Results of Round-Robin Test Program To Evaluate Rutting of Asphalt Mixes Using Loaded Wheel Tester

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The results of a round-robin test program to evaluate the loaded wheel tester (LWT) procedure developed by the Georgia Department of Transportation (DOT) are presented. The procedure is used for determining rutting susceptibility of asphalt mixes using an LWT. This program was sponsored by FHWA and had the participation of six state department of transportation laboratories. In the test program, the asphalt mix ingredients necessary for fabrication of the asphalt beam samples were prepared by Georgia DOT and shipped to each participating laboratory. Each laboratory used the same procedure to fabricate the beam samples and perform the LWT testing. Results from this test program indicated the following. On the beam sample fabrication, the within-laboratory beam density repeatability was excellent with a standard deviation of 8.1 kg/m^3 (0.5 pcf), whereas the between-laboratory beam density variability was high, primarily because of variations in the sample fabrication procedures used by each laboratory. On the LWT rutting test results, the within-laboratory rut depth repeatability was very good with a standard deviation of 0.04 cm (0.016 in.) over the mean rut depth value of 0.34 cm (0.133 in.), whereas the between-laboratory rut depth variability was quite high, primarily because of the high between-laboratory variability in beam density. On the basis of these findings, recommendations are offered for improving the LWT machine and the sample fabrication and testing procedure.

The loaded wheel tester (LWT) procedure was developed by Lai in collaboration with the Georgia Department of Transportation (DOT) to assess the rutting characteristics of asphalt mixes (*1–3*). The procedure has been used extensively by Georgia DOT for the past 6 years and has a demonstrated capability to evaluate the rutting behavior of asphalt mixtures. This has led to the development of a standard test procedure, Method of Test for Determining Rutting Susceptibility Using the Loaded Wheel Tester (GDT-115), by Georgia DOT. The procedure has been used as a supplement to the Marshall mix design method for the design of asphalt mixes in the laboratory in which mix design is first performed using the Marshall mix design procedure. The beam samples are then fabricated on the basis of the mix characteristics at the design asphalt content and are tested according to the GDT-115 procedure. Asphalt mixes that developed more than a 0.2-in. rut depth on the beam samples after 8,000 cycles of repetitions are deemed unsatisfactory in rutting resistance and are rejected. Using it with the 0.2-in. rut depth criterion, this supplemental LWT procedure has been able to screen off asphalt mixes of inadequate rutting resistance that otherwise would be acceptable according to the Marshall mix design criteria.

Florida DOT (*4*) used the LWT to evaluate asphalt mix performance. Figure 1(*a*) shows the results of the actual measured pavement rut depth values versus the accumulated traffic of three highway projects in Florida. Results of the rut depth values of the asphalt mixes from these three pavements evaluated by the LWT procedure versus number of load applications are shown in Figure 1(*b*). The trends between the increases of the rut depth on the pavements and the corresponding increases of the rut depth from the LWT testing among these three highway projects are very similar. Similar studies are currently under way in other states, including Utah, Wisconsin, Kentucky, and Maryland.

In 1990, the Demonstration Projects Division of FHWA sponsored a round-robin test program, in which six state highway departments participated, to further evaluate and verify the applicability of this testing procedure. In this evaluation program, Georgia DOT prepared all the materials needed for fabricating the asphalt beam samples, including the prebatched aggregate, asphalt cement, and lime, and shipped them to all the participating laboratories. Each participating laboratory used the compression machine available in its laboratory to prepare the asphalt beam samples according to the compaction procedure described in GDT-115. Loaded wheel tests were performed on the beam samples according to the procedure described in GDT-115. The LWT machines used by the participating laboratories were all identical.

The objective of this limited-scope round-robin test program was to obtain sufficient information for assessing the repeatability (within-laboratory variability) and reproducibility (between-laboratory variability) of this test procedure. Through this evaluation program, it was hoped that more definitive conclusions regarding the LWT procedure and constructive recommendations toward refining the machine and the procedure could be offered.

