Technical Report Documentation Page

1. REPORT No.
FHWA/CA/TL-88/03

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
Cost/Benefit Evaluation of End-Result Asphalt Concrete Compaction Specifications

5. REPORT DATE
June 1988

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT No.
54324-643384

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT No.
F85TL62

11. CONTRACT OR GRANT No.

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95814

13. TYPE OF REPORT & PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted as a state-financed research project under the title "Cost/Benefit Evaluation of End-Result Asphalt Concrete Compaction Specification."

16. ABSTRACT
This report is a summary of the California Department of Transportation's experience in applying end-result compaction specifications for asphalt concrete on a limited number of paving projects. The comments and observations of construction personnel, which were solicited through questionnaires and personal contacts, indicate that the concept is good. Many are convinced that the end-result compaction requirement should be included in all Caltrans paving projects.

Test data from the projects indicate that 95 percent relative compaction, as determined by California Test 375, is achievable with a reasonable effort on the part of the paving contractor.

Some deficiencies in the test method were revealed and are being corrected.

17. KEYWORDS
Asphalt concrete, asphalt pavement, compaction, compaction tests, density, nuclear density determinations

18. No. OF PAGES:
92

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1981-1988/88-03.pdf

20. FILE NAME
88-03.pdf

This page was created to provide searchable keywords and abstract text for older scanned research reports.
November 2005, Division of Research and Innovation

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

COST/BENEFIT EVALUATION OF END-RESULT ASPHALT CONCRETE COMPACTION SPECIFICATIONS

Study Supervised by ..... Robert N. Doty, P.E.

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88-03

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TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA/CA/TL-88/03		

4. TITLE AND SUBTITLE	5. REPORT DATE
COST/BENEFIT EVALUATION OF END-RESULT ASPHALT CONCRETE COMPACTION SPECIFICATIONS	June 1988
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Max L. Alexander, P.E.	54324-643384
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	11. CONTRACT OR GRANT NO.
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17. KEY WORDS	18. DISTRIBUTION STATEMENT
Asphalt concrete, asphalt pavement, compaction, compaction tests, density, nuclear density determinations.	

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

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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) pounds per square foot (psf)	6895 47.88	pascals (Pa) 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)

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ACKNOWLEDGEMENTS

The author acknowledges and expresses his appreciation to the District Construction and Materials Department personnel who contributed in many ways to this study. In many cases, completing the required testing necessitated adding to the responsibilities and increasing the working hours of those involved. Without this extra effort and commitment, it would not have been possible to make a proper evaluation of the test procedures and specifications. Because of the large number of persons that contributed to this study, it would not be possible to list their names without the risk of inadvertently overlooking someone. However, an extra note of thanks is extended to Mr. Robert Gates who, over a period for 28 months, tested a total of 364 test lots; nearly half of the total for this study. In addition, he offered several constructive ideas which are being considered for incorporation in the test method and specifications.

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B. California Standard Special Provisions 39.03 (Caltrans' End-Result Specification for Compacting AC Pavements)

C. California Standard Special Provision 39.01 (Caltrans' Supplemental Specification to Control the Thickness of AC Layers)

D. California Standard Specifications - Selected Portions from Section 39, Asphalt Concrete (Caltrans' Method Specification for Placing and Compacting AC Pavement)

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INTRODUCTION

In March, 1985 the Transportation Laboratory completed a study (1) to develop test procedures and end-result specifications that would be reliable for evaluating and controlling the compaction of asphalt concrete (AC) pavements. It was concluded from that study that backscatter nuclear gages currently in use provided a practical and effective means of determining the in-place density of compacted AC. It was also concluded that 95% relative compaction, based on the specified test methods, could be achieved when good construction practices are followed.

During the first half of 1985, the new end-result compaction specification was included, on an experimental basis, in the Special Provisions of sixteen Caltrans paving contracts. This study is an evaluation of the effectiveness of that specification and the associated test method used to control the compaction of AC pavement. This report consists of a review of the compaction test data and a summary of the observations and comments of personnel involved in the construction and testing.

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CONCLUSIONS

1. The end-result compaction specification for AC pavement should be adopted by Caltrans. The use of this specification has resulted in more attention being directed toward compaction by both the Contractor and Caltran's inspection personnel. This increased attention results in better compaction.

