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STANHOPE STUDY
OF
COMPACTION METHODS
FOR
BITUMINOUS STABILIZED BASE

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ABSTRACT

In September of 1970 the Equipment Committee of the New Jersey Department of Transportation conducted its third major evaluation test of compaction equipment for bituminous stabilized base course. The basic objective of the test was to evaluate the compaction capabilities of two vibratory rollers and a tandem roller as compared to that of the Department's standard compaction system (3-wheel breakdown with tandem finish rolling). Comparisons were made utilizing 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 25% more compaction time. In thick lift construction the Department's standard 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 so-called de-compaction or density drop off of the base material.

Pavement riding quality was not adversely affected by either of the vibratory compactors studied. In addition, no measurable improvement in riding quality was discernible when the tandem rather than the 3-wheel roller was used for breakdown compaction. Riding quality measurements further suggest that, when a manually controlled paver is employed, the riding surface on thick lift base construction would be significantly rougher than that for standard multiple lift paving.

KEY WORDS: bituminous stabilized base course; vibratory, 3-wheel and tandem rollers; multiple and thick lift paving methods; densification; roller efficiency; de-compaction; pavement riding quality.

NEW JERSEY DEPARTMENT OF TRANSPORTATION

Equipment Committee

STANHOPE STUDY
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FOR
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I. INTRODUCTION

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 inch thickness of plant-mixed bituminous stabilized base course (stone mix) was constructed at Stanhope, New Jersey on the southbound lanes of the Route 206 Connector for Interstate Route I-80, Section 1M.

The basic objective of the test was to compare the breakdown compaction capabilities of two vibratory rollers and a tandem roller to that of a standard 3-wheel roller. The capabilities to be studied encompass the important factors of densification, compaction efficiency and pavement smoothness. Current Department specifications require that all breakdown compaction of bituminous paving materials be accomplished with a 3-wheel roller having a total metal weight of not less than 10 tons, and having not less than 330 lbs per inch of width on the rear wheels.

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's first experimental use of a vibratory compactor on bituminous concrete was in 1967, on a small portion of Interstate Route 80, Section 3K. Unfortunately, the experiment proved inconclusive due to 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 evaluation tests at Stanhope resulted primarily from the successful nature of the Turnpike demonstration.

The two vibratory rollers used in this evaluation were supplied by Vibro Plus Products, Inc. and RayGo Inc. The specific models provided were, respectfully, the CA-25A* and Rustler 404. Both units are self propelled, two-axle, single vibratory drum compactors with rubber tires on the drive axle. Both rollers have the ability to change dynamic compactive force by varying their frequency of vibration. The Vibro Plus unit also has the capability of operating at two 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 several states may

*Note: Complete identification of roller unit is CA-25A S/N 251, see Appendix for additional comments by roller manufacturer.

be achieving markedly better riding pavements than New Jersey's through the use of tandem rather than 3-wheel rollers for initial mat compaction. 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 was shared by the various member Divisions of the Equipment Committee. Guidance in the use of the vibratory rollers was provided by representatives of Vibro-Plus Products, Inc. and RayGo Inc.

II. METH [illegible] UDY

To compare the breakdown compaction capabilities of the various rollers, the Stanhope Test Section was divided into eight (8) separate subsections. In subsections 1 thru 4, the compactors were to be evaluated in conjunction with the multiple lift mode of stabilized base construction (4" base constructed in two, 2" thick lifts). The same rollers were then to be used with single, or so called, thick lift construction in subsections 5 thru 8 (4" base constructed in one, 4" thick lift). Current Department specifications require that the multiple lift method be utilized 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.

In order to permit systematic comparison of the different rollers, the following compaction sequence was established for construction of the eight subsections.

Multiple Lift Construction (Subsections 1 thru 4)

1 3-wheel breakdown - Tandem Finish

2 Vibratory roller breakdown (Vibro-Plus CA-25A) Tandem Finish (if needed)

3 Vibratory roller breakdown (RayGo 404) Tandem Finish (if needed)

4 Tandem breakdown - Tandem Finish (if needed)

Single Lift Construction (Subsection 5 thru 8)

5 3-wheel breakdown - Tandem Finish

6 Vibratory roller breakdown (Vibro-Plus CA-25A) - Tandem Finish (if needed)

7 Vibratory roller breakdown (RayGo 404) - Tandem Finish (if needed)

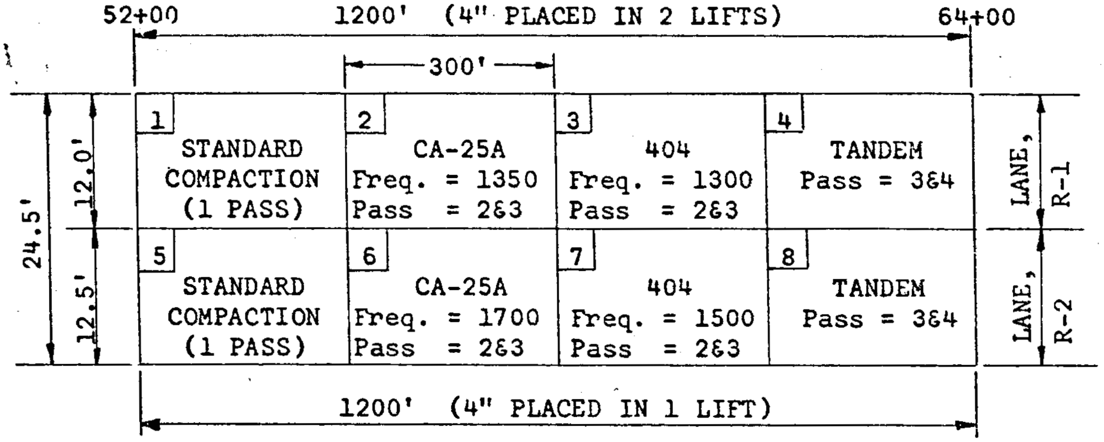
8 Tandem Breakdown - Tandem Finish (if needed)

The general layout developed for the test area as well as the construction requirements for each subsection were as presented in Figure 1. Details on the rolling procedure to be used by each compactor and a description of the relationship between the passes and coverages of these units is given in Exhibit 1 of the Appendix.

