fundamental measure of consistency for use at relatively high pavement service temperatures. It is less subject to test-imposed variables such as shear-susceptibility variations and less subject to binder-improved variables such as variations in inherent complex flow. On the other hand, penetration measurements as a control of the consistency of SEA would not be adequate to evaluate the temperature susceptibility of these binders.

2. At the average maximum service pavement temperature in Kuwait (≈60°C), the volume concentration of sulfur needed to maintain a relative viscosity of $\eta_{SEA}/\eta_{AC} = 1$ was found to be equal to 0.21, which is equivalent to 35 percent by weight. However, at 25°C, relative viscosity values of both SEA and FEA were found to be similar. These results are only valid for the materials used locally. Asphalt cements from different sources or of other grades may have a different effect on the rheological properties of SEA.

3. The dissolved sulfur in SEA (16-18 percent) results in lowering the viscosity of asphalt cement at a range of temperature between 140°C and 40°C and in an increase of the temperature-viscosity susceptibility. However, the suspended sulfur particles in SEA showed a similar effective volume concentration compared with that of limestone filler particles with reference to the increase in viscosity at temperatures below the melting point of sulfur. It is recommended that the filler effect of suspended sulfur particles in SEA be compared with that of other types of filler materials used in asphalt mixes.

4. Viscosities of SEA at temperatures above the melting point of sulfur were found to exist at all sulfur ratios lower than that of asphalt cement and much lower than that of FEA. This characteristic of SEA has a significant effect on improving the workability of the paving mix.

5. The crystallization process of sulfur in terms of dynamic growth of the sulfur crystals seems to be effective if SEA is mixed with mineral aggregates and represents the major part of the stiffness improvement of finished pavement with age. Increase in viscosity of SEA due to increase of effective volume concentration of dispersed sulfur particles represents only a minor part of the stiffening effect.

6. In paving mixtures, at temperatures of pavement use, SEA is admixed with a variety of mineral aggregates and forms binders varying greatly in properties from the original in bulk. The response of SEA to heating in the preparation of the hot paving mixture differs from that in the laboratory. Therefore, measurement of paving-mixture properties, rather than properties of SEA binder, appears to be a more rational approach. Generally, the responses for SEA, AC, and FEA to TFOT heating at 140°C are almost the same. The viscosity at 25°C is affected by heating more than that at higher temperatures.

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Predicting Surface Friction from Laboratory Tests

W.H. PARCELLS, JR., T.M. METHENY, AND R.G. MAAG

The objective was to develop and refine methods for preevaluating aggregates and paving mixtures so that predictions can be made of properties of proposed and in-service pavement types. A usable correlation was established between the field testing by using the data from the British portable tester and the locked-wheel pavement friction trailer at speeds of 40 and 55 mph. To extend this correlation, core samples were extracted from the locked-wheel tester skid path and were subjected to wear on the small-wheel circular track with periodic surface friction testing by using the British portable tester. The final step was to remix and remold the cored pavement samples or make samples with new materials to obtain an "as-new" surface and to subject these samples again to wear on the small-wheel circular track with periodic testing by using the British portable tester to find the British pendulum number (BPN). Other segments of the project included efforts to correlate (a) the stereophotography number (SPN) with the locked-wheel pavement friction tester skid number, (b) the SPN with BPN, and (c) the linear traverse number with BPN on the wear and polish machine. Research with various chat (chert) and limestone mixtures shows that the blend offers good skid resistance.

The objective was to develop and refine methods for preevaluating aggregates and paving mixtures so that predictions could be made of the skid-resistance

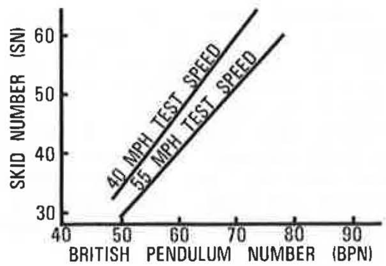


Figure 1. British portable tester versus locked-wheel tester for 17 HM-R/BM-1 test locations.

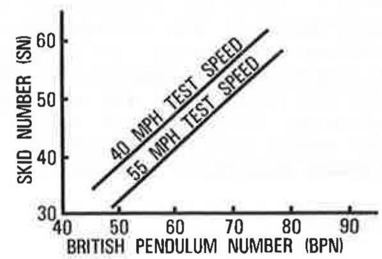


Figure 2. British portable tester versus locked-wheel tester for 18 HM-3/BM-2 test locations.