DESCRIPTION OF LWT MACHINE

Figure 2 shows the main features of the LWT. The beam sample, 7.5 × 7.5 × 37.5 cm (3 × 3 × 15 in.), is fabricated by a static compression machine. Before the testing, the beam sample is heated to the prescribed testing temperature, 40.5°C (105°F), in a separate temperature-conditioning chamber and transferred to the testing machine. The sample is then secured on the testing machine and is partially confined by a sample

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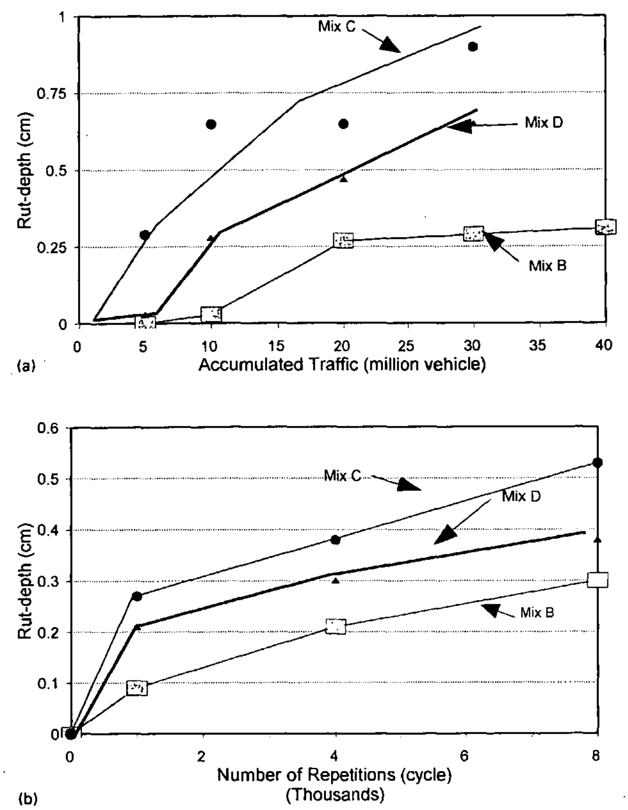

FIGURE 1 Three asphalt pavements in Florida: (*a*) rut depth versus traffic, (*b*) LWT results.

holder mold. A rubber hose is pressurized to 689 kPa (100 psi) and is positioned on top of the sample, aligned longitudinally along the center of the sample. An aluminum wheel is attached to the loaded reciprocating arm of the machine. During the testing, the loaded wheel moves along the pressurized hose at 45 cycles per minute and, at the point of contact, generates a contact pressure on the beam sample. The entire testing machine is enclosed in an environmental chamber for maintaining a constant temperature. The rutting profile along the beam sample is measured at a prescribed number of repetitions (usually 500, 1,000, 4,000, and 8,000 cycles). Detailed descriptions of the machine and the beam sample fabrication procedure were given previously (*1,2*).

DESCRIPTION OF THE LWT ROUND-ROBIN TEST PROGRAM

Participating Agencies

The following agencies participated in this round-robin test program and are referred to in this paper by laboratory number: Laboratory 1—Florida DOT, Materials Office; Laboratory 2—Kentucky DOT, Division of Materials; Laboratory 3—Maryland DOT, Materials Testing Division; Laboratory 4—Utah DOT, Materials and Research Section; Laboratory 5—Georgia DOT, Office of Materials and Research; and Laboratory 6—Wisconsin DOT, through the Department of Civil Engineering, Marquette University.

Materials and Specimens

The initial mix design of a standard Georgia DOT dense-graded surface mix was performed by Georgia DOT (Laboratory 5). Results of the mix design are shown in Table 1. This mix is very fine grained, and the gradation followed closely the ⅜-in. Fuller maximum density gradation.

