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DEPARTMENT OF TRANSPORTATION
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March 30, 1973

H.3.41

MEMORANDUM TO: J. R. Harbison
State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report, No. 362; "Vibratory Roller Evaluation;" KYP-72-41; HPR-1(8), Part III

The compaction process (densification) is conceptually simplified when described in terms of energy expended and work (classical) done. Energy expended without increasing density is wasted. Thus, excessive rolling is wasted energy. Beneficial work is done in compressing material to a higher density. The objective, of course, is to obtain the maximum beneficial work with the least energy. The ratio of beneficial work to energy input is efficiency. Doubtlessly, there is an optimum temperature for compacting bituminous base courses. There appears to be an optimum travel speed for rollers -- the cooler the material being rolled, the slower the speed for maximum compaction efficiency. Generally speaking, 2 mph appears to be about the maximum feasible working speed; and 215°F appears to be the minimum temperature for final coverages to be effective.

During a succession of passes, the imprint area of the roller wheel should decrease progressively. If the pavement becomes very stiff, a vibrating roller may tend to bounce out of contact with the surface. Of course, vibration should then be discontinued. There is also a possibility of the pavement layer itself becoming resonated (flutter up and down) a few feet away from the roller; vibration should be discontinued in order to avoid disintegration of the pavement layer.

The nuclear-density instrument (usable after each pass of the roller) together with the Heatspy-type temperature scope (or "gun") enables implementation of compaction controls never before achievable in such a convenient way. The statistical quality-control approach is readily implementable; and I recommend its adoption for all base-course construction. Indeed, such controls will provide assurances that a compacting procedure and the equipment used are matched for near-maximum efficiency.

It has been argued by others that density is not directly related to strength and that under-compaction is not very detrimental to the performance of a pavement. I reject these notions -- because they are somewhat paradoxical. It is possible to knead and work some mixtures to a point where they "flush" and lose stability (strength). It is also possible to grade mixtures to have a relatively low density (open-graded) and still achieve high stability or strength. Nevertheless, each type must be compacted to its respective, optimum condition. Uneven or non-uniform compactions can only lead to differential consolidation under traffic and unevenness in the pavement.

Previous reports related to compaction of bituminous concrete are cited below for reference and to indicate the recurring and residual aspects of the problem -- which is one reason why I favor a statistical quality-control specification. The last-cited report is an advance report on the current study.

1. "Evaluation of Vibratory Roller for Use in Compacting Bituminous Concrete Mixes," US 60, Olive Hill, FFG (13)8; R. C. Deen, February 1961.
2. "Study of Light Compaction Equipment for Maintenance Patching," R. L. Florence, September 1961.
3. "Test Rolling with the Buffalo-Springfield, PSR 14 Roller Equipped with Solid Rubber Tires," Research Division Memorandum Report (uncirculated, File H-2-9) R. L. Florence, October 29, 1963 (Mountain Parkway Extension; used Nuclear-Chicago Asphalt Density Probe).
4. "Comparative Evaluation of RayGo 404 Vibratory Roller," Research Report 328, KYP-72-41, April 1972.
5. "Vibratory Compaction of Asphaltic Concrete," J. E. McChord; prepared for SASHO, October 1972.

The forthcoming, I 64 paving east of Grayson may provide additional experience with vibrating rollers and statistical control of density.

Respectfully submitted,

Jas. H. Havens
Director of Research

JHH:dw
Attachment
cc's: Research Committee

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16. Abstract

In a field evaluation of vibratory rollers, an end-result specification based on a statistical analysis of densities obtained on previous construction projects indicated 98 percent of laboratory density (Marshall) to be desired for Bituminous Concrete, Class I Base. The minimum average of 5 density tests was set at 96.4 percent. Conventional rollers, vibratory rollers, and combinations thereof were qualified on the basis of density-growth curves determined on one or more 1000-foot test sections. An overall average compaction of 97.8 percent of Marshall density was obtained on the Cumberland Parkway project. Similar controls initiated on the Green River Parkway project were discontinued.

17. Key Words
Vibratory, Roller, Compaction, Density,
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Research Report
362

VIBRATORY ROLLER EVALUATION

KYP-72-41, HPR-1(8), Part III

by

D. C. Newberry, Jr.
Research Engineer Senior

Division of Research
Bureau of Highways
DEPARTMENT OF TRANSPORTATION
Commonwealth of Kentucky

April 1973

INTRODUCTION

Higher production of compaction equipment is necessary to match higher paver and hot-mix plant capacities and greater volumes of bituminous concrete required for full-depth pavements. Thus, the use of vibratory rollers for compaction of bituminous concrete in Kentucky has been considered. An opportunity to study vibratory rollers resulted when two parkway contracts (see Table 1) were let as full-depth structures. Change orders permitted, as an alternative, the use of vibratory rollers.

Section 306.3.7.A. of the Department of Highways standard specifications *(1)* contain a method-type criterion for compaction of bituminous concrete. Roller type, weight, and coverage are specified. Two- or three-axle, steel-wheeled, tandem rollers and pneumatic-tired rollers are permitted. Breakdown rolling is specified as one coverage of at least a ten-ton, steel-wheeled roller or a tandem roller. A minimum of three coverages of a pneumatic roller with tires inflated to 90 psi or more is required for intermediate rolling. Finish rolling requires use of an eight-ton, steel-wheeled, two- or three-axle, tandem roller.

The method-type criterion was considered unsatisfactory for the experimental purpose of evaluating vibratory rollers. It was decided to investigate the end-result type criterion as a substitute for the standard specification. A statistical analysis was made of density data from pavements on projects constructed by use of conventional type rollers. That analysis provided a numerical value for percent compaction to be used in the end-result approach and indicated the following, necessary, density control limits:

NUMBER OF TESTS	LOWER LIMITS (PERCENT OF MARSHALL LABORATORY DENSITY)	
	BASE COURSES	SURFACE COURSES
5	96.4	95.1
1	94.5	92.7
Desired	98.0	97.0

An end-result type specification (APPENDIX) was then prepared and made a part of the change orders. The type of vibratory rollers were left to the discretion of the contractors, based on availability of equipment from manufacturers and subsequent approval by the Department of Highways.

Aggregates from local sources used in the mixtures were dense graded aggregate and No. 57 stone. Gradations of the final aggregate mixtures for each project are presented in Table 2.

The Marshall laboratory test was based on 50 blow compaction for medium traffic intensity for both projects. Design data are presented in Table 3.

During construction of the Cumberland Parkway project, it was decided on September 19, 1972, to decrease the asphalt content by 0.2 percent and to reduce the aggregate passing the #100 sieve to 2 or 3 percent. Laboratory density of a trial mixture was 149.7 pcf. That density was used to determine percent compaction for all data collected after that date.

Mixing plants and pavers used on the projects are summarized in Table 4.

Three vibratory rollers were used on the two projects. An additional tri-axle static roller was used on one project for higher production. All three vibratory rollers were used on the Cumberland Parkway; only one (Buffalo Bomag BW-210A) was used on the Green River Parkway. The static, tri-axle roller was used only on the Cumberland Parkway. Descriptive data of the rollers are presented in Table 5. Photographs of the various rollers are shown in Figures 1, 2, and 3.

TABLE 1. PROJECT IDENTIFICATION

	CUMBERLAND PARKWAY	GREEN RIVER PARKWAY
Location	Barren County	Warren County
Project Number	BSP 11-1	BOP 11-1
Contract Number	S.P. 5-187	S.P. 114-113
Net Length	8.171 miles	7.101 miles
Contractor	Middle West Roads	Kapco Inc.
CBR	5	5
Total Depth	14 inches	15 inches
Course Depth	4-3.5 inches	5-3 inches

TABLE 2. AGGREGATE GRADATIONS

SIEVE SIZES	PERCENT PASSING CUMBERLAND PARKWAY	 GREEN RIVER PARKWAY
1"	100	100
1/2"	76	73
#4	38	40
#8	31	32
#16	22	22
#50	10	10
#100	5	6

TABLE 3. BITUMINOUS CONCRETE DESIGN DATA

	CUMBERLAND PARKWAY	GREEN RIVER PARKWAY
Apshalt	AC-10	PAC 5
Mix Temperature (°F)	285 ± 10	285 ± 10
Unit Weight (pcf)	152.8	152.1
Asphalt Content (%)*	4.6	4.7
Flow (in.)	0.18	0.21
Voids in Mix (%)	1.3	2.0
Maximum Specific Gravity	2.482	2.488
Stability (lbs.)	2500	2680

*An additional 0.5 percent asphalt was used in the first base course on both projects.

