STANHOPE STUDY OF COMPACTION METHODS FOR BITUMINOUS STABILIZED BASE

R. R. Santoro, K. C. Afferton, and J. A. Walz,
New Jersey Department of Transportation

In September 1970 the Equipment Committee of the New Jersey Department of Transportation conducted an evaluation test of compaction equipment for bituminous stabilized base course. The objective of the test was to evaluate the compaction capabilities of 2 vibratory rollers and a tandem roller and to compare them with the capabilities of the department's standard compaction system (3-wheeled roller with tandem finish). Comparisons were made by using both multiple- and thick-lift paving methods. The findings indicated that all rollers evaluated were capable of achieving acceptable densification levels in the stone mix, bituminous stabilized base course used in the test construction. In multiple-lift construction the vibratory compactors were found to attain essentially the same base density as that produced by the department's standard system. However, the vibratory units required approximately 30 percent more compaction time. In thick-lift construction the department's system was again found to be the optimum of the roller systems considered. The vibratory rollers were not observed, within the range of applications evaluated, to cause decompaction or density drop off of the base material. Pavement riding quality was not adversely affected by either one of the vibratory compactors studied.

•ON SEPTEMBER 30, 1970, the Equipment Committee of the New Jersey Department of Transportation conducted its third major evaluation test of compaction equipment for bituminous concrete. A test section consisting of a 4-in. thick, plant-mixed bituminous stabilized base course (stone mix) was constructed at Stanhope, New Jersey, on the southbound lanes of the NJ-206 connector for Interstate 80, section 1M. The basic objective of the test was to compare the breakdown compaction capabilities of 2 vibratory rollers and a tandem roller with those of a standard 3-wheeled roller. The capabilities to be studied encompassed the important factors of densification, compaction efficiency, and pavement smoothness.

Current specifications of the department require that all breakdown compaction of bituminous paving materials be accomplished with a 3-wheeled roller having a total weight of not less than 10 tons and having not less than 330 lb/in. of width on the rear wheels. A minimum of one breakdown pass with a 3-wheeled roller is specified.

The vibratory roller has been successfully used in bituminous pavement construction in Europe for several years. However, in the United States and particularly in New Jersey, the extension of vibratory compaction from soil aggregates to bituminous paving materials is still in its infancy. The New Jersey Department of Transportation first used a vibratory compactor on bituminous concrete experimentally in 1967 on a small portion of Interstate 80, section 3K. Unfortunately, the experiment proved inconclusive because of the extremely variable and uncontrollable operational characteristics of the roller. Two years later, the department also participated in the monitoring of an impressive demonstration of a dual-drum vibratory roller on bituminous construction for the New Jersey Turnpike. The decision to conduct the vibratory roller tests at Stanhope resulted primarily from the successful nature of the turnpike demonstration.

Sponsored by Committee on Flexible Pavement Construction.

The 2 vibratory rollers used in this evaluation were model CA-25A supplied by Vibro-Plus Products, Inc., and Rustler 404 supplied by RayGo, Inc. Both units were self-propelled, 2-axle, single vibratory drum compactors with rubber tires on the drive axle. Both rollers had the ability to change dynamic compactive force by varying their frequency of vibration. The Vibro-Plus unit also had the capability of operating at 2 different amplitude levels; only the high amplitude mode of operation was employed in the test work.

The inclusion of tandem breakdown rolling in the Stanhope test was prompted by findings in the committee's study of bituminous pavement riding quality. Investigations suggested that, through the use of tandem rather than 3-wheeled rollers for initial mat compaction, several states may be achieving markedly better riding pavements than those achieved in New Jersey. It was expected that, under the controlled conditions of a test section, the beneficial effects, if any, of tandem breakdown rolling on pavement smoothness could be quantified.

The planning, construction, control testing, and data evaluation for the Stanhope test section were shared by the various member divisions of the Equipment Committee. Guidance in the use of the vibratory rollers was provided by representatives of the 2 suppliers.

METHOD OF STUDY

The Stanhope test section was divided into 8 subsections. In subsections 1 through 4, the compactors were evaluated in conjunction with the multiple-lift mode of stabilized base construction (4-in. base constructed in two 2-in. thick-lifts). The same rollers were then used with single, or so-called, thick-lift construction in subsections 5 through 8 (4-in. base constructed in one 4-in. thick lift). Current department specifications require that the multiple-lift method be used in all bituminous base paving. However, recent successful trials of single, thick-lift paving suggest that this may soon be an acceptable alternate on department projects.