All the materials necessary for fabricating the asphalt beam samples, including the aggregate, asphalt cement, and lime, were obtained by Laboratory 5 and shipped to each participating laboratory. The aggregate shipped to each laboratory consisted of 18 bags of aggregate samples, each prebatched into 1642-g batch weight. Each bag of aggregate sample together with 17 g of lime and 102 g of asphalt cement are sufficient for making up a mixture for one-third weight of the beam sample at 2414 kg/m^3 (149 pcf) target mix density.

Fabrication of Asphalt Beam Samples

Six asphalt beam samples were fabricated by each participating laboratory according to the procedure described in GDT-115. The procedure is briefly described as follows. Each prebatched aggregate sample was heated to 193°C (380°F) and 17 g of lime was added to the heated aggregate. The aggregate and lime mixture was then dry mixed, and 102 g of asphalt cement at 165.5°C (330°F) was blended with the dry ingredients. The mix compaction temperature was from 149°C to 154°C. Three batches were prepared, and each batch of the mixture was placed in a container, covered with a lid, and stored in an oven at 177°C (350°F). During placement of the mixture in the heated beam mold, each batch of the mixture was successively emptied into the mold, spread, and spaded. After the mixture was leveled at the top of the mold and the temperature was checked in the mixture to within the specified compaction temperature, the compaction was begun. Each participating laboratory used a different compression machine available in its laboratory and a slightly different compaction process to fabricate the beam samples. Possible effects of these on the beam density will be discussed later.

The bulk density of each beam sample was measured. The target bulk density of the compacted mix (at 3.5 percent air voids) was 2414 kg/m^3 (149.0 pcf) and the theoretical voidless mix density was 2501 kg/m^3 (154.4 pcf). These values were used along with the bulk density measured from each compacted beam sample to calculate the percent compaction and percent air voids of each beam sample.

LWT

LWT was performed according to the procedure described in GDT-115. According to this procedure, 8,000 cycles of repeated loading were specified, and rut depth measurements were taken at the completion of the loading cycles. Measurements of rut depth were made on the top surface of the beam sample along the centerline at three measurement locations.

