ROAD PROFILE STUDY

FINAL REPORT

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ABSTRACT

Rough pavements are objectionable to the public and detrimental to the long term performance of the highway. In an effort to obtain smooth highways, states attempt to limit as built roughness. Roughness is measured with a variety of devices ranging in sophistication from relatively simple straightedges to complex electronic instruments. This report documents the evaluation of a moderately complex but non-electronic roughness measuring device; the Rainhart model profilograph.

The evaluation was accomplished by comparison testing the profilograph, the 10-foot rolling straightedge, and the Mays Ride Meter on several hot-mix asphalt concrete (HMAC) and portland cement concrete (PCC) pavements. In addition, the surface profiling ability of the profilograph was evaluated by testing it over an induced "artificial" road surface of known horizontal and vertical dimensions. Ease of transport operation and degree of maintenance was also considered.

The Rainhart profilograph graphical trace of the roadway surface profile was found to be repeatable and was found to be representative of the actual surface profile. The profilograph's digital roughness indicators were found to be unuseable. The measured graphical output correlated well with the 10-foot long rolling straightedge and Mays Ride Meter. The profilograph while not needing calibration, was found to have numerous operational and maintenance problems.

The results of this evaluation indicates that a profilograph type device can be a useable quality control and acceptance tool, especially suited for PCC pavements.

Recommendations are made to develop profilograph oriented specifications for use of this type of device for quality control and acceptance of PCC pavements.

METRIC CONVERSION FACTORS*

To Convert from	To	Multiply by
	Length	
foot	meter (m)	0.3048
inch	millimeter (mm)	25.4
yard	meter (m)	0.9144
mile (statute)	kilometer (km)	1.609
	Area	
square foot	square meter (m^2)	0.0929
square inch	square centimeter (cm^2)	6.451
square yard	square meter (m^2)	0.8361
	Volume (Capacity)	
cubic foot	cubic meter (m^3)	0.02832
gallon (U.S. liquid)**	cubic meter (m^3)	0.003785
gallon (Can. liquid)**	cubic meter (m^3)	0.004546
ounce (U.S. liquid)	cubic centimeter (cm^3)	29.57
	Mass	
ounce-mass (avdp)	gram (g)	28.35
pound-mass (avdp)	kilogram (kg)	0.4536
ton (metric)	kilogram (kg)	1000
ton (short, 2000 lbs)	kilogram (kg)	907.2
	Mass per Volume	
pound-mass/cubic foot	kilogram/cubic meter (kg/m^3)	16.02
pound-mass/cubic yard	kilogram/cubic meter (kg/m^3)	0.5933
pound-mass/gallon (U.S.)**	kilogram/cubic meter (kg/m^3)	119.8
pound-mass/gallon (Can.)**	kilogram/cubic meter (kg/m^3)	99.78
	Temperature	
deg Celsius (C)	kelvin (K)	$t_K=(t_C+273.15)$
deg Fahrenheit (F)	kelvin (K)	$t_K=(t_F+459.67)/1.8$
deg Fahrenheit (F)	deg Celsius (C)	$t_C=(t_F-32)/1.8$

*The reference source for information on SI units and more exact conversion factors is "Metric Practice Guide" ASTM E 380.

**One U.S. gallon equals 0.8327 Canadian gallon.

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INTRODUCTION

A rough pavement is uncomfortable to those occupying a vehicle as it travels the highway and in addition increases the cost of travel through increased fuel consumption and wear and tear on the vehicle. The motoring public judges the success of a new paving project, to a large extent, by the smoothness or ride quality of the roadway.

The ride quality of the roadway not only affects the motorists senses and pocketbook, but also affects the life of the pavement. According to the AASHTO design equasions a pavement built with a rough surface will have a shorter service life than that of the same pavement built with a smooth surface. A rough pavement is subject to increased detrimental stresses and strains by the action (impact loads) of vehicles "bouncing" across the pavement surface.

Louisiana specifies that pavements are to be constructed smooth by setting limits on allowable roughness. If a roadway is constructed and its degree of roughness is outside the specified limits then the contractor must take corrective actions. In some instances adjustments in the contracted unit price are also specified, as a disincentive mechanism.

All states want roads that are constructed smooth. To obtain smooth roads they used various devices to determine roughness during construction (quality control) and for project acceptance. Each state, based upon the degree of smoothness that they desire, specify limits of roughness suited for measurement by a particular device. Each type device "feels" and records roughness in a different manner. Therefore roughness data obtained in one state with one type of device is not necessarily useful to anyone outside that state. If all states measured roughness with the same device, use in the same manner, then many "universal" questions concerning how best to construct smooth roadways could possibly be answered. The rolling profilograph (such as the Rainhart model) has been suggested as a candidate for this universal device due to its graphical output format and purported accuracy and repeatability.

Louisiana currently uses the 10' rolling stredge to determine the degree of compliance to surface tolerance specifications. This equipment is relatively inexpensive and simple to operate and maintain, but requires frequent calibration. The straightedge roughness output is relatable to highway ride quality but does not measure the actual surface profile of the roadway.

The Rainhart profilograph is a more sophisticated roughness measuring device that the 10-foot rolling straightedge. The profilograph is purported to not need calibration and to produce a graphical trace which closely resembles the actual surface profile of the road, and of being more reflective of highway ride quality.

This study was undertaken to evaluate the overall usefulness of the Rainhart profilograph as a roughness measuring device.

OBJECTIVE

The objective of this study was to evaluate the Rainhart profilographs overall usefulness to the La. DOTD as a pavement roughness measuring device, as outlined by the following specific aims :

1. Ease of transport, maintenance and operation.
2. Repeatability of graphical and digital output.
3. Comparison of roughness measure to currently used (La. DOTD) measuring devices.
4. Surface profiling (mapping) ability.
5. Applicability of profilograph as a quality control and acceptance tool for new pavements.

SCOPE

This evaluation was accomplished through testing several newly constructed rigid and flexible paving projects with the Rainhart profilograph.

The general useability of the device was evaluated under field conditions during transport and project testing. Repeatability of the profilograph's digital and graphical outputs was determined by repeative testing of projects over various time periods and with using several operators. On each project tested with the profilograph, comparison testing was conducted with other roughness measuring devices currently in use by the La. DOTD. The data generated during comparison testing was evaluated in an effort to establish recommended roughness tolerances (profilograph) for possible use by the Department.

The ability of the graphical output of the profilograph to map the actual longitudinal surface profile of a roadway was investigated by testing on a surface with varied but known (induced) profile.

To add additional range to the degree of roughness encounted on new construction, several older projects were also tested.

METHOD OF PROCEDURE

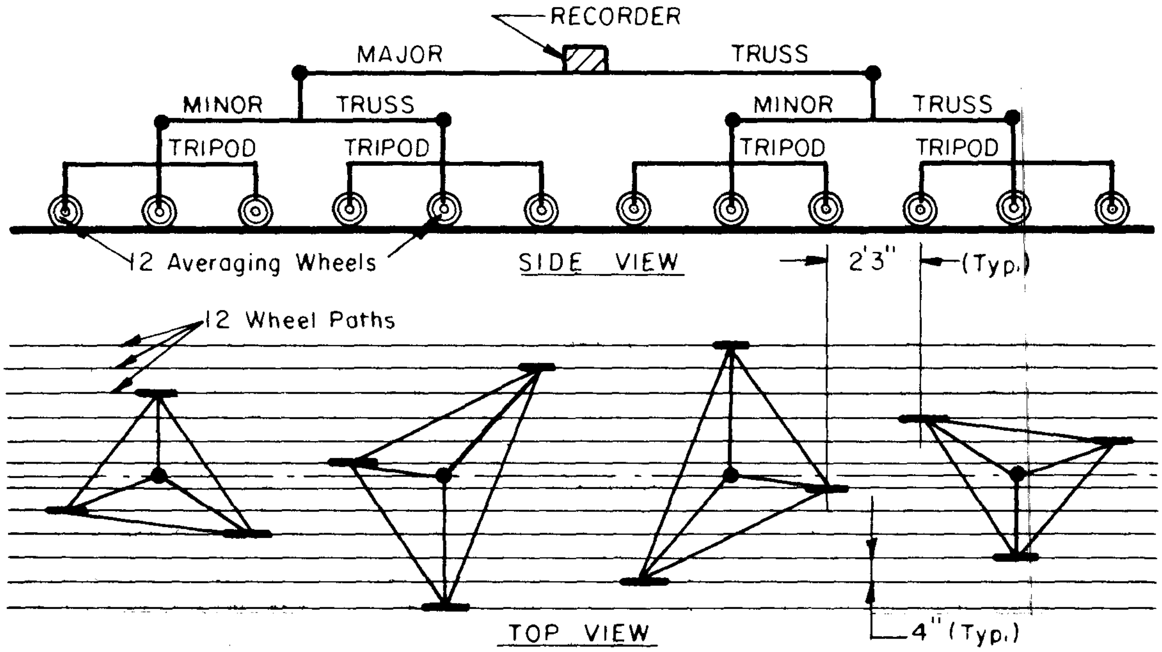
Equipment

The Rainhart Profilograph

The Rainhart profilograph is a 26 ft. long device composed of a major truss which is supported at each end by two minor trusses. The minor trusses are supported at each end by a tripod, each supported by 3 small wheels. The instrument that records roughness is centered on the device and is located at the top center of the main truss. The minor trusses are pinned to the main truss and the tripods are connected to the minor trusses with a ball and socket arrangement allowing partially independent movement of each major component of the device. The 12 small wheels that support the device are called averaging wheels, and each traverses a different path as the profilograph is pushed longitudinally along the roadway. Due to the geometrics of the profilograph, 1/12th of the vertical movement of an individual averaging wheel is transmitted mechanically to the center of the main truss where the recording instrument is located. A schematic diagram of the Rainhart profilograph is presented in Figure 1 on page 6 .

The roughness recording instrument is actuated mechanically during vertical distance changes between the recorder and a 5 ft. circumference recording wheel which rides on the pavement surface below the recorder. The recorder is a strip chart recorder which is also equipped with a digital longitudinal distance counter and two vertical roughness counters. As the 5 ft. recording wheel moves longitudinally and vertically along the pavement surface it mechanically drives the chart paper, pen carriage and counters.

The profilograph truss and averaging wheels are designed to provide a relatively consistant vertical frame of reference to the recorder



Schematic of the Rainhart Profilograph

FIGURE 1

band was used to discount small irregularities of the pavement surface, such as tining on concrete and the macrotexture of hot-mix, which do not contribute to a rough ride. This discounting of small surface irregularities is also a feature on one of the digital counters in that it discounts or "filters" the first 1/10 of an inch of movement of the measuring wheel, after it passes from a downstroke and starts an upstroke.

Rolling Straightedge

The 10-foot long rolling straightedge was used for comparison testing with the profilograph on the same projects and same testing paths. The La. DOTD specifies the rolling straightedge as its project quality control tool for both rigid and flexible pavements. The straightedge is also used to assess pay penalties and/or designate areas requiring corrective action.

The straightedge consists of a rigid metal beam (approximately 10 ft. long) that is supported at either end by two wheels. The wheel base is 10 ft. long. At the center of the beam is the roughness indicator. The roughness indicator, essentially consists of a scale wheel which is free to move vertically as it travels across the pavement, and a pointer/scale and miscroswitches that are activated by the movement of the scale wheel. As the straightedge is pulled along the pavement, vertical movement of the scale wheel in relation to the beam is indicated by the pointer. The scale and the microswitches can be set to activate a dye release mechanism at a pre-set degree of vertical movement. The microswitches and dye release mechanism, when activated spray a dye onto the pavement marking those areas outside the pre-set tolerance. These dye marks are measured and when divided by the total length tested, gives a roughness measurement that is expressed as the % of the tested length that exceeds the pre-set tolerance. Additional infomation as to the Department calibration and use of the rolling straightedge as well as pictures of the device may be found in the current addition of La. DOTD Testing Procedures Manual, Volume 2, designations TR 603-84 and TR 618-84.

One drawback to the rolling straightedge is that it requires frequent calibration. Another drawback is that it does not actually "map" or indicate the true surface profile. This is because 1/2 of the relative vertical movement of the front and/or the back wheels is transmitted to the roughness indicator. As an example, consider a straightedge being pulled along a planar surface which contains a 1 in. high bump. As the front wheels ride over this 1 in. bump, the indicator, located at the center of the beam, will rise 1/2 in. The device will react by indicating a 1/2 in. depression which does not actually exist located at the scale wheel.

The Mays Ride Meter

The Department uses the Mays Ride Meter to evaluate the roughness of existing pavements. The ride meter measures roughness response by recording the mechanical displacement created by the relative motion between the rear axle and frame of a test vehicle. This mechanical movement is converted into an electrical impulse through a photo-electric cell. The electrical signal is transmitted back into a mechanical movement which is recorded on graph paper. The Mays Ride Meter when installed in a passenger vehicle and operated at traffic velocities supplies a permanent graphical log of roughness summation. All roughness measurements are expressed in units of inches of roughness per mile. Additional information on the Departments calibration and use of the ride meter may be found in a report entitle "The Mays Ride Meter" preparted by the La. Department of Highways, Research and Development Section, Training Unit; 1975.

The ride meter was comparison tested with the profilograph and straightedge on each project.

Site Selection

Sites were selected, based upon availability, to provide a wide range of roughness. New construction did not provide the range of roughness needed, so some older, rougher, projects were included for testing. Both rigid and flexible projects were selected for testing, with an emphasis placed upon rigid pavements due to the semmingly shorter (less than 10 feet) wavelength of as built surface deviations usually encountered. The site selected for the testing of the profilograph mapping ability was chosen for its relative smoothness, its lack of traffic, and its closeness to the research facilities. Testing was accomplished by rolling the profilograph over boards of varied dimensions and spacing to simulate various degrees and types of roughness.

DISCUSSION OF RESULTS

Ease of Transport, Maintenance and Operation

The Rainhart profilograph is easily transported to the test site by trailering on its retractable trailer wheels. Due to its 26 ft. overall length some problems can be expected when towing in tight quarters. The length of the device may also be a problem when manually turning the instrument on roadways that are open to traffic. Caution must be used when turning the profilograph around to keep the end from extending into the lane adjoining the lane being tested.

Maintenance of the profilograph to date has been considerable. Under normal circumstances the only component that should require replacement is the recorder drive string, if it is broken, stretched or loosened. On two occasions, the rear tripod and wheel of the profilograph broke off while being towed to a test site. On one of these occasions the tripod was destroyed when run over by the vehicles following behind. This incident could have, but did not, cause a serious accident in the very heavy interstate traffic. Upon inspection, it was found that the bolt securing the tripod to the minor truss, had fatigued and broken, due to vibration while being towed. The tripod and averaging wheels were replaced by the manufacturer and a safety line is now used between the truss and tripod while the profilograph is being towed. Another maintenance problem that occurred often is that the steering wheel tended to slip on its shaft. This problem was solved by placing a pin through the steering wheels hub and the shaft.

Operating the profilograph has proved to be somewhat difficult. Because of its length and steering mechanism, the profilograph is not very easy to steer. It is difficult to hold a consistent line with the profilograph and it is necessary to make continual steering adjustments. The turning response time is very slow which makes oversteering a continuing problem. The steering is complicated by the relatively short walking space afforded the operator. The operator must take short strides to keep the back of their foot from being struck by the averaging wheel located approximately 3 ft. behind the steering wheel. Because of this, it is difficult for the operator to steer and help push at the same time, necessitating one or two other persons for efficient operation.

Another frequent and annoying problem encountered with the profilograph, involved the recorders chart paper feed and storage mechanisms. The sprockets, which pull the perforated chart paper past the recording pen, failed to release the paper causing it to become fouled between the stripper rod and sprocket. This problem persisted throughout the entire range of feed/tension adjustments and was not solved during this study. Other, less serious problems encountered were, tearing between chart paper perforations by the drive sprockets and failure of the recorder to fold the chart paper after release by the drive sprockets. The Rainhart profilograph utilizes a "Z - fold" chart paper which has a greater potential for feed problems than a rolled chart paper.

When compared to the rolling straightedge, the profilograph is harder to transport and handle during testing, but requires no calibration. If the persistent problems encountered with the recorder can be eliminated, the overall "ease" of maintaining and using the two devices could be considered comparable.

Since the profilograph and the Mays Ride Meter are two entirely different devices, no objective comparison was attempted with the respect to ease of transport, maintenance, etc.

Repeatibility

Selected projects were tested several times. To determine the repeatability of the profilograph roughness measuring system (graphical and digital). Repeat testing was conducted across time periods ranging from several minutes to several months, and using both single and multiple operators.

The graphical output was found to be very repeatable. When graphs of the same project and wheel paths were superimposed and laid on a light table, very little, if any difference between traces could be found. Variation in measuring the roughness (by the Georgia method, Appendix A) has been observed. Repeat measurements by an individual, or between individuals was observed to vary by as much as 3 or 4 inches of roughness per mile. This aspect of repeatability was not evaluated during this study. It is assumed that with practice and experience this variation can be reduced to acceptable levels. Different, less arbitrary methods of interpreting the graphical trace may also be developed. Because of this variation in measuring or interpreting the graphical output no statistical value could be assigned to the repeatability of the trace itself. Only visual observations could be made. Both of the digital roughness counters (1/10 in. filtered and unfiltered) were found to be very unrepeatable. Table 1 on page 15, presents the data obtained during repeatability testing of the profilographs digital counters, along with test section averages and ranges. The range in roughness data produced by the counters was found to be as much as 29.0 inches of roughness per 0.2 mile. The digital roughness counters were considered to be too variable for further use or evaluation during the remainder of this study. This variability is believed to be caused by design/mechanical problems in the counter system.