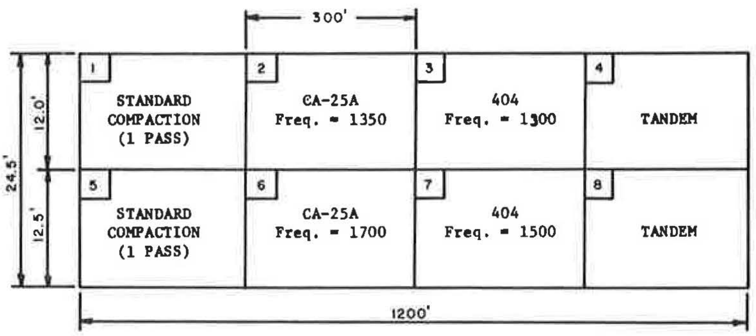
The general layout developed for the test area and the construction requirements for each subsection are shown in Figure 1. A complete description of the 4 compactors used in the study is given in Table 1.

In each subsection, the prescribed compaction sequence produced strips or zones having different numbers of roller coverages. It was expected that the density growth characteristics of each compactor could best be determined by evaluation of the coverage zones. As used in this paper, 1 coverage is defined as 1 pass over a point on the base of 1 rear wheel of the 3-wheeled roller, the rear drum of the tandem, or the vibrating drum of the vibratory compactors.

In subsections 1 and 5, where the department's standard method of stablized base compaction, used was the 3-wheeled roller applied the specification minimum of 1 breakdown pass. A pass in this instance means that the roller progressed from edge to edge uniformly lapping (one-half width of rear wheel) each preceding truck until the entire mat was rolled by the rear wheels. The roller overlaps associated with this pass produced 2 and 3 coverage zones in subsection 1. The same rolling procedure resulted in 2 and 4 coverage zones in subsection 5. The development of density growth data for the vibratory rollers was facilitated by providing 2, 3, and 5 coverage zones in the vibratory subsections. The manufacturers of the vibratory equipment estimated that 2 to 3 coverages at the frequencies they recommended would provide sufficient densification in subsections 2, 3, 6, and 7 (Fig. 1).

In subsections 4 and 8, which were to receive tandem breakdown rolling, only a tentative compaction sequence was established to produce 3, 4, and 6 coverage zones. The lack of experience with tandem rollers used in the breakdown position required that the Equipment Committee give construction control personnel the option of increasing roller coverages if the planned compaction proved inadequate. Nuclear density measurements (2 locations) were taken in the tandem breakdown subsections immediately after completion of compaction to determine the level of densification achieved. Additional coverages of either the tandem or 3-wheeled roller were to be applied if the nuclear measurements suggested air voids levels above that permitted in the department's standard specifications.

Figure 1. Stanhope test section.



STANDARD CONSTRUCTION
(PLACE 2 LIFTS, 2" THICK)

SUBSECTION NO. 1

1. Breakdown Rolling - 3 wheel
2. Finish Rolling - Tandem (passes as necessary)
3. Evaluate 2 & 3 coverage zones

SUBSECTION NO. 2

1. Breakdown Rolling - Vib. CA-25A
2. Frequency = 1350±50 V.P.M.
3. Finish Rolling if Needed - Tandem (passes as necessary)
4. Evaluate 2,3&5 coverage zones

SUBSECTION NO. 3

1. Breakdown Rolling - Vib. 404
2. Frequency = 1300±50 V.P.M.
3. Finish Rolling if Needed - Tandem (passes as necessary)
4. Evaluate 2,3&5 coverage zones

SUBSECTION NO. 4

1. Breakdown and Finish Rolling if Needed - Tandem
2. Evaluate - 3,4&6 coverage zones (If nuclear densities are inadequate, additional passes will be made and recorded.)

THICK LIFT CONSTRUCTION
(PLACE 1 LIFT, 4" THICK)

SUBSECTION NO. 5

1. Breakdown Rolling - 3 wheel
2. Finish Rolling - Tandem (passes as necessary)
3. Evaluate 2 & 4 coverage zones

SUBSECTION NO. 6

1. Breakdown Rolling - Vib. CA-25A
2. Frequency = 1700±50 V.P.M.
3. Finish Rolling if Needed - Tandem (passes as necessary)
4. Evaluate 2,3&5 coverage zones

SUBSECTION NO. 7

1. Breakdown Rolling - Vib. 404
2. Frequency = 1500±50 V.P.M.
3. Finish Rolling if Needed - Tandem (passes as necessary)
4. Evaluate 2,3&5 coverage zones

SUBSECTION NO. 8

1. Breakdown and Finish Rolling if Needed - Tandem
2. Evaluate - 3,4&6 coverage zones (If nuclear densities are inadequate, additional passes will be made and recorded.)

Table 1. Compaction equipment.

Equipment	Size	Equipment	Size
3-wheeled roller		RayGo	
Weight, tons	10 to 12	Shipping weight, lb	18,500
Rolling width, in.	84	Drum diameter, in.	59
Width of rear wheels, in.	24	Drum length, in.	84
		Variable frequency, vpm	1,150 to 1,500
Vibro-Plus		Reed vibration tachometer	
Overall net weight, lb	20,300	Static drum force[a], lb	12,000
Drum diameter, in.	60	Dynamic force[a], lb	27,000
Drum length, in.	84		
Variable frequency, vpm	To 2,400	Tandem roller	
Static drum force, lb	10,500	Weight, tons	10 to 12
Centrifugal force (high amplitude setting)[a], lb at 1,700 vpm	18,500	Width of rear roll, in.	54

[a]From equipment brochures.

