Criteria for Evaluation of Rutting Potential Based on Repetitive Uniaxial Compression Test

EL HUSSEIN H. MOHAMED AND ZHONGQI YUE

Tests conducted following the mix design stage, are unable to assess the rutting potential of asphalt concrete pavements. They range from moving a rubber tire on a slab and monitoring the rut depth to large-scale field tests using accelerated loading facilities. The Strategic Highway Research Program (SHRP) has proposed evaluating induced damage by determining the accumulated permanent shear strains based on a repetitive simple shear (constant height) test.

An investigation conducted at the Centre for Surface Transportation Technology of the National Research Council of Canada is aimed at developing a criteria for measuring rutting potential. A repetitive uniaxial compression test was used to determine accumulated permanent axial strain. Tests were conducted on cores recovered from the field and others compacted in the laboratory using a SHRP gyratory compactor. Test results indicate that the accumulated permanent axial strain undergoes three distinct stages: strain-hardening (volume change), shear flow, and, finally, fracture failure. During the secondary stage (shear flow) the rate of accumulation of permanent axial strain is constant and is sensitive to asphalt mix's resistance to rutting. Performance-related testing of the mix's resistance to potential rutting was carried out at different temperatures. Based on a proposed rutting criterion, one focused on the constant rate of permanent axial strain, the SHRP gyratory compactor simulates field compaction reasonably well. The influence of sample height, applied pressure, and compaction effort on the proposed rutting criterion also was investigated.

Rutting of asphalt pavements, primarily from high tire pressure and increased wheel loads of commercial vehicles, has increased in recent years. High stresses near the pavement surface induce high shear deformation and are considered responsible for rutting in asphalt concrete pavements. Difficulties associated with predicting the rutting susceptibility of asphalt concrete in the laboratory during the mix design stage have forced researchers to consider broad and expensive field testing (*1*). Disagreements about existing laboratory tests focus on the extent to which these tests simulate field conditions.

BACKGROUND

Many investigators consider rutting in asphalt concrete to be caused principally by shear deformations resulting from high shear stress near the surface. However, inadequate structural capacity as a result of improper designs and construction practices cannot be ruled out.

Recently, the Strategic Highway Research Program's (SHRP) asphalt research program described a series of tests for the evaluation of material properties related to permanent deformation (rutting) in asphalt concrete (*2*). In particular, a repetitive simple-shear test was recommended for determining the accumulated shear damage in asphalt concrete.

Reasons for Test Selection

In the authors' laboratory investigation, however, a repetitive uniaxial compression test was used to evaluate permanent deformation (rutting) of asphalt concrete. A repetitive uniaxial compressive load applied on the cylindrical samples of asphalt concrete can provide reasonable simulation of asphalt pavements subjected to repetitive heavy axle loads. Based on the test results of this study, a constant rate of accumulated permanent strain was found for all tested samples. This constant rate, which is unique for each mix, can be used as a criterion for evaluation of rutting potential of asphalt concrete.

Conventional mix-design procedures allow for additional densification of asphalt concrete under traffic loads. Compaction in the field seldom achieves densities specified in the laboratory. Therefore, any laboratory test designed for predicting rutting susceptibility of a new mix must account for permanent deformations following mix densification that are associated with changes in the mix microstructure. These factors influenced the selection of the appropriate test for this study. The uniaxial compression test can be used to determine reasonably the susceptibility of a mix to permanent deformations related to shear deformation as well as those associated with changes in the microstructure of asphalt concrete.

Uniaxial Compression Test

The components of the test, described in detail in an earlier publication (*3*), include the test set up (Figure 1), the choice of a load cycle, and a laboratory procedure for manufacturing samples. A SHRP gyratory compactor was chosen for sample preparation on the basis of results from a comprehensive investigation that compared many devices used to compact asphalt concrete in the laboratory (*4*). Gyratory compaction seems to produce compacted mixtures with engineering properties similar to those produced in the field. More evidence has been produced by the results of this investigation, further justifying the use of the SHRP gyratory compactor.

Repetitive compressive loading was used to simulate traffic loading on the basis of research conducted at Nottingham University, and a square wave load application was selected consistent with subsequent work. The square wave consisted of a constant loading period of 0.2 sec followed by a rest period of 1.8 sec. The axial pressure used was 690 kPa (100 psi), which was reduced to

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Centre for Surface Transportation Technology; National Research Council of Canada; Ottawa, Ontario, Canada K1A 0R6.