In each subsection, the prescribed compaction sequence was such as to produce 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. In subsections 1 and 5, which were to represent the Department's standard method of stabilized base compaction, the 3-wheel roller was to apply one breakdown pass to the mat. The roller overlaps (rear wheels) 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. To facilitate the development of density growth data for the vibratory rollers 2, 3 and 5 coverage zones were to be provided 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 (See Figure 1).

FIGURE 1

STANHOPE TEST SECTION
BITUMINOUS STABILIZED BASE COURSE, 4" THICK



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 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 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).

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 necessitated that the Equipment Committee give construction control personnel the option of increasing roller coverages if the planned compaction proved inadequate. Nuclear density measurements (two locations) were to be taken in the tandem breakdown subsections immediately after completion of compaction to determine the level of densification achieved. Additional coverage(s) of either the tandem or 3-wheel roller were to be applied if the nuclear measurements suggested air voids levels above that permitted in the Department's standard specifications.

Tandem finish rolling was to be used on any subsection where the mat surface was irregular following completion of breakdown rolling. 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 No. 1 of the 1968 Addenda A Revisions to the Department's standard specifications. The specific design characteristics of this material are presented in Exhibit 2 of the Appendix.

The entire test section was constructed over a 6 inch layer of dry-bound macadam base underlaid by 14 inches of granular subbase.

Department personnel monitored the material production at the ashpalt plant and the overall construction of the test area.

III. PLANT INSPECTION

The data recorded by the Department's materials inspection forces at the mixing plant is provided in Exhibits 2 and 3 of the Appendix.

Exhibit 2 contains the average results of two sets (6 plugs) of Marshall specimens molded at the plant on the day of the test pavement construction.

Exhibit 3 contains the results of four composition tests performed at the plant and the range (A.M. and P.M.) of plant temperature measurements taken from trucks on the day of the test pavement construction. Composition analysis of two 8 inch diameter pavement cores, one from the multiple lift and one from the thick lift construction are also shown in Exhibit 3.

A major objective of the plant inspection was to control the uniformity of material being supplied for the test pavement. This was necessary as a significant variability in material would prevent the making of valid statistical comparisons both within and between subsections. **The composition analysis of Exhibit 3 when compared to the job mix formula (Exhibit 2) reveal that the mixture control was most adequate. The bituminous stabilized base was in good conformity to the job mix formula.**

IV. CONSTRUCTION OBSERVATIONS

The bituminous stabilized base test pavement was constructed as originally planned, 1200 feet long and 24.5 feet wide. Each of the eight subsections was 300 feet long and approximately 12 feet in-width. A 100' 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 thru 4 (Lane, R-1), followed by the single thick lift construction of subsections 5 thru 8 (Lane, R-2). Paving of the test section was then completed by placing the top lift in Subsections 1 thru 4 (Lane, R-1).

In accordance with the test plan, each compactor involved in the study was used to achieve compaction on two of the subsections, (one multiple and one thick lift). For further details refer to Figure 1.

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

It should be noted that all maneuvering (lateral shifts) by vibratory rollers, required to complete their breakdown compaction sequence was performed on previously compacted material (100' 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

3-wheel 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 were observed in the mat after the <u>first passage</u> of the vibratory and tandem rollers, which were similar in nature to those made by the 3-wheel roller. However, these ridges or depressions were sufficiently eliminated during the remainder of the compaction sequence, such that; tandem finish rolling was not required on any of the subsections where vibratory or tandem breakdown compaction was performed.

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

The RayGo (404) 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.

Some of the field problems encountered during the test pavement construction were delays due to paver adjustments, an insufficient supply of material and a rain shower at the start of paving for the top lift of Subsection 3. During most delays, either the paver was held in areas where no density measurements were taken (dead zones) or no significant reduction in mat temperature occurred. It is considered that these problems did not significantly influence the results of the test.

Generally, the construction of the test section was in conformance with the planned procedures. Additional compactive effort was applied to Subsection 4, second lift (one pass with 3-wheel roller) and Subsection 8, thick lift (two 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 two nuclear density measurements in Subsection 4 were sufficiently high to indicate that the 3-wheel 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, these included:

(a) Paver and roller times for each subsection.

(b) Periodic checks of frequency of vibration with reed type hand vibrometers to establish vibratory roller compliance with recommended frequency levels.

(c) Setting of pavers vibrating screed-different intensity settings for each mode of construction (multiple and thick lift).

(d) Temperature measurements recorded by thermocouples installed either underneath or approximately at the mid-depth of mat (dead zone areas) and by probe thermometers.

(e) Documentation of air temperature during the day of the test, which ranged from a low of 42°F in the morning to a high of 58°F in the afternoon.

A record of the types, sizes and general characteristics of the equipment used to construct the test pavement was also recorded. Pertinent construction equipment details are contained in Exhibit 4 of the Appendix.

