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16. ABSTRACT
A summary of typical problems encountered when placing and compacting asphalt concrete pavements by the method specifications currently in use in California is presented.

Preliminary evaluations of alternative methods for determining the in situ density and relative compaction of asphalt concrete pavements are also discussed. These include laboratory specific gravity tests on core samples, reducing the effective measurement depth of conventional nuclear backscatter gages, and a new prototype nuclear backscatter gage designed to measure the density in the top 0.08' of the pavement.

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STATE OF CALIFORNIA
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DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

ASPHALT CONCRETE COMPACTION STUDY
(Interim Report)

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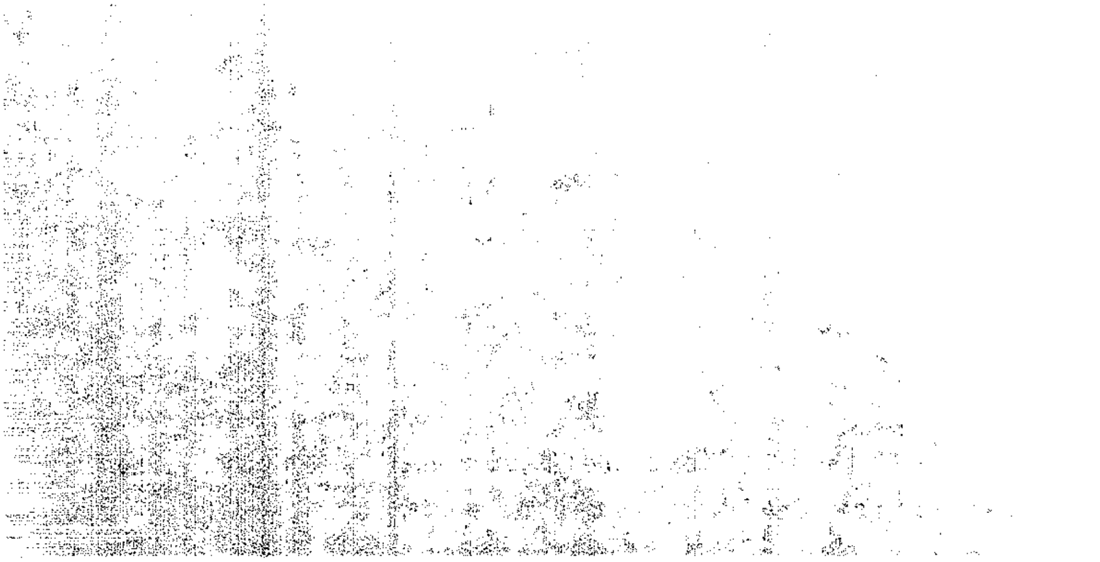

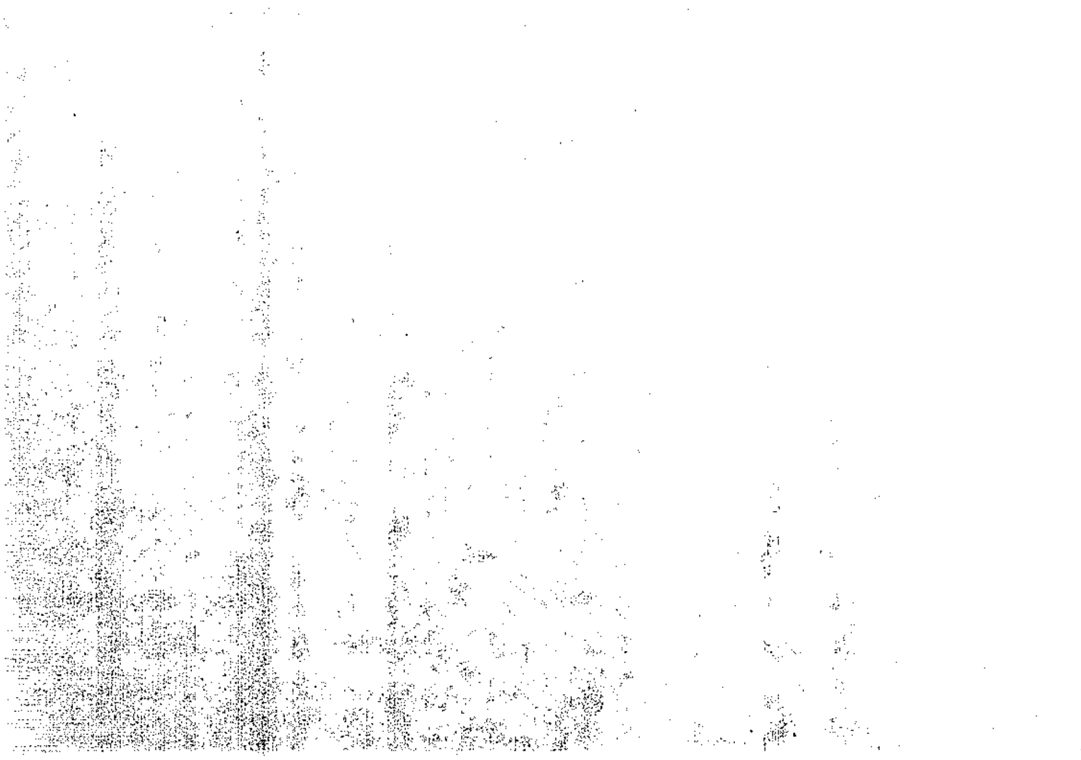

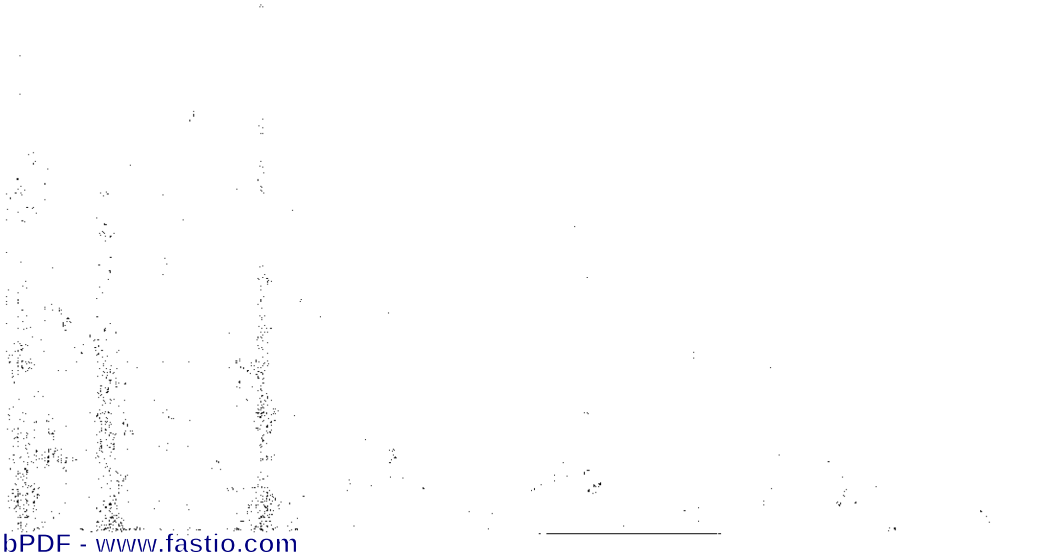

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time			
(Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/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)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal 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 (ft-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)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

ACKNOWLEDGEMENTS

Most of the research discussed in this interim report was conducted by James A. Cechetini who was Co-Investigator 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 was conducted by Frank Champion of the Transportation Laboratory.

Guidance for this study has been 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, and William B. Calland, Caltrans District 11 in San Diego.

The typing and editorial assistance provided by Darla Bailey and Eileen Howe is also acknowledged and appreciated.

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INTRODUCTION

The primary objective of this study is to develop modifications to the current Caltrans asphalt concrete (AC) compaction specifications and construction procedures to avoid a continuation of AC compaction problems now being encountered. Particular emphasis is being placed upon the development of fast, reliable test procedures which can be used to determine the in situ density of any thickness of asphalt concrete pavement including lifts less than 0.15' thick. The successful development of such a test, in conjunction with end-result density requirements, would be beneficial to both the contractor and the contracting agency. Although the contractor would have considerably more responsibility for adequate compaction, he would also have considerably more latitude regarding compaction equipment and procedure selection.

This interim report describes some of the problems encountered as a result of present Caltrans method specifications for AC compaction and presents the findings of preliminary investigations into alternate procedures for determining the in situ density of asphalt concrete pavements. Special emphasis is placed on thin layers of pavement which cannot be tested accurately using conventional nuclear gages and procedures.

