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This report is a summary of the California Department of Transportation's development of test procedures for determining the density and relative compaction of asphalt concrete (AC) and end-result specifications for the compaction of AC pavements.

The test method utilizes the backscatter mode of nuclear density gages currently in use by Caltrans. These gages were found to be reliable for determining the densities of layers 0.15 ft, or more, thick.

The specification is based upon a direct comparison between the density of the in-place pavement and laboratory-compacted samples of the same material. Test strips are not required.

Attempts to modify test procedures and to redesign a nuclear gage for testing layers less than 0.15 ft. thick are discussed also.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

CONTROL OF AC COMPACTION USING AN END-RESULT SPECIFICATION

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NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (1/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ ($MPa\sqrt{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ ($KPa\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{°F - 32}{1.8} = °C$	degrees celsius (°C)

ACKNOWLEDGEMENTS

The early phases of the research were conducted by James A. Cechetini who was one of the investigators on this project prior to his retirement in December 1980.

The prototype, thin-lift nuclear gage tested in conjunction with this study was developed by Patrick J. Campbell, President of the Campbell Pacific Nuclear Corporation. Laboratory calibration and testing of the nuclear gage were conducted by Frank Champion of the Transportation Laboratory.

Guidance for this study was provided by a steering committee composed of Chairman Raymond A. Forsyth of the Transportation Laboratory, David T. Powers of the Caltrans Headquarters Office of Highway Construction, William B. Calland (retired), Caltrans District 11 in San Diego, and Robert Findlay, Caltrans District 11, who filled the vacancy left by Mr. Calland's retirement.

The typing and editorial assistance provided by Lydia Burgin and the drafting done by Leoncio Lopez are acknowledged and appreciated.

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INTRODUCTION

Asphalt concrete (AC) pavements, in California, are placed under the premise that satisfactory compaction will be accomplished if procedures and conditions are standardized. One major deficiency of the procedural specification is the lack of flexibility necessary to compensate for allowable variations in asphalt concrete mixes and compaction equipment. California's many types of aggregate and aggregate-processing methods result in variations in angularity and texture. These, along with variations in the source and grade of asphalt, have a considerable influence on the AC's resistance to compaction. Also, rollers of various size and weight are qualified for use, but there are broad differences in the compactive effort they provide.

Another problem has been the inability of paving inspectors to verify temperatures and applied compactive efforts. Either of these procedural requirements could require full-time inspection to assure conformance.

This report discusses the California Department of Transportation's (Caltrans') efforts to develop and apply an end-result specification to the compaction of AC pavements. It is believed that replacing the current procedural specifications with an end-result specification will result in a more effective and enforceable means of controlling the compaction of AC.

CONCLUSIONS

1. An end-result specification, using nuclear gages to determine in-place density, is a practical and effective means of determining the degree of compaction of AC pavements.

2. Backscatter nuclear gages which meet Caltrans' specifications, and have been calibrated on the Transportation Laboratory (TransLab) standard blocks can provide a practical and effective means of determining the degree of compaction of pavements which are at least 0.15 ft thick.

3. Attempts to develop a backscatter nuclear gage which would provide a reliable method of determining the density of pavement as thin as 0.10 ft, and up to a thickness of 0.30 ft, were unsuccessful. (Reducing the effective depth of a nuclear reading renders it ineffective for thicker layers and intensifies the effects of variations in the pavement's surface and/or improper gage seating.)

4. Procedures designed to calculate the density of thin layers from measurements on composite layers are not reliable for determining contract compliance.

5. The requirements of the adopted end-result compaction specification are achievable when good construction practices are followed.

6. The compaction methods specified in the current Caltrans specifications are not necessarily the most appropriate methods for compacting all AC pavements. Some pavements can be compacted more effectively with fewer coverages, and less compactive force.

7. The effect of a rough pavement texture can be reduced substantially by filling the surface voids with fine sand prior to determining the in-place density with a nuclear gage.

8. An error in determining the in-place density can be introduced if an excess of sand prevents the nuclear gage from making intimate contact with the surface of the pavement.

9. Underlying materials can affect the in-place density determined for an AC pavement. This error will be less than one percent when the layer being tested is at least 0.15 ft thick and the in-place densities of the two layers do not differ by more than 5 percent.

RECOMMENDATIONS

1. It is recommended that California Test 375 "Determining the In-Place Density and Relative Compaction of AC Pavement" be applied as the specified procedure for determining the relative compaction of a significant number of AC pavements under construction during the 1985 construction season. Acceptance of the test as a routine procedure will be considered on the basis of these field trials.

2. Contractors should be allowed to use compacting equipment and procedures of their choice, with the approval of the Engineer, and subject to compliance with all contract requirements including compaction.

3. No further effort should be expended at this time to modify existing nuclear gages or test procedures for determining the density of layers less than 0.15 ft thick.

IMPLEMENTATION

Caltrans' Standard Special Provision 39.03, dated July 2, 1984 (Appendix A), includes the end-result specifications for asphalt concrete pavements. This specification is being included in the special provisions of several paving projects in each Caltrans highway district for the 1985 construction season.

California Test 375 "Determining the In-Place Density and Relative Compaction of AC Pavement" (Appendix B) is being published as an official California test procedure. It will be applied to determine the in-place density and relative compaction of AC pavements on projects which include the end-result specification.

Caltrans' Standard Special Provision 39.01, dated July 4, 1984 (Appendix C), which specifies a 0.15-ft minimum thickness for most AC layers, has been included in the specifications for most recent Caltrans projects. This specification will facilitate use of the nuclear gage and the end-result specification for measuring compaction of AC pavements.

BACKGROUND

Compaction is recognized as a critical factor in constructing a durable, smooth-riding, AC pavement. Unfortunately, compaction has been difficult to evaluate. Most methods used for determining in-place density and relative compaction of other materials are considered inappropriate for AC.

Because of this lack of accepted methods, Caltrans has relied upon procedural specifications to achieve satisfactory compaction. These procedural specifications are based on the premise that adequate compaction will be achieved by controlling rolling patterns, equipment type and size, the number of coverages, and temperature of the paving materials and environment.

The weight of a roller is not subject to significant change during the course of its use, but rolling patterns and AC temperatures are. Rolling patterns and the number of coverages depend upon the operator's skill and competence. Unexpected delays, such as mechanical breakdowns, also can affect rolling patterns as it becomes necessary to "catch up" to the paving operation. Because of the potential for variations, full compliance with specified rolling patterns and number of coverages can be assured only through full-time observation by an inspector.

Temperatures specified for the AC at the time of compaction also are difficult to verify. Heat is being lost constantly from the moment the AC is discharged from the mixing plant until it cools to ambient temperature. Since the temperature remaining in the material at the time of compaction is influenced by many procedural and climatic factors, compliance can be verified only by constant monitoring of the temperature immediately preceding and during compaction. Again, full-time inspection could be required.

Even when the paving and compaction are completed in full compliance with the procedural specifications other conditions and circumstances can affect compaction. Pavement thickness, aggregate gradation and angularity, source and grade of the asphalt, and the rigidity of the underlying layer each can affect the compactability of AC.

In addition there has been concern that the specified procedural requirements may be excessive under certain conditions or with some paving materials. At times, it has been necessary to reduce the compactive effort to prevent surface checking and lateral displacement, especially when placing thin layers or when "tender" mixes are encountered. This reduction in compactive effort does not necessarily mean a reduction in compacted density or relative compaction. Some materials are compacted more readily than others and it is believed that, in some cases, additional effort actually may be detrimental to the finished pavement. At times additional compactive effort or slight changes in the required temperature may be beneficial.

Although the Engineer has the authority to modify these procedural requirements as necessary, his ability to do so has been limited by the lack of an accepted test for determining the density of the finished pavement. Rejection of a pavement on the basis of procedural specifications is complicated further by the fact that measurements and observations cannot be repeated or verified because the conditions are constantly changing. For example, a temperature reading at a given time at a given location can never be repeated because of the constant, rapid loss of heat from the pavement.

The extent of this inability to enforce procedural specifications was made evident by a survey of Caltran's construction personnel who were asked to identify specific problem areas encountered when using the present specifications. This questionnaire and the responses are attached as Appendix D.

The ultimate goal of this study was to develop realistic specifications and reliable test procedures which allow the contractor greater latitude in his paving operation while assuring Caltrans that the asphalt concrete is compacted sufficiently to provide a durable pavement.

Preliminary findings from this study were reported in an interim report dated June, 1982(1). It was concluded at that time that laboratory procedures for determining the specific gravity of cored samples provide a good standard for evaluating the accuracy of other methods. It was also concluded that the prototype of a thin-lift nuclear backscatter gage, as well as modified applications of conventional nuclear backscatter gages, provided potential methods for determining the in-place density of pavements as thin as 0.08 ft (1 inch).

DISCUSSION

A. PROCEDURAL SPECIFICATIONS FOR COMPACTING AC

The current Caltrans standard specifications dictate the equipment and rolling patterns to be used in compacting AC pavements (see Appendix E). Under normal paving conditions, compaction must consist of three complete coverages with a static steel-drum breakdown roller weighing at least 12 tons followed by three coverages with a pneumatic roller which applies a minimum load of 2000 pounds per tire, and then finish rolling with a static steel-drum roller weighing at least 8 tons.

Other compacting equipment is permitted in lieu of the static steel-drum breakdown roller and the intermediate pneumatic roller, but only after prequalification in accordance with California Test 113(2). The operating conditions, such as rate of vibration and amplitude, forward speed, and number of coverages for vibratory rollers are established based on the compactive effort required to achieve 95% relative compaction. Once established, these same operating conditions are required any time that model of roller is used.

The procedural specification also states the acceptable temperature range for each step of the compaction process. Breakdown compaction, whether by static or vibratory roller, must begin while the temperature of the AC is at least 250°F and be completed before the temperature falls below 200°F. Compaction with the pneumatic roller must be completed before the temperature drops below 150°F. No temperature requirements are specified for finish rolling, but the specifications do state that finish rolling is to be completed "without delay." A minimum atmospheric temperature of 50°F is required for placement of most AC pavements.

B. END-RESULT SPECIFICATION FOR COMPACTING AC

A properly applied end-result specification based on in-place density determined with a nuclear gage should benefit not only the contracting agency but also the contractor. A primary benefit is the capability of evaluating the compaction of a large area via a statistical approach. Of particular benefit to the contracting agency would be a reduced demand on the inspectors time, an extended time period for testing, and test results which can be verified or repeated. At the same time, the contractor would be allowed to apply his experience and judgement in selecting equipment, techniques and conditions for constructing the required pavement.

Another objective of the end-result specification developed by Caltrans is to encourage the contractor to make a diligent effort to achieve the required degree of compaction. This was done by establishing a pay penalty with graduated deductions. The penalty is incorporated in the end-result specification which is included as Appendix A of this report.

A review of specifications used by other transportation agencies (Appendix F) indicates a broad range in the requirements for compaction. This is due basically to difference in the methods used to establish maximum density. Previous Caltrans studies have shown that 95%

relative compaction is a reasonable requirement when compaction procedures and test methods normally used in California are applied.

C. TEST METHODS UTILIZED IN END-RESULT SPECIFICATIONS

Although the concept of end-result testing may be accepted generally, its effectiveness depends entirely upon fast, reliable testing and measuring procedures for determining the maximum and in-place densities. Considerable effort was expended in evaluating existing test methods, and possible modifications, to select procedures which are most suitable for use with an end-result requirement. Procedures for compacting to maximum density in the laboratory, for determining the density of laboratory-compacted samples and core samples, and for determining the density of the in-place pavement are discussed below.

1. Compacting to Laboratory Maximum Density

A review of specifications used by other transportation agencies (Appendix F) revealed that several different procedures are being used to establish the maximum density. These include test strips as well as various laboratory procedures.

Because the compactive effort applied by the various procedures differs considerably, the derived maximum densities differ also. This, however, should not create a problem when the specified relative compaction is referenced to the method of determining maximum density. For instance, when the procedure used to establish the maximum density applies a large compactive effort, the specified relative compaction can be lower than when the method applies less compactive effort, which results in a lower maximum density.

Caltrans adopted California Test 304 as a convenient and reliable method of compacting AC to maximum density. This procedure, which is comparable to ASTM D-1561 and AASHTO T247, utilizes a California kneading compactor for preparing 2 1/2-inch thick by 4-inch diameter test samples. No other method was considered seriously since this procedure is the standard for preparing test samples for several other Caltrans tests on AC.

2. Determining Density in the Laboratory

In the laboratory, the volume and weight of a material are measured so that the specific gravity can be calculated. The specific gravity is then used to calculate the density or unit weight of the material. When the metric system of measurement is used, the specific gravity and density have the same numerical value.

California Test 308 includes two procedures for determining the volume of compacted AC samples. In one procedure the volume is determined from the external dimensions of the sample. This method is convenient for samples that have been compacted in fixed-dimension molds where the height of the sample is the only variable. Use of this procedure is limited to porous materials which are not suitable for testing by immersion in water.

In the second procedure, the volume of the test specimen is determined by weighing the specimen in air and in water.

To prevent water from penetrating into the sample, a paraffin coating is applied. This procedure is comparable to ASTM D-1188 and AASHTO T166, which are accepted widely as reliable methods for determining the densities of laboratory-compacted samples.

Since the water-displacement procedure is generally accepted for determining the specific gravity of laboratory-compacted samples, it has been assumed that this same technique is reliable for determining the specific gravity of core samples as well. It is doubtful, however, that test results could ever be available routinely on the same day that the pavement is placed. The equipment needed to perform the test could be set up near the job to eliminate lengthy delays encountered by transporting them to a central laboratory, but practical application of this procedure would still be limited. Coring machines and operators are not always available, and even when they are, the pavement cannot be cored until the asphalt has cooled sufficiently to resist disruption by the cutting tools. Normally this would mean waiting until the next day although cooling could be expedited by chilling the immediate area with dry ice.

3. Determining In-Place Density by Nuclear Gage

The nuclear gage is the only device having a recognized potential for providing a rapid method for determining the in-place density of AC pavement. Nuclear gages, however, are not without limitations. Before discussing the use of nuclear gages in this study, it would be in order to provide a brief description of the gage and an explanation of its application. If more detailed information on the theory or operation of these instruments is desired, the Caltrans "Training Manual for Nuclear Gage Operators" is suggested as a reference.

A nuclear density gage contains two basic components, a small source of gamma radiation and a radiation-detection device. An electronic digital counter records the number of gamma photons that travel from the source to the detector during a fixed period of time. Most nuclear gages are constructed so that two modes of operation are available. These are referred to as the direct-transmission mode and the backscatter mode.

The direct-transmission procedure has been used successfully by Caltrans for more than 20 years for determining the density of layers of soil and aggregate which are four inches or more in thickness. A rod containing the nuclear source, or with some gages, the detector, is inserted into a hole which has been drilled or punched in the material. The depth to which the rod is inserted is predetermined, based on the thickness of the material being tested. The other half of the emission-detection device rests on the surface of the layer and is offset a few inches from the hole. This arrangement requires that the gamma photons travel through the layer of material to reach the detection device. The density of the layer is inversely proportional to the number of gamma photons that penetrate through the layer from source to detector.

The backscatter procedure provides a method of determining the density of thinner layers and especially those thin layers which cannot be drilled or punched easily for insertion of the rod. For this procedure, both the nuclear source and the detection device are retained in the gage housing as it rests on the surface of the material. Lead shielding prevents the gamma photons from traveling in a straight line between the source and detector. Thus, the only gamma photons that can reach the detector are those that have passed by the edge of the shielding, penetrated into the material, and from there are deflected back through the material to the detector. Throughout this report reference to nuclear gages is limited to the backscatter mode unless otherwise noted.

Densities determined by the backscatter procedure normally are considered to represent the top three inches of compacted material. However, it is important to understand that all portions of the three-inch layer do not have an equal influence on the indicated density. The farther the material is below the surface, the less influence it will have.

The effective reading depth of a backscatter gage, and the relative influence of materials at different depths below the surface, can be evaluated by taking density readings on the surface as the thickness of cover material is increased over a second material which has a dissimilar density. In the laboratory, plates of aluminum and magnesium are excellent for this purpose. The aluminum and magnesium have vastly different densities that can be measured accurately with a nuclear gage (aluminum ≈ 2.55 g/cc; magnesium ≈ 1.76 g/cc).