V. PAVEMENT TESTS

Pavement tests consisted primarily of random nuclear densities taken during and after construction, the measurement of density of 4 inch 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 build-up during compaction in the vibratory and tandem subsections. Density growth data obtained in this latter fashion was to supplement the primary density growth information (final coverage zone densities).

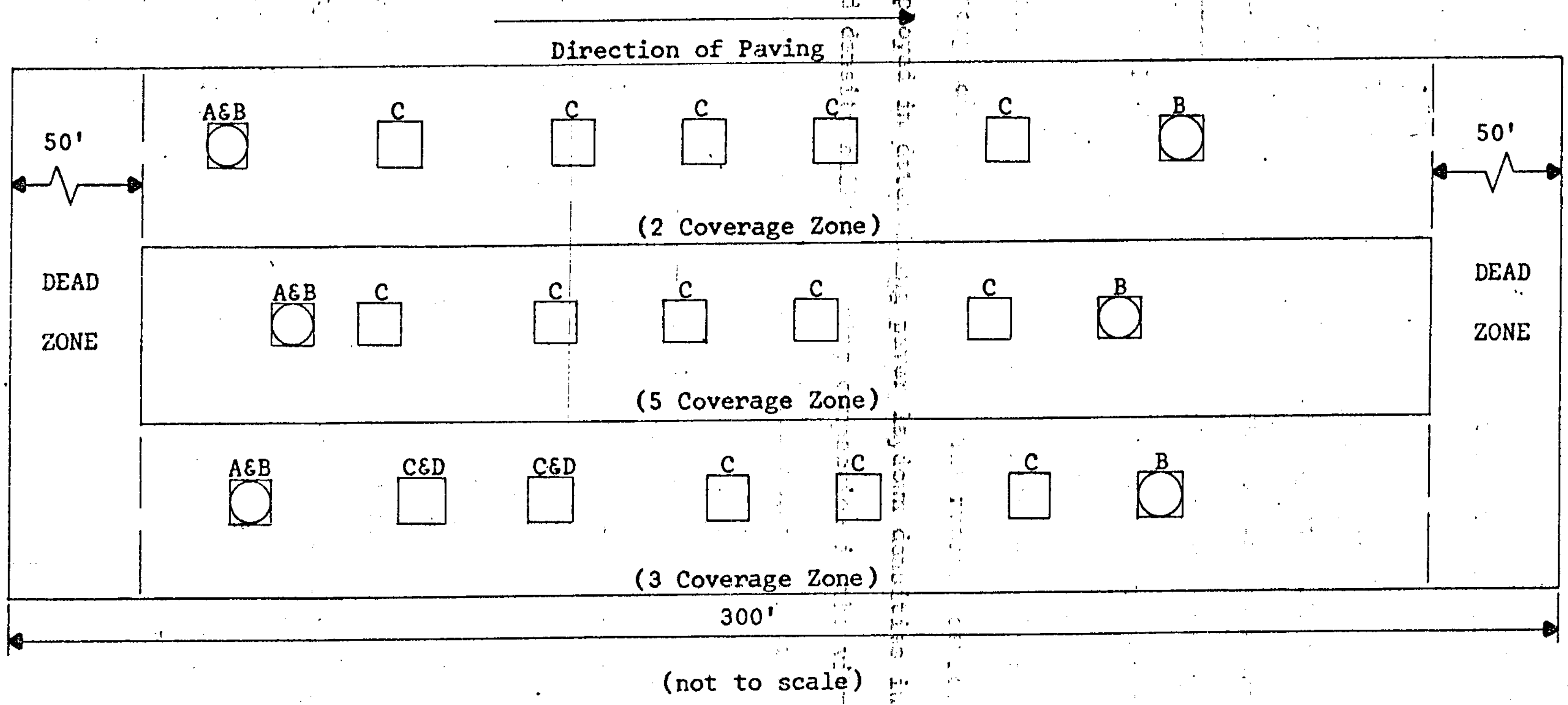
The density data required for analysis of the test section (total of 22 coverage zones) was obtained at 154 random locations (7 per each coverage zone). A nuclear density gauge was used to obtain paver laydown densities at two of these locations in each subsection. In the vibratory and tandem subsections, the nuclear device was further used for density measurements between roller coverages (two locations monitored per subsection). Determinations of final density with the nuclear gauge were made at all 154 random locations. To permit 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.

Since 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, wherever possible, a nuclear density measurement was repeated three times using a different method each time. A measurement was made with the gauge in the backscatter position, first without surface preparation, then with surface preparation (standard 20-30 Ottowa 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 T-166; maximum specific gravities were determined by the Department's solvent immersion test method.

FIGURE 2

TYPICAL DENSITY MEASUREMENT PATTERN FOR A SUBSECTION



Legend: □ = Random Test Locations

○ = 4" Diameter Core Locations

A = Nuclear density measurements - without surface preparation at paver laydown
B = Nuclear density measurements by all three methods taken after completion of compaction
C = Nuclear density measurements - with surface preparation and by the air-gap method taken after completion of compaction.
D = Nuclear density measurements with surface preparation taken between compaction coverages

It was stated previously that one of the important aims of the study was to evaluate the riding quality or pavement smoothness produced by each of the compactors tested. To accomplish this evaluation the smoothness of each subsection was measured utilizing two devices: a 10-foot rolling straightedge and a B.P.R. roughometer. The rolling straightedge indicates the span length and magnitude of surface deviations in the range of 1/8" to 1/2" in one eighth inch increments. The B.P.R. roughometer, consisting of a fifth wheel towed over the pavement surface at 20 m.p.h., yields an output referred to as the roughness index (R.I.). The R.I. is equivalent to the accumulated deviations in the pavement surface, in inches per mile. A high R.I. is thus indicative of a rough pavement surface.