TABLE 4. MIXING AND PAVING PLANTS

	CUMBERLAND PARKWAY	GREEN RIVER PARKWAY
Plant	Automatic Hetherington and Berner with baghouse collector	Automatic Cedarapids with baghouse collector
Capacity (lbs.)	10,000	8,000
Paver	Blaw Knox PF 180H	Two Cedarapids in echelon
Width (ft.)	24	12

TABLE 5. ROLLER DESCRIPTIONS

	VIBRATORY			STATIC
	RAYGO RUSTLER 404 B	BUFFALO BOMAG BW 210A	TAMPO RS-288A	BUFFALO SPRINGFIELD KX 25E
Dimensions:				
Length (ft.-in.)	16 - 11.5	16 - 11.5	26 - 5	22 - 10
Width (ft.-in.)	7 - 11.5	7 - 7	8 - 0	5 - 8.5
Height (ft.-in.)	8 - 5	7 - 2	8 - 2	8 - 1
Weight (lbs.)	18,300	18,500	34,100	27,370
Drum Diameter (in.)	59	59	60	F-48 R-60
Drum Length (in.)	84	84	84	54
Turning Radius (ft.-in.)	20 - 5	16 - 10	18 - 3	29 - 8
Wheel Base (ft.-in.)	9 - 0	9 - 0	19 - 9	17 - 4
Curb Clearance (in.)	15.5	15.5		18.5
Propulsion System:				
Speed (mph)			0 - 15	0 - 5
Gear: 1st	0 - 4.6	0 - 4.0		
2nd	0 - 7.0	0 - 7.8		
3rd	0 - 17.5	0 - 15		
Tires	16.9 x 30	13 x 24	16.9 x 30	
Vibration System:				
Dynamic Force (lbs.)	27,000	42,000	30,000/drum	
Frequency (vpm)		1100 - 2500	1100 - 1500	
High (vpm)	1200 - 1700			
Low (vpm)	1200 - 2300			
Power Unit:				
Engine	DD 3-53	GMC 4-53	DD 4-53	JXLD
Electrical (volts)	12	12	12	12
Fuel capacity (gal.)	50	44	50	30
Water System:				
Front (gal.)	168	150	150	
Rear (gal.)	15	40	150	
Manufacturer:	RayGo Inc.	Koehring Road Division	Tampo Manuf. Co.	Buffalo Springfield
Drum and Wheel Configuration:	One Vibrating Drum, Two Pneumatic Drive Tires	One Vibrating Drum, Two Steel Covered Drive Tires	Two Vibrating Drums, Two Steel Covered Drive Tires	Three-Axle Tandem, Lockable Center Axle

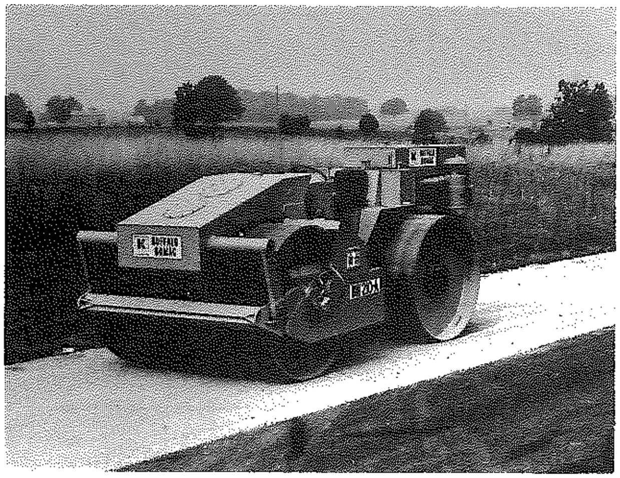
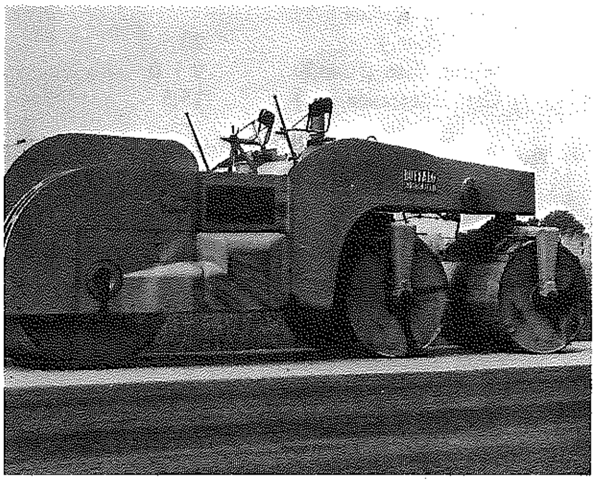


Figure 1. Buffalo Bomag BW 210A Vibratory Roller.

Figure 2. Buffalo-Springfield KX 25E Three-Axle Static Roller.



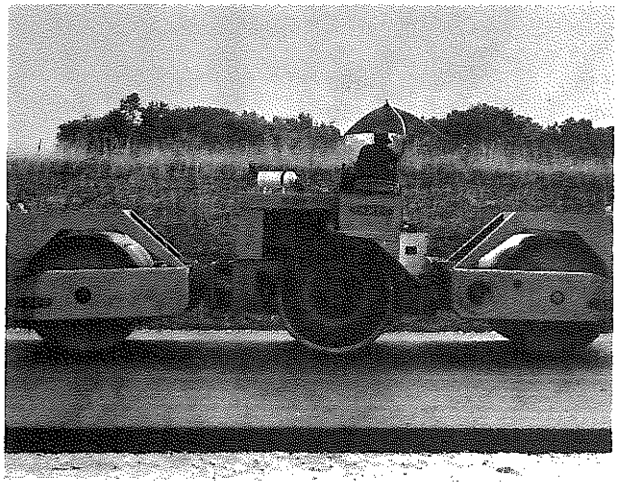


Figure 3. Tampo RS-288A Two-Drum Vibratory Roller.

FIELD PROCEDURES

Equipment used on both parkway projects for field testing included:

1) Seaman Nuclear Density Meter, Model 75 -- uses the air-gap method for density determination.
2) Remote, infrared thermometer -- to indicate surface temperature.
3) Stopwatch -- for determining speed of rolling.
4) Benkelman beam -- for wheel-track deflection measurements.
5) Dump truck -- loaded to 18,000 pounds on the rear axle for static loading for Benkelman beam measurements of deflection.
6) Road Rater -- a vehicle-mounted device which reads pavement deflection with electronic sensors while dynamically loading the surface with a vibratory head. The device can also be used to statically load the pavement.
7) Surface Dynamics Road Profilometer -- measures, and displays in analog and strip chart form, deviations of a roadway from a reference plane closely approximating the grade line.
8) Skid-Test Trailer -- measures frictional force developed between a braked wheel and pavement as the wheel is pulled at a constant velocity.

The original contract required that compaction be performed as specified in the 1965 Kentucky **Standard Specifications....** Change orders permitted deviations from those standards, but the contractor was required to maintain three rollers at the job site as a precautionary measure in the event of vibratory roller failure. Prior to arrival of vibratory units on the Cumberland Parkway, conventional rollers were used for comparison with the vibratory rollers.

Compaction with static-type rollers is generally accomplished in three or more operations as follows:

Breakdown: Initial rolling to set material in place.

Intermediate Rolling: Stage where the greatest compaction effort is brought to bear. Roller tends to walk or climb out when this stage of rolling is completed.

Finish Rolling: Refers to closing the surface texture. If no edge marks are created, light, small-wheeled, steel rollers would perform the required operation.

The vibratory roller was used singularly for all compaction operations. The only similarity, other than densification, between the vibratory and conventional rollers is the rolling pattern. Uniformity of rolling sequence must be rigidly maintained to obtain an appropriate crown and uniform density.

Density was controlled on both experimental projects in accordance with the end-result criterion (APPENDIX). Density tests were made at random stations and transverse locations. Pavement temperature was measured at each test site; the number of passes of the roller at each site was recorded. To assure data accuracy, cores were obtained and check Marshall tests were made periodically.

At the start of paving for each course, or change of roller type or mix design change, a 1,000-foot test section was used to develop roller density growth curves. Those curves were then used as a basis for control of compactive effort; test sections were used to determine the passes required to obtain desired density. Thereafter, five tests per day were used to determine compliance with density requirements.

RESULTS

Results of field nuclear density tests are summarized in Table 6. As a check on densities recorded by the nuclear density meter, cores and samples were obtained periodically. Densities of the cores were determined, and samples were molded in Marshall test molds for density determinations. Comparisons of these data with the nuclear density test results are summarized in Table 7. The average difference between cores and nuclear meter readings indicated a correction of plus 4 pcf; this was added to the meter values taken during the period from June 5, 1972 to July 6, 1972. On July 6, 1972, the correction factor was reduced to 2 pcf; this correction factor was used until completion of the projects on November 1, 1972.

Density test results compared vertically through the pavement structure are shown in Table 8 for the Cumberland Parkway (BSP 11-1). The distribution of test results around the mean for all rollers are shown in Figure 4. Superimposed on the data is a normal distribution curve to illustrate possible variation and scatter that may be experienced when using various combinations of rollers.