Table 2. Mix design.

Property	Quantity	Property	Quantity
Sieve, percent passing		Sieve, percent passing	
2 in.	100	No. 200	6.1
$1\frac{1}{2}$ in.	100	Asphalt cement, percent	4.3
$\frac{3}{4}$ in.	79	Air voids, percent	3.98 (6.1)[a]
No. 4	48	Average stability, lb	2,650 (2,050)[a]
No. 8	38	Average flow, in.	0.11 (0.11)[a]
No. 50	15	Weight, lb/ft^3	150 (149)[a]

[a]Average of 2 sets (6 plugs) of Marshall specimens molded at plant on day of test section construction. The maximum specific gravity of Marshall specimens was determined by the New Jersey Department of Transportation's solvent immersion test method.

Tandem-finish rolling was used on any subsection where the mat surface was irregular after breakdown rolling was completed. It was expected that tandem-finish rolling would not be necessary in the tandem breakdown subsections and, also, possibly not needed in the vibratory subsections.

The bituminous stabilized base used in construction of the test section was in accordance with the design and control requirements of mix 1 of the 1968 Addenda A Revisions to the department's standard specifications. The specific design characteristics of this material are given in Table 2. The entire test section was constructed over a 6-in. layer of dry-bound macadam base underlaid by 14 in. of granular subbase. Department personnel monitored the material production at the asphalt plant and the overall construction of the test area.

PLANT INSPECTION

The major objective of the plant inspection was to control the uniformity of material being supplied to the test pavement. This was necessary because a significant variability in material would prevent the making of valid statistical comparisons both within and between subsections.

The adequacy of the composition uniformity was determined by the analysis of 6 random samples of the plant's production. Extraction results indicated that the base material was well controlled and in good conformity with the job mix formula. Control of mixing temperature was also quite adequate for mixture temperatures ranging from 280 to 300 F.

Table 2 gives the average Marshall results for 2 sets (6 plugs) of specimens molded at the plant on the day of the test pavement construction. The Marshall test data are given for comparison with the job mix design values.

CONSTRUCTION OBSERVATIONS

The bituminous stabilized base test pavement was 1,200 ft long and 24.5 ft wide. Each of the 8 subsections was 300 ft long and approximately 12 ft wide. A 100-ft dead-zone area was provided at the interface of each subsection to facilitate construction equipment movements. The dead-zone areas were not included in the roller evaluation.

Paving operations began by placing the bottom lift in subsections 1 through 4 and continued by placing the single thick lift in subsections 5 through 8. Paving of the test section was then completed by placing the top lift in subsections 1 through 4. The breakdown compaction of each subsection was not started until the paver had completed laydown in that subsection.

Each compactor began breakdown rolling at the low edge of the uncompacted mat. Lateral displacement at the edge of the mat was not considered excessive during compaction of either the multiple-or the thick-lift sections. No initial or final static passes were applied by either one of the vibratory compactors.

All maneuvering (lateral shifts) by vibratory rollers required to complete their breakdown compaction sequence was performed on previously compacted material (100-ft dead-zone areas, static drum). This procedure was recommended by representatives of the vibratory roller equipment to avert any possibility of marring or rupturing the uncompacted mat. Both the tandem and the 3-wheeled rollers were capable of performing the maneuvering necessary to complete their breakdown compaction sequences on either the compacted or uncompacted mat without detrimental effects.

Slight ridges or depressions; which were similar in nature to those made by the 3-wheeled roller, were observed in the mat after the first passage of the vibratory and tandem rollers. However, these ridges or depressions were sufficiently eliminated during the remainder of the breakdown compaction sequence. Tandem-finish rolling was therefore not used on any of the subsections where vibratory or tandem breakdown compaction was performed. Finish rolling (2 coverages) with the tandem unit was applied to the 3-wheeled roller subsections.

The rubber tires of the vibratory rollers were not preheated, although both units utilized an additive to prevent tire pickup (buildup of fines from the mix). No significant tire pickup was noted on this particular mix by either of the vibratory rollers tested.

The RayGo compactor was observed to bounce off the mat severely for a short time during the compaction of subsection 3 (top lift); the vibrating drum was then brought back under control by the operator (manufacturer's representative). It appeared that this was accomplished by increasing the roller speed.

Generally, the construction of the test section was in conformance with the planned procedures. Additional compactive effort was applied to subsection 4, second lift (1 pass with 3-wheeled roller), and subsection 8, thick lift (2 additional passes with the tandem roller), as a result of nuclear density measurements taken in the 3 coverage zones at the completion of the prescribed rolling. The air voids level suggested by the average of 2 nuclear density measurements in subsection 4 were sufficiently high to indicate that the 3-wheeled rather than the tandem roller be used to achieve the necessary densification.