Measurements were obtained by the two devices in both wheel paths of each 300 ft. subsection (dead zones were excluded). Due to the short lengths measured (200 ft.) the roughometer made three repeat runs in each wheel path in an attempt to obtain the best estimate of the pavement smoothness or R.I.

VI. DISCUSSION OF FINDINGS

A. Temperature Measurements

The procedure established for the monitoring of pavement temperatures required the installation of one thermocouple in each lift of each subsection. Temperature measurements were to be 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, some of which were not immediately recognizable. 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.

At the start of paving an attempt was made to install thermocouples by placing them directly on the macadam base course ahead of the paver. This method proved inadequate as either thermocouples were sheared by the paver or their sensing tips were forced into contact with the macadam base course. For these reasons no reliable thermocouple temperature measurements were obtained for the bottom course of the multiple lift construction.

All remaining thermocouples were installed by furrowing a channel into the uncompacted mat, placing the thermocouple into the channel and replacing the previously removed material over the thermocouple.

Based on the thermocouple and probe thermometer measurements the laydown temperature for all subsections ranged from 270°F to 280°F.

For the thick lift constructed subsections all planned breakdown compaction was accomplished within the approximate temperature range of 245°F (start) to 215°F (finish). It is estimated that the two additional passes found necessary in tandem subsection eight were completed above 180°F.

For the multiple lift constructed subsections it was not possible to determine the exact temperature range during which breakdown compaction was performed. As previously indicated no reliable thermocouple temperature measurements were obtainable for the bottom course of the multiple lift construction. Temperature measurements for the top course were also judged inadequate as laydown temperatures recorded by the thermocouples were significantly lower than probe measurements. It is believed that material disturbance during installation of thermocouples in the thinner 2" lift caused a considerable decrease in the temperature of that material immediately surrounding the thermocouples. Based on initial laydown temperature discrepancies it appeared that the associated temperature loss was in the order of 20°F to 30°F.

All thermocouple measurements in the multiple lift subsections were increased accordingly to achieve an estimated breakdown temperature range from 240°F (start) to 190°F (finish). By extrapolating temperature data it is estimated the added pass (1) of the 3-wheel roller in Subsection 4 was accomplished between 145°F (start) and 125°F (finish).

The temperature monitoring procedures employed in the evaluation test, admittedly, did not prove as reliable as was expected. However, it is believed that the resulting temperature data was sufficiently dependable to indicate that no significant variability in temperature conditions occurred between subsections within each mode of construction.

B. Density and Air Voids 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 with the nuclear densities being the primary measure of pavement densification. In order to analyze the density data in one standard form, the nuclear density measurements were subsequently converted to predicted core density values by use of linear correlation equations. Core densities were predicted using only a few of the many correlation relationships established from the density measurements. The majority of density conversions were actually accomplished by one equation*, developed from paired core and air gap measurements, which was found to yield the most accurate predictions.

*Equation:

$$Y = 82.6 + 0.467\,X$$

where Y = Predicted core density value
X = Nuclear density measurement (air-gap method)

and correlation coefficient (r) = 0.75
standard error estimate (σ) = 1.27 P.C.F.

From the actual and predicted core densities (154 random locations) mean densities were determined for each of the 22 coverage zones in the eight subsections of the test pavement. A summary of these mean density values is given in Table 1. By comparing the average densities of the different coverage zones within each subsection it is possible to establish density growth patterns for the rollers under study. The density growth data collected during the actual compaction operations is given in Exhibit 5 of the Appendix and provides substantiation to the data of Table 1.

An important observation to be made from the density growth information is that the vibratory rollers, within the range of coverages considered (2-5), 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 objectively without first considering the level of densification actually needed in a stabilized base course. Through research and experience the Department has concluded that the durability of a stabilized base is significantly diminished when its air voids exceeds 10%. Current specifications therefore require that no portion of a stabilized base have air voids above 10% after compaction. Since there normally is a certain amount of density variability within a pavement course, a bituminous base's average air voids

TABLE 1

SUMMARY OF TEST SECTION

MEAN DENSITIES

Multiple Lift Construction	Mean Density (P.C.F.)		Single Lift Construction	Mean Density (P.C.F.)
Subsection No. 1		3-Wheel Roller	Subsection No. 5	
2 Cov. zone	146.1	"	2 Cov. zone	147.4
3 Cov. zone	146.6	"	4 Cov. zone	147.4
Subsection No. 2		Vibro-Plus CA-25A	Subsection No. 6	
2 Cov. zone	143.5	"	2 Cov. zone	143.7
3 Cov. zone	144.8	"	3 Cov. zone	145.0
5 Cov. zone	146.8	"	5 Cov. zone	146.8
Subsection No. 3		RayGo 404	Subsection No. 7	
2 Cov. zone	143.3	"	2 Cov. zone	144.9
3 Cov. zone	144.7	"	3 Cov. zone	146.1
5 Cov. zone	146.1	"	5 Cov. zone	146.3
Subsection No. 4		Tandem Roller	Subsection No. 8	
3 Cov. zone	144.8	"	5 Cov. zone	146.2
4 Cov. zone	144.1	"	7 Cov. zone	147.4
6 Cov. zone	145.3	"	10 Cov. zone	148.0

NOTE: Mean Density = Average of (7) measurements; 2, 4" diameter cores and 5 predicted core density values - based on nuclear density measurements (air-gap method).

must of necessity be much lower than the critical 10% limit. From current measures of variability, the average air voids level would generally have to be as low as 6% (2 standard deviations below 10% limit) to insure complete compliance with the Department's voids criterion.