Some observations and some data from the Cumberland and Green River Parkways indicated the temperature required to attain 98 percent compaction should be 225°F to 290°F.

Density growth curves for each roller are shown in Figure 5. Distributions of percent compaction attained for each roller pass are shown in Figures 6, 7, and 8.

A series of pavement tests was performed on the Cumberland Parkway project prior to the close of testing in November 1972 to gather data on Class I base construction that may be compared to other similar type projects. The test series made use of 1) Seaman nuclear density gage, 2) Road Rater, 3) Benkelman beams, 4) profilometer, and 5) skid-test trailer.

The density in pcf was determined for cold, cured bituminous concrete base for both east- and westbound lanes (see Table 9).

Deflections, as measured in inches by the Road Rater and by the Benkelman beam, are summarized in Table 10. Values for all lanes were averaged in this analysis. Values for the Road Rater are for readings directly under the center of the load at 20 cycles per second. Deflections of the Benkelman beam were obtained under a static load of 18,000 pounds. Road Rater deflections are illustrated in Figures 9 and 10; Benkelman beam deflections are in Figures 11 and 12.

Roughness measurements (in inches) made by the profilometer, are shown in Table 11 and are indicative of the smoothness compared to the specification limitation of 0.25 inches.

Skid-test trailer values are equivalent to the coefficient of skid resistance of the pavement. Values in Table 12 are for test speeds of 40 mph.

DISCUSSION

Results presented in the previous sections indicate that:

1. Vibratory rollers have the capability for compacting bituminous concrete to design density with fewer coverages than the conventional, non-vibratory rollers of equal static weight.
2. All types of rollers investigated have the capability for producing in situ densities at least 98 percent of the Marshall design density.
3. The tentative specification used for control during construction of the two experimental parkway projects appears feasible.

Control of the forward speed of vibratory rollers is required to obtain maximum efficiency to eliminate the possibility of undulations or deformations being compacted into the finished surface. For vibratory rollers, it has been shown *(2)* that

$$\lambda = 1056\ V/f, \qquad 1$$

where λ = distance between impact (in.),
f = frequency (vpm) (vibrations/min.), and
V = speed (mph).

A variation in the weight of rollers does not affect the distance between impact on the surface. A graphical solution of Equation 1 is shown in Figure 13.

Dynamic forces are normally developed by the rotation of an unbalanced weight offset from the central axle of the drum for most vibratory rollers. This weight and distance from the center of the mass to the center of the axle, when rotating, generates an eccentric excitation moment. The moment forces the entire drum to vibrate in simple harmonic motion. For a specific bituminous concrete mix, this simple harmonic motion system may be adjusted to obtain the desired density. A limitation inherent with the vibratory system involves the natural frequency of the pavement and drum system. The operating frequency of the drum must be adjusted to preclude equality with the natural frequency of the system. The natural frequency of a vibrating system is given by

$$f_n = \sqrt{k/m}/2\pi = \sqrt{kg/W}/2\pi.$$

If $W/k = d_s$, then

$$f_n = \sqrt{g/d_s}/2\pi = 3.127/\sqrt{d_s}, \tag{2}$$

where f_n = natural frequency,
k = spring constant,
m = mass = W/g,
W = weight,
g = acceleration due to gravity = 386 in./sec.^{2}, and
d_s = static displacement.

A mathematical expression of the force of the roller-pavement vibrating system is given by

$$F = ma \tag{3}$$

where a = acceleration. The static-force (F_s) portion of the system is

$$F_s = W \tag{4}$$

since a = g. The vibrating-force (F_v) portion of the system is given by

$$F_v = m'a' = W'a'/g \tag{5}$$

where W'/g = eccentric mass,
maximum a' = $4\pi^2f^2r'$,
r' = eccentric arm (in.), and
f = forced frequency (vpm).

Substituting and applying conversions, Equation 5 becomes

$$F_v = 2.8416 \times 10^{-5}\ W'f^2r'.$$

The total force (F_t) will be

$$F_t = F_s + F_v = k_sd_t, \tag{6}$$

where k_s = spring constant of pavement,
d_t = total displacement = $d_s + d'$,
d_s = static displacement, and
d' = vibratory displacement.

Substituting Equations 4 and 5 into 6,

$$F_t = W + 2.8416 \times 10^{-5}\ W'r'f^2 = k_s(d_s + d').$$

Solving for d',

$$d' = [(W + 2.8416 \times 10^{-5}W'r'f^2)/k_s] - d_s. \tag{7}$$

By use of the Chevron Research Company computer program for the elastic analysis of an n-layered pavement system *(3)*, solutions for d_s as a function of W have been plotted in Figure 14. Assuming values for W and d_s, then d' can be calculated for given values of W' and r'.

When $f = f_n$, where f = operating or forced frequency, the system is said to be in resonance *(4, 5, 6)*. The resonant frequency is

$$f = 3.127/\sqrt{d_t}. \tag{8}$$

The resonant amplitude (d_{res}) may then be determined from

$$d_{res} = d_t/2(n/p), \tag{9}$$

where d_t = F_t/k_s,
p = $\sqrt{k/m}$,
n = $c/2m$, and
c = coefficient of damping.

The critical damping $c_c = 2\sqrt{km} = 2\ mp = 2k/p$. The resonant amplitude is not the maximum amplitude; but for small damping, the two are practically the same. Since it is easier to find the resonant amplitude than the maximum amplitude, the resonant amplitude is usually used. The phenomenon of resonance was observed on the specific mixes used on both parkway projects as the rollers were being adjusted to obtain the desired density. A tell-tale sign of resonance is to observe daylight under the roller wheel. The rollers were immediately stopped and the eccentric readjusted to eliminate resonance. If this action had not been taken, rotation or translation of the aggregate particles would have precluded attainment of the desired density.

After assuming values of W and d_s, Equation 7 is used to determine d_t ($\approx d_s$), which may in turn be used in Equation 8 to determine an operating frequency. A graphical solution of Equation 8 is presented in Figure 15. As the pavement system stiffens as compaction progresses, d_s diminishes, and the likelihood of encountering resonance is greater during the final coverages and while compacting thin layers on a stiff foundation. If resonance is suspected, vibration should be discontinued.

The temperature during compaction is very critical and must be rigidly controlled when using vibrating rollers. A report on the state of the art of compaction of asphalt pavements indicated a minimum temperature of 175°F is generally accepted within the industry *(7)*. Data from the parkway projects indicated that the minimum compaction temperature should be 200°F for the specific bituminous concrete mixes used.

Roller capacity is of general interest to engineers and contractors and is often expressed in terms of the capacity in tons per hour. Another measure of capacity of rollers is square feet per hour. To find the number of passes required to obtain desired density, density growth curves must be used. One movement of a roller past a specific point on its longitudinal path defines a pass. A coverage is the number of passes required to completely cover the width of the pavement *(7)*. The number of coverages to roll an area to density is given by:

$$N_T = N_D W/(W_D - W_O) \qquad 10$$

where N_T = number of coverages required for density,
W = width of pavement (ft.),
W_D = width of roller drum (ft.),
W_O = width of drum overlap per pass (ft.), and
N_D = number of passes required for density.

To find the area to be rolled, the following equation can be used:

$$A = SW/N_T \qquad 11$$

where A = area to be rolled (ft.^{2}/hr.) and
S = speed (ft./hr. = 5280 x mph).

To find the length of the area, the following equation can be used:

$$L = S/N_T \qquad 12$$

where L = length of area (ft./hr.).

The above equations apply to all types of rollers, including static.

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7. *State of the Art: Compaction of Asphalt Pavements,* Special Report No 131, Highway Research Board, 1972.

TABLE 6. SUMMARY OF NUCLEAR DENSITY TESTS

ROLLER	AVERAGE NUMBER OF PASSES	NUMBER OF TEST DAYS*	AVERAGE PERCENTAGE COMPACTION	STANDARD DEVIATION	STANDARD ERROR OF MEAN	PERCENT COMPACTION		
						MAXIMUM	MINIMUM	RANGE
CUMBERLAND PARKWAY (BSP 11-1)								
Raygo 404B	8	9	96.8	1.5	0.5	98.3	93.5	4.8
Buffalo BW 210A	7	3	97.3	1.4	0.8	98.5	95.8	2.7
Tampo RS-288A and Buffalo KX 25E	5	25	98.3	0.7	0.1	99.4	96.9	2.5
Tampo RS-288A with one wheel vibrating	6	18	98.0	1.0	0.2	99.8	96.2	3.6
Tampo RS-288A with two wheels vibrating	5	45	98.0	1.1	0.2	100.4	94.5	5.9
All combinations of Tampo RS-288A	5	88	98.1	1.0	0.1	100.4	94.5	5.9
Conventional	7	3	94.0	1.2	0.7	95.2	92.8	2.4
All roller types combined	7	103	97.8	1.3	0.1	100.4	92.8	7.6
GREEN RIVER PARKWAY (BOP 11-1)								
Buffalo BW 210A	7	7	97.7	1.2	0.5	99.2	95.9	3.3
Conventional	13	11	95.3	2.4	0.7	98.0	91.2	6.8
All roller types combined	10	18	96.2	2.4	0.6	99.2	91.2	8.0

*Number of days during which 5 tests were performed for control purposes.

