# Laboratory and Field Study of Pavement Rutting in Saudi Arabia

BASSAM A. ANANI, FAHAD A. BALGHUNAIM, AND ABDULRAHMAN S. AL-HAZZAA

Potential asphalt-mix parameters that influence susceptibility of a mix to rutting during its service life are identified. Seven highways were selected where sections have suffered from rutting and where other sections, with identical loading conditions, have been rut free. Field samples, including both cores and slabs, were collected mainly from areas where original mix properties were assumed not to have varied in both sections. An extensive laboratory program was conducted to establish the properties of both the mix and its components (asphalt cement and aggregates). Because slabs were collected from the wearing course only, tests related to asphalt cement and aggregates were only established for the wearing course. Cores were used to determine the characteristics of both wearing and base courses. Statistical analysis by using the *t*-test was utilized to determine major factors in both wearing and base courses that affect rutting. The significant wearing-course tests were Hveem stability and modulus of resilience. For the base course, in addition to those two parameters, both Marshall stability and compactness showed a significant impact on rutting of asphalt mixes.

During 1395–1405 H. (1975–1985), 70 000 km of road network was constructed in the Kingdom of Saudi Arabia. This construction contributed to economic, agricultural, and industrial development (*1*). The highway network in the kingdom was subjected to high volumes of heavily loaded trucks. One survey showed that the amount of overload was approximately 160 percent of the legal limit. Such overloaded traffic has resulted in substantial damage to road pavements and bridges.

The problem of rutting is gaining widespread attention in many parts of the world. Rutting was observed in the kingdom a long time ago, but recently it has gained more attention for two reasons: the increasing number of roads that suffer from such distress and the occurrence of rutting in highways early in their service life.

In this study, descriptions of the field survey and several tests conducted on samples from road sections with and without rutting will be presented. The result of extensive laboratory testing on cores and slabs from both types of locations will be given. This will be followed by a statistical analysis to indicate the major factors contributing to rutting. The objective of this study is to determine the major factors related to mix properties that affect the degree of rutting in the field.

## BACKGROUND

Rutting is the formation of twin longitudinal depressions under the wheelpaths from a progressive accumulation of permanent deformation in one or more of the pavement layers.

Several studies have shown that the most significant portion of the rutting in the asphalt-bound layers occurs in the top 7 to 10 cm of the pavement (*2–7*). The rate and magnitude of rutting depend on external and internal factors. External factors include load and volume of truck traffic, tire pressure, temperature, and construction practices. Internal factors include properties of the binder, the aggregate, and mix, and the thickness of the pavement layers.

In recent years the trend toward heavier trucks, higher tire inflation pressure, and the substantial increase in the number of load repetitions has resulted in a significant increase in the extent and severity of rutting (*4*).

High tire inflation pressure causes significant levels of premature failure in pavement structures. Tire pressure exceeding 1034 kPa (150 psi) is very common in Saudi Arabia (*8*).

Phang (*9*) states that twin depression ruts appearing in Canada's highways are a consequence of a major change to the use of radial ply truck tires with inflation pressures of about 750 kPa (110 psi) from bias ply tires normally inflated to 500 kPa (75 psi). Load duration is another factor related to traffic that influences rutting. Rutting accumulates faster as the load duration increases. This is apparent in climbing lanes.

The ambient temperature and duration of pavement exposure to sunlight affect pavement layers. Bituminous materials are black and therefore easily absorb external heat while exhibiting a low coefficient of thermal conductivity (*3*).

In Kuwait, which has a similar environment to that of Saudi Arabia, Bissada (*10*) determined that the pavement temperature reaches 68°C when the average daily temperature is 35°C. In Saudi Arabia, rutting is significantly reduced, or even nonexistent, under bridges where the pavement is shaded by the bridge deck.

Several studies were made to identify the mix variables most responsible for rutting formation. Brown (*4*) studied five pavements, four of which were identified as experiencing rutting while the fifth was considered to have no rutting after 10 years of service. He concluded that the major causes of rutting were excessive asphalt content and low air voids in the asphalt mixtures. The Marshall flow appeared to be a good indicator of rutting potential, whereas the resilient modulus and indirect tensile strength values did not significantly relate to rutting potential.

Huber and Heiman (*11*) studied 11 pavement sections that carried similar traffic volumes but exhibited different rutting performance and concluded that asphalt content and voids filled with asphalt were the most basic parameters that affected rutting. Voids filled with asphalt included the effect of both air voids content and voids in the mineral aggregate (VMA).

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King Saud University, P.O.B. 2454, Riyadh 11451, Saudi Arabia.

Marshall stability and flow did not show any independent effect on rutting performance. Penetration and viscosity of asphalt did not demonstrate a significant effect on rutting rate either.

Carpenter and Enockson (*12*) studied 32 overlay projects placed over portland cement concrete pavements in Illinois. Analysis indicated that the majority of problems can be attributed to material properties in the gradation of the mixture. The tender mix phenomenon associated with a hump in the 0.45 power gradation curve had long been recognized as contributing to rutting. The percentage passing the No. 40 sieve and retained on the No. 80 sieve was found to influence rutting. Additional recommendations addressed control on density, air voids, and VMA during construction. The mix strength tests showed that resilient modulus and indirect tensile strength bear a strong relation to rutting.

Balghunaim et al. (*2*) evaluated and analyzed a large amount of data accumulated by studying nine roads that showed either excessive or premature rutting in Saudi Arabia. The conclusions of this evaluation follow:

1. Optimum asphalt contents obtained from mix designs were usually on the high side.
2. Asphalt content was frequently not well controlled during production of asphalt concrete mixes.
3. Aggregate gradation required by specifications for the roads studied was finer than the fuller maximum density curve. In addition, tests for aggregate gradation indicated that quality control was poor and resulted in an even finer gradation than required.
4. In most of the roads studied, the percentage of natural sand to be used as fine aggregate was not controlled.
5. Scalping of the aggregate before introduction into the crusher was not done properly. This resulted in the inclusion of a certain percentage of natural sand in the crusher-run material.
6. The use of "adjusted" bulk specific gravity of the compacted mix provided higher calculated air voids than those that would have been obtained by the Asphalt Institute procedure.
7. There was no control on the properties of the filler used.
8. All mixes in the roads studied possessed high Marshall stability values. This indicated that the Marshall stability may not eliminate mixes prone to rutting.
9. Rutting was found to be limited to asphalt-bound layers only.

Baird et al. (*13*) studied flexible pavements for the international airports in Saudi Arabia. These were pavements utilizing locally available materials and subjected to heavy channelized wheel loads in a hot climate. They concluded that the rutting problem was aggravated by the use of aggregates that were not of high quality.