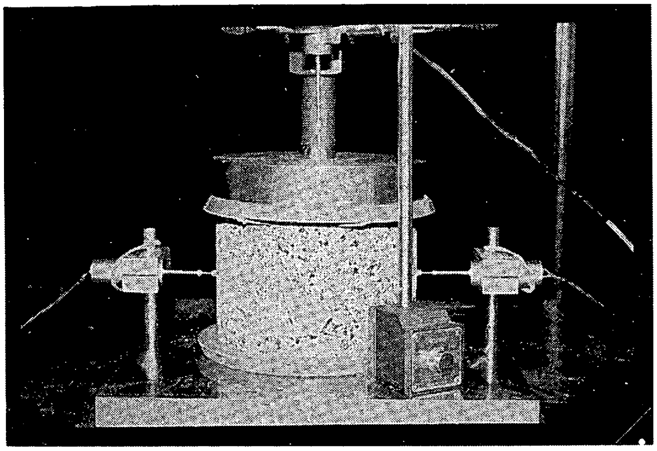

FIGURE 1 Repetitive uniaxial compression test setup.

2 percent of that level during the rest period to avoid separation of the loading head from the sample surface. The stress level was chosen on the basis of the tire pressure of commercial vehicles common to North American highways. Because plastic flow had been identified as the major cause of severe rutting, tests were conducted at 25°C and 40°C to account for the instability of asphalt cement at high temperatures.

EXPERIMENTAL INVESTIGATION

The testing program was designed to study the response of tested mixes to the repetitive uniaxial compression test, and to determine a performance indicator that could be adopted as a criterion for rutting. Factors influencing the rutting criterion were investigated:

- Height of the tested sample,
- Level of the applied pressure,
- Compaction effort,
- Laboratory compaction versus field compaction, and
- High-temperature environment.

Material

To determine the test's sensitivity to the type of mix, tests were conducted on two asphalt concrete mixes. These two mixes are known to exhibit significantly different rutting characteristics. One mix, a conventional dense hot asphalt mix, was designed following the Marshall mix design procedure. Details of the mix formula, referred to as HL4, are indicated in Table 1. The other mix (see Table 2) is a large aggregate asphalt mix developed at The Centre for Surface Transportation Technology of The National Research Council of Canada (CSTT/NRC) to provide high resistance to rutting (*5*). High resistance to rutting has been achieved with use of a stone-to-stone contact, which has offered higher resistance to traffic-induced stresses than have conventional mixes.

Sample Height

To study the influence of the sample height on accumulated permanent deformation, samples with heights ranging from 40 to 80 mm were manufactured from the conventional HL4 mix using a SHRP gyratory compactor. One set of samples was tested at 25°C

TABLE 1 H4 Mix Details

Sieve Designation	Percent Passing				
	Coarse Aggregate	Fine Agg. 1 (crusher screenings)	Fine Agg. 2 sand	Combined Agg. Mix	MTO^{X} specifications
26.5	100	-	-	-	-
19.0	100	-	-	100	100
16.0	97.2	-	-	98.7	98-100
13.2	78.1	-	-	89.9	83-95
9.5	48.8	100	100	76.4	62-82
# 4	9.6	100	100	58.4	40-67
# 16	2.5	80.1	79.5	44.2	27-66
# 50	2.0	35.2	36	20.2	4-27
# 100	1.7	9.9	4.8	4.3	1-10
# 200	1.5	4.8	0.7	2	0-6

x MTO - Ministry of Transportation of Ontario, Canada

The job mix formula used: coarse aggregate = 43.8%
crusher screenings = 17.4%
natural sand = 33.6%
asphalt cement (85/100) = 5.2%

TABLE 2 Large Aggregate Mix Details

Sieve Size (mm)	37.5 mm	Percent Passing			
		HL 3	Crusher Screenings	Sand	Combined Agg. Mix
37.5	100	-	-	-	100
25.0	90	-	-	-	95
16.0	25	100	-	-	61
11.0	5	90	-	-	49
8.0	2	47	100	-	40
#4	2	4	93	100	31
#10	1	1	56	93	24
#20	-	-	34	80	19
#40	-	-	22	49	12
#60	-	-	15	21	6
#100	-	-	10	5	3
#200	-	-	5	1	1

The job mix formula used:
38 mm McFarland Stone = 49.9%
HL3 stone = 17.3%
Quarry screenings = 11.5%
Field sand = 17.3%
Asphalt cement content (85/100) = 4.0%

and 690 kPa (100 psi). The minimum sample height was selected to satisfy requirements related to maximum aggregate size used in the tested mix. The maximum sample height was selected to represent maximum layer thicknesses used in stage construction. To account for the influence of temperature, a second set of samples was tested at 40°C.