Other studies (<u>1,2</u>)* conducted in Louisiana found that both the 10 - foot rolling straightedge and Mays Ride Meter have repeatabilities on (on HMAC) within useable limits, if maintained, calibrated and operated properly.

Towards the end of this study the profilograph was taken to Arkansas and tested along with Arkansas' Rainhart profilograph, on one test

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*Underlined numbers in parentheses refer to list of references.

TABLE 1

SUMMARY OF DIGITAL COUNTER DATA

SECTION NUMBER	DATE	OUTSIDE WHEEL PATH INCHES / 0.2 MILE		INSIDE WHEEL PATH INCHES / 0.2 MILE	
		FILTERED	UNFILTERED	FILTERED	UNFILTERED
01	04/26/83	18.3	51.7	15.3	45.4
		19.5	61.0	16.6	51.4
		20.4	65.0	17.3	53.7
	01/03/84	18.1	36.0	13.7	31.1
		17.8	36.2	14.2	31.1
	AVERAGE	18.8	50.0	15.4	42.5
	RANGE	2.6	29.0	3.6	22.6
03	04/08/83	6.5	17.1	9.8	27.9
		9.8	33.7	9.4	36.3
		10.8	37.8		
	04/19/83	10.9		11.7	
		11.8		13.7	
		12.3		14.9	
		14.0		14.0	
	04/25/83	11.6		12.9	
		12.0		13.0	
		13.7		13.4	
	08/23/83	5.5	16.1	6.1	16.2
	01/03/84	9.1	24.4	11.0	31.6
		9.6	27.2	10.4	30.8
	AVERAGE	10.6	26.0	10.8	28.6
	RANGE	8.5	21.7	8.8	20.1
09	03/15/83	5.5	14.7	9.8	26.3
		4.0	11.1	10.0	26.1
		3.3	12.4	7.3	19.2
		4.8	13.5	7.0	15.0
		2.0	5.7	7.8	16.4
	AVERAGE	3.9	11.5	8.4	20.6
	RANGE	3.5	9.0	3.0	11.3
12	06/02/83	19.7	74.3	13.6	46.7
		17.8	70.7	14.1	47.2
		25.8	93.7	14.7	54.1
	AVERAGE	21.1	79.6	14.1	49.3
	RANGE	8.0	23.0	1.1	7.4
13	04/25/83	11.0	43.3	11.1	39.3
		11.4	45.8	11.9	37.7
		12.1	47.7	11.6	38.4
	AVERAGE	11.5	45.6	11.5	38.5
	RANGE	1.1	4.4	0.8	1.6

section. The traces obtained from the two profilographs, when overlaid on a light table, matched almost exactly.

Comparison of Roughness Measure :

A direct numeric relationship between the devices was not expected or achieved because the devices "feel" and measure roughness in different manners. The following is a summary of some of the major differences that affect the roughness measure of the straightedge and profilograph.

1. Wheel Base : The wheel base of the measuring device to some extent determines which wavelengths of roughness (bumps and/or depressions) the device can measure. All normal ranges of wheelbases should be able to measure short, choppy surface deviations above that which is considered macro-texture, but neither type device can measure a deviation whose wavelength exceeds its wheelbase.

The wheelbase of the straightedge is 10 feet. The wheelbase of the profilograph is unknown due to the varied spacing of its 12 averaging wheels.

2. Unit of Measure : The two devices measure different "quantities" of roughness. The straightedge measures the linear footage of tested surface which exceeds a pre-set tolerance level. The profilograph graphically records the vertical deviation and length of each individual bump or depression within the tested length. When the graphical trace is evaluated using the 1/10 in. filter band then the unit of measure is the cumulative vertical inches of deviation of each individual bump or depression that exceed the height of the filter band per mile of surface tested. For example, if both devices were run over a 100 foot long planar surface with two surface deviations, one of which is 1 in. high x 4 ft. long and the other is 1 in. high x 2 ft. long, the following would be measured : The

straightedge (pre-set to 1/8 in. tolerance) theoretically would indicate 4 + 2 feet out of 100 feet or 6 % of the tested surface exceeded the 1/8 in. tolerance. The profilograph, run over the same bumps would theoretically indicate that the 100 foot long test length had 1 and 8/10 inches (1 in. minus 1/10 in. + 1 in. minus 1/10 in.) of roughness.

3. Diameter of Measuring Wheels : The diameter of the wheel which activates the indicator or recorder affects the degree to which the device measures very small surface deviations. A large wheel will tend to "ride over" small depressions while a smaller wheel will tend to "fall in" and measure these same depressions. The measuring wheel of the profilograph is 19 inches in diameter, while the measuring (scale) wheel of the straightedge is 4 inches in diameter.

4. Geometrics : The geometry of the measuring devices has a great influence on the "quantity" of roughness measured. The degree to which the indicator or recorder is shielded from the vertical movement of the traveling wheels is reflected in its roughness measure. For example, when the leading traveling wheels of a 10 ft. rolling straightedge first encounter a 1/2 in. high bump, the pointer on the indicator, which is located 5 ft. behind the front wheels will register the beginning of a 1/4 in. non-existent depression located 5 ft. away from the bump. This is because a 1/2 in. vertical rise of the traveling wheel will cause a 1/4 in. vertical rise of the indicator, creating a false 1/4 in. differential between the recorder and scale wheel. The geometry of the profilograph reduces the tendency of this type of equipment to falsify the location of surface deviation. When the leading traveling (averaging) wheel of the profilograph first encounters the same 1/2 in. bump, the recorder will theoretically registered a non-existent 1/12 of 1/2 in. depression located approximately 12 ft. before the bump. As each of the 12 averaging wheels pass over the bump, a non-existant depression is recorded and located at the various lateral positions of the recorder in relation to bump as measuring wheel/recorder approaches and then leaves to the bump.

This also holds true, but in the opposite sense, when a depression is encountered by either the straightedge or profilograph.

The above discussion does not include the differences in ability to "feel" and measure the pavement surface roughness between the Mays Ride Meter and the two devices which are manually operated, due to the ride meters vastly different design and operational characteristics.

Table 2 on page 19 presents the test results obtained during comparison testing of flexible and rigid pavements with the straightedge, ride meter and profilograph.

Regression techniques by a SAS (Statistical Analysis System) procedure were utilized to correlate the data obtained during this study. Table 3 on page 20 presents the results of this regression.

TABLE 2

COMPARISON TESTING DATA

HMAC TEST SECTIONS

TEST SECTION NUMBER	STRAIGHTEDGE % OVER 1/8" TOLERANCE	RIDE METER SI	PROFILOGRAPH IN / MILE
34	0.00	4.7	2.25
35	0.70	4.6	2.50
28	0.00	4.4	8.12
27	0.10	4.3	8.25
30	1.70	4.0	9.75
29	1.20	3.9	11.12
32	2.50	3.6	13.62
33	3.60	3.4	16.75
31	4.50	3.1	17.50

PCCP TEST SECTIONS

TEST SECTION NUMBER	STRAIGHTEDGE % OVER 1/8" TOLERANCE	RIDE METER SI	PROFILOGRAPH IN / MILE
17	0.55	4.6	13.50
18	0.50	4.5	15.60
26	0.60	4.4	13.75
40	1.20	4.2	**
41	1.30	4.2	**
38	1.60	4.2	**
37	1.90	4.2	**
39	1.20	4.0	**
12	3.80	4.0	*
23	2.00	4.0	29.50
24	2.80	4.0	38.13
25	2.60	4.0	29.25
03	1.70	3.9	23.50
08	4.50	3.9	*
13	1.00	3.9	*
43	1.20	3.8	**
09	2.20	3.7	*
21	7.20	3.6	39.87
19	7.40	3.5	51.87
20	6.00	3.5	43.50
36	4.50	3.5	**
06	7.70	3.4	*
22	7.40	3.4	46.63
04	7.00	3.2	*
07	8.90	3.2	*
42	6.80	3.1	**
05	7.60	3.0	*
10	11.20	2.8	61.00
01	17.33	2.6	60.50
16	12.90	2.6	66.50
14	30.00	2.3	*
15	16.40	2.2	85.00
02	23.20	2.0	78.37
11	44.00	2.0	*

** - NO PROFILOGRAPH RUN
* - NO GRAPHICAL OUTPUT OBTAINED

TABLE 3

Summary of Regression Analysis

Devices Compared	Surface Type	Equation of Best Fit Curve
Straightedge	JCP	$\text{In.} = 440.4 \times e^{(-1.311 \times \text{SI})}$ R squared = 0.83, C.V. = 49.04
vs.		
Mays	HMAC	$\text{In.} = 145.7 \times e^{(-1.152 \times \text{SI})}$ R squared = 0.99, C.V. = 14.92
Straightedge	JCP	$\% = 10^{(-2.27 + 1.852 \times \text{Log In.})}$ R squared = 0.89, C.V. = 27.90
vs.		
Profilograph	HMAC	$\% = 202.70 \times e^{(-6.133 + 0.117 \times \text{In.})}$ R squared = 0.99, C.V. = 14.92
Profilograph	JCP	$\text{In.} = 136.93 - 26.895 \times \text{SI.}$ R squared = 0.95, C.V. = 11.95
vs.		
Mays	HMAC	$\text{In.} = 49.47 - 9.866 \times \text{SI.}$ R squared = 0.98, C.V. = 9.80

SI. = Serviceability index (ride meter)

% = lineal % exceeding 1/8 in. tolerance (straightedge)

In. = inches/mile (profilograph)

Table 4 , on page 22, is a listing of the relative rankings (from smoothest to roughest) of the HMAC and PCCP test sections as determined by the three devices. For the HMAC test sections, the ride meter and the profilograph both rank all sections equally. The straightedge does not rank the sections in the same order as do the two devices, but does maintain the same relative ranking of smooth to rough sections. For the PCCP sections there are no two devices that consistantly rank the test sections equally, but as with the straightedge on the HMAC sections, a relativity of roughness ranking does exist between all three devices. In other words, all devices equally rank the same test sections as being relatively smooth, moderate or rough.

Surface Profiling (Mapping) Ability :

An evaluation of the ability of the profilograph to actually "map" the pavement surface profile was included to compare measured and known profiles. This portion of the study was conducted by Department personnel in cooperation with a study for a Masters Thesis by Cox, D.O.(3). The portion of this thesis concerning the mapping ability of the profilograph is reproduced in this report in Appendix B. Appendix B can be found beginning on page 41 of this report.

The surface profiling or mapping ability of the Rainhart profilograph was evaluated by testing the profilograph on a pavement surface containing induced roughness. A HMAC shoulder on a newly con-constructed roadway was selected as a test section. This test section was selected for its relative smoothness, lack of traffic and convenient locale. Roughness on this test section was induced by using full sheets of plywood laid upon the shoulder surface in various configurations. A baseline graphical trace of the HMAC shoulder was obtained by operating the profilograph over the 500 ft. test section without induced roughness. Graphs were obtained for the ten separate induced roughness test patterns which were set-up within the 500 ft. test section. The physical location and

TABLE 4

RELATIVE RANKINGS OF TEST SECTIONS

HMAC TEST SECTIONS

RANKING (SMOOTH TO ROUGH)	TEST SECTIONS		
	STRAIGHTEDGE	RIDE METER	PROFILOGRAPH
1	34	34	34
2	28	35	35
3	35	27	27
4	35	27	27
5	29	30	30
6	30	29	29
7	32	32	32
8	33	33	33
9	31	31	31

PCCP TEST SECTIONS

RANKING (SMOOTH TO ROUGH)	TEST SECTIONS		
	STRAIGHTEDGE	RIDE METER	PROFILOGRAPH
1	18	17	17
2	17	18	26
3	26	26	18
4	03	23	03
5	23	24	25
6	25	25	23
7	24	03	24
8	20	21	21
9	21	19	20
10	22	20	22
11	19	22	19
12	10	10	01
13	16	01	10
14	15	16	16
15	01	15	02
16	02	02	15

dimensions of the induced roughness was documented to enable accurate comparison to the graphical trace.

The results obtained during this portion of the study can be summarized as follows :

1. The profilograph accurately located the longitudinal position of the induced roughness where the wavelength of the roughness was less than the wheel base of the profilograph.

2. The profilograph does not accurately locate the longitudinal position of the induced roughness when the wavelength of the roughness approaches or exceeds the wheelbase length of the profilograph.

3. The profilograph closely approximates the actual vertical dimensions of the induced roughness, when the wavelength of the roughness is less than the wheelbase of the profilograph.

4. When the graphical trace is evaluated using the 0.1 inch filter band, the additional inches of roughness indicated above that of the baseline graph, closely approximates the inches of roughness actually added (induced).

5. The filter band tends to discount the majority of the "false" portion of the graphical trace. The false portions of the trace were expected due to the geometrics of the device.

As stated above the profilograph was able to graph the position and vertical dimension of the induced roughness. This is true only to the extent of the users ability to interpret the trace. In the induced roughness testing and evaluation, the interpretation of the trace was greatly enhanced by having a baseline trace, knowing the locations and dimensions of the boards and knowing where the profilograph first encountered and then left the artificial roughness.

Without this additional information, the profilograph mapping ability or rather the degree to which the user can interpret or use its mapping ability is reduced. As indicated earlier in this report, the geometrics of the profilograph somewhat inhibits a "true" mapping ability. The graphical trace output of the profilograph does not present the actual surface profile of the roadway but can be used to accurately identify the position and vertical magnitude of the intermediate and large bumps or depressions which cause the major decrease in ride quality. Small bumps intermixed within larger undulations may or may not be identifiable.

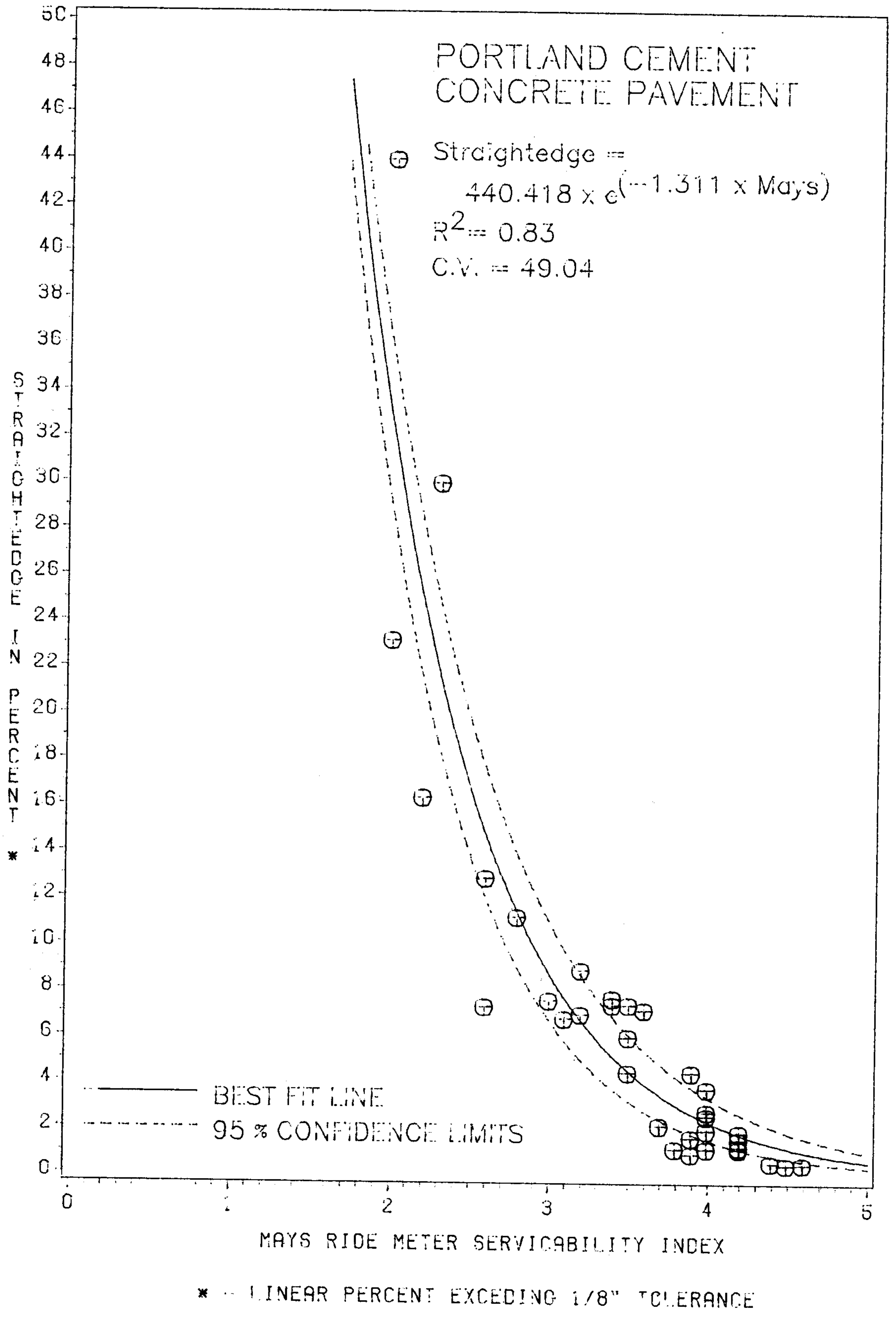
Applicability of Profilograph as a Quality Control and Acceptance Tool :

Louisiana currently specifies the 10-foot rolling straightedge as its quality control and acceptance tool. At the time this study was conducted requirements for mainline concrete pavements were that no more than 6 % of each lot tested could exceed the 1/8 in. high/low tolerance. Lots that exceeded this 6 % limit or had any vertical deviation in excess of 1/4 in. were subject to pay penalties and/or corrective measures. Current requirements for mainline PCC pavements are that 0.0% of each lot can exceed the 1/8 in. tolerance. Current reuirements for mainline HMAC pavements are that no more than 1% of each lot tested can exceed the 1/8 in. high/low tolerance. Lots that exceed this 1% limit or have any vertical deviation in excess of 1/4 in. are subject to pay penalties and/or corrective measures. The straightedge is run in each wheelpath in each lane for concrete and along a single longitudinal path in each lane for HMAC pavements.