Abdulshafi (*14*) studied two roads in Saudi Arabia that had rutted locations. He concluded that

1. Rutting of Saudi roads is more dominant in the surface course,
2. It is most likely that rutting of the pavement could be attributed to material properties of the asphalt concrete surface course,
3. The wearing course of rutted locations does not contain a sufficient percentage of coarse aggregate nor proper distribution,
4. The base course mixture and asphaltic concrete materials in the unrutted locations contain a larger percentage of coarse aggregate, and
5. The Marshall mix criterion does not satisfy the performance requirement for rutting.

In Kuwait, Bissada (*10*) measured instability failure of four test sections on each of two heavily trafficked roads constructed 5 years earlier. The pavement structure of the two roads consisted of 180-mm-thick asphalt concrete surface, binder, and base layers. The subbase layer of the first road was constructed of hot-mix sand-asphalt 120 mm thick and that of the second road was a 200-mm-thick gravel-sand mix. The following conclusions were reached:

1. For both pavement constructions, rutting depths measured at 2.2 to 2.5 million standard axle load repetitions (corresponding to 5 years of service) ranged between 27 and 44 mm at locations with slow traffic speeds and horizontal load components. However, the values measured at other locations with a relatively high uniform speed did not exceed 19 mm.
2. Densification contributed a significant amount to the total surface permanent deformation. At about $2.2 \times 10^6$ 80 kN standard axle load repetitions, "end values" were determined for air voids (minimum) and voids filled with bitumen or asphalt saturation (maximum), which were related to the instability failure measured.

Oteng-Seifah and Manke (*15*) investigated rutting in high-quality flexible pavements in 16 test sites. They reached the following conclusions:

1. Densification contributed a significant amount to the total surface rut depth.
2. Evidence of lateral creep or instability in the bituminous material layers was found at 11 of the 16 test sites.
3. Surface wear or attrition in the wheelpaths on heavily traveled lanes was an important contributing factor to rutting.
4. Base and subgrade deformation influenced the magnitude of rutting at many test sites. Extensive surface cracking and indications of surface subsidence were found at these sites. Consolidation and shear failure in these layers conceal the effects of lateral creep in the bitumen-bound material.

The major conclusion derived from this survey of literature indicates clearly that there is no common agreement as to which are the mix variables that affect rutting more appreciably than others. In addition, the best tests to characterize mixes with their susceptibility to rutting are not established.

## FIELD SAMPLING AND LABORATORY TESTING

### Criteria for Selecting Test Locations

As was explained, two groups of factors affected the degree of rutting in the field. This study will focus only on the set of variables pertaining to internal factors only. To accomplish this, it is essential that selection of field test sections be based on similar external factors. Owing to the difficulty in establishing many locations with such similarities, attention was focused on separate locations exposed to similar external factors where rutting was observed on some sections of the highway while no rutting was observed on the other. The following criteria were adopted while the final locations were selected:

1. A section should be considered "unrutted" if the maximum measured depth in the section is less than 0.7 cm. A section would be considered "rutted" if the measured rut depth were not less than 2.5 cm. These values were the average values from several references.
2. Both rutted and unrutted sections of the highway should exist in the truck, or slow, lane. In addition, the distance between the two sections should be as small as possible, with no exit or entry ramp between the two sections to ensure similar vehicle volume and loads and tire pressure.
3. Both rutted and unrutted sections should have the same geometric features to obtain the same power weight ratio of heavy vehicles on both sections.
4. Both rutted and unrutted sections should be chosen to fall in open areas (i.e., not in tunnels or on or under bridge decks) to have the same pavement surface temperature for both sections.

The final selection of test locations, using those criteria, was based on an extensive survey of the various highways and their degree of rutting. The final selection contained seven locations. Each location had one section rutted and another section unrutted. Seven locations were finally chosen, as shown in Figure 1, and the details for each location are given in Table 1.

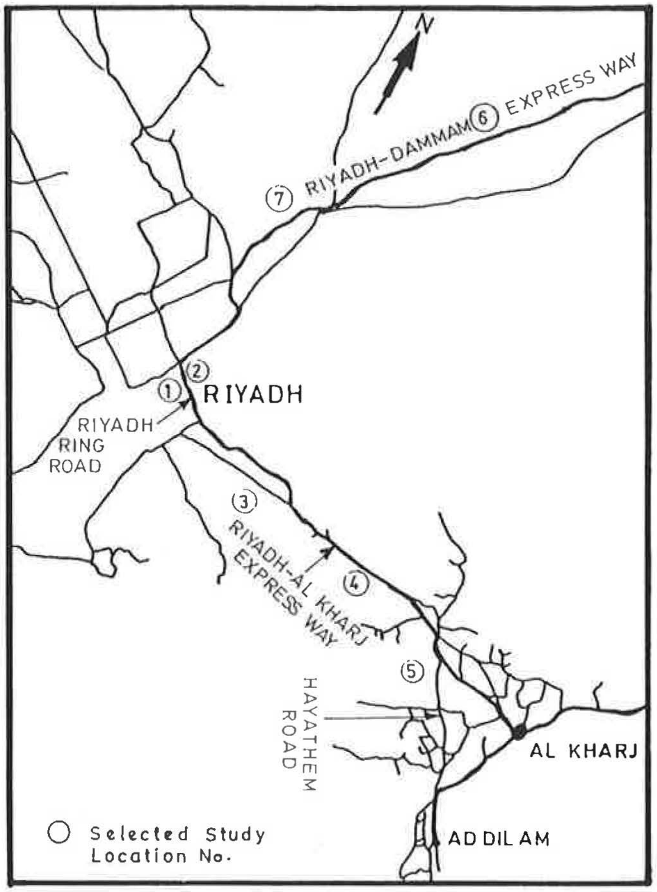


**FIGURE 1 Test sites location map.**

TABLE 1 TEST LOCATIONS USED FOR THE STUDY OF THE RUTTING PROBLEM

| Location # | Road Name | No. of lanes | Station | | Bound | Age of road (years) at sampling year (1407 / 1987) |
|---|---|---|---|---|---|---|
| | | | Unrutted | Rutted | | |
| 1 | Riyadh Ring Road - East leg | 6 | 0 - 700 | 1+550 | South | 2 |
| 2 | Riyadh Ring Road - East leg | 6 | 0 - 700 | 1+550 | North | 2 |
| 3 | Alkharj - Riyadh | 6 | 10 + 150 | 12 + 250 | North | 7 |
| 4 | Riyadh - Alkharj | 6 | 42 + 475 | 44 + 980 | South | 7 |
| 5 | Hayathem Road | 4 | 5 + 500 | 6 + 800 | South | 5 |
| 6 | Dammam - Riyadh | 6 | 60 + 00 | 58 + 700 | West | 5 |
| 7 | Damman - Riyadh | 6 | 29 + 50 | 29 + 00 | West | 5 |

A straightedge was used to establish the initial rut depth before samples were taken. Table 2 gives the results of rut depth measurements, which indicate that location 5 had the highest rut depth (approximately 6 cm). The corresponding unrutted section indicated a maximum rut depth value of 0.3 cm at a distance of 1500 m from the station where rutting was measured to be 5.7 cm.

