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EVALUATION OF THE PERFORMANCE
OF ULTRASONIC EQUIPMENT FOR
PAVEMENT THICKNESS MEASUREMENT

JULY 1968

NO. 14

by
C.F. SCHOLER
AND
R.D. PAVLOVICH

Joint
Highway
Research
Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

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Progress Report
EVALUATION OF THE PERFORMANCE OF ULTRASONIC EQUIPMENT
FOR PAVEMENT THICKNESS MEASUREMENTS

To: J. F. McLaughlin, Director
Joint Highway Research Project

July 12, 1968

File No.: 5-15-3

From: H. L. Michael, Associate Director
Joint Highway Research Project

Project No.: C-36-61-C

Attached is a Progress Report entitled "Evaluation of the Performance of Ultrasonic Equipment for Pavement Thickness Measurements" by C. F. Scholer and R. D. Pavlovich of our staff. The data were obtained by Professor Scholer and Mr. Pavlovich in connection with the HPR-1(5) research study on "Evaluation of the Performance of Ultrasonic Equipment for Pavement Thickness and Other Highway Applications."

The conclusion of this report is that the ultrasonic equipment that is presently available commercially does not provide adequate precision for determining pavement thickness.

The progress report is presented to the board for information.

Respectfully submitted,

Harold L. Michael
Associate Director

HLM:kj

Attachment

cc: F. L. Ashbaucher	J. A. Havers	C. F. Scholer
W. L. Dolch	V. E. Harvey	M. B. Scott
W. H. Goetz	G. A. Leonards	W. T. Spencer
W. L. Grecco	F. B. Mendenhall	H.R.J. Walsh
G. K. Hallock	R. D. Miles	K. B. Woods
M. E. Harr	J. C. Oppenlander	E. J. Yoder
R. H. Harrell		

Progress Report

EVALUATION OF THE PERFORMANCE OF ULTRASONIC EQUIPMENT
FOR PAVEMENT THICKNESS MEASUREMENTS

by

C. F. Scholer, Assistant Professor
of Civil Engineering

and

R. D. Pavlovich, Graduate Instructor
in Civil Engineering

Joint Highway Research Project

Project: C-36-61-C

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Bureau of Public Roads

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or the
Bureau of Public Roads

Purdue University
Lafayette, Indiana
July 12, 1968

EVALUATION OF THE PERFORMANCE OF ULTRASONIC EQUIPMENT FOR PAVEMENT THICKNESS MEASUREMENTS

Introduction

This study used the James Model C-4960 Ultrasonic V-Scope, Model C-4959 Ultrasonic E-Meter and apartment equipment (as supplied by James Electronics, Inc., 4050 North Rockwell Street, Chicago, Illinois) to measure the thickness of portland cement concrete pavements.

Pulse velocity and longitudinal resonant frequency in the thickness direction are determined by use of the ultrasonic equipment. Thickness is calculated by the relationship

$$t = \frac{V_p}{2N_R}$$

where t = slab thickness

V_p = pulse velocity through the slab

N_R = longitudinal resonant frequency of the slab

Field power (120 V a.c.) was provided by installing an a.c. inverter in a small station-wagon type van thus establishing a mobile and completely self contained unit.

Two series of tests are reported; one set consists of measurements of thickness of control slabs at the ISEC Research and Training Center and the other set was run on actual pavement slabs in the field.

Figure 1 shows the arrangement and actual thickness of control slabs at the Research and Training Center. Field test locations were

1. I-465; Indianapolis
2. U.S. 40; Terre Haute
3. U.S. 50; Versailles
4. I-70; Knightstown
5. I-65; Maubstadt

FIGURE 1. SCHEMATIC DIAGRAM SHOWING THE LAYOUT AND THICKNESS OF 5'x5' TEST SLABS AT I.S.H.C. RESEARCH AND TRAINING CENTER.

Sonic thickness measurements of pavement slabs were compared, at the site, with ISHC cores that were taken from the same location.

Summary of Results and Conclusions

The equipment as now commercially available does not provide sufficient precision to justify use as a means of determining thickness of pavement slabs.

Figure 2 shows a best fit line through data obtained from test slabs and Figure 3 shows cumulative number of tests versus percent error for all tests conducted.

It should be noted that only about 40 percent of the tests provide precision of ± 5 percent; this error amounts to a deviation of one half inch for a ten inch pavement slab. Figure 4 shows a plot of sonic thickness versus actual thickness for all measurements. ± 5 percent limits are included to show scatter of these data.

Table I is a tabulation of reduced data from the test slabs and Figure 5 is a plot of average sonic thickness versus actual slab thickness.

Discussion

A brief introduction to the principles of operation of this equipment is included to show why errors are introduced and perhaps how these can be overcome.

Thickness determination is based on measuring two parameters: pulse velocity and slab resonant frequency. Pulse velocity is the speed that sound travels through a material and resonant frequency is that condition where the slab will vibrate at the same frequency as some outside source.

n = no. observations
 t_s = average sonic thickness
 $s_{ts}^2 = \frac{n \sum t_s^2 - (\sum t_s)^2}{n(n-1)}$

TABLE I
Individual test
Slab Data

Slab (t_c)	n	$\sum t_s^2$	$\sum t_s$	s_{ts}^2	s_{ts}	(Ave.) $\bar{t}_s$	Range
6.9	10	483.48	69.4	0.20	0.45	6.9	6.1 - 7.7
8.3	12	753.31	94.9	0.26	0.51	7.9	7.1 - 8.9
9.0	12	1016.21	110.1	0.55	0.74	9.2	8.1 - 10.5
9.2	6	644.35	62.1	0.32	0.57	10.4	9.5 - 11.1
9.4	6	634.99	61.5	0.92	0.96	10.2	8.6 - 11.2
10.2	26	2871.99	272.5	0.63	0.79	10.5	8.8 - 12.2
10.3	8	993.29	89.1	0.13	0.36	11.1	10.7 - 11.8
11.2	14	1809.21	158.9	0.44	0.66	11.4	10.0 - 12.3

FIGURE 2. SONIC THICKNESS (t_s) VS. ACTUAL THICKNESS (t_a) FOR TEST SLABS.