Applied Pressure

Although a pressure of 690 kPa (100 psi) has been adopted to simulate tire pressure of commercial vehicles, a number of gyratory-compacted HL4 mix samples were tested using different uniaxial pressure levels. During the loading cycle pressure ranging from 345 kPa (50 psi) to 1034 kPa (150 psi) was changed from one sample to another.

Compaction Effort

Compaction specifications for laboratory tests to be used for quality control in the field are expected to adopt the number of gyrations used to achieve the required compaction quality. The relationship between the number of gyrations and compaction quality factor was studied in this investigation by compacting, varying the number of gyrations, testing samples that had the same initial uncompacted height, and using a SHRP gyratory compactor. Initial material weight was equivalent to that used earlier in order to achieve a sample height of 64 mm with 250 gyrations. These data illustrate that inadequate structural capacity resulting from improper construction practices contribute to rutting potential.

Laboratory Mix Versus Field Compaction

To investigate the ability of SHRP gyratory compaction to simulate field compaction, a number of cores representing the two mixes described earlier were recovered from full-scale, field-compacted test sections and were tested following the procedures used for laboratory-compacted samples. Unlike samples prepared in the laboratory, cores recovered from across the width of the experimental road sections showed high variation in physical properties, as reflected by bulk-specific gravity values. The average bulk-specific gravity of cores recovered from the road was determined according to ASTM D2726-90, on the basis of saturated surface dry specimens. The air-voids content for all samples used for comparison was determined according to ASTM D3203-88, using values of theoretical maximum-specific gravity as determined by ASTM D2041. Cores with average bulk-specific gravity close to that of laboratory-compacted samples were then selected for testing using the uniaxial compression test. Note that these samples were recovered from sections that were constructed 7 months apart; so to compare them with the laboratory results, one must consider the different aging periods and resulting difference in stiffness of the cores.

TEST RESULTS

Stages of Permanent Strain

Plots of the permanent axial strain accumulated under cyclic loading exhibit a readily identifiable trend. Figure 2 shows the typical relationship between accumulated permanent strain and the number

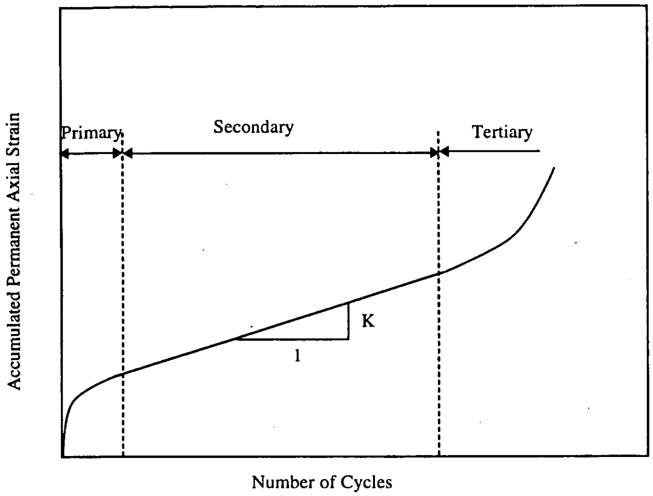

FIGURE 2 Typical relationship between permanent axial strain and number of cycles.

of cycles. The test results indicate that the accumulated permanent axial strain undergoes three distinct stages with increasing number of cycles. The three stages are referred to as primary, secondary and tertiary stages.