The densification needs for a bituminous base can also be considered in another manner. Most bituminous base mixtures for Department projects are designed to densify to about 4% voids (center of permitted design range, 2% to 6%) under laboratory Marshall compaction. The 6% average field voids requirement for such material would then correspond to approximately 98% of the design or Marshall density. This means that on most stabilized bases a roller or roller system must be capable (on the average) of achieving at least 98% of the laboratory Marshall density to satisfy voids requirements. Higher degrees of field densification would, of course, be needed for base mixtures having Marshall design voids above the 4% norm (up to 6% allowed).

To permit comparison to the preceding, the test pavement density data of Table 1 was refashioned in terms of percent of Marshall density and air voids. The resulting values are presented in Table 2. A review of this latter information discloses a salient inconsistency. In spite of the fact that the mixture for the test pavement was originally designed at the normal 4% voids level, 98% Marshall density is seen to correspond to over 8% voids rather than the expected 6%.

Analysis of the Marshall specimens molded during the test (see Exhibit 2) reveals that under Marshall compaction the mixture actually densified to about 6% voids as compared to the 4% of the

TABLE 2

MARSHALL DENSITY AND
AIR VOIDS SUMMARY (%)

Multiple Lift Construction				Single Lift Construction		
	Subsection No. 1		3-Wheel Roller		Subsection No. 5	
	Marshall Density (%)	Air Voids (%)			Marshall Density (%)	Air Voids (%)
2	98.1	8.8	"	2	99.0	7.9
3	98.5	8.4	"	4	99.0	7.9
	Subsection No. 2		Vibro-Plus CA-25A		Subsection No. 6	
2	96.4	10.4	"	2	96.5	10.3
3	97.2	9.6	"	3	97.4	9.4
5	98.6	8.3	"	5	98.6	8.3
	Subsection No. 3		RayGo 404		Subsection No. 7	
2	96.2	10.5	"	2	97.3	9.5
3	97.2	9.6	"	3	98.1	8.8
5	98.1	8.8	"	5	98.3	8.6
	Subsection No. 4		Tandem Roller		Subsection No. 8	
3	97.2	9.6	"	5	98.2	8.7
4	96.8	10.0	"	7	99.0	7.9
6	97.6	9.3	"	10	99.4	7.6

NOTES: 1) $\%\ \text{Marshall Density} = 100 \times \frac{\text{Mean Density}}{\text{Marshall Density}}$

2) $\%\ \text{Air Voids} = 100 - [\frac{\text{Mean Density}}{D_T} \times 100]$

Where: Mean Density is Average of (7) measurements; 2, 4" diameter cores and 5 predicted core density values - based on nuclear density measurements (air-gap method).

Marshall Density is average of two sets of Marshall specimens (6 plugs molded at plant on day test pavement was constructed).

D_T = The average of thirty maximum density values obtained from 4" diameter pavement cores (160.1 P.C.F.).

design. Therefore, the voids characteristic of the test mixture was obviously not the same as that prescribed in the original design. A significant shift in voids could be attributed to several factors such as changes in aggregate specific gravities, in particle shape, in mixture composition, etc. In this instance it is speculated that the explanation for the difference lies with either the producer's failure to use accurate aggregate specific gravities in his design calculations, or a substantial change having occurred in an aggregate gravity after formulation of the design. In any event, the consequence of the difference is that normally adequate roller compaction in terms of percent of Marshall density did not achieve desired voids levels in the test pavement.

In view of the relatively poor compaction characteristics of the test mixture, the only objective way to compare roller compaction capabilities is to consider densification in terms of percent of Marshall density rather than air voids. An additional requirement, of course, is that such comparisons be able to distinguish between real or significant differences and those differences resulting simply from normal variation in measurements. For this reason, a statistical, one-tail, t score test was used in the study to analyze density differences within and between subsections.

Considering again the data of Table 2, it is apparent that the Department's standard compaction system (3-wheel breakdown, tandem finish) equaled or bettered the critical 98% Marshall density level in both multiple and thick lift construction. Furthermore, statistical analysis indicates that the additional 3-wheel breakdown coverages investigated in the study did not affect any significant density increase in either paving mode.

The vibratory rollers are seen to have behaved much differently than 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 is seen to have occurred with the RayGo vibratory roller. However, in deep lift construction (Subsection 7), the RayGo 404 was unable to cause a significant density increase with its final two applications. In this particular instance, however, the RayGo unit did surpass the important 98% Marshall density level with only three roller coverages while in all other vibratory subsections (multiple and single lift construction) five coverages were needed.

Before considering the performance of the tandem roller 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 doubtful that the added compaction was justified as the decision was made on the basis of air voids not percent of Marshall density. The high air voids condition indicated by the monitoring tests at completion of the planned compaction sequence was actually similar to that achieved by the other rollers. In view of the unexpected change in the air voids characteristics of the base mixture, the added compaction was applied more as a result of an inadequately designed mixture rather than poor compactive effort.