### Field Sample Collection

Because the original mix properties of the asphalt layers in a section might vary as a result of rutting or under the repeated action of traffic as evidenced by further compaction of such layers, a major assumption was made: The original mix properties have been maintained in the shoulder and "yellow strip" of the outer lane. In other words, because very little traffic activity uses the shoulder or yellow strip, it is logical to assume that the mix properties were not affected by traffic.

For each section (a total of 14 sections), six cores and one slab were extracted. Three cores were taken from the outer wheelpath of the truck lane. Three cores were taken from the right yellow line.

The yellow line was intact and was not used by vehicles as shown by a lack of rubber tracks in all the selected locations except for the two rutted sections in locations 3 and 5. The excessive rutting in these locations has apparently forced vehicles to shift to the right to avoid rutting channels. Therefore, samples were taken from the left yellow line, close to the inside shoulder. Construction reports indicated that the same mix was used for the whole cross section. The general layout for the sample location is given in Figure 2.

TABLE 2 RESULTS OF RUT DEPTH AND CORE THICKNESS MEASUREMENTS

| Location # | Rut-depth Measurement (mm) (1) | | Average Cores Thickness (mm) (2) | |
|---|---|---|---|---|
| | Unrutted Sec. | Rutted Sec. | Unrutted Sec. | Rutted Sec. |
| 1 | 5 | 30 | 203 | 209 |
| 2 | 5 | 30 | 193 | 224 |
| 3 | 7 | 52 | 240 | 278 |
| 4 | 3 | 45 | 243 | 222 |
| 5 | 3 | 57 | 227 | 255 |
| 6 | 7 | 40 | 193 | 175 |
| 7 | 0 | 53 | 182 | 228 |

(1) Rut depth was measured in the outer wheel path adjacent to where the slab and cores were taken.

(2) Thickness measurement were taken from yellow line cores except for locations 1 and 2 which were from outer wheel path cores.

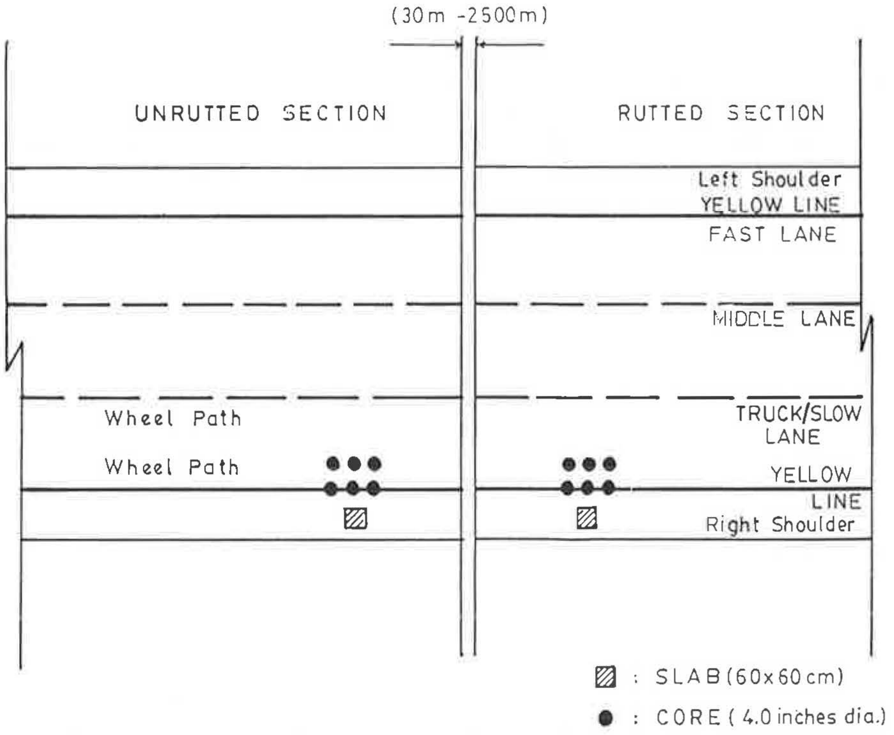


FIGURE 2 Typical layout for sample locations.

The total number of cores extracted for this study was 84, and only 14 slabs were taken. The samples were properly coded and then stored at room temperature for further preparation and testing.

## Field Sample Processing

The cores collected from the field were extracted through the total depth of the asphalt layer (including both wearing course and base course). The distinction between the two courses was not obvious in all samples. The thickness of cores ranged between 175 and 278 mm, as shown in Table 2.

To conduct separate tests on the wearing and base courses, it was necessary to establish identical procedures for layer identification for all cores. Owing to the unevenness in the top and bottom surfaces of the cores, the top 1 to 2 cm of each core was sawed. A sample thickness of 6.25 cm (2.5 in.) was then sawed from the top to constitute the wearing course sample. The same procedure was repeated for the bottom to establish the base course sample. The remaining middle part of the core varied, depending on the original pavement thickness of the road.

## Laboratory Test Plan

After samples had been collected and prepared, a comprehensive laboratory testing program was established to characterize both the mixes and the constituting materials for all sections as shown in Figure 3. The tests were conducted in two stages. The first stage was conducted on slabs taken from the shoulders to determine both the asphalt content and the aggregate gradation of the original mix and their characteristics. For establishing original mix properties, cores taken from the yellow line were exclusively used for this purpose. The cores taken from the rutted path were used only to test the amount of further compaction caused by traffic.

Review of the literature was used to select the variables to be evaluated in this study. These variables were associated either with the asphalt binder or with the aggregate or the combined mix. The general approach of the study was to try to determine the variables that can differentiate between rutted and unrutted mixes. Table 3 shows a list of the variables evaluated in this study. The values for these variables were determined either from laboratory testing or from calculations based on laboratory test values.