In addition to the overall supervision of the test project, several specific phases of the test construction were monitored and recorded by Department personnel and include the following:

1. Paver and roller times for each subsection;
2. Periodic checks of frequency of vibration with a reed type of hand vibrometer to establish vibratory roller compliance with recommended frequency levels;
3. Setting of pavers vibrating screed-different intensity settings for each mode of construction (multiple and thick lift);
4. Temperature measurements recorded by thermocouples installed either underneath or approximately at the mid-depth of mat (dead-zone areas) and by probe thermometers; and
5. Documentation of air temperature during the day of the test (temperatures ranged from a low of 42 F in the morning to a high of 58 F in the afternoon).

PAVEMENT TESTS

Pavement tests consisted primarily of random nuclear densities taken during and after construction, the measurement of density of 4-in. cores cut from the pavement, and the measurement of pavement riding quality.

Final test section densification was initially to be evaluated on the basis of cores, which is the department's normal method of determining pavement density. However, it was subsequently considered impractical to cut the number of cores required to amass significant data. It was, therefore, decided to obtain the majority of the density observations by means of nuclear density devices. Nuclear density measurements were to be utilized in predicting core density values through correlation equations. The nuclear devices were also to be employed in determining paver laydown densities in all subsections and density buildup during compaction in the vibratory and tandem subsections. Density growth data obtained in this latter fashion were to supplement the primary density growth information (final coverage zone densities).

The density data required for analysis of the test section (total of 22 coverage zones) were obtained at 154 random locations (7 per each coverage zone). A nuclear density gauge was used to obtain paver laydown densities at 2 of these locations in each subsection. In the vibratory and tandem subsections, the nuclear device was further used for density measurements between roller coverages (2 locations monitored per subsection). Determinations of final density with the nuclear gauge were made at all 154 random locations. For use in the development of a predictor equation for core density, cores were cut at 2 of the 7 locations in each coverage zone resulting in a total of 44 cores. A typical density measurement pattern for a subsection is shown in Figure 2.

Because this was the first instance in which the department was to place primary reliance on nuclear devices to obtain pavement density measurements, there was strong concern as to the particular method to follow in using a nuclear gauge. It was not initially evident which of the currently used methods would provide the best marriage between core density correlation and simplicity of use. For this reason, a nuclear density measurement was repeated 3 times wherever possible, and a different method was used each time. A measurement was made with the gauge in the backscatter position without surface preparation, then with surface preparation (standard 20-30 Ottawa sand), and finally with the air-gap method (including surface preparation).

The 44 cores taken from the test area were analyzed in the department's central laboratory to determine bulk and maximum specific gravities. Bulk specific gravities were obtained by AASHO Method T166; maximum specific gravities were determined by the department's solvent immersion test method.

A stated previously, one of the important aims of the study was to evaluate the riding quality or pavement smoothness produced by each of the compactors tested. That was accomplished by measuring the smoothness of each subsection with 2 devices: a 10-ft rolling straightedge and a BPR roughometer. The rolling straightedge indicates the span length and magnitude of surface deviations in the range of ⅛ to ½ in. in ⅛-in. increments. The BPR roughometer, consisting of a fifth wheel towed over the pavement surface at 20 mph, yields an aoutput referred to as the roughness index (RI). The RI is equivalent to the accumulated deviations in the pavement surface, in in./mile. A high RI is thus indicative of a rough pavement surface.

Measurements were obtained by the 2 devices in both wheelpaths of each 300-ft subsection (dead zones were excluded). Because of the short lengths measured (200 ft), the roughometer made 3 repeat runs in each wheelpath in an attempt to obtain the best estimate of the pavement smoothness or RI.

DISCUSSION OF FINDINGS

Temperature Measurements

The procedure established for the monitoring of pavement temperatures required the installation of 1 thermocouple in each lift of each subsection. Temperature measurements were recorded by a potentiometer attached to the thermocouples.

It was not originally planned to take probe thermometer measurements, except from trucks. However, during construction, several problems developed with the thermocouple equipment and the installation procedures employed. It was, therefore, necessary to take probe measurements, although it was not possible to fully supplement the voluminous number of temperature observations planned for the thermocouples.

Based on the combined data from the thermocouples and probe thermometers, the laydown temperature for all subsections ranged from 270 to 280 F. For the thick-lift constructed subsections, all planned breakdown compaction was accomplished within the approximate temperature range of 245 (start) to 215 F (finish). It is estimated that the 2 additional passes found necessary in tandem subsection 8 were completed above 180 F.

The thermocouple and probe thermometer measurements in the multiple-lift subsections indicated a breakdown temperature range from 240 (start) to 190 F (finish). By extrapolating some of the temperature data, we estimate that the added pass of the 3-wheeled roller in subsection 4 was accomplished between 145 (start) and 125 F (finish).