TABLE 7. COMPARISON OF DENSITIES FROM CORES, MARSHALL TESTS, AND NUCLEAR TESTS

		UNIT WEIGHTS (PCF)				
DATE 1972	PARKWAY	CORE	MARSHALL DESIGN	MARSHALL MOLDED	NUCLEAR METER*	TYPE OF ROLLER
May 25	Cumberland	145.3	152.4		144.0	Static
June 2	Cumberland	150.5	152.4		149.6	Vibratory
June 2	Green River	149.4	152.1		149.3	Static
June 26	Cumberland	146.2	152.8		145.0	Vibratory
August 3	Cumberland	152.6	152.8		150.6	Vibratory
August 24	Cumberland	151.6	152.8		148.5	Vibratory
August 24	Cumberland	151.0	152.8		150.6	Vibratory
August 24	Cumberland	151.6	152.8		150.7	Vibratory
August 24	Cumberland	150.4	152.8		154.4	Vibratory
August 24	Cumberland	152.3	152.8		152.3	Vibratory
August 24	Cumberland	152.3	152.8		152.0	Vibratory
August 24	Cumberland	149.1	152.8		150.2	Vibratory
October 5	Cumberland		150.4	150.4	150.1	Vibratory
October 14	Cumberland		150.4	150.5	152.3	Vibratory
October 19	Cumberland		150.4	149.7	148.6	Vibratory

*Corrected for meter calibration.

TABLE 8. VARIATIONS OF DENSITIES WITH DEPTH

BASE COURSE*	NUMBER OF TESTS	AVERAGE PERCENT COMPACTION	STANDARD DEVIATION	STANDARD ERROR OF MEAN	PERCENT COMPACTION		
					MAXIMUM	MINIMUM	RANGE
1	95	98.1	2.0	.2	101.2	90.2	11.0
2	103	97.8	1.7	.2	101.0	92.0	9.0
3	72	98.0	1.3	.2	101.0	94.4	6.6
4	86	98.5	1.5	.2	101.8	95.5	6.3

*The base courses are numbered from bottom to top.

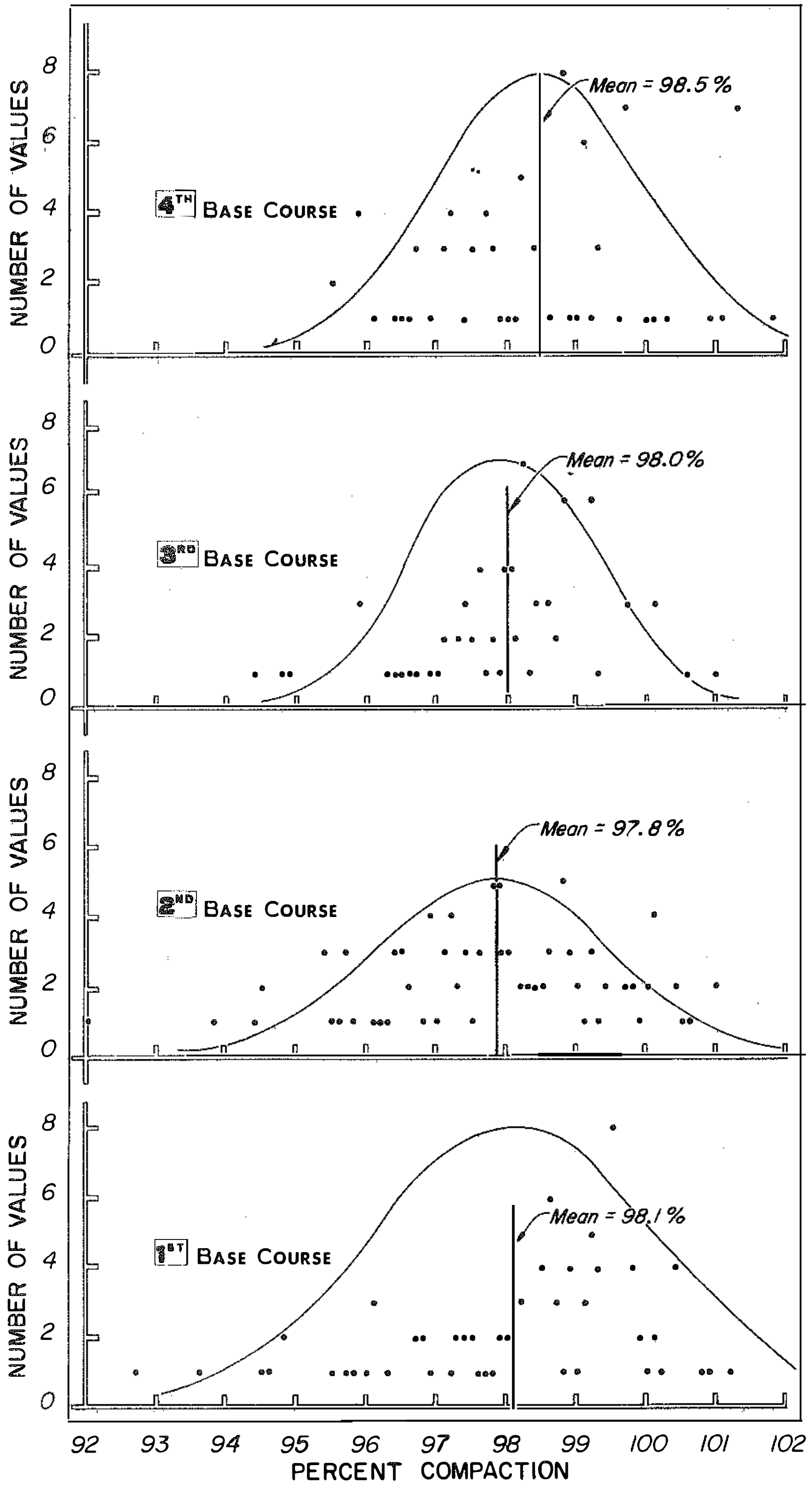

Figure 4. Density Test Results for All Rollers.