FIGURE 3. CUMULATIVE PERCENTAGE CURVE FOR THE PER CENT ERROR IN THICKNESS MEASUREMENTS OF TEST SLABS AND PAVEMENTS.

FIGURE 4. SONIC THICKNESS (t_s) VS. ACTUAL THICKNESS (t_c) FOR TEST SLABS AND PAVEMENT.

FIGURE 5. MEAN SONIC THICKNESS VS. ACTUAL THICKNESS FOR TEST SLABS.

The heart of the measuring system is a transducer that will convert mechanical energy (vibrations) to measurable electrical energy or vice versa. Piezoelectric crystals (Rochelle salts in this equipment) exhibit the property that when compressed they emit an electrical impulse. Conversely when an electrical charge is imposed on the crystal, it responds by dilating or compressing. The equipment then functions by detecting and measuring the current emitted from the crystals or by electrically exciting these crystals thus causing them to vibrate.

One other property of a piezoelectric material worthy of note is the curie point. At some temperature, dilations or compression of the crystal will produce no current or it will be so low as to not be measurable with ordinary amplification. If the curie point is above normal operating conditions no problems of loss of sensitivity arise. However, the transducers for the instruments used for this study exhibited total loss of sensitivity at temperatures above 90°F. Solution of this problem consisted of storage of the transducers in an ice chest and exposing them to high temperatures for no longer than necessary to make measurements. There are now available synthetic piezoelectric materials that have curie points at temperatures considerably higher than those which would be encountered on highway pavements.

Pulse velocity is determined by placing a driving transducer a known distance from a receiver and measuring the time that a pulse takes to travel from the driver, through the concrete, and then compress the receiving crystal. The James "V-Scope" functioned very well and provided good, reproducible measurements of the pulse velocity of concretes. It should be mentioned that pulse velocity of a material is a function of several variables including temperature and water content

and that one cannot assume that pulse velocity once determined will be a constant value.

The other parameter in thickness determination, resonant frequency, is not as simple a proposition as was pulse velocity. The concept of resonance as applied to pavement slabs is as follows:

If a transducer was placed on the surface of a slab and this transducer was caused to vibrate at a known low frequency, slab response would be relatively limited. As the vibratory frequency of the transducer is increased, there occurs a frequency at which the slab will vibrate at exactly the same rate as the transducer. This frequency is called slab resonant frequency; a receiver placed on the slab near the driving transducer is used to determine this frequency. The James "E-Meter" shows when resonance occurs.

The determination of resonant frequency with the equipment investigated was most difficult and appears to be the cause of errors in determining slab thickness.

When the driver is vibrating at some known frequency the slab not only resonates but the receiver also has a given resonant frequency. The geometry and material properties of the transducers are such that resonance between transducers occurs at frequencies in the neighborhood of the resonant frequency of the slab. Experiments using different size and weight transducers failed to provide adequate differentiation between transducer and slab resonance.

Recommendations for Further Experiments

Since the primary source of error at this stage appears to be the differentiation between slab resonance and natural resonance of the transducers the next logical step is to take measures to provide this differentiation or elimination of the transducer resonance.

Cursory experiments conducted by the authors at the laboratories of the supplier have shown that there are transducers available that have resonant frequencies several orders of magnitude higher than resonant frequencies of pavement slabs. These transducers were not available at the beginning of this project so could not be included in this phase of the study. Synthetic crystals used in these transducers are reported to have curie points in the vicinity of 400°F thus eliminating the problem of loss of sensitivity at higher temperatures exhibited by presently used transducers.

Signals from the improval transducers are quite weak and cannot be measured with the existing electronics but minor modification by adding amplifiers provides a workable means of reading their output.

If experimentation shows that the use of improved transducers and amplification provide an adequate means of determining pavement thickness, other necessary studies can be initiated. Among these are the determination of the effect of subbase materials on the output of the instruments, and other conditions that may effect precision of determinations.

Operation and Maintenance in the Field

The electrical portion of this measuring system is very stable, portable and rugged. Mechanical and electrical malfunctions were rare and minor and easily repaired. Exposure to field conditions and field use presented no problems to adequate functioning of the instruments.

Operation of the instruments is simple and should be able to be taught to a technician in a matter of three or four hours. Interpretation of output from the cathode ray tube for resonant frequency and calculation of thickness is likewise a relatively simple matter.

Core Sampling and Sonic Techniques Compared

Due to variations in determining resonant frequency, four sonic measurements were made at each core location. Times for making sonic determinations were about the same as those involved in obtaining a core sample with the drill crew occasionally working faster on green concrete or on those with softer aggregates. It is the opinion of the investigators that with ideally operating sonic gear, production rates could be from three to five times that of conventional drilling operations.

Sonic operations involve two persons and one vehicle whereas core sampling includes two to three persons, a drill rig and one to two other vehicles.