Density Determination

A basic assumption in the Stanhope test was that roller compaction capabilities could be evaluated by comparison of density levels achieved both within and between subsections. This assumption is essentially valid if subgrade support conditions and bituminous base composition were uniform throughout the test area. Observations prior to construction indicated that the macadam base had been adequately densified to afford a consistent, stable subgrade for the bituminous base. Also, statistical analysis of laboratory extraction test results revealed that sufficient uniformity of mixture composition was maintained during the test pavement construction.

As previously stated, both nuclear and core density determinations were utilized in this study, and the nuclear densities were the primary measure of pavement densification. To analyze the density data in one standard form required that the nuclear density measurements be subsequently converted to predicted core density values by use of linear correlation equations. Core densities were predicted by using only a few of the many correlation relations established from the density measurements. Most

Figure 2. Typical density measurement pattern for subsection.

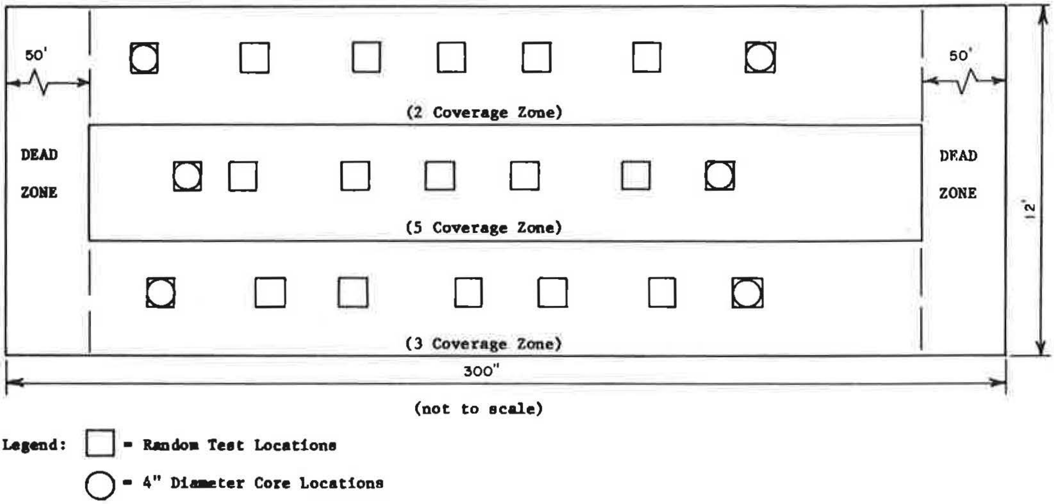


Table 3. Mean densities.

	Multiple-Lift Construction			Single-Lift Construction		
Compactor	Sub-sec-tion	Cover-ages	Mean Density[a] (lb/ft^3)	Sub-sec-tion	Cover-ages	Mean Density[a] (lb/ft^3)
3-wheeled roller	1	2	146.1	5	2	147.4
		3	146.6		4	147.4
Vibro-Plus	2	2	143.5	6	2	143.7
		3	144.8		3	145.0
		5	146.8		5	146.8
RayGo	3	2	143.3	7	2	144.9
		3	144.7		3	146.1
		5	146.1		5	146.3
Tandem roller	4	3	144.8	8	5	146.2
		4	144.1		7	147.4
		6	145.3		10	148.0

[a]Average of 7 measurements: two 4-in. diameter cores and five predicted core density values based on nuclear density measurements (air-gap method).

Table 4. Mean densities as a percentage of Marshall density.

	Multiple-Lift Construction			Single-Lift Construction		
Compactor	Sub-sec-tion	Cover-ages	Percent of Marshall Density[a]	Sub-sec-tion	Cover-ages	Percent of Marshall Density[a]
3-wheeled roller	1	2	98.1	5	2	99.0
		3	98.5		4	99.0
Vibro-Plus	2	2	96.4	6	2	96.5
		3	97.2		3	97.4
		5	98.6		5	98.6
RayGo	3	2	96.2	7	2	97.3
		3	97.2		3	98.1
		5	98.1		5	98.3
Tandem roller	4	3	97.2	8	5	98.2
		4	96.8		7	99.0
		6	97.6		10	99.4

[a]Marshall density = 100 x (mean density/Marshall density). Mean density is average of 7 measurements: two 4-in. diameter cores and five predicted core density values based on nuclear density measurements (air-gap method). Marshall density is average of 2 sets of Marshall specimens (6 plugs molded at the plant on the day the test pavement was constructed).

of the density conversions were actually accomplished with the following equation, developed from paired core and air-gap measurements and found to yield the most accurate predictions:

$$Y = 82.6 + 0.467\ X$$

where

Y = predicted core density value, lb/ft^3; and
X = nuclear density measurement, air-gap method, lb/ft^3.