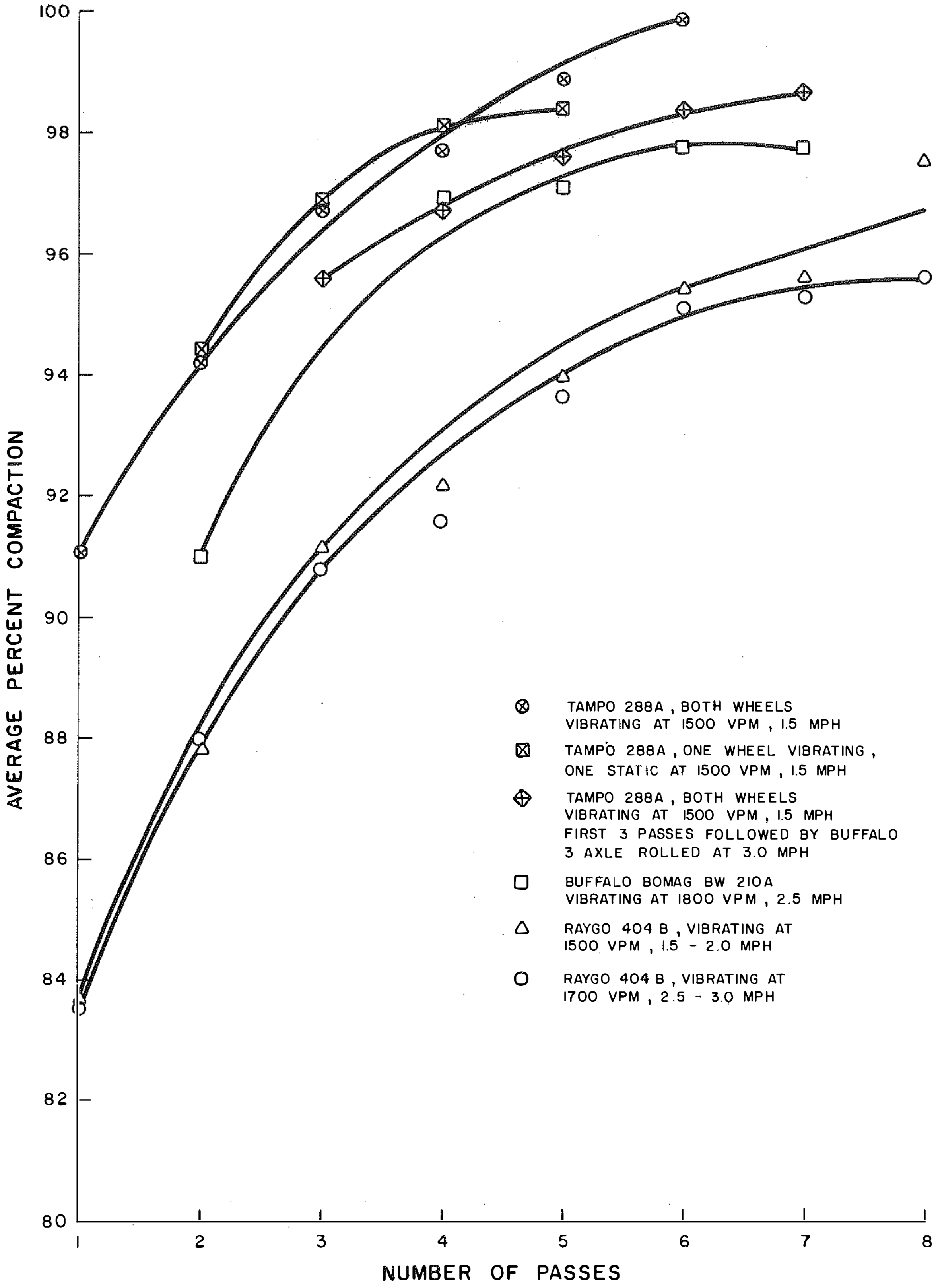

Figure 5. Density Growth Curves for the Cumberland Parkway Project, BSP 11-1.

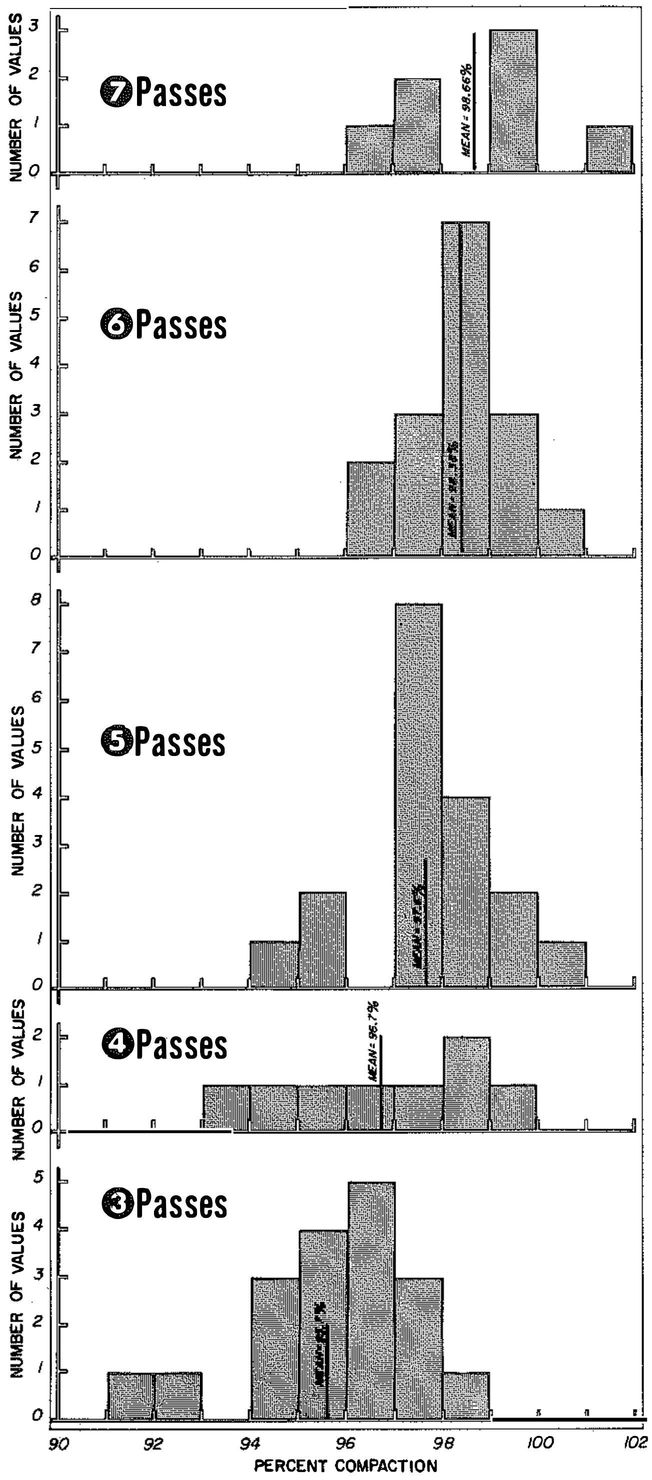

Figure 6. **Distributions of Percent Compaction for the Tampo Roller (with Both Wheels Vibrating) Followed by the Buffalo KX 25E Roller.**

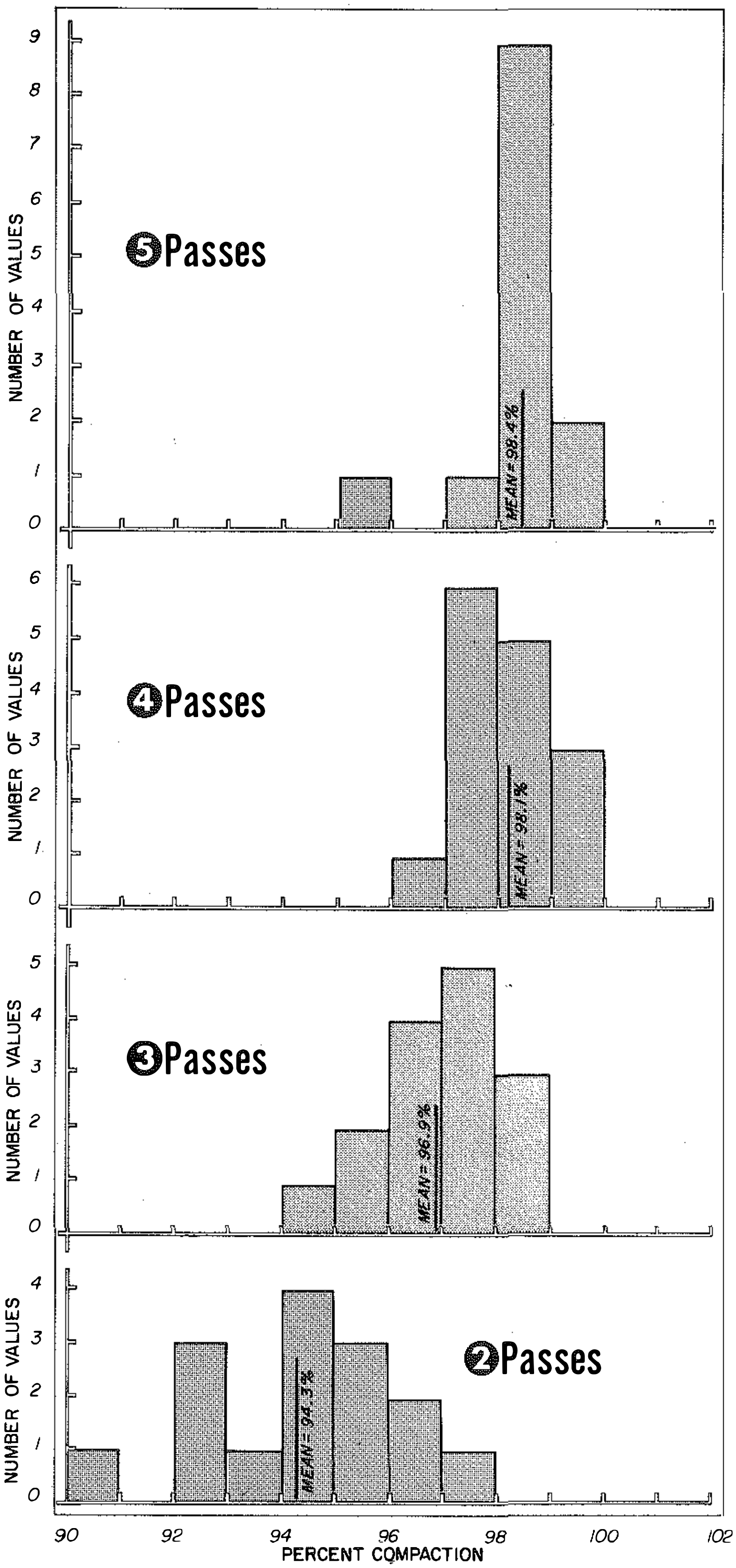

Figure 7. Distributions of Percent Compaction for the Tampo Roller (with One Wheel Vibrating at 1500 vpm) at 1.5 mph.