2. The concept of using an end-result specification as a means of evaluating contract compliance was generally accepted. There was, however, a broad range in enthusiasm toward routinely applying the specification to AC paving. Some construction personnel favored using it on all paving projects, while others did not believe that the quality of the finished pavement was improved enough to justify the time and expense of performing the tests.

3. Successful application of the end-result compaction specification requires that test results be immediately available to the Contractor.

4. Ninety-five percent relative compaction, as determined by California Test 375, is a realistic requirement for the AC pavement. Although the relative compaction was predominately below 95% on several projects, the test data indicates that 95% was achievable and, in fact, was achieved on portions of all projects.

5. Variations in compaction procedures have a significant effect on the relative compaction of the finished pavement. Deficiencies in relative compaction on several projects were traced directly to inadequate compactive effort and/or low mix temperature at compaction.

6. Calibration of the nuclear gage, in accordance with California Test 111 and the special instructions in California Test 375, is essential to accurate measurement of in-place density. It is also essential that the technician performing the tests be alert to unexplained changes in standard counts and count ratios which may indicate that the gage is no longer in calibration.

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RECOMMENDATIONS

The recommendations listed below are based on the findings and conclusions reported in this study.

1. Adopt the end-result compaction specification.

2. Modify California Test 375 and the specifications to allow the use of the most up-to-date maximum density data even though it may not be from the lot being tested in the field.

3. Continue to study methods of detecting and/or evaluating changes in nuclear gages that can affect density determinations. This would include such items as shifts in the standard count and the sensitivity of the gages to high temperatures.

IMPLEMENTATION

At the request of several districts, the instructions for the use of Standard Special Provision 39.03 were revised effective March 30, 1987, to remove it from "experimental" status and allow it to be used as a district option.

TransLab will revise California Test 375 to incorporate changes referred to in the Recommendations along with other appropriate modifications suggested by field personnel who used the procedure during this study.

A study is currently in progress to develop a rapid field procedure for determining the maximum density of asphalt concrete.

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BACKGROUND

During the course of a study completed in 1985 (1), Caltrans developed and adopted, on an experimental basis, an end-result compaction specification (2) and a test procedure (3) for determining the in-place density and relative compaction of asphalt concrete pavement. The purpose of this specification was to allow the Contractor greater freedom in selecting compaction equipment and procedures without sacrificing the quality of the finished pavement. Preliminary testing, both in the laboratory and in the field, indicated that the test procedure provided reliable results and that the specification requirements were reasonably attainable.

Most of the in-place density data presented in the 1985 report was gathered by TransLab personnel from projects which were being controlled by Standard Specification (4) procedural requirements. Although these data indicated that the proposed relative compaction requirements were generally achievable, with no increase in the compactive effort required by the method specifications, very little information was developed regarding the cost-effectiveness of the end-result approach.

The primary objective of this study was to determine if the end-result compaction specification should be incorporated into the Standard Specifications for general use on AC paving projects. To make this determination, it was necessary to first evaluate its effect on the cost of placing AC pavement, the cost of inspection, the quality of the finished pavement, changes in applied compactive effort, contractor/engineer relations, etc.

When the project was initiated, it was intended that the new specification would be included in the Special Provisions of up to forty projects scheduled to go to contract during the first half of 1985. Due to the lack of suitable projects in some districts and a hesitancy of construction personnel in others, the end-result compaction specification was actually included in the Special Provisions for only sixteen projects during the designated time period. The findings and conclusions presented in this report are based on data and observations accumulated during the construction of these projects.

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DISCUSSION

Three approaches were used to evaluate the application of the end-result compaction specification and the test method used to determine in-place density and relative compaction. The first was a solicitation of opinions and comments from the resident engineers and other construction personnel directly involved with the use of this approach. This was accomplished primarily by the use of a questionnaire.

The second was a comparison of prices of AC, as reported in the Bid Summaries, for contracts which did and did not include the end-result AC compaction specification. The third was a review of the contract compliance test data from the projects. Summaries of the findings per each method of evaluation are included in the following pages.

A. Caltrans Construction Personnel Response

The primary source of information was the responses to a questionnaire sent to resident engineers (RE) assigned to the projects on which the end-result AC compaction specification was used. In some cases the street inspectors also provided considerable input. Additional information and insight was also gathered from memos and discussions with personnel in the District Construction offices. The questions asked, and a summary of the responses, are listed and discussed individually below.

