Performance Prediction for Large-Stone Mixes Using the Repetitive Simple Shear Test at Constant Height

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Transfer functions have been developed that permit prediction of vertical rut depth versus equivalent single axle loads in situ using the repetitive simple shear test at constant height (RSST-CH). These transfer functions are based on statistical correlation of field performance and laboratory testing of field cores from Strategic Highway Research Program General Pavement Sections, with conventional binders and gradations and 19-mm (¾ in.) maximum aggregate. A comparison is presented between measured field performance of large-stone mixes in situ and the performance predicted using the current RSST-CH transfer functions. Because of the larger aggregates contained in the mixes, the RSST-CH specimen diameter and height were increased to maintain a similar aspect ratio between the aggregate and specimen dimensions. New techniques for controlling specimen height during the test were also developed. The results of the comparison indicate that the RSST-CH and previously developed transfer functions are useful in predicting in situ rutting for large-stone mixes.

As part of the recently completed Strategic Highway Research Program Project A-003A (SHRP A-003A), test methods and analysis procedures were developed to predict the rutting performance of asphalt-aggregate mixes. For rapid prediction of rutting performance for typical mixes, the repetitive simple shear test at constant height (RSST-CH) was recommended by SHRP A-003A because it applies the primary distress mechanism responsible for rutting in the field to the laboratory specimen.

The RSST-CH is performed at a temperature at which most permanent deformation will occur at the project site. To predict the vertical rut depth in situ caused by traffic loading, transfer functions are applied to the output from the RSST-CH, which is permanent shear strain caused by simple shear load repetitions.

The transfer function relating permanent shear strain in the RSST-CH to vertical rut depth in situ is based on comparison of RSST-CH results from laboratory-prepared specimens with finite element analysis that include a nonlinear viscoelastic constitutive relation and materials properties from results of a set of tests on the same materials (*1*). A linear relation was found between permanent shear strain in the RSST-CH and vertical rut depth in the pavement.

A transfer function relating RSST-CH load repetitions to equivalent single axle loads (ESALs) in situ was developed by Sousa and Solaimanian (*2*) from statistical correlation of RSST-CH results and traffic and rut depth measurements from SHRP General Pavement Sections (GPS). The mixes in the GPS used for development of the transfer function only included 19-mm maximum aggregate, dense gradations, and conventional asphalt binders. However, because the RSST-CH measures the response of the material to the primary distress mechanism responsible for rutting, it is proposed in many cases that the use of the relation developed from the GPS can be extrapolated to large-stone mixes (LSMs) and mixes with modified binders with a reasonable degree of accuracy.

It is known that the response of asphalt-aggregate mixtures is nonlinear with respect to changes in simple shear stress in the laboratory and to changes in tire pressures and loads in situ. Successful application of the transfer function to mix types outside of the GPS data base requires that the nonlinearity not be significantly affected by binder modification or gradation changes. The portability of the transfer function must be determined through experimentation. This type of experimentation has been executed on a limited basis for asphalt-rubber hot mix with a gap-graded aggregate component, recycled asphalt pavement, stone-mastic asphalt with rubber- and polyolefin-modified binders (*3;* Harvey et al., paper in this Record), and dense-graded asphalt concrete with PBA-6 (Harvey et al., paper in this Record) and PG-70 (Sousa et al., paper in this Record) modified binders, all with successful results to date.

The results of RSST-CH testing on field cores from sections containing LSMs and control sections are presented, as well as a comparison of predicted rutting performance with in situ traffic and rut depth measurements. New techniques for the RSST-CH developed for LSMs are also described.

TEST PROCEDURE

Description of RSST-CH

The test used to evaluate the permanent shear deformation resistance of the field cores was the RSST-CH, developed as part of SHRP Project A-003A (*1*). The test was performed using the prototype Universal Testing System (UTS) device built by James Cox and Sons and in operation at the University of California at Berkeley (UCB) since 1991. The UTS has two hydraulic actuators under closed-loop digital control, one horizontal and one vertical. For the RSST-CH, the specimen is bonded to platens, which are then clamped to the actuators. The vertical actuator is used to maintain the specimen at a constant height, and the horizontal actuator applies a repetitive haversine shear stress. For this project the RSST-CH was performed using a 68.9-kPa (10-psi) shear stress, with 0.1 sec loading time followed by 0.6 sec rest period. Each specimen was subjected to approximately 10,000 load repetitions.