The data plotted in Figure 1 show the densities indicated by a CPN Model B nuclear gage as half-inch-thick plates of either aluminum or magnesium were stacked on top of the

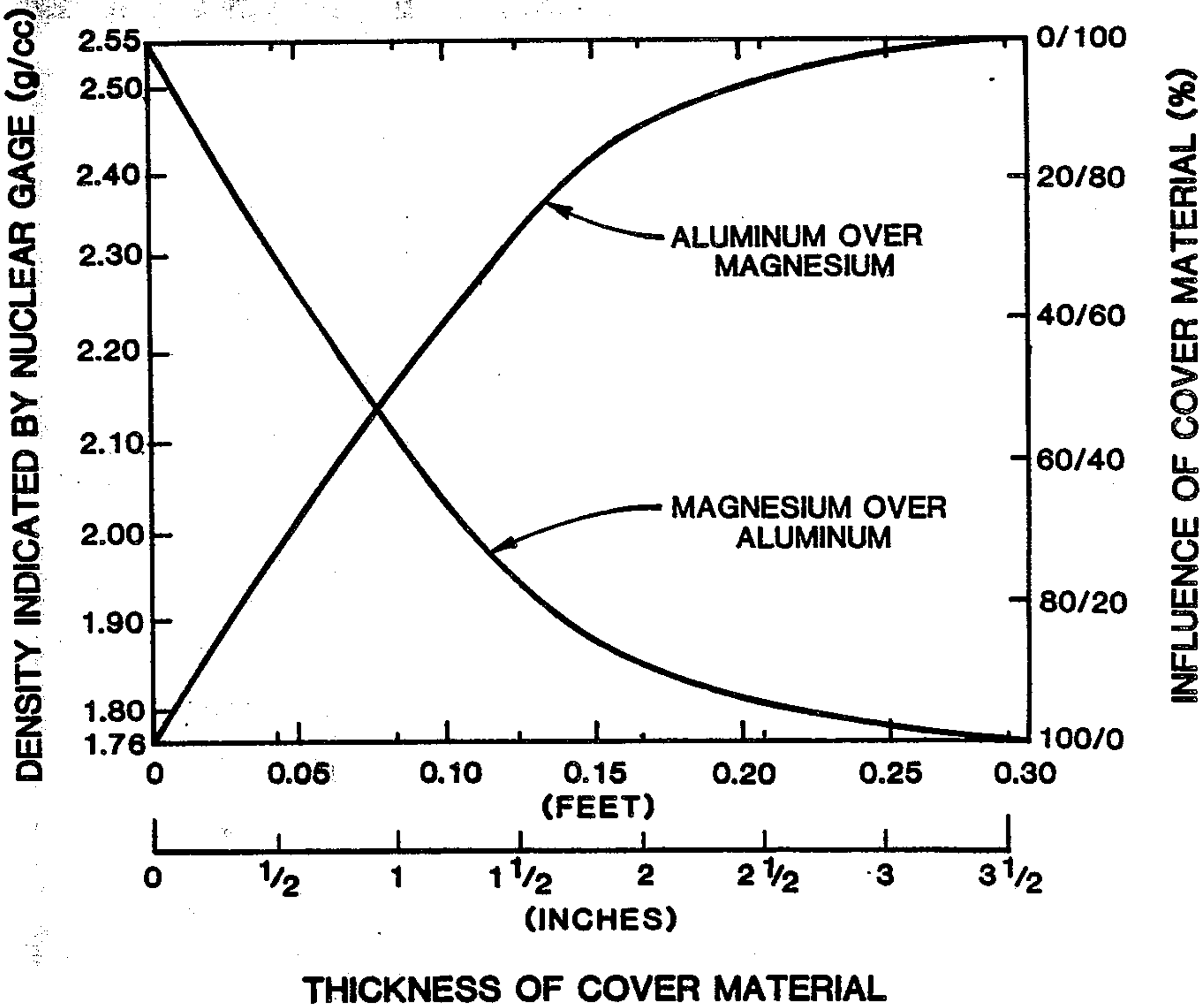

Fig. 1. INFLUENCE OF UNDERLYING MATERIAL ON DENSITY INDICATED BY NUCLEAR GAGE (CPN PORTAPROBE MODEL B BACKSCATTER MODE)

other material. In addition to the measured densities the influence of the surface material is shown as a percentage. This value was calculated using the formula:

$$\% \text{ Influence} = \frac{D_n - D_u}{D_c - D_u}$$

Where:

% Influence is the contribution of the surface material to the composite density indicated by the nuclear gage.

D_n = Density indicated by nuclear gage.

D_u = Density of underlying material.

D_c = Density of cover material.

These data show that the top 1/2 inch accounts for approximately 30% of the density indicated by the nuclear gage and the top 1 inch accounts for approximately 55%. The density of the cover material apparently has some effect on the depth of influence; however, even with the wide difference in the densities of these two materials, their influences on the density readings are very similar.

When the thickness of the cover material is increased to 1 1/2 inches, its influence increases to approximately 75%. At 2 inches the surface material contributes more than 90% of the density reading.

Similar evaluations were made using other models of gages. These results are plotted along with the results from the CPN Model B gage in Figure 2. The results with the Troxler Model 3411-B are very similar to the results with the CPN Model B. When the CPN Model MC-1 gage is used, the top

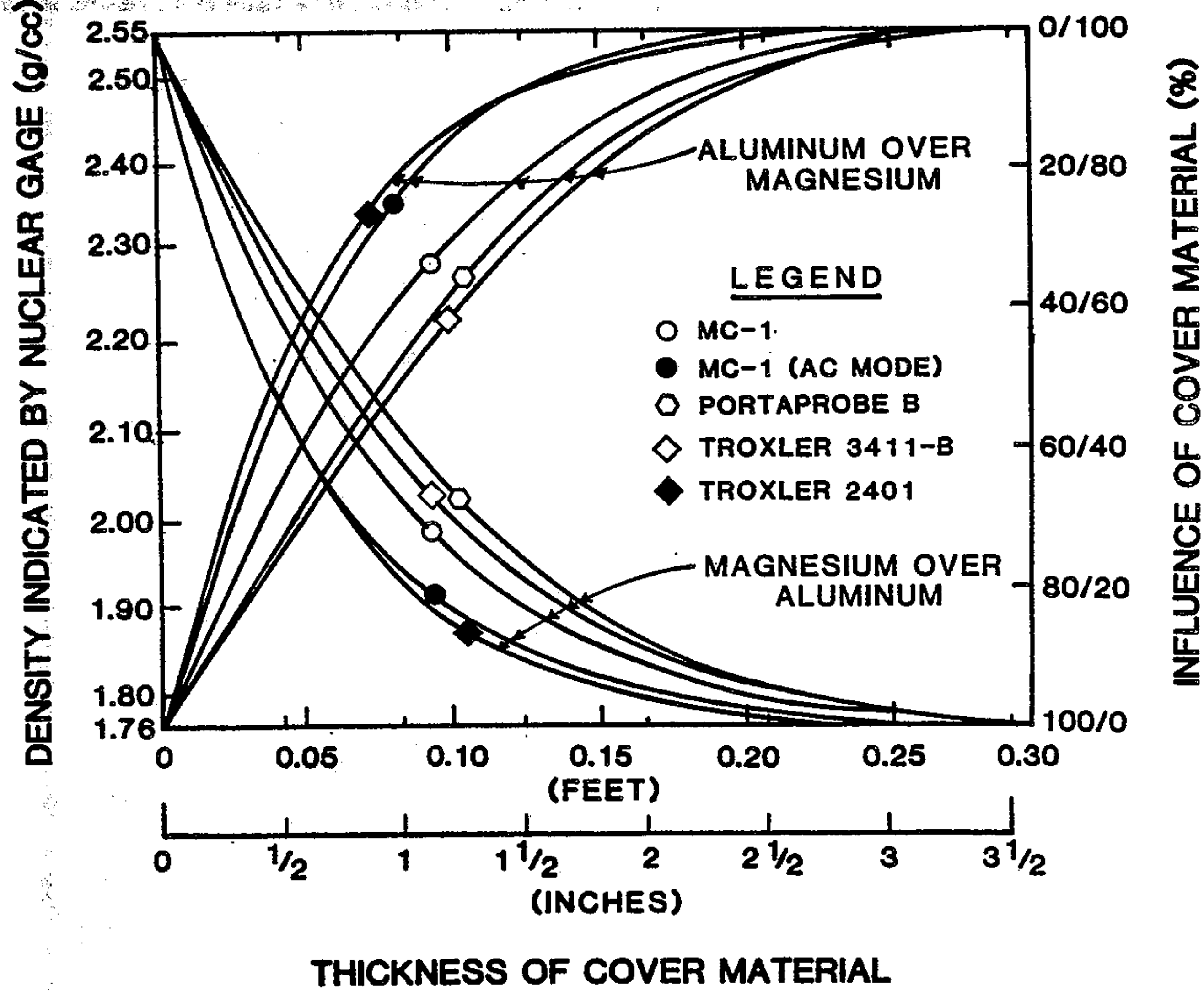

Fig. 2. INFLUENCE OF UNDERLYING MATERIAL ON THE DENSITY INDICATED BY VARIOUS NUCLEAR GAGES

inch of material accounts for more than 60% of the density reading, and the top 1-1/2 inches account for approximately 80% of the reading.

Some CPN gages are constructed with two backscatter mode settings. In addition to the normal backscatter (BS) setting, a second setting, identified by the manufacturer as the "AC" setting, is intended to be more effective for testing layers as thin as two inches. In this setting the nuclear source is closer to the surface of the pavement, and thus allows a higher concentration of the gamma radiation to exit the gage at a flatter angle. The data plotted in Figure 2 show that the effective reading depth is measurably less when using either the CPN gage's "AC" setting, or the Troxler 2401. With these two gages, the top 1-inch accounts for 75 to 80% of the density reading. This could be beneficial when testing thin layers, but it must also be recognized that errors due to surface texture and irregularities are magnified as the gage is modified to limit the depth of influence.

D. RELIABILITY OF DENSITY MEASUREMENTS BY NUCLEAR GAGE

There has been considerable apprehension regarding the use of nuclear gages for determining the in-place density of AC pavements. An apparent lack of correlation with laboratory densities determined for cored samples, and observed differences between the results of different gages are the major concerns. Data which identify the causes of some of these deviations are discussed in the following pages. Another concern has been the influence that underlying materials can have on the density reading. This also will be discussed later in this report.

1. Repeatability of Densities Determined by Nuclear Gages

It is important to understand that radiation from a nuclear source is emitted at a random rather than constant rate. As a result, replicate density determinations with a nuclear gage are subject to variations even though the material and the position of the gage remain unchanged.

The data summarized in Table 1 represent two series of thirty density determinations, at a single test site, using two different nuclear gages. These data were gathered by testing personnel in one Caltrans district who became very alarmed at the apparent lack of repeatability and reproducibility.

Table 1

Repeatability of In-place Density
Determined by Backscatter Nuclear Gages
(Based on One-Minute Counts)

	Gage 1	Gage 2
Number of Determinations	30	30
Average Density (g/cc)	2.20	2.23
Range of Density Measurements	2.16-2.23	2.19-2.26
Standard Deviation	0.013	0.018

In each series of tests, the maximum difference between any two individual readings was 0.07 g/cc (4.4 pcf). The standard deviations from the average were 0.013 and 0.018, respectively, for the two gages. This indicates that 95% of the readings from gage 2 should be within 0.036 g/cc (1.6%) of the mean value. These results are comparable to the findings reported in a previous Caltrans study(3) of the precision of nuclear gages.

2. Reproducibility of Densities Determined by Nuclear Gages

The data summarized in Table 1 also indicate a difference of 0.03 g/cc in the average densities indicated by the two gages. This difference causes a difference of approximately 1.3% in the relative compaction indicated by the two gages.

The same district also used three different gages to determine in-place densities on a cold-recycled AC project which included end-result compaction requirements. Tests using each of the three gages at the same twenty locations indicated extremely poor reproducibility between gages. Data from these tests are summarized in Table 2.

Table 2

Reproducibility of In-place Density Determined by Different Gages

	Gage 1	Gage 2	Gage 3
Number of Determinations	20	20	20
Average Density (g/cc)	1.97	1.93	1.85
Range of Density Measurements	1.91-2.01	1.87-1.97	1.78-1.90
Standard Deviation	0.030	0.029	0.027

The ranges in results and the standard deviations of the data indicate that the repeatabilities of the individual gages are comparable. There was, however, poor reproducibility (i.e., a significant difference in the average densities) indicated by the three gages.

In an attempt to determine the reason for this discrepancy, Gages 2 and 3 were returned to Sacramento for inspection and laboratory evaluation. When these gages were recalibrated on the TransLab standard blocks, it was found that the count-ratio/density curve for Gage 3 had shifted by 0.11 g/cc. As a result, a count-ratio which indicated a density of 1.85 g/cc based on the curve developed during the annual calibration now indicated a density of 1.96 g/cc based on the new curve.

The cause of this change could not be positively identified. The only clue came from testing personnel who reported finding a loose radiation detection tube in one of the gages as it was being serviced. The identity of the gage was not recorded, but it is certain that any shift in the position of the detector tube, either during the time it was loose or as it was refastened into its proper position, could have had a significant effect on the readings.

No evidence has been found of other incidents where Caltrans has had problems with changes in the density curve similar to the case described above. It becomes very clear, however, that personnel working with nuclear density gages must be encouraged to stay alert to significant changes in the densities of materials they are testing, as well as changes in the standard counts. When unexplainable changes occur, the gage should be checked immediately on the standard blocks.

A much broader study of the reproducibility of nuclear gages was made by reviewing the records for the annual calibration of nuclear gages. More than 100 state-owned nuclear gages are calibrated each year using a set of six standard blocks which are maintained by TransLab. As count-ratio/density curves are developed for each gage, all of the gages within a district are used to establish an average density for two additional standard blocks which are maintained in that district.

The 1982 calibration data, representing 105 Caltrans gages in backscatter mode, are summarized in Table 3. These data should provide a good indication of the reproducibility of nuclear gages currently in use by Caltrans. It should be kept in mind that several models of Troxler and Campbell Pacific Nuclear gages, some more than 10 years old, are represented in this summary.

Since the standard blocks in each district are similar to, but not necessarily the same as, the blocks in each of the other districts, it was necessary to evaluate the test results from each district separately.

When determining the densities of the high density blocks, the maximum difference between the results of any two gages in the same district was 0.07 g/cc. Based on an assigned density of approximately 2.50 g/cc, the maximum variation between gages was 2.8%. When the densities determined by individual gages are compared to the assigned densities of the respective blocks, the maximum deviation was 0.04 g/cc or 1.6%.

The results of tests on the low density blocks were not so consistent. The greatest difference between the results of any two gages in the same district was 0.12 g/cc. Based on an assigned block density of approximately 1.85 g/cc the maximum variation between gages was 5.9%. The maximum deviation from the assigned density of the respective block was 0.07 g/cc or 3.8%. Most of the larger deviations occurred with only a few gages. By eliminating the results of only three gages, one in District 8 and two in District 4, the maximum range in measured densities was reduced from 0.12 to 0.07 g/cc. The maximum deviation from the assigned density of the block also was reduced from 0.07 to 0.05 g/cc.

The average of the standard deviations shown in Table 3 is less than 0.020 g/cc. Therefore, densities determined by Caltrans' backscatter nuclear gages should be accurate within ±0.04 g/cc, 95% of the time. Since virtually all AC in California has a laboratory maximum density of at least 2.10 g/cc, the indicated densities should be accurate within 1.9%, 95% of the time.

3. Correlation of Densities Indicated by Nuclear Gage With Densities Determined in the Laboratory

The most serious concern over the reliability of nuclear gages arises from the observation that densities determined by the nuclear gage frequently are not the same as densities determined from cored samples that have been tested in the laboratory.

Data gathered in conjunction with this study revealed that differences in densities determined by nuclear and water-displacement methods can amount to as much as 0.11 g/cc (6.9 pcf). In every instance where the difference was significant, the density indicated by the nuclear gage had the lower value.

Table 3

Summary of Density Measurements
Recorded During 1982 Statewide
Calibration of Caltrans' Backscatter Gages

		Low Density (District) Block				High Density (District) Block			
District	Gages	Avg.Den.	High	Low	Std.Dev.	Avg.Den.	High	Low	Std.Dev.
01	10	1.90	1.93	1.87	0.019	2.49	2.52	2.47	0.016
02	5	1.80	1.81	1.79	0.012	2.46	2.47	2.45	0.007
03	11	1.83	1.86	1.81	0.012	2.44	2.46	2.41	0.016
04	18	1.86	1.91	1.80	0.025	2.45	2.48	2.42	0.021
05	10	1.84	1.88	1.82	0.019	2.49	2.52	2.46	0.018
06	6	1.80	1.82	1.77	0.016	2.48	2.50	2.46	0.015
07	10	1.81	1.86	1.79	0.026	2.46	2.49	2.43	0.022
08	8	1.84	1.89	1.77	0.039	2.43	2.46	2.41	0.018
09	6	1.80	1.82	1.79	0.012	2.42	2.42	2.41	0.006
10	10	1.85	1.86	1.81	0.017	2.47	2.51	2.44	0.020
11	11	1.87	1.90	1.84	0.019	2.46	2.49	2.42	0.022
Combined	104				0.021 avg.				0.017 avg.

There has been much speculation regarding the reasons for these observed differences in densities, and which of the two test methods provides the more reliable results. Arguments and theories have been offered in favor of each method, but thus far there has been no explanation which satisfies everyone.

Most engineers support the view that the water-displacement method is the more reliable method. By this method, the specific gravity of the test sample can be measured precisely, thus providing an exact measurement of the density.

ASTM accepts this position and states in its nuclear method D2950 that the density results obtained by nuclear gage are relative and that if "actual" densities are required, a conversion factor must be developed to convert from nuclear density to "actual" density. This is done by determining the density by each method at randomly selected locations.

On the other hand, there are those who contend that the density of the AC is altered during coring and is therefore inaccurate. The most frequent argument supporting this view is that the water used to cool the core barrel is being forced into the core, thus increasing the weight of the core.

Laboratory tests failed to confirm that the densities of cores are being altered during the coring operation by the introduction of water. The normal procedure followed by Caltrans is to provide a period of air drying to allow free water to escape from the cored sample prior to testing. If time does not permit several days of air drying at room temperature, the cores are placed in a circulating air drying chamber for a shorter period of time at a temperature not exceeding 100°F. To substantiate or disprove the presence of water, several cores were oven-dried following determination of the specific gravity. The cores were placed in a 230°F oven until the wax coating and asphalt binder softened. The softened cores were then broken and spread over the bottom of a flat pan, and dried to constant weight. Data from eight cores, representing three projects, are shown in Table 4. The greatest measured loss of weight was 4 grams from a 600-gram core. This 0.7% reduction in weight is minor when compared to the 1.5 to 5% differences commonly found between densities measured by nuclear and water-displacement methods.

Table 4

Moisture Lost from Cores
During Oven-Drying at 230°F

	Project A			Project B		Project C		
Wet Weight (g)	570	579	550	599	627	528	548	491
Dry Weight (g)	568	575	548	595	625	525	546	488
Loss (g)	2	4	2	4	2	3	2	3
% Moisture	0.4	0.7	0.4	0.7	0.3	0.6	0.4	0.6

In an attempt to answer questions concerning the accuracy and reliability of the two procedures, three AC blocks were fabricated for correlation testing. Each block was prepared from representative portions of a 1/2-inch medium grading, Type B AC. The finished blocks were 18 inches square and either 4 or 3 inches thick. Compaction was accomplished by static load using a 100,000-pound-capacity testing machine and the densities were varied by applying different maximum loads to each block.

The specific gravity of each block was determined first by calculation using the measured dimensions and weights. Then densities were determined using several different brands and models of nuclear gages. Nuclear readings were taken at four different locations on both the top and bottom surfaces of each block.

Eight 4-inch diameter cores were cut from each block. The specific gravity was determined for each core by weighing the uncoated cores in air and in water. Four cores from each block were sliced into 1-inch thick segments. After air-drying, the segments were coated with wax, and the specific gravity of each segment was determined. The specific gravities determined for each block and core segment are recorded in Table 5.

Subsequent testing revealed that when the top and bottom surface voids were included in the volume of the cores, the specific gravities were much closer to the specific gravity of the total block. To include the volume of the surface voids and depressions, the surface was coated with wax and smoothed with a hot spatula so that the surface of the wax was flush with the high points of the AC surface. These recalculated specific gravities also are included in Table 5.