Because slab samples were collected only from the wearing course in the field, tests reported here for base course include only the mix category, where cores were collected from both wearing and base courses. Regarding both asphalt cement and aggregate categories, no tests were conducted for base course.

## Special Testing Considerations

The original mix properties were established for both rutted and unrutted pavements by using cores collected from the yellow line. Because only three cores were collected from each section, it was necessary to follow a testing sequence in which a destructive type of test (Marshall test) was done at the last stage. Figure 3 shows the testing sequence followed in this study. All tests were conducted according to ASTM standards. However, some special considerations were made for some tests.

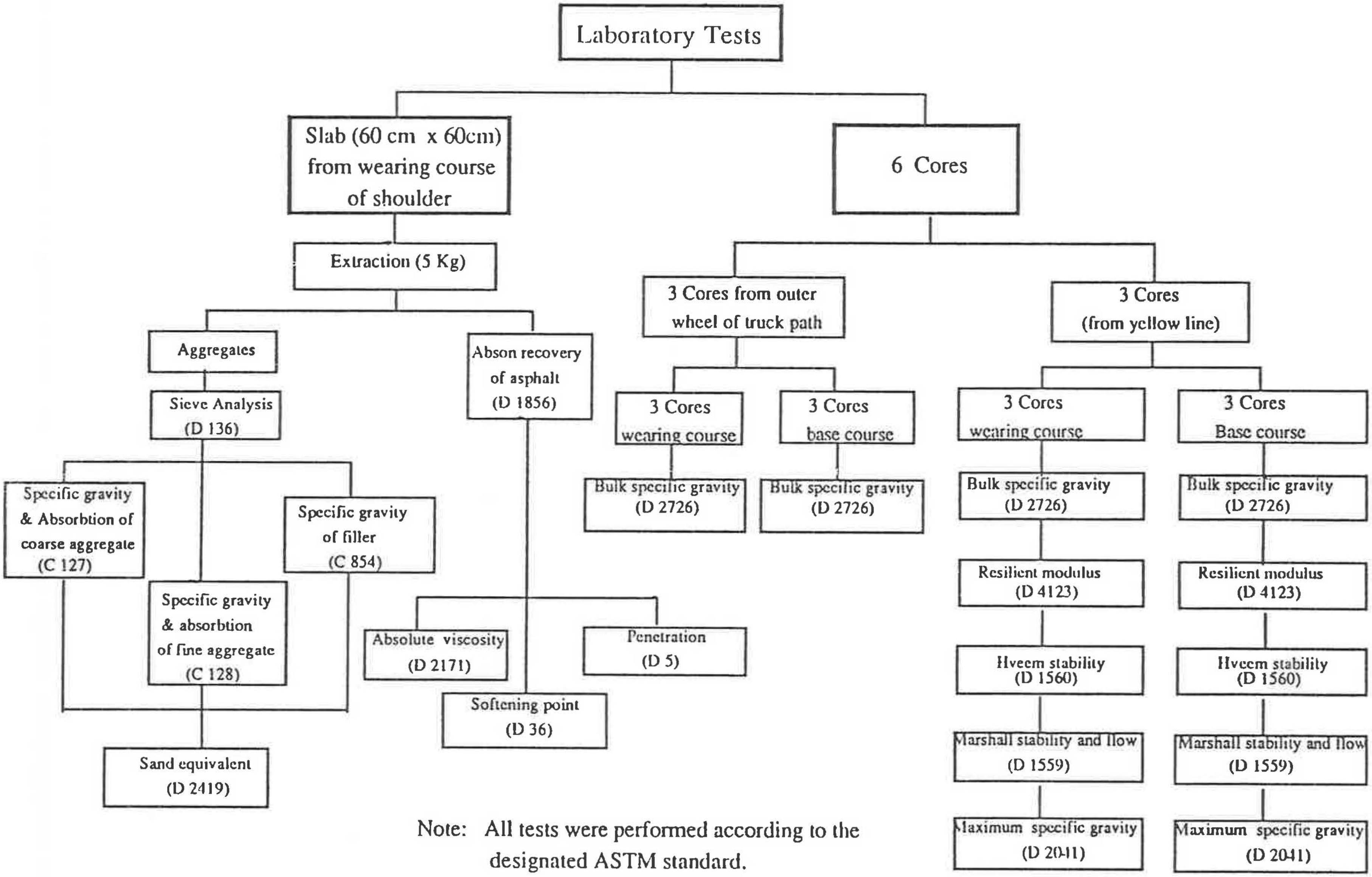
TABLE 3 LIST OF VARIABLES EVALUATED IN THIS STUDY

| Variables Considered in the Study | Symbols |
|---|---|
| **(Mix Variables)** | |
| Bulk specific gravity of core samples | GMB |
| Modulus of resilience | MR |
| Hveem stability | HV |
| Marshall stability | MS |
| Marshall flow | MF |
| Marshall stability/flow | QU |
| Maximum specific gravity of mix | GMM |
| Asphalt content | AC |
| Filler/asphalt ratio | FA |
| Air voids in compacted mix | AV |
| Compactness | CP |
| **(Aggregate Variables)** | |
| Percentage of aggregate passing sieve No. 4 | P4 |
| Percentage of aggregate passing sieve No. 30 retained on sieve No. 50 | P35 |
| Percentage of aggregate passing sieve No. 40 retained on sieve No. 80 | P48 |
| Percentage of aggregate passing sieve No. 200 | P200 |
| Surface area of aggregates | SA |
| Fineness modulus | FM |
| Hump value | HP |
| Voids in the mineral aggregates | VMA |
| Sand Equivalent | SE |
| Specific gravity of filler | SFL |
| Bulk specific gravity of fine aggregate | SGF |
| Bulk specific gravity of coarse aggregates | SGC |
| Absorption of fine aggregates | ABF |
| Absorption of coarse aggregates | ABC |
| **(Binder Variables)** | |
| Asphalt-cement penetration | PN |
| Softening point of asphalt-cement | SFT |
| Absolute viscosity of asphalt cement at 60° C | VS |

The modulus of resilience for samples was determined at load values ranging between 150 and 200 lb/in. of specimen thickness. Load frequency was 0.5 cycle/sec with a dynamic load duration of 0.1 sec. A static load of 40 lb was also used to hold the specimens in place.

For two locations (i.e., 4 and 5) the specimens had small diameters, 93 and 95 mm, respectively. Therefore, it was not possible to determine reliable Hveem or Marshall stability values for these samples.