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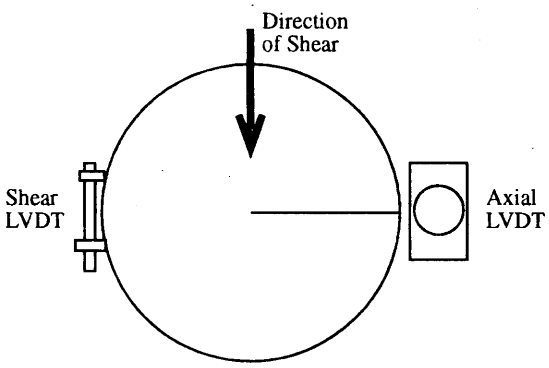
Special RSST-CH Procedures for LSMs

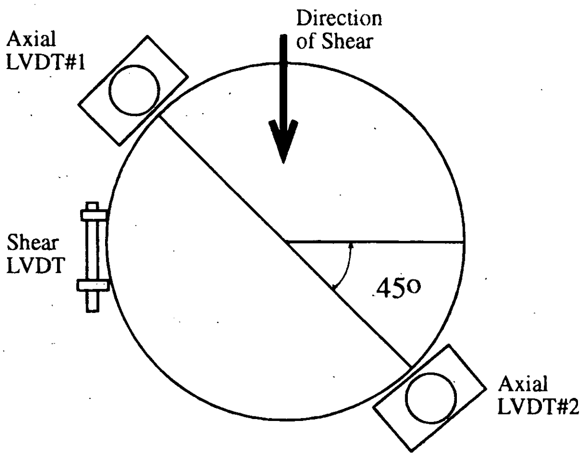
Applying RSST-CH procedures to LSM specimens required the use of larger specimens and modifications in the placement of the instrumentation on the specimen. The UTS was initially designed to accommodate specimens 150 mm (6 in.) in diameter with room on both sides to mount necessary instrumentation. In the original setup, a linear variable differential transformer (LVDT) was mounted on one side of the specimen to measure the shear displacement between two horizontal planes in the specimen. On the opposite side an LVDT was mounted to measure and control the distance between the top and bottom platens [see Figure 1(*a*)]. For the LSM, testing specimens 200 mm (7.75 in.) in diameter were used, each with two axial LVDTs mounted at 45 degrees from the front and back of the specimen [see Figure 1(*b*)].

Specimen Size

If the results of materials testing are to be used in mechanistic analysis or for correlation of mechanistic concepts with empirical data, it is important to select a specimen size that will provide repeatable results and allow the application of the defined state of stresses, strain, or both, for the range of materials to be compared. To obtain repeatable results in RSST-CH testing of asphalt-aggregate mixes, a specimen must be large enough so that one or two of the larger aggregates do not control the material behavior; if two large aggregates were located one on top of the other such that they bridged a large portion of the specimen height, they might cause a much different result than if they were located elsewhere. Moreover, other work has indicated that a more uniform shear stress distribution is obtained using larger-diameter specimens (*1*).



a) 150 mm (6 in.) diameter specimen



b) 200 mm (7.75 in.) diameter specimen

FIGURE 1 Schematic drawing of LVDT mountings on specimens.

For these reasons, larger specimen dimensions are called for in the use of the RSST-CH with mixes of larger aggregates. However, to use the transfer functions developed for the smaller specimens, the larger specimens must maintain a similar state of stresses and strains, that is, constant height during testing and a similar ratio between height and diameter.

Because of the size of the stones in the LSMs, a larger specimen was selected to maintain the ratio of stone size to specimen height used for conventional gradations. Instead of the usual cylindrical specimen 150 mm in diameter by 50 mm thick (6 in. × 2 in.), specimens 200 mm by 75 mm (7.75 in. × 3 in.) were used. The 200-mm (7.75-in.)-diameter specimen is shown compared with the 150-mm (6-in.) and 100-mm (4-in.)-diameter specimens in Figure 2.