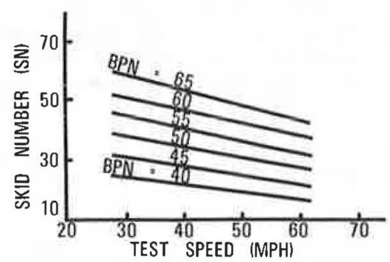


Figure 3. Test speed versus locked-wheel tester with constant BPN for 17 HM-R/BM-1 test locations.

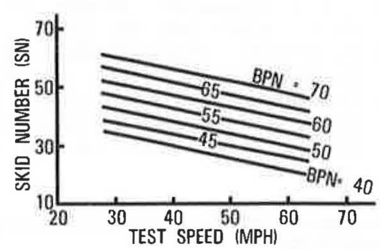


Figure 4. Test speed versus locked-wheel tester with constant BPN for 18 HM-3/BM-2 test locations.

properties of proposed and in-service pavement types. The procedure used in conducting the test was patterned after the work done under the direction of Mullen (1). The small-wheel circular-track wear and polish machine was built by Kansas Department of Transportation (KsDOT) personnel according to plans obtained from Mullen. The locked-wheel pavement-surface friction tester (skid trailer) was built by K.J. Law Engineers, Inc., and conforms to ASTM E-303-69.

PRELIMINARY FIELD-CORRELATION RESEARCH

The testing was conducted on two dense-graded bituminous pavement types in Kansas. One is now designated BM-2, but in the past it was known as HM-3. Eighteen sections of HM-3/BM-2 pavement were selected across the state. The age of the pavement sections varied from zero to 17 years. The second pavement type tested is currently designated BM-1 and in the past it was called HM-R. Seventeen sections of HM-R/BM-1 pavement were chosen and the age of these pavement sections ranged from zero to nine years. At each location the pavement friction property was tested by using the locked-wheel trailer to determine the skid number (SN) at 40 mph (SN_{40}) and at 55 mph (SN_{55}) both in the left wheel path and between the wheel paths.

This procedure resulted in 10 skid paths (five in the wheel path and five between wheel paths) at each of the 35 locations and both an SN_{40} and an SN_{55} for every skid path. The usual length of such a test location is 2 miles if the pavement surface being tested is long enough but may be shorter if necessary in order to contain the entire series of tests on a specific pavement surface.

The British portable tester, also known as the British pendulum, was used in determining all 350 skid paths and was cycled seven times in each path. The resulting SNs were averaged to provide a single British pendulum number (BPN) for each of the 350 skid paths. The data collected by locked-wheel testing and British pendulum testing were used to establish a set of correlation curves (Figures 1-4). A Hewlett-Packard Model 65 programmable calculator and statistical program 1-22A for linear regression was used to make the calculations to establish the best-fit lines shown in Figures 1-4. For the test locations of BM-1 pavement, the calculated correlation coefficient was 0.66 at 55 mph and 0.73 at 40 mph. The calculated correlation coefficient for the BM-2 test locations was 0.65 at 55 mph and 0.68 at 40 mph. It should be remembered, however, that SN reflects both macrotexture and microtexture, whereas BPN primarily reflects only the microtexture (2).

After completion of these two tests, a series of core samples 6 in in diameter was obtained from the pavement. Eight samples were taken from one of the five spots where the trailer tire had been skidded in the wheel path and seven samples were taken from one of the five spots where the trailer tire had been skidded between the wheel paths at each of the 35 locations. There was a total of 525 field samples for laboratory testing.

SELECTION OF COMPACTION METHOD

Three methods of compaction were tried on laboratory samples by using a 6-in mold. They were static-load compaction of 2000 psi for 2 min; electric-vibratory-hammer compaction of 15 s, 30 s, and 60 s; and 50 blows to one side of the sample by using the Marshall hammer, which weighs 22.5 lb. Laboratory samples made by using each compaction method were exposed to the North Carolina wear and polish machine concurrently with a core sample from the field and the results indicated that the sample made by using the Marshall hammer most closely paralleled the field sample in BPN versus time of exposure on the wear and polish machine. The asphalt was extracted from samples made by each method and aggregate gradation was performed. The results indicated that the Marshall-hammer method caused less aggregate fracturing. The Marshall-hammer method also resulted in higher compaction levels and greater stability.

