Vibratory Compaction of Asphalt Concrete

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Over the last few years, the New York State Department of Transportation has been investigating the feasibility of using vibratory compaction on asphalt concrete. A total of 10 different roller models were used on three overlay contracts and seven new construction projects. The rollers represented a wide range of dimensional and operating characteristics, which initially led to greatly varying results. Discovery of two important operating parameters resulted in development of performance criteria applicable to any roller. These parameters—the spacing of drum impacts and their magnitudes—can be controlled by adjusting forward speed, drum frequency, and drum amplitude. Impact magnitude, termed unit total applied force, was correlated with layer thickness to produce the ranges necessary for each lift. As expected, the force necessary for adequate compaction increased with lift thickness, but on lifts thinner than 76 mm (3 in) the maximum force applied was found to be equally critical. When the force was too great, roller rebound occurred, which reduced densities. Vibratory rollers also compacted single-lift wearing courses and base courses—6.3 to 20.3 cm (2.5 to 8 in) thick respectively—more efficiently than conventional rolling. When operated properly, vibratory rollers were found to be effective in compacting asphalt concrete. Operating criteria were developed to determine the ability of any roller to compact a given lift thickness.

For many years, the concept of vibrating during compaction to seat individual particles better and to produce a denser layer has been employed in working with granular materials. During the 1960s, engineers in several European countries—notably Germany and Sweden—began applying these principles to asphalt paving. Eventually, manufacturers in the United States began experimenting with vibratory rollers on asphalt, and their inquiries addressed to the New York State Department of Transportation were received with interest.

A study was initiated to evaluate use of these rollers on asphalt courses. Ultimately 10 different rollers were tested on 10 construction projects. Both standard lift thicknesses and experimental "thick-lift" sections were compacted under a variety of conditions. The standard comparison was made with results obtained from the conventional rolling trains—a steel-wheel breakdown roller, a pneumatic roller, and a steel-wheel finish roller. These comparisons were used to determine whether vibratory rollers could achieve at least comparable densities with less equipment and lower labor costs.

Initially, the study was designed to determine the feasibility of using the vibratory concept on asphalt, but the rollers represented so wide a range of design and operating characteristics, that we achieved a more thorough analysis of these attributes than anticipated. The result was a comprehensive evaluation of roller variables in terms of the finished pavement.

INVESTIGATION

Test Program

The 10 projects comprise 3 resurfacings and 7 new construction projects. Figure 1 shows job locations and roller models used, and Table 1 lists the various courses compacted by vibratory rollers at each site. Both standard and experimental lift thicknesses were constructed on most jobs. The standard thicknesses were either 7.6 or 10.2 cm (3 or 4 in) for base course, 3.8 cm (1.5 in) for binder, and 2.5 cm (1 in) for top.

Measurements

Test sections 457 m (1500 ft) long and one lane 3.7 m (12 ft) wide were established, and all measurements were made in those areas. Several roller operating characteristics were checked or verified before each test. Frequencies were measured with a vibrating reed tachometer, and roller speeds were monitored by timing them over premeasured distances. Generally, because there were no methods for measuring drum amplitudes or static weights, the manufacturers' figures were used. Operators in the conventional train

Figure 1. Numbered job locations.

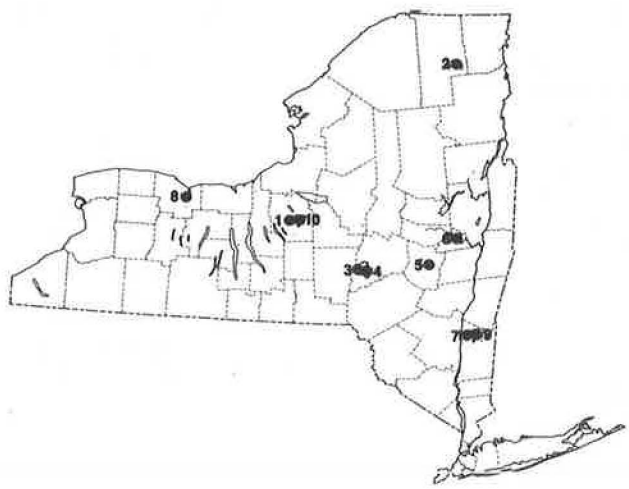


Table 1. Types of courses and rollers at job locations.

Job	Location	Rollers[a]	Base Course	Wearing Course
1	I-690 Syracuse	A, E	Two 10.2-cm lifts One 20.3-cm lift	3.8-cm binder 2.5-cm top
2	NY-30 Tupper Lake	D, F	Two 7.6-cm lifts One 15.2-cm lift	3.8-cm binder 2.5-cm top
3	County Rt-47 Oneonta	H	Two 7.6-cm lifts One 15.2-cm lift	3.8-cm binder
4	NY-205 Oneonta	A, B, G	—	3.8-cm binder
5	NY-20 Carlisle	F	Resurfacing (no base needed)	2.5-cm top 6.4-cm top
6	NY-147 Glenville	E	Resurfacing (no base needed)	2.5-cm top 6.4-cm top
7	I-684 Golden's Bridge	B, C	Two 10.2-cm lifts One 20.3-cm lift	3.8-cm binder 10.2-cm top 2.5-cm top
8	NY-19 Rochester	I	Resurfacing (no base needed)	2.5-cm top
9	I-684 Golden's Bridge	C	—	6.4-cm top
10	I-690 Syracuse	J	—	6.4-cm top

Note: 1 cm = 0.39 in.