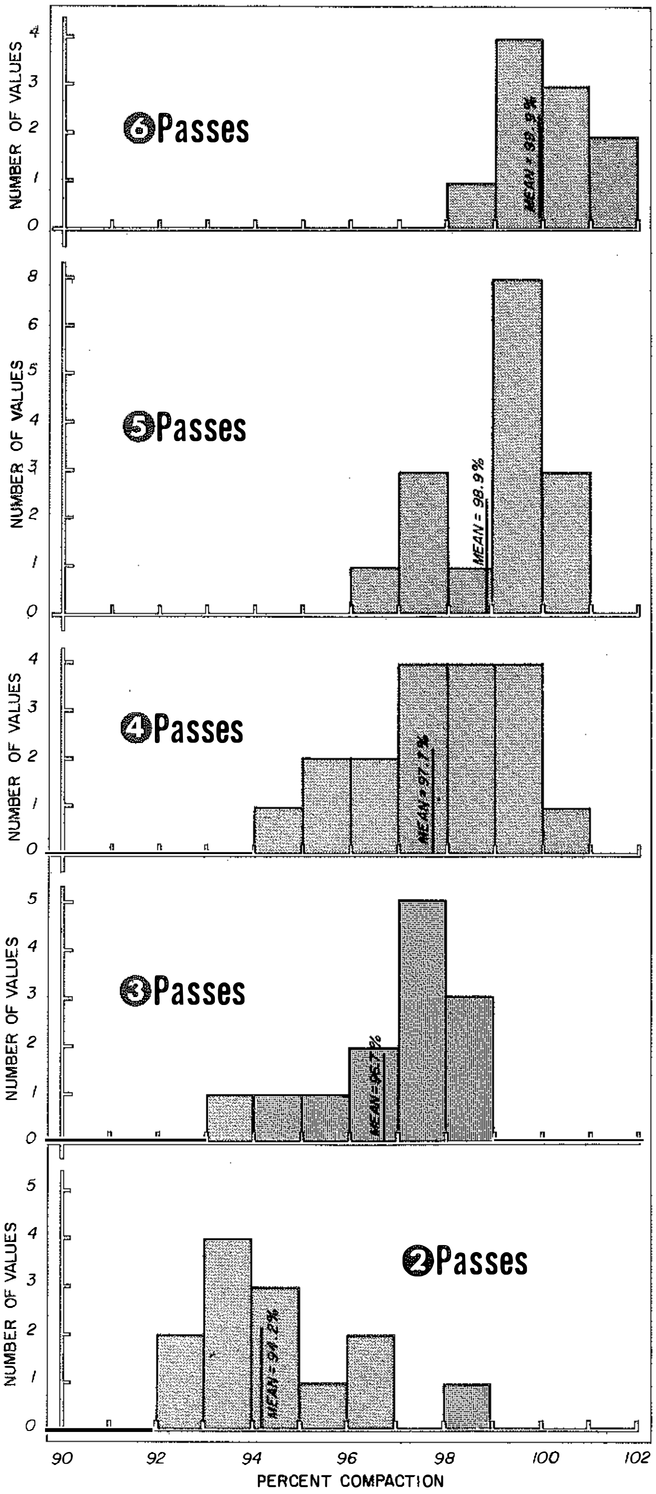

Figure 8. **Distributions of Percent Compaction for the Tampo Roller (with Both Wheels Vibrating at 1500 vpm).**

TABLE 9

DENSITY OF CURED BITUMINOUS CONCRETE PAVEMENT

Number of Tests	33
Average Percent Compaction	97.7
Standard Deviation	3.1
Standard Error of Mean	0.5
Maximum	101.7
Minimum	88.6
Range	13.1

TABLE 10

ROAD RATER AND BENKELMAN BEAM DEFLECTIONS (INCHES)

	ROAD RATER DEFLECTIONS	BENKELMAN BEAM DEFLECTIONS
Number of Tests	68	40
Average Deflection	1.91×10^{-4}	3.96×10^{-3}
Standard Deviation	2.82×10^{-5}	1.02×10^{-3}
Standard Error of Mean	3.43×10^{-6}	1.62×10^{-4}
Maximum	2.7×10^{-4}	7.0×10^{-3}
Minimum	1.5×10^{-4}	2.0×10^{-3}
Range	1.2×10^{-4}	5.0×10^{-3}

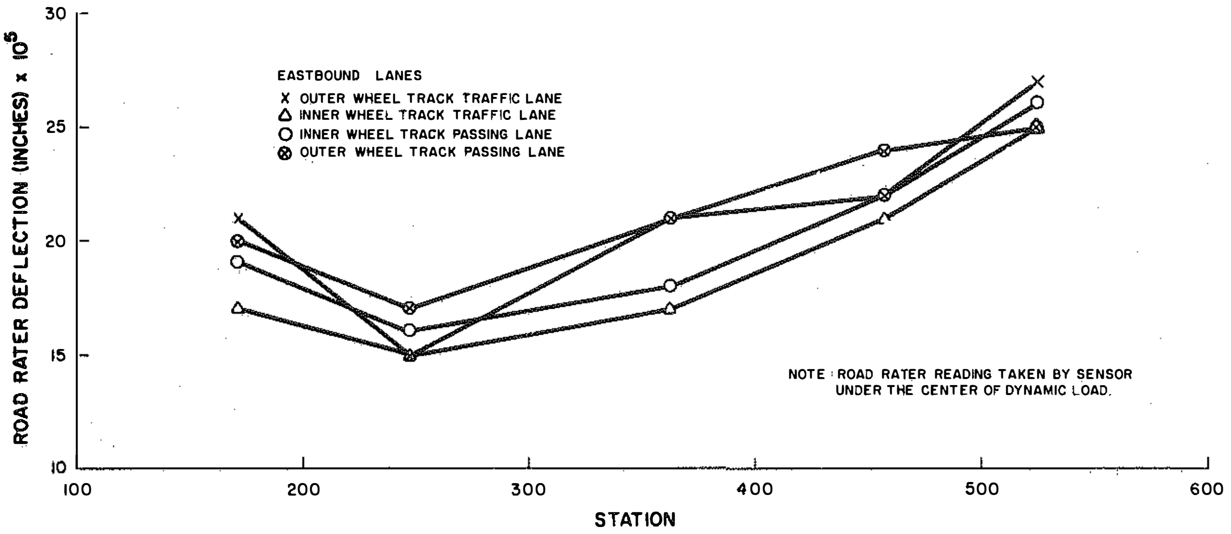

Figure 9. **Road Rater Deflections, Eastbound Lanes, for Cumberland Parkway Project, BSP 11-1.**

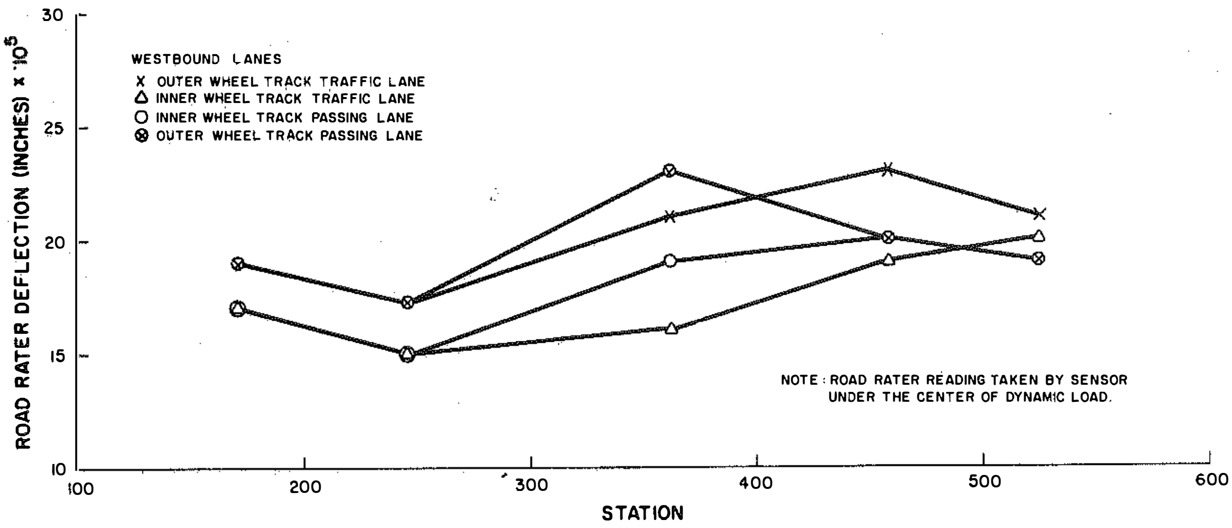

Figure 10. **Road Rater Deflections, Westbound Lanes, for Cumberland Parkway Project, BSP 11-1.**