LABORATORY TESTING OF FIELD CORES

The next procedure was to prepare the core samples by sawing them to a thickness of 1.87 in and mounting them in the small-wheel circular track (Figure 5) for exposure to wear and polish (Figure 6). Three samples from each location were used, which allowed four skid-path locations to be tested simultaneously. Three other samples from each location were heated, remixed, and remolded before exposure to the wear and polish machine in an effort to ob-

Figure 5. Pavement core samples mounted on circular track.

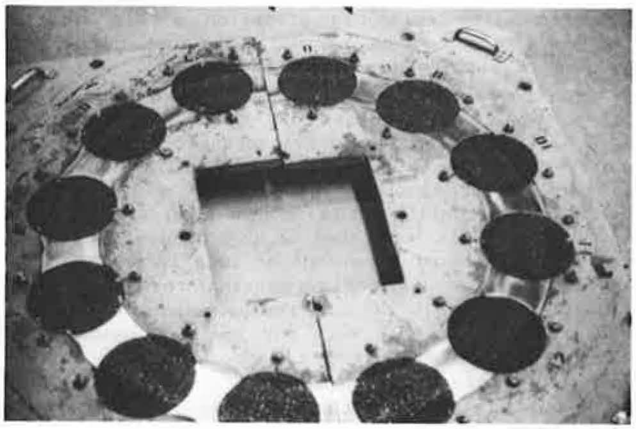


Figure 6. North Carolina small-wheel circular-track wear and polish machine.

tain an "as-built" surface. At least one sample was used for asphalt extraction and aggregate gradation tests.

British pendulum readings (Figure 7) were taken at 0, 10, 20, and 30 min and 1, 1.5, 2, 2.5, 3, 4, 6, 8, 10, and 12 h of exposure on the wear and polish machine. At each time interval, the pendulum was cycled eight times and the last seven readings were recorded and averaged. This yielded more than 21 000 recorded BPN readings, which were used to establish the graphs of BPN versus time of exposure (T) on the small-wheel circular track (Figures 8 and 9). As had been noted in the study by North Carolina University (1), the samples reach terminal polish very early in the cycle and are near the BPN low-point reading within the first hour. The rapid change in BPN indicates that BPN readings should be recorded at shorter intervals during the first 30 min of exposure to the small-wheel circular track so a more sensitive curve could be generated. All the data gathered for this report were obtained by using a tire 5.2 in wide on the wear and polish machine. Use of the narrower 3.5-in tire was discontinued because of the small wear surface on the sample, which made operation of the British portable tester difficult, and because the narrow tire raveled and rutted the pavement samples more severely. Since all testing was subsequently done by using the wider tire, no correlation was attempted with the narrow-tire data.

Figure 7. British portable tester on wear and polish samples.

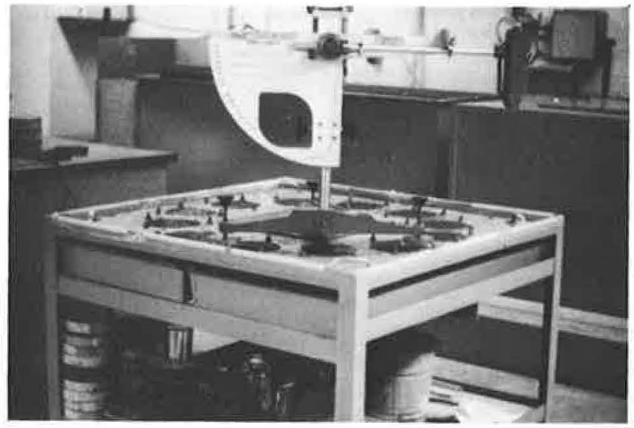


Figure 8. British portable tester readings versus time during wear and polish testing of HM-R/BM-1 field core samples.

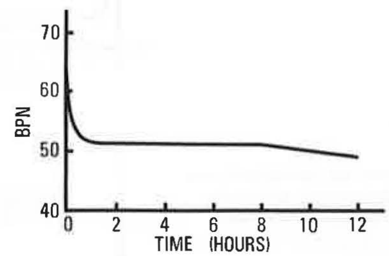
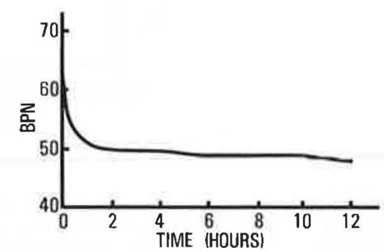


Figure 9. British portable tester readings versus time during wear and polish testing of HM-3/BM-2 field core samples.