Primary Stage

Upon the initial load-application stage, large deformation occurs during a short period of time, indicating a very high rate of deformation (slope of the curve). This condition is followed by a rapid decrease in the rate of deformation with an increased number of cycles. Mechanisms that may act during this early stage of the test and lead to the observed behavior are summarized:

- The initial relatively high rate of deformation implies an immediate decrease in the sample height during the first few seconds that the load pulse is applied. One factor may be that the irregular surface of the sample leads to stress concentrations at relatively elevated points, resulting in the high deformations observed. Other mechanisms, such as densification of the mix as a result of reduced air voids, may lead to similar high rates of deformation.
- The rapid decrease in the rate of deformation within this primary stage may be the result of strain-hardening. The change in the microstructure of an asphalt concrete mix associated with aggregate reorientation leads to a dense mix with increased resistance to deformation.

Primary deformations could significantly contribute to rutting in the field under traffic loading. However, there are inadequate data from these tests to distinguish between deformation that is an artifact of the test procedure and true rutting deformation.

Secondary Stage

During the secondary stage, the rate of accumulation of permanent deformation remains constant. Surface irregularities are no longer a factor because load application during the primary stage flattened the surface. Also strain-hardening is balanced by the recovery process, as the controlling microstructure remains essentially unchanged. Aggregates are not expected to reorient more, because they probably have reached a preferred orientation for the particular energy level applied during the test. The permanent deformation during this stage is mainly caused by shear flow.

The rate of deformation during the secondary stage is essentially a constant, (K); This constant was selected for use in evaluating the rutting potential of different mixes. In this investigation, two mixes under different stress and temperature conditions provided uniquely different values of the constant K, indicative of their actual performance. High K values indicate high rutting susceptibility.

Tertiary Stage

In this final stage, the rate of deformation seems to accelerate until complete failure takes place. This stage is usually associated with the formation of cracks, suggesting that fatigue could be the primary cause of failure. However, other factors such as non-homogeneity of the mix, eccentricity of the loading plate, and surface inclination of the sample also may lead to premature failure.

Constant Rate of Deformation

Considering the uncertainties associated with the primary and tertiary stages, we concentrated on the secondary stage and investigated the constant rate of deformation (K) associated with this stage, considering it an indicator of rutting potential. The rest of the paper discusses the influence of various loading and temperature conditions on the value of K for different mixes.

The constant slope (K) was determined on the basis of the best fit of the straight line at the secondary stage. Test results obtained during the experimental investigation were processed by means of a computer program to determine:

- The accumulated permanent strain corresponding to the number of load cycles. This exercise includes eliminating the elastic portion of the deformation from the total deformation recorded during the test.
- The rate of permanent deformation, K, during the secondary stage using linear regression. The lowest correlation coefficient obtained, considering all samples reported in this study, was 0.993; the highest residual value was 0.34×10^{-3}

Influence of Sample Height

The relationship between accumulated permanent strain and the number of cycles for tests conducted at 25°C is plotted in Figure 3. Results of tests conducted at 40°C are plotted in Figure 4. The corresponding values of K that were determined for both temperature conditions are also indicated in the figures.

Clearly, sample height has little or no influence on accumulated deformations at either temperature. Variables related to compaction that seem to slightly influence the bulk-specific gravity of various samples, have no effect on the value of K determined at 25°C, (standard deviation $S = 0.01$). However, at the higher temperature, the difference between the bulk-specific gravity values seems to influence the determined values of K, as indicated by the relatively

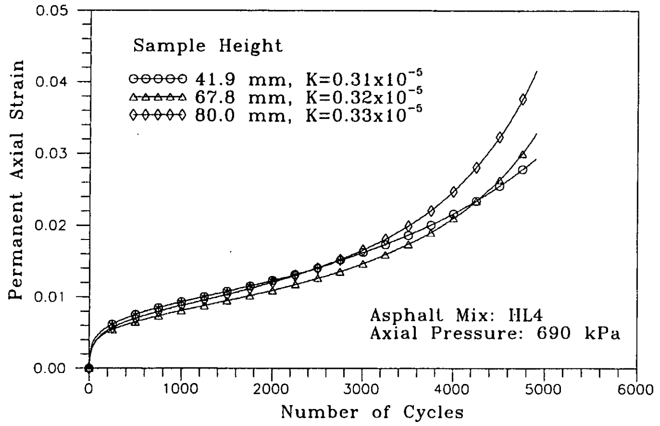

FIGURE 3 Effect of sample heights on accumulated permanent axial strain; tested at 25°C.