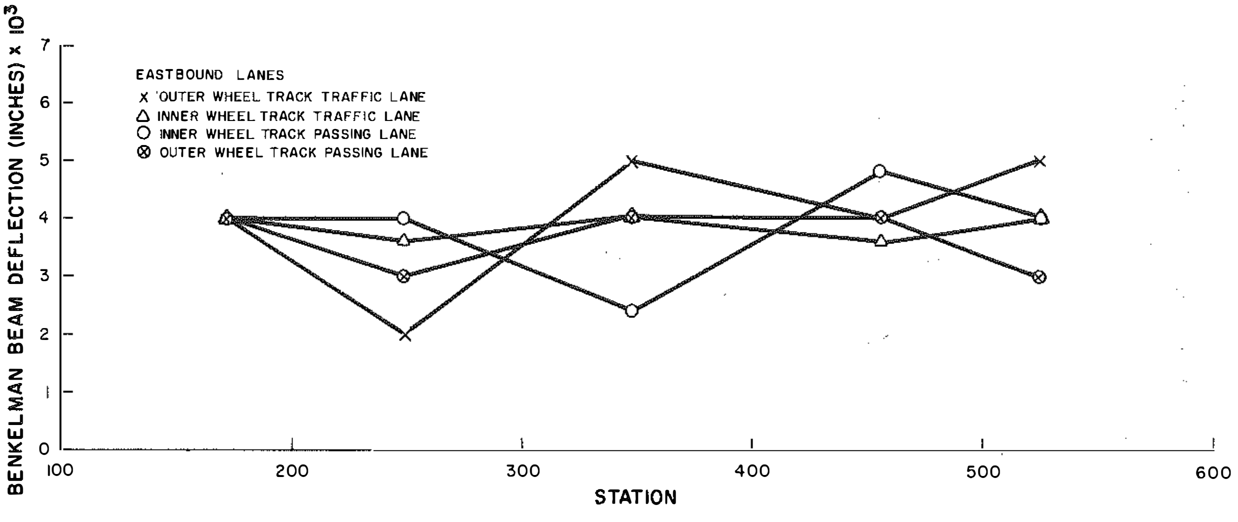

Figure 11. **Benkelman Beam Deflections, Eastbound Lanes, for Cumberland Parkway Project, BSP 11-1.**

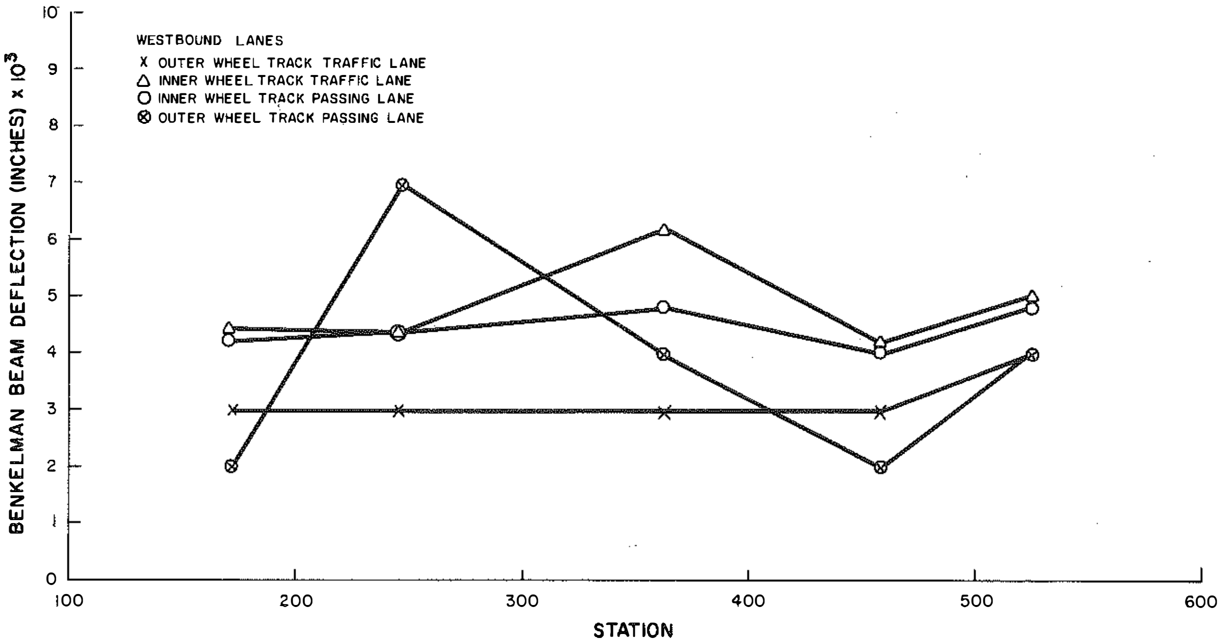

Figure 12. **Benkelman Beam Deflections, Westbound Lanes, for Cumberland Parkway Project, BSP 11-1.**

TABLE 11. PROFILOMETER MEASUREMENTS

LANES	NUMBER OF TESTS	SURFACE VARIATION (INCHES)	STANDARD DEVIATION	STANDARD ERROR OF MEAN	SURFACE VARIATION MAXIMUM	MINIMUM	RANGE
EB outer	109	0.0046	0.0466	0.0045	0.190	- 0.103	0.293
EB inner	111	0.0032	0.0426	0.0040	0.100	- 0.140	0.240
WB inner	110	0.0070	0.0384	0.0037	0.125	- 0.083	0.208
WB outer	110	0.0051	0.0423	0.0040	0.100	- 0.100	0.200

TABLE 12. COEFFICIENTS OF FRICTION

Number of Tests	63
Skid Resistance Factor	.514
Standard Deviation	.0512
Standard Error of Mean	.0064
Maximum	0.62
Minimum	0.38
Range	0.24

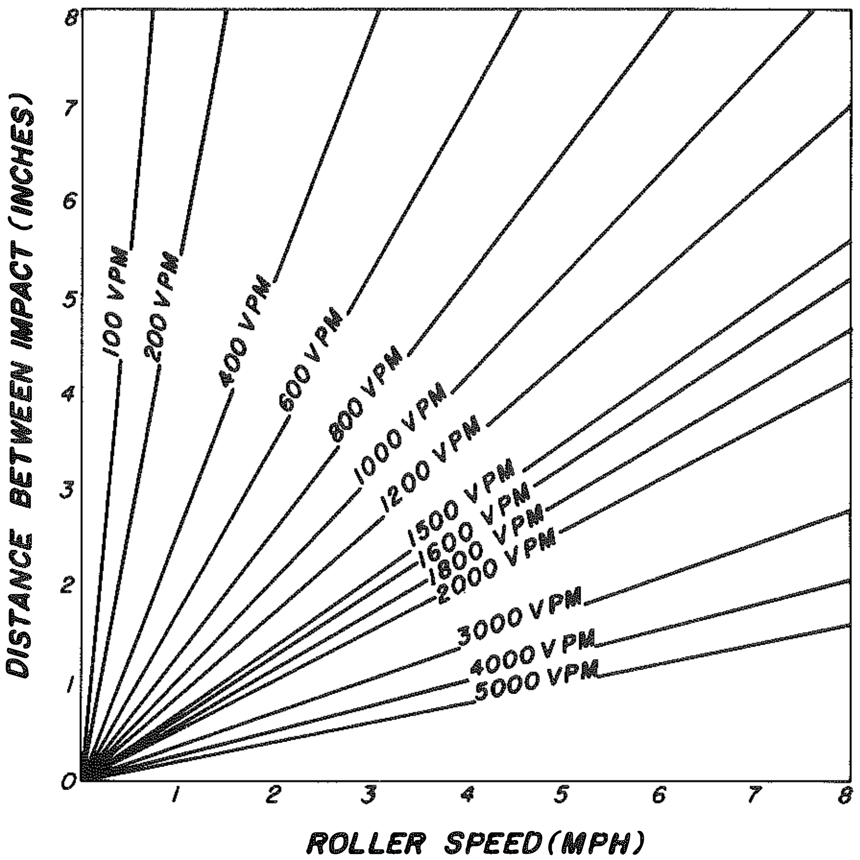

Figure 13. Distance between Impacts as a Function of Roller Speed.