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

It must be noted that in both tandem subsections the added compaction was accomplished at relatively low temperatures (180° thick, 140° multiple). There is, therefore, strong doubt especially in multiple lift construction that the supplemental roller passes increased densification. The lack of difference between density measurements before and after the extra rolling at the monitoring locations lends support to this doubt.

A review of the mean densities for Subsection 8 reveals that the tandem roller reached the 98% Marshall density level with five coverages. Also, at seven coverages the tandem roller reached what might be considered its optimum densification level for the test - 99% of the Marshall value. The statistical test indicated that no significant increase in density occurred between seven and ten tandem coverages.

Comparing the performance of the various rollers on multiple lift construction, it appears that the Department's standard compaction system (3-wheel breakdown, tandem finish) was the optimum densification system tested. The 98% Marshall density level was attained with only two 3-wheel breakdown coverages (plus 2 tandem finish passes) - the vibratory rollers required five 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 that achieved by any of the other rollers. However, it is of value to note that in thick lift paving the RayGo did reach the 98% Marshall level after only three applications.

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

C. 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 a parameter termed "roller efficiency" was utilized. Roller efficiency was taken to be the change in density affected by a roller divided by its expended compaction time. Table 3 lists the roller efficiency value for each compactor and coverage level evaluated.

To facilitate uniform comparisons the efficiency values have been calculated by assuming the pertinent roller coverages to be placed over the entire width of a 12 foot wide mat. The compaction times used in these calculations were all actual, as measured, times for the 3-wheel and tandem rollers. For the vibratory compactors, the compaction times were estimated 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 it is necessary to keep in mind that a bituminous base must normally be densified to 98% of the Marshall density (average level) to insure compliance with Department air voids criterion. The efficiency which rollers exhibit in reaching this density level is therefore of major importance in considering their use on Department projects. A review of Table 3 shows that in multiple lift construction the Department's presently specified roller system (3-wheel breakdown with tandem finish) was more efficient than the vibratory compactors in reaching the critical 98% 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 than on the multiple lift paving. This is due to the fact that the standard 3-wheel, tandem system produced 99% rather than 98% of the Marshall density. If comparisons were made on the 99% level, the 3-wheel, tandem system would definitely be the most efficient. This system required less time to reach 99% density than that needed by the other rollers in achieving lower densities. The only comment that can be offered concerning comparisons at 98% Marshall density level is that the RayGo (404) was more efficient than both the Vibro-Plus (CA-25A) and tandem compactors.

TABLE 3

ROLLER EFFICIENCY

	Subsection	Coverage Zone	Equipment	Mean Density (P.C.F.)	% Std. Density	% Marshall Density	(2) Total Compaction Time (min.)	(3) Roller Efficiency (P.C.F./min.)	(4) % Std. Roller Efficiency	(5) % Roller Efficiency (Mult. Lift)
Multiple Lift	1	2	(1) 3-wheel with Tandem Finish	146.1	100	98.1	46*	0.398	100	--
	2	5	Vibro-Plus (CA-25A)	146.8	100.5	98.6	60	0.317	80	--
	3	5	RayGo (404)	146.1	100.0	98.1	60	0.305	77	--
Thick Lift	5	2	(1) 3-wheel with Tandem Finish	147.4	100	99.0	22*	0.850	100	214
	6	5	Vibro-Plus (CA-25A)	146.8	99.6	98.6	30	0.603	71	190
	7	3	RayGo (404)	146.1	99.1	98.1	12	1.450	171	309
		5	"	146.3	99.3	98.3	20	0.880	104	289
	8	5	Tandem	146.2	99.2	98.2	26	0.673	79	--

NOTES:

1. Department's standard (Std.) compaction used for comparison purposes.
2. Determined from average compaction time per coverage.
3. Roller efficiency = $\frac{\text{Final - Average Laydown Density}}{\text{Total Compaction Time (Min.)}}$
4. % Std. roller efficiency = $\frac{\text{Roller Efficiency (Any cov.zone)}}{\text{Std. Roller Efficiency (3-wheel)}} \times 100$
5. % Roller efficiency (Mult. lift) = $\frac{\text{Roller Efficiency (Thick Lift)}}{\text{Roller Efficiency (Mult. Lift)}} \times 100$
6. Subsection 4 not included due to application of one 3-wheel roller pass on top lift.

*Includes tandem finish rolling and all maneuvering time.

Average Laydown Density

Thick Lift = 128.7 P.C.F.
Multiple Lift = 127.8 P.C.F.

As would be expected, Table 3 also shows that all rollers increased their efficiency and reduced their compaction times significantly in going from multiple lift to thick lift construction. This is clearly shown by inspection of the % roller efficiency achieved on thick vs multiple lift construction.

D. Riding Quality

The riding quality measurements obtained in the Stanhope evaluation test are summarized in Table 4. In interpreting this riding quality data it must be kept in mind that the information presented was obtained on relatively short (200 feet) pavement lengths. A good 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 size construction project.

The BPR roughometer data is presented in the form of average roughness index values for each subsection. These values, which are each an average of six measurements, are observed to range from a low of 140 inches/mile to a high of 191 inches/per mile. On a typical, full size, paving project in New Jersey, the top of stabilized base would be expected to have a roughness index somewhere between 120 and 180 inches/mile.

Comparing the roughness for the multiple lift subsections, it appears that the two vibratory rollers and the Department's standard compaction system (3 wheel breakdown, tandem finish) all produced about the same level of pavement smoothness. Tandem breakdown rolling, in contrast, resulted in a surprisingly rougher pavement. These same findings also apply to the thick lift mode of construction with the exception of the RayGo 404 vibratory roller. In thick lift compaction the RayGo 404 seems to have produced a smoother riding surface (lower roughness index) than that attained by any of the other compactors.