Table 5

Specific Gravity of AC Blocks Determined by Various Displacement Procedures

AC Block	Specific Gravity									
	Total Block (by Dimension & Weight)	Core (Non-Waxed)	Core Segments Waxed					With End Voids Included in Core Volume		
			Top	2nd	3rd	Bottom	Avg.	Full Core	Top Half	Bottom Half
#1	2.18	2.23 avg.								
A-1		2.20	2.19	2.22	2.20	2.18	2.20			
A-2		2.22						2.19		
B-1		2.22	2.20	2.22	2.24	2.19	2.21			
B-2		2.21							2.16	2.15
C-1		2.24	2.25	2.28	2.24	2.21	2.25			
C-2		2.23							2.20	2.19
D-1		2.25	2.26	2.23	2.25	2.23	2.24			
D-2		2.24						2.21		
#2	2.05	2.14 avg.								
A-1		2.14	2.15	2.14	-	2.10	2.13			
A-2		2.13						2.08		
B-1		2.14	2.16	2.19	-	2.12	2.16			
B-2		2.14							2.06	2.04
C-1		2.14	2.15	2.15	-	2.10	2.13			
C-2		2.15							2.09	2.06
D-1		2.15	2.12	2.13	-	2.14	2.13			
D-2		2.15						2.10		
#3	2.18	2.22 avg.								
A-1		2.24	2.22	2.22	-	2.24	2.23			
A-2		2.22							2.16	2.18
B-1		2.22	2.22	2.20	2.23	2.22	2.22			
B-2		2.21						2.19		
C-1		2.22	2.19	2.19	2.22	2.20	2.20			
C-2		2.22							2.17	2.18
D-1		2.22	2.20	2.19	2.21	2.23	2.21			
D-2		2.21						2.17		

A review of these methods and their respective calculations revealed possible reasons for at least some of the observed differences. According to definitions in ASTM Designation E-12, bulk specific gravity is calculated from the unit volume which includes both permeable and impermeable voids. The specific gravities calculated from the external dimensions of the blocks would satisfy this definition since all surface voids and depressions are included in the calculated volume. On the other hand, the specific gravities of the cores which were determined by water-displacement methods, (such as California Test 308 and ASTM D 1188) are not true bulk specific gravities as indicated by the test method titles. These procedures are actually designed to exclude the surface voids from the volume measured. According to the ASTM definition, the volume determined by water-displacement includes only the impermeable portion of the voids and provides a measure of "apparent" specific gravity. A review of studies by other agencies revealed that this discrepancy has not been totally unnoticed. In a report published in the Netherlands(4), there is a statement recognizing the fact that if the voids in the core's surface are measured by filling them with paraffin, and then subtracted from the bulk volume, the indicated volume will be smaller and the resulting specific gravity will be greater.

Subsequent testing revealed that when the top and bottom surface voids were included in the volume of the cores, the specific gravities were much closer to the specific gravity of the total block. To include the volume of the surface voids and depressions, the surface was coated with wax and smoothed with a hot spatula so that the surface of the wax was flush with the high points of the AC surface. These recalculated specific gravities also are included in Table 5.

When testing by nuclear methods, the gage rests on the surface of the pavement. Since the gage is supported by the highest points of the surface, any surface voids and depressions become part of the volume being irradiated by the nuclear gage. Thus, densities determined by nuclear methods at least come close to meeting the ASTM definition for bulk density.

Based on this analysis, the differences noted between nuclear and core densities may not indicate an error in either method but instead, reflect the difference in the methods of measurement.

4. Reproducibility of Densities Measured by Nuclear Gages in the Laboratory

Because of reports of poor reproducibility of results from different nuclear gages, testing of the AC blocks described above included density determinations with eight different nuclear gages representing five models from two manufacturers. These included one each of Troxler Models 3401 and 2400, four Campbell Pacific Nuclear (CPN) Model MC-1, one CPN Portaprobe Model B, and one experimental gage designed by CPN specifically for use on thin layers of AC.

One of the MC-1 gages, the Portaprobe gage, and the CPN "thin-lift" gage were constructed with an "AC" mode as well as the normal backscatter mode. By including data from both modes, the effective number of gages included in this study was increased to eleven.

The densities of the blocks were determined from both the top and bottom surfaces, thus providing six series of tests with each of the 11 gages. The data from these tests are recorded in Table 6 and plotted in Figure 3. Each density recorded is the average of at least 16 readings. These readings were concentrated about four locations, each six inches from the mid-point of one edge of the block on both the top and bottom surfaces. With the gage centered over these points, it was rotated in 90° increments to obtain four readings at each location. In most cases, duplicate readings were taken to provide a total of 32 individual readings on each block with each gage.

A wide range of densities is indicated by the various gages. However, those densities that are farthest from the average were determined by the experimental thin-lift gage and the older model 2401 Troxler gage. When the data from these gages are eliminated, the correlation among gages is improved significantly. Excluding these two gages results in reductions of up to 0.04 gm/cc in the standard deviations of the data.

Even after excluding the data from these two gages, the variation between gages appeared to be excessive in some cases. One suspected cause of this remaining variation was the method that Caltrans was using to calibrate and standardize nuclear gages.

All nuclear gages used by Caltrans are calibrated annually using a set of six standard reference blocks of "known" density(5). These standard blocks are stored at the Transportation Laboratory in Sacramento where they are available for research studies and acceptance testing of new gages. Each of the eleven Transportation Districts has two standard reference blocks which are used to verify calibration of the gages during the year.

Table 6

Density of Laboratory Compacted AC Blocks
Using Various Nuclear Gages
(District Gages Calibrated on District Standard Blocks)

Gage	Density (g/cc)					
	Block #1		Block #2		Block #3	
	Top	Bottom	Top	Bottom	Top	Bottom
CPN Portaprobe (BS)	2.17	2.19	2.09	2.10	2.15	2.21
CPN Portaprobe (AC)	2.17	2.21	2.09	2.11	2.16	2.13
CPN MC-1 (BS1*	2.19	2.19	2.11	2.11	2.17	2.24
CPN MC-1 (AC)*	2.21	2.22	2.15	2.15	2.18	2.27
CPN MC-1 (BS)*	2.19	-	2.12	2.12	2.17	2.22
CPN MC-1 (BS)*	2.20	-	2.13	2.13	2.18	2.22
CPN MC-1 (BS)*	2.19	-	2.14	2.12	2.18	2.22
Troxler 3401 (BS)*	2.21	2.21	2.14	2.13	2.19	2.26
Troxler 2401 (BS)*	2.10	-	2.07	2.04	2.07	2.20
CPN Thin Lift (BS)	2.10	2.16	2.04	2.05	2.13	2.22
CPN Thin Lift (AC)	2.05	2.15	2.00	2.03	2.08	2.21
Average	2.16	2.19	2.10	2.10	2.15	2.23
Standard Deviation	0.054	0.026	0.047	0.040	0.041	0.021
Excluding Thin-Lift Gage and Troxler 2401						
Average	2.19	2.20	2.12	2.12	2.17	2.23
Standard Deviation	0.016	0.013	0.023	0.016	0.013	0.021

*Density tables based on 2-point curve using district standard blocks.

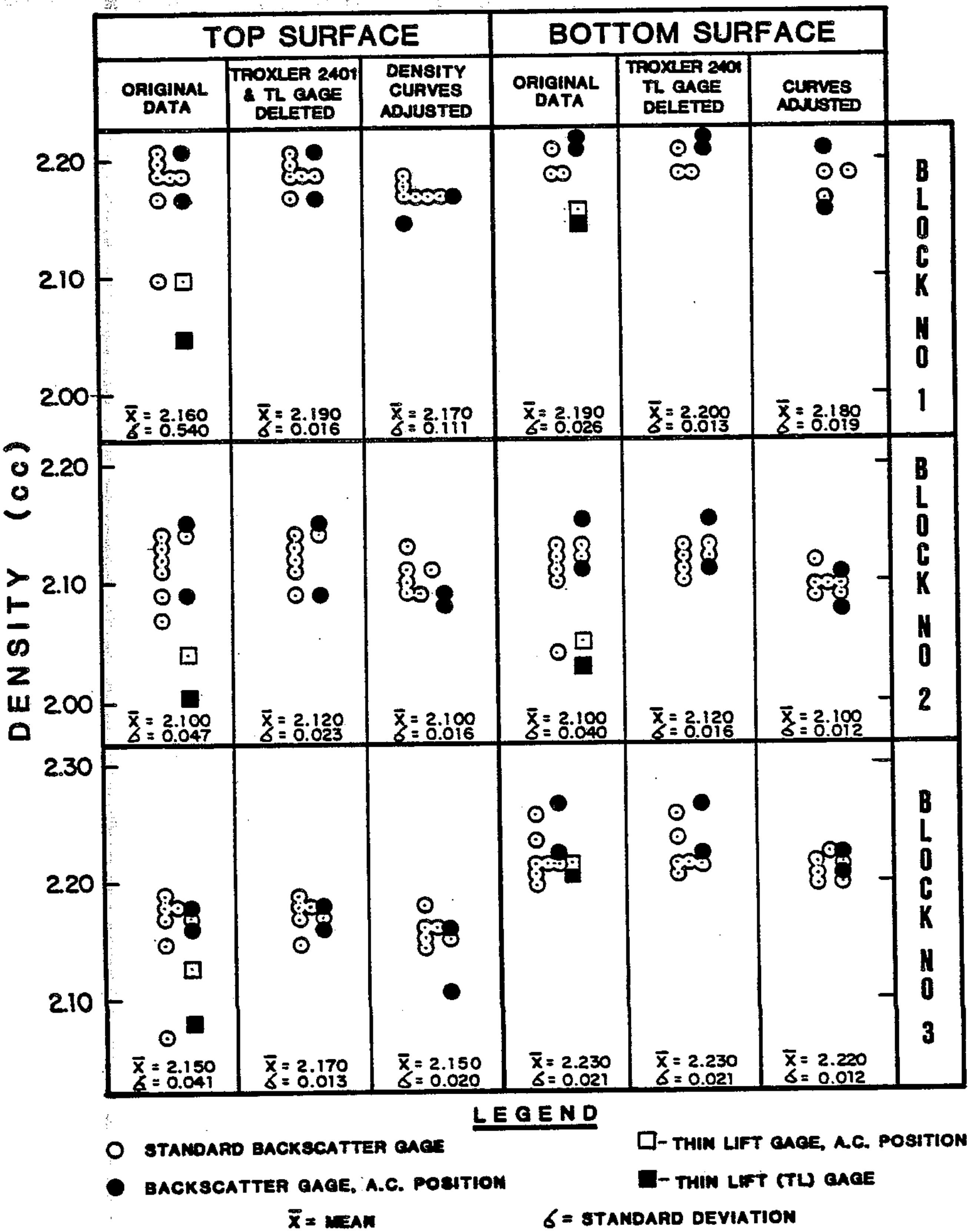

Fig. 3 NUCLEAR DENSITIES OF LABORATORY-COMPACTED A. C.

A review of the procedures used to develop the density tables based on these standard blocks revealed a practice which could significantly affect the field densities indicated by individual gages. During the annual calibration, count-ratio/density curves are prepared for each gage based on nuclear counts on the six standard blocks. The densities of the district's two reference blocks are then determined with each of the calibrated gages. The densities determined by each of the individual gages are averaged to establish the assigned density for the reference blocks. The final count-ratio/density tables for the individual gages are then adjusted to correlate with the average densities assigned to the reference blocks.

At times, the densities of the district reference blocks, as indicated by each of the several gages, varied considerably. Since the gages are always placed in the same position on the blocks, it has been assumed that these variations were due to small differences in the nuclear gages or random errors in their use. It has been assumed also that the average of the densities from the different gages provides a statistically accurate indication of the true density of the district reference blocks. After further consideration, it is now believed that the gage readings are accurate indications of what the individual gage is measuring. Because of differences in the design and construction of the gages, it is possible that various gages are measuring the densities of slightly different portions of the blocks. It is known, for example, that the influence of material near the surface of the layer being tested can be varied by changing the position of the nuclear source in relation to the surface and the lead shielding. It is also possible that relatively small errors in establishing the average densities of the district's blocks could have significant adverse effects on the density tables established for individual gages.

The density tables for six of the gages used in this study were prepared originally using the district's two-block procedure. These density tables later were adjusted based on the original six-block calibration, and then the densities for the AC blocks were determined according to these new tables. These revised data are listed in Table 7 and replotted in Figure 3.

Again, there was a marked improvement in the correlation among gages when measuring the densities of some of the AC blocks. This indicates that the reliability of the backscatter gages can be improved by developing the density tables (curves) directly from the readings on the six standard blocks.

5. Reproducibility of Densities Measured by Nuclear Gages in the Field

There were a few opportunities to compare densities determined in the field with two different nuclear gages. In each case one gage was the CPN Model B used by TransLab, and the second was one of the CPN MC-1 gages which are used extensively in the Caltrans districts. The results of these comparisons which are listed in Table 8, show good correlation.

Table 7

Density of Laboratory-Compacted AC Blocks
Using Various Nuclear Gages
(All Gages Calibrated on TransLab Standard Blocks)

Gage	Density (g/cc)					
	Block #1		Block #2		Block #3	
	Top	Bottom	Top	Bottom	Top	Bottom
CPN Portaprobe (BS)	2.17	2.19	2.09	2.10	2.15	2.21
CPN Portaprobe (AC)	2.17	2.21	2.09	2.11	2.16	2.23
CPN MC-1 (BS)	2.17	2.17	2.09	2.09	2.14	2.22
CPN MC-1 (AC)	2.15	2.16	2.08	2.08	2.11	2.21
CPN MC-1 (BS)	2.17	-	2.11	2.10	2.16	2.20
CPN MC-1 (BS)	2.17	-	2.10	2.09	2.15	2.20
CPN MC-1 (BS)	2.18	-	2.13	2.12	2.18	2.22
Troxler 3401 (BS)	2.19	2.19	2.11	2.10	2.16	2.23
Average	2.17	2.18	2.10	2.10	2.15	2.22
Standard Deviation	0.011	0.019	0.016	0.012	0.020	0.012

Table 8

Comparison of Densities Measured by Different Gages

Density (g/cc)					
Project 1		Project 2		Project 3	
District	TransLab	District	TransLab	District	TransLab
2.20	2.20	2.40	2.38	1.97	1.95
2.18	2.18	2.48	2.49	1.96	1.95
2.19	2.21	2.39	2.39	2.05	2.01
2.14	2.13	2.42	2.41	2.01	1.97
2.15	2.17	2.46	2.46	2.01	1.96
2.21	2.23	2.38	2.39	2.02	2.00
2.25	2.23	2.38	2.39	2.05	2.04
2.10	2.08	2.46	2.46	2.05	2.02
2.08	2.08	2.36	2.34	2.06	2.03
2.28	2.27	2.36	2.36	2.05	2.06
$\bar{X}$ 2.18	2.18	2.35	2.35	$\bar{X}$ 2.02	2.00
σ 0.063	0.064	2.43	2.41	σ 0.036	0.040
		2.46	2.46		
		2.37	2.38		
		2.37	2.40		
		2.31	2.30		
		2.32	2.33		
		2.34	2.37		
		2.36	2.37		
		2.33	2.32		
		$\bar{X}$ 2.39	2.39		
		σ 0.050	0.050		

6. Necessity for Test-Site Preparation

It was pointed out earlier that densities determined by nuclear gages are influenced more by material near the surface than by material deeper in the pavement. It follows then that surface irregularities can have a significant effect on the density readings. Properly placed and compacted AC pavements usually will be free of ridges, humps and depressions, but surface texture can vary greatly. Fine sand can be used as a filler to minimize the effect of surface voids caused by the texture of the pavement.

The data tabulated in Table 9 indicate that the filler sand usually had only a minor effect on the density readings from these three projects. This is due primarily to the smoothness of the finished pavements being tested. When the pavement surface is smooth, there will be very few surface voids to retain the filler sand.

It can be seen, however, that a few readings in each series were significantly higher when the filler sand was used. Although no specific notes were made of the surface texture at these locations, it is probable that a large volume of surface voids was responsible. When the air gaps between the pavement and the bottom surface of the gage are filled with sand, the measured density will increase.

The data in Table 10 were gathered from several projects to demonstrate the increase in measured density when filler sand is used on a very coarse, open-textured surface. The necessity of the filler sand becomes very obvious from this set of data. In each case, the difference in densities would have a significant effect on the evaluation of the compaction on a project.

Table 9

Effect of Filler Sand on Density Determinations

	Density (g/cc)								
	Project 1			Project 2			Project 3		
	W/OSand	W/Sand	Diff	W/OSand	W/Sand	Diff	W/OSand	W/Sand	Diff
	2.06	2.08	+0.02	1.97	1.98	+0.01	2.01	2.02	+0.01
	2.08	2.07	-0.01	1.94	1.95	+0.01	2.01	2.04	+0.03
	2.13	2.13	0 0	1.90	1.97	+0.07	2.03	2.04	+0.01
	2.09	2.12	+0.03	1.96	1.98	+0.02	2.01	2.02	+0.01
	2.08	2.12	+0.04	1.93	1.97	+0.04	2.01	2.04	+0.03
	2.08	2.07	-0.01	1.97	1.94	-0.03	2.01	2.02	+0.01
	2.08	2.06	-0.02	1.97	1.97	0.0	2.01	2.02	+0.01
	2.12	2.10	-0.02	1.89	1.97	+0.08	2.00	2.02	+0.02
	2.07	2.08	+0.01	1.88	1.88	0.0	2.00	1.99	-0.01
	2.10	2.11	+0.01	2.01	1.98	-0.03	1.97	1.98	+0.01
	-	-	-	2.04	2.02	-0.02	-	-	-
$\bar{X}$	2.089	2.094	+0.005	1.951	1.965	+0.014	2.006	2.019	+0.013
σ	0.022	0.025		0.049	0.034		0.015	0.020	

Table 10

Effect of Sand Filler on Densities Determined on Coarse-Surfaced Pavements

Density (g/cc)		
Without Sand	With Sand	Difference
2.20	2.27	+.07
2.02	2.11	+.09
2.23	2.32	+.09
1.92	1.98	+.06
1.86	1.95	+.09
1.97	2.02	+.05

It is also apparent from the data in Table 9 that occasionally the measured density decreases when the filler sand is used. The reduced densities shown in this table may be nothing more than random variations in gage readings. They do, however, raise a question which can be answered by referring to data gathered from another construction project.