[a] Manufacturers' roller names are A = Vibro-Plus CA 25A, B = Vibro-Plus CC 42A, C = Vibro-Plus CC 50A, D = Galion VOS-84, E = Bros SPV-735VA, F = Raygo 404B, G = Buffalo Bomag BW 210-A, H = Hyster C615-A, I = Tampo RS-166A, and J = Ingersoll-Rand SPA-54.

used normal techniques while rolling; operators of vibratory rollers attempting to achieve proper density relied (primarily on earlier jobs) on the advice of manufacturers' representatives who recommended that they vary the rolling patterns, speeds, or frequencies. However, this type of consultation became less important as operators gradually identified the proper parameters.

OPERATING PARAMETERS

Vibratory rollers compacted the various asphalt courses to at least the same densities as the conventional rolling train and, in the latter portions of the study, to slightly greater densities. Table 2 gives results from jobs 1 and 7. Densities from vibratory rollers on job 1 are slightly lower than, but statistically equal to those on job 7, where, however, they are slightly higher on the base course and significantly higher on the binder and top. This improvement in vibratory densities resulted from identifying and quantifying the following two basic relations among several roller variables:

1. Proper matching of the roller's forward speed and the vibrating drum's frequency, a combination that determines the spacing of impacts along the pavement, and
2. Several static and dynamic characteristics of each roller that produce the force applied to the pavement.

Both relations became apparent about a third of the way through the sequence of jobs and were verified and refined on the remainder.

Impacts Per Meter

The need to carefully match the roller's forward speed with drum frequency became obvious in two ways.

The first was physical. When the intervals between impacts were too long, ripples were left in the pavement surface. Although this is not critical on base course layers, it becomes intolerable on binder and top courses. One remedy was following the vibratory roller with a steel-wheel static roller that ironed out the ripples if applied before much additional cooling occurred.

Second, problems began to appear when data were being compiled and summarized. Base course data from jobs 1 and 2 were as follows (1 kg/m^3 = 0.062 lb/ft^3).

Job	Roller	Density (kg/m^3) Vibratory Rolling	Density (kg/m^3) Static Rolling
1	E_1	1888	1878
	E_2	1811	
2	D_1	1821	1811
	D_2	1829	
	D_3	1747	
	F	1809	

Each density figure is an average of about 60 nuclear density readings. On each job, one vibratory rolled section's density (E_2, D_3) is well below that of the conventionally rolled, while others are similar. Reexamination of the data showed that, for sections with higher densities, the combination of roller speed and frequency resulted in the drum's hitting the pavement at 20.3 and 25.3 impacts/m (6.2 and 7.7 impacts/ft). Conversely, on low-density sections, these figures were 12.1 and 16.0 impacts/m (3.7 and 4.8 impacts/ft).

To check the premise that this impact spacing was the cause of the lower densities, we varied roller speed on the 3.8-cm (1.5-in) binder course of one job and maintained a frequency of 1700 vibrations/min (vpm). The results for one roller pass at each speed were as follows (1 km/h = 0.62 mph; 1 m = 3.28 ft; 1 kg/m^3 = 0.062 lb/ft^3).

Speed (km/h)	Impacts per Meter	Nuclear Density (kg/m^3)
3.2	31.5	2023
3.9	26.2	2005
4.5	22.6	1995
6.4	15.7	1958

On another job, where a dual-drum roller was being tested, two speeds—4.0 and 9.7 km/h (2.5 and 6.0 mph)—were checked on a 2.5-cm (1-in) top course. At a 2300-vpm frequency, this produced 34.1 and 14.1 impacts/m (10.4 and 4.3 impacts/ft), which resulted in respective nuclear densities of 2323 and 2238 kg/m^3 (144.8 and 139.5 lb/ft^3).

Finally, another change was tried. Frequency was increased with speed. The net result was a drop in the number of impacts per meter from 27.9 to 22.3 (8.5 to 6.8 impacts/ft) and a slight drop in density from 1833 to 1813 kg/m^3 (114.3 to 113.0 lb/ft^3) compared with the density of 1837 kg/m^3 (114.5 lb/ft^3) under conventional rolling.

Because much of this is obvious (fewer impacts mean lower density) the natural response might be to increase the number of roller passes. Unfortunately, this defeats the roller operator's primary reason for increasing speed: keeping up with the paver. The result was the decision that speed and frequency should be matched to produce at least 21.3 impacts/m (6.5 impacts/ft).

Unit Total Applied Force

Although the primary aim of this study was to determine the feasibility of using vibratory compaction on asphalt, the number of roller models provided by the manufacturers presented an excellent opportunity to determine which roller characteristics best achieve sufficient densities. Conversely, this presented additional problems by bringing together rollers with a wide range of static and dynamic properties (1 cm = 0.39 in; 1 mm = 0.039 in; and 1 kg = 2.2 lb).

Property	Maximum	Minimum
Drum width, cm	216	168
Low frequency, vpm	2200	900
High frequency, vpm	2500	1700
Amplitude, double, mm	2.7	0.8
Net roller weight, kg	13 733	7059
Drum weight, kg	7131	3790

Table 2. Nuclear densities on jobs 1 and 7.