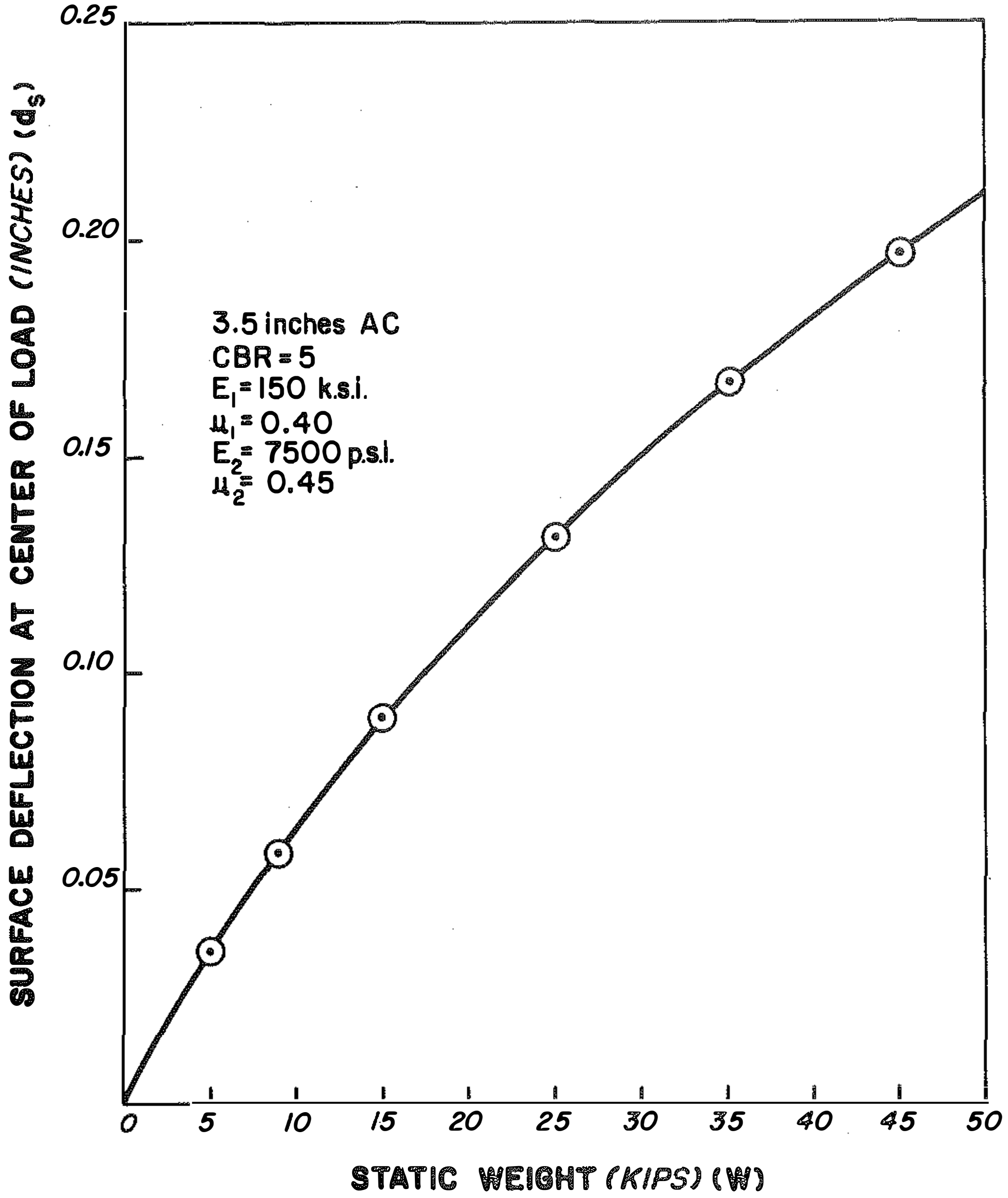

Figure 14. Surface Deflection as a Function of Static Weight.

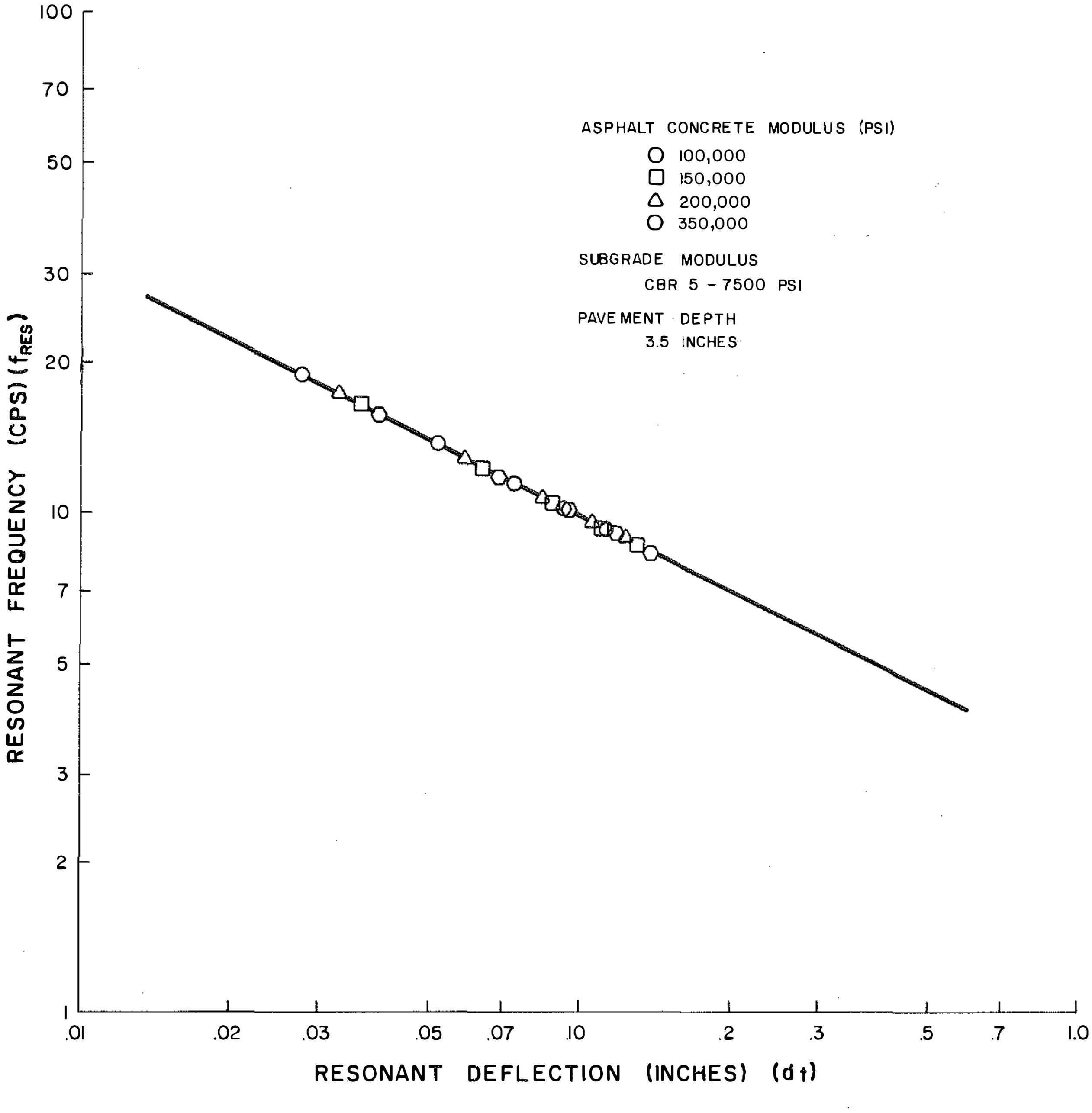

Figure 15. Resonant Frequency as a Function of Resonant Deflection.

APPENDIX

COMPACTION AND DENSITY REQUIREMENTS FOR CLASS I BASES

Roller requirements and numbers of coverages specified in Articles 306.3.2 G and 306.3.7 A of the 1965 **Standard Specifications...** may be superseded under the following conditions. Rollers and(or) other compaction equipment selected by the contractor shall be subject to the approval of the engineer. The number of compacting units, sequence of coverages, speed, echelon operations, and the rolling pattern shall be sufficient to compact the paving course to a prescribed, required density. Any compaction device or mode of operation found to be damaging to the pavement shall be discontinued.

The density of Class I Base courses shall average 98% of laboratory density. Laboratory density test results shall be provided by the Division of Materials before paving is begun and during the progress of the work as adjustments in the mixture and check tests are made. At the beginning of paving, density tests may be made by Department personnel after each pass of the compactor(s) in order to develop density-vs-coverage graphs. Such information may be used to establish a rolling pattern and to guide intensification thereof if such need arises. The necessary, preliminary information and pattern shall be obtained within the first one thousand feet of paving.

To determine compliance with the density requirement, 5 consecutive, randomly spaced nuclear density tests shall be made on the compacted course. The lowest allowable average of these tests (each expressed as a percentage of laboratory density) shall be 96.44% of laboratory density. The lowest allowable, individual test value shall be 94.50% of laboratory density. Not less than 5 consecutive tests shall be made each day of paving unless work is discontinued for cause. Failure to comply with these requirements shall be cause for increasing the rolling pattern or intensity of compaction.