This was an AC recycling project and one of the first Caltrans projects to include an end-result specification for compaction of AC. The field inspector was using a filler sand on the surface, but he was not using the straightedge correctly to remove all of the excess sand. As a result, the nuclear gage was actually resting on a thin layer of sand rather than on the high points of the pavement. When this condition was observed, the straightedge was applied correctly to finish removing the excess sand. The densities determined before and after removing the excess sand are tabulated in Table 11. The differences were not always large but, in nearly every case, the excess sand on the surface caused a lower density reading.

Table 11

Effect of Excess Filler Sand on Density Determinations

	Density (g/cc)	
Excess Sand	Correctly Applied Sand	Difference
1.96	1.98	+0.02
2.01	2.00	-0.01
2.01	2.03	+0.02
1.98	1.99	+0.01
1.95	1.97	+0.02
1.95	1.98	+0.03
2.01	2.06	+0.05
1.97	1.98	+0.01
1.96	2.01	+0.05
2.00	2.03	+0.03
2.04	2.06	+0.02
2.02	2.03	+0.01
2.03	2.04	+0.01
2.06	2.03	-0.03
$\bar{X}$ 2.00	2.01	0.02
σ 0.035	0.031	

The data included in this section verify the need for proper test-site preparation. Surface voids should be filled with a fine filler sand, but care must be tâken to avoid leaving excess sand on the surface.

E. ALTERNATIVE NUCLEAR PROCEDURES FOR THIN LAYERS

During the period of time that this study was in progress, a significant portion of the asphalt concrete pavement in California was being placed in layers approximately 0.1 ft thick or less. Since nuclear gages are influenced by materials to a depth of approximately 0.25 ft, they are not considered to be appropriate for use on these thin layers. Several equipment and procedural modifications were tried in an attempt to overcome this problem. The most desirable approach seemed to be the development of a nuclear gage which would limit the depth of significant influence to the top 0.1 ft. Another approach was a mathematical determination derived from densities measured on the underlying material and then the new layer. The use of inserts, or materials of fixed thickness and known density, between the gage and the pavement was tried in an effort to limit the influence of the gage to the top 0.1 ft. These procedures are discussed individually below.

1. Thin-Lift Gage

In an effort to provide a nuclear gage which would effectively limit the depth of measurement to the top 0.1 ft, CPN Corporation modified the internal configuration of an MC-1 gage. The revised configuration altered the angle at which the gamma radiation was emitted from the source and also modified the shielding and position of the detector tube to capture only the radiation which travels through the upper portion of the layer.

The data plotted in Figure 4 indicate that this prototype thin-lift nuclear gage does restrict the effective depth of the nuclear reading to approximately 0.1 ft. Laboratory tests using varying thicknesses of aluminum and magnesium show that more than 95% of the nuclear reading is from the top 0.1 ft of the pavement.

Laboratory tests on compacted AC blocks, which were discussed earlier in the section on "Reproducibility of Nuclear Gages," indicate, however, that densities determined by the thin-lift gage are often much lower than the densities indicated by standard nuclear gages. Since the densities determined with the thin-lift gage represent material closer to the surface, it must be concluded that at least some of the differences in measured densities were due to actual differences at various depths in the block. It must also be recognized that surface voids and irregularities have a much greater influence on densities determined with the thin-lift gage than on densities determined with a standard gage.

2. Composite Layers Approach

Another approach used in determining the density of thin surface layers was to adjust the density indicated by the standard gage based on the density of the underlying material.

Simple calculations can be used to determine the average density of a conglomerate mass if the volume and density of

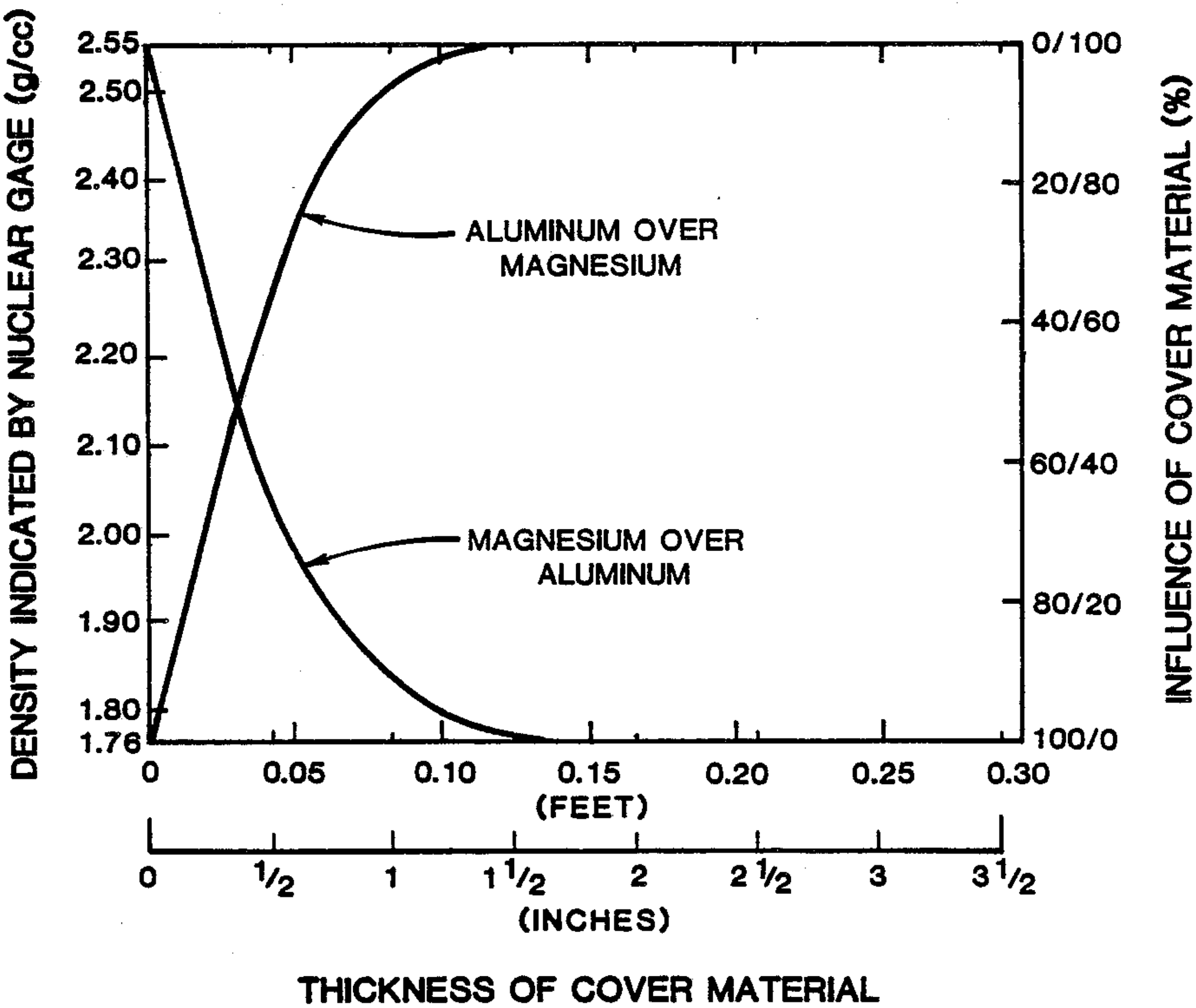

Fig. 4. INFLUENCE OF UNDERLYING MATERIAL ON DENSITY INDICATED BY PROTOTYPE THIN-LIFT NUCLEAR GAGE

each component are known. Conversely, the density of one component can be calculated if its volume and the volume and average density of the total mass are known. It follows, then, that the density of an AC surface course, which cannot be measured independently because of its shallow depth, could be calculated after determining the density of the underlying material and the composite density of the pavement.

This approach was tried on eight test sections representing five paving projects, where the surface layer was 0.10 ft thick. Each test section consisted of 10 individual test sites. A CPN Portaprobe gage was used to measure the density of the existing pavement and to determine a composite density at the same locations after the 0.10 ft AC surface course was placed. It was assumed, based on data presented earlier, that the surface layer contributed approximately 65% of the composite density reading. The densities of the surface courses were "adjusted" using the Formula:

$$D_s = \frac{D_c - (D_u \times .35)}{.65}$$

where: D_s = adjusted density of the surface course
D_c = composite density of surface and underlying material
D_u = density of underlying material.

Cored samples were taken from each test site and the densities were determined in the laboratory.

The average adjusted densities of the surface course are compared to the densities of cored samples from the same test sites in Table 12.

Table 12

Comparison of Adjusted Nuclear Densities and Core Densities on Thin AC Pavements

Project and Section	Core Density (g/cc)	Adjusted Nuclear Density (g/cc)	Difference (g/cc)
1-1	2.09	2.08	-.01
2-1	2.18	2.18	0
2-2	2.16	2.05	-.11
3-1	2.29	2.19	-.10
3-2	2.28	2.19	-.09
4-1	2.14	2.11	-.03
5-1	2.28	2.21	-.07

The adjusted nuclear densities of the surface course were less than the densities of the cores for each test section. At least part of this difference is due to the method of determining the volume of the cores, as was explained previously. Retesting of several cores from each project, and including the voids in the top surface in the volume of the core, resulted in the core densities being lowered by as much as 0.05 g/cc.

It is obvious, however, that other factors are contributing to the observed differences. The AC surface courses placed in Test Sections 2-1 and 2-2 were from the same source and were placed and compacted under the same conditions. The core densities confirm that the compacted densities were similar. The only difference noted was the surface condition of the existing pavement. In the area of Test Section 1, the pavement being covered included a chip seal which left the surface very coarse and open. As a result, the nuclear densities for this material were very low. When these low values for the existing pavement were used in the calculation, the calculated densities of the surface course were higher than they would have been otherwise.

One manufacturer has developed a nomograph which can be used with his nuclear gages to adjust the measured densities of thin layers when the densities of the underlying materials are known. The use of a similar nomograph is demonstrated in Figure 5 where densities of 2.16 g/cc and 2.08/cc are assumed, respectively, for the existing (bottom layer) pavement and the composite pavement which includes a 1-inch layer of new AC. The density of the existing pavement is plotted on the left edge of the nomograph, and the density of the composite pavement is plotted on the line representing the thickness of the new layer. A straight line between these two points is extended to the right edge of the nomograph where a density of 2.01 g/cc is indicated for the new top layer.

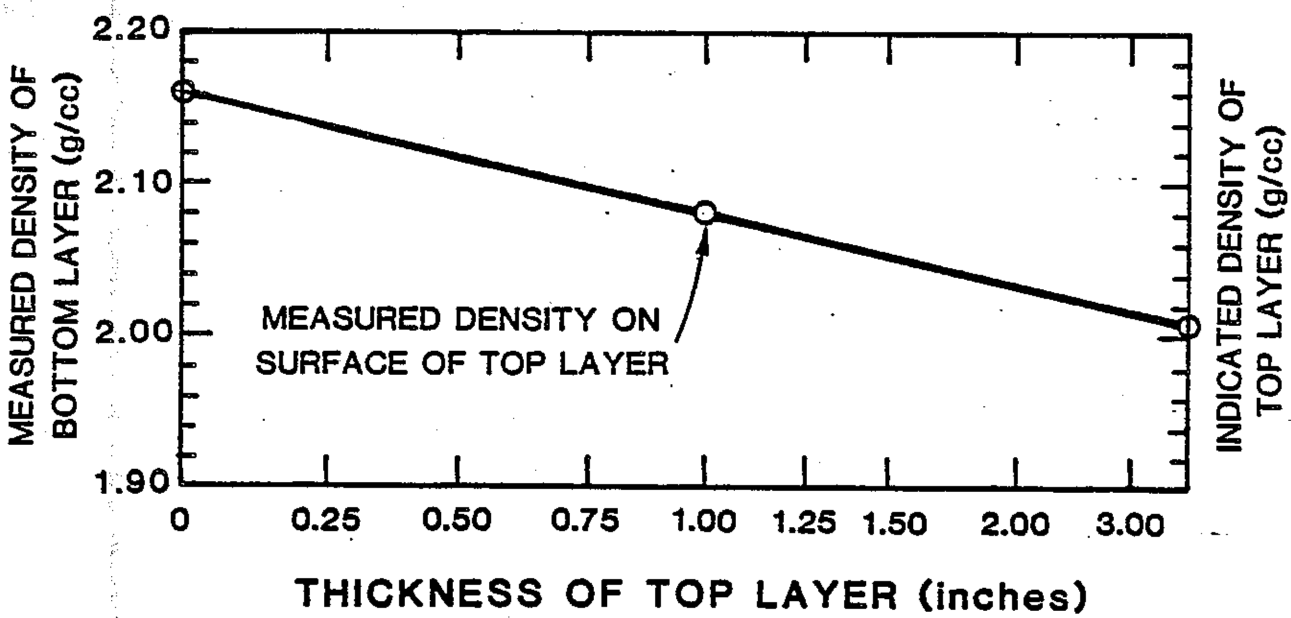

Fig. 5. NOMOGRAPH FOR DETERMINING DENSITY OF THIN LIFT OVERLAYS

This procedure has been used with apparent success by other agencies. However, it can be shown that a relatively minor error in one of the nuclear readings, and/or in the assumed AC layer thickness, can result in a significant error in determining the density of the top layer. For example, a 0.03 g/cc error in the density measured on the top surface would result in a 0.06 g/cc error in the indicated density of the top layer.

3. Surface Spacer Approach

A variation of the composite-density calculation procedure was to insert a pad of known density between the nuclear gage and the pavement. The density of the top portion of the pavement could be determined by measuring the composite density of the pavement and pad, and then adjusting for the influence of the pad. This procedure was thought to have several advantages over the composite-pavement calculation discussed earlier. It was assumed that only the composite-density reading would be required since the pad's density is known. The thickness and density of the pad would not change and, after being established, would remain constant in the formula. Also, the thickness of the pad could be selected based on the thickness of the pavement layer to be tested.

In the laboratory, aluminum and magnesium plates have shown potential as constant density pads. The rigidity of these metal plates, however, restricts intimate contact with a coarse-textured pavement. Any protrusion or irregularity on the surface of the AC will prevent contact with the entire area. On the other hand, a semirigid pad, such as a piece of rubber would allow much better contact between the pavement and pad.

Laboratory tests indicated that the effective reading depth of a nuclear gage could be limited to the top 0.10 ft of AC by using a 1 1/4-inch rubber pad between the gage and the pavement. However, preliminary testing in the field was not encouraging.

The procedure was tried on five test sections representing four paving projects using a CPN Model B gage. Each test section consisted of 10 individual test locations. Densities were calculated using the formula:

$$D_s = \frac{D_c - (D_p \times .70)}{.30}$$

where D_s = density of the surface course
D_c = composite density of surface course and inserted rubber pad
D_p = density of rubber pad.

The average adjusted densities and the densities of core samples from the same test sites are recorded in Table 13.

Table 13

Comparison of Nuclear Densities Using Rubber Pad and Core Densities

Project and Section	Core Density (g/cc)	Adjusted Nuclear Density (g/cc)	Difference g/cc
1-1	2.08	2.08	0.00
2-1	2.18	2.10	-.08
2-2	2.16	2.07	-.09
3-1	2.29	2.16	-.13
4-1	2.14	2.09	-.05

The difference between the core density and the adjusted nuclear density is significant in most cases. One major drawback to using the rubber pad is that it contributes so much to the nuclear density determination (approximately 70%) that relatively minor deviations in the composite density reading are reflected as large differences in the calculated density of the pavement.

Consideration was given to the possibility of eliminating the need to adjust the density reading by establishing the count-ratio/density table with the rubber pad placed on the standard blocks in the same way it would be used in the field. A series of tests was run with the CPN Portaprobe Gage to evaluate the reliability of the density determinations and the effective depth of the nuclear readings.

In this series of tests, six 1/2-inch sheets of aluminum were stacked on top of six 1/2-inch sheets of magnesium. The rubber pad was placed between the top surface of the aluminum sheets and the nuclear gage. The aluminum plates were removed one at a time after each successive reading so that density determinations were made at each 1/2-inch increment of aluminum thickness. This procedure was then repeated with the magnesium plates on top of the aluminum. When these data are plotted (Figure 6), the relative influence of the surface material's thickness can readily be seen.