It was observed that if a second core was obtained within a relatively close distance to the first, say three or four feet, differences of one half inch between core lengths could be measured. Sonic gear on the other hand averages the thickness of a circle of approximately six feet in diameter.

Acknowledgments

The authors wish to acknowledge the assistance of the Bureau of Public Roads, U. S. Department of Transportation, Federal Highway Administration; Bureau of Materials and Tests, Research and Training Center, Indiana State Highway Commission who supported the investigation and James Electronics, Inc. and Mr. Richard Muenow who provided extra transducers and considerable technical assistance during the investigation.

Laboratory testing was carried out in the Concrete Materials Laboratory of the Joint Highway Research Project at Purdue University and at the Indiana State Highway Commission Research and Training Center, Lafayette, Indiana.

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Appendix A

Typical Field Data

SONIC PROJECT

0201-62-284

TEST SERIAL 256 DATE July 25, 1967

LOCATION Test Slab #3 (10.2")

73°F point 75°F air 53°F Chest 0745

Small Transducer (Receiver)

<u>Run No. 1</u>				<u>Run No. 2</u>			
Time (6")	<u>40</u>	v_p (6")	<u>12,500</u>	Time (6")	<u>39</u>	v_p (6")	<u>12,820</u>
Time (12")	<u>74</u>	v_p (12")	<u>13,514</u>	Time (12")	<u>72</u>	v_p (12")	<u>13,889</u>
Time (24")	<u>153</u>	v_p (24")	<u>13,072</u>	Time (24")	<u>149</u>	v_p (24")	<u>13,423</u>
N_R	<u>7535</u>	v_{ave}	<u>13,029</u>	N_R	<u>7205</u>	v_{ave}	<u>13,377</u>
Thickness	<u>10.37</u>			Thickness	<u>11.14</u>		
<u>Run No. 3</u>				<u>Run No. 4</u>			
Time (6")	<u>41</u>	v_p (6")	<u>12,195</u>	Time (6")	<u>39</u>	v_p (6")	<u>12,820</u>
Time (12")	<u>72</u>	v_p (12")	<u>13,889</u>	Time (12")	<u>71</u>	v_p (12")	<u>14,084</u>
Time (24")	<u>146</u>	v_p (24")	<u>13,699</u>	Time (24")	<u>149</u>	v_p (24")	<u>13,423</u>
N_R	<u>8074</u>	v_{ave}	<u>13,261</u>	N_R	<u>8001</u>	v_{ave}	<u>13,442</u>
Thickness	<u>9.85</u>			Thickness	<u>10.08</u>		

Remarks: Ave. thickness = 10.3"

APPENDIX B

TEST SLABS
FIELD DATA t_s = sonic thickness t_c = actual slab thickness

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>
171	10.1	11.2	286	8.8	10.2	352	10.4	9.2
172	9.7	10.2	289	6.4	6.9	353	11.2	9.4
173	8.1	8.3	290	8.9	9.0	354	11.1	10.2
174	9.7	10.2	291	9.8	10.2	355	11.3	10.3
175	8.7	9.0	292	8.0	8.3	356	11.1	9.2
176	6.1	6.9	293	11.3	11.2	357	11.1	9.4
237	11.0	11.2	294	11.4	11.2	358	11.7	10.2
251	12.2	10.2	295	10.5	10.2	359	7.4	6.9
252	12.3	11.2	296	7.7	8.3	360	8.1	9.0
253	11.5	11.2	297	7.0	6.9	361	11.6	10.2
254	10.4	10.2	298	9.0	9.0	362	7.6	8.3
255	7.4	8.3	299	10.2	10.2	363	11.4	10.2
256	10.3	10.2	300	7.7	8.3	364	11.8	11.2
256-1	10.5	9.0	301	10.0	10.2	369	6.8	6.9
257	7.0	6.9	302	10.9	11.2	370	8.9	9.0
258	10.7	10.3	303	10.7	10.3	372	11.1	10.2
259	10.6	9.2	304	9.9	9.2	374	7.9	8.3
260	10.5	9.4	305	11.4	11.2	375	8.9	8.3
261	11.5	11.2	306	10.2	10.2	376	9.8	10.2
264	11.3	10.3	307	8.4	8.3	377	9.8	10.0
265	10.6	9.2	334	7.0	6.9	379	8.6	9.4
266	10.3	9.4	335	10.1	9.0	380	6.9	6.9
267	10.2	10.2	339	12.3	11.2	381	9.0	9.0
272	10.1	11.2	340	11.0	10.3	382	10.4	10.2
273	9.6	10.2	341	7.1	6.9	383	8.5	8.3
275	9.3	9.0	342	8.2	9.0	384	10.3	10.2
277	7.1	8.3	343	11.6	10.2	385	11.6	11.2
278	10.7	10.2	344	7.6	8.3	386	11.0	10.3
280	10.1	9.0	346	11.1	10.2	387	9.5	9.2
281	7.7	6.9	347	11.7	11.2	388	9.8	9.4
282	9.3	9.0	350	11.3	10.3	389	10.3	10.2
283	9.8	10.2	351	11.8	10.3			