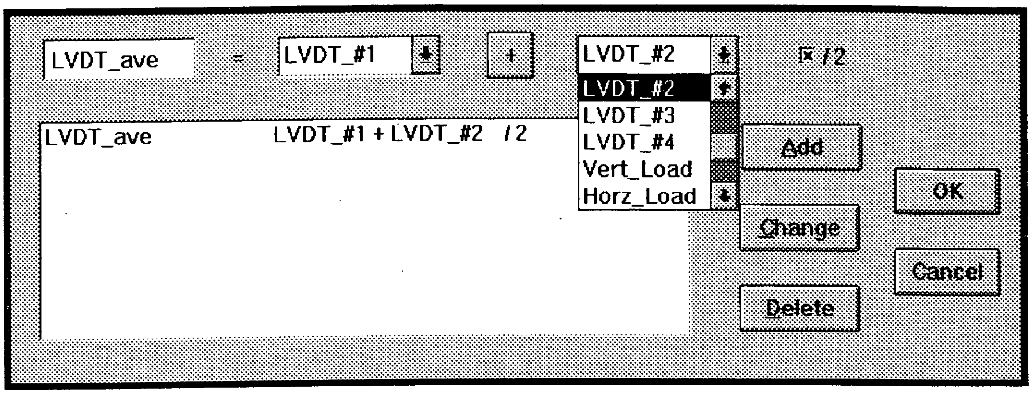
Instrumentation

To accommodate the larger specimens, larger platens had to be manufactured by Cox and Sons. Because of a lack of space in the load frame of the prototype UTS, it was no longer possible to mount the axial LVDT on the side of the specimen. An option may have been to mount one LVDT in the front or the back of the specimen. However, in that case the software would maintain the height constant in the front or the back, not in the center as is the case with the 150-mm (6-in.)-diameter specimens typically used for the RSST-CH.

To remedy this problem, two LVDTs were mounted at 45 degrees [see Figure 1(*b*)], one in front and one in back, so that the ATS software could control the *average* readings of both LVDTs. To do this, advantage was taken of the ATS software's virtual channels feature, which permits the creation of a virtual channel with the sum, average, or difference between any two real channels. As Figure 3 shows, a virtual channel called LVDT_ave was created by assigning to it the average of the two real channels, LVDT_#1 and LVDT_#2. After this assignment, the software uses the virtual channel as if it were any other channel; it can be used as a feedback control, as a limit detector, or as a repository for data. During tests executed for this project, the virtual channel LVDT_ave was used to close the feedback loop for the vertical actuator to ensure that the center of the specimen was maintained at a constant height.

A 200-mm (7.75-in.) specimen with instrumentation is shown in Figure 4. The two LVDTs were used to control the vertical actuator (*4*). A third LVDT, to control the horizontal actuator, was mounted on the center axis of the specimen 90 degrees from the direction of shear. This arrangement prevents the LVDT from reading any possible angular movements between the platens due to the flexibility of loading frame. With this system, the center distance of the platens is kept constant, but there is no guarantee that the front and back of the specimen are maintained at a constant distance. The parallelism of the platens during testing will depend on the rigidity of the testing system.

The location of the LVDT would become irrelevant if the testing frame could be made infinitely rigid. In an effort to control



LVDT_ave = LVDT_#1 + LVDT_#2 ☒ /2

LVDT_ave LVDT_#1 + LVDT_#2 /2

FIGURE 2 Window from ATS software used to create virtual channels.

parallelism, FHWA's request to procure the SHRP shear tester specifies that the test platens must remain parallel within ±0.00635 mm in 150 mm (±0.00025 in. in 6 in.) (*5*). Without this specification, machines of different flexibilities might yield different results. The specification for maintaining constant height requires that the change in height during a pulse be maintained below $\pm 1.3 \times 10^{-3}$ mm (5×10^{-5} in.) as recommended in AASHTO TP7 (*5*).