CONCLUSIONS

1. The current method specifications for placing and compacting asphalt concrete pavements(1) are applicable to thin layers (<0.15') of asphalt concrete.

2. Laboratory procedures for determining the specific gravity of cored samples(2) provide an accurate method of evaluating the relative compaction of asphalt concrete pavements. While this method would not be practical for field control of most projects, it does provide a good standard for evaluating the accuracy of other methods.

3. The prototype, thin-lift, nuclear backscatter gage developed by Campbell Pacific Nuclear Corporation has an effective depth for density measurement of approximately one inch. If the accuracy of this gage is determined to be adequate, it could provide a means for evaluating the compaction of asphalt concrete placed in layers too thin to be tested accurately with conventional nuclear gages.

4. Methods of decreasing the effective measurement depth for conventional nuclear backscatter gages also show promise. Additional field trials will be required to evaluate these procedures.

BACKGROUND

The California Department of Transportation (Caltrans) relies upon method specifications(1) to assure adequate compaction of asphalt concrete (AC) pavements. These specifications are based on the premise that proper control of conditions and procedures will result in a satisfactory end product.

There are often times when it is extremely difficult to verify complete compliance to all specification requirements affecting compaction. For example, verification of correct roller patterns and AC temperature over all areas of the roadway could exceed the capability of a single street inspector. Verification of conformance to other requirements, such as roller weights, requires the use of weighing equipment which is not normally conveniently available. As a result, complete conformance to the present method specification is seldom achieved.

Current specifications also allow the use of vibratory compactors in place of the steel drum breakdown rollers and pneumatic intermediate rollers, provided the vibratory roller has been prequalified in accordance with California Test 113(2). Acceptance of the vibratory roller is dependent upon its capacity to compact the AC pavement to an average density equal to at least 95% of the density that is achieved in the laboratory using the procedures in California Test 304(2). When a vibratory roller meets the prequalification requirements, it is then acceptable for use on any AC project.

In June of 1977, a telephone survey was made of the Caltrans District Material Engineers to solicit their opinions on the use of vibratory rollers for AC compaction. Although some indicated that they had had very little experience with vibratory rollers, several concerns were expressed.

The most commonly voiced concern pertained to the use of vibratory rollers for compacting thin AC lifts (<0.15'). One of those querried reported that checking developed in the surface of some projects. This condition, however, may be limited to the heavier rollers when operated at high amplitude. Another reported that the vibrations were so severe that the petroelastic crack filler from the existing pavement was forced through the one inch thick blanket. He also expressed the belief that the vibratory roller was responsible for reflective cracking in the blanket.

There were also some inconsistent responses. For example, one engineer's main concern was that the vibratory roller was not providing adequate compaction because the steel drums allowed bridging of rutted and depressed areas. Another engineer, however, felt that the AC was subject to much more lateral movement under the vibratory roller.

Concern was also expressed that the amplitude and frequency settings used during the vibratory roller acceptance test may not be appropriate on all projects with various mix designs. In addition, there was concern that the same settings on different rollers of the same model, or even the same roller after having been moved from job to job, might not produce the same amplitude and frequency.

In February 1978, the Construction Engineer of the California Department of Transportation requested that TransLab undertake an investigation of compaction requirements for thin lift, dense graded asphalt concrete. He expressed concern that the compaction requirements in effect at the time might be inappropriate and perhaps even detrimental to the finished pavement. There was particular concern that the rolling required by the Standard Specifications might be excessive and that certain types of rolling equipment might be injurious not only to the completed surface, but to the underlying structural section.

In a memo dated April 18, 1978, the Deputy District Director of Caltrans' District 11 expressed concern for the finished surface of the pavement. As a result of unsuitable finished surfaces, that district has frequently modified the Standard Specifications in an effort to improve this condition.

With these various potential difficulties in mind, the initial work plan for this study was developed by the Principal and Co-Investigators and a Steering Committee composed of the Chief of the Soil Mechanics and Pavement Branch of the Transportation Laboratory, a representative of Headquarters Office of Highway Construction and a representative of Caltrans District 11. It was agreed that the primary objective of this study was to develop modifications to the current Caltrans' AC compaction specifications to avoid the problems being encountered.

DISCUSSION

Application of Method Compaction Specifications to Thin Layers of Asphalt Concrete

The first phase of this study included a series of tests to determine if method specifications for compacting asphalt concrete would be applicable when the AC is being placed in thin lifts. Several combinations of rollers and number of coverages were tried on four construction projects where AC was being placed in 0.08 foot or 0.10 foot lifts. The effectiveness of the compaction procedures was evaluated using a nuclear gage to determine the relative density within each test section. Although standard nuclear gages are affected by materials to a depth of approximately three inches, the test results on these thinner sections were considered to be satisfactory for comparing the relative effectiveness of the various procedures.

The initial plan also called for determining the permeability of the AC. However, this was not possible since three of the four projects were opened to traffic shortly after finish rolling was completed. The results are summarized in Table 1.

Table 1

Project	Test Section	AC Temp. Breakdown	Compaction Coverages(1) Breakdown	Inter	Finish	Density Max.(2)	In-Place Nuclear	In-Place Core	Rel. Comp. Nuclear	Rel. Comp. Core	Permeability Ml/Min.
A	1	---	3,10-12S	3,Pneu	1,10-12S	146	138.3	144.3	94.7	98.3	124(3)
0.1 ft.	2	---	2,10-12S	2,Pneu	1,10-12S	146	137.8	140.4	94.4	95.9	151
1/2" med. AC	3	---	1,10-12S	3,Pneu	1,10-12S	146	133.3	138.5	91.3	94.8	302
5.3% asph.	4	---	1,10-12S	1,Pneu	1,10-12S	146	133.3	136.3	91.3	93.3	433
AR-4000	5	---	---	3,Pneu	1,10-12S	146	127.3	Broke	87.0	--	255
B	1	285°F	2,11.8S	2,Pneu	1,11.8S	143	137.1(4)		95.9		
0.08 ft.	2	250°F	2,11.8S	--	1,8.2S	143	134.6		94.1		
1/2" Type A	3	210°F	3,11.8S	--	1,8.2S	143	134.6		94.1		
5.8%	4	260°F	1,11.8S	1,Pneu	1,8.2S	143	132.1		92.4		
AR-4000	5	250°F	2,12,DA-50	--	1,8.2S	143	142.0		99.3		
C	1	250°F	2,11,CC42A	--	1,8.55S	146.4	142.4		97.3		
0.1 ft.	2	290°F	2,11,CC42A	--	1,8.55S	146.4	143.8		98.2		
1/2" Type A	3	250°F	1,11,CC42A	--	1,8.55S	146.4	143.5		98.0		
5.6%	4	270°F	1,11,CC42A	--	1,8.55S	146.4	142.0		97.0		
AR-4000	5	240°F	2,13.9,2-84	--	1,8.55S	146.4	145.7		99.5		
	6	250°F	1,13.9,2-84	--	1,8.55S	146.4	143.5		98.0		
	7	260°F	1,8.55S	--	1,11S	146.4	131.8		90.0		
	8	250°F	2,8.55S	--	1,11S	146.4	137.8		94.1		
D	1	310°F	2,10.5S	--	1,8S	140.6	134.1		95.4		
0.08 ft.	2	330°F	3,10.5S	--	1,8S	140.6	136.2		96.9		
1/2" Type B	3	---	1,10.5BW210	--	1,8S	140.6	136.9		97.4		
6.5%	4	---	2,10.5BW210	--	1,8S	140.6	139.2		99.0		
AR-4000											

(1) First number represents coverages, second number indicates weight of roller in tons, S = static steel, Pneu = pneumatic, DA-50 = Ingersoll-Rand vibratory roller, CC-42 = Dynapac vibratory roller, 2-84 = Ray-Go vibratory roller, BW210 = Buffalo-Bomag vibratory roller.
(2) Average density of 5 laboratory compacted test specimens.
(3) Includes one location compacted at 165°F. Permeability = 30 ml/min. when this location is omitted.
(4) Density values shown here calculated from recorded max. den. and relative comp. data. Actual readings not available.

The general trend indicated by these data is that the density increases as the compactive effort increases. There are, however, several exceptions. On Project A, the difference in densities between rolling patterns of 3 static steel (s) - 3 pneumatic tired (pneu) - 1 static steel (s) and 2s-2pnue-1s was insignificant when measured by nuclear gage. Also, the densities were equal when either the 1s-3pneu-1s or the 1s-1pneu-1s rolling patterns were used. In both cases, however, there was some increase in density per the core data. The primary implication of this group of tests is that the pneumatic roller contributed very little to the final inplace density as measured with the nuclear gage.