Serial	t_s	t	t_c	Residual $\frac{t-t_c}{t_c}$
352	10.4	9.9	9.2	-0.7
353	11.2	10.5	9.4	-1.1
354	11.1	10.4	10.2	-0.2
355	11.3	10.6	10.3	-0.3
356	11.1	10.4	9.2	-1.2
357	11.1	10.4	9.4	-1.0
358	11.7	10.8	10.2	-0.6
359	7.4	7.8	6.9	-0.9
360	8.1	8.3	9.0	+0.7
361	11.6	10.8	10.2	-0.6
362	7.6	8.0	8.3	+0.3
363	11.4	10.6	10.2	-0.4
364	11.8	10.9	11.2	+0.3
369	6.8	7.4	6.9	-0.5
370	8.9	8.9	9.0	+0.1
372	11.1	10.4	10.2	+0.2
374	7.9	8.2	8.3	+0.1
375	8.9	8.9	8.3	-0.6
376	9.8	9.5	10.2	+0.7
377	9.8	9.5	10.0	+0.5
379	8.6	8.7	9.4	+0.7
380	6.9	7.5	6.9	-0.6
381	9.0	9.0	9.0	0
382	10.4	9.9	10.2	+0.3
383	8.5	8.6	8.3	-0.3
384	10.3	9.9	10.2	+0.3
385	11.6	10.8	11.2	+0.4
386	11.6	10.4	10.3	-0.1
387	9.5	9.3	9.2	-0.1
388	9.8	9.5	9.4	-0.1
389	10.3	9.9	10.2	+0.3

E = +0.4

APPENDIX C

TEST SLABS

Regression Analysis

Test Slab Data

Let X = sonic thickness, t_s .

Y = actual thickness, t_c .

$$\sum X_i Y_i = 8981.76$$

$$\sum Y_i = 902.6$$

$$\sum X_i^2 = 9302.67$$

$$\sum X_i = 928.3$$

$$n = 95$$

$$\bar{x} = 928.3 \div 95 = 9.7716$$

$$\bar{y} = 902.6 \div 95 = 9.5010$$

$$\sum Y_i^2 = 8722.70$$

$$b_1 = \frac{\sum X_i Y_i - [(\sum X_i)(\sum Y_i) \div n]}{\sum X_i^2 - (\sum X_i)^2 \div n}$$

$$= \frac{8981.76 - (928.3)(902.6) \div 95}{9302.67 - (928.3)^2 \div 95}$$

$$= \frac{8931.76 - 8819.83}{9302.67 - 9070.96} = \frac{161.93}{231.71} = \underline{\underline{0.6988}}$$

$$b_0 = \bar{y} - b_1 \bar{x} = 9.5010 - 0.6988 (9.7716) = \underline{\underline{2.6726}}$$

$$\hat{y} = 2.6726 + 0.6988 X$$

$$\text{or } t = 2.6726 + 0.6988 t_s$$

Where $\hat{t}$ = predicted slab thickness

t_s = sonic thickness

Appendix D

$$\hat{t} = 2.6726 + 0.6988t_s$$

 $\hat{t}$ = Predicted slab thickness

 t_s = Sonic Thickness

TEST SLABS

PREDICTED SLAB THICKNESSES
AND RESIDUALS

Serial	t_2	t	t_c	Residual $t_c - t$	Serial	t_s	t	t_c	Residual $t_c - t$
171	10.1	9.7	11.2	+1.5	286	8.8	8.8	10.2	+1.4
172	9.7	9.5	10.2	+0.7	289	6.4	7.1	6.9	-0.3
173	8.1	8.3	8.3	0	290	8.9	8.9	9.0	+0.1
174	9.7	9.5	10.2	+0.7	291	9.8	9.5	10.2	+0.7
175	8.7	8.8	9.0	+0.2	292	8.0	8.3	8.3	0
176	6.1	6.9	6.9	0	293	11.3	10.6	11.2	+0.6
237	11.0	10.4	11.2	+0.8	294	11.4	10.6	11.2	+0.6
251	12.2	11.2	10.2	-1.0	295	10.5	10.0	10.2	+0.2
252	12.3	11.3	11.2	-0.1	296	7.7	8.1	8.3	+0.2
253	11.5	10.7	11.2	+0.5	297	7.0	7.6	6.9	-0.7
254	10.4	9.9	10.2	+0.3	298	9.0	9.0	9.0	0
255	7.4	7.8	8.3	+0.5	299	10.2	9.8	10.2	+0.4
256	10.3	9.9	10.2	+0.3	300	7.7	8.1	8.3	+0.2
256-1	10.5	10.0	9.0	-1.0	301	10.0	9.7	10.2	+0.5
257	7.0	7.6	6.9	-0.7	302	10.9	10.3	11.2	+0.9
258	10.7	10.1	10.3	+0.2	303	10.7	10.1	10.3	+0.2
259	10.6	10.1	9.2	-0.9	304	9.9	9.6	9.2	-0.4
260	10.5	10.0	9.4	-0.6	305	11.4	10.6	11.2	+0.6
261	11.5	10.7	11.2	+0.5	306	10.2	9.8	10.2	+0.4
264	11.3	10.6	10.3	-0.3	307	8.4	8.5	8.3	-0.2
265	10.6	10.1	9.2	-0.3	334	7.0	7.6	6.9	-0.7
266	10.3	9.9	9.4	-0.5	335	10.1	9.7	9.0	-0.7
267	10.2	9.8	10.2	+0.4	339	12.3	11.3	11.2	-0.1
272	10.1	9.7	11.2	+1.5	340	11.0	10.4	10.3	-0.1
273	9.6	9.4	10.2	+0.8	341	7.1	7.6	6.9	-0.7
275	9.3	9.2	9.0	-0.2	342	8.2	8.4	9.0	+0.6
277	7.1	7.6	8.3	+0.7	343	11.6	10.8	10.2	-0.6
278	10.7	10.1	10.2	+0.1	344	7.6	8.0	8.3	+0.3
280	10.1	9.7	9.0	-0.7	346	11.1	10.4	10.2	-0.2
281	7.7	8.1	6.9	-1.2	347	11.7	10.8	11.2	+0.4
282	9.3	9.2	9.0	-0.2	350	11.3	10.6	10.3	-0.3
283	9.8	9.5	10.2	+0.7	351	11.8	10.9	10.3	-0.6