In addition, Hveem testing requires that the height ranges of overall samples be between 51 and 76 mm to correct the Hveem stabilometer values to the standard height of 64 mm. However, the correction curves for overall specimen heights more than 64 mm had to be extended to correct for Hveeem values measured outside the specified range.



Note: All tests were performed according to the designated ASTM standard.

**FIGURE 3** Laboratory test program flow chart.

## Analysis of Results

The results of the various tests were tabulated for further analysis. A summary of all test results is given in Table 4. It was essential to consider both the measured values for each type of test and the difference in test value between unrutted and rutted sections to determine major mix variables that could affect rutting.

In addition, new parameters (mainly derived from gradation analysis) were calculated. Such parameters were reported by various researchers to potentially affect the rutting characteristics of a mix. The statistical *t*-test was conducted to see if the means of each variable of the data for the two sections were equal.

A paired *t*-test was used because the two sections (rutted and unrutted) of each location have the same age and were subjected to the same loadings and environmental conditions. The *t*-test was conducted for the wearing courses and base courses separately. All statistical analysis was performed by using the SAS program.

Table 5 summarizes the results of the statistical analysis performed. The *t*-test results shown in the table indicate that the significance of any variable is established by the probability that there are significant differences in the means of this variable for both rutted and unrutted sections. For the wearing course, the significant variables according to this test ($\alpha = 0.05$) were VMA and modulus of resilience (MR). For the base course the results indicate that the significant variables according to this assumption of $\alpha = 0.05$ were Hveem stability (HV), MR, and Marshall stability (MS).

Because the statistical analysis revealed that only a few variables were to have significant differences between rutted

TABLE 4 SUMMARY OF TEST RESULTS

| Variable | Unit | Location | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| | | Unrut | Rut | Unrut | Rut | Unrut | Rut | Unrut | Rut | Unrut | Rut | Unrut | Rut | Unrut | Rut |
| (A) Wearing Course | | | | | | | | | | | | | | | |
| AC | % | 4.40 | 4.54 | 4.80 | 4.07 | 4.29 | 4.04 | 4.31 | 4.79 | 4.86 | 4.62 | 4.77 | 4.08 | 4.46 | 4.62 |
| | | 4.59 | 4.45 | 4.63 | 4.14 | 4.62 | 4.14 | 4.51 | 4.77 | 4.46 | 4.60 | 4.62 | 3.95 | 4.35 | 4.74 |
| | | 4.58 | 4.34 | 4.88 | 4.23 | 4.26 | 4.02 | 4.20 | 4.70 | 4.65 | 4.77 | 4.41 | 4.12 | 4.32 | 5.34 |
| | | 4.53 | 4.34 | 4.56 | 4.06 | 4.16 | 4.05 | 4.17 | 4.78 | 5.19 | 4.61 | 4.88 | 3.98 | 4.52 | 4.50 |
| PN | 0.1 mm | 23 | 22 | 21 | 54.7 | 36.9 | 20.4 | 27.4 | 40.8 | 25.1 | 28.8 | 14.3 | 15.3 | 17.3 | 17.9 |
| | | 23 | 23 | 22 | 54.6 | 35.7 | 21.3 | 27.6 | 41.3 | 24.3 | 28.9 | 14.5 | 15.5 | 17.8 | 19.5 |
| | | 23 | 22 | 21 | 52.7 | 34.6 | 20.9 | 27.05 | 43.3 | 25.4 | 28.3 | 14.3 | 15.6 | 17.8 | 19.4 |
| VS | 10E+3 | 179.9 | 161 | 177 | 11.1 | 19.2 | 224.9 | 82.9 | 11.2 | 55.8 | 31.9 | 165.9 | 300.3 | 160.3 | 85.0 |
| | Poise | 221 | 159.8 | 177.9 | 10.1 | 19 | 233.6 | 73.1 | 11 | 53.3 | 33.2 | 162.7 | 315.3 | 178.4 | 84.0 |
| SFT | °C | 72 | 69.5 | 72 | 57 | 61 | 71.5 | 67.5 | 57.2 | 66.4 | 66 | 72.6 | 75.6 | 71.6 | 70.4 |
| | | 72 | 69.5 | 72.5 | 58 | 61.5 | 71.5 | 68 | 57 | 66.6 | 66 | 72.8 | 75.8 | 72.2 | 70.8 |
| MR | 10E+6 | 1.574 | 0.919 | 1.550 | 1.297 | 1.642 | 0.992 | 1.704 | 1.056 | 1.166 | 1.218 | 1.486 | 1.197 | 1.607 | 0.915 |
| | PSI | 1.528 | 0.748 | 1.493 | 1.647 | 1.750 | 1.072 | 1.663 | 1.324 | 1.201 | 0.683 | 1.301 | 1.748 | 1.685 | 0.775 |
| | | 1.675 | 0.911 | 1.475 | 1.780 | 1.278 | 1.144 | 1.625 | 1.144 | 1.340 | 0.699 | 1.745 | 1.226 | 1.553 | 1.194 |
| HV | | 79.5 | 34.5 | 72.5 | 49.5 | 60 | 45.5 | 30 | 30 | 35 | 16.5 | 57.5 | 40 | 63 | 20 |
| | | 70.5 | 39 | 55 | 56 | 48 | 50 | 35 | 26 | 37 | 22 | 50 | 40.5 | 50 | 26.5 |
| | | 71.5 | 28 | 57 | 55.5 | 40 | 41 | 28 | 26.5 | 30 | 20 | 37 | 39 | 47.5 | 16 |
| MS | lbs. | 3499 | 3089 | 2905 | 3065 | 3993 | 3732 | 3840 | 2668 | 3638 | 1936 | 3385 | 3198 | 3408 | 2693 |
| | | 3129 | 3485 | 2804 | 3073 | 3791 | 3473 | 4521 | 3212 | 3381 | 2212 | 3591 | 2811 | 2889 | 2837 |
| | | 2881 | 2615 | 2920 | 3244 | 3825 | 3286 | 4002 | 3413 | 3603 | 2394 | 3146 | 2891 | 3281 | 2840 |
| MF | 0.25 mm | 29.9 | 24.7 | 21.8 | 24.7 | 22.8 | 25.6 | 27.9 | 36.3 | 30.9 | 33.6 | 20.6 | 26.6 | 32.4 | 19.5 |
| | | 25.9 | 21.8 | 23 | 22.5 | 21.7 | 23.7 | 29.4 | 43.6 | 33.9 | 40.3 | 23 | 21.3 | 29.1 | 25.2 |
| | | - | 21.6 | 24 | 19.2 | 23.1 | 21.3 | 27.9 | 43.7 | 32.3 | 39 | 22 | 23.9 | 30.3 | 21 |
| (B) Base Course | | | | | | | | | | | | | | | |
| MR | 10E+6 | 1.641 | 0.736 | 1.548 | 1.567 | 1.470 | 0.985 | 1.482 | 1.368 | 0.939 | 0.631 | 1.233 | 0.591 | 1.649 | 0.93 |
| | PSI | 1.804 | 0.726 | 1.841 | 1.265 | 1.573 | 0.89 | 1.196 | 1.097 | 1.220 | 1.553 | 1.121 | 0.537 | 1.687 | 1.120 |
| | | 1.573 | 0.860 | 1.463 | 1.162 | 1.272 | 0.825 | 1.554 | 1.261 | 0.901 | 1.545 | 1.447 | 0.664 | 1.699 | 0.882 |
| HV | | 80 | 28 | 72.5 | 45 | 62 | 33 | 37 | 18.5 | 32.5 | 31 | 42 | 23 | 67 | 31 |
| | | 61 | 29 | 80 | 49.5 | 49.5 | 35 | 39 | 20 | 27 | 37.5 | 39 | 20 | 59 | 36 |
| | | 79.5 | 36 | 72 | 50 | 41 | 38 | | 22 | 27 | 20 | 40 | 25.5 | 82 | 33 |
| MS | lbs. | 4273 | 2471 | 3385 | 2934 | 3918 | 3485 | 3449 | 3401 | 2347 | 2865 | 2799 | 1828 | 4051 | 2510 |
| | | 3337 | 2239 | 3781 | 3087 | 3670 | 2902 | 3678 | 4636 | 2918 | 2861 | 2664 | 1359 | 3936 | 2646 |
| | | 3747 | 3360 | 2890 | 3292 | 4264 | 2638 | 2796 | 3811 | 3778 | 2394 | 2812 | 1719 | 3965 | 2603 |
| MF | 0.25 mm | 33.5 | 20 | 38.8 | 19.8 | 29.1 | 29.3 | 38.1 | 45.7 | 25.2 | 36.3 | 17.2 | 32.9 | 20.8 | 22.2 |
| | | 21.5 | 22.8 | 27.8 | 20.6 | 31.2 | 24.3 | 31.1 | 49 | 32.4 | 32.2 | 18.3 | 28.7 | 21.1 | 25.9 |
| | | 24.5 | 23.3 | 24.5 | 19.2 | 19.2 | 22.1 | 32.2 | 45 | 29.9 | 42 | 19.3 | 26.1 | 19.8 | 22.7 |