Testing of Two BM-1 Mix Designs

A set of 12 laboratory samples of a recent BM-1 mix design was made by using 50 blows from a 22.5-lb Marshall hammer on one side of the 6-in mold. After aging at room temperature for one week, the samples were tested on the North Carolina small-wheel circular-track wear and polish machine. Readings were taken with the British portable tester at 1-min intervals for the first 10 min and then at 5-min intervals for up to 30 min total time and thereafter at 1, 1.5, 2, 3, 4, and 6 h of wear.

After 6 h, six of the samples were removed, reheated, remixed, remolded, aged for one week, and put back in their respective locations in the wear and polish machine. The process was repeated as described above for an additional 6 h. The six original samples were removed and wear was continued on the six remixed samples up to 12 h total time with a final reading at 12 h. This last step was done to again verify that little or no change in BPN occurs with extended exposure to wear and polish (Figure 10).

Another set of six laboratory samples of a different recent BM-1 mix design was made and exposed to the North Carolina wear and polish machine. Readings were again taken with the British portable tester at 1-min intervals for the first 10 min, then

Figure 10. British portable tester readings versus time during first wear and polish testing of BM-1 laboratory samples.

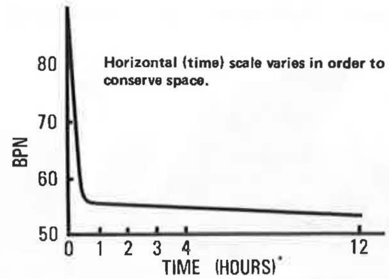


Figure 11. British portable tester readings versus time during another wear and polish testing of BM-1 laboratory samples.

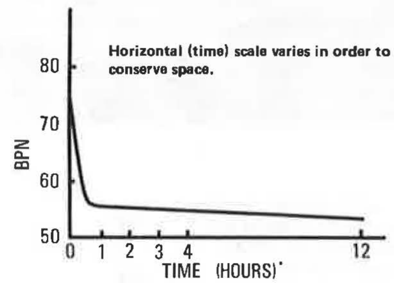
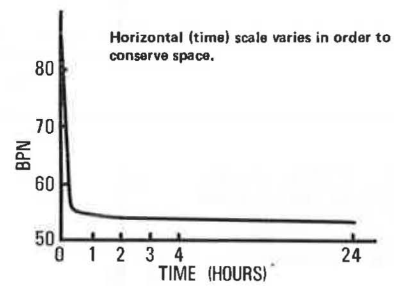


Figure 12. British portable tester readings versus time during wear and polish testing of BM-2 laboratory samples.



at 5-min intervals for up to 30 min total time, and then at 1, 6, and 12 h. The resulting curve of BPN versus time very closely resembles those of previous groups of samples (Figure 11). No remixing or extractions were performed on this test group.

Testing of One BM-2 Mix Design

A set of 12 laboratory samples of a recent BM-2 mix design was made and exposed for 12 h on the small-wheel circular track, and BPN readings were taken at 0, 5, 10, 15, 20, 30, and 60 min and at 1.5, 2, 3, 4, 6, 8, 10, and 12 h. Six of the samples were then removed from the small-wheel wear and polish machine and were heated, remixed, remolded, and aged for one week as before. The 12 samples (six remixed and six with 12 h wear) were again exposed for 12 h more on the wear and polish machine. BPN readings were taken each minute for the first 5 min and then on the same schedule as that for the first 12 h. On completion of the second 12 h, the six original samples, which had a total of 24 h exposure, were removed and the six remixed samples were run an additional 12 h for a total of 24 h (Figure 12).

ASPHALT EXTRACTION AND AGGREGATE GRADATION

Asphalt extraction and aggregate gradation were performed on one sample of the original group and on one sample of the remixed group in the BM-1 and the BM-2 test groups. In the BM-1 group the results showed less than 1 percent variation between the washed-gradation results of the remixed sample compared with those of the original sample. There was a slight loss of all sizes when washed gradation was compared with design-mix gradation. This loss is primarily due to the removal of fines during the process of washing the extracted samples.