TEST SLABS

Readings vs.
Actual Thickness
and Error
(Raw Data)

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Error</u>	<u>% Error</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Error</u>	<u>% Error</u>
171	10.1	11.2	- 1.1	- 9.8	286	8.8	10.2	- 1.4	- 15.7
172	9.7	10.2	- 0.5	- 4.9	289	6.4	6.9	- 0.5	- 7.2
173	8.1	8.3	- 0.2	- 2.4	290	8.9	9.0	- 0.1	- 1.1
174	9.7	10.2	- 0.5	- 4.9	291	9.8	10.2	- 0.4	- 3.9
175	8.7	9.0	- 0.3	- 3.3	292	8.0	8.3	- 0.3	- 3.6
176	6.1	6.9	- 0.8	-11.6	293	11.3	11.2	+ 0.1	+ 0.9
237	11.0	11.2	- 0.2	- 1.8	294	11.4	11.2	+ 0.2	+ 1.8
251	12.2	10.2	+ 2.0	+19.6	295	10.5	10.2	+ 0.3	+ 2.9
252	12.3	11.2	+ 1.1	+ 9.8	296	7.7	8.3	- 0.6	- 7.2
253	11.5	11.2	+ 0.3	+ 2.7	297	7.0	6.9	+ 0.1	+ 1.4
254	10.4	10.2	+ 0.2	+ 2.0	298	9.0	9.0	0	0
255	7.4	8.3	- 0.9	-10.9	299	10.2	10.2	0	0
256	10.3	10.2	+ 0.1	+ 1.0	300	7.7	8.3	- 0.6	- 7.2
256-1	10.5	9.0	+ 1.5	+16.7	301	10.0	10.2	- 0.2	- 2.0
257	7.0	6.9	+ 0.1	+ 1.4	302	10.9	11.2	- 0.3	- 2.7
258	10.7	10.3	+ 0.4	+ 3.9	303	10.7	10.3	+ 0.4	+ 3.9
259	10.6	9.2	+ 1.4	+15.2	304	9.9	9.2	+ 0.7	+ 7.6
260	10.5	9.4	+ 1.1	+11.7	305	11.4	11.2	+ 0.2	+ 1.8
261	11.5	11.2	+ 0.3	+ 2.7	306	10.2	10.2	0	0
264	11.3	10.3	+ 1.0	+ 9.5	307	8.4	8.3	+ 0.1	+ 1.2
265	10.6	9.2	+ 1.4	+15.2	334	7.0	6.9	+ 0.1	+ 1.4
266	10.3	9.4	+ 0.9	+ 9.6	335	10.1	9.0	+ 1.1	+ 12.2
267	10.2	10.2	0.0	0	339	12.3	11.2	+ 1.1	+ 9.8
272	10.1	11.2	- 1.1	- 9.8	340	11.0	10.3	+ 0.7	+ 6.8
273	9.6	10.2	- 0.6	- 5.9	341	7.1	6.9	+ 0.2	+ 2.9
275	9.3	9.0	+ 0.3	+ 3.3	342	8.2	9.0	- 0.8	- 8.9
277	7.1	8.3	- 1.2	-14.5	343	11.6	10.2	+ 1.4	+ 13.7
278	10.7	10.2	+ 0.5	+ 4.9	344	7.6	8.3	- 0.7	- 8.4
280	10.1	9.0	+ 1.1	+12.2	346	11.1	10.2	+ 0.9	+ 8.8
281	7.7	6.9	+ 0.8	+11.6	347	11.7	11.2	+ 0.5	+ 4.5
282	9.3	9.0	+ 0.3	+ 3.3	350	11.3	10.3	+ 1.0	+ 9.7
283	9.8	10.2	- 0.4	- 3.9	351	11.8	10.3	+ 1.5	+ 14.6

Ave. error = 6.7%

TEST SLABSReadings vs.
Actual Thickness

(Raw Data)

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Error</u>	<u>% Error</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Error</u>	<u>% Error</u>
352	10.4	9.2	+ 1.2	+13.0					
353	11.2	9.4	+ 1.8	+19.2					
354	11.1	10.2	+ 0.9	+ 8.8					
355	11.3	10.3	+ 1.0	+ 9.7					
356	11.1	9.2	+ 1.9	+20.7					
357	11.1	9.4	+ 1.7	+18.1					
358	11.7	10.2	+ 1.5	+14.7					
359	7.4	6.9	+ 0.5	+ 7.3					
360	8.1	9.0	- 0.9	-10.0					
361	11.6	10.2	+ 1.4	+13.7					
362	7.6	8.3	- 0.7	- 8.4					
363	11.4	10.2	+ 1.2	+11.8					
364	11.8	11.2	+ 0.6	+ 5.4					
369	6.8	6.9	- 0.1	- 1.4					
370	8.9	9.0	- 0.1	- 1.1					
372	11.1	10.2	+ 0.9	+ 8.8					
374	7.9	8.3	- 0.4	- 4.8					
375	8.9	8.3	+ 0.6	+ 7.2					
376	9.8	10.2	- 0.4	- 3.9					
377	9.8	10.0	- 0.2	- 2.0					
379	8.6	9.4	- 0.8	- 8.5					
380	6.9	6.9	0	0					
381	9.0	9.0	0	0					
382	10.4	10.2	+ 0.2	+ 2.0					
383	8.5	8.3	+ 0.2	+ 2.4					
384	10.3	10.2	+ 0.1	+ 1.0					
385	11.6	11.2	+ 0.4	+ 3.6					
386	11.0	10.3	+ 0.7	+ 6.8					
387	9.5	9.2	+ 0.3	+ 3.3					
388	9.8	9.4	+ 0.4	+ 4.3					
389	10.3	10.2	+ 0.1	+ 1.0					