Selection of Test Temperature

The temperature used for testing for this project was the 7-day maximum average temperature, $T_{7\text{daymax}}$, calculated from weather station data and latitude (*6*). The calculated test temperatures are included in Table 1.

Field Cores

Cores were taken in the field at each test section. According to the records available, the cores were taken primarily in the wheel path, although it is unknown whether several were from outside the wheel path (*7*). All field cores had approximately a 200-mm (7.75-in.) diameter.

Air void contents were calculated using the bulk specific gravity determined using parafilm (*8*) and the maximum specific gravity found using the Rice method (ASTM D2041). Air void contents are shown in Table 1.

DESCRIPTION OF LSM TEST SECTIONS

The field cores tested were taken from four sites constructed between 1989 and 1992, two in Colorado and two in Wyoming, as part of a research project performed by the Texas Transportation Institute (TTI). The following site descriptions and information (from a condition survey performed in 1993) are taken from the interim report for that project (*7*). The rut depths noted in the condition survey did not distinguish between densification of the mix and plastic flow. However, it should be noted that densification and plastic flow were not measured separately on the SHRP GPS sections used for original development of the RSST-CH transfer functions (*1,2*).

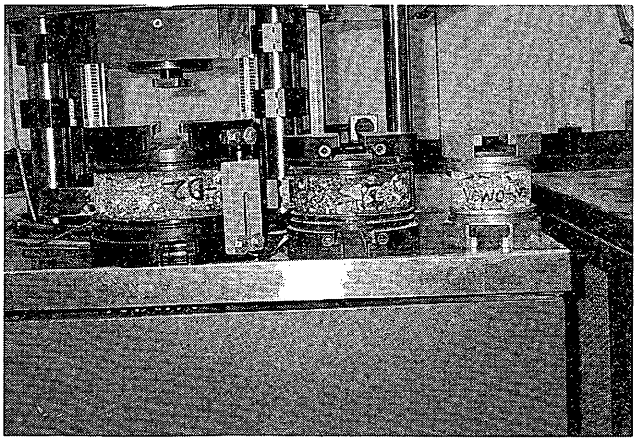


FIGURE 3 Comparison of 200-mm, 150-mm, and 100-mm specimens and platens.

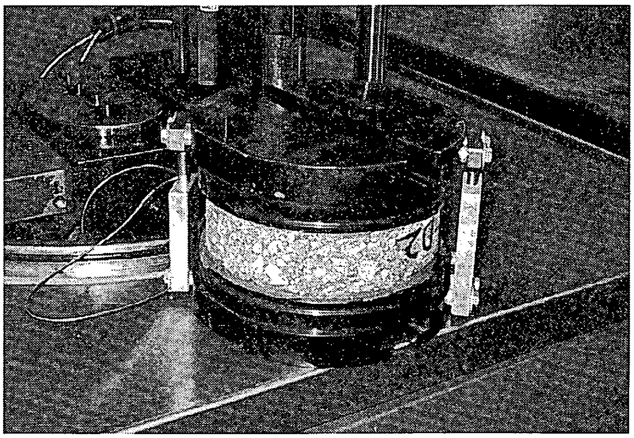


FIGURE 4 LVDT mounting on 200-mm specimen for height control (horizontal LVDT to measure shear deformation not shown).

TABLE 1. Summary of Test Information, Core Location, in Situ Rut Depth and Traffic Data, RSST-CH Results; and Predicted ESALs to in Situ Rut Depth