When compared with the initial BM-2 mix design, there was a 2.5 percent loss of the largest size (3/8 in), probably due to fracturing of large stones during compaction, and a loss of 2-2.5 percent on sieves smaller than No. 30, primarily because the extraction/gradation is a washed analysis, whereas the original mix was based on dry gradation. There was a variation of 1 percent or less in the percentage retained on each sieve during the extraction/gradation analysis of the remixed samples compared with the samples that were not remixed, which indicated minor changes in mix composition due to remolding. There was also a slight (0.4 percent) loss of asphalt, probably through adherence to mixer, bowl, mold, compaction head, etc. (Table 1).

CORRELATION OF STEREOPHOTOGRAPHY NUMBER WITH SN AND BPN

A method of classifying pavement surface texture and determining skid resistance from stereophotographs was developed by Schonfeld (3) of the Ministry of Transportation and Communications in Ontario. This method, which is designated ASTM E557-75T, was studied and compared with skid-resistance values obtained by the Law friction tester as part of this study and an earlier study of skid resistance made by the KsDOT Research Section (4).

The stereophotographs of the pavement surface were obtained by the use of a camera box that had self-contained illumination. The camera box was constructed by the KsDOT Research Section from information in publications by Schonfeld. Stereophotographs were obtained of a variety of surface textures from throughout the State of Kansas. The pictures were taken of the pavement in place and in the track of the skid test by the locked-wheel trailer. It is essential that the pavement be dry and that the pictures be carefully focused for clear, sharp image reproduction. These stereophotographs were interpreted according the instructions in Skid Resistance Photo-Interpreter's Guide by Ma and Musgrove (5). Some variation from their instructions was necessary because the mirror-stereoscope used was not equipped for higher magnifications. Approximately 300 pairs of stereophotographs of existing pavement were analyzed.

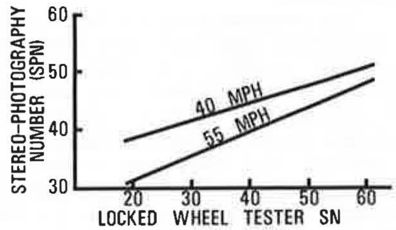
A Hewlett-Packard Model 65 programmable calculator and statistical program 1-22A for linear regression were used to make the calculations to establish the best-fit lines of stereophotography number (SPN) versus locked-wheel tester SN for 40 and 55 mph (Figure 13). The calculated correlation coefficients are 0.66 for 40 mph and 0.72 for 55 mph.

An attempt was also made to correlate the SPN with the BPN of samples of pavement mounted in the North Carolina small-wheel circular-track wear and polish machine. The 6-in samples tested were of two types--core samples of existing pavement and samples made in the laboratory. About 120 pairs of photographs were analyzed at various time intervals during the wear and polish procedure. The resulting data did not formulate a satisfactory correlation. The BPN data indicated a rapid decrease during the first few minutes of wear and polish testing. Conversely, the SPN appeared to increase as time increased on the wear and polish, primarily because the spalling and raveling of aggregate made the surface appear rougher, which would indicate a higher SPN. This divergence possibly is because BPN is more sensitive to microtexture (2) and SPN is a mea-

Table 1. Asphalt-extraction and aggregate-gradation data.

Test Group	Sieve Size (% retained)								Asphalt (%)
	3/8 in	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	
BM-1 mix design	1.0	24.0	42.0	56	69	85	90	92	6.0
Washed uncompacted sample	0.3	23.3	40.1	52.7	65.8	81.4	86.7	88.5	–
Original sample	0.5	23.0	40.8	53.1	65.8	80.8	86.2	88.1	6.1
Remixed sample	0.2	23.0	40.3	52.7	65.2	80.2	85.6	87.5	5.8
BM-2 mix design	24	39	53	64	75	89	92	94	5.5
Washed uncompacted sample	22.9	39.7	52	62.5	74.1	87.5	90.7	92.4	–
Original sample	21	39	52	62	73	86	90	91.3	5.1
Remixed sample	22	40	52	62	73	86	89	90.1	5.1

Figure 13. Correlation between locked-wheel tester SN at 40 and 55 mph and SPN.



sure of macrotexture and microtexture. Another difficulty experienced was that the 6-in sample provides a restricted surface area to analyze by stereophotographs. It was also noted that the large aggregate in the laboratory samples was often fractured during compaction, which affected the stereophotograph analysis and contributed to increased spalling when compared with field cores.