The data from Project B indicate that use of the pneumatic roller, in conjunction with a somewhat higher compaction temperature, contributed significantly to the final density. The two coverages with the pneumatic roller, after two coverages with the static steel roller, increased the density by 2.5 pcf. A third coverage with the static steel had no effect on the density. The use of a vibratory roller in lieu of a static steel roller also resulted in a significant increase in density (99.3% "relative compaction" vs 94.1%).

On Projects C and D, where both the static steel roller and vibratory rollers were again used, the densities obtained with the vibratory units were consistently greater than the densities achieved using only the static steel drum rollers. Although the second coverage with each of the vibratory compactors caused a significant increase in density, only one coverage by any one of the three units was sufficient to achieve the desired results. The data also indicate that only two breakdown coverages with the static steel roller were necessary to approximate 95% relative compaction on Project D. On Project C, the relative compaction was still less than 95% after two coverages with the static steel roller.

A review of the construction conditions on each project and in each test section revealed several factors, beside the type of compactor, which could have contributed to the variability in relative compaction. For example, the weights of the rollers varied from 8.5 to 12 tons. Also, the temperature of the AC when compaction started was reported to be from 210°F to 330°F. The influence of the underlying pavement on the magnitude of the "in situ" density is another possible source of variability.

Based on the data reported for these four projects, it appears that compliance with the method specifications currently used for asphalt concrete compaction results in adequate compaction (approximately 95%) when the AC is placed in thin lifts. The data also indicate, however, that there may be numerous materials and equipment variables which can affect the compacted density of the AC. Since certain combinations of these variables could result in inadequate compaction while other combinations could result in satisfactory compaction with less applied effort, it would be advantageous to both the contractor and the contracting agency to develop an accurate method of measuring in-place density of these thin layers which would permit application of an end-result compaction specification.

Review of Conformance to Current Specifications

In June of 1979, a questionnaire was distributed to Caltrans construction personnel for the purpose of identifying specific problem areas encountered when enforcing the 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. See Appendix A for a copy of the questionnaire and a complete summary of the responses.

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 Caltrans construction personnel 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 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 250°F. Thus, although the temperature range was quite broad, the number of projects apparently in compliance with the specifications was encouraging in that 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 approximatly 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 response to this questionnaire and the first-hand observations of numerous Caltrans' Headquarters personnel, it is concluded that conformance to the current equipment and procedural specifications for asphalt concrete compaction is marginal on many projects.

Review of Compaction 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 their 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 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. Some of the responses were much less detailed than others and it was at times difficult to interpret the exact meaning of some of the replies. Following is a summary of the response to this questionnaire.

The required relative compaction ranged from 90 to 98 percent of maximum density for the surface course. The most probable reason for this broad variation is the variety of methods used to determine maximum density. Twenty-three states indicated that they use the Marshall method for maximum density determination. All but three of these required at least 95 percent relative compaction with one requiring 98 percent. The three that required less than 95 all specified 93. Five states indicated that they use the California kneading compactor method for determining maximum density. Each uses a different requirement for the relative density. These range from 91 to 95 with one requiring 3-8 percent air voids in the pavement. The reason for the lower relative compaction requirement when this method is used is that its use generally results in a higher density than when the Marshall method is used. (A study by B. A. Vallerga [1951 AAPT] indicates differences in densities by the two methods of up to 12-1/2 pcf, depending on the source of aggregate and asphalt content.)

The remaining specifications were based on several different criteria or the method was not indicated. Those mentioned were the Texas method, AASHTO T-167 and AASHTO T-209. The two states which provided no description of a maximum density procedure indicated the use of a control strip so it is assumed that this was the only criteria for control.

Nineteen states reported the use of control strips as a criteria for field control. The majority indicated that they require the mean density of the area being tested to be at least 98 percent of the mean density of the control strip. Only three specified densities less than 98 percent of the control strip density. These were 97.5, 96 and 95. Three others did not state their compaction requirements.

Compaction of the control strip is usually controlled by compaction 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 have some minimum relationship to the density of laboratory compacted samples.

Nuclear gages are used widely to determine densities of the AC pavement. However, many states test cores or pieces sawed from the pavement to determine densities. In several cases, either method is permissible. At least two states require that a correlation be established between densities determined by nuclear gage and densities determined on cored samples.

Most of the compaction requirements were apparently developed from practical experience — either their own or some other agency's. Only two states indicated that any kind of formal study had been made to evaluate pavement performance with respect to compaction. More than half the states indicated that the same compaction requirements are applied to very thin layers (0.10 foot or less) as are used for thicker layers. The remainder of those responding to this question either eliminated the compaction requirement for thin layers or applied a method specification.

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 a combination of end-result and method specifications. Some even appear to place the contractor in double jeopardy in that he must follow specified procedures and also meet minimum compaction requirements.

Densities of Core Samples

The most reliable method of determining the degree of compaction of asphalt concrete is by direct comparison of the density of samples taken from the street (such as cores) with the density of the same material when compacted by standard laboratory procedures. Standard test procedures are available which provide this capability.

California Test 308(2) provides two methods which can be used to determine the specific gravity of core samples taken from in situ asphalt concrete. Method A is considered to be the most reliable of the two procedures since errors caused by absorption of water are eliminated by coating the test sample with paraffin. Method C is somewhat less time consuming, since paraffin coating is not required, but some error may be introduced due to the porosity of the test sample. California Test 304(2) provides a standard procedure for preparing and compacting asphalt concrete samples in the laboratory.

Because of the bond that develops between layers of asphalt concrete, obtaining a core sample representing only the desired layer can be difficult. There is also the possiblity that determining the density of thin layers may be somewhat less accurate due to the reduced size of the sample and possible distortion caused during separation of the layers.

To provide information on the practicality of using these procedures for evaluating the compaction of thin AC layers, core samples were taken from two projects and their densities determined by the procedures noted above.

The first project consisted of recycling and relaying the existing asphalt concrete and then adding a layer of new AC. The cores from this project remained intact for the entire thickness of the combined AC layers. The density of each core was first determined by Method C of California Test 308. The core was then separated into three portions by sawing along the compaction planes. Each layer was then tested individually by Method A. The results presented in Table 2 show significant differences in the densities of the different layers. The average densities determined by mathematically averaging the densities of the three layers of the same core are also recorded and show a satisfactory comparison with the densities of the full core.

The second project was a 0.1 foot overlay over existing AC. The cores from this project had more of a tendency to separate into layers during the sampling. Only one of the five cores remained completely intact. The others separated on at least one of the two layer interfaces. Method C was used to determine the densities of each portion recovered from the coring procedure. The layers that had remained bonded were then separated by sawing and the density of each layer was determined by Method A. All of the data from this second project are also recorded in Table 2.

Table 2

Densities of Asphalt Concrete Cores
California Test 308, Methods A and C

Project	Core	Total Core By Method C Thick.	Total Core By Method C Density	Core Segments By Method A Thick.	Core Segments By Method A Density	Combination of Core Segments Thick.	Combination of Core Segments Density	Difference Method C minus Method A
1	1	.52	138.5	.29	140.4	.49	137.7	-0.8
				.10	138.5			
				.10	129.2			
1	2	.64	137.9	.30	141.0	.61	137.1	-0.8
				.16	138.5			
				.15	127.9			
1	3	.65	137.3	.36	138.5	.62	136.9	-0.4
				.13	141.0			
				.13	128.5			
1	4	.60	139.8	.26	144.8	.52	140.6	+0.8
				.13	141.0			
				.13	131.7			
1	5	.46	137.3	.18	139.8	.44	135.5	-1.8
				.13	139.8			
				.13	125.4			
2	1	.46	137.6*			.46	136.3	-1.3
		.10	137.3	.10	136.0			-1.3
		.20	135.4	.20	134.2			-1.2
		.16	140.4	.16	139.2			-1.2
2	2	.62	138.5*			-	135.9	-2.6
		.37	138.5	.10	135.4]		135.8	-2.7
				.21	136.0]			
		.25	138.5	.25	136.0			-2.5
2	3	.57	138.4*			.53	137.5	-0.9
		.37	137.3	.10	136.0]		136.9	-0.4
				.23	137.3]			
		.20	140.4	.20	138.5			-1.9
2	4	.56	137.9*			.55	136.9	-1.0
		.36	137.9	.12	139.2]		137.1	-0.8
				.23	136.0]			
		.20	137.9	.20	136.7			-1.2
2	5	.48	137.9	.10	134.2	.46	-	
				.27	137.9			
				.09	Cracked			
Average								-1.2

*Calculated by combining densities of core segments

In every instance but one, the density determined by Method A was slightly less than that determined by Method C. The average difference between the results of the two methods was 1.2 pcf and the largest observed difference was 2.7 pcf.