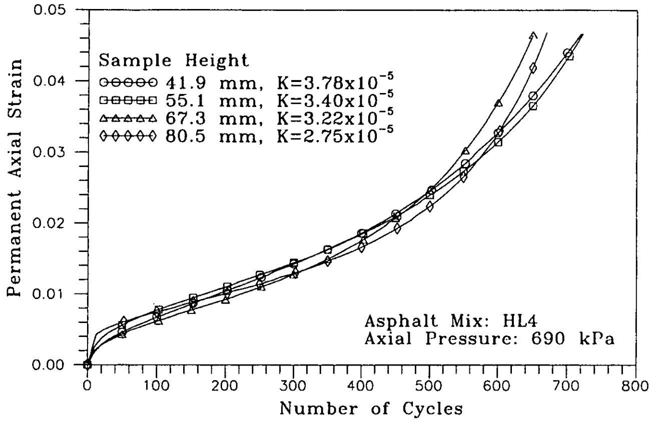

FIGURE 4 Effect of sample heights on accumulated permanent axial strain; tested at 40°C.

high standard deviation ($S = 0.42$). Another observation related to compaction deals with quality of compaction and is associated with the thickness of the sample. Compaction by the gyratory compactor of thinner samples proved less effective because there was little space for aggregate movement to a preferred orientation. The thickness is not a factor when the sample height is more than 60 mm.

Although the determined value of the rate of accumulated axial strain (K) is independent of the sample height, it is necessary to consider the difference in density that may have a direct link to the microstructure of the mix. Comparing results for the two test temperatures, we found the value of K increased by ten-fold on average when the temperature was increased from 25°C to 40°C. The increase is a natural result of more shear flow at low asphalt viscosity.

Another difference in performance related to temperature was observed at the transition from the secondary to tertiary stage. The number of cycles required to cause the transition from the secondary stage dropped approximately 10 times at high temperatures. Perhaps this transition point could be used in the future as another performance indicator. The decision whether to test rutting potential at an elevated temperature should be made based on the prevailing temperature of the region where the mix will be used.

Effect of Applied Pressure

The effect of varying the pressure levels applied during cyclic loading is illustrated in Figure 5. Accumulated permanent axial strain increased with increased pressure. The values of K determined for each pressure level are plotted in Figure 5.

Values of K are plotted against applied pressure in Figure 6. The plot of K against axial pressure suggests that this relationship may be represented by two linear functions with a transition pressure at 0.69 MPa.

$$10^5K(\sigma) = \begin{cases} 0.52\sigma - 0.07, \text{ for } \sigma \le 0.69 \text{ MPa} \\ 1.83\sigma - 0.98, \text{ for } \sigma \ge 0.69 \text{ MPa} \end{cases}$$

where K equals the rate of accumulated axial strain at secondary stage and σ equals the applied axial pressure (MPa).

From the equation it is apparent that there is a dramatic change (350 percent) in the rate of increase of K for axial pressures above 0.69 MPa. It is particularly interesting that this transition pressure is very close to the compaction pressure used to prepare the samples

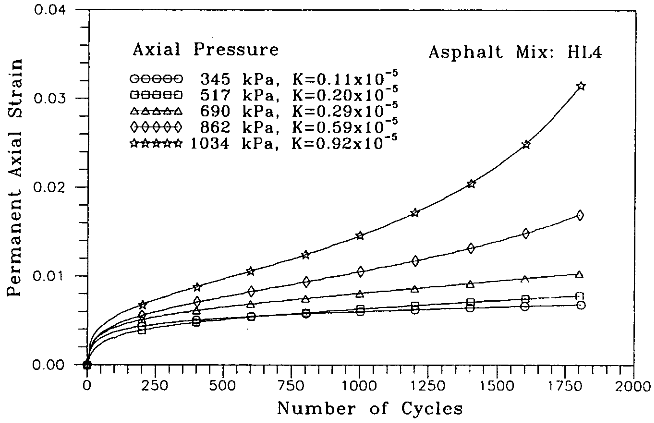

FIGURE 5 Effect of axial pressure on accumulated permanent axial strain; tested at 25°C.