These data indicate that the 1 1/4-inch rubber pad actually does very little to limit the effective depth of the nuclear gage. With a 1-inch thick surface layer, approximately

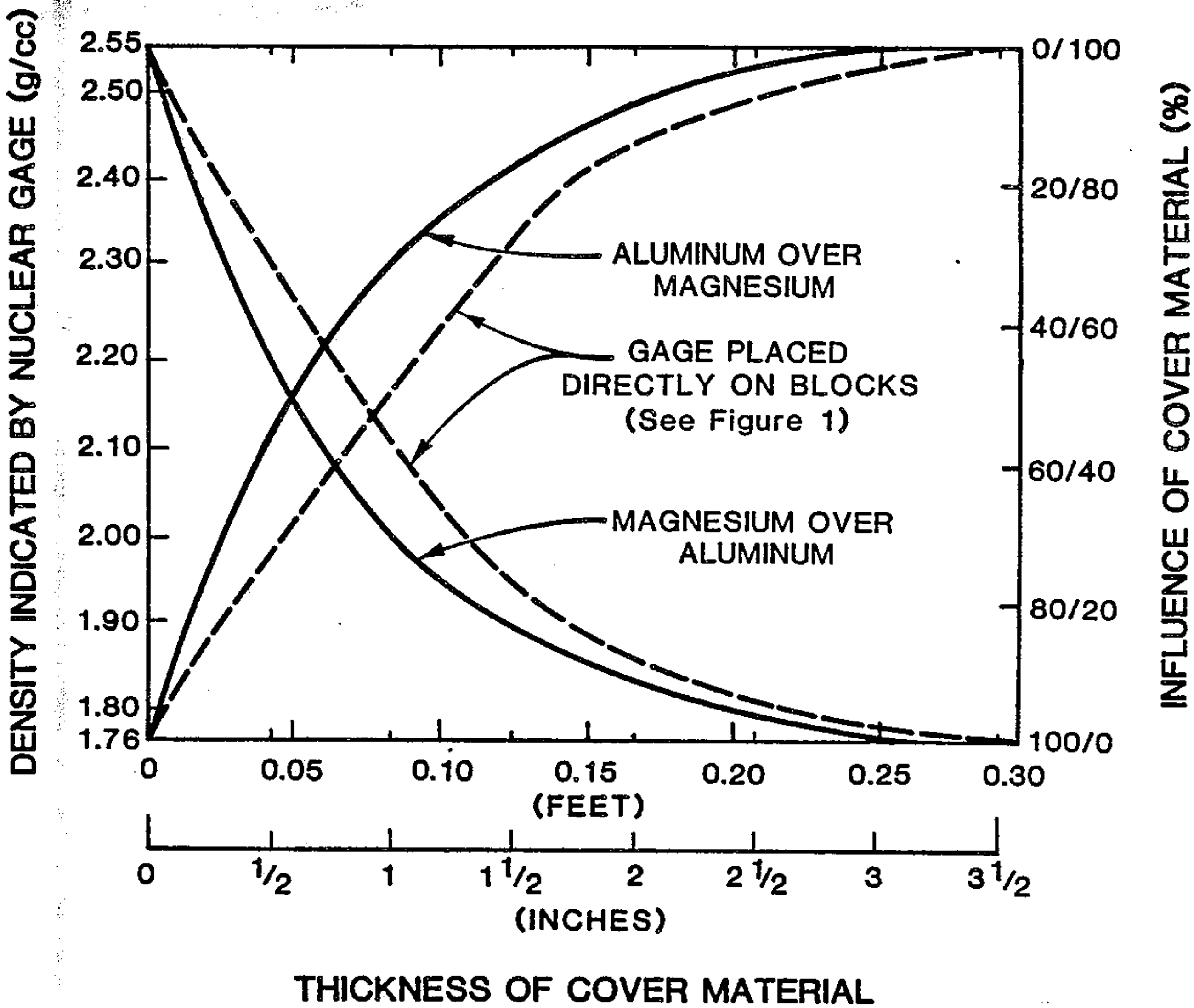

Fig. 6. INFLUENCE OF UNDERLYING MATERIAL ON DENSITY INDICATED BY NUCLEAR GAGE WHEN GAGE IS PLACED ON RUBBER PAD (CPN PORTAPROBE MODEL B BACKSCATTER MODE)

30% of the indicated density was the result of the material below one inch. It was concluded that there is no apparent advantage in using the rubber spacer when determining the density of thin layers of AC.

4. Standard Nuclear Gage

Commonly available nuclear gages have been used by Caltrans for many years to evaluate the compacting capabilities of AC rollers. Use of this method has been limited, however, by the practice of placing AC pavements in 0.10-ft increments. Placing AC pavements in thin layers is a practice adopted primarily to limit the drop-off between adjacent lanes during construction and to improve the ride quality of the finished pavement. Since it is known that the nuclear gage is influenced by materials to a depth of approximately 0.25 ft, application of the gage for determining the density of these thin layers is inappropriate.

Assume, for example, that a 0.10-ft layer of AC is being placed over an aggregate base from a different aggregate source. When compacted on the street, the AC has a density of 2.40 g/cc (150 pcf), while the base has a density of 2.08 g/cc (130 pcf). Based on the data in Figure 2, which shows that the base material would contribute about 30% of the density reading, the density of the AC indicated by the nuclear gage would be approximately 2.30 g/cc; an error of 0.10 g/cc or 4% (2.40 x 0.70 + 2.08 x 0.30 = 2.30) because of the influence of the underlying base material.

Recent changes in Caltrans' specifications governing the construction of AC pavements require minimum surface layer thicknesses of 0.15 ft in most cases. With this increase in thickness, the nuclear gage has become much more reliable for determining in-place density. Using the density values from the example above, the error caused by the underlying base would be reduced to 0.05 g/cc or 2% (2.40 x 0.85 + 2.08 x 0.15 = 2.35).

A further increase in the thickness of the AC layer would result in a corresponding reduction in the error introduced by the underlying materials. Also, the error would be much less if the aggregates used for the AC and AB were similar. By the same token, the density determinated on subsequent layers of AC from the same source will be much more reliable because of the similarity of materials.

Assume that a 0.15-ft layer of AC is placed over a 0.10-ft AC base course of the same material. The laboratory maximum density is 2.53 g/cc. For some unknown reason, the base course is compacted to only 2.28 g/cc or 90% relative compaction (RC) instead of the required 2.40 g/cc (95% RC). Since the nuclear gage cannot be relied upon for testing this first thin lift, its low density is not detected. When the next 0.15-ft layer is placed and compacted to a density of 2.40 g/cc (95% RC), the nuclear gage will indicate a density of 2.38 g/cc (2.40 x 0.85 + 2.28 x 0.15 = 2.38) or 94.1% RC A contractor could argue that the test is in error because of the influence of the underlying material; however, the proposed specification would not require a penalty until the indicated density dropped to 2.35 g/cc. This would not occur until the density of the top layer dropped to 2.36 g/cc or 93.3% RC (2.36 x 0.85 + 2.28 x 0.15 = 2.35).

It is concluded that an underlying layer of material will have only minor influence on nuclear-density determinations of AC pavement layers which are at least 0.15 ft thick. It is concluded also that nuclear density determinations will be reliable for testing AC pavements which have been placed in multiple, thin layers provided the material which is within 0.15 ft of the surface of the layer being tested is from the same source.

F. APPLICATION OF END-RESULT SPECIFICATIONS

Caltrans' first draft of an end-result specification required 95% RC with increasing penalties to be imposed as the RC fell below 95%. Material having an RC of less than 92% was to be removed. Because of the depth of influence of the nuclear gages, application of this requirement was restricted to layers that were at least 0.15 ft thick.

On the first Caltrans project to include this end-result requirement for compaction, the first of three planned 0.15-ft layers failed to meet the specified relative compaction. The average densities determined in the two test areas (lots) indicated relative compactions of 93.3% and 92.9% respectively. It was obvious, however, that the contractor's paving operation would not have complied with several of the normal procedural requirements. Instead of trying to improve the end-result densities by correcting his paving operation, the contractor chose to circumvent application of the density requirement by placing the remainder of the pavement in three 0.10-ft layers.

The same end-result requirement for compaction was included in a second contract, but this time its use was thwarted even before construction commenced when the contractor elected to place the 0.30 ft of AC in three 0.10-ft layers instead of two 0.15-ft layers. Even though the individual layers were too thin to meet the requirements of California Test 375, unofficial nuclear-density tests were performed on each of the three layers. The average RC's were 94.9, 96.7 and 95.8 percent respectively for the top, middle and bottom layers.

The density readings on each of these layers were influenced, to some extent, by the layer immediately below. Even so, the densitites determined on the top and middle layers are representative of AC placed under this contract. The readings on the bottom layer, however, may not reflect the quality of the contractor's work. Based on the data in Figure 2 the underlying layer contributes approximately 30% of the density reading. This means that the bottom layer could have been compacted to relative compaction of 94% and still indicate 95.8% RC if the underlaying material had an in-place density equal to the density at 100% RC (1.00 x .30 + .94 x .70 = .958).

Because of the potential for small errors in nuclear test results and slight differences between the results of different nuclear gages, the end-result compaction requirement for compaction was modified before inclusion in two additional projects during 1984. The revised specification still required 95% RC but no price-adjustment penalty was imposed until the RC dropped below 93%. Removal was required when the RC was below 90%. The area between 95 and 93% RC served as a warning zone to the contractor that his operation was marginal and might require modification.

Application of the end-result specification to a third project was frustrated once again when the contractor elected to place the pavement in thin layers. It should be noted, however, that the nuclear gage was used unofficially to evaluate the compaction of 0.4-ft thick AC base placed in dig-out areas and 0.3-ft thick AC base placed to widen the shoulders by two feet. The test results indicated that the AC placed in the dig-out areas was being compacted satisfactorily. This was not true, however, of the AC placed in the shoulder-widening strip. The contractor initially attempted to use a steel-drum roller to compact this narrow strip, but because it was much wider than the strip being compacted, the roller rode on the old pavement and consolidated the new AC only to the level of the existing pavement's surface. When the density gage revealed how ineffective this procedure was, the contractor was required to revise his compacting procedures. Although it was not intended that the end-result compaction requirement be applied to this phase of the construction, application of the test did reveal the inadequacy of some compacting procedures.

The fourth and final Caltrans contract to include the proposed end-result specification for compaction also included a requirement that the top 0.20 ft of AC be placed in a single layer. On this project, the No. 1 lane and median shoulder were placed as a unit. The No. 2 lane and the outside shoulder were placed as individual units. To avoid a drop-off between adjacent lanes, both traffic lanes were paved to the same point each day. The outside shoulder was added the next working day. The pavement on this project was divided into twenty-one test lots. Each lot represented substantially all of the material placed during a day in one of the lanes. Each day's paving was divided into two lots, each representing one of the two lanes.

The first two lots placed had relative compactions of 94.3% and 93.4%. After the first day, the contractor replaced the breakdown roller and added a pneumatic secondary roller. The result was an average relative compaction of 95%. The minimum relative compaction (the average of 10 measurements) of any individual lot placed after this change was 94.3%.

An attempt was made to include the end-result requirements for compaction in several cold recycling projects. It was determined, however, that 95% RC is not appropriate for this material. In most cases, the compaction specifications were modified to require only 87% RC before opening the recycled material to traffic and 92% RC before placing the surface course of hot AC

G. CORRELATING DENSITIES TO COMPACTING PROCEDURES

Even though end-result requirements for compaction have been applied successfully to only one project, sufficient data are available to show that the proposed limits are reasonable. Previous Caltrans studies(6) have shown that 95% relative compaction can be achieved when the current procedural specifications are met.

Caltrans has also used nuclear gages and end-result requirements for compaction to evaluate the compacting capabilities of numerous vibratory compactors. More than twenty-five models of vibratory rollers have been accepted on the basis that they have achieved 95% relative compaction on AC pavements placed and tested according to California Test 113.

In conjunction with the study reported herein, the densities of compacted AC layers were determined on several projects which were being controlled by the procedural specifications. The object of these tests was to further verify that the proposed end-result requirements for compaction can be met with a reasonable effort on the part of the contractor. These selected projects included AC layers that ranged in thickness from 0.08 ft (1-inch) to 0.22 ft. A summary of the data from these projects is presented in Table 14.

Not all tested lots were compacted to 95% relative compaction. Most, however, exceeded 93% RC and thus would not have required removal or penalizing the contractor.

In most cases where the RC was less than 93%, there was also an obvious failure to comply fully with the procedural specifications. On Project 1, for example, the breakdown roller did not keep up with the paving machine and the AC cooled excessively before compaction.

Project 5 consisted of placing 0.20 ft of new AC over an existing mountain road with sharp curves and steep grades. The established operating conditions for the vibratory roller used on this project required two coverages with the drums vibrating at high amplitude. This was apparently excessive under the job conditions and resulted in excessive shoving and surface checking, especially on steep grades and cross-slopes. To overcome this problem, the roller was operated at low amplitude. The data for Lots 1 and 2, shown in Table 14, indicate that adequate compaction was achieved by reducing the amplitude and increasing the number of coverages. In other areas, however, where the

Table 14

COMPACTION EVALUATION BY NUCLEAR GAGE

PROJECT / LOT	PAVEMENT THICKNESS	LAYER TESTED	LAB DENSITY	TEST SITES	AVERAGE DENSITY	REL. COMP.	COMMENTS
1 / 1	0.45' AC	bot, 0.15'	2.39	8	2.23	93.3	The pavement failed to meet the specified end-result compaction requirements. The compaction procedures and AC temperatures also failed to meet the Standard Specification procedural requirements through most of the project.
2	0.45' AC	bot, 0.15'	2.39	8	2.22	92.9	
3	0.45' AC	2nd, 0.10'	2.39	8	2.21	92.5	
4	0.45' AC	2nd, 0.10'	2.39	8	2.23	93.3	
5	0.45' AC	3rd, 0.10'	2.39	8	2.20	92.1	
6	0.45' AC	3rd, 0.10'	2.39	8	2.22	92.9	
2 / 1	0.32' AC	top, 0.10'	2.14	42	2.03	94.9	Project included end-result compaction requirements which could not be applied because of thin layers.
2	0.32' AC	mid, 0.12'	2.14	42	2.07	96.7	
3	0.32' AC	bot, 0.10'	2.14	42	2.05	95.8	
3 / 1	0.30' AC	top, 0.20'	2.12	10	2.00	94.3	Project included end-result compaction requirements.
2	0.30' AC	top, 0.20'	2.12	10	1.98	93.4	
3	0.30' AC	top, 0.20'	2.12	10	2.02	95.3	
4	0.30' AC	top, 0.20'	2.12	10	2.02	95.3	
5	0.30' AC	top, 0.20'	2.12	10	2.01	94.8	
6	0.30' AC	top, 0.20'	2.12	10	2.00	94.3	
7	0.30' AC	top, 0.20'	2.12	10	2.02	95.3	
8	0.30' AC	top, 0.20'	2.12	10	2.02	95.3	
9	0.30' AC	top, 0.20'	2.12	4	2.00	94.3	
10	0.30' AC	top, 0.20'	2.12	10	2.01	94.8	
11	0.30' AC	top, 0.20'	2.12	10	2.00	94.3	
12	0.30' AC	top, 0.20'	2.12	10	2.01	94.8	
13	0.30' AC	top, 0.20'	2.12	10	2.00	94.3	
14	0.30' AC	top, 0.20'	2.12	10	2.03	95.8	
15	0.30' AC	top, 0.20'	2.12	10	2.03	95.8	
16	0.30' AC	top, 0.20'	2.12	10	2.01	94.8	
17	0.30' AC	top, 0.20'	2.12	10	2.03	95.8	
18	0.30' AC	top, 0.20'	2.12	10	2.00	94.3	
19	0.30' AC	top, 0.20'	2.12	6	2.04	96.2	
20	0.30' AC	top, 0.20'	2.12	6	2.03	95.8	
4 / 1	0.22' AC	top, 0.22'	2.23	10	2.13	95.5	
2	0.22' AC	top, 0.22'	2.23	10	2.13	95.5	
5 / 1	0.20' AC	top, 0.22'	2.35	10	2.23	94.9	Vib. roller, 3 coverages, low amp.
2	0.20' AC	top, 0.22'	2.35	10	2.24	95.3	Vib. roller, 3 coverages, low amp.
3	0.20' AC	top, 0.22'	2.35	10	2.17	92.3	Vib. roller, 2 coverages, high amp.
4	0.20' AC	top, 0.22'	2.35	10	2.23	94.9	Vib. roller, 2 coverages, high amp.
5	0.20' AC	top, 0.22'	2.35	10	2.18	92.8	Vib. roller, 1 coverage, high amp.
6	0.20' AC	top, 0.22'	2.35	10	2.19	93.2	Vib. roller, 1 coverage, high amp.
7	0.20' AC	top, 0.22'	2.35	10	2.16	91.9	Vib. roller, 1 coverage, low amp.
6 / 1	0.20' AC	top, 0.20'	2.34	21	2.19	93.6	Reduced compactive effort because of surface checking on steep grades.
2		top, 0.20'	2.34	10	2.17	92.7	
3		top, 0.20'	2.34	12	2.13	91.0	Third area also subject to inclement weather.
7 / 1	0.40' AC	top, 0.17'	2.21	5	2.19	99.1	
8 / 1	0.32' AC	top, 0.16'	2.27	10	2.21	97.4	
2	0.20' AC	top, 0.10'	2.27	8	2.19	96.5	
9 / 1	0.15' AC	top, 0.15'	2.32	42	2.21	95.3	
2		top, 0.15'	2.31	28	2.25	97.4	
3		top, 0.15'	2.34	29	2.22	94.9	
10 / 1	0.40' AC	2nd, 0.15'	2.38	10	2.26	95.0	
11 / 1	0.45' AC	top, 0.15'	2.46	10	2.34	95.1	
12 / 1	0.08' AC	top, 0.08'	2.27	10	2.12	93.4	The density readings could have been influenced by dissimilar underlying pavement.
2	0.08' AC	top, 0.08'	2.27	10	2.10	92.5	
13 / 1	0.08' AC	top, 0.08'	2.20	10	2.09	95.0	The density readings could have been influenced by dissimilar underlying pavement.
14 / 1	0.30' AC	top, 0.10'	2.34	10	2.19	93.6	
2		mid, 0.10'	2.34	10	2.19	93.6	
15 / 1	0.25' AC	top, 0.13'	2.31	10	2.20	95.2	
2	0.25' AC	top, 0.13'	2.31	10	2.18	94.4	
3	0.25' AC	top, 0.13'	2.31	10	2.17	93.9	
4	0.25' AC	bot, 0.13'	2.31	9	2.18	94.4	
16 / 1	0.25' AC	top, 0.13'	2.56	29	2.38	93.0	Vibratory roller used in low amplitude in lieu of high amplitude through entire project.
2	0.25' AC	top, 0.13'	2.56	12	2.38	93.0	
3	0.25' AC	top, 0.13'	2.56	9	2.39	93.4	
4	0.25' AC	top, 0.13'	2.56	21	2.38	93.0	
5	0.25' AC	top, 0.13'	2.56	18	2.42	94.5	
6	0.25' AC	bot, 0.12'	2.56	30	2.29	89.6	Bottom layer placed over ATPM.
17 / 1	0.40' AC	top, 0.10'	2.38	10	2.26	95.0	The density reading could have been influenced by dissimilar underlying pavement.
2	0.10' AC	top, 0.10'	2.38	10	2.26	95.0	
18 / 1	0.35' AC	top, 0.10'	2.31	10	2.17	93.9	Vib. roller, 2 coverages, low amp.
2	0.35' AC	top, 0.10'	2.31	10	2.18	94.4	Vib. roller, 2 coverages, low amp.
3	0.35' AC	top, 0.10'	2.31	10	2.12	91.8	Vib. roller, 1 coverage, low amp.
4	0.35' AC	top, 0.10'	2.31	20	2.18	94.4	3 cov. static, 3 cov. pneumatic
5	0.35' AC	mid, 0.10'	2.31	10	2.14	92.6	Vib. roller, 2 coverages, low amp.

compactive effort was reduced even further, there was a corresponding decrease in the in-place densities.