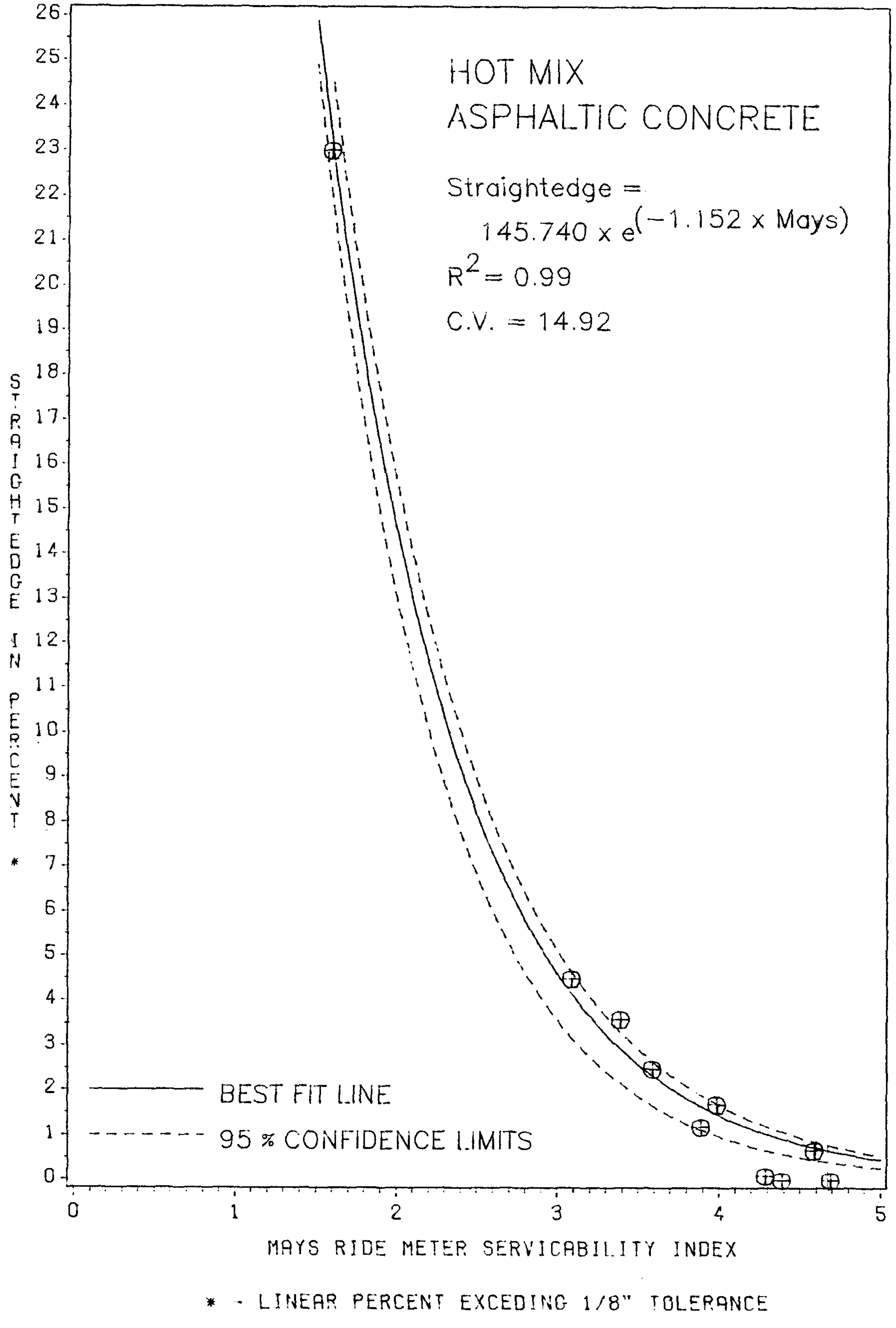
The Mays Ride Meter, being housed in a vehicle, cannot be used for timely quality control on green concrete. Louisiana uses the ride meter for survey and management purposes.

Figures 4,5,6,7,8, and 9 on pages 26 through 31, are plots of the data obtained from comparison testing of the three roughness measuring devices. Included in these plots is the best fit curve, as determined by the SAS procedures for regression analysis, for each pavement type. From a comparison of these plots, for concrete pavements, it can be seen that the 6% (allowable straightedge) limit is approximately equal to 44 in/mile (profilograph) which is approximately equal to a SI of 3.4 (ride meter). By updating tolerance requirements to 0.0% of the lot allowed to exceed 1/8 in. SI levels of 4.5 may be achieved. For the HMAC surfaces, the same comparison, indicates that the 1% (allowable straightedge) limit is approximately equal to 6 in/mile (profilograph), which is approximately equal to a SI of 4.4.

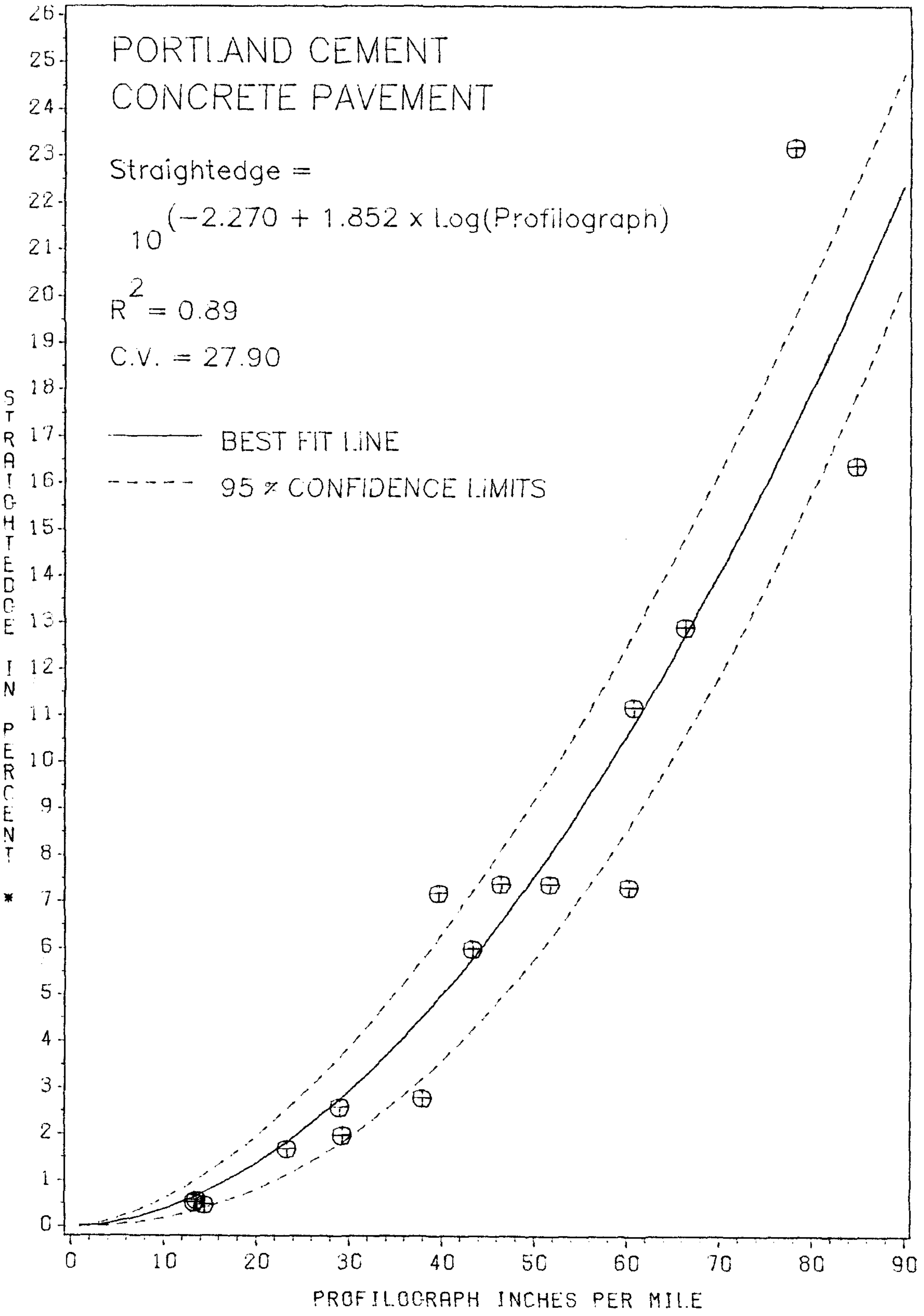
As indicated previously both the straightedge and profilograph tend to distort the accurate measurement of roughness. As long as this distortion is realized and accounted for, the profilograph, as is the straightedge, is suitable for quality control and acceptance of newly constructed pavements.



Graph of Best Fit Curve
(Straightedge vs. Mays Ride Meter) PCC
FIGURE 4



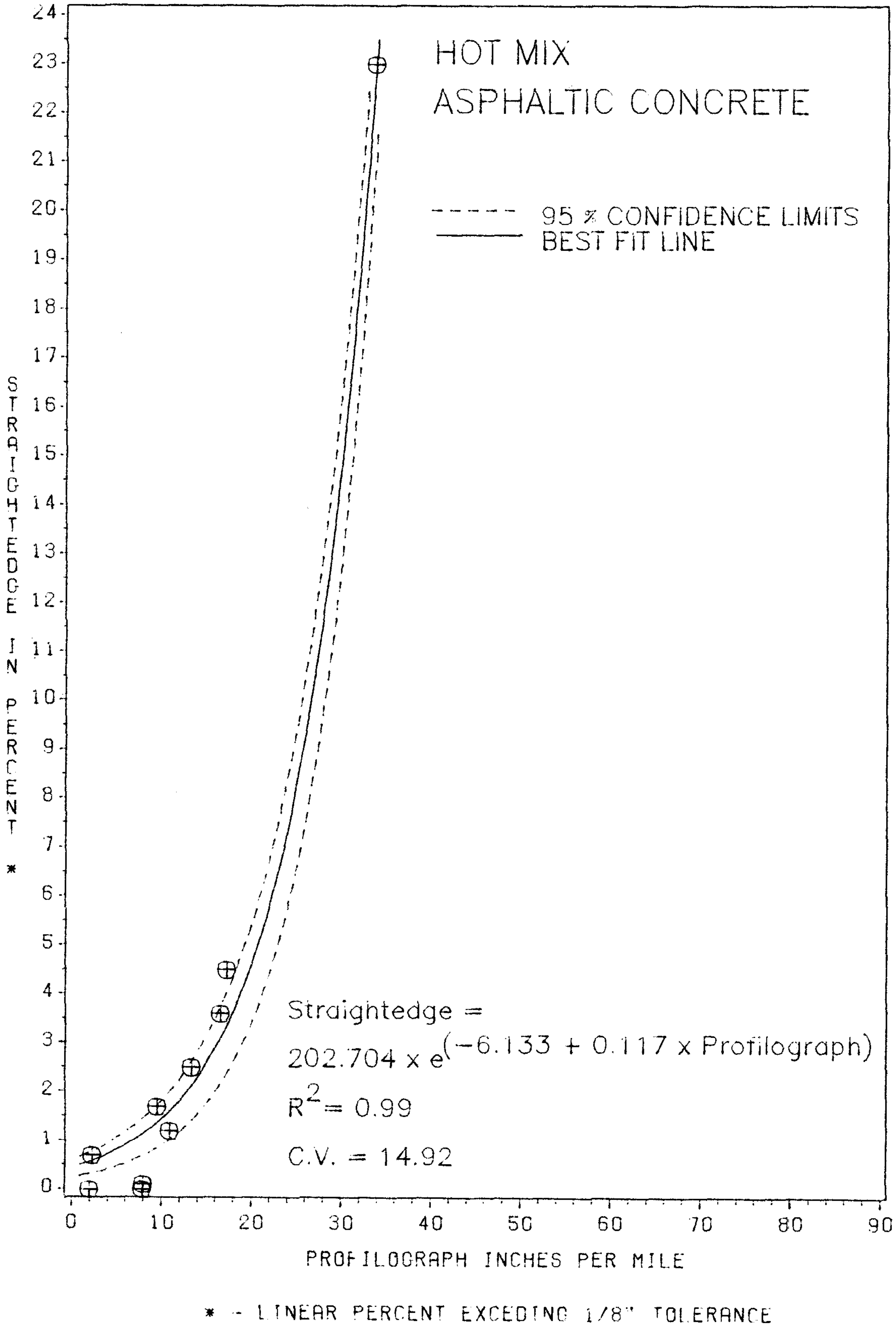
Graph of Best Fit Curve
(Straightedge vs. Mays Ride Meter) HMAC
FIGURE 5



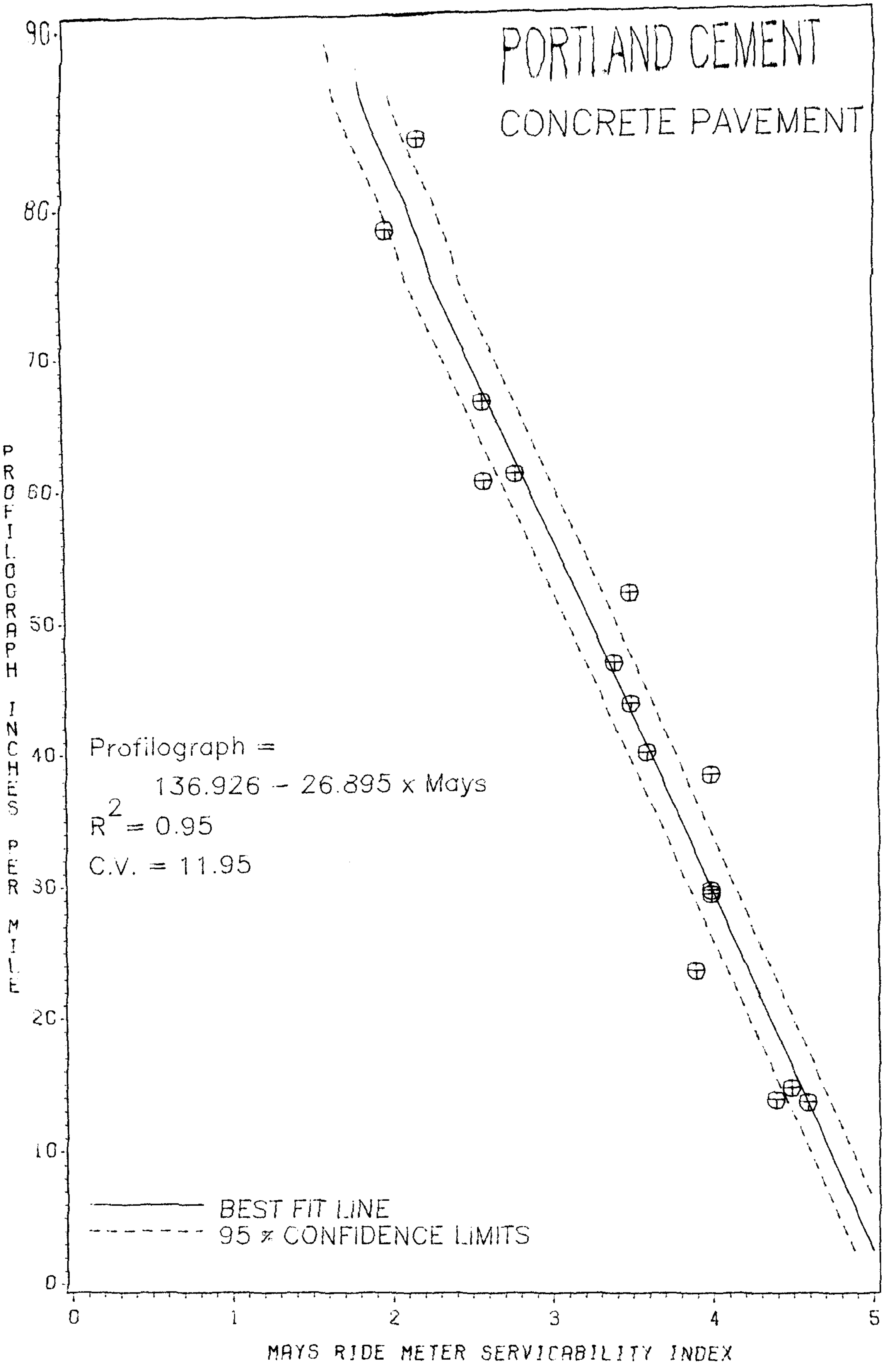
* - LINEAR PERCENT EXCEDING 1/8" TOLERANCE

Graph of Best Fit Curve (Straightedge vs. Profilograph) PCC

FIGURE 6



Graph of Best Fit Curve
(Straightedge vs. Profilograph) HMAC
FIGURE 7



Graph of Best Fit Curve
(Profilograph vs. Mays Ride Meter) PCC

FIGURE 8

CONCLUSIONS

The following conclusions are based upon the observations made and data obtained during the course of this study :

1. The profilograph can be considered unwieldy during testing and requires frequent maintenance but is easily transported and needs no calibration.

2. The strip chart recorder did not feed or store the chart paper properly during testing. Improvement in this area could be obtained by replacing the "Z fold" paper with rolled paper, as utilized by the California style profilograph.