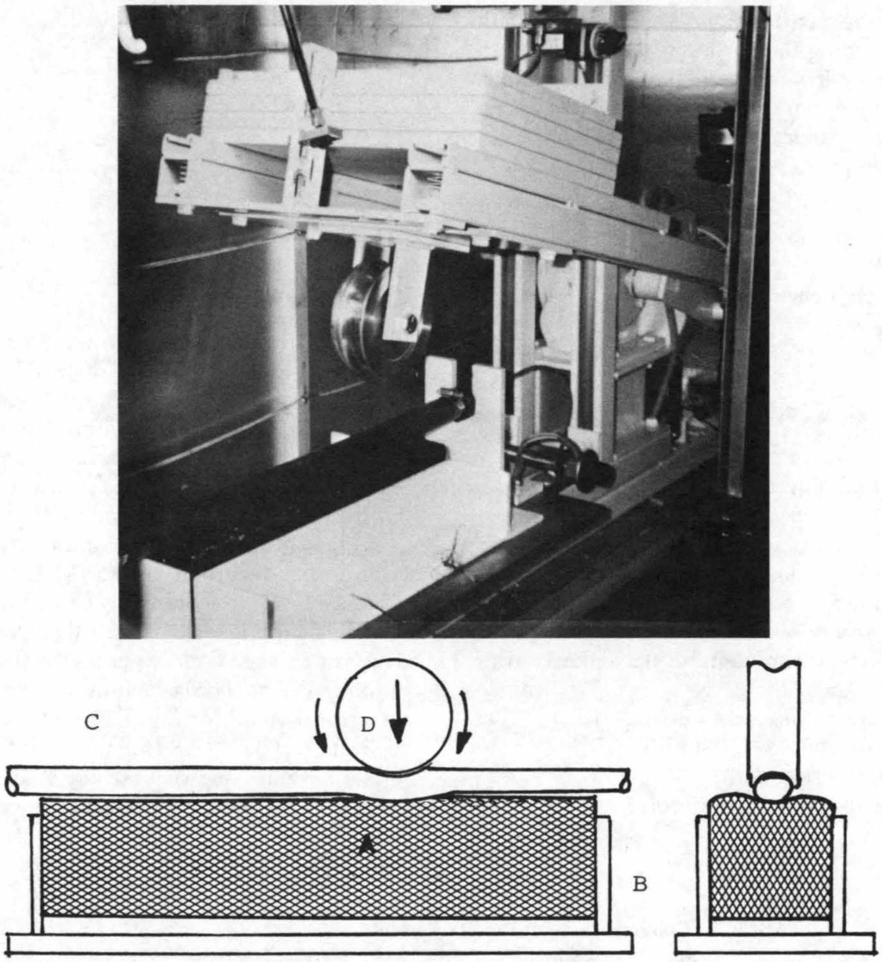

FIGURE 2 LWT machine: (*A*) beam sample, (*B*) sample holding mold, (*C*) pressurized hose, (*D*) loading wheel.

TABLE 1 Asphalt Mix Design for Round-Robin Test Program

Aggregate:

Agg. Size	% passing Comb. Grad
1/2	100
3/8	99
#4	69
#8	45
#16	33
#30	24
#50	16
#100	10
#200	6

Agg. gradation includes 1% lime by wt. of agg.

Effect. sp. gr. of comb. agg. = 2.708

Asphalt Mix Properties:

Asphalt content (AC-30) =	5.80%
Voidless mix density =	2501 kg/m^3 (154.4 pcf)
Design bulk density =	2414 kg/m^3 (149.0 pcf)
Design air voids =	3.5%
Design VMA =	17.0%
Stability kg.) =	1190 (2620 lb)
Flow (mm) =	3.3 (12.9/100 in.)

Beam Sample (7.5 x7.5 x38.1 cm)

Total Wt. (grams) =	5283
Wt. of agg. =	4926
Wt. of lime =	51
Wt. of asphalt =	306

The average of these three measurements yielded a rut depth value for the test. Regarding the variation of the rut depth measurements at the three locations, in 20 of the test results the maximum and the minimum rut depth readings are within 20 percent of the average value, and in the remaining eight tests the readings are within 30 percent of the average value.

RESULTS AND ANALYSES

Precision of Beam Sample Fabrication

The bulk density values of the beam samples from all the participating laboratories are shown in Table 2. Using the procedure of ASTM E691-87, the following statistical parameters were calculated:

/x = cell (individual laboratory) average,
s = cell standard deviation,
//x = average of cell average,
d = cell deviation (/x − //x),
s_x = standard deviation of cell average,
s_r = repeatability (within-laboratory) standard deviation,
s_R = reproducibility (between-laboratory) standard deviation,
h = between-laboratory consistency statistic (d/s),
k = within-laboratory consistency statistic (s/s_r),
p = number of laboratories, and
n = number of test results per laboratory.

s_x, s_r, and s_R are given by Equations 1, 2, and 3, respectively:

$$s_x = \sqrt{\sum_1^p d^2/(p-1)} \quad (1)$$

$$s_r = \sqrt{\sum_1^p s^2/p} \quad (2)$$

$$s_R = \max(s_r, \sqrt{(s_x)^2 + (s_r)^2(n-1)/n}) \quad (3)$$

The critical values for h, a measure of the between-laboratory test consistency, depend on the number of laboratories participating in the interlaboratory study. The critical values for k, a measure of within-laboratory test consistency, depend on the number of laboratories and number of replicate test results. In ASTM E691, critical values of h and k at the 0.5 percent significance level are listed for various numbers of participating laboratories and for various numbers of replicate tests. According to ASTM E691, the 0.5 percent significance level was commonly chosen on the basis of the judgment and experience that the 1.0 percent resulted in too many data being flagged out, whereas the 0.1 percent level resulted in too few. For the six laboratories participating in the study the critical value for h is 1.92 and that for k is 1.68 (for six replicate tests) or 1.98 (for three replicate tests).