TABLE 5 *t*-TEST RESULTS FOR BOTH WEARING AND BASE COURSE VARIABLES

| Variable | Wearing Course | | Base Course | |
|---|---|---|---|---|
| | T-value | PR>-T- | T-value | PR>-T- |
| HV | 2.40 | 0.0746 | 5.13 | 0.0068 |
| MR | 3.87 | 0.0082 | 2.98 | 0.0245 |
| AV | 1.96 | 0.0973 | 0.44 | 0.6731 |
| CP | 0.45 | 0.6711 | 2.32 | 0.0595 |
| MS | 1.63 | 0.1788 | 3.51 | 0.0247 |
| MF | 1.18 | 0.3046 | 0.43 | 0.6902 |
| VMA | 20.62 | 0.0001 | * | * |
| HP | -1.57 | 0.1683 | * | * |
| SE | -0.57 | 0.5872 | * | * |
| GMB | -2.07 | 0.0843 | * | * |
| P4 | 1.84 | 0.1161 | * | * |
| P10 | 0.71 | 0.5062 | * | * |
| P200 | -2.00 | 0.0922 | * | * |
| P35 | -0.42 | 0.6858 | * | * |
| FM | 1.15 | 0.2950 | * | * |
| SA | -1.64 | 0.1528 | * | * |
| ABC | -0.42 | 0.6891 | * | * |
| ABF | 1.36 | 0.2219 | * | * |
| AC | 1.02 | 0.3492 | * | * |
| VS | 0.08 | 0.9408 | * | * |
| SFT | 0.75 | 0.4794 | * | * |
| PEN | -0.22 | 0.8856 | * | * |
| FA | -1.99 | 0.0934 | * | * |

* Data not available

and unrutted sections, only those variables will be presented and discussed subsequently.

The test results for MR are shown in Figure 4 for both wearing and base courses. They show that the MR values for the unrutted sections of the wearing course are generally higher than those of the rutted sections (except slightly for location 2). The same was true in the case of the base course (except for location 5). The consistency of the higher values of MR for the unrutted sections classifies it as a major factor to be considered when characterizing asphalt mixes for rutting control. However, from the study of MR values it is not possible to define a range of values above which rutting will not occur and below which rutting will occur.

The results for Hveem stability are shown in Figure 5 and indicate that HV is consistently higher for the unrutted sections. Results for locations 4 and 5 are shown in the figure only for completeness but were not used in the *t*-test statistical analysis. This was, as was explained, because the core diameters were less than required.

The results for MS are shown in Figure 6 for both wearing and base courses. The MS values are generally higher for the unrutted section than the rutted section except for location 2. However, the difference in MS values is not as significant as in the Hveem test. Results for locations 4 and 5 are only shown for completeness but were not used in the *t*-test statistical analysis, as was explained. It is not possible to establish a threshold value above which rutting might not occur.

VMA has been shown by several researchers to affect the rutting susceptibility of asphalt concrete mixes. VMA is highly affected by gradation of the aggregate and by asphalt content during compaction. Figure 7 shows the test for VMA of the wearing course. Except for locations 4 and 5, VMA of the unrutted section is higher than that of the rutted section, which is consistent with several researcher recommendations