Course	Rolling	Job 1 Density (kg/m^3) No.	Job 1 Density (kg/m^3) Mean	Job 1 Density (kg/m^3) SD	Job 7 Density (kg/m^3) No.	Job 7 Density (kg/m^3) Mean	Job 7 Density (kg/m^3) SD
Base, first lift	Conventional	58	1873.6	139.2			
	Vibratory	119	1896.0	80.0			
Base, second lift	Conventional	61	1896.0	115.2	51	1966.4	137.6
	Vibratory	191	1883.2	83.2	51	2003.2	134.4
Binder	Conventional	61	2004.8	88.0	51	1926.6	89.6
	Vibratory	60	1980.8	52.8	51	2054.4	88.0
Top	Conventional	62	2046.4	59.2	87	2214.4	54.4
	Vibratory	156	2033.6	126.4	121	2278.4	44.8

Note: 1 kg/m^3 = 0.062 lb/ft^3.

These ranges, plus the fact that not all these data were initially available, made comparisons difficult. Because this and not the certification of individual rollers was the concept being investigated, it was important that a common measure be developed for a roller's ability to compact asphalt. This was further emphasized by the range and variation in densities at initial test sites. Ultimately, the actual force with which each roller impacted the asphalt was calculated, and we found a factor that standardized the compactive ability of otherwise widely different rollers

This factor was named "unit total applied force" (UTAF) by the Construction Industry Manufacturers Association (1) and is expressed in kilograms per linear centimeter. These linear measurements refer to the width of the roller drum. The UTAF factor can be calculated by using

$$UTAF = (F + S)/L \quad (1)$$

where

$F = (A/2)(w)\,[4\pi^2/g(60^2)]\,(f^2)$,
S = static drum reaction (including weight of drum, yoke, and all other equipment attached to drum) in kilograms;
L = drum width in centimeters;
A = peak-to-peak amplitude in centimeters;
W = drum weight (only drum and internal parts) in kilograms;
f = frequency in vibrations per minute; and
g = acceleration of gravity [979 cm/sec^2 (385.6 in/sec^2)].

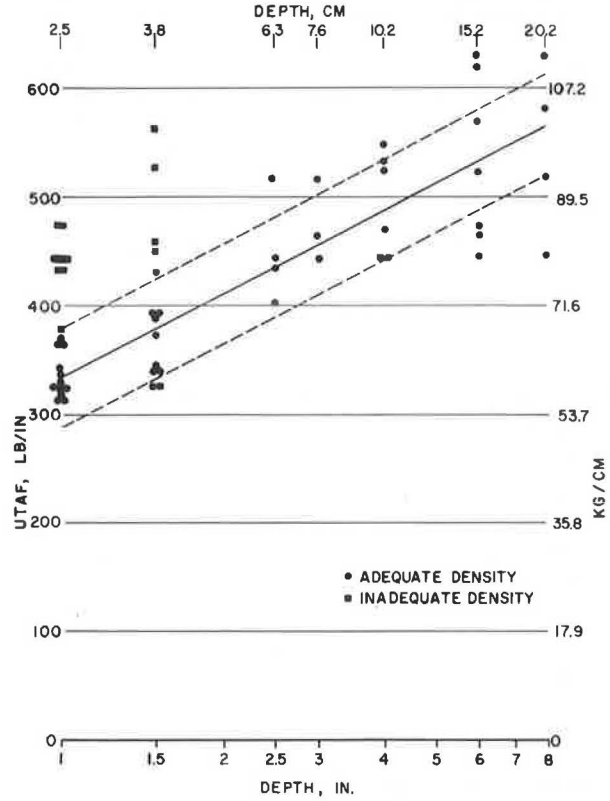
This was the key to understanding why sufficient densities were not achieved on some test sections. Figure 2 shows results of a regression analysis comparing UTAFs with lift thickness where satisfactory densities were achieved. Included in the figure, but not in the regression analysis, are results from test sections where less than satisfactory densities were achieved. As might be expected, the UTAF across the drum that was required increased with thickness, from about 53.6 kg/cm (300 lb/in) for 2.5-cm (1-in) top course to about 98.3 kg/cm (550 lb/in) for the experimental 20.3-cm (8-in) base course.

However, Figure 2 also shows that most of the unsatisfactory results occurred on the 2.5- and 3.8-cm (1.0- and 1.5-in) lifts, where UTAF was high in all but one case. This was probably caused by roller rebound, which is the impact force reflected off the underlying layer. If the layer being compacted is too thin to absorb the force in its total travel down to the underlying course and back up, the shock waves reach the surface and counteract the roller and make it bounce irregularly. Thus, impact UTAF, particularly on thin lifts, must be carefully controlled to achieve compaction but to avoid the rebound phenomenon.

The UTAF concept ties in directly with impacts per meter and illustrates why there is a limit on roller speed. Because frequency is a factor in determining UTAF, it cannot be increased indiscriminately, particularly on the thinner courses. Although each roller's exact limits might differ from those of other rollers, it was found that, at speeds above 4.0 to 4.8 km/h (2.5 to 3.0 mph), achieving satisfactory densities presented problems.

The amplitude, frequency, and ballast must be coordinated to produce the proper UTAF. In turn, the roller's forward speed must be linked to its frequency to ensure sufficient compaction and to avoid a rippled surface. In the course of investigating the various rollers, the optimum settings for each lift thickness were determined for all rollers. These were used on the last few jobs with encouraging results.

Figure 2. Effects of various UTAFs on lifts of various thicknesses.



It should be noted that both the compacting techniques and the material lay-down temperatures were similar on the test sections compacted by vibratory rollers. On every test section the vibratory roller was kept close behind the paver, at no time exceeding a distance greater than 76.2 m (250 ft) from it. The average and most common distance between paver and roller was approximately 45.7 m (150 ft).