The k values shown in Table 2 all fall below the critical value of 1.68, indicating reasonable consistency of the beam

TABLE 2 Compacted Beam Density Results

LAB ID	1	2	3	4	5	6	
Density	2371.7	2332.8	2332.8	2349.0	2353.9	2289.7	
(kg/m^3)	2383.0	2332.8	2332.8	2366.8	2350.6	2280.5	
	2373.3	2315.0	2315.0	2357.1	2336.0	2283.6	
		2327.9	2318.2	2352.2		2286.1	
		2329.6	2329.6	2352.2		2280.5	
		2327.9	2327.9	2362.0		2262.0	
Averaged	2376.0	2327.7	2326.1	2356.6	2346.8	2280.4	
STD	5.01	6.01	6.96	6.19	7.75	8.83	
AVE Cell Ave							2335.6
Dev	40.42	-7.92	-9.53	20.97	11.26	-55.19	
STD Cell Ave, Sx							32.86
Repeatability STD, Sr							7.56
Reproducibility STD, SR							33.60
h-value	1.230	-0.241	-0.290	0.638	0.343	-1.679	
k-value	0.662	0.795	0.921	0.818	1.025	1.168	
Averaged:							
% AirVoid	5.01%	6.94%	7.01%	5.79%	6.17%	8.83%	6.62%
% Compact	98.4	96.4	96.4	97.6	97.2	94.5	

95% repeatability confidence limit r = 2.8 Sr = 1.38 pcf.
95% reproducibility confidence limit R = 2.8 SR = 5.86 pcf.

1 kg/m^3 = 0.0617 pcf.

densities obtained by each laboratory. The corresponding 95 percent repeatability confidence limit value of 22.5 kg/m^3 (1.39 pcf) shown in Table 2 also indicates this consistency. For the *h* values, Laboratory 6 stands out with large value, close to the 0.5 percent significance level critical value. Table 2 shows that the average beam density of Laboratory 6 is 2280 kg/m^3 (140.77 pcf), which is significantly lower than the group average beam density of 2335 kg/m^3 (144.1 pcf). The corresponding average air voids content for the Laboratory 6 beam samples is 8.83 percent versus 6.65 percent for the group average value. The *h* value for Laboratory 1 is also high, with the average beam density 41 kg/m^3 (2.54 pcf) higher than that of the group average value.

These precision statistics indicate that, by following the GDT-115 procedure, the actual beam sample compaction procedures used by each laboratory could fabricate beam samples with reasonably consistent densities within each laboratory. However, the significant difference in the between-laboratory results indicates that the actual procedures used by various laboratories were apparently different enough to affect the beam densities. This appears to indicate that, with respect to the beam sample fabrication, the GDT-115 procedure may need to be modified to make it more precise and less ambiguous. This will be discussed later.

The individual laboratory (cell) average values /*x*, and the average of all cell average values //*x*, shown in Table 2, represent the "precision" values. Bias cannot be established directly from the test results. However, in this round-robin test program a 97 percent target compaction [97 percent × 2414 kg/m^3 = 2341 kg/m^3 (144.5 pcf)] was expected for the beam samples. If this target value were used as the acceptable reference value, the bias of 7 kg/m^3 (0.40 pcf), the difference between the target beam density and the group average beam density, would be quite small.