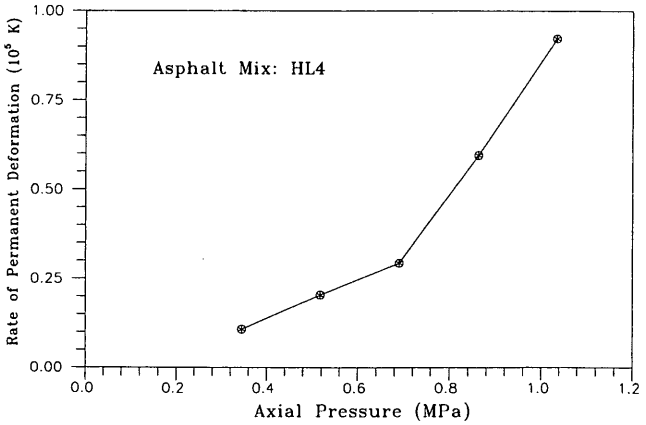

FIGURE 6 Effect of axial pressure on the constant rate (K) of accumulated permanent axial strain during the secondary stage; tested at 25°C.

(0.6 MP). In the future it will be interesting to determine whether a similar relationship exists between compaction pressure and increased value of *K* for different laboratory-compaction pressures.

Compaction Effort

Results of the repetitive uniaxial compression tests conducted on laboratory samples compacted by an SHRP gyratory compactor on basis of different numbers of gyrations are compiled in Figure 7. The results clearly demonstrate the effect of compaction effort on the mix's resistance to permanent deformation. Determined values of *K* for these samples, corresponding to the number of gyrations used during compaction, are also shown in Figure 7. The accumulated permanent strain decreased dramatically as the number of gyrations increased. After the number of gyrations reached 150, the rate of decrease in the *K* value dropped dramatically.

Larger accumulated deformation during the primary stage with a lower number of gyrations was expected because of the sample's probable restructuring. However, the values of the rate of accumulation of axial strain indicate that the value of *K* is also sensitive to the quality of compaction. The bulk-specific gravity values ranged from 2.290 after 30 gyrations to 2.394 after 250 gyrations. The bulk-specific gravity values clearly indicate that 200 gyrations bring the sample close to a refusal density for which the difference achieved at 250 gyrations is less than 1 percent. The small change in the values of *K* for the samples compacted to 200 gyrations as compared with samples compacted to 250 gyrations was an indication that shear flow will dominate close to refusal density.

Laboratory Compaction versus Field Compaction

This part of the experimental investigation was designed to confirm the suitability of the SHRP gyratory compactor to produce samples for laboratory evaluation of the rutting potential of various mixes using the uniaxial compression test. However, it is essential to consider the effect of variations in physical properties contributed by field compaction, when comparing them to test results for laboratory-compacted samples. In an effort to reduce the influence of properties such as bulk-specific gravity and air-void content on performance, cores from the field with properties close to that of laboratory samples were intentionally selected. The properties for the field-compacted samples listed are averages for the selected samples:

Mix Type	*Bulk-Specific Gravity*		*Air Void Percentage*	
	Laboratory	*Field*	*Laboratory*	*Field*
HL4	2.411* [0.006]	2.409	2.0* [0.006]	2.5
Large Aggregate Mix	2.401* [0.010]	2.395	3.0* [0.025]	2.0

* *Value represents average of samples compacted by SHRP gyratory compactor; numbers in brackets represent standard deviation*

Both theoretical maximum-specific gravity and bulk-specific gravity differ for field and laboratory samples. As a result, laboratory samples for a large aggregate mix have more air voids than can be achieved by field compaction. The differences in physical properties between the field and laboratory samples are expected to slightly influence the resistance of the tested mixes to permanent deformation, which must be considered when reviewing the results described here.

Figure 8 shows the results of the repetitive uniaxial compression test (24°C) conducted on a laboratory-compacted sample and a core recovered from the field for the same mix (HL4). Whereas values of the total permanent axial strain were different for the two samples, the rate of deformation (*K*) was approximately the same (0.35×10^{-5}). The difference in the shape of the deformation curve between the two compaction types (field and gyratory compaction) was limited to the primary and tertiary stages. As dicsussed before, the primary stage is partially influenced by the nature of the sample surface. For cores recovered from the field, the surface was rough compared with the texture of the laboratory-prepared sample, which explains the high rates of accumulation of permanent strain. The transition from secondary to tertiary stage took place at lower numbers of cycles in the gyratory-compacted sample. The difference in performance at this stage between the two samples may be related to the difference in curing periods in this particular experiment. As mentioned earlier, the field cores were 7 months older than the laboratory-prepared samples.