The next step was to determine if the density of the surface layer could be calculated when only the density of the entire core, and the density of the lower portion of the core, could be established by test. In order to calculate the density of the surface layer, it was necessary to first adjust the known values so that all densities represented determinations by the same test procedure. This was done by applying a correction factor of -1.2 to the densities determined by Method C. The calculated densities of the surface layers are tabulated in Table 3 along with the corrected density of the total core, and the densities of the upper and lower segments of the cores. There is obviously some error introduced by the several determinations and calculations. However, the calculated densities for the surface layers remain reasonably comparable to the densities determined by actual test in several instances.

It is concluded that in situ densities and, therefore, the relative compaction of thin asphalt concrete layers can be determined with fair reliability by adaptation of California Tests 304 and 308. When it is not possible to obtain a representative core of the desired layer by itself, the density of that layer can still be determined with reasonable accuracy if a core of the full depth of AC can be obtained and tested before and after removal of the layer. However, time delays, along with manpower and

Table 3

Corrected Total Core(Z)		Measured Bottom Layer(Y)		Measured Top Layer		Calculated Top Layer(X)	Difference
Thick.	Density*	Thick.	Density	Thick.	Density	Density	(Measured-Calculated)
.52	137.3	.20	133.9	.32	140.4	139.4	+1.0
.64	136.7	.31	133.2	.33	141.0	140.0	+1.0
.65	136.1	.26	134.8	.39	138.5	137.0	+1.5
.60	138.6	.26	136.3	.34	144.8	140.4	+4.4
.46	136.1	.26	132.6	.20	139.8	140.7	-0.9
.46	136.4	.36	136.4	.10	136.0	136.4	-0.4
.56	137.3	.46	136.0	.10	135.4	143.3	-7.9
.53	137.2	.43	137.9	.10	136.0	134.2	+1.8
.55	136.7	.43	136.3	.12	139.2	138.1	+1.1
.48	136.7	-	-	.10	134.2		

*Method C unit weight corrected by -1.2

Density of top layer calculated from measured density of total core and bottom layer using the formula:

$$\text{Density X} = \frac{\text{Density Z} - \left[\text{Density Y}\left(\frac{\text{Thickness Y}}{\text{Total Thickness}}\right)\right]}{\left(\frac{\text{Thickness X}}{\text{Total Thickness}}\right)}$$

equipment requirements, would probably all but eliminate this procedure from practical application. It may, however, provide a good standard for evaluating other potential methods.

Densities Determined by Conventional Nuclear Gage

A primary objective of this study was to evaluate the use of nuclear gages for determining the in situ density of asphalt concrete and to evaluate potential modifications to the procedures or equipment so that nuclear gages can be used to determine the density of thin layers of AC.

In-place densities determined by backscatter nuclear gages generally reflect the condition of the material which is within approximately 0.25 foot of the surface. It is therefore possible to determine the density of asphalt concrete (AC) pavement using a backscatter gage when the AC has been placed in 0.2 to 0.4 foot layers.

Even this relatively shallow depth of measurement is excessive, however, when determining the density of AC blankets which may be as thin as 0.08 foot. When the densities of these thin layers are determined using backscatter gages, the results are significantly influenced by the density of the underlying material. The extent of this influence depends on the thickness of the surface course and the difference in density between the two layers.

The influence of the underlying material on densities determined with backscatter nuclear gages is demonstrated by the data presented in Table 4. These date are from the same two projects discussed in the previous section. The nuclear density determinations were made before and after placement of the surface layer and at the same locations that the cores were taken. In an effort to alleviate some of the shortcomings of the nuclear gage when testing thin layers of AC, several alternative approaches were also considered. These are discussed below.

It has been possible to determine the effective "depth of measurement" of backscatter nuclear gages by taking density readings on progressively increasing thicknesses of one material over another. As the thickness of the upper material increases, the influence of the underlying material decreases until it no longer affects the density reading of the gage. For example, 1/2-inch thick magnesium or aluminum plates have been stacked on standard calibration blocks and density readngs taken at each 1/2-inch increment up to eight inches. The data plotted in Figure 1 are typical of readings taken "through" these magnesium plates. In this example, the 170 pcf standard block has no further effect on the density determination when four or more magnesium plates (2 inches and over) are between the gage and the standard block.

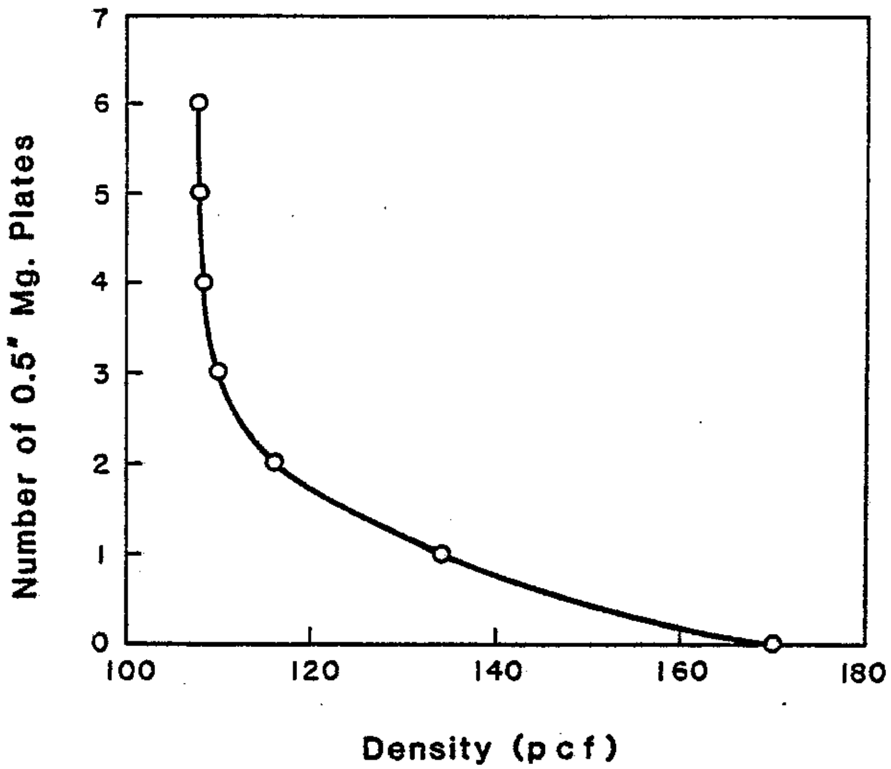
It was anticipated that a conventional backscatter nuclear gage could be used to determine the compacted density of thin AC layers if the depth of measurement could be controlled by proper insert selection. Therefore, in-place density tests using this approach were attempted on the same two projects at the same test locations as the core

Table 4

Comparison of Densities of Cores and
Densities Determined by Nuclear Gage

Project	Location	Core Thick.	Segment Density*	Nuclear Density	Difference
1	1	.29	140.4	140	-0.4
		.10	138.5	132	-6.5
		.10	129.2		
1	2	.30	141.0	142	+1.0
		.16	138.5	134	-4.5
		.15	127.9		
1	3	.36	138.5	143	+5.5
		.13	141.0	140	-1.0
		.13	128.5		
1	4	.26	144.8	141	-3.8
		.13	141.0	140	-1.0
		.13	131.7		
1	5	.18	139.8	140	+0.2
		.13	139.8	136	-3.8
		.13	125.4		
2	1	.10	136.0	139	+3.0
		.20	134.2	135	+0.8
		.16	139.2		
2	2	.10	135.4	139	+3.6
		.21	136.0	137	+1.0
		.25	136.0		
2	3	.10	136.0	138	+2.0
		.23	137.3	135	-2.3
		.20	138.5		
2	4	.12	139.2	138	-1.2
		.23	136.0	132	-4.0
		.20	136.7		
2	5	.10	134.2	142	+7.8
		.27	137.9	136	-1.9
		.09	Cracked		

*TM 308 Method A



EFFECT OF MAGNESIUM PLATES ON INDICATED DENSITY OF 170 PCF CALIBRATION BLOCK

FIGURE 1

tests discussed earlier. On each project, the density of the compacted AC was determined at selected locations using a standard backscattear gage. Inserts of known thickness and density were then placed on the pavement and the density of the insert/pavement "composite" determined (see Figures 2, 3 and 4). Tests were made using either one or two 1/2-inch thick magnesium plates or a 1-inch thick piece of elastomeric bridge bearing pad. The results from these tests are presented in Tables 5, 6 and 7.