Precision of Rut Depth Results

The rut depth measurements obtained from the LWT by all the participating laboratories are presented in Table 3. The potential effect of the variations of beam density on rut depth of asphalt beam samples cannot be overlooked. This was because each participating laboratory performed the LWT using beam samples fabricated by themselves instead of samples fabricated by a single source. Therefore a large between-laboratory variability of the beam sample densities could be expected to affect the between-laboratory variability of the rut depth results. This effect can be seen from a plot of the average rut depth values versus the average beam densities for the six laboratories (Figure 3). The same statistical analysis procedure is applied to analyze the rut depth test values. The within-laboratory consistency statistics, *k* values, shown in Table 3, all fall below the 0.5 percent significance level (*k* = 1.70), indicating reasonable consistency of the rut depth results from the LWT performed by each participating laboratory. Among the six participating laboratories, Laboratories 2 and 6 have relatively larger within-laboratory variability. The possible causes will be discussed later.

The between-laboratory consistency statistics (*h* values) shown in Table 3 indicate that Laboratory 6 has a large value (1.87), which is close to the 0.5 percent significance level critical value. The average rut depth of Laboratory 6 is 0.566 cm (0.223 in.), which is 0.008 cm (0.09 in.) larger than that of the group average value. The average rut depth value from Laboratory 1 is substantially lower than the group average (0.203 versus 0.338 cm). Deviations of the rut depth values of these two laboratories could be attributable to the extreme beam densities as shown in Figure 3.

It appears that, if the variation of beam density can be controlled to within a more acceptable range through a better

TABLE 3 Summary of Rut Depth Results (Six Laboratories)

LAB ID	1	2	3	4	5	6	
Rut-Depth	0.180	0.343	0.305		0.328	0.470	
(cm)	0.185	0.323	0.295		0.358	0.546	
	0.260	0.368	0.384	0.299	0.358	0.541	
		0.274	0.335	0.285		0.617	
		0.216	0.315	0.273		0.587	
		0.366	0.287	0.230		0.635	
MEAN	0.208	0.315	0.320	0.272	0.348	0.566	
STD	0.037	0.054	0.032	0.026	0.014	0.055	
AVE Cell Ave							0.338
Deviation	-0.130	-0.023	-0.018	-0.066	0.010	0.228	
STD Cell Ave, Sx							0.122
Repeatability STD, Sr							0.043
Reproducibility STD, SR							0.128
h-value	-1.067	-0.191	-0.149	-0.545	0.080	1.871	
k-value	0.852	1.266	0.752	0.599	0.335	1.278	

1 in. = 2.54 cm

sample compaction procedure and if the correct rut depth testing procedure is followed, the variability of the rut depth test results can be reduced. To make this assessment, the rut depth values from Laboratories 6 and 1 are temporarily dropped because of the large deviations of the beam densities, and the statistical analysis is performed using the results from the remaining four laboratories. The results of the analysis are shown in Table 4. The critical values for h and k at the 0.5 percent significance level for four laboratories are 1.49 and 1.60, respectively. The h values shown in Table 4 all fall below the critical value, indicating reasonable consistency of the rut depth test results among these four laboratories.

The precision statistics from Table 4 indicate that at a 95 percent confidence level the rut depth test results from LWT could be expected to vary within ±0.10 cm (2.8 s_r) and ±0.11 cm (2.8 s_R), respectively, for the within-laboratory and between-laboratory results when the test results from four laboratories are used in the analysis.

Aside from the beam density variations, other factors could contribute to the variations of the rut depth results. One of the factors was the variation of the temperatures during LWT. In Laboratory 2 LWT there were substantial differences between the temperatures at the beginning of each test (from 32°C to 40°C) and the temperatures at the end of each test