A fourth factor that may have had some influence on the correlation was the axis of the pair of photographs. In the field the long axis of the stereo pair was perpendicular to the flow of traffic. Because of physical limitations of equipment, the long axis of the pair of stereophotographs in the laboratory was parallel to the direction of movement of the wear and polish tires. The influence of this last item, however, was felt to be minor when it was compared with the influence of the raveling discussed earlier.

CORRELATION OF LINEAR TRAVERSE NUMBER WITH BPN

During the project, some effort was made to determine whether there existed any correlation between surface roughness as measured by a linear traverse device (6,7) and readings obtained with the British portable tester during the wear and polish testing discussed earlier. The device used allowed the sample to move horizontally while it was being scanned with a microscope. The vertical deformations were registered by changes in the focus knob of the microscope, and both horizontal and vertical movements were recorded on a continuous-line graph that gave a cross section of the sample.

This cross section was then enlarged three times by using a pantograph to facilitate measuring the length of the line. The central 9-in horizontal-measure portion of the enlarged graph was then measured by using an irregular-line rolling-wheel measuring device called a map measure. The measured length of the irregular line within the 9-in horizontal boundaries was recorded in an effort to obtain an objective measure of surface roughness and then correlate that with the BPN.

Two types of samples were tested. The first type were core samples from existing pavement that had some wear from exposure to traffic before being exposed to the wear and polish machine. The second type were new or remixed samples made in the laboratory that had had no previous wear before exposure to the wear and polish machine. The initial traverse was made of each sample before polishing. The samples were then mounted in the wear and polish machine and BPN readings were taken as discussed above. After 12 h of wear, the samples were removed from the wear and polish machine and the second linear traverse reading was made. In some cases the samples had raveled so badly that the 12-h reading could not be made. In all, more than 560 samples were traversed; they represent approximately 46 test locations.

Efforts to calculate a correlation between the linear traverse number (LTN) and the BPN were not successful. The situation was similar to that involving the stereophotography method discussed earlier. It is now evident that the length-of-line method used in this study does not provide differentiation between one large hole or piece of protruding aggregate and a series of small holes or small pieces of protruding aggregate, which could result in traverse lines of the same length. The same problem existed when the area below the line was used instead of the line length. A visual analysis of the irregularities of the profile appears necessary. Also, as the samples raveled and became rougher the length of the traverse line tended to increase, which indicated an upward trend in skid resistance, whereas the BPN indicated a drop between the zero-time and the 12-h exposure on the wear and polish machine.

Another cause of the divergence could be that the LTN, at least at the magnification used in this study, was primarily sensitive to macrotexture, whereas BPN is sensitive to microtexture (2). Based on previous research studies (2), other profiling techniques have been shown to yield a usable correlation with BPN.

CHAT AND LIMESTONE-MIX EXPERIMENT

In an effort to provide an asphalt concrete that maintains its high skid-resistance property, some experimentation was conducted mixing various percentages of chat aggregate with limestone aggregate. Chat, as used here, is a waste product of the lead and zinc mining operations of southeast Kansas and is composed primarily of the rock chert. It was anticipated that the very angular, sharp, hard chat aggregate would provide initial surface friction due to its angular and sharp properties. It should also provide prolonged surface friction through differential wear and the softer limestone and asphaltic medium compared with the harder chat as well as through its angular and sharp properties.

Initial testing by using 6-in samples and the North Carolina small-wheel circular-track wear and polish machine with periodic testing by using the British portable tester did not indicate any appreciable advantage of the mixture. The initial BPN before exposure to the wear and polish machine was approximately 77. As was characteristic of other mix design samples, the BPN dropped rapidly, and at

20 min exposure on the wear and polish machine, the BPN was 57. After 4 h of exposure to the wear and polish machine, the BPN was approximately 56. At that point the samples had each begun to ravel, so BPN readings were stopped. The wear and polish was continued until 12 h of exposure and all samples were severely raveled.

A test area of field exposure was constructed in 1980, and tests were run with the locked-wheel surface-friction tester. The results of the field testing indicate that initially the frictional property of the chat/limestone mixture is essentially the same as that of the standard BM-1 surface-course mixture. Tests run in 1981 indicated that the chat/limestone mix was providing excellent skid resistance after one year's exposure to Interstate traffic. Subsequent testing after extended time and exposure to traffic will indicate whether the chat/limestone mixture results in prolonged retention of surface friction.