					In Situ Rut Depth			*RSST-CH reps*		*Predicted ESALs to in-situ rut depth*	
Specimen	Max Agg Size (mm)	Air-Voids	Depth to Layer Top (mm)	Test Temp (C)	Min Rut Depth (mm)	Max Rut Depth (mm)	ESALs to in-situ Rut Depth	to perm shear strain		log(RSST-CH) = -4.36 + 1.24log(ESAL) Equiv ESALs to Rut Depth (mm)	
Laramie, WY								1.0%	2.0%	2.5	5.0
LAA13	19.0	5.2	38	47.2	0.0	5.0	1.86E+06	2.46E+03	1.28E+04	1.78E+06	6.73E+06
LAA14	19.0	7.3	38	47.2	0.0	5.0	1.86E+06	6.66E+02	2.55E+03	6.21E+05	1.83E+06
LAB2	31.8	4.7	38	47.2	2.5	5.0	1.86E+06	1.49E+04	4.95E+04	7.63E+06	2.00E+07
LAB16	31.8	5.4	38	47.2	2.5	5.0	1.86E+06	7.98E+02	5.01E+03	7.19E+05	3.16E+06
Cedar Point, CO								1.0%	8.0%	2.5	20.0
CP34711	19.0	3.9	0	51.1	2.5	2.5	8.17E+05	5.60E+01		8.43E+04	
CP34767	19.0	1.9	0	51.1	2.5	2.5	8.17E+05	8.74E+03		4.95E+06	
CP348612	38.0	6.5	0	51.1	2.5	20.0	8.17E+05	1.19E+07	1.98E+12	1.67E+09	2.71E+13
Flagler, CO								1.0%	2.0%	2.5	5.0
FL3743	38.0	5.1	0	53.9	2.5	5.0	2.70E+05	2.19E+03	1.16E+04	1.62E+06	6.23E+06
FL3746	38.0	6.3	0	53.9	2.5	5.0	2.70E+05	5.57E+03	4.93E+04	3.44E+06	2.00E+07
FL3955	38.0	3.6	50	53.9	0.0	0.0	2.70E+05	1.98E+02		2.33E+05	
FL39514	38.0	4.1	50	53.9	0.0	0.0	2.70E+05	8.70E+01		1.20E+05	
Rock Springs, WY								1.0%		2.5	
RSA7	38.0	3.7	38	48.9	0.0	0.0	1.25E+06	2.30E+01		4.11E+04	
RSA111	38.0	5.7	38	48.9	0.0	0.0	1.25E+06	1.80E+01		3.38E+04	
RSA112	38.0	6.4	38	48.9	0.0	0.0	1.25E+06	1.05E+02		1.40E+05	

Cedar Point, Colorado

An LSM [38 mm (1.5 in.) maximum aggregate] and a control mix [19 mm (0.75 in.) maximum aggregate] were constructed at this site in the westbound lanes of Highway 70, approximately 125 km (75 mi) east of Denver. The section containing the control mix consisted of a 38-mm (1.5-in.) layer of dense-graded asphalt concrete over a 44-mm (1.75-in.)-thick dense-graded binder/leveling course. Both mixes were of the same type (Colorado Type C). The condition survey indicated extensive fatigue cracking in the overlay and rut depths less than 2.5 mm (0.1 in).

The LSM at this site was used as an 83-mm (3.75-in.)-thick surface material during the period between construction and condition survey. The surface was found to have extensive alligator cracks in the wheel paths. Rut depths ranged between 2.5 and 20 mm (0.1 and 0.8 in). The Colorado Department of Transportation has confirmed that much of the rutting occurred in the underlying layers because of water penetrating the cracked surface rather than rutting in the mix because of low permanent deformation resistance.

Both the control and LSM overlays were constructed in August 1989. The average number of daily ESALs in the design lane is approximately 571.

Flagler, Colorado

Two test sections containing LSM were investigated at this site on Interstate 70. Both were constructed in September 1991. The LSM was used as a 75-mm (3-in.)-thick surface material at Milepost 374. This section was found to have random longitudinal cracking and rut depths of 2.5 to 5 mm (0.1 to 0.2 in).

At Milepost 395 section, the LSM was placed as a 95-mm (3.75-in.)-thick layer below 50 mm (2 in.) of asphalt concrete with a 19-mm (0.75-in.) maximum aggregate (Colorado Type C) containing an asphalt-rubber binder. This section was found to have little or no rutting. The average number of daily ESALs in the design lane is 404.

Rock Springs, Wyoming

This section was in the eastbound lane of Interstate 80 east of Rock Springs. The 64 mm-(2.5-in.)-thick LSM layer on this section was placed below a 38-mm (0.75-in.)-thick seal in September 1991. The condition survey indicated no cracking or rutting. The average number of daily ESALs in the design lane is 1,870.