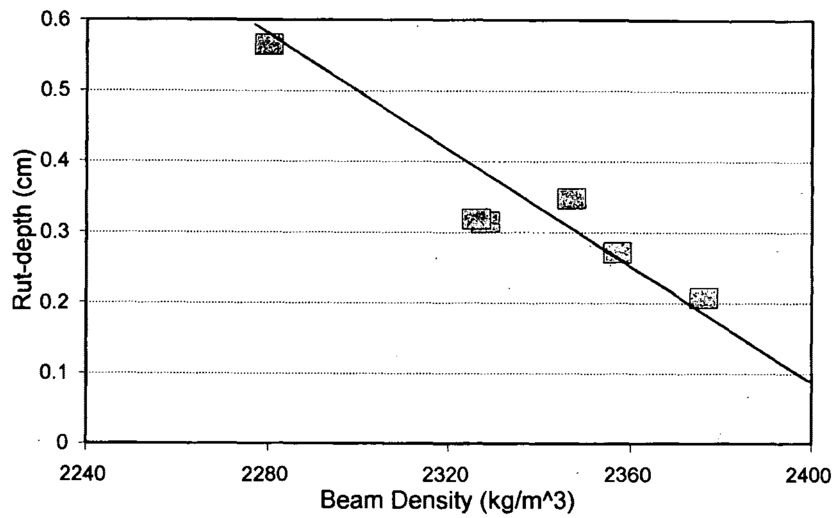

FIGURE 3 LWT results: average rut depth versus beam density.

TABLE 4 Summary of Rut Depth Results (Four Laboratories)

LAB ID	1	2	3	4	5	6	
Rut-Depth		0.343	0.305		0.328		
(cm)		0.323	0.295		0.358		
		0.368	0.384	0.299	0.358		
		0.274	0.335	0.285			
		0.216	0.315	0.273			
		0.366	0.287	0.230			
MEAN		0.315	0.320	0.272	0.348		
STD		0.054	0.032	0.026	0.014		
AVE Cell Ave							0.314
Deviation		0.001	0.006	-0.042	0.034		
STD Cell Ave, Sx							0.031
Repeatability STD, Sr							0.035
Reproducibility STD, SR							0.044
h-value		0.039	0.201	-1.330	1.090		
k-value		1.559	0.926	0.737	0.412		

1 in. = 2.54 cm

(42.8°C to 45.4°C). The weighted average temperatures based on the temperature histories are given in Table 5 along with the rut depth values of the tests. The results indicate that at the lower weighted average temperatures the rut depth values could be significantly affected by the temperature.

BEAM SAMPLE FABRICATION

The beam samples fabricated by each participating laboratory using the GDT-115 procedure in general produced very consistent beam density. The standard deviations of the bulk density of the beams fabricated by each participating laboratory varied between 5 and 8.8 kg/m^3 (0.31 to 0.54 pcf). This was remarkable because various types of compression machines were used and most persons involved in the fabrication of the beam samples, except for those from one participating laboratory, had little previous experience in working with this procedure. However, the variability between laboratories in some instances was quite high. In this section sources contributing to the causes, and ways to improve the variability, of the beam density will be presented.

Beam Sample Fabrication Facility

Various types of compression machines were used by the participating laboratories to compact the beam samples. One laboratory used a Satec computer-controlled testing machine very close to the asphalt mixing facility. Four laboratories used manually controlled hydraulic-type universal machines. Among them, two machines were in the same room in which asphalt mix batching was performed, and the other two machines were found at various locations around the asphalt mix batching facilities. One laboratory used a concrete cylinder tester, with the machine and the asphalt mix batching facility located in other buildings. Even with such varieties of sample fabrication facilities, the within-laboratory repeatability standard deviations of 7.56 kg/m^3 (0.50 pcf) shown in Table 3 were quite small. This indicated that the asphalt beam samples could be fabricated with acceptable consistency by the GDT-115 procedure using various types of compression machines readily available in a testing laboratory. This was one of the objectives of developing this compaction procedure.

The present sample fabrication facilities have some drawbacks. They are considered too cumbersome because of the effort required to handle the heavy steel beam mold at high temperatures. The other drawback is that the mode of compaction did not adequately simulate compaction in the field. A new version of a dedicated beam sample compaction machine presently under development should overcome these drawbacks.

Beam Sample Preparation Procedure

The use of various compression machines and the differences in the compaction environments among the participating laboratories could affect the precision of the beam density fabricated among participating laboratories, although the within-laboratory precision is acceptable. These factors resulted in a relatively high between-laboratory variability; there are, however, steps that would reduce the variability.