3. The profilograph digital recording of roughness is not repeatable. The graphical trace of roughness is very repeatable but the interpretation (measure) of this trace is not as repeatable.

4. The graphical trace of the surface profile as indicated by two Rainhart profilographs matched each other during very limited testing.

5. The profilograph does not accurately "map" the pavement surface profile. It does however properly identify the location and magnitude of intermediate and large bumps/depressions when their wavelengths are less than the wheelbase length of the profilograph. Mapping and identification of large wavelength and/or small vertical dimension roughness is restricted due to the geometrics of the profilograph.

6. On PCC pavements, the profilograph may be better suited to enable more accurate measurement of roughness than the straightedge.

7. On HMAC pavements, no particular advantage in ability to measure the as built (long wavelength) roughness, was indicated by the profilograph, straightedge or ride meter.

8. The profilograph, with some minor modifications (steering, paper feed), could be a useful quality control and acceptance tool.

RECOMMENDATIONS

Although the profilograph may be better suited to enable more accurate measurement of roughness that the straightedge, consideration should not be given at this time to replacing the straightedge with a profilograph as LA.DOTD acceptance tool for PCC pavements. Consideration to replacing the straightedge with a profilograph type device should only be given at such a time that problems experienced with the interpretation and measurement of the graphical trace are remedied.

LIST OF REFERENCES

1. Law S.M., Rolling Straightedge Correlation Study, Louisiana Department of Highways, Research Report No. , June 1967.

2. Shah S.C., Correlation of Various Smoothness Measuring Systems for Asphaltic Concrete Surfaces, Louisiana Department of Highways, Research Report No. , June 1974

3. Cox, D.O., Applicability of the Rainhart Profilograph as a Specification Tool for Louisiana Pavements, Louisiana State University, Master's Thesis, December 1984.

APPENDIX A

GEORGIA HIGHWAY DEPARTMENT TEST METHOD G.H.D. 78

GHD-78

METHOD OF TEST FOR DETERMINING PROFILE INDEX VALUE

A. SCOPE: This method describes the procedure used for determining the Profile Index from profilograms of pavements made with the Rainhart type profilograph.

The profilogram is recorded on a scale of one-inch equal to 25 feet longitudinally and full scale vertically. The determination of the Profile Index involves measuring "scallops" that appear outside a "blanking" band.

B. EQUIPMENT:

The only special equipment needed to determine the Profile Index is a clear plastic scale 1.50 inches wide and 11.0 inches long. Near the center of the scale is an opaque band 0.1 inch wide extending the entire length of 11.0 inches. On either side of this band are scribed lines 0.1 inch apart, parrallel to the opaque band. These lines serve as a convenient scale to measure deviations of the graph above or below the blanking band. These are called "scallops."

C. PROCEDURES:

Place the plastic scale over the profile in such a way as to "blank out" as much of the profile as possible. When this is done, scallops above and below the blanking band will be approximately balanced. See Figure I.

The profile trace will move from a generally horizontal position when going around super-elevated curves, making it impossible to blank out the central portion of the trace without shifting the scale. When such conditions occur the profile should be broken into short sections and the blanking band repositioned on each section. See Figure II.

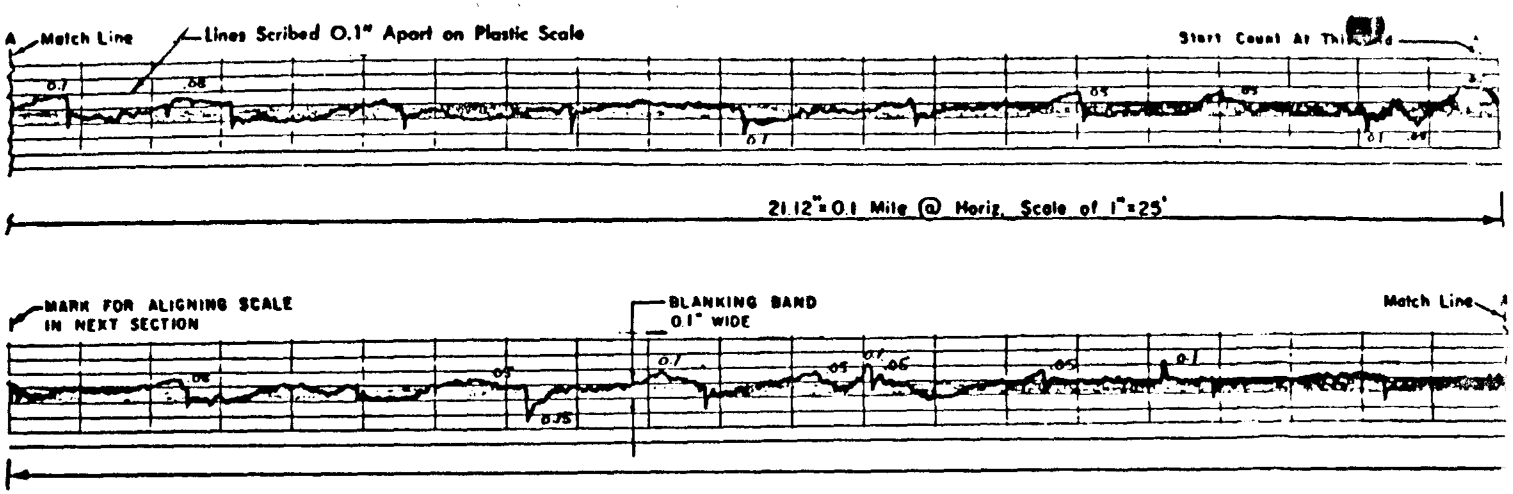
Beginning at the right end of the scale, measure and total the height of all the scallops appearing both above and below the blanking band. Each scallop is to be measured to the nearest 0.05 inch (half a tenth.) Short portions of the profile line may be visible outside the blanking band, but unless they project 0.03 inch or more and extend longitudinally for two feet (0.08 inch on the profilogram) or more, they are not included in the count. See Figure I for special conditions.

When scallops occuring in the first scale length are totaled, slide the scale to the left aligning the right end of the scale with a small mark made at the end of the first scale length.

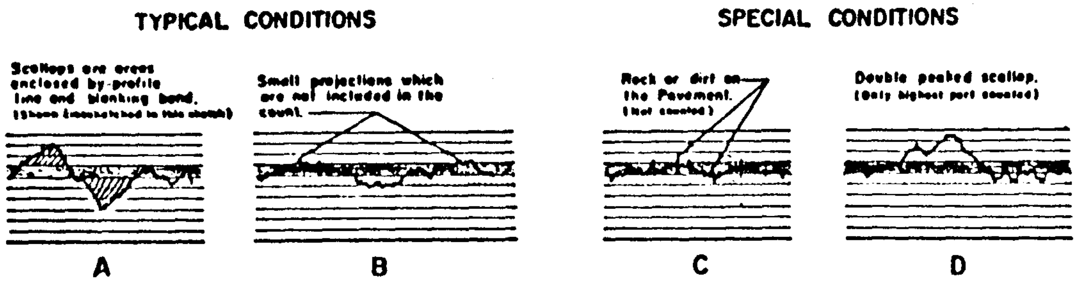
D. CALCULATIONS:

The Profile Index is determined as "inches per mile in excess of the 0.1 inch blanking band." The formula for calculating Profile Index is as follows:

$$\text{Profile Index} = \frac{\text{1 mile}}{\text{length of section in miles}} \quad \text{X} \quad \text{total count in inches}$$



Total count for this 0.1 mile section is 13 tenths of an inch, or 13.0 inches per mile.



EXAMPLE SHOWING METHOD OF DERIVING PROFILE INDEX FROM PROFILOGRAMS

FIGURE 1

METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION

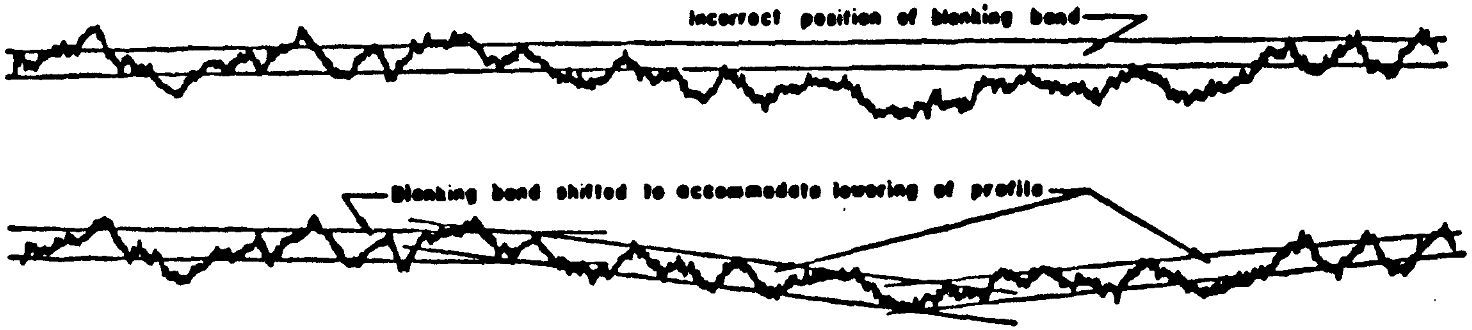


FIGURE 2

APPENDIX B

APPLICABILITY OF THE RAINHART PROFILOGRAPH AS A SPECIFICATION TOOL FOR LOUISIANA PAVEMENTS

(PARTIAL REPRODUCTION -- MASTERS THESIS)

APPENDIX B

APPLICABILITY OF THE RAINHART PROFILOGRAPH AS A SPECIFICATION TOOL FOR LOUISIANA PAVEMENTS

(PARTIAL REPRODUCTION)

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

In

The Department of Civil Engineering

By
David Oren Cox
B.S., Oregon State University, 1970
December 1984

APPLICABILITY OF THE RAINHART PROFILOGRAPH
AS A SPECIFICATION TOOL FOR
LOUISIANA PAVEMENTS

(PARTIAL REPRODUCTION)

Induced Roughness Tests

Having demonstrated the graphical repeatability of the Rainhart both over a substantial period of time and through a variety of variables, the results of this first group of tests were then used as a base value upon which to judge the results of a second series of tests.

This second series of tests has been identified as the "Induced Roughness" tests. These tests were designed to evaluate the ability of the Rainhart to accurately determine known values of roughness in a wide variety of situations. The tests were structured in such a manner as to subject the machine to numerous roughness patterns and different size deviations in an attempt to determine the accuracy of both the digital and the graphical outputs. These roughness patterns were chosen to approximate either those which may occur during construction or which might be present in a pavement being evaluated for rehabilitation.

The tests were conducted at the same Thompson Creek site described earlier, but this time bumps and depressions in the pavement profile were artificially created using pieces of plywood and masonite. These sheets of plywood were 8 feet long and 4 feet wide with thicknesses ranging in 1/8-inch increments from 1/8 inch to 1 inch. They were placed on the pavement surface with the long axis perpendicular to the test centerline so that each deviation was shown on the profile as being 4 feet long. This 4-foot deviation size was purposely chosen as being representative of actual field conditions as previous research has shown that the common size of a surface profile deviation is between 4 and 6 feet long for many types of paving methods and equipment.[5]

It was originally thought that these artificial deviations would have to be physically secured to the pavement to prevent movement during testing. However, preliminary tests showed that this was not necessary and instead, where

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[5] Shah, S. C., A Correlation of Various Smoothness Measuring Systems for Asphaltic Concrete Surfaces, Louisiana Highway Research and Development Section, 1974.

additional support was necessary, the individual boards were held in place by weighting them with sandbags.

This series of tests encompasses ten different test patterns which were established to represent roughness situations with varying deviation sizes, a range of deviation spacings, differing deviation amplitudes and lengths, and includes both positive (bumps) and negative (holes) deviations (see Appendix C). Each test pattern was run twice as a further test of repeatability under these extreme test conditions.

These induced roughness tests are discussed below either individually or, where appropriate, in similar groups. All of these tests were conducted in June of 1984. In an attempt to minimize the effects of the change in the digital readings over time, the digital readings obtained during these tests are compared only to those control readings obtained in May 1984. However, the graphical results are compared to the average of the entire series of graphical control tests.

Induced Roughness Test No. 1

The purpose of this test was to determine the response of the profilograph to deviations of a known height encountered on an individual basis. The test was also intended to measure the accuracy of the graphical display both vertically and longitudinally as well as to give an indication of the accuracy of the 0.1-inch digital filter.

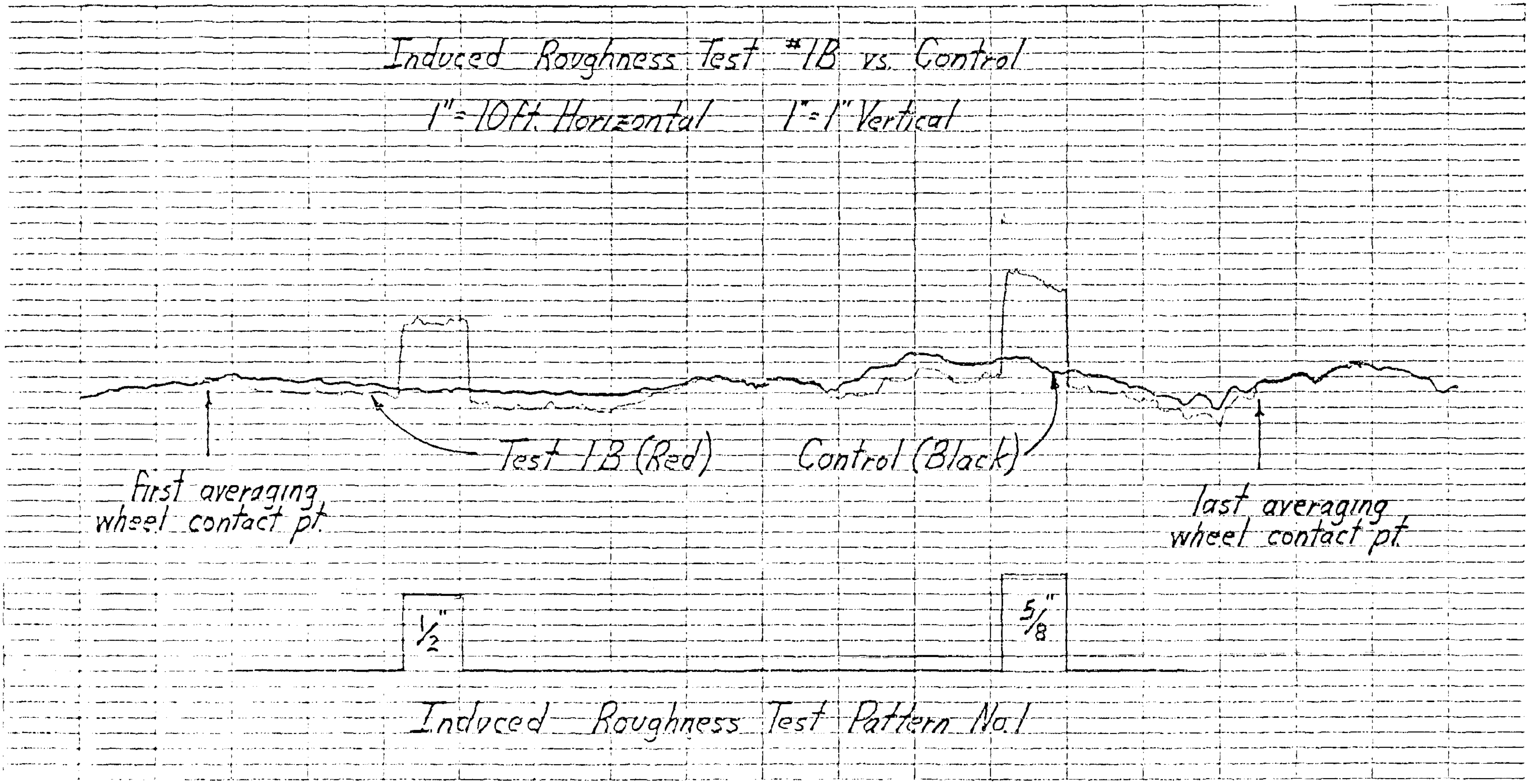
In all a total of 1.75 inches of induced roughness was added to the test section at five different locations. The individual deviations varied in height from 1/8 inch to 5/8 inch and were spaced widely enough so that all the wheels of the profilograph could traverse one deviation prior to encountering the next.

Results - Test No. 1

The graphical display successfully plotted the beginning and ending location of each deviation with an accuracy of ± 0.5 foot. The width of these four-foot deviations was shown graphically as being 4 feet at the top of the vertical display but as varying between 4 and 5 feet wide at the bottom of this display.