t_s = Sonic Thickness t_c = Core Thickness Δ = Errors $t_s - t_c$ Sonic Thickness and
Core Thickness Compared

I-465

Indianapolis

Serial	t_s	t_c	Δ	% Error	Serial	t_s	t_c	Δ	% Error
122	8.7	10.1	- 1.4	-14.0	157	9.3	10.3	- 1.0	- 9.7
123	8.8	9.6	- 0.8	- 8.3	158	9.6	10.8	- 1.2	-11.1
124	9.5	9.8	- 0.3	- 3.1	159	8.9	10.1	- 1.2	-11.9
125	9.6	10.4	- 0.8	- 7.7	160	9.3	10.4	- 1.1	-10.6
126	9.9	10.1	- 0.2	- 2.0	161	9.3	10.3	- 1.0	- 9.7
127	9.6	10.8	- 1.2	-11.1	308	10.5	10.6	- 0.1	- 0.9
128	10.0	10.0	--	0	309	10.4	10.2	+ 0.2	+ 2.0
129	10.0	10.0	--	0	310	10.9	10.2	+ 0.7	+ 6.9
130	11.1	11.0	+ 0.1	+ 0.9	311	10.6	10.4	+ 0.2	+ 1.9
131	11.0	10.4	+ 0.6	+ 5.8	312	10.4	10.0	+ 0.4	+ 4.0
132	11.3	10.5	+ 0.8	+ 7.6	313	10.6	10.4	+ 0.2	+ 1.9
133	11.4	10.2	+ 1.2	+10.2	314	11.6	10.3	+ 0.3	+ 2.9
134	11.6	10.8	+ 0.8	+ 7.4	315	10.9	10.2	+ 0.7	+ 6.9
135	11.1	10.0	+ 1.1	+11.0	318	10.2	10.3	- 0.1	- 1.0
136	11.5	10.2	+ 1.3	+12.7	319	10.9	10.4	+ 0.5	+ 4.8
137	9.3	10.6	- 1.3	-12.3	320	11.1	10.5	+ 0.6	+ 5.7
138	8.8	10.6	- 1.8	-17.0	321	11.0	10.3	+ 0.7	+ 6.8
139	11.9	11.0	+ 0.9	+ 8.2					
140	10.9	10.2	+ 0.7	+ 6.9					
141	10.3	10.0	+ 0.3	+ 3.0					
142	11.1	10.2	+ 0.9	+ 8.8					
143	10.8	11.0	- 0.2	- 1.9					
144	9.4	9.8	- 0.4	- 4.1					
145	9.3	10.1	- 0.8	- 7.9					
146	9.2	10.4	- 1.2	-11.5					
147	9.6	10.5	- 0.9	- 8.6					
148	9.4	10.3	- 0.9	- 8.7					
149	8.7	10.4	- 1.7	-16.3					
150	8.9	10.3	- 1.4	-13.6					
151	9.2	10.4	- 1.2	-11.5					
152	9.2	10.0	- 0.8	- 8.0					
153	9.1	9.9	- 0.8	- 8.1					
154	8.8	10.3	- 1.5	-14.6					
155	9.0	9.8	- 0.8	- 8.2					
156	9.3	10.1	- 0.8	-7.9					

FIELD DATA

Sonic Thickness and
Core Thickness Compared
U.S. 50
Versailles

 t_s = Sonic Thickness

 t_c = Core Thickness

 Δ = Error = $t_s - t_c$

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Δ</u>	<u>% Error</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>Δ</u>	<u>% Error</u>
189	7.9	8.7	- 0.8	- 9.2	226	8.3	9.5	- 1.2	-12.7
190	8.6	9.4	- 0.8	- 9.5	227	7.1	9.4	- 2.3	-24.5
191	8.6	9.0	- 0.4	- 4.4	228	7.3	9.2	- 1.9	-20.7
192	8.6	9.1	- 0.5	- 5.5	229	8.4	9.8	- 1.4	-14.3
193	8.8	9.4	- 0.6	- 6.4	231	7.7	8.8	- 1.1	-12.5
194	8.6	9.4	- 0.8	- 8.5	232	8.5	9.3	- 0.8	- 8.6
195	8.5	9.1	- 0.6	- 6.6	234	7.6	9.2	- 1.6	-17.4
196	8.2	9.1	- 0.9	- 9.9	235	8.6	9.5	- 0.9	- 9.5
197	8.6	9.0	- 0.4	-4.4					
198	8.6	9.0	- 0.4	- 4.4					
200	8.4	9.0	- 0.6	- 6.7					
201	7.9	9.0	- 1.1	-12.2					
202	8.0	9.1	- 1.1	-12.1					
203	7.8	9.1	- 1.3	-14.3					
204	8.2	8.9	- 0.7	- 7.9					
205	8.0	8.9	- 0.9	-10.1					
206	8.6	9.1	- 0.5	- 5.5					
207	8.9	9.3	- 0.4	- 4.3					
208	8.6	9.3	- 0.7	- 7.5					
209	8.8	9.4	- 0.6	- 6.4					
210	9.0	9.8	- 0.8	- 8.2					
211	8.6	9.7	- 1.1	-11.3					
212	8.5	9.2	- 0.7	- 7.6					
213	8.3	9.3	- 1.0	-10.8					
214	8.5	9.1	- 0.6	- 6.6					
215	8.2	9.2	- 1.0	-10.9					
216	8.2	9.2	- 1.0	-10.9					
217	8.4	9.6	- 1.2	-12.5					
218	8.5	9.2	- 0.7	- 7.6					
219	8.5	9.7	- 1.2	-12.4					
220	7.8	8.9	- 1.1	-12.4					
221	8.6	9.5	- 0.9	- 9.5					
222	8.9	8.9	--	0					
224	8.4	9.7	- 1.3	-13.4					