TESTING OF OPEN-GRADED MIXTURE

In 1974, seven different semi-open-graded pavement surface mixtures were applied as test overlay sections in various areas throughout the state. Subsequent outflow-meter testing indicated a densification of all samples on exposure to weather and traffic. This densification somewhat defeated the subsurface drainage characteristics of the various mixtures. The higher asphalt cement content plus the densification also lowered the surface friction characteristic of one section after exposure to traffic. Only two of the initial test sections remain in service. The other five locations were overlaid during the normal resurfacing cycle for the road but not because of any surface deterioration in the open-graded test locations. The latest tests on the remaining two sites indicated that the SN had increased as much as 20 numbers since installation and was well above average for the bituminous concrete surfaces in Kansas.

INFORMATION ESTABLISHED BY TESTING

Several items of information were verified or established by this testing. First, all samples had reached the practical low-point BPN within 2 h of exposure on the North Carolina small-wheel circular-track wear and polish machine, and extended running on the machine is not necessary on asphaltic-concrete types of pavement.

Second, the most critical time zone is the first 30 min, and readings should be taken each minute for the first 10 min, each 5 min thereafter to 30 min total elapsed time, and then each 30 min to 2 h total time. After 2 h, wear and polish testing could be stopped or readings could be taken each 2 h or only at the end of 6 or 12 h since there is very little change in BPN after 2 h.

Third, the wear and polish machine and the British portable tester will give consistent results regardless of the location of the sample in the mounting platform on the wear and polish machine. This was indicated by the similarity of the curves for BPN versus time for the original samples of a group and for the remixed samples of a group. The beginning points (0 min) for the remixed samples were lower than those for the original samples but the curves converged within the first 20-30 min. The data are not sufficient to determine what caused the initial variation.

Another interesting phenomenon was that the remixed samples appeared to be more resistant to wear and raveling than the original samples. This was characteristic of both the BM-1 and BM-2 mix design sample groups. Additional testing and exposure to actual traffic of recycled asphaltic pavement may provide some indication of whether this apparent increase in durability for remixed samples can be a prediction of improved behavior of recycled pavement as well.

The data collected with the locked-wheel pavement surface friction tester for use during this study were considered reasonable. Since field BPN readings were taken at approximately the same time as the SN data were, neither temperature variations nor seasonal variations were considered a significant influence in the field correlation study as it was conducted.

The considerable variation between field BPN and laboratory BPN for the same sample remains unexplained except for the following factors, which possibly contributed: (a) washing action while core drilling, (b) washing action while sawing the core to the proper height to mount on the wear and polish machine, (c) temperature and humidity change from field to laboratory, and (d) orientation of the sample to traffic flow in the field and to the path of the wear and polish wheels.

DESIGN PREDICTION RESULTS

On completion of the laboratory testing, an effort was made to predict what the SN_{40} would be in a field test that used the locked-wheel pavement friction test trailer for both of the BM-1 sample mix designs. To accomplish this, the average field BPN of 56 for the field core samples of the 17 HM-R/BM-1 locations was projected onto the plot of BPN versus time in Figure 14. The corresponding time of 5.5 min was then projected onto the plot of BPN versus time for the mix design to establish the predicted BPN of 58, as shown in Figure 15. The data for Figures 14 and 15 were the same as those for Figures 8 and 10, respectively, but they were expanded to show only the first 30 min, since that appears to be the critical portion of the graph. The predicted BPN can then be entered on either the plot of SN versus BPN (Figure 16) or the plot of SN versus test speed (Figure 17) to establish the predicted SN for the desired speed.

The two field projects that correspond to the BM-1 mix designs used in the lab were tested with the locked-wheel pavement friction test trailer. The result of the first correlation was a predicted SN_{40} of 45, whereas the average SN_{40} in the field was 42.

The result of the second attempt to predict SN was about the same. The predicted SN_{40} was 43 and the locked-wheel test results ranged from 44 for the portion of the project surfaced in 1979 when the prediction and field testing was done to 35 for the portion of the project constructed a year earlier. The lower SN was believed to be the result of a slightly higher percentage of asphalt in the mix used on the highway.