Vertically, the height of the deviations was accurately displayed within 1/16 inch of the actual height of the deviation even for the 5/8-inch board. It was noted on the graph that the profile in the vicinity of the 5/8-inch board was shown to be as much as 1/10 inch lower than its actual location as depicted on the control profiles (see Figure 9). This is a good illustration of the effects of the averaging wheels. When the averaging wheels in advance of the measuring wheel encounter a high spot in the pavement, they lift the platform or frame of the profilograph which in turn causes the measuring wheel to give a false indication of a

Figure No. 9


Induced Roughness Test #1B vs. Control
1" = 10 ft. Horizontal   1" = 1" Vertical
Test 1B (Red)
Control (Black)
first averaging wheel contact pt.
last averaging wheel contact pt.
1/2"
5/8"
Induced Roughness Test Pattern No. 1

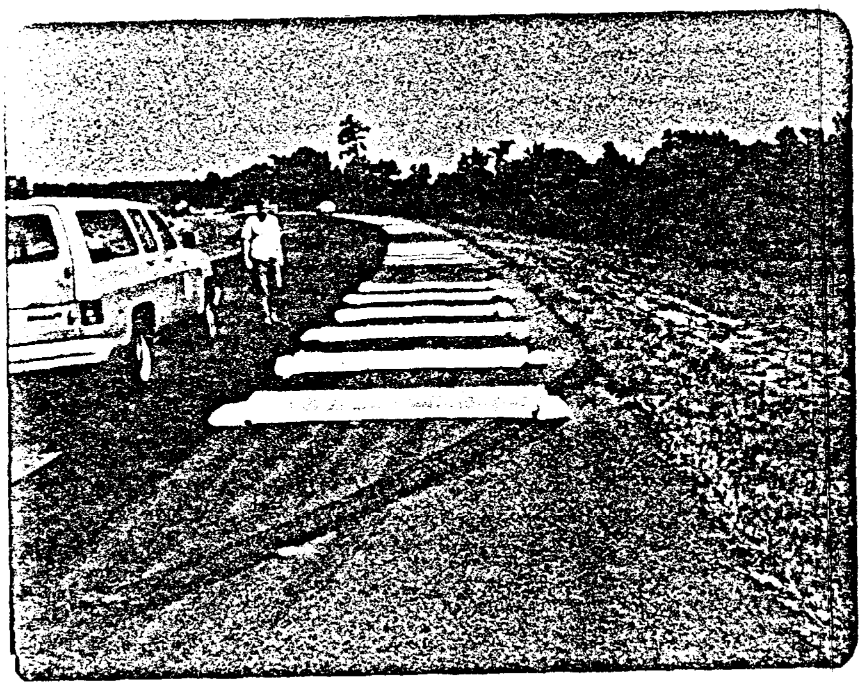
depression on the graph. In this test a maximum of two averaging wheels was always on the four-foot-wide board. Thus for the 5/8-inch board this false depression should have been shown as 5/8" x 2(1/12) or approximately 0.1", almost precisely its actual measurement.

The digital recorder showed the section to contain 7.02 total inches of roughness and 4.05 inches using the 1/10-inch filter, an increase of approximately 3.25 total inches and 2.1 filtered inches as compared to the actual addition of 1.75 inches of roughness. Thus, both of the digital displays overstated the actual increase in roughness. The graphical methods also overstated the increase in roughness, showing the addition of approximately 2.1 inches.

Induced Roughness Tests No. 2 and No. 3

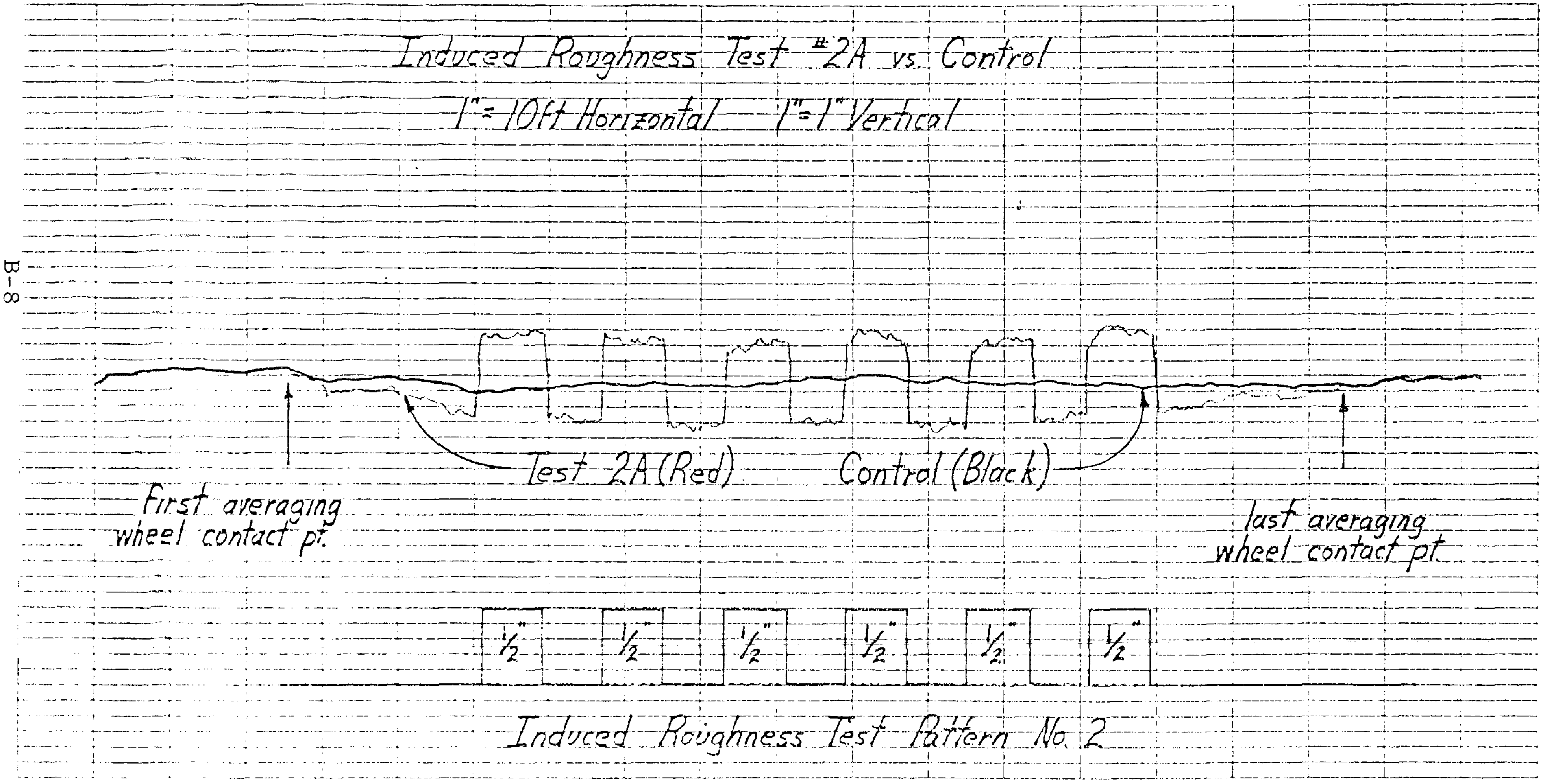
The purpose of these tests was to determine the response of the profilograph to a series of grouped deviations. As in the previous test, these deviations range from 1/8 inch to 5/8 inch in height in 1/8-inch increments. However, in these tests six deviations of each height, each four feet wide, were spaced in a group with four feet between deviations. This resulted in several test patterns each 44 feet in length, a distance sufficiently long so as to engage all of the averaging wheels at the same time. The individual groups of deviations were however, sufficiently separated so as to allow the profilograph to completely disengage from one set

FIGURE 10



INDUCED ROUGHNESS TEST PATTERN NO. 2

Figure No. 11


Induced Roughness Test #2A vs. Control
1" = 10ft Horizontal 1" = 1" Vertical
Test 2A (Red)
Control (Black)
First averaging wheel contact pt.
last averaging wheel contact pt.
1/2"
1/2"
1/2"
1/2"
1/2"
1/2"
Induced Roughness Test Pattern No. 2

prior to encountering the next set (see Figure 10).

In both tests No. 2 and No. 3 a total of 7.5 inches of induced roughness was added to the control section. However, test pattern No. 2 contained a set of six 1/8-inch boards while the smallest boards used in the third test pattern were 1/4 inch high. Thus presumably the unfiltered roughness of both runs should have been the same while it would be expected that the filtered readings would be lower for test No. 2 than test No. 3.

Results - Tests No. 2 and No. 3

Again it is clear that the profilograph very accurately located the longitudinal position of the test bumps, in all cases plotting them graphically within 0.5 foot of their measured location. The overall height of the bumps, that is the size of the vertical deviations, was also shown quite accurately especially for the 1/8-inch and 1/4-inch groups. In the larger groups, the vertical height of the deviation as measured from the graphical output, ranged from 0.05 inch to 0.15 inch larger than the actual height of the deviations.

The effects of the averaging wheels was again revealed when comparing the induced roughness graphs to the control graphs at the same location. From the point at which the first averaging wheels of the profilograph engage the first raised board the roadway profile is shown as steadily descending from its "true" position. This continues to the point where the measuring wheel encounters that first bump, at which point this "depression" is approximately one-fourth the height of the board. This "depressed" reading for the original ground continues as the profilograph continues across the raised boards. Near the center of the set, where the averaging wheels are equally divided between those supported by the raised deviations and those supported by the original ground, the "depressions" are shown to actually descend as far below the true grade as the projections are shown to raise above it (see Figure 11). As might be expected, when the averaging wheels begin to exit from the raised boards, the elevation of the "original ground" indication also begins to raise again until it returns to its true position when the last averaging wheel leaves the last board.

As predicted, the filtered readout of the test No. 2 run was lower than that of test No. 3. In fact, the average filtered readout of run No. 2 was approximately 0.7 inch lower than that of the third run. It is presumed that this is primarily due to the fact that the six 1/8-inch boards are just barely discernible above the 1/10-inch filter in the second run, while the third run contained none of the smaller 1/8-inch deviations. However, the unfiltered readings of the third run are also lower than the unfiltered readings of the second run. This discrepancy between the unfiltered readings can probably be attributed to the previously discussed tendency of the profilograph to exaggerate the height of the deviations in excess of 1/4 inch high which were more numerous in the third test pattern than in the second.

A comparison was made between the graphical display of the grouped boards to the graphical display of single boards of the same height. This revealed that the 1/8-inch deviations were shown in a virtually identical manner whether encountered singly or in a group. The 1/4-inch deviations were consistently shown to be slightly larger than 1/4 inch (approximately 0.3 inch) when in a group except for the last deviation of those six encountered by the profilograph. This was almost identical to the display of the single 1/4-inch deviation and was shown accurately to be 0.25 inch high. The grouped 3/8-inch boards were almost identical in size and height to the single 3/8-inch board, but both displays measure approximately 0.425 inch high as opposed to the actual 0.375-inch height. However, it should be noted that the original ground at the site of the 3/8-inch group was quite rough, making comparisons difficult. The 1/2-inch display compared in a manner very similar to the 1/4-inch display with the individuals in the grouped set being shown on an average as approximately 0.1 inch higher than they actually are.

As stated earlier, in each test a total of 7.5 inches of induced roughness was added to the control section. Yet, the unfiltered digital readout exceeded the average control value by approximately 11.6 inches for test No. 2 and a surprisingly high 13 inches for test No. 3. The 0.1-inch filtered digital readout exceeded the control average by approximately 9 inches in test No. 2 and 9.7 inches in test No. 3. Finally, the graphical display was rated by the 0.1-inch blanking band to have increased 7.25 inches for test No. 2 and 7.65 inches for test No. 3.

As with test No. 1, both digital readouts for tests No. 2 and No. 3 greatly exaggerated the actual roughness contained in the test sections, the worst of these being the unfiltered readouts which indicated an average of 64% more roughness than was actually present. The filtered readings did better but were themselves approximately 25% above the actual roughness. Only the graphical calculations accurately indicated the total amount of induced roughness, showing that an average of 7.45 inches or 99% of the actual value was added to the test course.

The fact that the graphical blanking band calculations are so close to reality in these tests was unexpected. After all, the blanking band actually subtracts 0.1 inch from the roughness of each deviation. However, this subtracted 0.1 inch appears to have been almost exactly replaced by the exaggerated height which is shown graphically for the deviations over 1/4 inch high. This unexpected coincidence increases the credibility of this method of calculating roughness and offers an added reason for using the 0.1-inch blanking band instead of the 0.2-inch blanking band.

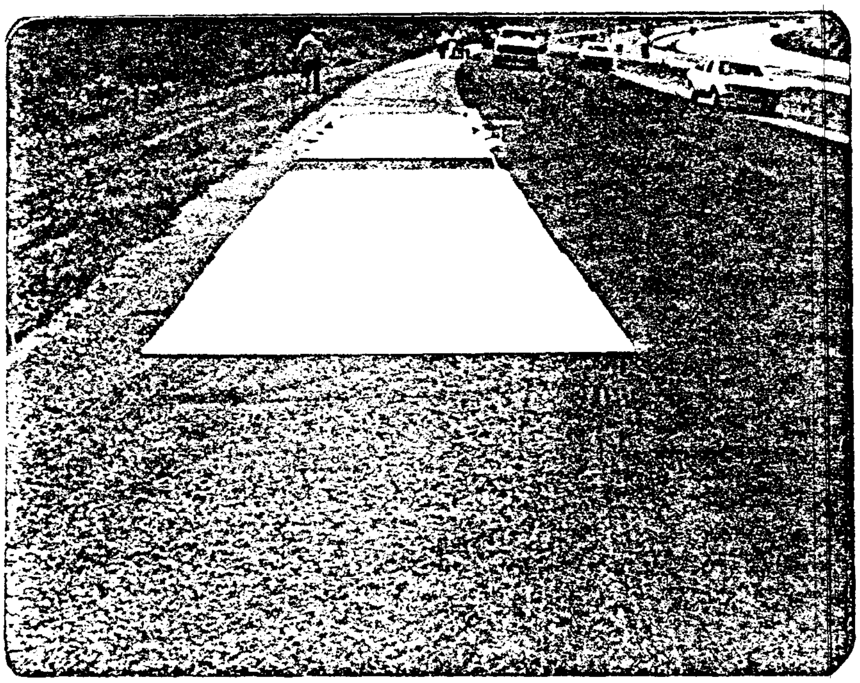
Induced Roughness Tests No. 4, No. 5 and No. 6

The purpose of these tests was to determine the response of the profilograph to a simulated depression in the pavement surface. This depression was constructed of boards laid edge to edge for a total distance of 24 feet. This elevated pattern was followed by a four-foot section of original ground, which in turn was followed by another 24-foot section of boards laid end to end. Test run No. 4 was constructed using 3/8-inch-thick boards, test No. 5 used 1/2-inch boards, and test No. 6 used 5/8-inch boards. Thus, a "hole" four feet wide and either 3/8, 1/2 or 5/8 inch deep was simulated between these two raised surfaces (see Figure 12). In all a total of 0.75 inch of induced roughness was added to the test section in run No. 4, 1.0 inch in run No. 5 and 1.25 inches in run No. 6.

Results - Test No. 4

Again, the graphical plot was extremely accurate in locating the longitudinal position or "station" of the test boards. The most interesting feature in this regard was the width of the 4-foot gap which was shown to be exactly 4 feet at the top of the "hole" but quickly tapered to near 3-1/2 feet at the bottom of the "hole." This is in stark contrast to the

FIGURE 12

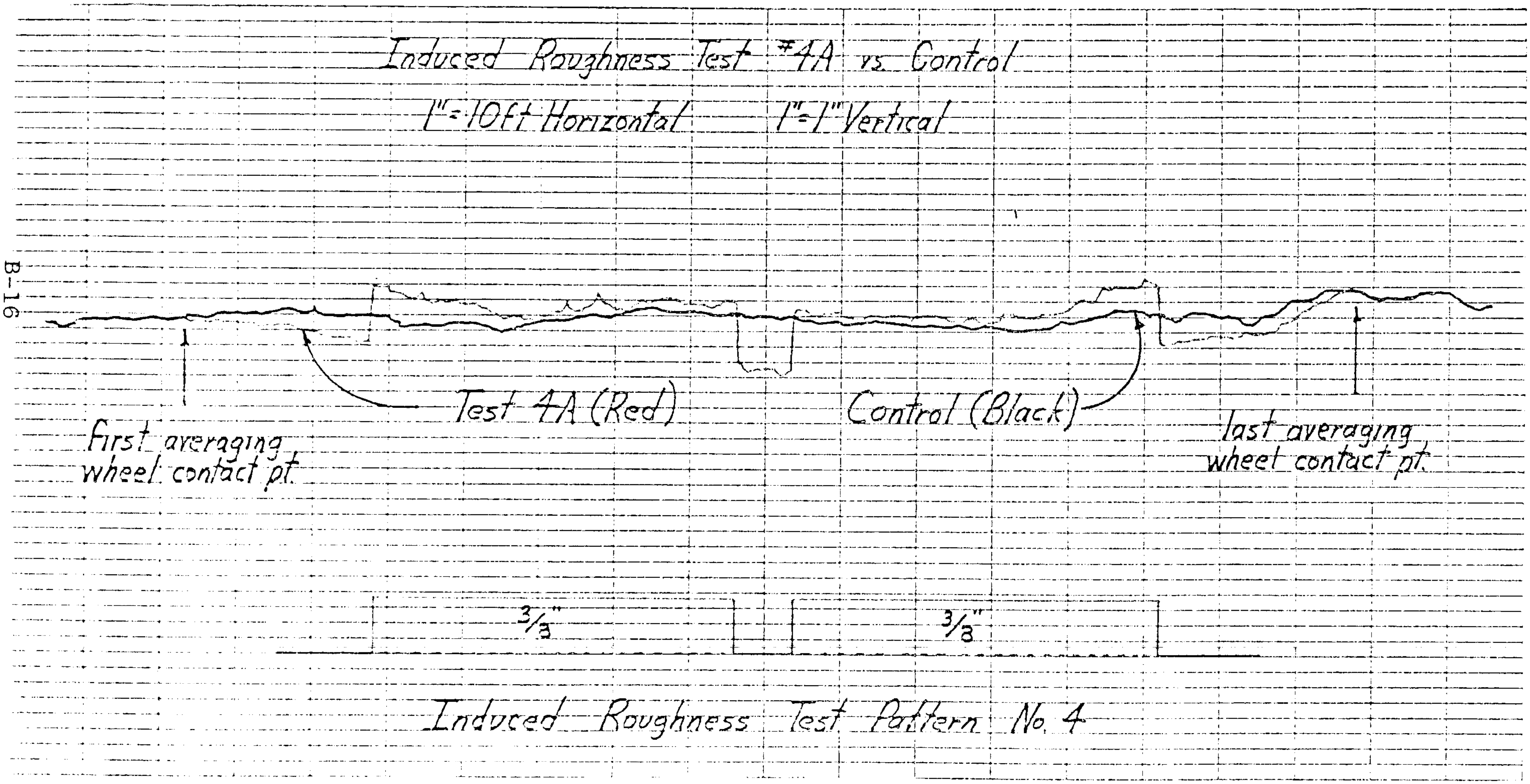


INDUCED ROUGHNESS TEST PATTERN NO. 6

induced "bumps" which were shown graphically to be approximately 1/2 foot wider at the bottom than they are at the top. However, in both cases the true or actual dimension is the reading taken at the high point on the graph. Each of the three tests in this group are discussed below. One of the most interesting features of test No. 4 can be seen when the "hole" is isolated from the remainder of the display. The depth of this 3/8-inch hole is then measured on the graph paper to be 0.45 inch deep, slightly more than its actual dimension. However, when plotted against the graph of the original ground at this location, the picture is further distorted from the actual condition (see Figure 13).