After selecting the most roller passes required on any given test section—on the thinnest course of pavement [2.5 cm (1 in)], under the coldest ambient air temperature, with the lowest lay-down mat temperature, and at the greatest distance possible between the paver and roller [76.2 m (250 ft)]—the longest time required for complete rolling and compacting the material at any given spot to a desired density was 7.5 min. The maximum time for effective compaction of a freshly placed mat, under the worst conditions this investigation encountered, was 10 min. This calculation (Table 3) is based on an Illinois study (2).

DENSITY OF INDIVIDUAL COURSES OF STANDARD LIFT THICKNESSES

Results for each pavement course are given in Table 4, which includes job and test numbers, vibratory roller identification, speed, impacts per meter, and nuclear densities. Results for conventional static rolling are also listed. Even though several vibratory tests were made on most jobs, only one control section was measured. However, considering the number of readings taken, these results were representative. Density values were obtained with a nuclear device, so they do not represent absolute values. The primary evaluation was a comparison of rolling methods, and, as all read-

Table 3. Vibratory compaction time for a 2.5-cm wearing course.

Job	Test	Roller	Mat Temperature (° C)	Ambient Air Temperature (° C)	Time to Complete Compaction (min)	Maximum Time Allowed for Effective Compaction[a] (min)
1	13	A	137.8	25.6	6.5	15
	14	E_1	140.5	27.2	6.5	15
	15	E_2	140.5	27.2	6.5	15
2	34	D	140.5	23.9	6.5	13
	35	F_1	140.5	23.9	6.5	13
5	47	F_2	143.3	15.6	6.5	11
7	65	B_1	143.3	17.8	6.0	10
	66	B_2	143.3	17.8	7.5	10
	67	C	143.3	17.8	3.5	10
8	70	I_1	137.8	16.7	7.5	10
	71	I_2	148.9	16.7	7.5	12

Note: 1°C = (1°F - 32)/1.8 and 1 cm = 0.39 in.

[a] Maximum time for effective compaction of a freshly placed mat, derived from a University of Illinois study (2).

ings were made with the nuclear gauge, these comparisons are valid.

Base Course

Table 4 summarizes all test sections established on the 7.6- and 10.2-cm (3- and 4-in) base course lifts. On jobs 1 and 7, the design called for a 20.3-cm (8-in) base course constructed in two 10.2-cm (4-in) lifts, while jobs 2 and 3 had 15.2-cm (6-in) bases placed in two 7.6-cm (3-in) lifts. Densities the vibratory rollers achieved were generally the same as those the conventional roller train produced. That is, there was no statistical difference at the 95 percent confidence level. In the few cases where they did differ, vibratory rolling appeared to be insufficient.

The two cases on the first lift have already been discussed in connection with impacts per meter. A similar situation existed on the second lift, where roller H was operated at 8 km/h (5 mph) and gave only 13.4 impacts/m (4.1 impacts/ft) and densities on two sections significantly lower than on the control section. A third section was established on job 3, where a static steel-wheel roller followed the vibratory roller. This increased density but considerably reduced the value of using the vibratory roller.

This illustrates that, while slower operation is more time consuming, it saves time and effort in the long run by eliminating the need for a second roller. Unfortunately, this job was investigated before impacts per meter and UTAF (1 kg/cm = 5.6 lb/in) were found to be the keys to successful vibratory rolling; no tests were run at slower speeds.

Base Course, Both Lifts

Roller	Frequency (vpm)	Amplitude Setting	UTAF (kg/cm)
C	2400	High	113.2
D	1700±25	Normal	93.1
E	1650	High	98.6
F	1700	High	80.3
H	1800	Normal	83.3

Binder Course

Results of vibratory compaction on the 3.8-cm (1.5-in) binder courses were similar to those on base courses:

Table 4. Comparative nuclear densities by paving course.

		Vibratory Rolling							Static Rolling				
						Density (kg/m³)				Density (kg/m³)			
Course	Job	Test No.	Roller	Speed (km/h)	Impacts/m	No.	Mean	SD	Test No.	No.	Mean	SD	Significance (95% confidence level)
Base, first lift	1	4	E	4.8	20.5	61	1883.2	78.4	3	61	1873.6	139.2	No
		5	E	8.0	12.2	60	1806.4	83.2					Yes
	2	20	D	4.8	21.1	60	1816.0	89.6					No
		21	D	4.0	25.4	61	1823.4	104.0	19	61	1807.2	105.6	No
		22	D	6.4	15.8	62	1743.2	120.0					Yes
		23	F	4.8	21.1	59	1804.2	121.6					No
Base, second lift	1	6	E	3.2	31.0	71	1859.4	102.4	1	61	1839.7	155.2	No
		8	E	4.8	20.5	61	1889.6	83.2	7	61	1896.0	115.2	No
		9	E[a]	4.8	20.5	59	1907.4	70.4					No
	2	24	F	4.8	21.1	59	1762.4	140.8					No
		25	F	4.8	21.1	61	1779.7	112.0	16	61	1752.0	107.2	No
		26	D	4.0	25.4	61	1764.8	112.0					No
		27	D	4.8	21.1	66	1722.6	113.6					No
	3	38	H	8.0	13.5	61	1795.5	107.2					Yes
		39	H	8.0	13.5	61	1796.8	100.8	36	61	1853.0	128.0	Yes
		40	H[a]	8.0	13.5	61	1843.8	104.0					No
	7	59	C	4.8	30.0	51	2003.2	134.4	57	51	1966.4	137.6	No
Binder	1	11	A	4.8	28.7	60	1980.8	52.8	10	61	2004.8	88.0	Yes
	2	29	D_1	3.2	28.1	61	1829.3	76.8					No
		30	D_2	4.8	22.4	61	1807.8	120.0	28	61	1831.2	84.8	No
		31	F_1	5.6	22.4	61	1837.3	118.4					No
		32	F_2	5.6	18.2	61	1824.0	102.4					No
	3	42	H	8.0	13.5	61	1938.2	148.8	41	61	2012.2	99.2	Yes
		43	H	8.0	13.5	61	1950.7	132.8					Yes
	4	45	B	4.0	37.6	36	2052.8	83.2	44	36	2041.6	89.6	No
	7	61	C	4.8	28.7	51	2054.4	88.0	60	51	1926.6	89.6	Yes
Top	1	13	A	4.8	28.7	62	2062.2	59.2					No
		14	E_1	4.8	21.1	62	2027.4	73.6	12	62	2046.4	59.2	No
		15	E_2	4.8	21.1	32	1988.0	73.6					Yes
	2	34	D	4.8	22.4	61	2104.2	62.4	33	62	2119.7	56.0	No
		35	F_1	4.8	28.7	61	2078.1	67.2					Yes
	5	47	F_2	4.8	23.1	32	2156.8	41.6	46	32	2158.4	51.2	No
	7	65	B_1	9.6	14.9	43	2231.8	48.0					No
		66	B_2	4.0	36.0	27	2316.2	33.6	64	36	2240.0	51.2	Yes
		67	C	4.8	27.1	51	2299.4	52.8					Yes
	8	70	I_1	4.0	33.0	22	2164.3	33.6	68	40	2076.8	94.4	Yes
		71	I_2	4.0	33.0	33	2091.2	33.6	69	24	2012.8	94.4	Yes