Project 6 was also a mountain road. In addition to sharp curves and grades up to 14%, portions of this road were above 9000 ft. The contractor attempted to use one of the largest vibratory rollers available to compact the pavement on this project. Shoving and checking were so extensive in some locations that the vibratory roller was replaced with a static steel-drum roller and a pneumatic roller. The shoving and cracking were reduced, but the in-place densities were inadequate. Observation indicated that this was due mainly to the contractor's failure to apply the specified number of roller coverages while the AC remained in the appropriate temperature range. During later portions of the project, inclement weather further hampered the paving operation.

The extremely low relative compaction (89.7%) on a portion of Project 16 was the result of attempting to test a thin layer of AC which had been placed over a layer of asphalt treated permeable material (ATPM). In this case, the indicated density of the 0.12-ft layer of AC was influenced by the low unit weight of the underlying ATPM. The low relative compaction on the remainder of this project probably was caused by the vibratory roller being operated in the low-amplitude mode instead of the specified high amplitude.

Data from several of the projects show that the relative compaction can be varied by manipulation of the compacting procedures. The number of roller coverages and the settings on vibratory compactors often are critical factors.

In some cases, a reduced compactive effort actually resulted in a better pavement. Project 5, which was discussed earlier, was one example. Another example is Project 7, where the compactive effort was reduced from 2 coverages with the vibratory roller in high amplitude to one coverage in low amplitude. This project consisted of placing 0.30 to 0.40 ft of new AC pavement over an existing PCC pavement. When the vibratory roller was used according to specified procedures, there was obvious checking and disruption of the AC. By applying a much reduced compactive effort, 99% relative compaction was achieved.

The variations in compacting procedures and the relative compactions achieved, as recorded in Table 14, strengthen the opinions of many who believe that a single procedure for compaction is not appropriate for all materials and conditions. These data also show that 95% relative compaction is a reasonable target density when applying the specifications and test procedures presented in this report.

H. COMPACTION OF AC PLACED OVER RUTTED SURFACES

Originally it was intended that this study would include an evaluation of differential compaction when AC is placed over uneven or rutted surfaces. The bridging that occurs when a steel drum roller is used to compact new AC placed over a rutted pavement was of primary concern. A review of the "Pavement Management System Flexible Pavement Condition Inventory" indicated, however, that rutting is seldom a significant problem on state and federal highways in California.

When rutting does occur because of instability, the normal practice is to dig out and repair these areas before resurfacing. When ruts develop in a stable pavement, the depressions normally are filled, or the high points are ground, prior to resurfacing. Because of this lack of need, as well as the lack of opportunity, study of compaction on an uneven surface was not necessary.

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APPENDIX A

Caltrans' End-Result Specifications for Compacting AC Pavements (California Standard Special Provision 39.03, 7-2-84)

Types A, B, and C asphalt concrete placed in layers less than 0.15-foot in compacted thickness, asphalt concrete base placed in layers less than 0.15-foot in compacted thickness, and Open Graded asphalt concrete shall be spread and compacted with the equipment and by the methods specified in said Section 39. All other asphalt concrete shall be spread and compacted in conformance with said Section 39, amended as follows: 1

Section 39-5.02, "Compacting Equipment," is amended to read: 1a

The Contractor shall furnish a sufficient number of rollers to obtain the compaction and surface finish required by these specifications. 1a1

All rollers shall be equipped with pads and water systems which prevent sticking of asphalt mixtures to the pneumatic- or steel-tired wheels. A parting agent, which will not damage the asphalt mixture, as determined by the Engineer, may be used to aid in preventing the sticking of the mixture to the wheels. 1a2

The first paragraph of Section 39-6.01, "General Requirements," is amended to read: 1b

Asphalt concrete shall be spread with an asphalt paver and shall be compacted by any means to obtain the specified density and surface finish to the lines, grades and cross section shown on the plans. 1b1

The twelfth paragraph of said Section 39-6.01 is amended to read: 1c

At locations where the asphalt concrete is to be placed over areas inaccessible to an asphalt paver, the asphalt concrete shall be spread by any means that will obtain the specified results and shall be compacted to the specified density and to the required lines, grades and cross sections. 1c1

Section 39-6.03, "Compacting," is amended by deleting the fourth thru twelfth paragraphs and adding the following after the fourteenth paragraph: 1d

Asphalt concrete shall be compacted to relative compaction of not less than 95 percent. 1d1

Relative compaction will be determined by California Test 375. Laboratory specimens will be compacted in conformance with California Test 304. The asphalt concrete will be tested by lots, as specified in California Test 375. If any lot tested has a relative compaction below 95.0 percent, but above 92.9 percent, the Contractor will be advised that he is not attaining the desired relative compaction and that his materials or his procedures, or both, need adjustment. Any lot of asphalt concrete that has a relative compaction of less than 93.0 percent shall be removed and replaced by the Contractor at no cost to the State, except that, if requested in writing by the Contractor, a lot with a relative compaction of 90.0 percent or greater may be accepted on the basis of a reduced payment. 1d2

Section 39-8.02, "Payment," is amended by adding the following after the first paragraph: 1e

Asphalt concrete in a lot that is accepted on the basis of reduced payment will be paid for at the contract prices for the items of asphalt concrete involved multiplied by the following factors: 1e1

Relative Compaction (Percent)	Pay Factor	Relative Compaction (Percent)	Pay Factor
93.0	1.000	91.4	0.938
92.9	0.998	91.3	0.932
92.8	0.996	91.2	0.925
92.7	0.994	91.1	0.918
92.6	0.991	91.0	0.910
92.5	0.988	90.9	0.902
92.4	0.985	90.8	0.892
92.3	0.982	90.7	0.882
92.2	0.978	90.6	0.871
92.1	0.974	90.5	0.858
92.0	0.970	90.4	0.843
91.9	0.966	90.3	0.825
91.8	0.961	90.2	0.804
91.7	0.956	90.1	0.775
91.6	0.950	90.0	0.700
91.5	0.944		

California Test 375
October 1984

DETERMINING THE IN-PLACE DENSITY AND RELATIVE COMPACTION OF AC PAVEMENT

A. SCOPE

This procedure is used when determining the average in-place density and relative compaction of asphalt concrete (AC) pavements. It may be applied to an individual layer of AC which has a compacted thickness of at least 0.15 ft., or to the combination of two thinner layers of AC produced from the same source which have an accumulated thickness of 0.15 ft. or more. The in-place density shall be determined before the pavement is opened to public traffic. Procedures for random selection of test sites, taking nuclear gage readings, and calculating relative compaction are described.

B. APPARATUS

1. Nuclear gage and standardizing block conforming to the Caltrans' "Specifications for Nuclear Density-Moisture Gage" in effect at the time of purchase.

2. Distance measuring device suitable for determining the longitudinal and transverse locations of the test sites.

C. STANDARDIZATION AND CALIBRATION OF THE NUCLEAR GAGE IN BACKSCATTER MODE

1. Determine the standard count at the beginning of each day's testing according to the instructions in California Test 111 and the following modifications.

   a. After the specified warm-up, take 12 one-minute counts or 3 four-minute counts with the gage in the safe position.

   b. The average of the 12 one-minute counts, or 3 four-minute counts, is the standard count for the gage.

2. Develop the density calibration table according to the instructions in California Test 111 and the following modifications.

   a. The backscatter density calibration table shall be developed individually for each gage using the six California Transportation Laboratory Master Standard Density Blocks (CTLMSDB).

b. The calibration table shall not be adjusted based on average density determinations on the two Transportation District reference standard blocks.

c. The density count for each CTLMSDB shall be the average of two four-minute counts or eight one-minute counts.

D. LOT AND TEST SITE SELECTION

1. The pavement shall be divided into lots which can be defined by specific parameters such as location, layer, or time of placement. The size and number of lots shall be sufficient to include substantially all of the pavement and to isolate significant variations in materials, structural section, equipment, construction procedures, etc. Under normal continuous operating conditions, two lots per day are sufficient. Smaller lots may be more effective during the early stages of a project or when paving conditons vary. Care must be taken to exclude areas of pavement which do not have a COmbined layer thickness of at least 0.15 foot.

2. The lots shall be separated into two categories as indicated below. Consideration must be given to such factors as production rate; location, i.e., main line, shoulders, ramps, etc; lift thickness and differences in the AC mix being supplied.

a. Major lots. Pavements having a surface area of 2500 sq. yds. or more.

b. Minor lots. Pavements having a surface area of less than 2500 sq. yds.

3. Test site selection shall be by random procedures. The number of test sites will vary with the size of the lot being tested.

a. Major lots. Select 10 test sites using one of the following random procedures:

1) The Nonbiased Sampling Plan in California Test 231.

2) The Sequential Random Numbers in Table 1. (The numbers in this table were randomly selected and then arranged in sequential order for groups of 10.)

Table 1

Sequential Random Numbers

.053	.730	.035	.627	.231	.870	.081	.040	.106	.239
.081	.948	.137	.163	.251	.114	.285	.542	.231	.291
.095	.726	.164	.093	.271	.505	.324	.538	.253	.858
.576	.482	.225	.921	.396	.025	.470	.414	.398	.761
.609	.824	.334	.417	.427	.392	.522	.235	.517	.463
.669	.899	.356	.850	.549	.760	.569	.608	.640	.993
.810	.159	.434	.838	.690	.405	.579	.977	.749	.919
.892	.277	.554	.375	.860	.507	.751	.592	.904	.501
.971	.468	.576	.155	.935	.806	.815	.787	.986	.031
.982	.801	.794	.638	.997	.884	.879	.871	.998	.222
.068	.025	.109	.548	.021	.887	.100	.472	.335	.683
.165	.059	.127	.964	.150	.169	.123	.086	.348	.996
.371	.996	.209	.064	.195	.979	.396	.355	.358	.743
.470	.535	.412	.356	.289	.187	.423	.460	.601	.595
.477	.101	.587	.284	.448	.894	.673	.652	.698	.539
.509	.815	.622	.862	.654	.169	.817	.259	.740	.466
.566	.342	.667	.843	.767	.985	.833	.317	.796	.212
.788	.682	.757	.283	.919	.962	.890	.665	.864	.019
.874	.242	.831	.908	.942	.313	.925	.404	.896	.247
.901	.420	.873	.218	.947	.215	.928	.305	.909	.326
.009	.663	.157	.077	.069	.117	.104	.265	.058	.284
.153	.592	.181	.269	.263	.239	.205	.217	.082	.802
.399	.928	.331	.447	.428	.491	.441	.307	.195	.146
.551	.772	.503	.137	.454	.333	.619	.879	.220	.696
.564	.875	.552	.574	.659	.364	.716	.755	.425	.887
.629	.721	.614	.486	.666	.731	.798	.007	.428	.075
.732	.508	.629	.666	.759	.998	.830	.649	.432	.659
.800	.420	.665	.606	.865	.463	.890	.841	.631	.422
.892	.310	.721	.399	.870	.176	.917	.062	.892	.391
.937	.975	.914	.150	.945	.390	.994	.446	.919	.939

a) Select a block of random numbers. The method of selection shall be such that all blocks have an equal chance of being selected. For example, number the blocks from 1 through 15, then draw a number from a hat and use the random numbers contained within the corresponding block.

b) Beginning with the numbers at the top of each column, use each successive pair of numbers to determine the longitudinal and transverse location of consecutive density tests.

c) Multiply the numbers in the left column by the length of the lot to determine the distance from the starting point.

d) Multiply the numbers in the right column by the width of the lot, in feet, minus one. Round the product up to the next whole number to determine the transverse distance from the edge of the mat being tested.

e) Reference all test sites to identifiable locations; i.e., stationing, edge of pavement, centerline, etc.

b. Minor lots. The number of test sites within each lot may vary with the size of the lot. The minimum number of sites shall be two (2) for each 500 sq. yds. or fraction thereof. Select the test site locations using one of the following random procedures:

1) The Nonbiased Sampling Plan in California Test 231.

2) The Random Numbers in Table 2.

a) Select a block of random numbers. The method of selection shall be such that all blocks have an equal chance of being selected. For example, number the blocks from 1 through 35, then draw a number from a hat and use the random numbers contained within the corresponding block.

b) Beginning with the numbers at the top of each column, use each successive pair of numbers to determine the longitudinal and transverse location of the density tests. When all five numbers in a block have been used in order, proceed to the next block in sequence.

TABLE 2

TABLE OF RANDOM NUMBERS

.576	.730	.430	.754	.271	.870	.732	.721	.998	.239
.892	.948	.858	.025	.935	.114	.153	.508	.749	.291
.669	.726	.501	.402	.231	.505	.009	.420	.517	.858
.609	.482	.809	.140	.396	.025	.937	.310	.253	.761
.971	.824	.902	.470	.997	.392	.892	.957	.640	.463
.053	.899	.554	.627	.427	.760	.470	.040	.904	.993
.810	.159	.225	.163	.549	.405	.285	.542	.231	.919
.081	.277	.035	.039	.860	.507	.081	.538	.986	.501
.982	.468	.334	.921	.690	.806	.879	.414	.106	.031
.095	.801	.576	.417	.251	.884	.522	.235	.398	.222
.509	.025	.794	.850	.917	.887	.751	.608	.698	.683
.371	.059	.164	.838	.289	.169	.569	.977	.796	.996
.165	.996	.356	.375	.654	.979	.815	.592	.348	.743
.477	.535	.137	.155	.767	.187	.579	.787	.358	.595
.783	.101	.434	.638	.021	.894	.324	.871	.698	.539
.566	.815	.622	.548	.947	.169	.817	.472	.864	.466
.901	.342	.873	.964	.942	.985	.123	.086	.335	.212
.470	.682	.412	.064	.150	.962	.925	.355	.909	.019
.063	.242	.667	.356	.195	.313	.396	.460	.740	.247
.874	.420	.127	.284	.448	.215	.833	.652	.601	.326
.897	.877	.209	.862	.428	.117	.100	.259	.425	.284
.875	.969	.109	.843	.759	.239	.890	.317	.428	.802
.190	.696	.757	.283	.666	.491	.523	.665	.919	.146
.341	.688	.587	.908	.865	.333	.928	.404	.892	.696
.846	.355	.831	.218	.945	.364	.673	.305	.195	.887
.852	.227	.552	.077	.454	.731	.716	.265	.058	.075
.464	.658	.629	.269	.069	.998	.917	.217	.220	.659
.123	.791	.503	.447	.659	.463	.994	.307	.631	.422
.116	.120	.721	.137	.263	.176	.798	.879	.432	.391
.836	.206	.914	.574	.870	.390	.104	.755	.082	.939
.636	.195	.614	.465	.629	.663	.619	.007	.295	.456
.630	.673	.665	.666	.397	.592	.441	.649	.270	.612
.834	.112	.331	.606	.551	.923	.830	.841	.602	.183
.360	.193	.181	.399	.564	.772	.890	.052	.919	.875
.183	.651	.157	.150	.500	.875	.205	.446	.648	.685

(Excerpted from "THE STATISTICAL APPROACH TO QUALITY CONTROL IN HIGHWAY CONSTRUCTION")
(Bureau of Public Roads, April 1965)

c) Arrange the pairs in sequential order of the numbers in the left column.

d) Multiply the numbers in the left column by the length of the lot to determine the distance from the starting point.

e) Multiply the numbers in the right column by the width of the lot, in feet, minus one. Round the product up to the next whole number to determine the transverse distance from the edge of the mat being tested.

f) Reference all test sites to identifiable locations; i.e., stationing, edge of pavement, centerline, etc.

E. FIELD DENSITY DETERMINATIONS

1. Fill the surface voids with fine aggregate.

   a. Use aggregate passing the No. 16 sieve.

   b. Use a straightedge to work the fine aggregate back and forth over the surface until all imperfections are filled.

   c. Scrape off all excess fine aggregate.

2. Set the nuclear gage on the test site and seat it on the pavement by applying a light vertical pressure while working the gage back and forth in a short horizontal arc.

3. Obtain a one-minute density count reading at each test site with the nuclear gage in the backscatter mode. (BS position for gages which have both BS and AC backscatter positions.)

4. Calculate the count ratio, and determine the density from the count ratio/density table established for the gage.

F. TEST MAXIMUM DENSITY

The test maximum density (TMD) is the maximum compaction achievable in the laboratory using the method outlined in California Test 304.

1. During the course of a paving operation, the TMD shall be determined as follows on the AC mixture being produced by the Contractor:

a. Obtain a representative sample from each lot of AC placed on the street following the instructions in Section 6-39 of the Construction Manual.

b. Compact five (5) briquettes from each sample according to the procedures for making stabilometer test specimens in California Test 304. (When preparing test specimens of cold recycled AC, the mix shall be cured according to the procedures in California Test 378 immediately prior to compaction.)

c. Determine the density of each briquette to the nearest 0.01 g/cc (0.5 pcf) by following the procedures in California Test 308, Method A.

d. Calculate the TMD by averaging the densities of the five briquettes to the nearest 0.01 g/cc (0.5 pcf).

2. AC batched in the laboratory may be used to establish a preliminary TMD for use until material from the street can be sampled and tested. These samples shall:

a. Be batched from representative processed aggregate submitted by the contractor in compliance with Section 39-3.03 of the Standard Specifications, and

b. have an asphalt content within the recommended range established by California Test 367.

3. Testing for TMD may be waived for selected samples of a given mix providing the following conditions are met:

a. The TMD of three or more consecutive samples do not differ by more than 1%,

b. at least one sample is tested for TMD each five paving days,

c. at least one sample is tested for TMD whenever there is a significant change in the AC mix, and

d. street samples not tested initially are retained for verification testing on any lot which is subject to rejection or pay reduction.

G. CALCULATIONS AND REPORTING OF RESULTS

1. Calculate the average in-place density to the nearest 0.01 g/cc (0.5 pcf). Values of 0.005 or more shall be rounded to the next higher 0.01. The density at each individual test location in the lot shall be included in the average.