Based on the suggested evaluation criterion for rutting, (*K*), gyratory compaction produced a mix that behaves quite similar to

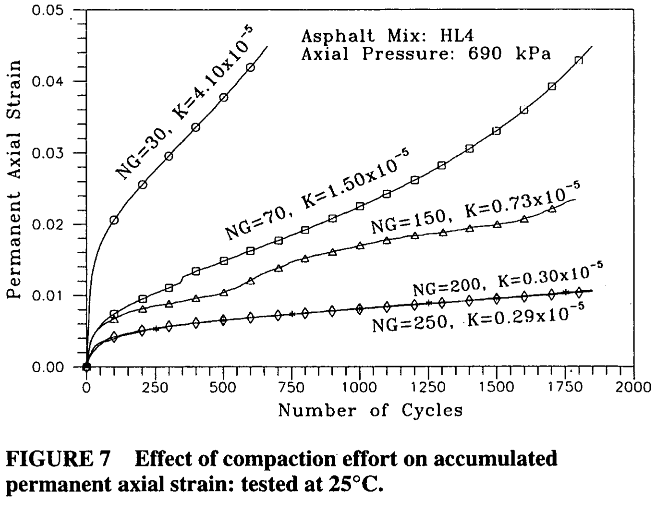

FIGURE 7 Effect of compaction effort on accumulated permanent axial strain: tested at 25°C.

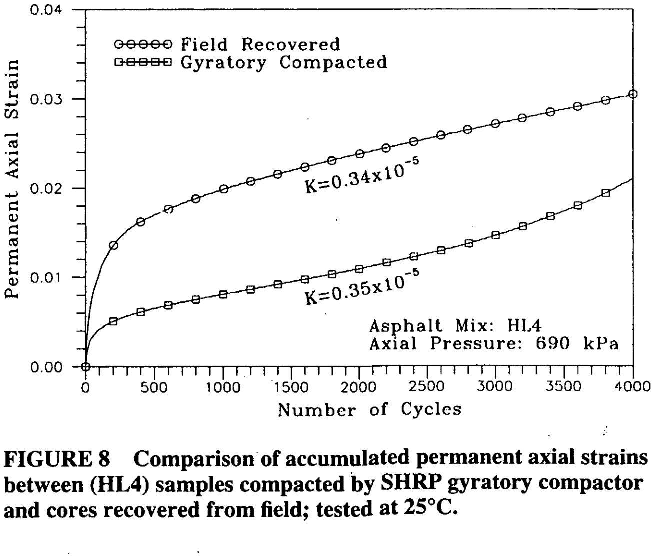

FIGURE 8 Comparison of accumulated permanent axial strains between (HL4) samples compacted by SHRP gyratory compactor and cores recovered from field; tested at 25°C.

that which is compacted in the field. A second test was conducted on similar samples at 40°C to study the effect of a high-temperature environment; the results are plotted in Figure 9. The values of *K* were found to be approximately equal (3-percent difference). The difference between the two compaction types at the primary and tertiary stage was magnified in the test conducted at the higher temperature. Behavior at the primary stage can be explained by the effect of differences in the sample's surface condition and in the compaction effort. There is no definite explanation for the considerable difference in the behavior of tested samples at the tertiary stage.

The same experiment was performed at 40°C on a large aggregate mix developed at CSTT/NRC. The test results are plotted in Figure 10. Similar to the above experiment, the gyratory compactor produced a mix with a *K* value equivalent to that of a core recovered from the field (1-percent difference). The deviations observed at the primary and tertiary stages in the HL4 mix were repeated with the large aggregate mix.