Note: 1 km/h = 0.62 mph; 1 m = 3.28 ft; and 1 kg/m³ = 0.062 lb/ft³.
For specific roller frequencies, amplitude settings, and UTAFs, see the text tables on the base, binder, top courses.

[a] Followed by steel-wheel roller.

they equaled conventional rolling at the 95 percent level, with a few exceptions. In all but one case, where the two methods did not achieve similar densities, compaction by vibratory rolling was lower.

On job 1, where vibratory densities were significantly lower, the UTAF was found to be 68.1 kg/cm (325 lb/in) below the one standard error limit in Figure 2. The other low densities were on job 3, where roller H again was operated at 8 km/h (5 mph) and produced only 13 impacts/m (4.1 impacts/ft). Thus, on these jobs the two important criteria were not met, and adequate densities were not achieved.

Two other important points are evident in Table 4. The first is on job 4, where roller B produced a UTAF of 60.8 kg/cm (340 lb/in) (1 kg/cm = 5.6 lb/in), close to the lower limit, but compacted the asphalt to a slightly higher higher density than conventional rolling.

Binder Course

Roller	Frequency (vpm)	Amplitude Setting	UTAF (kg/cm)
A	2300	Low	58.5
B	2500	Low	61.2
C	2300	Low	69.7
D_1	1500	–	77.8
D_2	1800	–	101.2
F_1	2100	Low	70.2
F_2	1700	High	80.3
H	1800	–	83.3

Apparently, what counteracted this low UTAF was the very high frequency, which resulted in 37.4 impacts/m (11.4 impacts/ft). Also, on job 2, two test sections were each compacted with rollers D and F, with operational changes for each.

All densities were statistically equal to conventional densities, but there were practical differences. Roller D was run initially at 3.2 km/h (2 mph) and a frequency of 1500 vpm, then at 4.8 km/h (3 mph) and 1800 vpm, lowering the impacts per meter from 27.9 to 22.3 (8.5 to 6.8 impacts/ft) and increasing the UTAF from 77.2 to 100.4 kg/cm (432 to 562 lb/in). The net result was a drop in density of 20.8 kg/m^3 (1.3 lb/ft^3), which illustrates too great a UTAF for the thickness of the asphalt being compacted.

A similar situation resulted when the frequency was reduced on roller F from 2100 to 1700 vpm and the amplitude changed from 1.3 to 2.3 mm (0.05 to 0.09 in), while maintaining a forward speed of 5.6 km/h (3.5 mph). The net result was an increase in UTAF from 69.7 to 79.7 kg/cm (390 to 446 lb/in) and a drop in density of 13.3 kg/m^3 (0.83 lb/ft^3). In this instance, the impacts per meter dropped from 22.3 to 18.0 (6.8 to 5.5 impacts/ft), and the UTAF was at the upper limit.

Top Course

The 2.5-cm (1-in) top course required the most care in establishing and maintaining proper roller operating characteristics. However, it also appeared to benefit most from vibratory rolling in terms of density (Table 4). On the first three jobs (1, 2, and 5) the vibratory rolling produced significant density differences (lower) on two test sections. Conversely, on the last two jobs (7 and 8), four of five sections showed significant differences (higher) with vibratory rolling.

These figures again indicate that, once limits were determined for impacts and UTAF, results improved. It should be noted that the UTAF was over 71.5 kg/cm (400 lb/in) (1 kg/cm = 5.6 lb/in) on three test sections and that density was lower than conventional on all three, on two of them significantly.