Laramie, Wyoming

This site included a control section on I-80 containing a 19-mm (0.75-in.) maximum aggregate asphalt concrete base course 76 mm (3 in.) thick below a 19-mm (0.75-in.)-thick wearing course. The control section had no cracking and a 2.5- to 5-mm (0.1- to 0.2-in.) rut depth.

The LSM section had the same cross section as the control section, except that the base course was an open-graded LSM with a maximum aggregate of 31.8 mm (1.25 in.). This section was found to have no cracking and a 2.5- to 5-mm (0.1- to 0.2-in.) rut depth. Both sections were constructed in July 1992. The average number of daily ESALs in the design lane is 2,550.

TEST RESULTS AND ANALYSIS

Analysis Method

The method used to make the comparison between performance predicted from laboratory testing and measured field performance is based on a statistical correlation between field measurement of rut depth, ESALs, and maximum 7-day average temperature ($T_{7\text{daymax}}$) at SHRP GPS test sites and laboratory measurement of permanent shear deformation on field cores from the same GPS sites at temperature $T_{7\text{daymax}}$ for each GPS section using repetitive simple shear loading with the specimen maintained at constant height (*2*).

To correlate these measurements, permanent shear strain from the RSST-CH was related to vertical rut depth on the basis of finite element analysis as part of SHRP Project A-003A (*1*). During a test, the permanent shear strain increases with each load application. Using the finite element analysis, permanent shear strain in the RSST-CH has been estimated to correspond to vertical rut depth in situ as follows: vertical rut depth = A permanent shear strain, where A = approximately 276 mm (11 in.) for thick lifts. The value for A was found to decrease with decreasing layer thickness (*1*).

The analysis method assumes that nearly all permanent deformation will occur in situ at temperatures approximately 5°C (9°F) below and above $T_{7\text{daymax}}$. Load repetitions (RSST-CH) to the vertical rut depth of interest are converted to ESALs using the following equation, developed from the GPS data by Sousa and Solaimanian (*2*): $\log(\text{RSST-CH load repetitions}) = -4.36 + 1.240 \cdot \log(\text{ESAL})$.

It is important to note that this relation is based on cores taken from both inside and outside the wheelpath. Increase in permanent shear deformation resistance due to densification and other effects of trafficking is important and must be partially responsible for the variance in the original results from the GPS sections and any other comparisons of actual and predicted performance, such as those found in this study. Changes in the mix are also caused by environmental factors (e.g., aging and moisture damage). The best validation of the transfer functions used for this study will occur when field performance is compared with mix design results. A few projects of that type have been completed (Harvey et al., paper in this Record; Sousa et al., paper in this Record). It is important to compare all useful data available in order to evaluate the applicability of any proposed mix design methods, bearing in mind the possible sources of bias and variance that may exist in the data.

It has been shown previously that the laboratory compaction method can have an even greater effect than densification on permanent shear deformation resistance (*9*). If the transfer functions described here are to be used effectively, the compaction method that best produces the same permanent shear deformation resistance as field cores should be used to produce specimens for mix design.

Performance Prediction and Comparison with Field Data

RSST-CH results were used with the method described previously for prediction of ESALs to a selected rut depth. The selected rut depths for this project were those measured during the condition surveys described. These results are shown in Table 1 along with the accumulated ESALs measured in situ between the time of construction and the condition survey. Except for the Cedar Point sections, the predicted performance compares reasonably well with the measured results. It bears repeating that the Cedar Point LSM

