The big difference in friction coefficients between the driving and passing lanes could be a serious problem. A need for further study and research into this problem is definitely needed.

Concrete bridge decks proved to have a lower skid resistance than the decks which had been overlaid with bituminous mixes. More testing of other deck surfaces should be performed before definite conclusions are drawn, as only 42 tests were included in this study.

The histograms show the frequency of occurence of the friction coefficients for the different surface types.

RECOMMENDATIONS

This study proved beneficial not only to the Bureau of Public Roads, but also to the four participating states. A working knowledge of the skid resistance of existing roads is, and will continue to be, extremely helpful to highway engineers. It is recommended that all states incorporate into their systems a surface condition study of skid resistance to be conducted periodically. From the standpoint of safety, skid resistance is becoming a more important factor in developing safer highways, and a good skid resistance program is a giant step towards achieving this goal.

Based on the results and analysis of this study the author recommends the use of plant-mix seals as the best means now available for insuring a high quality skid-resistance surface not only as an overlay on existing surfaces but also in the construction of new pavements.

ACKNOWLEDGMENTS

The author wishes to acknowledge the cooperation of the U. S. Bureau of Public Roads and the state highway departments of Colorado, Wyoming, Utah, and New Mexico. The opinions and conclusions expressed are those of the author and not necessarily those of the Bureau of Public Roads. Special appreciation is expressed to Emery L. Shaw and William L. Eager for their advice and guidance throughout the study and the preparation of this paper.

REFERENCES

1. Kullberg, Costa. Methods and Equipment for Continuous Measuring of the Coefficient of Friction at Incipient Skid. HRB Bull. 348, p. 18-35, 1962.
2. Eager, W. L. Plant Mix Seal Coats. Region 9 Bureau of Public Roads.