Top Course

Roller	Frequency (vpm)	Amplitude Setting	UTAF (kg/cm)
A	2300	Low	58.5
B_1	2400	Low	58.6
B_2	2400	Low	58.7
C	2200	Low	66.6
D	1800	–	101.2
E_1	1700	½	65.2
E_2	1700	¾	84.1
F_1	2300	Low	79.7
F_2	1850	Low	59.4
I_1	2200	Medium	60.8
I_2	2200	Medium	60.8

In both latter cases, two sections were compacted with each roller, and changes were made in their operation. On roller E the amplitude setting was changed and on roller F the frequency. In the former, changing the amplitude from 1.1 to 1.6 mm (0.042 to 0.063 in) increased the UTAF from 64.7 to 83.5 kg/cm (362 to 467 lb/in) and decreased the density by 40.1 kg/m^3 (2.5 lb/ft^3). Roller F's frequency was changed from 1850 to 2300 vpm, increasing the impacts per meter from 23.0 to 28.5 (7.0 to 8.7 impacts/ft) and the UTAF from 59 to 79 kg/cm (330 to 443 lb/in), resulting in a 78.6-kg/m^3 (4.9-lb/ft^3) density decrease.

In both cases, the excess force apparently resulted in roller rebound, which demonstrates that, on thin asphalt courses, the maximum force is as important as the minimum. It also demonstrates the danger of increasing frequency in a way that might increase roller speed.

On the last two jobs, only one of five sections, job 7 with roller B_1, was not significantly better than conventional rolling. This was caused by the low number of impacts per meter—14.8 (4.5 impacts/ft)—as the roller was operated at 9.7 km/h (6 mph). The reason it was even close to the conventional figures was that three additional passes were made. When slowed to 4 km/h (2.5 mph), with 35.8 impacts/m (10.9 impacts/ft), density increased to 85.0 kg/m^3 (5.3 lb/ft^3).

DENSITY OF EXPERIMENTAL THICK LIFTS

Thick-Lift Wearing Course

The qualified success of vibratory rollers on the earlier jobs made possible another study, that of constructing the wearing course in one lift instead of separate binder and top lifts. Basically, effort was directed to finding means of prolonging the paving season. There was a secondary advantage however: more efficient operation with fewer passes of the paving train and fewer mix changes at the batch plant.

The anticipated problems of compacting thicker lifts of the New York State top course mix with vibratory rollers did not materialize, but several attempts to use conventional rollers resulted in excessive shoving of material both longitudinally and laterally.

Table 5 summarizes nuclear densities measured on four jobs where the single-lift wearing course was tested. These are given here to show the effectiveness of vibratory rolling and the roller adjustments used (1 kg/cm = 5.6 lb/in).

Thick-Lift Wearing Course

Roller	Frequency (vpm)	Amplitude Setting	UTAF (kg/cm)
C	2400	Low	72.7
E	1600	¾	77.6
F	1700	High	80.3
J	2200	–	85.5

Table 5. Comparative nuclear densities for experimental lift thicknesses.

		Vibratory Rolling							Static Rolling				
						Density (kg/m³)				Density (kg/m³)			
Course	Job	Test No.	Roller	Speed (km/h)	Impacts/m	No.	Mean	SD	Test No.	No.	Mean	SD	Significance (95% confidence level)
Thick-lift wearing	5	48	F	4.0	25.4	36	2233.6	60.8	46	30	2158.4	51.2	Yes
		49	F	4.0	25.4	35	2249.6	40.0					Yes
		51	F	4.0	25.4	33	2276.8	60.8	50	36	2222.4	44.8	Yes
		52	F[a]	4.0	25.4	36	2238.4	41.6					Yes
	6	54	E	4.0	24.1	36	2198.4	73.6					Yes
		53	E[a]	4.0	24.1	36	2259.2	67.2	53	36	2169.6	83.2	Yes
		55	E[a]	4.0	24.1	35	2243.2	65.6					Yes
	9	73	C	4.0	36.0	51	2292.8	43.2	72	51	2196.8	59.2	Yes
		74	C	4.0	36.0	51	2241.6	52.8					Yes
	10	76	J	4.0	33.0	51	2140.8	48.0					No
		77	J	4.0	33.0	51	2224.0	54.4	75	51	2140.8	56.0	Yes
		78	J	4.0	33.0	51	2145.6	65.6					No
Thick-lift base	1	2	E	4.8	21.1	65	1807.8	120.0	1	61	1839.7	155.2	No
	2	17	F	4.8	21.1	61	1767.8	121.6	16	61	1752.0	107.2	No
		18	D	4.8	22.4	64	1742.4	110.4					No
	3	37	H	4.8	22.4	61	1816.2	91.2	36	61	1853.0	128.0	No
	7	58	C	4.0	36.0	51	1955.2	185.6	57	51	1966.4	137.6	No

Note: 1 km/h = 0.62 mph; 1 m = 3.28 ft; and 1 kg/m³ = 0.062 lb/ft³.
For specific roller frequencies, amplitude settings, and UTAFs, see the text tables on the thick-lift wearing and base courses.
[a] Followed by steel-wheel roller.

Other factors are covered in greater detail in a separate report on that study (3). The figures for conventional rolling represent not only a three-roller train, but also a conventional two-lift wearing course. Table 5 shows that densities on all test sections are statistically the same as, or greater than those achieved on conventionally constructed sections.

Thick-Lift Base Course

In 1970, New York experimented with a thick-lift base course, putting down 15.2 cm (6 in) of asphalt in one lift. That test, using a heavy "air-on-the-run" pneumatic roller for breakdown rolling, was successful (4), but two rollers and at least 15 passes were needed to achieve adequate compaction. Once the new study was under way, it was proposed that a vibratory roller could accomplish this more efficiently. Sections on four jobs were constructed in one lift. These were from 457 to 853 m long (1500 to 2800 ft), 20.3 cm (8 in) thick on jobs 1 and 7, and 15.2 cm (6 in) thick on jobs 2 and 3.