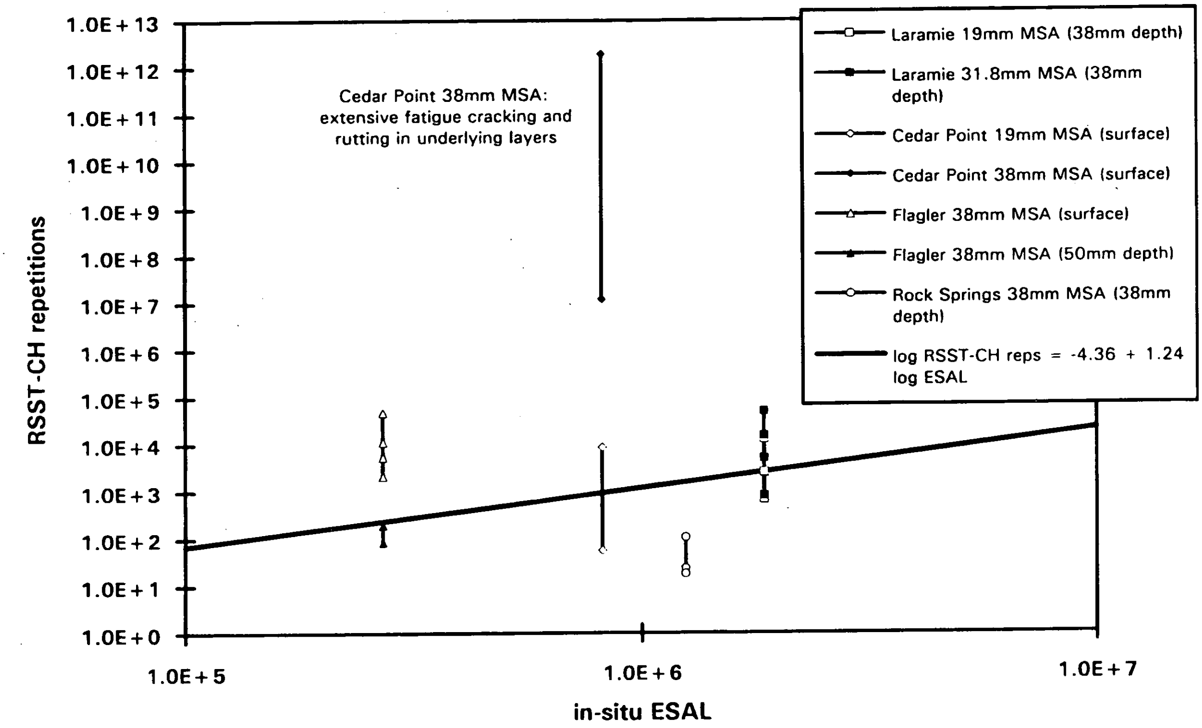


FIGURE 5 Comparison of LSM data with Sousa and Solaimanian transfer function.

sections were badly cracked and that some of the rutting observed on that section was confirmed by the Colorado Department of Transportation as having occurred in the underlying layers because of moisture passing through the cracked surface.

The Sousa and Solaimanian transfer function is shown in Figure 5, plotted with the data presented in this study. Again, except for the Cedar Point LSM, the data presented here generally fit the relation generated from the GPS site data. This indicates that the shift factor is portable to LSMs despite their lack of representation in the original GPS data base.

SUMMARY AND CONCLUSIONS

Data are presented from LSM field cores using the RSST-CH. These results, and measured in situ rut depths and ESAL data, were used to evaluate the transfer function developed by Sousa and Solaimanian. Both the RSST-CH and the Sousa and Solaimanian transfer function were developed as part of SHRP Project A-003A. New techniques for the RSST-CH developed for LSMs were also presented.

The following conclusions can be drawn from the study:

1. The new techniques developed for testing LSMs with the RSST-CH were effective and, in combination with a larger specimen, appear to result in good data for this type of mix.
2. The Sousa and Solaimanian transfer function appears to be applicable to LSMs despite having been developed from a GPS data base that did not include LSMs.

It is recommended that further validation of the RSST-CH and transfer functions for use in predicting rutting performance for asphalt-aggregate mixes be performed.

ACKNOWLEDGMENTS

The work described in this paper was performed at UCB as a subcontract to the Texas Transportation Institute, Texas A&M University, as part of NCHRP Project HR4–18. The authors would like to thank the Colorado and Wyoming departments of transportation for their efforts in obtaining cores and performance data, James Cox and Sons, Inc., for the design and fabrication of the large-size platens, and Ed Nicks for fabrication of instrumentation. The help of Clark Scheffy, Maggie Paul, and the rest of the UCB Asphalt Research Program technical staff is also appreciated.

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The views expressed in this paper are those of the authors only, and do not necessarily reflect those of their institutions or the project sponsor.

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