The correlation coefficient is 0.75, and the standard error of estimate is 1.27 lb/ft^3.

From the actual and predicted core densities (154 random locations), mean densities were determined for each of the 22 coverage zones in the 8 subsections of the test pavement. A summary of these mean density values is given in Table 3. Comparing the average densities of the different coverage zones within each subsection makes it possible to establish density growth patterns for the rollers under study. The density growth measurements collected during the actual compaction operations were in good agreement with the data given in Table 3.

An important observation to be made from the density growth information is that the vibratory rollers, within the range of coverages considered (2 to 5), continued to increase density with each added coverage. The higher number of coverages did not cause loosening of the material or the density reduction that often occurs with increased vibratory roller applications on cohesionless soil materials.

The density data for the various rollers cannot be evaluated further without first considering the level of densification actually needed in a stabilized base course. After a good deal of investigation, the department formulated in 1968 a pavement specification that essentially requires a contractor to achieve an average air voids level of not more than 6 percent in a bituminous base. Unfortunately, this requirement has little meaning for most highway engineers for other states normally evaluate compaction in terms of relative density rather than air voids. On a relative-density basis, the 6 percent air voids limit corresponds to approximately 98 percent of the Marshall density when the department's design criteria are taken into account. This means that on most stabilized bases a roller or roller system must be capable (on the average) of achieving at least 98 percent of the laboratory Marshall density to satisfy voids requirements.

So that a comparison could be made, the test pavement density data given in Table 3 were refashioned in terms of percentage of Marshall density. The resulting values, given in Table 4, can be correctly evaluated by distinguishing between real or significant differences and those resulting simply from normal variation in measurements. For this reason, a statistical, 1-tail t-test was used in the study to analyze density differences within and between subsections.

The information given in Table 4 reveals that the department's standard compaction system is equal to or better than the critical 98 percent Marshall density level in both multiple- and thick-lift construction. Furthermore, statistical analysis indicates that the additional 3-wheeled roller breakdown coverages investigated in the study did not effect any significant density increase in either paving mode.

The vibratory rollers behaved much differently from the standard compaction system. In both its multiple- and single-lift subsections the Vibro-Plus roller significantly increased mat densification with increased coverages. The same situation occurred with the RayGo vibratory roller. However, in deep-lift construction (subsection 7), the RayGo compactor was unable to cause a significant density increase with its final 2 applications. In this particular instance, however, the RayGo unit did surpass the important 98 percent Marshall density level with only 3 roller coverages; in all other vibratory subsections (multiple- and single-lift construction), 5 coverages were needed.

Before the performance of the tandem roller is considered, it is necessary to comment on the decision made during construction that modified the tandem roller's planned compaction sequence. The special monitoring used with the tandem roller resulted in additional compactive effort being applied to its subsections. In retrospect, it is questionable whether the added compaction was completely justified inasmuch as the decision was made on the basis of air voids, and not percentage of Marshall density. After the test section was constructed, it was discovered that all subsections generally had a higher than expected air voids level. Further investigation of the plant's mix design uncovered an error that had caused the base mixture to exhibit slightly less than normally desired compaction characteristics (somewhat elevated Marshall air voids). Based on the implications of this finding, the added compaction in the tandem subsections was applied more as a result of a mix design deficiency than of a poor compactive effort.

The additional compactive effort used in tandem roller subsection 4 was 1 pass of a 3-wheeled roller on its top lift. Unfortunately, this change in roller type makes it impossible to establish the tandem roller's compaction capabilities in multiple-lift construction from the final density measurements. In thick-lift construction, the extra compactive effort was applied with 2 additional passes of the tandem unit; the added applications are reflected in the data given in Table 4. Analysis of final densities in this instance is, therefore, valid.

In both tandem subsections the added compaction was accomplished at relatively low temperatures (180 F for thick, and 140 F for multiple). There is, therefore, strong doubt especially in multiple-lift construction that the supplemental roller passes increased densification. This doubt is supported by the fact that measurements before and after the extra rolling at the monitoring locations failed to detect a density increase.

A review of the mean densities for subsection 8 reveals that the tandem roller reached the 98 percent Marshall density level with 5 coverages. Also, at 7 coverages the tandem roller reached what might be considered its optimum densification level for the test—99 percent of the Marshall value. The statistical test indicated that no significant increase in density occurred between 7 and 10 tandem coverages.

Comparing the performance of the various rollers on multiple-lift construction, it appears that the department's standard compaction system was the optimum densification system tested. The 98 percent Marshall density level was attained with only two 3-wheeled breakdown coverages (plus 2 tandem finish passes); the vibratory rollers required 5 coverages to achieve essentially the same density condition. In thick-lift construction the standard compaction system again seems to have been the optimum method of compaction. It produced higher densities, with less breakdown coverages, than those achieved by any one of the other rollers. However, in thick-lift paving the RayGo compactor did reach the 98 percent Marshall level after only 3 applications.