To minimize the uncontrollable heat loss from the asphalt mix during sample preparation, the asphalt mix batching facility and compaction machine should be in the same room or near each other. If this is not feasible, use of an oven near the compaction machine to reheat the loose asphalt mix could help to control the temperature in the asphalt mix during the compaction.

It was observed that some beam samples were unevenly compacted. Uneven compaction could occur if the compressive load were not uniformly applied on the beam sample during compaction. In addition, some test data have indicated that an unevenly compacted beam sample could develop uneven rutting. Because most of the compression machines are equipped with a swivel head, the beam sample should be properly centered under the loading head to ensure that a uniform compressive load is exerted on the sample. The proper position of the beam mold under a compaction machine can be premarked on the platform of the machine to ease this positioning problem. The other cause that might have contributed to the uneven beam thickness was that the loose asphalt mix might not have been spread evenly in the beam

TABLE 5 Rut Depth Versus Weighted Test Temperatures (Laboratory 2)

Test No.	weighted Temp. °C	Rut-Depth (cm) @ 8000 Cy
Test 1	43.5	0.343
Test 6	42.4	0.366
Test 3	40.9	0.368
Test 2	40.2	0.323
Test 4	39.1	0.274
Test 5	37.7	0.216

A weighted average temperature is computed based on the proportion of the test time and the temperature in that time duration mold. This problem can be resolved easily by using a suitable leveling tool and a simple depth gauge to ensure even spreading of the loose asphalt mix.

Control Beam Density

In this test program the average beam density obtained from Laboratory 6 was substantially lower, whereas that from Laboratory 1 was higher. Several causes might contribute to the variations: too high or too low compaction temperature, too high or too low magnitude of the applied loads, too long or too short duration of each compaction cycle, and differences in the machine characteristics. The use of different asphalt mixes in the same compaction procedure could generate significantly different compaction results. The following suggested practice can be used to help maintain the consistency of the compaction. The present compaction apparatus includes a heavy rectangular steel loading plate (top loading head) that is used to transmit the compressive load evenly to the beam sample. The four sides of the loading plate can be inscribed with sharp line marks at such a position that, when these line marks on four sides are level with the top edges of the beam mold during compaction, the asphalt beam samples are being compacted to exactly 3 in. high. The line marks can also be used to check the evenness of the compaction. Use of these reference marks on the top loading head can detect the variation of the compaction to within 1 percent difference. Thus, if the batch weight of the mix is correctly determined according to the target density of the mix and the correct amount of the mixture is placed in the mold, visual observation of these reference marks on the top loading head should enable one to achieve the compaction requirement to within 1 percent of the target compaction.

CONCLUSIONS

The following conclusions can be drawn from the results of this limited-scope, round-robin test program:

1. The asphalt beam samples can be fabricated with acceptable consistency according to the GDT-115 procedure using different types of compression machines. Certain steps suggested in this paper can be taken to further minimize the variability.
2. The rut depth results determined from the LWT can be significantly affected by the bulk density of the beam samples. Therefore, it is important to control the density of the asphalt beam samples fabricated in the laboratory to minimize the variability of the rut depth test results. Extreme temperature variations could also affect the results.
3. Reasonable consistency of rut depth results from the LWT was achieved by each participating laboratory. The within-laboratory repeatability standard deviation was 0.043 cm (0.017 in.) over the group average value of 0.338 cm (0.133 in.).
4. The between-laboratory variability of rut depth results was quite high. The between-laboratory reproducibility standard deviation was 0.128 cm (0.05 in.). The poor reproducibility of rut depth results was primarily caused by a large deviation of beam densities between laboratories. By eliminating rut depth results from two laboratories because of their extreme beam densities, the between-laboratory reproducibility standard deviation of the four remaining laboratories became 0.044 cm (0.017 in.) over the average rut depth value of 0.314 cm (0.123 in.).

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