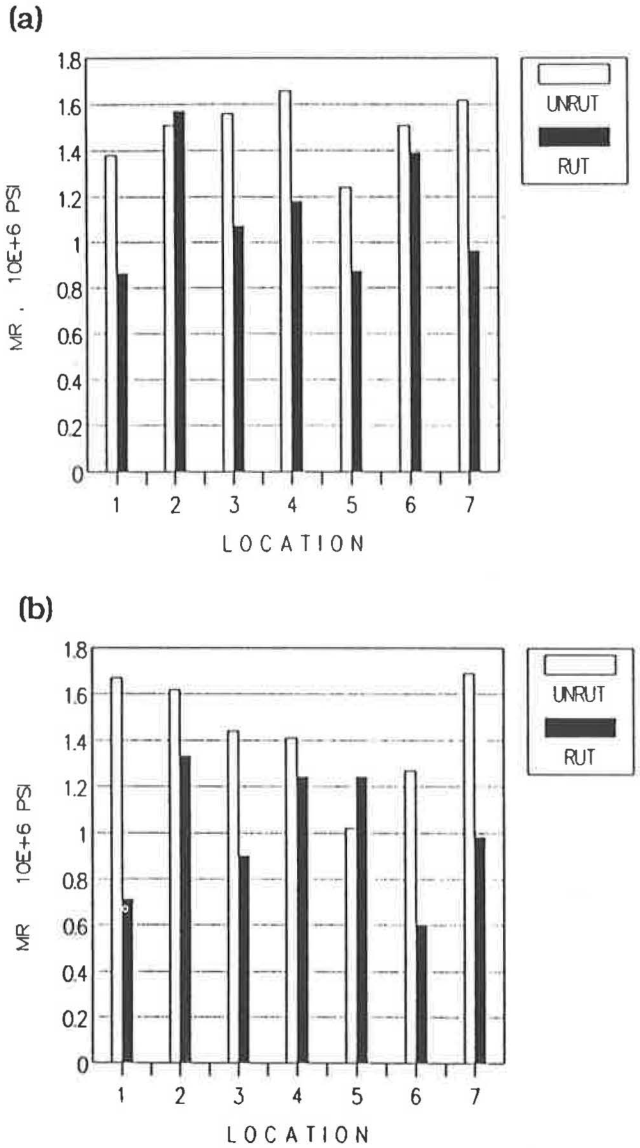


**FIGURE 4** Results for modulus of resilience for selected test locations: (a) wearing course and (b) base course.

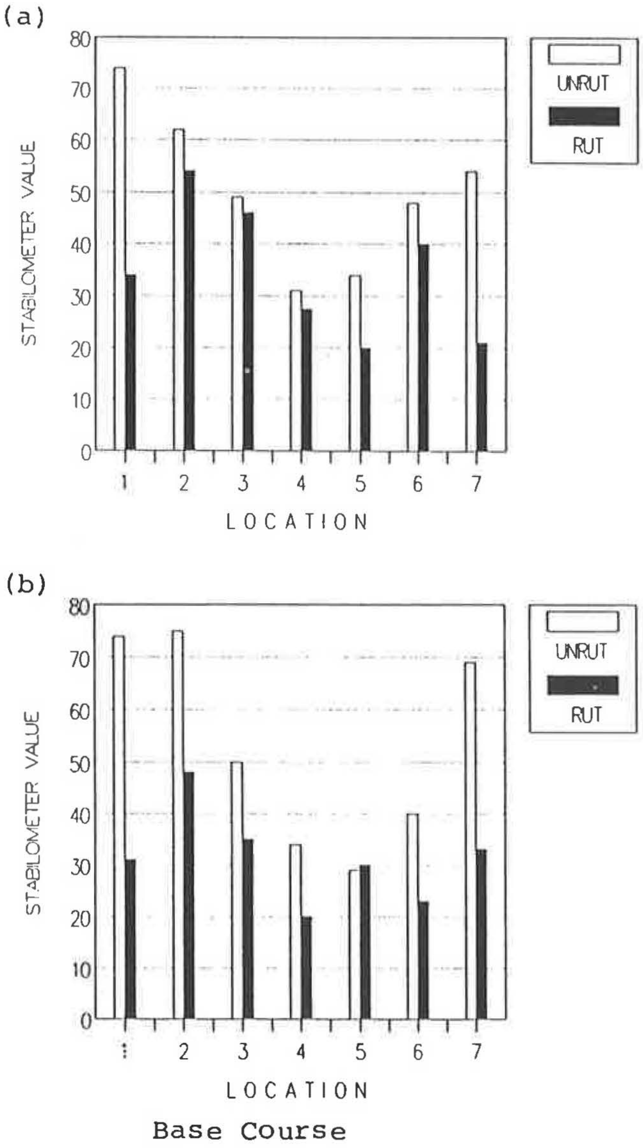


**FIGURE 5** Results for Hveem stability for selected test locations: (a) wearing course and (b) base course.

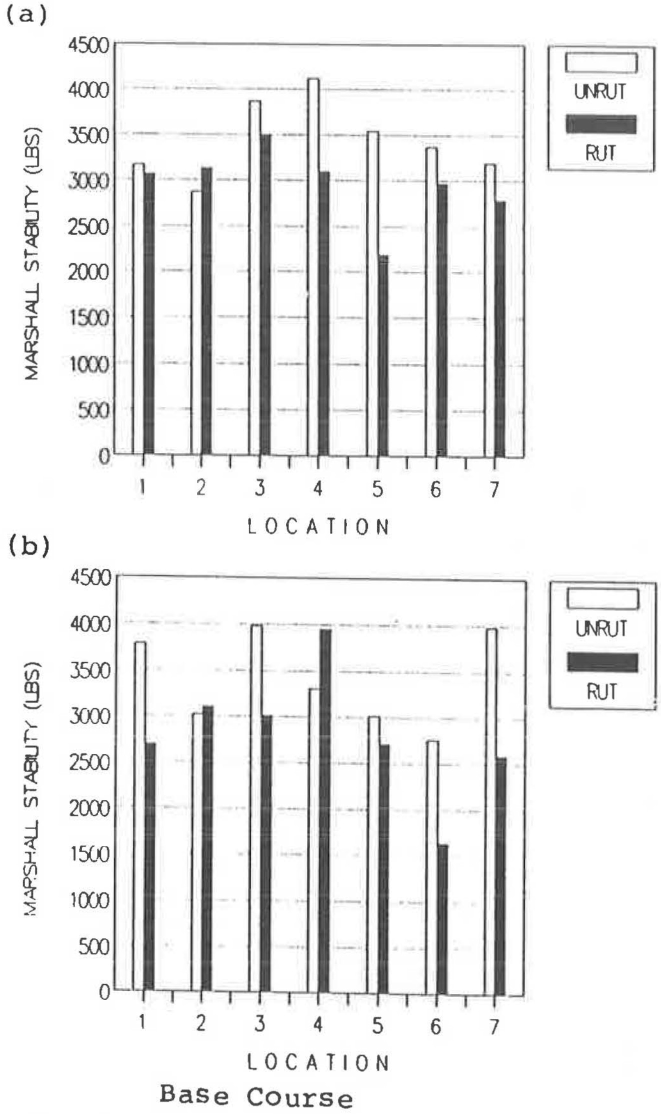


**FIGURE 6** Results for Marshall stability for selected test locations: (a) wearing course and (b) base course.

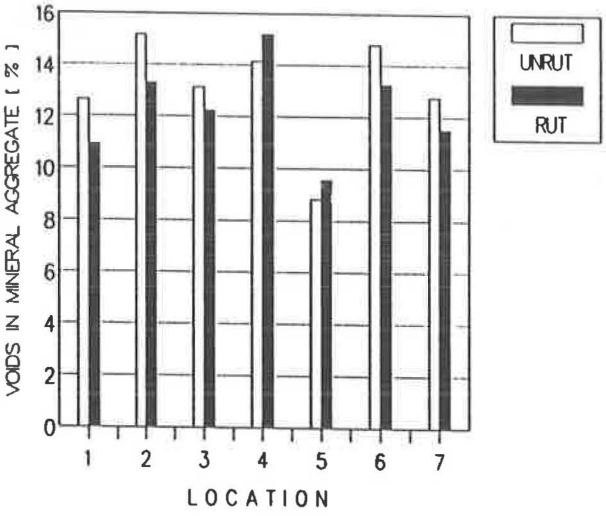


**FIGURE 7** Results of voids in mineral aggregate for wearing course of selected test locations.

to increase VMA as a step toward improving the resistance to permanent deformation. Since field slabs were taken only from the wearing course, VMA data were not obtained for the base course.

Gradation analysis is a significant factor that affects behavior of asphalt mixes, especially pavement deformation resistance. A typical wearing course gradation is shown in Figure 8 for location 5. The rutted section has a gradation outside recommended specification limits and has coarser aggregates retained on sieve No. 4. Generally, analysis of the gradation results has shown that the second observation was consistently valid, which suggests that using finer gradation of the coarse portion of the aggregate (+ No. 4) in the mix will give more tendency toward unrutting of asphalt mixes.