As the profilograph mounts the first 3/8-inch plateau with the first averaging wheel the graph begins a steady fall from the position of the actual ground until, at the point the measuring wheel encounters the plateau, it is approximately 0.2 inch below natural ground (approximately one-half the depicted height of the plateau). This is the same phenomenon described in tests No. 2 and No. 3 and is consistent with the averaging tendencies of the profilograph. Then, at the point the measuring wheel strikes the plateau the graph jumps to a point approximately 0.2 inch above normal ground. However, the plot proceeds downward from this point until, at the position where the last averaging wheel encounters the plateau, it is at almost the same position as natural ground. The plot stays at or slightly above

Figure No. 13


Induced Roughness Test #4A vs. Control
1" = 10ft Horizontal
1" = 1" Vertical
Test 4A (Red)
Control (Black)
First averaging wheel contact pt.
last averaging wheel contact pt.
3/8"
3/8"
Induced Roughness Test Pattern No. 4

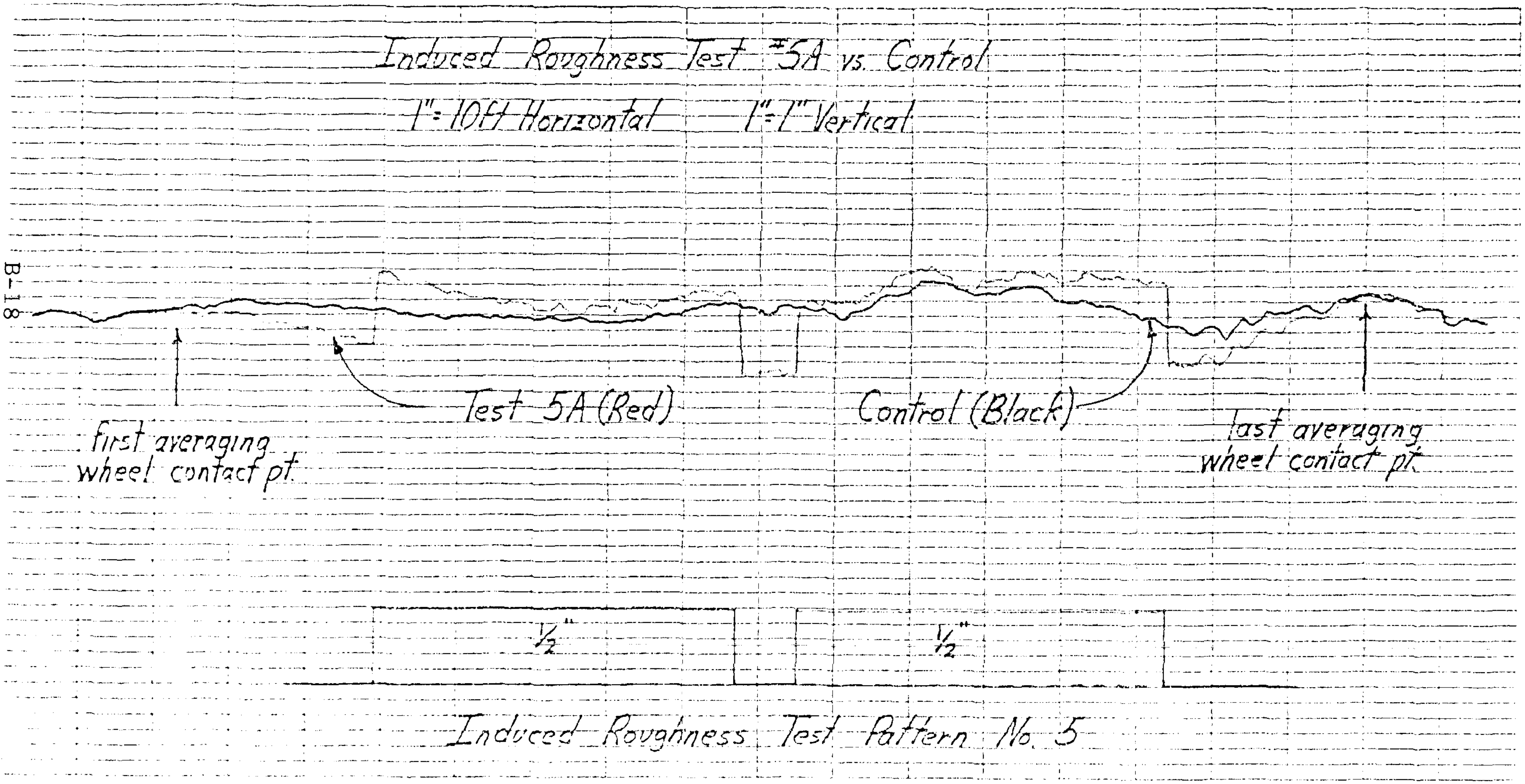
the natural ground position until the depression is encountered, at which point it falls approximately 0.45 inch to a position approximately 0.35 inch below the true location of natural ground. The plot is very nearly symetrically centered around the depression, gradually rising again to a point approximately one-half the height of the plateau as the measuring wheel leaves the last board, then dropping an equal distance below natural ground only to gradually rise to meet the true location of natural ground as the last averaging wheel leaves the last board.

The unfiltered digital readouts of the No. 4 runs average 5.9 inches of roughness. This is approximately 2.15 inches above the measured control reading even though only 0.75 inch of induced roughness was added to the course. The 0.1-inch filtered readings averaged 3.3 inches total or 1.35 inches above the control. The graphical method also yielded an answer 1.35 inches above the control.

Thus, with all three methods the actual roughness was significantly overstated, ranging from 180% to 285% of the actual value.

This test pattern, along with tests No. 5 and No. 6, was devised to simulate faulted slabs which are common to older jointed concrete pavements and "punch-outs," a type of failure most frequently associated with continuously reinforced pavements. Thus these findings, that the profilograph overstates the actual roughness present in these

Figure No. 14


Induced Roughness Test #5A vs. Control
1" = 10 ft Horizontal 1" = 1" Vertical
Test 5A (Red)
Control (Black)
first averaging wheel contact pt.
last averaging wheel contact pt.
1/2"
1/2"
Induced Roughness Test Pattern No. 5

situations, should be taken into account prior to setting a specification limit for the repair and/or rehabilitation of failed concrete pavements.

Results - Test No. 5

The concept of this test was similar to test No. 4 in that it measured the response of the profilograph to a simulated faulted slab and a punch-out, the only difference being that in this test the raised plateaus were made of 1/2-inch boards rather than the 3/8-inch boards used in test No. 4. Although the graphical display of the profilograph did reflect the increased depth of the hole, it was otherwise just as described in test No. 4 (see Figure 14).

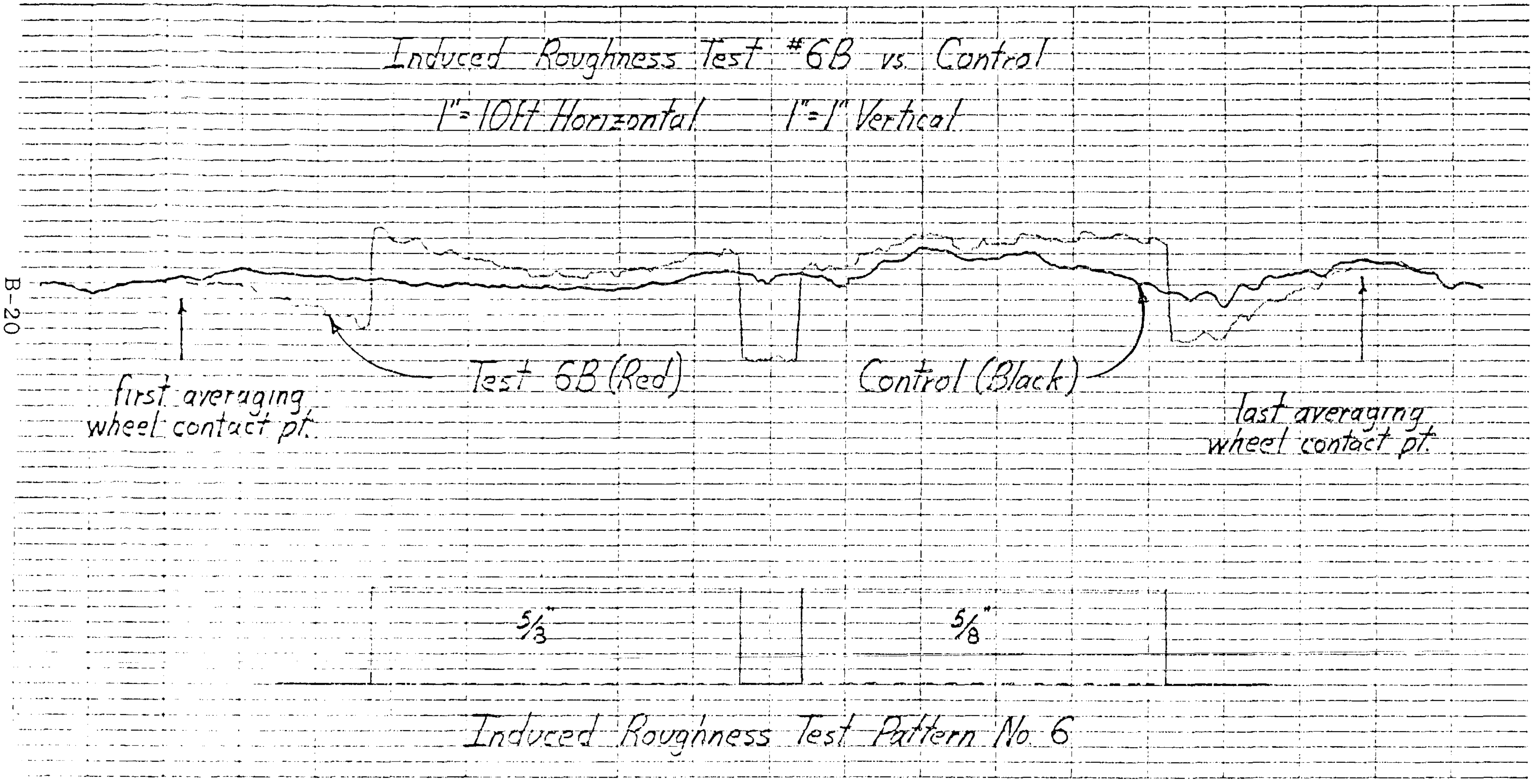
In all, a total of 1 inch of induced roughness was actually added to the control; but the unfiltered roughness readings for run No. 5 averaged 6.05 inches, approximately 2.3 inches above the average unfiltered reading of the control. The filtered digital readings were 1.7 inches above the corresponding control and the graphical calculations averaged 1.2 inches above the control.

As in test No. 4, each method significantly overstated the actual roughness added to the test course, with this difference ranging from 230% for the unfiltered digital readout to 120% for the 0.1-inch graphical filter band method.

Results - Test No. 6

This test was identical to test No. 4 and test No. 5 except

Figure No. 15


Induced Roughness Test #6B vs. Control
1" = 10ft Horizontal   1" = 1" Vertical
Test 6B (Red)
Control (Black)
first averaging wheel contact pt.
last averaging wheel contact pt.
5/3"
5/8"
Induced Roughness Test Pattern No. 6

that this time the raised platforms were constructed using 5/8-inch-thick boards. Again, the action of the profilograph was very similar to that described in tests No. 4 and No. 5. The indicated depth of the hole was approximately 0.7 inch, slightly larger than its actual 0.625-inch depth, but it is below or lower than its actual position (see Figure 15).

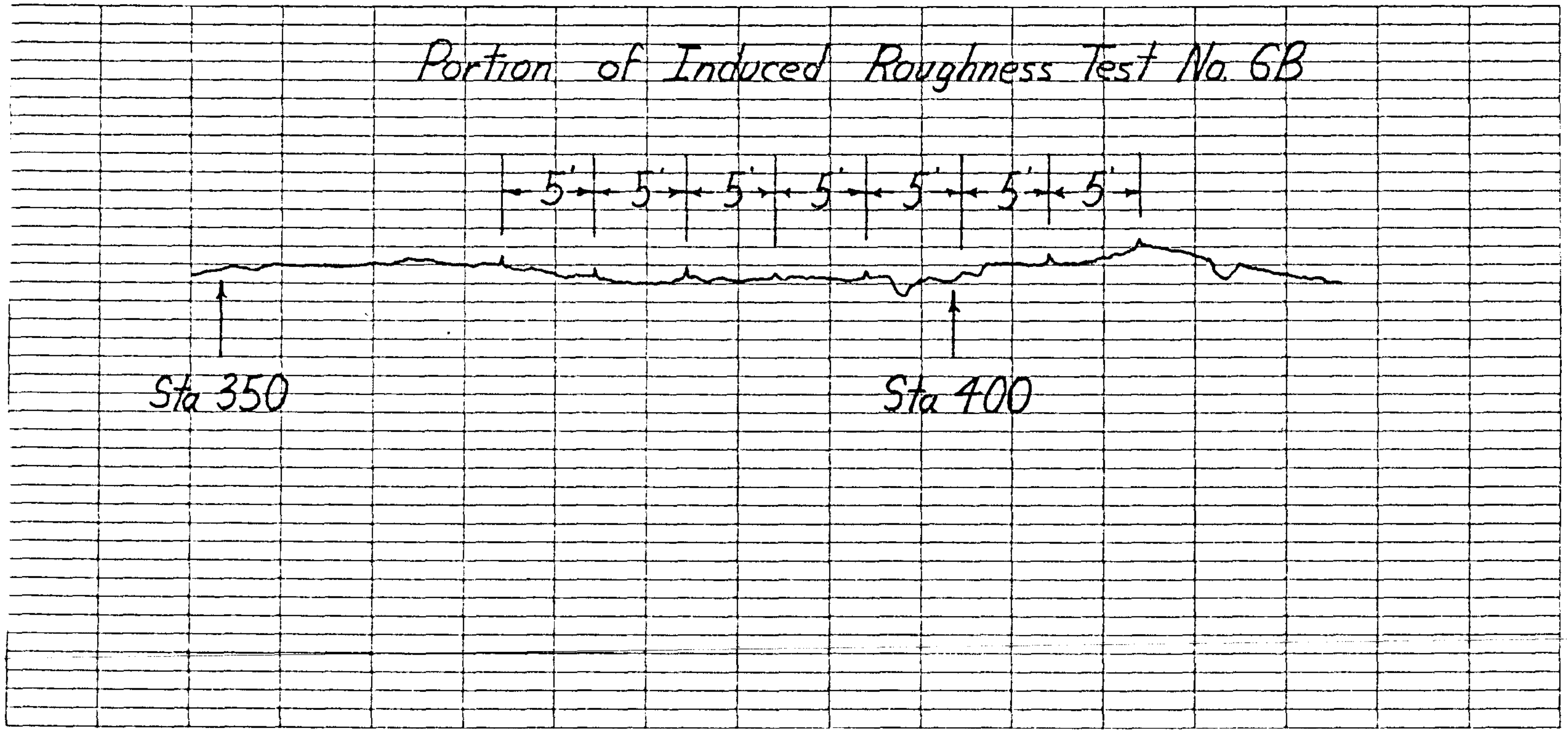
In all, a total of 1.25 inches of induced roughness was added to the test course in these runs. The unfiltered roughness increased by approximately 2.15 inches, the filtered roughness increased by approximately 1.95 inches, and the graphical calculation increased by 1.4 inches. Again, this represents an overstatement of the actual roughness ranging from 172% to 112%.

Comment

An interesting occurrence can be illustrated using the graphical display of this last test. The digital readouts for test run 6B have been noticeably increased by an object becoming fixed to the measuring wheel, and thus this test was disregarded when computing the digital averages stated above. The presence of this object can be very clearly seen by observing the graph of the 6B run beginning with station 365. At this point regular spikes begin to appear in the graph (see Figure 16).

These spikes are spaced at precisely 5-foot intervals, the exact circumference of the measuring wheel. Although the

Figure No. 16



Portion of Induced Roughness Test No. 6B cause of the spikes in this test is not known, similar spikes have been observed when asphalt-covered pebbles became stuck to the measuring wheel.