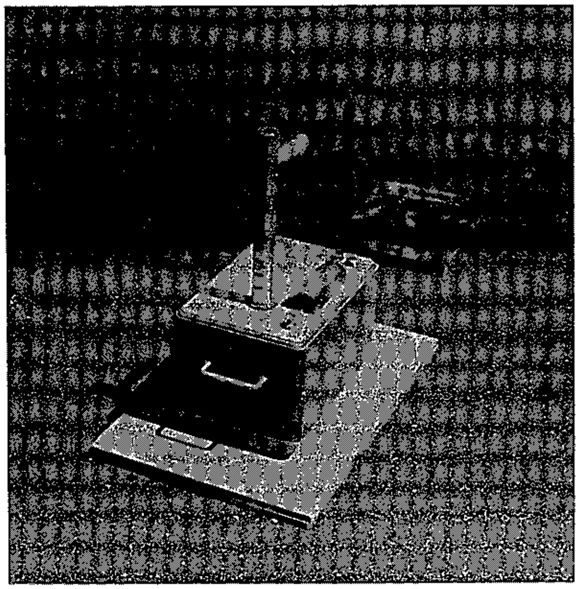
The densities of the inserts were determined by physical measurements whereas the densities of the pavement and the densities of the insert/pavement composite were determined by nuclear gage. The formulas presented below were then used to evaluate the insert approach.

$$D_a = \frac{100}{\frac{P_1}{D_1} + \frac{P_2}{D_2}} \qquad t_2 = \frac{t_1(D_a - D_1)}{(D_2 - D_a)}$$

where: D_a = average density
P_1 = percent influence of surface layer
D_1 = density of surface layer
P_2 = percent influence of underlying layer
D_2 = density of underlying layer
t_2 = portion of underlying layer contributing to average density
t_1 = thickness of surface layer

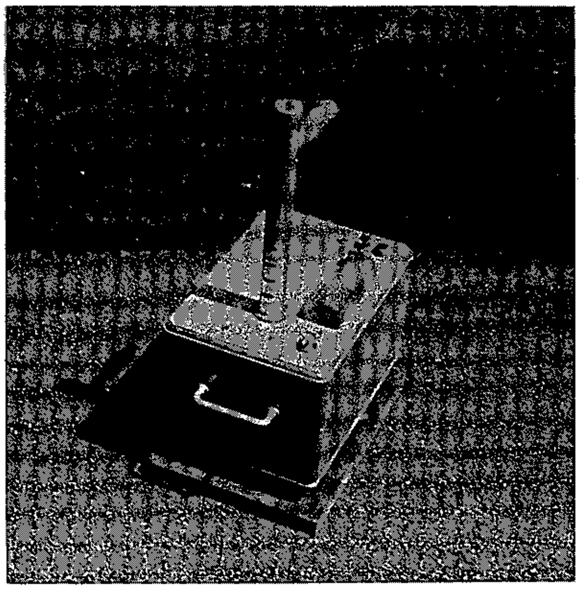
CONVENTIONAL NUCLEAR GAGE USING 0.5" MAGNESIUM INSERT

FIGURE 2



CONVENTIONAL NUCLEAR GAGE USING TWO 0.5" MAGNESIUM INSERTS

FIGURE 3



CONVENTIONAL NUCLEAR GAGE USING 1.0" ELASTOMERIC BRIDGE BEARING PAD INSERT

FIGURE 4

Table 5

Influence of a 1-Inch Thick Elastomeric Pad Insert on Nuclear Density

Project	Location	Insert Thick. (t_1)	Insert Density (D_1)	Pavement Nuclear Density (D_2)	Combined Nuclear Density (D_a)	Depth of Penetration into Pavement (t_2)	Influence from Rubber Insert (P_1)
1	1 Surf.	.08'	195.6 pcf	140 pcf	180 pcf	.031'	78.2%
	1 Level	"	"	132	178	.031	79.5
	2 Surf.	"	"	142	181	.030	78.6
	2 Level	"	"	134	178	.032	78.5
	3 Surf.	"	"	143	179	.037	74.8
	3 Level	"	"	140	180	.031	78.2
	4 Surf.	"	"	141	178	.038	74.5
	4 Level	"	"	140	179	.034	76.6
	5 Surf.	"	"	140	178	.037	75.1
	5 Level	"	"	136	180	.028	80.2
2	1 Surf.	"	"	139	178.4	.035	76.3
	1 Level	"	"	135	179.7	.028	80.3
	2 Surf.	"	"	139	179.1	.033	77.4
	2 Level	"	"	137	177.8	.035	76.6
	3 Surf.	"	"	138	179.7	.031	78.8
	3 Level	"	"	135	178.5	.031	78.7
	4 Surf.	"	"	138	180.3	.029	79.7
	4 Level	"	"	132	177.2	.033	78.4
	5 Surf.	"	"	142	180.3	.032	77.5
	5 Level	"	"	136	177.2	.036	76.3

$\overline{X}$ = 77.7
SD = 1.73

Table 6

Influence of a 1/2-Inch Thick Magnesium Plate Insert on Nuclear Density

Project	Location	Insert Thick. (t_1)	Insert Density (D_1)	Pavement Nuclear Density (D_2)	Combined Nuclear Density (D_a)	Depth of Penetration into Pavement (t_2)	Influence from Magnesium Insert (P_1)
1	1 Surf.	.04'	113.3 pcf	140 pcf	130 pcf	.067'	32.6%
	1 Level	"	"	132	124	.054	39.1
	2 Surf.	"	"	142	133	.088	26.7
	2 Level	"	"	134	123	.043	48.9
	3 Surf.	"	"	143	129	.045	41.4
	3 Level	"	"	140	129	.057	36.2
	4 Surf.	"	"	141	131	.071	31.2
	4 Level	"	"	140	130	.067	32.6
	5 Surf.	"	"	140	122	.029	62.6*
	5 Level	"	"	136	126	.051	39.6
2	1 Surf.	"	"	139	130	.074	30.5
	1 Level	"	"	135	126.5	.062	35.1
	2 Surf.	"	"	139	129	.063	34.2
	2 Level	"	"	137	129	.079	29.6
	3 Surf.	"	"	138	128	.059	35.8
	3 Level	"	"	135	128.5	.094	26.4
	4 Surf.	"	"	138	122	.022	60.2*
	4 Level	"	"	132	125	.067	33.9
	5 Surf.	"	"	142	128	.042	43.2
	5 Level	"	"	136	129	.090	27.1

$\overline{X}$ = 37.3 34.7**
SD = 10.03 6.04**

*Looks questionable
**Questionable data not included

Table 7

Influence of Two 1/2-Inch Thick Magnesium Plate Inserts on Nuclear Density

Project	Location	Insert Thick. (t_1)	Insert Density (D_1)	Pavement Nuclear Density (D_2)	Combined Nuclear Density (D_a)	Depth of Penetration into Pavement (t_2)	Influence from Magnesium Insert (P_1)
1	1 Surf.	.08'	113.7 pcf	140 pcf	120 pcf	.025'	72.1%
	1 Level	"	"	132	119	.033	67.9
	2 Surf.	"	"	142	124	.046	58.3
	2 Level	"	"	134	117	.016	81.4*
	3 Surf.	"	"	143	121	.027	70.6
	3 Level	"	"	140	122	.037	63.8
	4 Surf.	"	"	141	123	.041	60.9
	4 Level	"	"	140	122	.037	63.8
	5 Surf.	"	"	140	122	.037	63.8
	5 Level	"	"	136	120	.032	68.0
2	1 Surf.	"	"	139	123	.047	58.5
	1 Level	"	"	135	120	.034	66.7
	2 Surf.	"	"	139	123	.047	58.5
	2 Level	"	"	137	122	.044	60.0
	3 Surf.	"	"	138	122	.042	61.4
	3 Level	"	"	135	121	.042	61.8
	4 Surf.	"	"	138	130	.163	28.8*
	4 Level	"	"	132	119	.033	67.9
	5 Surf.	"	"	142	132	.146	30.4*
	5 Level	"	"	136	122	.047	58.5

$\overline{X}$ = 61.2   63.7**

SD = 12.2   4.48**

*Looks questionable

**Questionable data not included

The data in Table 5 indicate that approximately 78% of the combined density measured by the nuclear gage was attributed to the elastomeric pad. The data in Tables 6 and 7 indicate that the magnesium plates accounted for approximately 37 and 61% of the combined density, respectively, when one or two of the 1/2-inch plates were used.