Figure 9 shows the asphalt content for both rutted and unrutted sections to establish how the asphalt content of a mix affects rutting. The scatter of data indicates no clear trend. In general, unrutted sections contain higher asphalt content, contrary to the finding of other researchers, who indicate that increasing asphalt content can significantly increase rutting potentiality. This should not be taken to mean that increasing asphalt content improves the resistance of a mix to permanent deformation.

## CONCLUSIONS

The conclusions of this study can be summarized as follows:

1. Although most of the literature has assumed rutting to occur basically in the wearing course, results of this study reveal the base course to be a significant factor in the rutting of asphalt pavements.
2. Statistical analysis by using *t*-tests has shown that VMA and MR give consistent indication of improving rutting resistance of wearing course mixes. For base courses, the significant variables were found to be HV, MR, and MS, all of which are strength tests.
3. Most of the unrutted sections investigated in this study indicated that finer proportions were used for the coarse aggregate portion.
4. Contrary to previous findings, decreasing asphalt contents of a mix were not shown to be a significant factor affecting rutting.
5. The results of this study indicate that the properties of the bituminous mix have more influence on the rutting susceptibility than the properties of the individual ingredients (asphalt or aggregates).

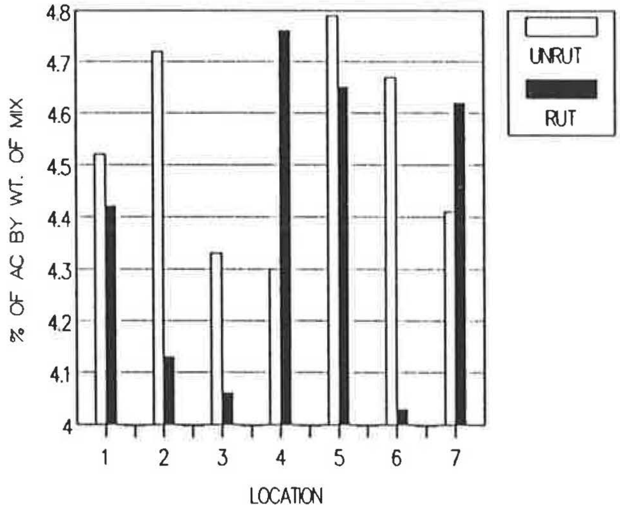


**FIGURE 9 Results of asphalt content for wearing course of selected test locations.**

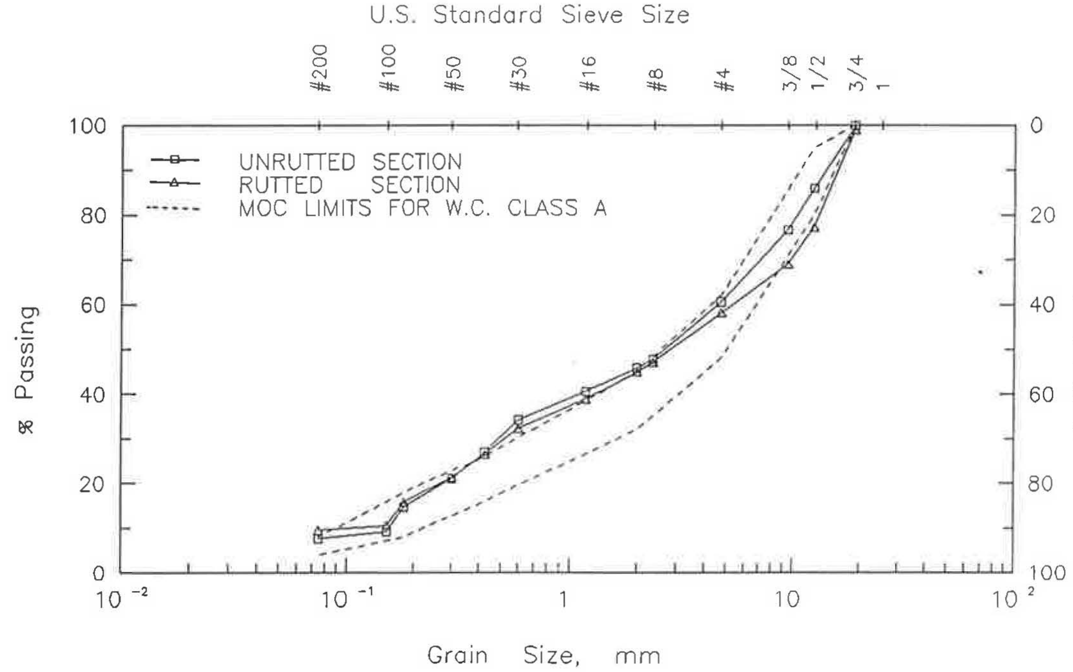


**FIGURE 8 Typical gradation for location 5.**

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*Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.*