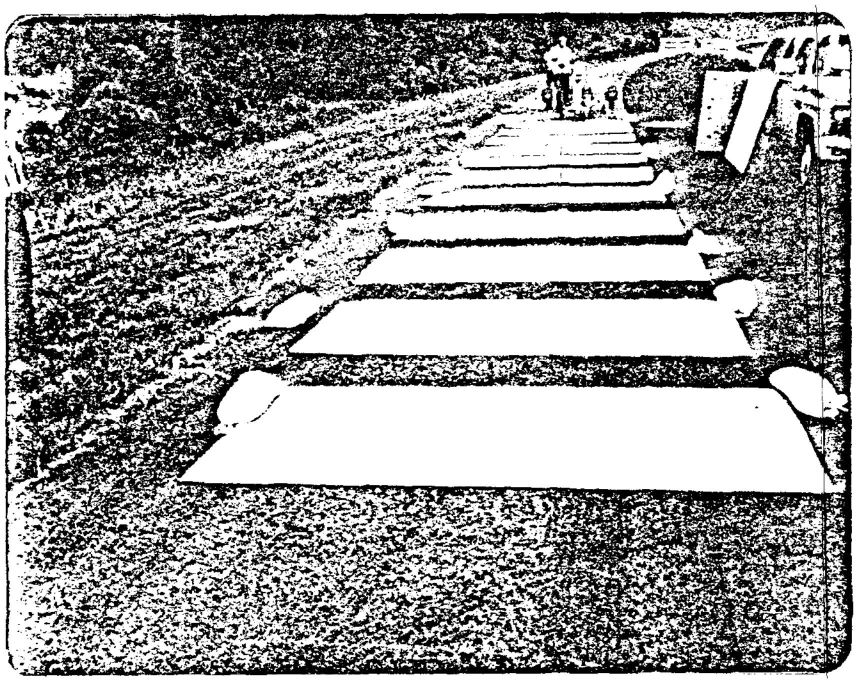
Induced Roughness Tests No. 7, No. 8 and No. 10

The purpose of these tests was to determine the impact to the profilograph which would occur when the spacing between the individual deviations was varied. In these three tests the same total inches of induced roughness and the same sequence of "bumps" were used in each case. Only the distance between the individual bumps was varied. This distance between bumps was maintained at the previously used 4 feet in test No. 7, was decreased to 2 feet in test No. 8 and increased to 8 feet in test No. 10 (see Figure 17). As explained earlier, the 4-foot spacing is thought to be representative of the most common bump frequency encountered in a normal portland cement pavement. The 8-foot spacing may be closer to that encountered in a slip form operation while the 2-foot spacing might be representative of a formed city street.

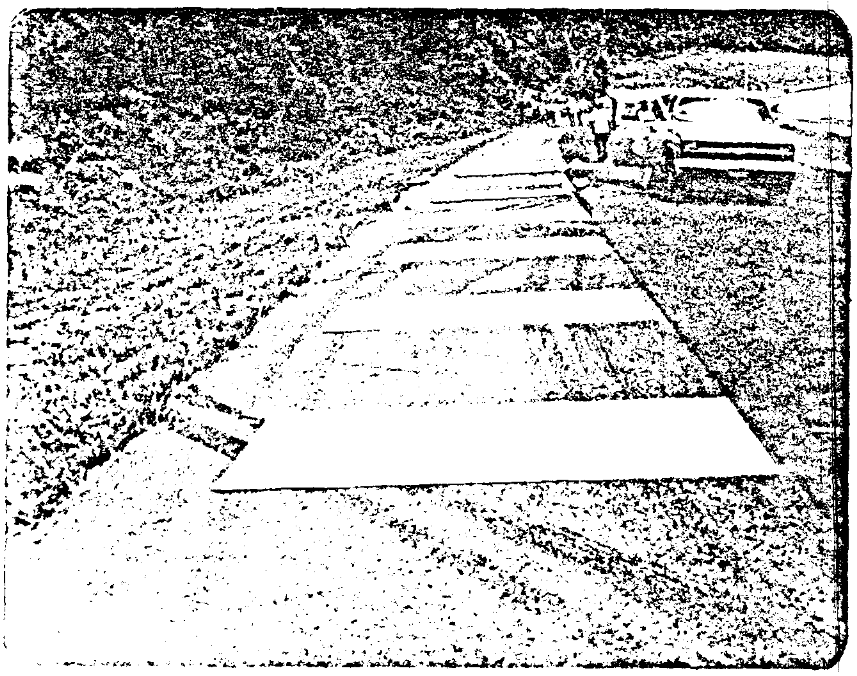
Discussion of Results

Again, the graphical outputs very accurately plotted the locations of the induced bumps. The vertical height of the bumps as shown on the graphs is also very close to the actual height of the projections but, as in other tests, is as much as 0.1 inch high.

FIGURE 17



INDUCED ROUGHNESS TEST PATTERN NO. 8



INDUCED ROUGHNESS TEST PATTERN NO. 10

In total, 4.75 inches of induced roughness was added to the control roughness in each of the three tests, yet the numerical readouts from the digital counters were quite different as shown below.

TABLE 3

DIGITAL RESULTS OF INDUCED ROUGHNESS TESTS NO. 7, NO. 8 AND NO. 10

Run No.	Gap Size	Unfiltered Inches Above Control	% of 4.75	Filtered Inches Above Control	% of 4.75
7	4 feet	8.03	169	5.57	117
8	2 feet	8.65	182	6.55	138
10	8 feet	9.0	189	6.63	140

One interpretation of these results is that where gap size is equal to bump size the averaging characteristics of the profilograph interpret the projections as if they were a series of bumps and depressions rather than just bumps. Thus, the 1/8-inch boards are filtered out completely and the 1/4-inch boards are just barely visible above the 0.1-inch filter. The validity of this theory can be judged by examining the graphical displays when plotted against the control profile. In test No. 7 where the "bump" length is equal to the spacing between "bumps" the high and low points of the test pattern are plotted approximately equidistant above and below the actual grade line. When the "bumps" are spaced further apart as in test No. 10, more averaging wheels at any one time are on the original ground than are on the raised deviations, and thus the graphical profile shows higher projections above the original grade than below it. With the closer spacing (test No. 8) the reverse is true with the projections above the original profile being much smaller than those below it (see Figure 18).

It is only when using the filter band method that the actual value of 4.75 inches of added roughness can be closely approximated.

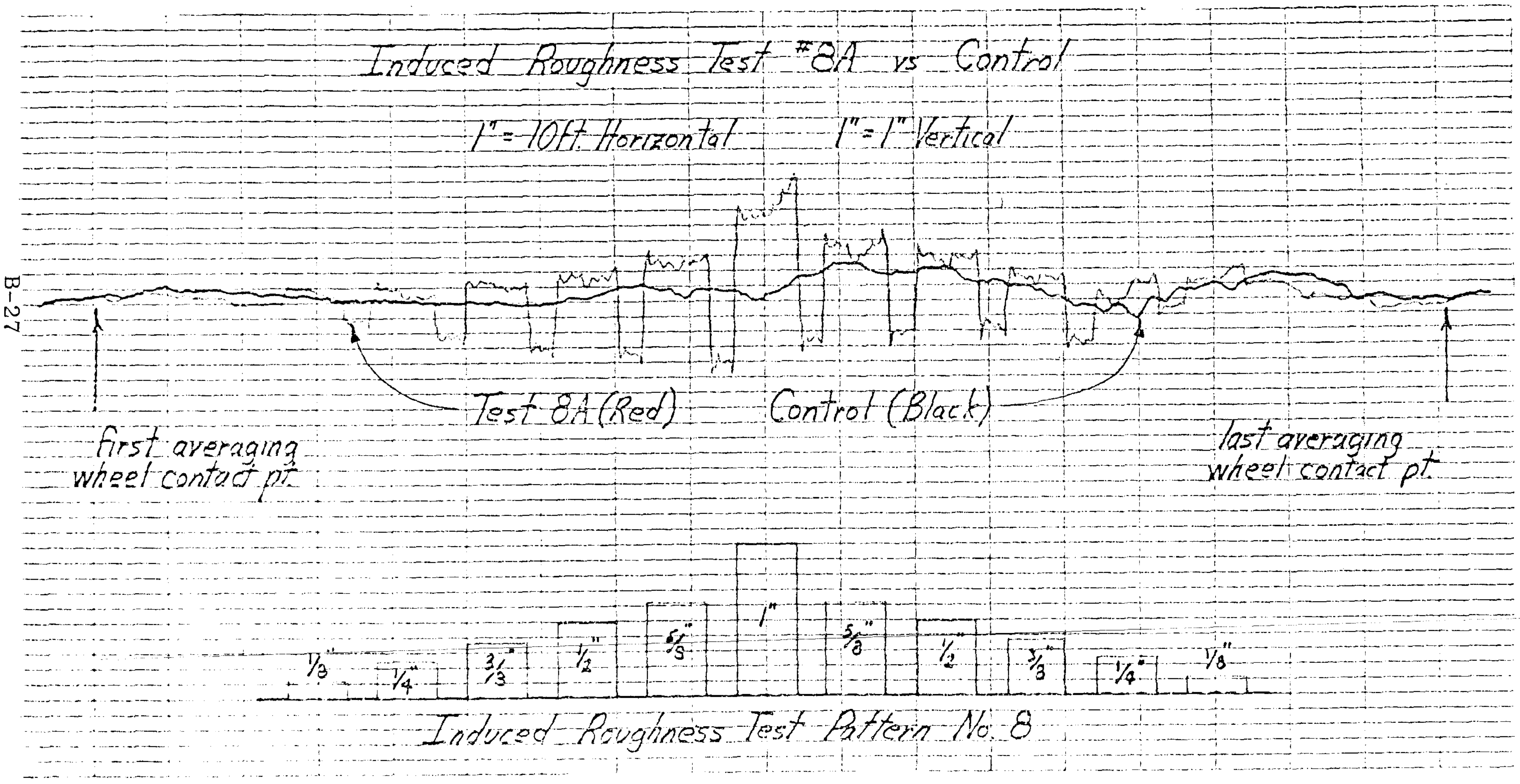
TABLE NO. 4

FILTER BAND RESULTS OF INDUCED ROUGHNESS
TESTS NO. 7, NO. 8 AND NO. 10

Run No.	Original Control	Average Total From Filter Band Inches	% of 4.75
7	1.25	4.70	99
8	1.25	4.65	98
10	1.25	4.98	105

In judging the impact of these variations as to the frequency of the deviations, it can be seen that there is very little difference in the amount of added roughness between the 2-foot spacing and the 4-foot spacing, with the filter band measurements very accurately indicating the total value of the actual roughness. However, in both the digital readouts and the filter band calculations the 8-foot spacing did produce a roughness value which was actually higher than the true figure. While this may indeed indicate a tendency toward a slight overstatement of the roughness of widely

Figure No. 18


Induced Roughness Test #8A vs Control
1" = 10ft. Horizontal
1" = 1" Vertical
Test 8A (Red)
Control (Black)
first averaging wheel contact pt.
last averaging wheel contact pt.
1/8"
1/4"
3/8"
1/2"
5/8"
1"
5/8"
1/2"
3/8"
1/4"
1/8"
Induced Roughness Test Pattern No. 8

spaced deviations, the approximately 5% difference found when using the graphical method is not statistically significant and at any rate is not large enough to warrant any special consideration of bump spacing when calculating roughness.

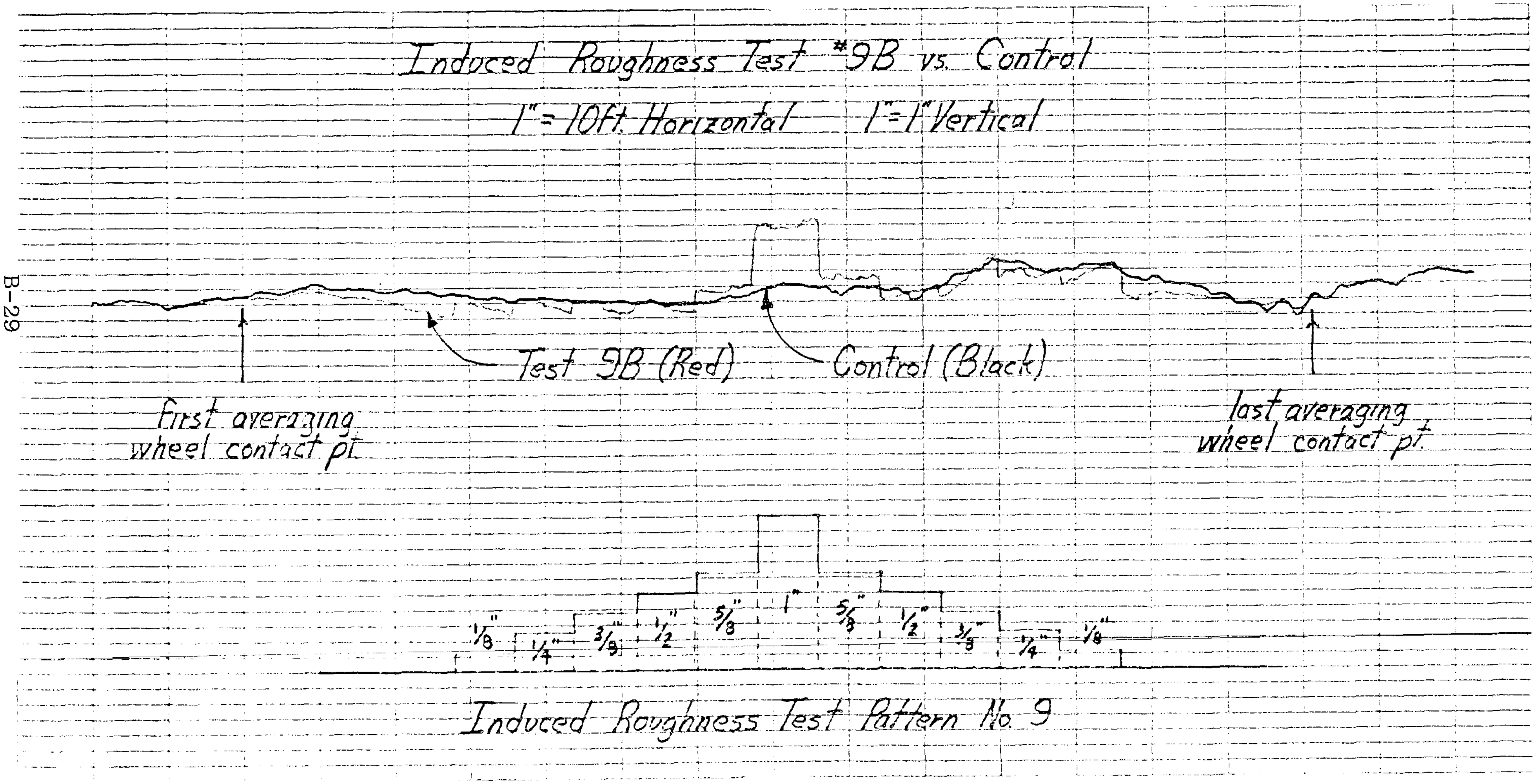
Induced Roughness Test No. 9

The purpose of this test was to determine the response of the profilograph to a very long wave length deviation. To construct this test pattern the individual sheets of plywood were laid side by side in a stepped configuration beginning at 1/8-inch thickness and proceeding through 1/4-inch, 3/8-inch, 1/2-inch, 5/8-inch and 1-inch thicknesses. The configuration was symmetrical about the 1-inch board stepping down again to the 5/8-, 1/2-, 3/8-, 1/4- and 1/8-inch thicknesses. In all, the test pattern was 44 feet long and consisted of a total induced roughness of 1 inch.

Results - Test No. 9

As usual, the graphical display very accurately located the beginning and ending points of the test pattern, showing them to be nearly exactly 44 feet apart. Because the total length of the test pattern was almost twice the length of the wheel base of the profilograph and because the 1/8-inch height of the steps was so small, it was difficult to predict the response of the profilograph. However, as is quite clearly shown on the display (Figure 19), the roughness

Figure No. 19


Induced Roughness Test #9B vs. Control
1" = 10ft. Horizontal 1" = 1" Vertical
Test 9B (Red)
Control (Black)
first averaging wheel contact pt.
last averaging wheel contact pt.
1/8"
1/4"
3/8"
1/2"
5/8"
1"
5/8"
1/2"
3/8"
1/4"
1/8"
Induced Roughness Test Pattern No. 9

created by the 1/8-inch steps up are shown on the graph to be below the actual grade, as are the steps down. Only the 1-inch board is shown accurately, projecting 0.4-inch above the surrounding 5/8-inch boards, but the vertical position of this board is shown to be approximately 1/2-inch below its actual position.

In all, a total of 1 inch of induced roughness was added to the test strip; however, the unfiltered digital readings increased by approximately 2.3 inches while the filtered digital readings went up 1.2 inches. Using the 0.1-inch filter band, the increase is clearly understated being only approximately 0.85 inch.

As can be seen in Figure 19 with the induced roughness display of test No. 9 superimposed over the original ground display, the long wave length deviation is virtually invisible to the profilograph, the exception being, of course, the 1-inch board which in this case significantly projects above the surrounding boards.

If this display were presented to a contractor, the only corrective action indicated would be to grind approximately 0.4 inch from the center projection.

This test clearly illustrates the limitations of the profilograph when dealing with deviations which have a wave length longer than the wheel base of the machine.

The results of the entire series of Induced Roughness Tests are displayed in Table 5 and shown graphically in Figure 20. As can be seen, the three methods of determining roughness yielded widely different results for each test. However, in each case the unfiltered digital reading was the largest and the 0.1" graphical filter band reading was either the smallest or tied for the smallest. In particular it should be noted that in all cases both the unfiltered and the filtered digital readings exceeded the actual roughness. By contrast, the graphical filter band method yielded a result with an equal tendency to be either slightly above or slightly below the actual value and which in all cases was closer to the actual roughness than either of the two digital methods.