2. Calculate the relative compaction of the lot to the nearest 0.1 percent.

$$\text{Relative Compaction} = \frac{\text{Average In-place Density}}{\text{Test Maximum Density}} \times 100$$

3. Record the specified information on Form HMR-T-3112 or DCR-TL-2148.

APPENDIX C

Caltrans' Asphalt Content and Layer Thickness Requirements for AC Pavements (California Standard Special Provision 39.01, 7-4-84)

10-1.___ ASPHALT CONCRETE.--Asphalt concrete shall be ______________________________ and shall conform to the provisions in Section 39, "Asphalt Concrete," of the Standard Specifications and these special provisions. *

The first paragraph in Section 39-3.04, "Mixing," of the Standard Specifications is amended to read: 2

Aggregate, supplemental fine aggregate, and asphalt binder shall be mixed in a batch mixer, continuous pugmill mixer, or drier-drum mixer. The asphalt content of the asphalt mixture will be determined by extraction tests in accordance with California Test 310 or 362, or will be determined in accordance with California Test 379. The bitumen ratio (pounds of asphalt per 100 pounds of dry aggregate including supplemental fine aggregate if used) shall not vary by more than 0.5-pound of asphalt above or 0.5-pound of asphalt below the amount designated by the Engineer. Compliance with this requirement, except for Open Graded asphalt concrete, will be determined by testing samples taken from the mat behind the paver before initial or breakdown compaction of the mat. 2a

For Open Graded asphalt concrete, compliance with this requirement will be determined either by taking samples from trucks at the plant or from the mat behind the paver before initial or breakdown compaction of the mat. If the sample of Open Graded asphalt concrete is taken from the mat behind the paver, the bitumen ratio shall be not less than the amount designated by the Engineer, less 0.7-pound of asphalt per 100 pounds of dry aggregate, nor more than the amount designated by the Engineer, plus 0.5-pound of asphalt per 100 pounds of dry aggregate. 2b

The fourth and sixth paragraphs of Section 39-4.03, "Pavement Reinforcing Fabric," of the Standard Specifications are amended by deleting the word "stretched,". 3

The first three sentences of the fifth paragraph of Section 39-6.01, "General Requirements," of the Standard Specifications are amended to read: 4

When the total compacted thickness of asphalt concrete is shown on the plans to be less then 0.25-foot, asphalt concrete shall be spread and compacted in one layer. All other asphalt concrete shall be spread and compacted in layers. The top layer of asphalt concrete shall be not more than 0.20-foot nor less than 0.15-foot in compacted thickness. The next lower layer shall be not more than 0.25-foot nor less than 0.15-foot in compacted thickness unless the total thickness is shown on the plans to be less than 0.30-foot, and any lower layers shall be not less than 0.15-foot nor more than 0.40-foot in compacted thickness. Asphalt concrete base shall be spread and compacted in one or more layers; each layer shall not exceed 0.40-foot in compacted thickness. 4a

APPENDIX D

Survey of Conformance to Caltrans' Procedural Specifications

Early in this study, a questionnaire was distributed to Caltrans construction personnel for the purpose of identifying specific problem areas encountered when enforcing the current Caltrans Standard Specification and Standard Special Provision requirements for asphalt concrete placement and compaction. Street inspectors, as well as resident engineers and construction seniors, were requested to submit input. A copy of the questionnaire and a complete summary of the responses is attached.

Sixty-seven questionnaires were returned. In response to the question, "Do you think the specifications were adequate?", 43 responded affirmatively and 13 did not respond at all. Nine responded with suggestions on how specific areas might be improved. Several of these suggestions referred to some phase of the specifications other than placement and compaction. This apparent general endorsement of the compaction specifications suggested that if compaction problems existed, they had not yet been recognized by the majority of the those responding to the questionnaire.

The response to other questions indicates, however, that there are broad variations in procedures and conditions during paving. For example, the reported temperature of the mix delivered to the street varied from less than 200°F to over 310°F. Four of those responding (6%) reported delivery temperatures of less than 250°F. Another seven

(10%) did not answer this question or stated that they did not know the temperature. More than 80% reported temperatures above 250°F which is the minimum breakdown temperature permitted by current Caltrans Standard Specifications. It was much more difficult to determine the temperature variations at the time compaction actually began. This question was not answered on 24 of the questionnaires. Of those that did respond, 3 reported breakdown compaction temperatures below the required 250°F. Thus, although the temperature range was quite broad, the number of projects apparently in compliance with the specifications was encouraging. (TransLab personnel making field reviews of construction projects in the past have frequently measured windrow temperatures of 200-250°F.)

One factor that influences compaction temperature is windrow length. The questionnaires showed windrow lengths of up to one-half mile, although the response indicated that approximately 90% did not exceed 1000 feet and more than 50% were 300 feet or less.

The size and operating conditions of the compaction equipment were also possible sources of variation in compacted density of asphalt concrete pavements. Twenty of those responding to the questionnaire did not know, or at least did not state, the rated weight of the rollers used for breakdown compaction. Only one stated that the weight of the roller had been verified. Less than 40% responded to specific questions regarding pneumatic and vibratory rollers.

Approximately 30% did not respond to the questions regarding the number of coverages during the breakdown and intermediate rolling procedures.

Based on the repsonse to this questionnaire and the first-hand observations of numerous Caltrans' Headquarters personnel, it is concluded that conformance to the current procedural specifications for asphalt concrete compaction is marginal on many projects.

SUMMARY OF RESPONSES TO AC PAVEMENT CONSTRUCTION QUESTIONNAIRE

I. MIXING CONDITIONS

1. Time of year paving was done

Spring	Summer	Fall
1	58	18

2. Type of plant

Batch	Drier Drum	No Answer
54	12	2

3. Production rate (tons/day)

<600	600-700	1000-1900	2000-2500	2600-3000	>3000	Variable	No Answer
2	7	27	8	3	14	4	6

4. Air Temperature (°F)

Cold	45-50	51-60	61-70	71-80	81-90	91-100	>101	Warm	No Answer
1	4	6	5	12	14	13	6	3	3

5. Did the weather affect the quality of the finished job?

Yes	No	No Answer
29	36	1

6. In what way?

Improved Quality	No Effect	No Answer
18	20	28

II. HAULING

1. Type of trucks

End Dump	Bottom Dump	Flow Boy
22	43	2

2. Haul distance (miles)

5-10	11-15	16-20	21-25	26-30	31-35	36-40	>50	No Answer
20	10	7	6	2	11	4	5	1

3. Loads covered during hauling

Yes	No	Sometimes	No Answer
9	51	3	3

4. Coating used in truck beds to avoid sticking

Diesel	Detergent	Not Known	No Answer
60	1	4	2

III. SPREADING

1. Typical temperature of delivered mix (°F)

<200	200-230	231-250	251-270	271-290	291-310	>310	Not Known	No Answer
1	2	1	13	31	11	1	2	5

2. Location where temperature was checked

In Truck	After Dumping	After Spreading	In Paving Hopper	No Answer
9	47	6	1	3

3. Was temperature of underlying layer determined?

Yes	No	No Answer
8	53	5

4. Windrow operation - maximum windrow length (feet)

200	300	600	1000	2600
12	8	8	8	3

5. Type of paving machine

Blaw Knox	Barber Green	Cedarapids	No Answer
41	18	3	4

6. Width of spread (feet)

8-11	12	13-16	17-19	35	86	No Answer
10	23	25	2	1	1	4

7. Wings used on spreader

Yes	No	No Answer
47	19	4

8. Paving machine equipment checks

Screed and Crown	Pavement	None	Not Known	No Answer
44	3	6	2	7

9. Paving machine ran continuously (without intermittent stops waiting for trucks)

Yes	No	No Answer
5	59	2

IV. COMPACTING EQUIPMENT

1. Steel Wheel Rollers
   a. (Manufacturer)

Hyster	Galion	Rex	Bomag	Ingersoll-Rand	No Answer
30	9	7	3	3	14

   b. (Rated Weight-tons)

8-10	10-12	No Answer
11	36	20

   c. (Actual Weight)

No response

2. Pneumatic Rollers
   a. (Manufacturer)

Hyster	Bros	Galion	Ingram	Tampo	Michigan	No Answer
16	7	3	1	2	1	36

   b. (Model, Weight, Width, Tire Size, Pressure, etc.)

No response from more than 60%

3. Vibratory Rollers
   a. (Manufacturer)

Dynapac	Tampo	RayGo	Ingersoll-Rand	No Answer
14	7	3	1	15

   b. (Model, Weight, Drum Length)

No Response from more than 60%

c. (Operating Frequency-VPM)

2200	2300	2400	2500	2750	3000	No Answer
1	4	6	2	1	3	13

d. (Operating Amplitude)

High	Low	Not Known	No Answer
7	6	1	16

e. (Operating Speed - MPH)

2.0	2.5	3.0	4.0	0-7	No Answer
1	3	9	2	1	13

V. COMPACTION

1. Temperature at breakdown rolling (°F)

<230	230-250	251-270	271-290	>290	No Answer
2	1	22	16	2	24

2. Number of breakdown roller coverages

1	2	3	No Answer
5	19	22	20

3. Temperature at intermediate rolling (°F)

150-170	171-190	>190	No Answer
2	2	15	20

4. Number of intermediate roller coverages

1	2	3	>3	No Answer
4	7	20	1	14

5. Temperature at final rolling (°F)

100	150-170	171-190	>190	No Answer
1	6	7	10	25

6. How were roller weights verified?

Verification reported by only one person.

7. Vibratory rollers checked for frequency, amplitude and operating speed

Yes	No	No Answer	Not Applicable
5	20	12	28

8. Comments on preceding question

"Not aware frequency should be checked"
"Have no idea how to check amplitude and frequency"
"Too impractical"
"Did not have tools"

VI. FINISHING

1. Method of evaluation

Straight edge?	Profilograph?
34	6

2. Describe any remedial work that was done.

There were 42 reports of remedial work. Mostly repair of construction joints.

3. Were you satisfied with the finish and riding quality?

Yes	No	No Answer
49	11	6

4. Would you do anything different?

Yes	No	No Answer
24	36	7

5. Comments on preceding question

"Eliminate rubber tires on thin blankets"
"Keep a man at hot plant for constant temperature of mix"
"AR-4000 too soft"
"Investigate lower temperature when using AR-2000"

VII. GENERAL

1. Do you think the specifications were adequate?

Yes	No	No Answer
43	9	13

2. If not, please elaborate and include any changes you would like to see in the specifications.

"Should have profilograph with grinding requirements. These could be modified by specials for slow speed jobs"
"Continuous forward movement cannot be attained with end dumps"

APPENDIX E

Caltrans Procedural Specifications for
Spread and Compacting AC
(California Standard Specifications, July 1984)

39-5 SPREADING AND COMPACTING EQUIPMENT

39-5.01 Spreading Equipment.—Blading equipment shall consist of pneumatic-tired motor graders having a blade not less than 12 feet long and a wheel base not less than 17 feet long. The motor graders shall be free from appreciable lost motion in the blade control and shall have rigid frames.

Asphalt pavers shall be self-propelled mechanical spreading and finishing equipment, provided with a screed or strike-off assembly capable of distributing the material to not less than the full width of a traffic lane. Screed action shall include any cutting, crowding or other practical action which is effective on the mixture without tearing, shoving or gouging, and which produces a surface texture of uniform appearance. The screed shall be adjustable to the required section and thickness. The paver shall be provided with a full width roller or tamper or other suitable compacting devices. Pavers that leave ridges, indentations or other marks in the surface shall not be used unless the ridges, indentations or other marks are eliminated by rolling or prevented by adjustment in operation.

The asphalt paver shall operate independently of the vehicle being unloaded or shall be capable of propelling the vehicle being unloaded in a satisfactory manner and, if necessary, the load of the haul vehicle shall be limited to that which will insure satisfactory spreading. While being unloaded the haul vehicle shall be in contact with the machine at all times, and the brakes on the haul vehicle shall not be depended upon to maintain contact between the vehicle and the machine.

The procedure whereby material is deposited in a windrow, then picked up and placed in the asphalt paver with loading equipment, will be permitted for all asphalt concrete except Open Graded, provided the asphalt paver is of such design that the material will fall into a hopper which has a movable bottom conveyor to feed the screed and the loading equipment is constructed so that substantially all of the material deposited on the roadbed is picked up and deposited in the paving machine.

No portion of the weight of hauling or loading equipment, other than the connection, shall be supported by the asphalt paver, and no vibrations or other motions of the loader, which could have a detrimental effect on the riding quality of the completed pavement, shall be transmitted to the paver.

39-5.02 Compacting Equipment.—For each asphalt paver, the Contractor shall furnish a minimum of one steel-tired roller weighing not less than 8 tons and, except for placing Open Graded asphalt concrete, one steel-tired roller weighing not less than 12 tons and one pneumatic-tired roller. Each roller shall have a separate operator. All rolling equipment shall be self-propelled and reversible. The minimum number, weight, and type of rollers required may be reduced or modified in accordance with the provisions of Section 39-6.03, "Compacting," for low rates of production or when alternative equipment is approved by the Engineer.

All rollers shall be equipped with pads and water systems which prevent sticking of asphalt mixtures to the pneumatic- or steel-tired wheels. A parting agent, which will not damage the asphalt mixture, as determined by the Engineer, may be used to aid in preventing the sticking of the mixture to the wheels.

Other equipment, approved by the Engineer in accordance with California Test 113, may be substituted for 3-wheel or tandem rollers when used as specified in Section 39-6.03, "Compacting."

Pneumatic-tired rollers shall be the oscillating type having a width of not less than 4 feet with pneumatic tires of equal size, diameter and having treads satisfactory to the Engineer. Wobble-wheel rollers will not be permitted. The tires shall be spaced so that the gaps between adjacent tires will be covered by the following tires, or shall be spaced so that any resulting uncovered gap will not exceed 1 ½ inches in width when the tires are inflated to 90 pounds per square inch and the operating weight is 2,000 pounds per tire.

When the pneumatic-tired roller furnished by the Contractor is constructed so that there is a resulting gap between tire tracks as permitted in the preceding paragraph, the complete coverages of asphalt concrete with the roller required in Section 39-6.03, "Compacting," shall be increased by one complete coverage for each ½ inch, or fraction thereof, of the maximum uncovered gap between any 2 tire tracks.

The tires shall be inflated to 90 pounds per square inch, or such lower pressure as designated by the Engineer, and maintained so that the air pressure will not vary more than 5 pounds per square inch from the designated pressure. Pneumatic-tired rollers shall be constructed so that the total weight of the roller can be varied to produce an operating weight per tire of not less than 2,000 pounds. The total operating weight of the roller shall be varied as directed by the Engineer.

Pneumatic-tired rollers will not be required when approved vibratory rollers are furnished and used as specified in Section 39-6.03, "Compacting."

39-6 SPREADING AND COMPACTING

39-6.01 General Requirements.—Unless lower temperatures are directed by the Engineer, all mixtures, except Open Graded asphalt concrete, shall be spread, and the first coverage of initial or breakdown compaction shall be performed when the temperature of the mixture is not less than 250° F., and all breakdown compaction shall be completed before the temperature of the mixture drops below 200° F. Open Graded asphalt concrete shall be spread at a temperature of not less than 200° F. and not more than 250° F., measured in the hopper of the paving machine.

Type A, Type B, or Type C asphalt concrete shall be placed only when the atmospheric temperature is above 50° F. Asphalt concrete base shall be placed only when the atmospheric temperature is above 40° F.

Open Graded asphalt concrete shall be placed only when the atmospheric temperature is above 70° F. and, where placement is to be on bridges or other structures, when the surface temperature of such structure is above 60° F.

Asphalt concrete and asphalt concrete base shall not be placed when the underlying layer or surface is frozen, or when, in the opinion of the Engineer, weather conditions will prevent the proper handling, finishing, or compaction of the mixtures.

Asphalt concrete and asphalt concrete base shall be spread and compacted in layers. The top layer of asphalt concrete shall not exceed 0.20-foot in compacted thickness. The next lower layer shall not exceed 0.25-foot in compacted thickness, and any lower layers shall not exceed 0.40-foot in compacted thickness. Each layer of asphalt concrete base shall not exceed 0.40-foot in compacted thickness. No layer shall be placed over a layer which exceeds 0.25-foot in compacted thickness until the temperature at mid depth, of the layer which exceeds 0.25-foot in compacted thickness, is not more than 160° F.

Asphalt concrete and asphalt concrete base to be placed on shoulders, and other areas off the traveled way having a width of 5 feet or more, shall be spread in the same manner as specified above. When the shoulders and other areas are less than 5 feet in width, the material may be deposited and spread in one or more layers by any mechanical means that will produce a uniform smoothness and texture. Unless otherwise shown on the plans, asphalt mixtures shall not be handled, spread or windrowed in a manner that will stain the finished surface of any pavement or other improvements.

The completed mixture shall be deposited on the roadbed at a uniform quantity per linear foot, as necessary to provide the required compacted thickness without resorting to spotting, picking-up or otherwise shifting the mixture.

Segregation shall be avoided, and the surfacing shall be free from pockets of coarse or fine material. Asphalt concrete containing hardened lumps shall not be used.

Longitudinal joints in the top layer shall correspond with the edges of proposed traffic lanes. Longitudinal joints in all other layers shall be offset not less than 0.5-foot alternately each side of the edges of traffic lanes. The Engineer may permit other patterns of placing longitudinal joints if he considers that such patterns will not adversely affect the quality of the finished product.

Unless otherwise provided herein or permitted by the Engineer, the top layer of asphalt concrete for shoulders, tapers, transitions, road connections, private drives, curve widenings, chain control lanes, turnouts, left turn pockets, and other such areas, shall not be spread before the top layer of asphalt concrete for the adjoining through lane has been spread and compacted. At locations where the number of lanes is changed, the top layer for the through lanes shall be paved first. When existing pavement is to be surfaced and the specified thickness of asphalt concrete to be spread and compacted on the existing pavement is 0.20-foot or less, shoulders or other adjoining areas may be spread simultaneously with the through lane provided the completed surfacing conforms to the requirements of these specifications. Tracks or wheels of spreading equipment shall not be operated on the top layer of asphalt concrete in any area until final compaction has been completed.

At locations shown on the plans, specified in the special provisions or as directed by the Engineer, the asphalt concrete shall be tapered or feathered to conform to existing surfacing or to other highway and non-highway facilities.

At locations where the asphalt concrete is to be placed over areas inaccessible to spreading and rolling equipment, the asphalt concrete shall be spread by any means to obtain the specified results and shall be compacted thoroughly to the required lines, grades and cross sections by means of pneumatic tampers, or by other methods that will produce the same degree of compaction as pneumatic tampers.

39-6.02 Spreading.—In advance of spreading asphalt concrete over an existing base, surfacing, pavement, or bridge deck, if ordered by the Engineer, asphalt concrete shall be spread to level irregularities, and to provide a smooth base in order that subsequent layers will be of uniform thickness. The asphalt concrete may be spread with any equipment conforming to the requirements in Section 39-5.01, "Spreading Equipment." No additional compensation will be allowed for spreading asphalt concrete as above specified, and full compensation for all work incidental to such operations will be considered as included in the contract price or prices paid for the asphalt concrete.