A comparison of the density levels attained in the thick-lift and multiple-lift construction reveals additional performance differences. As the Equipment Committee found in past studies, the single-lift paving method generally resulted in higher degrees of bituminous base densification. Analysis of the individual density measurements further disclosed that, in terms of variance, σ^2, the thick-lift base had less than half the longitudinal variability of the multiple-lift base. It is believed that the higher mat temperatures intrinsic to thick-lift construction provided for the improved pavement densification.

Roller Efficiency

Although it is valuable to compare the various rollers in terms of density levels achieved, an equally important factor is the compaction time employed. To account for both the densification and time characteristics, we used a parameter termed "roller efficiency." Roller efficiency was taken to be the change in density effected by a roller divided by its expended compaction time. Table 5 gives the roller efficiency value for each compactor and coverage level evaluated.

The efficiency values have been calculated by assuming that the pertinent roller coverages were placed over the entire width of a 12-ft wide mat. The compaction times used in these calculations were all actual, as-measured times for the 3-wheeled and tandem rollers. For the vibratory compactors, the compaction times were esti-

Table 5. Rolling efficiency.

Compactor	Multiple-Lift Construction: Subsection	Coverages	Compaction Time (min)	Density vs. Compaction Time[a] (lb/ft³/min)	Thick vs. Multiple Lift[b] (percent)	Thick-Lift Construction: Subsection	Coverages	Compaction Time (min)	Density vs. Compaction Time[a] (lb/ft³/min)	Thick vs. Multiple Lift[b] (percent)
3-wheeled roller	1	2	46[c]	0.398	—	5	2	22[c]	0.850	214
Vibro-Plus	2	5	60	0.317	—	6	5	30	0.603	190
RayGo	3	5	60	0.305	—	7	3	12	1.450	309
							5	20	0.880	289
Tandem roller						8	5	26	0.673	—

[a]Final average laydown density/total compaction time, where average laydown density = 128.0 lb/ft³.
[b](Thick lift/multiple lift)/100.
[c]Includes tandem-finish rolling and all maneuvering time.

Table 6. Riding-quality measurements.

Compactor	Multiple-Lift Construction: Sub-Section	Roughometer[a]	Straightedge[b]	Thick-Lift Construction: Sub-Section	Roughometer[a]	Straightedge[b]
3-wheeled roller	1	141	4	5	168	14
Vibro-Plus	2	146	4	6	179	12
RayGo	3	140	2	7	143	9
Tandem roller	4	171	5	8	191	12

[a]Average equivalent roughness index, in./mile. Values and average of 6 roughometer measurements per subsection, 3 repeat measurements in each of 2 wheelpaths. Based on variability of repeat measurements, the 95 percent confidence limits, or tolerance, for each average value is +25 in./mile.
[b]Number of deviations in wheelpaths of individual subsections.

Table 7. Centrifugal forces of Vibro-Plus compactor.

vpm	Dynapac Compaction Effort During the Test—High Amplitude	Dynapac Compaction Effort Since the Test: High Amplitude	Low Amplitude
2,400	Not available for test[a]	36,000	18,000
1,700	18,060	18,060	9,030
1,350	11,390	Not recommended	Not recommended

[a]The CA-25 S/N 251A was tested at 1,700 vpm because a 2,400-vpm motor was not available in time. The machine has a considerably higher compaction effort and effect at 2,400 vpm than at 1,700 vpm.

mated by using the recorded, average time per coverage multiplied by the number of coverages being considered. In all instances the average densities achieved in the subsections were used to determine related density changes.

To evaluate the roller efficiency data, one must keep in mind that a bituminous base must normally be densified to 98 percent of the Marshall density (average level) to ensure compliance with department air voids criterion. The efficiency that rollers exhibit in reaching this density level is therefore of major importance in considering their use on department porjects. A review of data given in Table 5 shows that in multiple-lift construction the department's specified roller system was more efficient than the vibratory compactors in reaching the critical 98 percent Marshall density plateau. This system had the highest efficiency value and, accordingly, had the lowest compaction time of all the compaction units evaluated.

It is more difficult to compare roller efficiencies on the thick-lift and the multiple-lift paving. This is due to the fact that the standard 3-wheeled, tandem system produced 99 percent level, the 3-wheeled, tandem system would definitely be the most efficient. This system required less time to reach 99 percent density than the other rollers did to achieve lower densities. The only comment that can be offered concerning comparisons at the 98 percent Marshall density level is that the RayGo compactor was more efficient than both the Vibro-Plus and the tandem compactors.

As would be expected, the data given in Table 5 show that all rollers increased their efficiency and reduced their compaction times significantly in going from multiple-lift to thick-lift construction.

Riding Quality

The riding-quality measurements obtained in the Stanhope evaluation test are given in Table 6. The data were obtained on relatively short (200 ft) pavement lengths. A great deal of judgment would have to be exercised in extrapolating the riding qualities achieved in the short subsections of this test to those achievable over the entire length of a full-sized construction project.