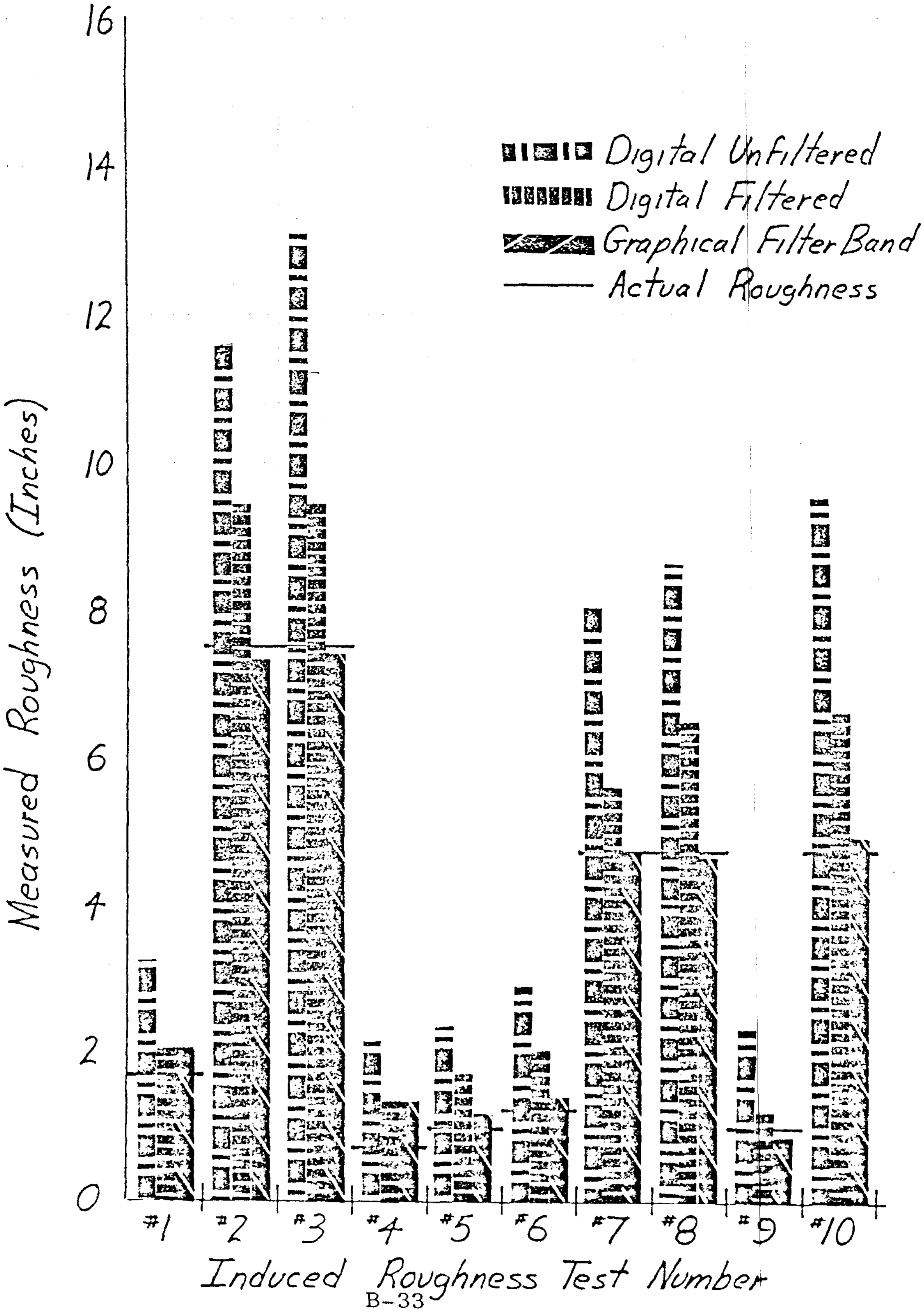
TABLE 5

SUMMARY OF INDUCED ROUGHNESS TEST RESULTS

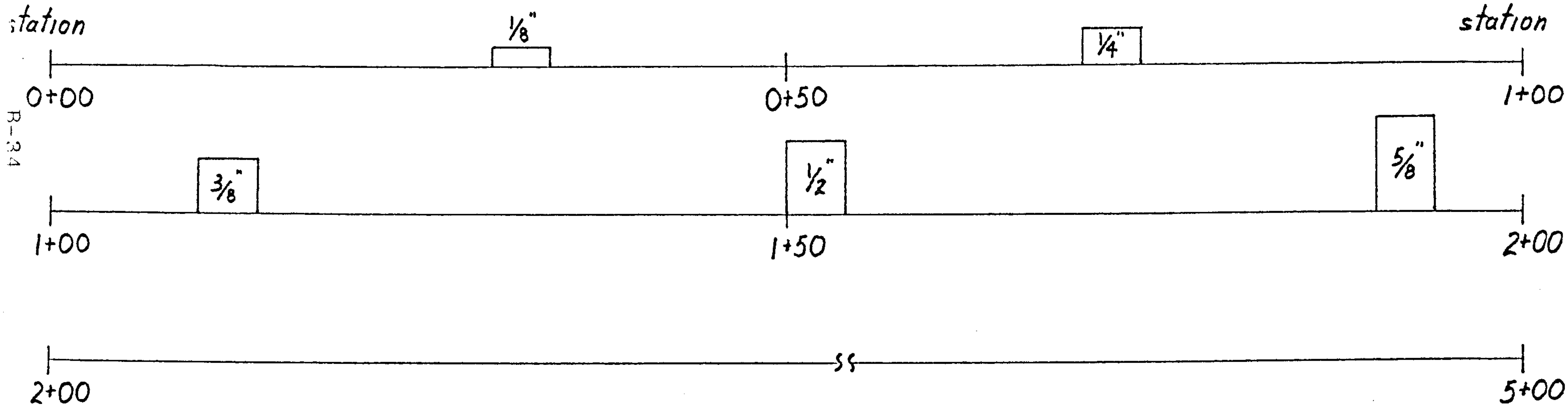
	Measured Roughness (Inches)			
		Digital		Graphical
Test Number	Actual	Unfiltered	Filtered	0.1-inch Filter Band
1A	1.75	3.2	2.1	--
1B	1.75	3.35	2.1	2.15
2A	7.5	11.4	9.85	7.15
2B	7.5	11.75	9.05	7.40
3A	7.5	12.80	9.5	7.60
3B	7.5	13.20	9.95	7.70
4A	0.75	2.25	1.45	1.45
4B	0.75	2.05	1.25	1.25
5A	1.00	3.05	1.85	1.20
5B	1.00	1.55	1.55	1.20
6A	1.25	2.15	1.95	1.40
6B	1.25	3.60	2.1	1.45
7A	4.75	8.1	5.5	4.60
7B	4.75	7.95	5.65	4.80
8A	4.75	8.95	6.65	4.75
8B	4.75	8.35	6.45	4.55
9A	1.00	2.95	1.45	0.90
9B	1.00	1.65	0.95	0.80
10A	4.75	8.35	5.85	4.90
10B	4.75	10.65	7.40	5.05

Figure No. 20

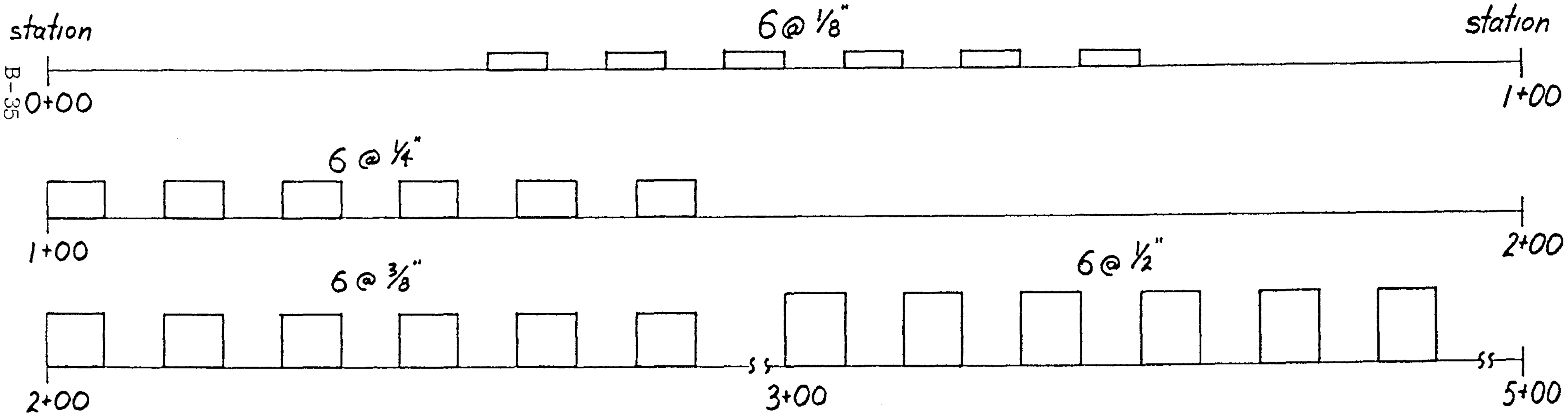
Induced Roughness Test Results



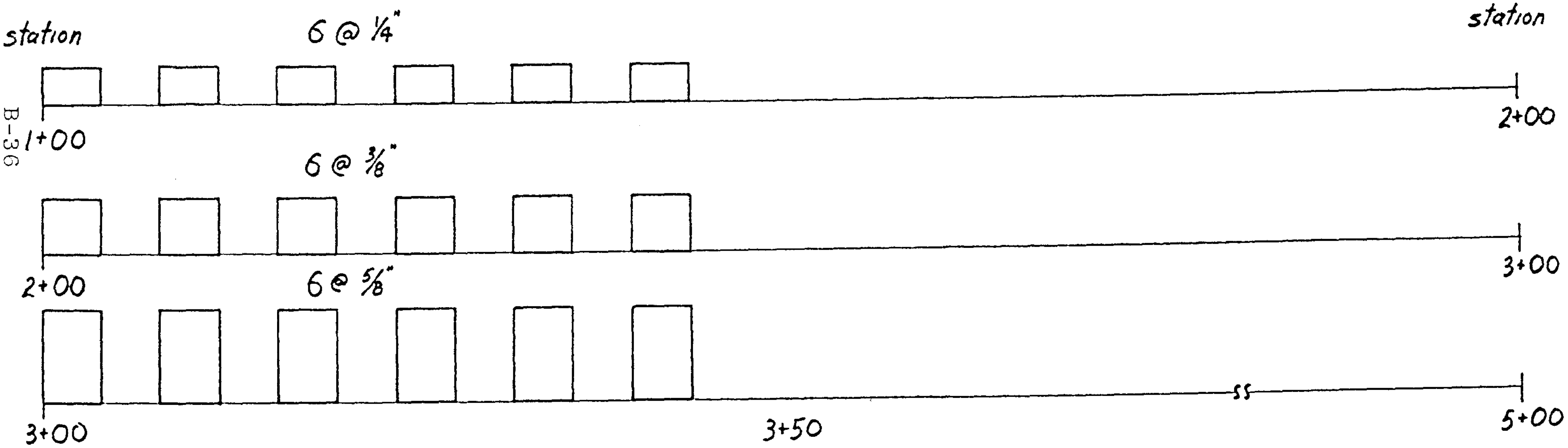
Induced Roughness Test Pattern No. 1



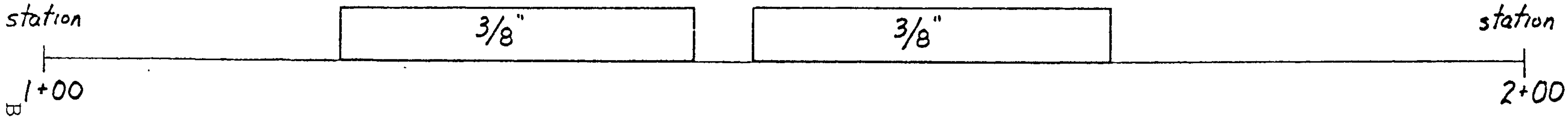
Induced Roughness Test Pattern No. 2



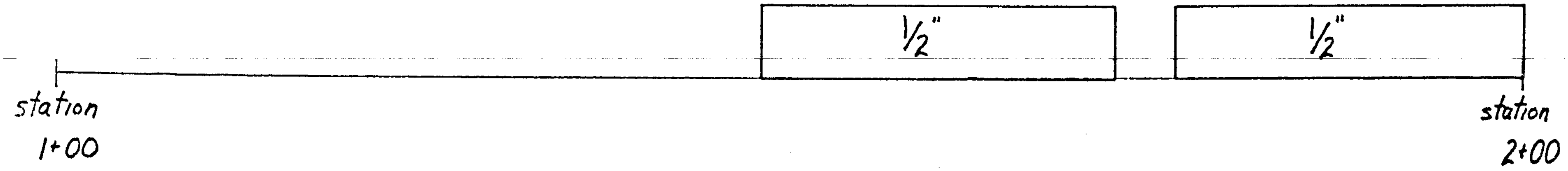
Induced Roughness Test Pattern No 3



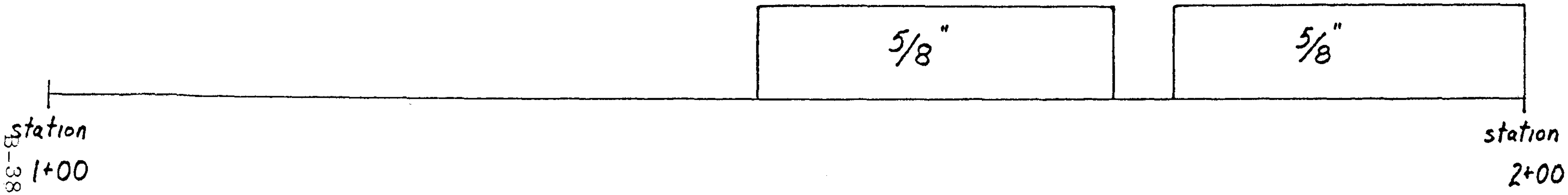
Induced Roughness Test Pattern No. 4



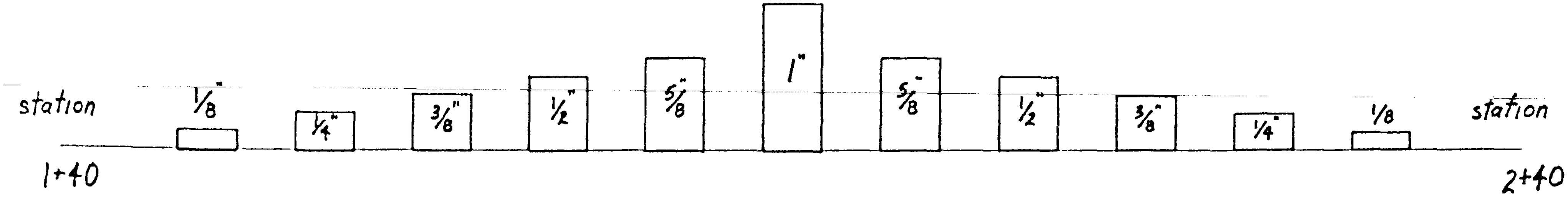
Induced Roughness Test Pattern No. 5



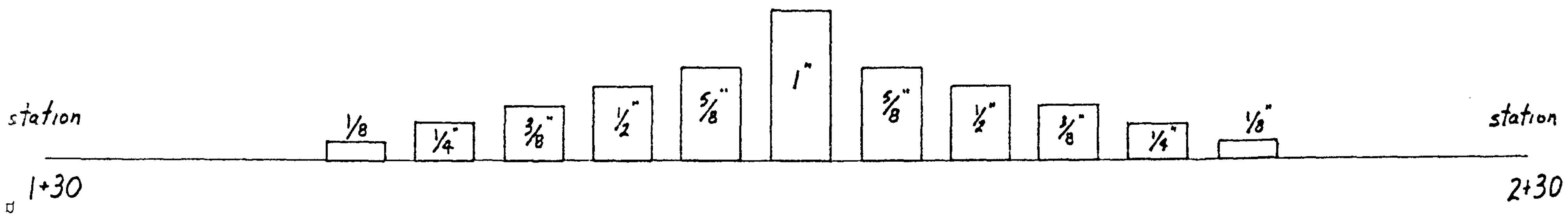
Induced Roughness Test Pattern No. 6



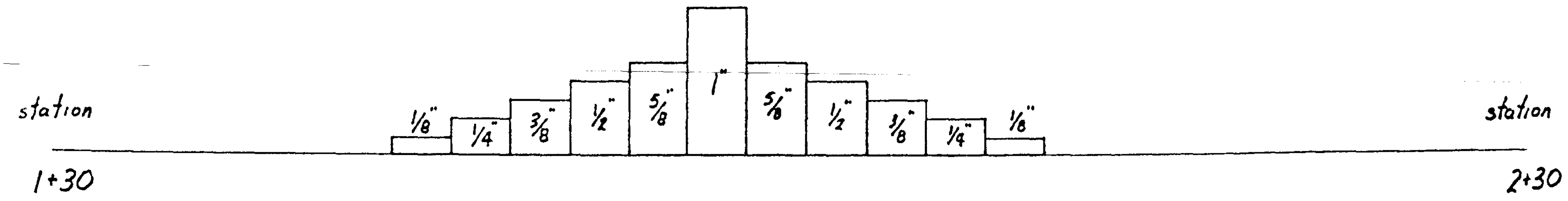
Induced Roughness Test Pattern No. 7



Induced Roughness Test Pattern No. 8



Induced Roughness Test Pattern No. 9



Induced Roughness Test Pattern No. 10