Table 5 densities show no significant differences between thick-lift bases compacted conventionally or with vibratory rollers. Four sections received 20 to 23 impacts/m (6 to 7 impacts/ft) and a fifth almost 36 impacts/m (11 impacts/ft); UTAFs ranged from 79.7 to 112.4 kg/cm (446 to 629 lb/in). The two lowest UTAFs were actually below the lower limit but produced adequate densities. This indicates that, above a certain thickness, there is little need to increase the UTAF. Nor should there be concern about exceeding any magnitude of UTAF (1 kg/cm = 5.6 lb/in).

Thick-Lift Base Course

Roller	Frequency (vpm)	Amplitude Setting	UTAF (kg/cm)
C	2400	High	113.2
D	1800	—	101.3
E	1700	Full	102.8
F	1700	High	80.3
H	1800	—	83.3

Twenty-seven cores were taken from the 20.3-cm (8-in) thick-lift base section on job 1 to determine density uniformity down through the layer. They were cut into thirds horizontally, and bulk density was measured. These results and, for comparison, those from the earlier study were as follows (1 kg/m³ = 0.062 lb/ft³).

Portion Tested	Job 1 (kg/m³)	Earlier Study (kg/m³)
Top third	2117.3	2152.6
Middle third	2125.3	2279.3
Bottom third	2110.9	2144.5
Whole core	2115.7	2138.1

The same pattern is evident in both cases: greatest density in the center and least at the bottom. Results from vibratory rollers are more uniform, however, and indicate better seating of aggregates through the entire lift.

OTHER FINDINGS

Roller Passes

Before the impacts per meter and UTAF factors were accurately quantified, attempts to improve inadequate densities consisted primarily of additional roller passes. The results, however, were typical of what occurs with conventional rolling: density increases up to a certain point, then levels off or even decreases with further passes.

Figure 3 shows the results of varying the number of passes on several courses. In each case, an optimum

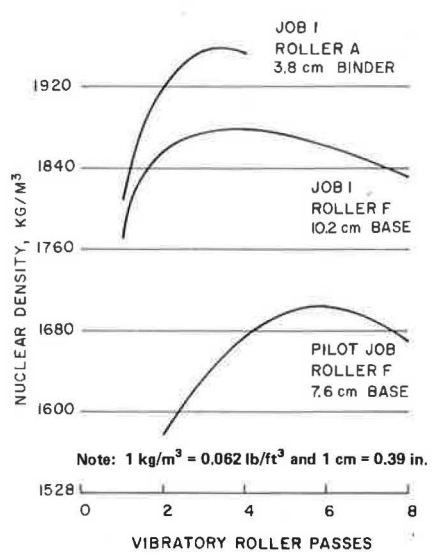


Figure 3. Effects of additional roller passes on asphalt density.

number is apparent and produces maximum density on a given course. Densities on the earlier jobs were sometimes insufficient, because rollers were not necessarily operating properly.

Once impacts per meter and UTAF were identified as the critical operating factors, determining optimum total roller passes for each course was relatively simple. (It should be noted that a roller pass is one passage of a vibrating drum over a given spot on the pavement.) In the later stages of this study, several rollers with two vibrating drums were evaluated. By definition, one dual-drum passage equals two roller passes.

Before regulating impacts per meter and UTAF, up to ten passes were being made on the 7.6- and 10.2-cm (3- and 4-in) base courses. Once these factors were controlled, three to four passes sufficed. Similarly, four passes were generally sufficient for thick-lift base course, although occasionally six were needed. For binder, two passes generally sufficed. The top needed only two, while the 7.6-cm (3-in) wearing course required four.

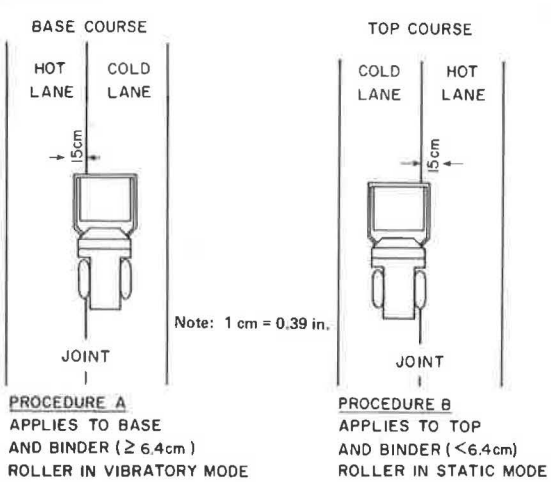
In some instances, additional static passes rolled out either ridges formed by not overlapping sufficiently or ripples resulting from too few impacts per meter. These problems were more critical on the binder or top courses, and in many instances a 9091- to 10 909-kg (10- to 12-ton) steel-wheel roller followed up on the top course.

Joint Construction

Construction of longitudinal joints differed with each course. For either normal or thick-lift base course, one of two procedures was used: the roller pinched the joint either from the cold lane in the static mode or from the hot lane in the vibratory mode, in both cases with the drive wheel centered on the joint (Figure 4). It could not vibrate while rolling on the cold lane, however, without causing roller rebound.

The same procedure can be used for binder, and the best results were achieved with procedure A in Figure 4. Top course required procedure B. The drum pinching the joint from the hot lane resulted in loss of pavement crown and in a corrugated or undulating surface when used on the top course.