The effects of the elastomeric pad were much more consistent than those of the magnesium plates. In this trial series consisting of 20 measurements by each method, the effect of the elastomeric pad varied from 74.5% to 80.3%. The effect of one magnesium plate varied from 26.4 to 62.6% and the effect of two magnesium plates varied from 28.8 to 81.4%. A few of the recorded densities were judged by observation to be questionable. When these results were removed from the analysis, the ranges in test values were reduced to 26.4-48.9 and 58.3-72.1, respectively, while the approximate effect of the elastomeric pad changed only slightly. Several factors may have contributed to these variations. The rigidity of the magnesium plates would result in even a single high point in the AC preventing full, intimate contact with the AC whereas the elastomeric pad could deflect enough to provide more intimate contact. The larger surface area of the magnesium plates would also increase the chance of airgaps between the insert and the pavement due to protruding aggregate as well as undulations in the AC surface. Regardless of the cause of these variations, the fact that they do exist makes the use of the magnesium inserts ineffective.

Densities Determined by Prototype Thin-Lift Nuclear Gage

Another approach was the redesign of the backscatter nuclear gage so that it would measure the density of only the top 0.1 foot of the pavement. This was discussed with Patrick Campbell, President of Campbell Pacific Nuclear Corporation (CPN) who agreed to develop an experimental gage which could be used on thin (<0.15') AC layers. Because AC is normally placed in thicknesses of 0.2 to 0.4 foot, it was agreed that it would be desirable to design the gage so that it would also be effective when testing these thicker layers.

The depth of effective measurement of backscatter gages is influenced to some extent by the degree of "columnation" provided (i.e., the extent to which the nuclear source is withdrawn into the protective shielding). This, in effect, prevents the gamma radiation from leaving the gage at a shallow angle. The new gage was therefore constructed with an "AC" position for thin layers (less than 0.15 foot thick) and a "BS" position for thicknesses of 0.15 foot or greater by providing different degrees of columnation at each position. Because of the necessary changes in the configuration and arrangement of the nuclear source, shielding and detector to accomplish this, the chemical error of the prototype gage was somewhat greater than that found in most modern nuclear gages. The gage did, however, meet the chemical error limitations of the current California specifications for Nuclear Density-Moisture Gages. Preliminary tests also indicated that the new design was more sensitive to air gaps between the gage and the material being tested.

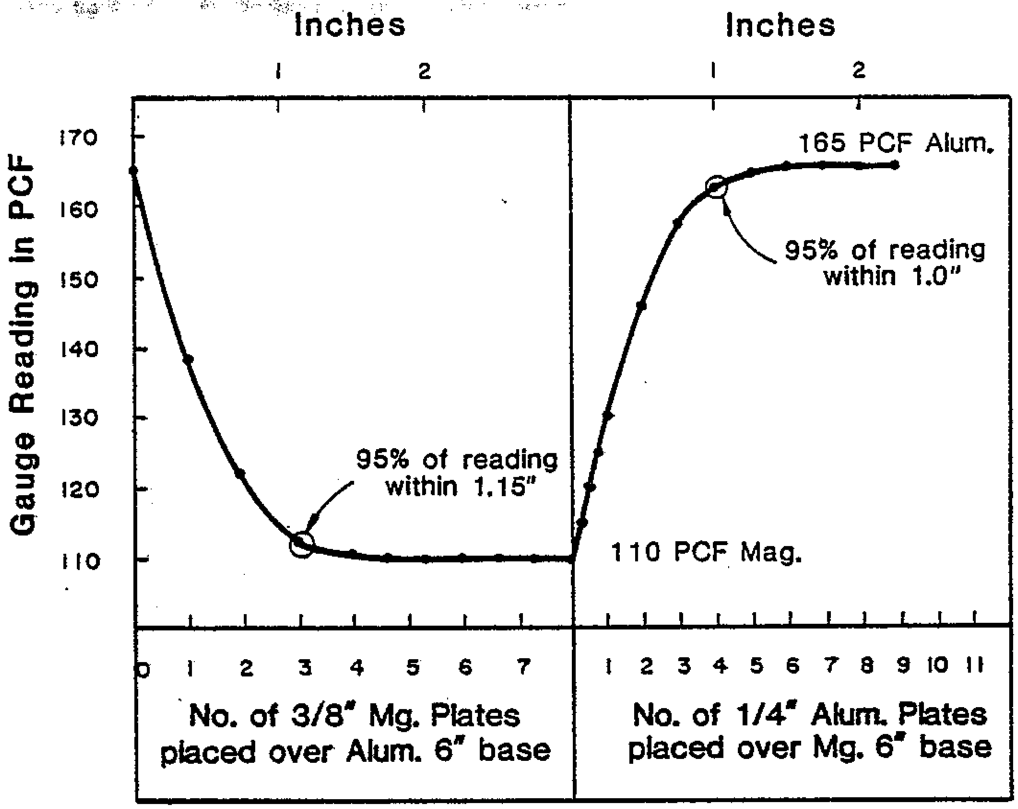
The most important objective of the new gage was to limit the depth of measurement to the top 0.1 foot of material. Both laboratory and field tests were performed to evaluate this capability. Laboratory tests using thin sheets of magnesium and aluminum were performed by CPN to evaluate the depth of measurement. Based on these data, which are reproduced in Figure 5, approximately 95% of the density reading came from the top 0.1 foot of these materials.

The gage was then taken into the field to evaluate its density measuring capabilities on a newly placed 0.1 foot thick AC blanket. Three test sites were selected and density measurements were made in both the AC and BS modes. At each location, four one-minute density counts were taken in each mode without moving the gage.

The gage was then rotated 90° and four more counts taken in each mode. The density measurements on this first field trial were so erratic that the gage was returned to CPN for modification.

After minor modifications, the gage was tried again on a second project. This project required placement of two 0.1 foot layers of AC over distressed portland cement concrete (PCC) pavement. The density tests were made after both AC layers were placed.

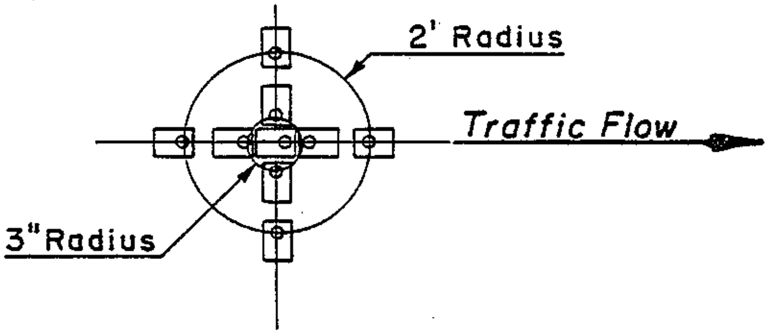
At each of two test sites, nine density readings were taken in each gage mode. The first one-minute reading for each mode was taken with the gage directly over the center of the test site. The second through fifth readings were taken at equal intervals around the center of the test site with the nuclear source positioned three inches from



DEPTH OF MEASUREMENT
THIN-LIFT ASPHALT GAUGE PROTOTYPE
(UNDER DEVELOPMENT - CPN CORP.)

FIGURE 5

the center of the site. The final four readings were also taken at equal intervals around the center of the test site but with the nuclear source positioned two feet from the center of the site. The diagram below shows the pattern of testing.



The results of these two series of tests are presented in Table 8. The average density for each site was the same, or very close, whether the gage was used in the BS mode or the AC mode which suggests that the depth of AC measured when in the new AC position was essentially identical to that measured when in the conventional BS position. Although more variation between individual readings was observed when testing was done in the AC mode, this decreased repeatability may be tolerable if the gage will allow testing of thin sections without being influenced by underlying materials.

Additional tests were made at several locations to determine the effect of pavement surface roughness and to evaluate the use of fine sand as a filler. The first two test sites were the same sites used in the gage evaluation discussed above (Table 8). Two other sites were selected on the basis of surface appearance. At these sites there were streaks of smooth surface immediately adjacent to areas of very rough surface. The surface at the second of these sites was in fact so rough that its acceptability was questioned. The final site tested was on the PCC pavement ahead of the resurfacing operation.

Density readings were taken in both the BS and AC backscatter positions. The first series of readings was taken with the nuclear gage resting directly on the pavement surface. Fine sand was then sprinkled on the pavement surface and scraped back and forth with a straight edge until the surface voids were filled and the excess sand removed. The density readings were then repeated at the same locations. The results of these tests are presented in Table 9.

These data generally show an increase in density when sand filler is applied. Since the density of the loose filler sand was approximately 100 pcf, it could never completely eliminate the effect of surface voids in AC pavement. It does, however, result in densities that are in closer agreement with the core densities than those measured without using the filler. There exists the distinct possibility that the sand filler could also have an adverse effect on the density determination as excessive sand on the surface would decrease the density measured by the nuclear gage.