FIGURE 6. PER CENT ERROR DISTRIBUTION FOR TEST SLABS AND PAVEMENTS.

t_s = SONIC THICKNESS

t_c = CORE THICKNESS

Δ = ERROR = $t_s - t_c$

FIELD DATA

SONIC THICKNESS AND CORE

THICKNESS COMPARED

I-70 KNIGHTSTOWN

Serial	t_s	t_c	Δ	%Error
322	10.1	10.0	+0.1	+1.0
323	10.3	10.4	-0.1	-1.0
324	10.4	10.5	-0.1	-1.0
325	9.0	10.0	-1.0	-10.0
326	10.7	10.2	+0.5	+4.9
327	10.2	10.1	+0.1	+1.0
365	8.2	10.2	-2.0	-19.6

I-64 HAUBSTADT

Serial	t_s	t_c	Δ	%Error
269	8.0	10.5	-2.5	-23.8
270	10.3	9.9	+0.4	+ 4.0
271	10.1	10.6	-0.5	- 4.7

U.S. 40 TERRE HAUTE

Serial	t_s	t_c	Δ	%Error
240	7.8	9.6	-1.8	-18.8
241	7.8	10.6	-2.8	-26.4
242	8.0	9.5	-1.5	-15.8
244	10.0	9.8	+0.2	+ 0.2
245	10.1	10.2	-0.1	- 1.0
246	10.3	10.2	+0.1	+ 1.0
247	9.4	9.8	-0.4	- 4.1

APPENDIX F

Data in Ranking Order
of Increasing % Error

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>
128	10.0	10.0	0	244	10.0	9.8	+ 2.0
129	10.0	10.0	0	254	10.4	10.2	+ 2.0
222	8.9	8.9	0	301	10.0	10.2	- 2.0
267	10.2	10.2	0	309	10.4	10.2	+ 2.0
298	9.0	9.0	0	377	9.8	10.0	- 2.0
299	10.2	10.2	0	382	10.4	10.2	+ 2.0
306	10.2	10.2	0	173	8.1	8.3	- 2.4
380	6.9	6.9	0	383	8.5	8.3	+ 2.4
381	9.0	9.0	0	253	11.5	11.2	+ 2.7
130	11.1	11.0	+ 0.9	261	11.5	11.2	+ 2.7
293	11.3	11.2	+ 0.9	302	10.9	11.2	- 2.7
308	10.5	10.6	- 0.9	295	10.5	10.2	+ 2.9
245	10.1	10.2	- 1.0	314	11.6	10.3	+ 2.9
246	10.3	10.2	+ 1.0	341	7.1	6.9	+ 2.9
256	10.3	10.2	+ 1.0	141	10.3	10.0	+ 3.0
318	10.2	10.3	- 1.0	124	9.5	9.8	- 3.1
322	10.1	10.0	+ 1.0	175	8.7	9.0	- 3.3
323	10.3	10.4	- 1.0	275	9.3	9.0	+ 3.3
324	10.4	10.5	- 1.0	282	9.3	9.0	+ 3.3
327	10.2	10.1	+ 1.0	387	9.5	9.2	+ 3.3
384	10.3	10.2	+ 1.0	292	8.0	8.3	- 3.6
389	10.3	10.2	+ 1.0	385	11.6	11.2	+ 3.6
290	8.9	9.0	- 1.1	258	10.7	10.3	+ 3.9
370	8.9	9.0	- 1.1	283	9.8	10.2	- 3.9
307	8.4	8.3	+ 1.2	291	9.8	10.2	- 3.9
257	7.0	6.9	+ 1.4	303	10.7	10.3	+ 3.9
297	7.0	6.9	+ 1.4	376	9.8	10.2	- 3.9
334	7.0	6.9	+ 1.4	270	10.3	9.9	+ 4.0
369	6.8	6.9	- 1.4	312	10.4	10.0	+ 4.0
237	11.0	11.2	- 1.8	144	9.4	9.8	- 4.1
294	11.4	11.2	+ 1.8	247	9.4	9.8	- 4.1
305	11.4	11.2	+ 1.8	207	8.9	9.3	- 4.3
143	10.8	11.0	- 1.9	388	9.8	9.4	+ 4.3
311	10.6	10.4	+ 1.9	191	8.6	9.0	- 4.4
313	10.6	10.4	+ 1.9	197	8.6	9.0	- 4.4
126	9.9	10.1	- 2.0	198	8.6	9.0	- 4.4