Figure 4. Alternative longitudinal joint compaction procedures.



Aggregate Fracture

Aggregate fracture was another concern with vibratory rollers, but visual observations showed it to be no worse than that produced by conventional rolling.

Drive Wheels

Vibratory rollers with both pneumatic and steel drive wheels were included in this study, and both presented problems. Pneumatic wheels tended to pick up asphalt when they were cold. Steel wheels, although they operated well on binder and top courses, had problems obtaining proper traction on the base course—a situation aggravated on grade. Dual-drum rollers, which by definition and necessity use the vibrating steel drum for traction, had no such problems on any course.

Operating Considerations

Several practical precautions in operating vibratory rollers should be discussed. One noted earlier bears repeating: they should not be turned on fresh asphalt. When they must be moved laterally, it should be on material that is fully compacted. Another precaution is never to stop these rollers while the drum is vibrating, or a depression will result. This is particularly important when reversing direction, when the operator is more likely to overlook the fact that the drum is being allowed to vibrate in place, however briefly. Several rollers did have an automatic shutoff for the vibrating mechanism when roller speed dropped below 0.8 km/h (0.5 mph).

After the early jobs were completed, optional vibratory rolling was allowed on several projects. Unfortunately, rippled surfaces and inadequate densities appeared. The cause was generally excessive roller speeds, which must be watched carefully because operators new to vibratory rollers seem to feel they must avoid falling behind the paver. However, a few simple calculations involving the various speeds show that this will not occur.

Drum Width

Most rollers tested had a drum width of 210 cm (84 in). Several were narrower, however, 170 and 180 cm (60 and 72 in), and required a third pass for a 3.6-m (12-ft) lane, to ensure sufficient overlap. If a pavement is being placed full width—two lanes or 7.2 m (24 ft)—the situation changes. While two lanes still require one additional pass, in such paving this means five passes instead of four, rather than three instead of two as on a single lane.

Drum Diameter

All machines with a drum width of 216 cm (84 in) had a drum diameter of about 152 cm (60 in), and the machines with a drum width of 167 cm (66 in) had a diameter of 122 cm (48 in).

SUMMARY AND CONCLUSIONS

Vibratory rollers can compact New York State asphalt mixes to densities at least equal to those achieved by the conventional three-roller train. To accomplish this, they must operate within certain limits of speed, frequency, and amplitude, but, because the range of these factors as well as weights varied considerably among rollers, general guidelines could not be established to govern frequency and amplitude of all rollers. Fortu-

nately, this proved to be an advantage that allowed development of a more specific method of determining what was necessary to compact the various layers of asphalt.

The method involves calculating the force being applied to the asphalt and includes vibration frequency, vibration amplitude, and roller weight. This UTAF concept not only simplified roller evaluation but also provided a method for determining in advance whether a specific roller could compact a given layer.

Thus, the most significant result of this study was developing and relating this dynamic force concept to the degree of compaction achieved. Other specific conclusions in the course of this study included the following.

1. The force each roller applied to the asphalt under any given set of operating conditions (UTAF) is determined by the expression

$$\text{UTAF} = \left\{ [A(w)/2]\,[4\pi^2/g(60^2)]\,(f^2) + S \right\}/L \qquad (2)$$

2. The desired UTAF ranges (1 cm = 0.39 in and 1 kg/cm = 5.6 lb/in) for each pavement course were found to be

Course (cm)	UTAF Range (kg/cm)
Base, ≥10.2	78.6 to 107.2
Base, 7.6	72.4 to 88.5
Binder, 3.8	59.0 to 75.0
Top, 2.5	51.8 to 66.1
Top, 6.4	69.8 to 85.9

Up to about 10.2 cm (4 in), the minimum force increased linearly, then appeared to level off. Also, up to about 7.6 cm (3 in), the maximum limit is extremely important, because layers are not thick enough to absorb the additional energy and the roller may rebound.

3. The spacing of vibratory drum impacts is critical to producing both adequate densities and smooth surfaces. Forward speed of the roller must be coordinated with drum frequency to produce at least 19.7 impacts/m (6 impacts/ft).

4. Vibratory rollers can effectively replace the conventional three-roller train and produce equivalent densities with considerably fewer roller passes. On all courses 7.6 cm (3 in) or thicker, four to six vibratory passes were sufficient; three to four were needed on 3.8-cm (1.5-in) binder and two on 2.4-cm (1-in) top course.

5. Occasionally static passes were required to remove ripples or ridges, but judicious operators can virtually eliminate these. Transverse ripples are avoided by proper coordination of forward speed and drum frequency; longitudinal ridges are eliminated by sufficient overlapping of succeeding roller passes.

6. Apart from proper adjustments, the most critical factor in producing a smooth, well-compacted mat is a well-trained operator. There are three important operating considerations: never exceed a speed of 4.8 km/h (3 mph) or one that will produce less than 19.7 impacts/m (6 impacts/ft), never turn on uncompacted asphalt, and never leave the drum vibrating when the roller is stopped.

7. Thick-lift wearing and base courses, both tried experimentally on several jobs, were adequately compacted by vibratory rollers.

8. The amount of aggregate fracture was not increased by vibratory rollers.

9. Rubber drive wheels, although they tend to pick up asphalt when cold, provide better traction on courses more than 3.8 cm (1.5 in) thick, except for dual-drum rollers, which had no traction problems.

10. Longitudinal joints should be rolled either statically with the roller on the cold lane or vibrated with it on the hot lane.

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