Table 8

AC Density per CPN Thin-Lift Gage

	Test Site #1		Test Site #2	
	BS	AC	BS	AC
1	142.3	139.5	140.2	139.0
2	141.0	139.7	142.7	141.7
3	142.0	142.5	141.5	143.7
4	139.5	138.6	142.2	140.2
5	140.2	140.5	139.8	139.5
6	139.5	141.5	141.5	143.7
7	140.5	137.7	143.0	142.7
8	138.5	137.7	140.5	141.1
9	140.7	140.5	140.7	140.2
Average	140.5	139.8	141.3	141.3
Standard Deviation	1.22	1.64	1.13	1.75
Range	(138.5-142.3)	(137.7-142.5)	(139.8-143.0)	(139.0-143.7)

Table 9

Effect of Sand Filler on Density Determinations

Test Site	Core Density	Density by Nuclear Gage: BS Mode W/O Sand	BS Mode With Sand	AC Mode W/O Sand	AC Mode With Sand	Surface Condition
1	142.9	142.3	141.1(-1.2)	139.5	143.4(+3.9)	
2	—	140.2	143.0(+2.8)	139.0	141.9(+1.9)	
3a	—	140.2	139.7(-0.5)	139.7	141.0(+1.3)	Smooth AC
3b	—	137.3	141.5(+4.2)	136.7	140.5(+3.8)	Rough AC
4a	—	139.8	142.7(+2.8)	137.7	140.2(+2.5)	Smooth AC
4b	—	126.0	131.5(+5.5)	120.2	129.2(+9.0)	Extremely Rough AC
5	145.0	139.0	144.8(+5.8)	135.7	142.5(+6.8)	Rough PCC

Under most circumstances, nuclear density tests on asphalt concrete would be made immediately after finish rolling. Per previous field experience, the temperature of the AC at this stage of placement is still high enough for the surface to be malleable. This condition usually makes it possible to achieve intimate contact of the bottom of the gage with the AC pavement by applying a vertical pressure and rotating the gage back and forth in short horizontal movements. High points which would cause air gaps between the gage and AC can usually be eliminated in this manner so that the need for adding a filler sand is eliminated. Also, this procedure is faster and probably more effective than the use of filler sand. However, if the surface cannot be smoothed sufficiently, or if surface voids are excesive, the filler sand does provide a method of compensating, at least partially, for the resultant air gap.

The final tests in this field trial were a direct comparison of the densities determined with the new gage and densities determined with a standard density gage in backscatter mode. These test results, which are listed in Table 10, show a good correlation between the densities determined using the two gages.

Table 10

Comparison of Densities Determined by Thin Lift and Standard Gages

Density by Thin-Lift Nuclear Gage				Density by Standard Gage in BS Mode	
BS Mode		AC Mode			
W/O Sand	With Sand	W/O Sand	With Sand	W/O Sand	With Sand
139.8	139.2	139.7	140.2	141.0	141.0
		140.2			141.0

Following completion of this series of tests, the gage was once again returned to CPN, at the manufacturer's request, for additional minor modifications. The most significant change was to replace the solid base plate so that the gage had the capacity of being used as a direct transmission gage as well as a backscatter gage.

When the gage was again returned by the manufacturer, it was tested for conformance to Caltrans specifications for nuclear density-moisture gages. Moisture determining capabilities were not considered because this prototype gage did not include this feature. Calibration tests were made on TransLab's standard blocks. The results are recorded in Table 11.

These data indicate that the modified gage did not meet current Caltrans requirements for standard nuclear gages. The modifications which were necessary to reduce the effective depth of measurement of the gage apparently resulted in a reduction in the accuracy of the gage. The researchers believe, however, that this reduction in accuracy can be tolerated if the gage otherwise proves to be reliable for measuring the density of thin layers.

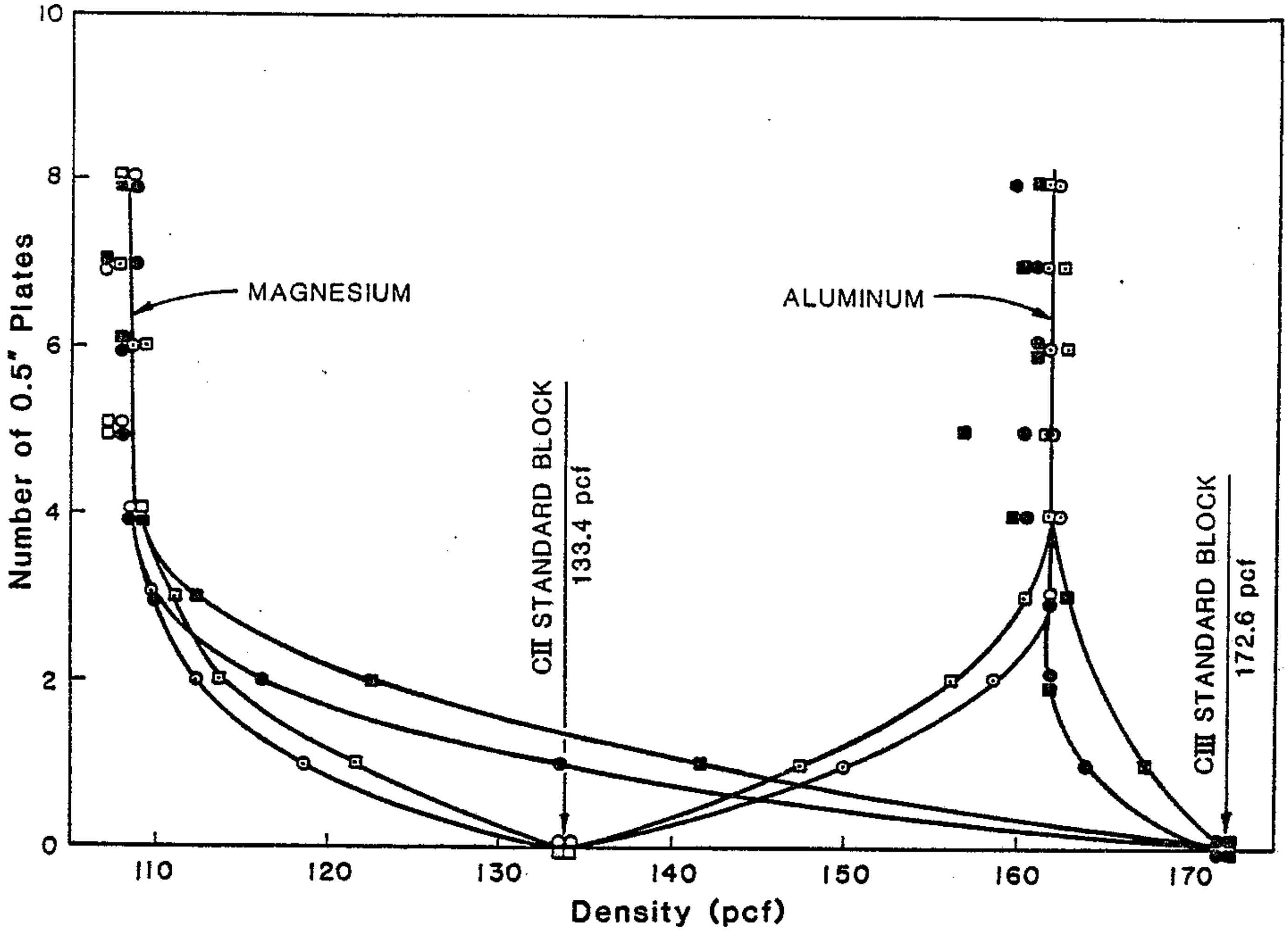
Table 11

Conformance of Thin-Lift Gage to Standard Performance Requirements

Test	Mode	Measured	Specification
Sensitivity Ratio-Density	BS	1.3	1.5 min.
	AC	1.3	
	2-in DT	1.4	
	4-in DT	1.5	
	6-in DT	1.7	
	8-in DT	1.9	2.0 min.
Effect of Chemical Comp.	BS	3.7	2.5 max.
	AC	2.8	
	2-in DT	2.3	
	4-in DT	1.2	
	6-in DT	3.1	
	8-in DT	3.1	2.5 max.
1-Minute Count	BS	25,611	10,000 min.
	8-in DT	22,799	11,000 min.

The effective depth of measurement of the modified gage was retested in the laboratory using varying thicknesses of magnesium and aluminum. The data plotted in Figure 6 show the densities determined at each 1/2-inch increment when magnesium or aluminum plates were stacked on standard calibration blocks of different densities. These data show that the underlying block has very little, if any, influence on the density determined by the AC mode when the thickness of cover was 1-1/2 inches or more. When the gage was in BS mode, the underlying block still had a measureable effect until the thickness of cover reached 2 inches.