When directed by the Engineer, paint binder shall be applied to any layer in advance of spreading the next layer.

Before placing the top layer adjacent to cold transverse construction joints, such joints shall be trimmed to a vertical face and to a neat line. Transverse joints shall be tested with a 12-foot straightedge and shall be cut back as required to conform to the requirements specified in Section 39-6.03, "Compacting," for surface smoothness. Connections to existing surfacing shall be feathered to conform to the requirements for smoothness. Longitudinal joints shall be trimmed to a vertical face and to a neat line if the edges of the previously laid surfacing are, in the opinion of the Engineer, in such condition that the quality of the completed joint will be affected.

All layers, except as otherwise provided in Section 39-6.01, "General Requirements," and in this Section 39-6.02, shall be spread with an asphalt paver. Asphalt pavers shall be operated in such a manner as to insure continuous and uniform movement of the paver.

39-6.03 Compacting.—Compacting equipment shall conform to the provisions of Section 39-5.02, "Compacting Equipment."

A pass shall be one movement of a roller in either direction. A coverage shall be as many passes as are necessary to cover the entire width being paved. Overlap between passes during any coverage, made to insure compaction without displacement of material in accordance with good rolling practice, shall be considered to be part of the coverage being made and not part of a subsequent coverage. Each coverage shall be completed before subsequent coverages are started.

Rolling shall commence at the lower edge and shall progress toward the highest portion, except that when compacting layers which exceed 0.25-foot in compacted thickness, and if directed by the Engineer, rolling shall commence at the center and shall progress outwards.

Initial or breakdown compaction shall consist of 3 coverages of a layer of asphalt mixture and shall be performed with a 2-axle or 3-axle tandem or a 3-wheel roller weighing not less than 12 tons and having rolling wheels with a diameter of 40 inches or more. Where the thickness of the layer of asphalt mixture is less than 0.15-foot, fewer coverages than specified above may be ordered by the Engineer if necessary to prevent damage to the layer being compacted.

The initial or breakdown compaction shall be followed immediately by additional rolling consisting of 3 coverages with a pneumatic-tired roller. Coverages with a pneumatic-tired roller shall start when the temperature of the mixture is as high as practicable, preferably above 180° F., and shall be completed while the temperature of the mixture is at or above 150° F.

Excepting Open Graded asphalt concrete, each layer of asphalt concrete and asphalt concrete base shall be compacted additionally without delay by a final rolling consisting of not less than one coverage with a steel-tired roller weighing not less than 8 tons. Except as otherwise provided for low rates of production, a separate finish roller will be required.

Open Graded asphalt concrete shall be rolled only with a steel-tired, 2-axle tandem roller weighing not more than 10 tons.

Rolling shall be performed so that cracking, shoving or displacement will be avoided.

Rolling, where 3-axle tandem rollers may be used as specified in this Section 39-6.03, shall be under the control of the Engineer, but in general, no 3-axle tandem roller shall be used in rolling over a crown or on warped sections when the center axle is in the locked position.

Provided it is demonstrated to the satisfaction of the Engineer that one roller can perform the work, the required minimum rolling equipment specified above may be reduced to one 2-axle tandem roller, weighing at least 8 tons, for each paver under any of the following conditions:

(1) When asphalt concrete is placed at a rate of 50 tons, or less, per hour at any location.

(2) When asphalt concrete is placed at a rate of 100 tons, or less, per hour and at the locations or under the conditions as follows:

(a) Placed on miscellaneous areas in accordance with the provisions in Section 39-7.01, "Miscellaneous Areas."

(b) When the width to be placed is less than 8 feet.

(c) When the total thickness to be placed is less than 0.1-foot.

(3) When the total amount of asphalt concrete included in the contract is 1,000 tons, or less.

When rolling equipment is reduced as provided in this Section 39-6.03, the rolling requirements may be reduced to at least 3 complete coverages with said tandem roller.

Alternative compacting equipment, approved by the Engineer in accordance with California Test 113, may be used for the initial or breakdown compaction if operated according to the procedures and under the conditions designated in the approval. Additional compaction with pneumatic-tired rollers will not be required when approved alternative equipment has been used for the initial compaction. A vibratory roller may be used as the finish roller provided that it meets the requirements for a finish roller and is operated with the vibratory unit turned off.

During rolling operations, and when ordered by the Engineer, the asphalt concrete shall be cooled by applying water. Applying water shall conform to the provisions in Section 17, "Watering." No layer shall be cooled with water unless so ordered or permitted by the Engineer.

The completed surfacing shall be thoroughly compacted, smooth, and free from ruts, humps, depressions, or irregularities. Any ridges, indentations or other objectionable marks left in the surface of the asphalt concrete by blading or other equipment shall be eliminated by rolling or other means. The use of any equipment that leaves ridges, indentations, or other objectionable marks in the asphalt concrete shall be discontinued, and acceptable equipment shall be furnished by the Contractor.

When a straightedge 12 feet long is laid on the finished surface and parallel with the center line, the surface shall not vary more than 0.01-foot from the lower edge of the straightedge. The transverse slope of the finished surface shall be uniform to a degree such that no depressions greater than 0.02-foot are present when tested with a straightedge 12 feet long laid in a direction transverse to the center line and extending from edge to edge of a 12-foot traffic lane.

Pavement within 50 feet of a structure or approach slab shall conform to the smoothness tolerances specified in Section 51-1.17, "Finishing Bridge Decks."

APPENDIX F

National Survey of Specifications Used by Other Transportation Agencies

In the winter of 1972-73, the Engineering and Development Bureau (New York DOT) conducted a mail survey of the 50 state highway departments and the District of Columbia to solicit information on then current practices regarding the specification and control of density in asphalt concrete pavements. The responses to that questionnaire were summarized by W. P. Chamberlin and W. C. Bernett in NYDOT Special Report 30 dated April 1975. Of special interest to Caltrans were the testing procedures and acceptance criteria used by the forty-three states that reported using some form of density specification for asphalt concrete pavements.

To supplement the information already available from the New York study, additional information was requested from those states using density requirements. Thirty-seven responded to the five-question questionnaire that was sent out. One state reported they were no longer using end-result density specifications because of a shortage of nuclear testing devices. Another indicated that compaction requirements are based on void content. Thus, the information accumulated from this questionnaire represents responses from thirty-five states.

Some of the responses were much less detailed than others, and it was difficult to interpret the exact meaning of some of the replies. Our interpretations of the responses are summarized in Table F-1 and discussed below.

In response to the question, "What percent relative compaction do you require?", the specified requirement ranged from 90% to 98% for surface courses. Eight states indicated that they assign different compaction requirements to the base and/or binder courses than are assigned to the surface course. These differences ranged from 1 to 5%. None, however, was less than 90% relative compaction.

In response to the second question, "What is your basis for selecting this value?", nearly all responded that it was "through experience." Two indicated they were attempting to achieve a specific void content in the finished pavement and three indicated that they had made an "informal" study but no reports were available.

The responses to the third question, "What method is used to measure the test maximum density?", partially explain why there was such a broad range in specified relative compaction. Six laboratory procedures, including two different compactive efforts for the Marshall Test, are being used to determine the laboratory maximum density. The relative compaction specified for each maximum density procedure are tabulated in Table F-2.

Twenty-one states indicated that they use the Marshall method for determining the test maximum density. Eighteen states required at least 95% relative compaction, and three specified 93%. Only two states indicated that they use the 75-blow compactive effort in lieu of the 50-blow procedure. The relative compaction required by these two were 93 and 97%.

Four states indicated that they use the California kneading compactor to compact laboratory samples to test maximum density. The relative compaction requirements for field densities range from 91 to 95%. The trend toward a lower required relative compaction when the California kneading compactor procedure is used probably is due to the higher densities that are achieved when this method is used in lieu of the Marshall method. One study(7) reported a difference in density by the two methods of up to 0.18 g/cc.

Five states indicated that the field densities are compared to maximum theoretical densities. The range in specified relative compaction for this group was from 90 to 96%.

Seventeen states indicated that control strips are used to establish the target density. Twelve of these require that the pavement be compacted to at least 98% of the density of the control strip. Only three states specified a relative compaction of less than 98% and these were one each at 95, 96 and 97.5%. One state requires that the density of the pavement be no more than one pound per cubic foot less than the control strip, which will result in relative compaction greater than 98%. Another uses the measured density in an acceptance formula instead of using the unmodified relative compaction as the criterion.

A minimum relative compaction for the individual test sites, as well as the minimum average for all tested sites in a lot, is required in ten of the specifications which are based on control strips. Seven allow the individual test site to be 3% below the required minimum for the average. The other 3 set the minimum for the individual test at 2% below the average. Only one of the specifications indicated that the minimum relative compaction was to be applied only to the individual test sites. The remaining six specifications did not state specifically if the required relative compaction applied to the average or to individual test values. It is assumed, however, that it applied to the average.

Compaction of the control strip usually is controlled by compacting procedures or by monitoring progress until additional compactive effort provides no significant increase in density. Some states also require that the density of the control strip must have some minimum relationship to the density of laboratory compacted samples.

Nuclear gages are used widely to determine the densities of the AC pavements. However, many states test cores or pieces sawed from the pavement to determine densities. In several cases, either method is permissible and at least two states require calibration of nuclear gage based on densities determined on cored samples.

Question 4 asked if a study had been made to evaluate pavement performance as related to AC density prior to adoption of a specification for relative compaction. Only one state indicated that a formal study had been made and a final report written.

The last question asked if the same requirement for relative compaction was applied to thin lifts ($\leq$0.10 ft) as to thicker lifts. The response was split, with 18 responding "yes" and 17 responding "no". Seven of those responding negatively stated that the minimum thickness for applying the compaction specification was more than 0.10 ft. Six set the minimum thickness at 1 1/2 inches, one required 2 inches, and three others required 1 inch.

The overall impression created by the response to this questionnaire suggested that many of the specifications described were not true "end-result" specifications. Many were combinations of end-result and method specifications. Some even appear to place the contractor in double jeopardy since he must follow specified procedures and also meet minimum compaction requirements.

Table F-1. Results of National Survey on AC Compaction (1972-73)

State	Relative Compaction Requirements: % of Lab Density 90	91	92	93	94	95	96	97	98	% of Test Strip 93	94	95	96	97	98	Requirements of Control Strip	In-Place Density: Cores	Nuclear	Basis for Density Requirement	Test Max. Density Method 1	2	3	4	5	6	7	Does Specification Apply to Thin Lifts: Yes	No	*Comments
Alabama						x						I			A		x	x	prevent rutting	x	x				x			x	
Alaska				x								I			A	Specified procedure		x	historic data	x					x			x*	1 1/2" minimum thickness
Arizona			x															x*	field evaluation			x					x		Calibrated against cores
Arkansas						*											x		experience	x		x					x		Air void content for surface course
Colorado				*															experience				x					x	Individual test
Connecticut						x											x*	x	experience	x								x	If nuclear densities fail
Deleware	B					x							I		A	No additional density 95% of lab density		x	experience	x							x		
Dist.of Colum					B		x												informal study	x							x		
Florida															x	92-95% of lab density		x	study(no report)	x							x		
Georgia							*							x		94% of Theoretical	x*	x*				x							Small jobs - Nuclear not available - Calibrated against cores
Hawaii						x										No additional density	x	x*	exper/literature				x		x*		x		Selected projects
Idaho										Control Strip-1 pcf						No additional density		x	experience				x				x		
Illinois				x								I				No additional density 95% of lab density	x	x	experience	x							x		
Indiana															x	No additional density		x	experience						x			x	
Kansas					B		x											x*	experiment	x								x*	Calibrated against cores, 1 1/2" min.
Kentucky						I	A											x	experience	x								x	2" min.
Maine	B	S																	experience				x				x		Average density
Maryland				I		A											x		experience	x								x	1 of 4 below 93
Minnesota						x									*	No additional density 96% of lab density	x	x	engr. judgement	x					x*			x	Mean Relative Density - (.60xrange) Nuclear with control strip 1 1/2 min.
Mississippi								x											3-5% voids		x							x	1" min.
Missouri						B			x										experience					x			x		
Montana						x							I		A	No additional density		x	experience	x							x		When unable to comply with 95% of lab density
Nebraska	x																x		experience			x						x*	Over 1"
New Jersey	Air Voids 2-8%																x		experience	x							x		
New Mexico							x					I			A	No additional density	x	x	experience	x							x		
N.Carolina					B	S						I			A	No additional density	x	x	experience	x								x*	1" min.
N.Dakota						I		A										x		x							x		
Oklahoma						x											x		experience							x	x		
Oregon			x									I			A	Approved rollers	x	x	studies				x					x	2 x max agg. size
Pennsylvania	B					S									x	92% theoretical No additional density	x	x		x								x	1 1/2" min.
So.Carolina																													As of 9/79 SC had discontinued use of density specs.
So.Dakota						x													others	x								x	1 1/2" min.
Tennessee	I			A						I			A			No additional density		x			x*							x*	Theoretical max. density used with some mixes. Min. varies
Vermont								x				I			A	No additional density 97% of lab	x	x	≤8% voids	x							x*		95% RC when AC ≤1"
Virginia			x									I			A		x	x	experience			x					x*		<1 1/4" not tested by cores
Wisconsin				B		S											x	x	experience	x							x		
W.Virginia												I						x										x	1 1/2" min.

x reported without comment
* see comments
I individual test
A average of area
B base or binder course
S surface course

1 Marshall 50 blows
2 Marshall 75 blows
3 Rice Theoretical
4 Kneading Compactor
5 AASHTO Designation: T167
6 Control Strip
7 Texas Gyratory

Table F-1. Results of National Survey on AC Compaction (1972-73)

State	Relative Compaction Requirements: % of Lab Density (90–98)	Relative Compaction Requirements: % of Test Strip (93–98)	Requirements of Control Strip	In-Place Density: Cores	In-Place Density: Nuclear	Basis for Density Requirement	Test Max. Density Method (1–7)	Does Specification Apply to Thin Lifts: Yes	Does Specification Apply to Thin Lifts: No	*Comments
Alabama	x (95)	I (95), A (98)	Specified procedure	x	x	prevent rutting	x (1), x (2), x (6)		x	
Alaska	x (93)	I (95), A (98)			x	historic data	x (1), x (6)		x*	1 1/2" minimum thickness
Arizona	x (92)				x*	field evaluation	x (3)	x		Calibrated against cores
Arkansas	* (95)			x		experience	x (1), x (3)	x		Air void content for surface course
Colorado	* (93)					experience	x (4)		x	Individual test
Connecticut	x (95)			x*	x	experience	x (1)		x	If nuclear densities fail
Deleware	B (90), x (95)	I (96), A (98)	No additional density 95% of lab density		x	experience	x (1)	x		
Dist.of Colum	B (94), x (96)					informal study	x (1)	x		
Florida		x (98)	92-95% of lab density		x	study(no report)	x (1)	x		
Georgia	* (96)	x (97)	94% of Theoretical	x*	x*		x (3)			Small jobs - Nuclear not available - Calibrated against cores
Hawaii	x (95)		No additional density	x	x*	exper/literature	x (4), x* (6)	x		Selected projects
Idaho		Control Strip-1 pcf	No additional density		x	experience	x (4)	x		
Illinois	x (93)	I (95)	No additional density 95% of lab density	x	x	experience	x (1)	x		
Indiana		x (98)	No additional density		x	experience	x (6)		x	
Kansas	B (94), x (96)				x*	experiment	x (1)		x*	Calibrated against cores, 1 1/2" min.
Kentucky	I (95), A (96)				x	experience	x (1)		x	2" min.
Maine	B (90), S (91)					experience	x (4)	x		Average density
Maryland	I (93), A (95)			x		experience	x (1)		x	1 of 4 below 93
Minnesota	x (95)	*	No additional density 96% of lab density	x	x	engr. judgement	x (1), x* (6)		x	Mean Relative Density - (.60xrange) Nuclear with control strip 1 1/2 min.
Mississippi	x (97)					3-5% voids	x (2)		x	1" min.
Missouri	B (95), x (98)					experience	x (5)	x		
Montana	x (95)	I (96), A (98)	No additional density		x	experience	x (1)	x		When unable to comply with 95% of lab density
Nebraska	x (90)			x		experience	x (3)		x*	Over 1"
New Jersey	Air Voids 2-8%			x		experience	x (1)	x		
New Mexico	x (96)	I (95), A (98)	No additional density	x	x	experience	x (1)	x		
N.Carolina	B (94), S (95)	I (95), A (98)	No additional density	x	x	experience	x (1)		x*	1" min.
N.Dakota	I (95), A (97)				x		x (1)	x		
Oklahoma	x (95)			x		experience	x (7)	x		
Oregon	x (92)	I (95), A (98)	Approved rollers	x	x	studies	x (4)		x	2 x max agg. size
Pennsylvania	B (90), S (95)	x (98)	92% theoretical No additional density	x	x		x (1)		x	1 1/2" min.
So.Carolina										As of 9/79 SC had discontinued use of density specs.
So.Dakota	x (95)					others	x (1)		x	1 1/2" min.
Tennessee	I (90), A (93)	I (93), A (96)	No additional density		x		x* (2)		x*	Theoretical max. density used with some mixes. Min. varies 95% RC when AC ≤1"
Vermont	x (97)	I (95), A (98)	No additional density 97% of lab	x	x	≤8% voids	x (1)	x*		
Virginia	x (93)	I (95), A (98)		x	x	experience	x (3)	x*		<1 1/4" not tested by cores
Wisconsin	B (93), S (95)			x	x	experience	x (1)	x		
W.Virginia		x (95)			x				x	1 1/2" min.

x reported without comment
* see comments
I individual test
A average of area
B base or binder course
S surface course

1 Marshall 50 blows
2 Marshall 75 blows
3 Rice Theoretical
4 Kneading Compactor
5 AASHTO Designation: T167
6 Control Strip
7 Texas Gyratory

Table F-2

Number of States Using Relative Compaction Requirements Based on Various Tests Methods

Maximum Density Procedure	Requred Relative Compaction %									
	90	91	92	93	94	95	96	97	98	Other
Control Strip						1	1	1	12	2
Marshall	(2)*			2(1)*	(3)*	11	4	2		
Marshall (75)				1				1		
Kneading	(1)*	1	1	1		1				
Theoretical	1		1	1		1	1			
Texas Gyratory										
AASHTO T167						(1)*			1	

( )* Requirement for base or binder course when specification is different from surface course.