A comparison of roughometer data for the thick lift subsections to that for the multiple lift subsections reveals an additional interesting factor. The thick lift subsections are all, to varying degrees, rougher than their comparable multiple lift subsections. Apparently, when using a manually controlled paver, it is not possible with one lift of base to overcome as much subgrade roughness as with two lifts.

The riding quality measurements made with the rolling straightedge are given on the right hand side of Table 4. For each subsection, the table shows the number of surface deviations in the wheel paths to be in excess of one eighth of an inch. To interpret this data it must be realized that good riding pavements normally have few deviations while rough pavements have many deviations. Based on this consideration it is apparent 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 construction over the thick lift construction.

The preceding comments must be tempered by two additional considerations. First, the repeat readings with the roughometer on any one subsection were more variable than had been anticipated. Although a total of six measurements were averaged in each subsection, their variability was such as to cause the resulting average to be of rather low precision. The 95% confidence limits for each average was approximately ± 25 inches/mile. This basically means that the difference in roughness index between any two subsections must be in the order of at least 25 inches per mile before it could be considered real and significant.

The second tempering factor relates to the poor riding quality 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 super elevation changes may have had some detrimental effect on the surface smoothness achieved in these areas.

TABLE 4

RIDING QUALITY MEASUREMENTS

		B. P. R. Roughometer Data	Straightedge Data
Multiple Lift Subsections	Station	Average Equivalent Roughness Index (in./mile)*	Number of Deviations in Wheelpaths Of Individual Subsections
1 (3-wheel)	52 + 50 to 54 + 50	141	4
2 (CA-25A)	55 + 50 to 57 + 50	146	4
3 (RayGo 404)	58 + 50 to 60 + 50	140	2
4 (Tandem)	61 + 50 to 63 + 50	171	5
Thick Lift Subsections			
5 (3-wheel)	52 + 50 to 54 + 50	168	14
6 (CA-25A)	55 + 50 to 57 + 50	179	12
7 (RayGo 404)	58 + 50 to 60 + 50	143	9
8 (Tandem)	61 + 50 to 63 + 50	191	12

*Values given are average of six roughometer measurements per subsection - three repeat measurements in each of two wheel paths. Based on the variability of the repeat measurements, the 95% confidence limits, or tolerance, for each average value is ± 25 inches/mile.

II. CONCLUSIONS

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

1. Analysis showed that under laboratory Marshall compaction the base mixture densified to only 6% air voids as compared to the original design of 4%. The consequences of this change was that normally adequate roller compaction did not achieve a desired voids level. For this reason, in evaluating the compaction capabilities of the rollers tested, it was necessary to consider the Department's densification requirements in terms of percent Marshall density, rather than on an air voids basis. For most base mixtures (designed at 4% Marshall air voids) a roller system must be capable, on the average, of attaining at least 98% of the Marshall density to satisfy the Department's voids specification.
2. All roller systems evaluated were able to achieve the critical 98% Marshall density plateau. However, it is to be noted that due to 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.
3. The vibratory rollers did not produce base densities equivalent to those achieved by the Department's standard compaction system within the coverage range (2-3) recommended by the manufacturers of the units.

8. Pavement riding quality was not adversely affected by either of the vibratory compactors tested. In addition, no measurable improvement in riding quality was discernible when the tandem rather than the 3-wheel roller was used to perform breakdown compaction.
9. 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 one roller and one operator, rather than two rollers and two operators, could affect a reduction in construction costs.
10. The findings of this evaluation showed that when a manually controlled bituminous paver is utilized, the resulting riding surface on thick lift base construction is significantly rougher than that for standard multiple lift paving.
11. This study substantiated previous findings that generally higher bituminous base density is achieved in thick lift paving as compared to the Department's multiple lift mode of construction. Furthermore, less compaction time is required.

APPENDIX

EXHIBIT 1

ROLLING PROCEDURE, PASS AND COVERAGE DEFINITIONS

3 WHEEL ROLLER (10 - 12 Ton)

A. *Rolling Procedure

1. Rolling shall progress from low to high.
2. Complete specified number of passes (1).

B. Definition of a Pass and Resulting Coverages

1. Rolling shall proceed uniformly lapping (one half width of rear wheel) each preceding track until the entire mat surface has been rolled by the rear wheels.
2. One pass results in pavement strips or zones having 2 & 3 coverages in subsection 1 and 2 & 4 coverages in subsection 5 (due to wider mat width) for evaluation.

VIBRATORY ROLLERS (Vibro-plus, Model CA-25A and RayGo Rustler, Model 404)

A. *Rolling Procedure

1. Rolling shall progress from low to high.
2. Maintain specified frequency of vibration.
3. Complete number of specified passes (2 full width of mat and 1 partial width).

B. Definition of a Pass and Resulting Coverages

1. Movement of vibrating drum from point A to point B.
2. Two full width passes and one partial width pass results in pavement strips or zones having 2, 3 & 5 coverages for evaluation.

EXHIBIT 1 (Continued)

TANDEM BREAKDOWN ROLLER (10 - 12 Ton)

A. *Rolling Procedure

1. Rolling shall progress from low to high.
2. Complete specified number of passes (3 full width of mat and 1 partial width).