No prediction attempt was made on the BM-2 mix design because in 1978 and 1979 that particular mix was used as a surface material only on some paved shoulders, which made testing with the locked-wheel tester unsafe and impractical.

As a sidelight, it should be mentioned that worn skid-trailer tires no longer suitable for testing purposes are transferred to KsDOT maintenance forces to be used as front tires on tractors and mowing equipment. Thus the many miles of life remaining in the tire are not wasted. When the tires are no longer serviceable on the maintenance equipment, they along with other tires are sold to bulk-rubber dealers for recycling.

Figure 14. Expansion of British portable tester readings versus time during wear and polish testing of HM-R/BM-1 field core samples.

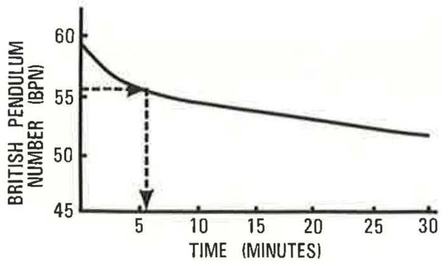


Figure 15. Expansion of British portable tester readings versus time during wear and polish testing of BM-1 laboratory samples.

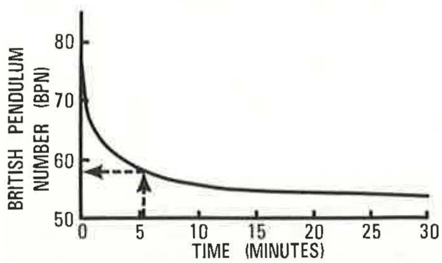


Figure 16. British portable tester versus locked-wheel tester for 17 HM-R/BM-1 test locations.

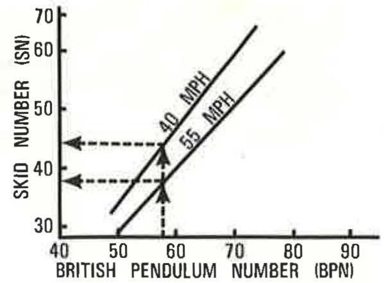
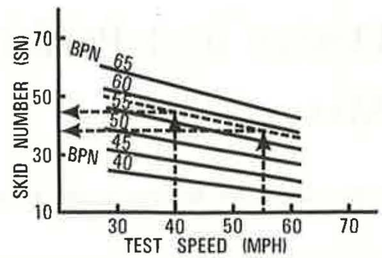


Figure 17. Test speed versus locked-wheel tester with constant BPN for 17 HM-R/BM-1 test locations.



CONCLUSIONS

A field correlation between SN and BPN for an asphalt concrete pavement type can be established, as indicated by the correlation established in this study for BM-1 and BM-2 mixes. A graph of BPN versus time can be drawn from data provided by wear and polish testing. A prediction of field SN can be made by using the above information and the graph of the wear and polish BPN versus time established by testing samples of the proposed mix of asphalt concrete. If the field mix is allowed to vary from the tested laboratory mix, however, the predictions will be subject to considerable potential for error. An increase of 0.5-1 percent in asphalt concrete content can result in SNs 20-30 points below a predicted level. Variations in aggregate gradation do not appear to be so critical in their effect on the SN.

In view of the effect that variation in asphalt content has on SN, it appears that educating field construction inspectors on the importance of adhering to designed mix proportions would be advisable so that tighter control might be exercised, especially on the percentage of asphalt concrete.

A satisfactory correlation was calculated between the SPN of pavement photographed in place and the SN obtained with the locked-wheel tester. However, efforts that used the data obtained during the testing of samples on the North Carolina small-wheel wear and polish machine to correlate SPN with BPN were not successful. Similarly, efforts that used data collected during this study to correlate LTN with BPN were not successful. Extended operation of the wear and polish machine beyond 2 h on a set of bituminous pavement samples does not provide any additional significant data.

If more research is conducted, it should start with more trial implementation of the procedure to determine whether acceptable predictions can be made repeatedly. Further study might also produce a correlation between time on the wear and polish device and number of wheel passes on the pavement in the field, which might indicate a prediction of pavement life via laboratory testing.

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The contents of this report reflect our views and we are responsible for the facts and accuracy of the data presented here. The contents do not necessarily reflect the views or policies of the State of Kansas or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Design and Performance of Bituminous Friction-Course Mixes

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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).