It is concluded that the prototype nuclear gage appears to be capable of measuring the in situ density of AC. The AC mode would be used for layers less than 0.15' thick and the BS mode would be used for thicker layers. The accuracy of the gage remains an unknown pending additional efforts to "fine-tune" the equipment.



□ & ■ Gage in Backscater Mode

⊙ & ● Gage in AC Mode

THIN-LIFT AC DENSITY GAGE DEPTH OF MEASUREMENT

FIGURE 6

SCHEDULED FOLLOW-UP STUDIES

Work presently in progress or planned for the near future includes the following tasks. The results of these studies will be included in the project final report.

1. The prototype, thin layer nuclear gage will be used on several additional asphalt concrete overlay projects to further evaluate its accuracy and potential for measuring the in situ density of thin lifts of AC.

2. Additional testing will be done using filters, or inserts, between conventional nuclear gages and the surface of thin asphalt concrete (<0.15') layers. If this method can be developed, it will provide the capability of testing thin lifts without the expense of purchasing new gages or modifying conventional models.

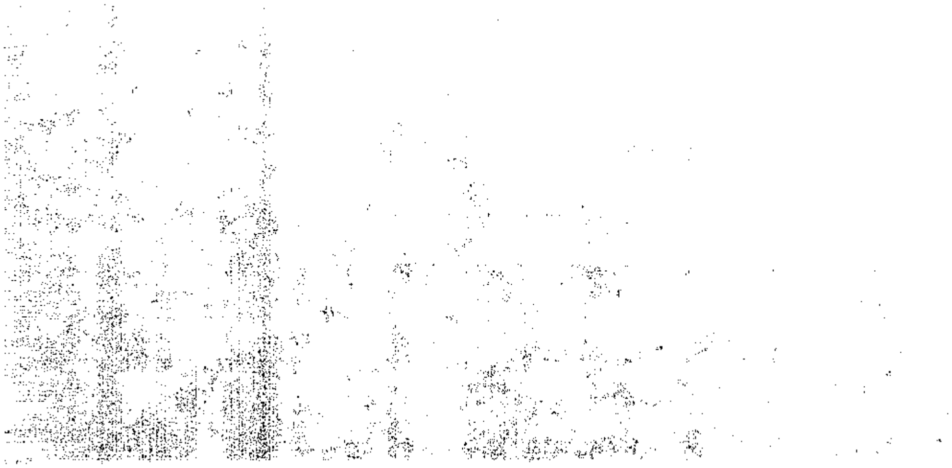
3. The feasibility of determining the density of in-place pavement prior to placing an overlay and then mathematically correcting the density measured by placing the gage on the overlay will be investigated. This approach, if successful, would also make it possible to use conventional gages for determining the densities of thin layers.

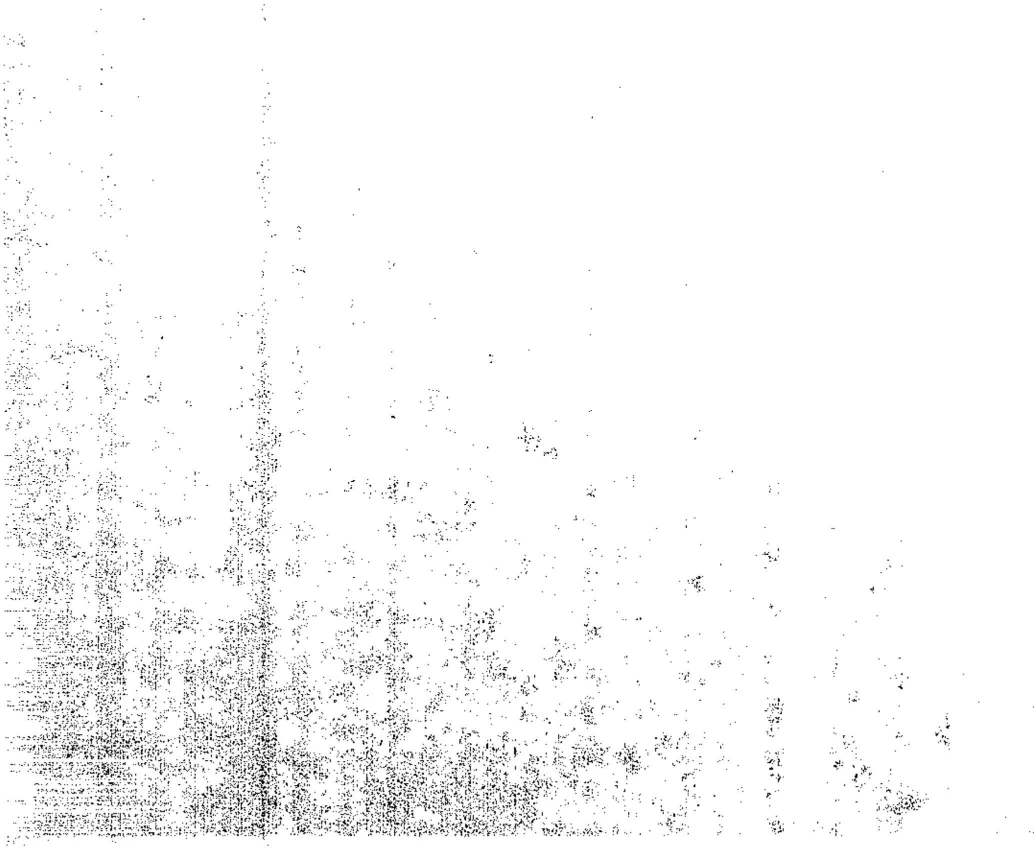
4. Core samples will be taken and used as standards for evaluating the accuracy of density determinations made using nuclear gages.

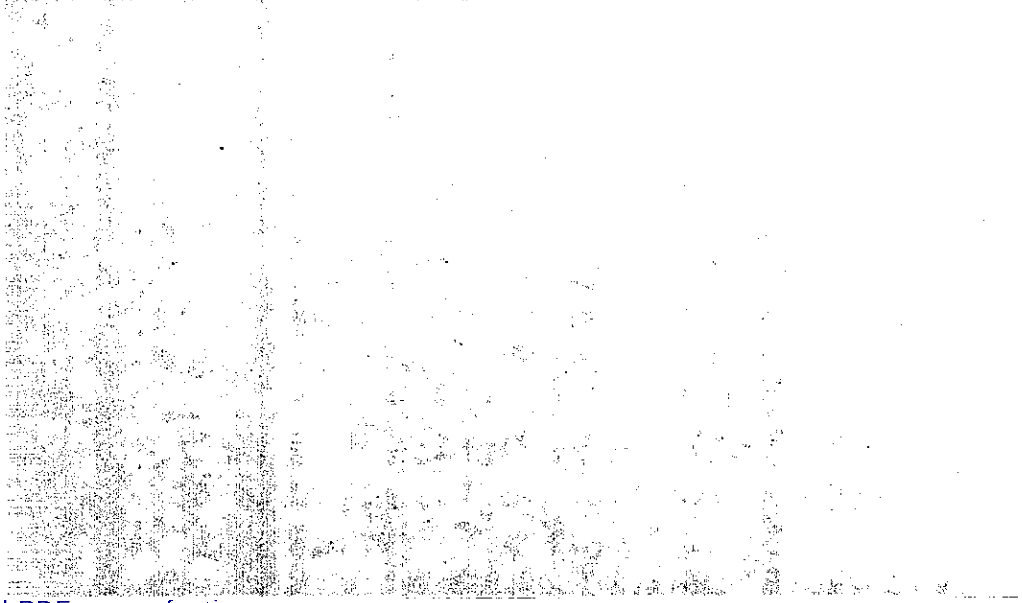
5. The use of recently developed end-result relative compaction specifications for conventional AC pavements will be monitored and evaluated.

6. The effects of, and need for, pneumatic compaction of thin lift AC will be determined with respect to density and permeability.

7. Alternate amplitude and frequency settings will be tried for vibratory rollers used on thin layers of AC if field observations indicate a need.







REFERENCES

1. Standard Specifications, State of California, Department of Transportation.

2. Manual of Tests, State of California, Department of Transportation.

3. Memo, J. A. Cechetini to R. N. Doty, August 1, 1978.

4. Memo, J. A. Cechetini to R. N. Doty, September 28, 1978.

5. Memo, J. A. Cechetini to R. N. Doty, September 25, 1978.

6. Memo, J. A. Cechetini to R. N. Doty, December 12, 1978.

APPENDIX A

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 night 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"