B. Definition of a Pass and Resulting Coverages

1. Rolling shall proceed uniformly lapping (one half width of rear drum) each preceding track until the entire mat surface has been rolled by the rear drum.
2. Three full width passes and one partial width pass results in pavement strips or zones having 3, 4 & 6 coverages for evaluation.

TANDEM FINISH ROLLER (10 - 12 Ton)

A. *Rolling Procedure

1. Rolling shall progress from low to high.
2. Complete number of passes necessary to eliminate pavement marks left by the breakdown roller.

B. Definition of a Pass

Same as for "Breakdown Tandem Roller" (above)

DEFINITION OF COVERAGE (All Compactors)

A coverage is further defined as ONE passage over a point on the mat of one rear wheel of the 3-wheel roller, the rear drum of the tandem or the vibrating drum of the vibratory compactors.

The number of coverages made in the specific pavement strips or zones to be evaluated in each subsection were established by pass definitions, number of passes specified and roller and mat dimensions.

*Breakdown rolling will not begin until paver has completed laydown in the subsection.

EXHIBIT 2

MIX DESIGN

Theoretical Gradation

Sieve #	Total % Passing
2"	100
1-1/2"	100
3/4"	79
#4	48
#8	38
#50	15
#200	6.1

Percent Asphalt Cement...4.3%

Percent Air Voids........3.98% (6.1%)*

Average Stability.....2650 lbs (2050 lbs.)*

Average Flow.............0.11" (0.11")*

Weight Per Cu. Ft......150 lbs (149 lbs.)*

*Average of two 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.

EXHIBIT 3

COMPOSITION ANALYSIS AND PLANT MIXTURE TEMPERATURES

Part 1 Extraction Test Results at Plant (% Passing)

Sieve Size	Test 1	Test 2	Test 3	Test 4
2"	100	100	100	100
1-1/2"	100	100	100	100
3/4"	80	81	68	79
#4	46	46	39	47
#8	41	41	34	40
#50	16	16	14	16
#200	6.1	6.5	5.8	5.4
A.C. (%)	4.4	3.8	3.7	4.3

Part 2 Extraction Test Results From 8" Diameter Pavement Cores (% Passing)

Sieve Size	Test 5 Top Lift	Test 6 Bottom Lift	Test 7 One Lift
2"	100	100	100
1-1/2"	100	100	100
3/4"	79	77	70
#4	42	44	40
#8	37	39	36
#50	16	15	16
#200	4.9	5.6	7.7
A.C. (%)	3.9	4.4	4.3

Part 3 Plant Mixture Temperatures

Time	Range of Temperatures (°F)
7:00 - 12:00 a.m.	280 - 300
12:00 - 3:30 p.m.	285 - 295

EXHIBIT 4

CONSTRUCTION EQUIPMENT DETAILS

Equipment Type	
(1) Paver	12 foot paving width, Manual control for line and grade Depth feelers for automatic feed vibrating screed (variable intensity)
(2) 3-Wheel Roller	10-12 Tons Rolling width - 7' or 84" Width of rear wheels - 24"
(3) Tandem Roller	10 to 12 Tons Width of rear roll - 4.5' or 54"
(4) Vibratory Rollers	Vibro-Plus, Model CA-25A S/N 251 Overall net weight - 20,300 lbs. Drum diameter - 60" Drum Length - 84" Frequency-Variable to 2400 V.P.M. *Static Drum Force - 10,500 lbs. *Centrifugal Force (High Amplitude Setting) - 18,500 lbs. @ 1700 V.P.M.
*Note: Static and dynamic force values taken from equipment brochures.	RayGo, Model 404 Shipping weight - 18,500 lbs. Drum diameter - 59" Drum length - 84" Variable frequency - 1150 to 1500 V.P.M. Reed Type Vibration Tachometer *Static Drum Force - 12,000 lbs. *Dynamic Force - 27,000 lbs.

EXHIBIT 5

SUMMARY OF DENSITY GROWTH MEASUREMENTS (3 COVERAGE ZONES)

STANDARD MULTIPLE LIFT CONSTRUCTION (2 Lifts, 2" Thick)

SUBSECTION	LOCATIONS	AVERAGE LAYDOWN DENSITY (P.C.F.)	AVERAGE OF TWO DENSITIES(P.C.F.)AFTER COVERAGE			
			ONE	TWO	THREE	FOUR
2	17&18	127.8	142.5	144.3	144.9	--
3*	38&39	127.8	--	--	--	--
4	58&59	127.8	143.3	144.4	144.2	143.7

SINGLE OR DEEP LIFT CONSTRUCTION (1 Lift, 4" Thick)

SUBSECTION	LOCATIONS	AVERAGE LAYDOWN DENSITY (P.C.F.)	AVERAGE OF TWO DENSITIES(P.C.F.)AFTER COVERAGE				
			ONE	TWO	THREE	FOUR	FIVE
6	109&110	128.7	144.4	144.8	145.6	--	--
7	128&129	128.7	139.8	136.9**	146.6	--	--
8	149&150	128.7	142.7	144.3	145.3	--	145.5

Note:

1. Density values are predicted core densities based on nuclear density measurements.

2. (*)Data for Subsection 3 omitted due to inconsistency with density growth patterns of other subsections. It is suspected that the inconsistencies are attributable to insufficient adherence to prescribed test methods caused by time limitations between coverages.

3. Average laydown densities are equivalent to the mean density achieved separately in Lane, R-1 (thin lift) and Lane, R-2 (thick lift) at paver laydown.

4. (**)As with the data of Subsection 3, it is believed that this average is in error due to difficulties in completing measurement procedures.