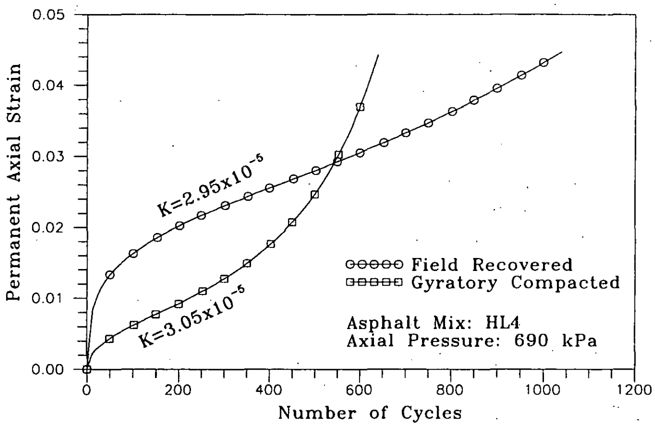

FIGURE 9 Comparison of accumulated permanent axial strains between (HL4) samples compacted by SHRP gyratory compactor and cores recovered from field; tested at 40°C.

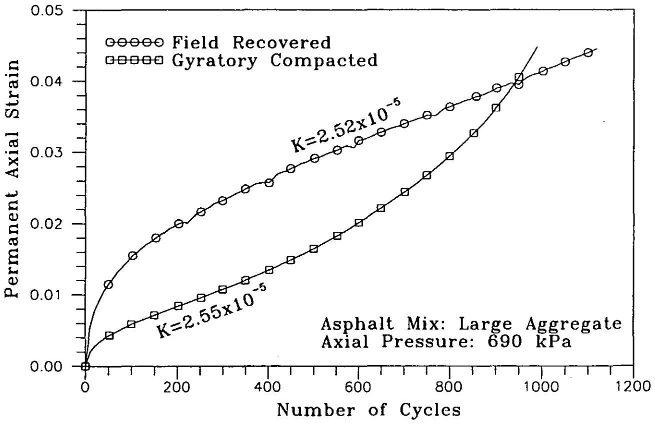

FIGURE 10 Comparison of accumulated permanent axial strains between samples (large aggregate mix) compacted by SHRP gyratory compactor and cores recovered from field; tested at 40°C.

Mix Rating

The ability of the defined rutting criteria (*K*) to rate various mixes can be demonstrated by comparing results of two uniquely different mixes with known resistance to rutting. Test results can be used to rate the performance of these two mixes with respect to each other of the HL4 and the large aggregate mixes shown earlier in Figures 9 and 10. As anticipated, the tests, conducted at 40°C, illustrated the high resistance to rutting offered by the large aggregate mixes—a direct consequence of the favorable microstructure of the large aggregate mix. Based on these results, the *K* value of the large aggregate mix is 17 percent less than that of the HL4 mix. The difference between the two mixes continued beyond the secondary state to the tertiary stage. The increased rate of deformation occurred much earlier in the HL4 mix. It is not yet possible to explain why this occurred based on the data available.

CONCLUSIONS AND RECOMMENDATIONS

This paper is a progress report on the ongoing effort at CSTT/NRC to develop a prediction procedure for rutting of asphalt concrete pavement. The authors acknowledge the need for sufficient replicates of the obtained test results to make statistically significant conclusions. The authors chose to investigate the large number of variables involved in developing a prediction procedure in order to identify areas that require additional effort. Further work is already in progress to determine the reproducibility of the test results and to expand analysis to the primary and tertiary stages of the test. The following are conclusions based on the test results presented in this paper:

1. The constant rate of deformation (*K*) within the secondary stage, as identified by this study, is a suitable criterion for rating the resistance to permanent deformation, for use in predicting rutting potential in the field.
2. The SHRP gyratory compactor produces samples with rutting characteristics equivalent to that of cores recovered from the field as far as the rate of deformation within the secondary stage is concerned.
3. The sample height has no effect on the value of *K* when tests are conducted at room temperature. However, the value of K determined by tests conducted at elevated temperatures (40°C) is influenced by variations in density associated with differences in the microstructure.
4. Increasing the applied pressure during test at elevated temperature that was used during compaction seems to result in a dramatic increase in the rate of permanent deformation. Data from more specimens at various applied pressure levels are needed to verify this finding and to establish a relationship between the two pressure types.
5. The selected criterion (*K*) has been proven sensitive to permanent deformation associated with the degree of laboratory compaction used to simulate the quality of field compaction during construction.
6. Distinguishing between factors that contribute to the accumulated permanent strain during the primary and the tertiary stage is necessary if the test is to be used for quantifying rutting potential. Additional work is underway at CSTT/NRC to determine these factors and to collect the necessary data on rutting from the field to support the findings of the laboratory evaluation procedure.

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