The BPR roughometer data are given in the form of average roughness index values for each subsection. These values, which are each an average of 6 measurements, range from 140 to 191 in./per mile. On a typical, full sized, paving project in New Jersey, the top surface of a completed stabilized base would be expected to have a roughness index somewhere between 120 and 180 in./mile.

On the multiple-lift subsections, the 2 vibratory rollers and the department's standard compaction system produced about the same level of pavement smoothness. In contrast, tandem breakdown rolling resulted in a surprisingly rougher base surface. These same findings also apply to the thick-lift construction with the exception of the RayGo vibratory roller. In thick-lift compaction the RayGo roller seems to have produced a smoother riding surface (lower roughness index) than that attained by any one of the other compactors.

A comparison of roughometer data for the thick-lift subsections and for the multiple-lift subsections reveals an additional interesting factor. The thick-lift subsections are all, to varying degrees, rougher than corresponding multiple-lift subsections. Apparently, when a manually controlled paver is used, it was not possible to overcome as much subgrade roughness with 1 lift of base as with 2 lifts.

The riding quality measurements made with the rolling straightedge are also given in Table 6. For each subsection, the number of surface deviations in the wheelpaths is more than $\frac{1}{8}$ in. Good riding pavements normally have few deviations, and rough pavements have many deviations. It is apparent, therefore, that the straightedge observations substantiate, in a general way, the findings from the roughometer measurements. This is particularly true in regard to the indicated advantage in riding quality of the multiple-lift over the thick-lift mode of construction.

The preceding comments must be conditioned on 2 additional considerations. First, the repeat readings with the roughometer on any one subsection were more variable than had been anticipated. Although 6 measurements were averaged in each subsection, their variability was such as to cause the resulting average to be of rather low precision. The 95 percent confidence limits for each average was approximately -25 in./mile. This basically means that the difference in roughness index between any 2 subsections must be in the order of at least 25 in./mile before it could be considered real and significant. Second, poor riding quality was exhibited by the tandem breakdown subsections, unlike the rest of the test pavement, these subsections were on the beginning of a slight horizontal curve. The related superelevation changes may have had some detrimental effect on the surface smoothness achieved in these areas.

CONCLUSIONS

The results of this bituminous base compaction study are summarized by the following conclusions:

1. All roller systems evaluated were able to achieve the critical 98 percent Marshall density required to satisfy department air voids specifications. However, because of a change in the planned roller sequence during construction, it was not possible to evaluate the compaction capabilities of the tandem roller in the multiple-lift paving mode.
2. The vibratory rollers did not produce base densities equivalent to those achieved by the department's standard compaction system within the coverage range (2 to 3) recommended by the manufacturers of the units.
3. In multiple-lift construction, 5 coverages of the vibratory compactors were necessary to produce essentially the same pavement density as that attained by the department's standard system. The associated densification approximated the normally needed 98 percent level of Marshall density. However, the vibratory rollers required nearly 30 percent more time than the standard system to achieve this density level.
4. In thick-lift construction, the department's standard compaction system was the most efficient of the rollers studied in achieving 99 percent Marshall density. The only conclusion that can be made pertaining to roller-compaction characteristics at the important 98 percent Marshall density level is that the RayGo unit was more efficient than both the Vibro-Plus and the tandem rollers. Unfortunately, no comparison can be made with the department's standard system for it achieved higher base densification (above 98 percent Marshal) with the minimum number of coverages evaluated.
5. Decompaction or density drop off of the bituminous base mixture was not found to occur within the range of vibratory roller coverages (2 to 5) evaluated.
6. Pavement riding quality was not adversely affected by either one of the vibratory compactors tested. In addition, no measurable improvement in riding quality was discernible when the tandem rather than the 3-wheeled roller was used to perform breakdown compaction.
7. The pavement surface produced by the vibratory and tandem rollers on the test mixture, after breakdown compaction, was such that finish rolling was not necessary. This suggests that, in instances where compaction time is not critical, certain economies could be realized by using the vibratory or tandem rollers instead of the department's standard system. The ability to achieve a smooth base of adequate density with 1 roller and 1 operator, rather than 2 rollers and 2 operators, could effect a reduction in construction costs.

DISCUSSION

M. Geller, Vibro-Plus Products, Inc.

The test results obtained from the use of the Vibro-Plus CA-25 S/N 251A at Stanhope in October 1970 should not be used as an indication of the current performance of the CA-25A. For the Stanhope test, the CA-25 S/N 251A utilized for the first time a dual-amplitude device that was intended to function at 2,400 vpm. During the test, the frequency was 1,700 vpm for the 4-in. lift and 1,350 vpm for the 2-in. lift.

Table 7 gives the centrifugal forces that CA-25 S/N 251A developed for the test and the forces that are now available at 2,400 vpm.