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>
347	11.7	11.2	+ 4.5	145	9.3	10.1	- 7.0
271	10.1	10.6	- 4.7	156	9.3	10.1	- 7.9
319	10.9	10.4	+ 4.8	204	8.2	8.9	- 7.9
374	7.9	8.3	- 4.8	152	9.2	10.0	- 8.0
172	9.7	10.2	- 4.9	153	9.1	9.9	- 8.1
174	9.7	10.2	- 4.9	139	11.9	11.0	+ 8.2
278	10.7	10.2	+ 4.9	155	9.0	9.8	- 8.2
326	10.7	10.2	+ 4.9	210	9.0	9.8	- 8.2
364	11.8	11.2	+ 5.4	123	8.8	9.6	- 8.3
192	8.6	9.1	- 5.5	344	7.6	8.3	- 8.4
206	8.6	9.1	- 5.5	362	7.6	8.3	- 8.4
320	11.1	10.5	+ 5.7	194	8.6	9.4	- 8.5
131	11.0	10.4	+ 5.8	379	8.6	9.4	- 8.5
273	9.6	10.2	- 5.9	147	9.6	10.5	- 8.6
193	8.8	9.4	- 6.4	232	8.5	9.3	- 8.6
209	8.8	9.4	- 6.4	148	9.4	10.3	- 8.7
195	8.5	9.1	- 6.6	142	11.1	10.2	+ 8.8
214	8.5	9.1	- 6.6	346	11.1	10.2	+ 8.8
200	8.4	9.0	- 6.7	354	11.1	10.2	+ 8.8
321	11.0	10.3	+ 6.8	372	11.1	10.2	+ 8.8
340	11.0	10.3	+ 6.8	342	8.2	9.0	- 8.9
386	11.0	10.3	+ 6.8	189	7.9	8.7	- 9.2
140	10.9	10.2	+ 6.9	190	8.6	9.5	- 9.5
310	10.9	10.2	+ 6.9	221	8.6	9.5	- 9.5
315	10.9	10.2	+ 6.9	235	8.6	9.5	- 9.5
289	6.4	6.9	- 7.2	264	11.3	10.3	+ 9.5
296	7.7	8.3	- 7.2	266	10.3	9.4	+ 9.6
300	7.7	8.3	- 7.2	157	9.3	10.3	- 9.7
375	8.9	8.3	+ 7.2	161	9.3	10.3	- 9.7
359	7.4	6.9	+ 7.3	350	11.3	10.3	+ 9.7
134	11.6	10.8	+ 7.4	355	11.3	10.3	+ 9.7
208	8.6	9.3	- 7.5	171	10.1	11.2	- 9.8
132	11.3	10.5	+ 7.6	252	12.3	11.2	+ 9.8
212	8.5	9.2	- 7.6	272	10.1	11.2	- 9.8
218	8.5	9.2	- 7.6	339	12.3	11.2	+ 9.8
125	9.6	10.4	- 7.7	196	8.2	9.1	- 9.9
304	9.9	9.2	+ 7.6	360	8.1	9.0	-10.0

<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>	<u>Serial</u>	<u>t_s</u>	<u>t_c</u>	<u>% E</u>
325	9.0	10.0	-10.0	203	7.8	9.1	-14.3
205	8.0	8.9	-10.1	229	8.4	9.8	-14.3
133	11.4	10.2	+10.2	277	7.1	8.3	-14.5
160	9.3	10.4	-10.6	154	8.8	10.3	-14.6
213	8.3	9.3	-10.8	351	11.8	10.3	+14.6
215	8.2	9.2	-10.9	358	11.7	10.2	+14.7
216	8.2	9.2	-10.9	259	10.6	9.2	+15.2
255	7.4	8.3	-10.9	265	10.6	9.2	+15.2
135	11.1	10.0	+11.0	242	8.0	9.5	-15.8
127	9.6	10.8	-11.1	149	8.7	10.4	-16.3
158	9.6	10.8	-11.1	256-1	10.5	9.0	+16.7
211	8.6	9.7	-11.3	138	8.8	10.6	-17.0
146	9.2	10.4	-11.5	234	7.6	9.2	-17.4
151	9.2	10.4	-11.5	357	11.1	9.4	+18.1
176	6.1	6.9	-11.6	240	7.8	9.6	-18.8
281	7.7	6.9	+11.6	353	11.2	9.4	+19.2
260	10.5	9.4	+11.7	251	12.2	10.2	+19.6
363	11.4	10.2	+11.8	365	8.2	10.2	-19.6
159	8.9	10.1	-11.9	228	7.3	9.2	-20.7
202	8.0	9.1	-12.1	356	11.1	9.2	+20.7
201	7.9	9.0	-12.2	269	8.0	10.5	-23.8
280	10.1	9.0	+12.2	227	7.1	9.4	-24.5
335	10.1	9.0	+12.2	241	7.8	10.6	-26.4
137	9.3	10.6	-12.3				
219	8.5	9.7	-12.4				
220	7.8	8.9	-12.4				
217	8.4	9.6	-12.5				
231	7.7	8.8	-12.5				
136	11.5	10.2	+12.7				
226	8.3	9.5	-12.7				
352	10.4	9.2	+13.0				
224	8.4	9.7	-13.4				
150	8.9	10.3	-13.6				
286	8.8	10.2	-13.7				
343	11.6	10.2	+13.7				
361	11.6	10.2	+13.7				
122	8.7	10.1	-14.0				