1. **"Number of persons simultaneously assigned to your project to perform California Test 375. If more than one, state purpose of additional person(s); i.e., safety, reduce testing period, site location and preparation, etc."**

   On most projects, the in-place density determinations were handled by one person. In a few instances a second person assisted, primarily as a safety precaution, and secondarily, to expedite the testing.

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2. **"Actual time required, per lot, to perform California Test 375. (Do not include laboratory time to determine maximum density.)"**

The reported time varied from 30 minutes to 4 hours. Much of this variation was apparently due to differences in construction procedures and traffic control. When the road was completely closed to traffic, the tester could wait until the test lot was finished and then complete the testing in an hour or less. If it was necessary to keep lane closure to a minimum by opening portions of the road as they were completed, then it was necessary to test individual sites within the lot as they were finished.

In some cases the tester had no other duties and his entire time was charged to testing the in-place density. The ideal situation would be for the tester to have other responsibilities so that only an hour or so would be expended on the required testing after the completion of each lot. Even when using "moving" lane closures, it may be possible to drop back as necessary to test one site at a time without hampering the Contractor's ability to maintain appropriate traffic control.

Part 2 of this question asked for the "estimated time, per lot, for individual tasks:

a. Gage standardization
b. Site selection
c. In-place densities
d. Relative compaction calculations and report"

Gage standardization (determining standard count) varied from 12 minutes to 1 hour. Since the test method requires 12 one-minute counts, or 3 four-minute counts, to determine the daily standard count, it is obvious that more than 12 minutes is required just to take the readings. Thirty minutes, a more typical reply, allows

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time to remove the gage from storage, warm up the gage, and calculate the average standard count.

The time required for site selection was typically 30 to 45 minutes. At least one tester found it possible to make the necessary calculations for selecting test sites while standardizing the gage.

Determining in-place densities reportedly required from 2 minutes per test site to 1 hour for a lot consisting of up to 10 test sites. Up to 1 hour is probably not unreasonable considering the time required to move from site to site, locate the exact location for the test, and make the necessary site preparations.

Times ranging from 5 minutes to 1 hour were reported for calculating densities and relative compaction. Fifteen to 30 minutes were, however, the most common responses. Some testers found that the calculations for one site could be made while waiting for the gage count at the next site.

With the exception of projects where traffic control requires that each site be tested as it is finished, it appears that 90 minutes is adequate for an experienced operator to complete all phases of the required testing for a lot consisting of up to a half-day of paving.

3. **"Time lapse between the initial street sampling of the AC and notification by the laboratory of the maximum density value."**

The time required to determine the maximum density was a major problem on some projects, and at least a minor drawback on all projects. The shortest time lapse reported was 6 hours. This project was within a few minutes' driving time of the district laboratory so there was very little time required to transport the

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street samples to the laboratory. Time lapses of 1 and 2 days were the most common, but there were also reports of delays from 7 to 19 days.

Since the test method requires that the maximum density of the AC be determined from representative samples compacted with a kneading compactor, it is necessary to determine maximum density in the district laboratory. When the street sample cannot be delivered to the laboratory before the sample cools, it is necessary to reheat the material before compaction. Depending upon the actual time of arrival in the laboratory, it could easily be 2 days from the time of sampling until the results are reported. Longer delays would depend on the laboratory workload, availability of personnel, and established priorities.

For the end-result compaction specification to be applicable for acceptance testing, it is absolutely essential that relative compaction test results be available to the Contractor almost immediately following completion of the in-place density determinations. When the AC is being produced from a source that is in continuous use, it should be acceptable to apply maximum densities determined from previous production until the results can be verified. When the AC is to be produced from a new or occasional source, sufficient testing should be done during the mix design testing to establish a tentative maximum density. When AC production actually begins for the project, this AC should be sampled immediately and tested as quickly as possible to verify the tentative maximum density.

It should not be necessary to determine a maximum density for each lot as AC produced from any single source will normally remain relatively consistent. When it has been established that the maximum density is relatively constant, a periodic check test should be sufficient. At the same time, it would be prudent to hold in abeyance a sample from each lot as a safeguard against disputes or claims.

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On one large project, it was found that a moving average of the maximum density results provided an excellent standard. Averaging eliminated the small day-to-day differences in test maximum density caused by normal test variability, and provided a standard for immediate evaluation of the compaction.

It has been the opinion of TransLab engineers that each test lot should be immediately accepted or rejected on the basis of available test data. When there are delays in receiving the test maximum density results from the laboratory, the relative compaction should be determined based on design samples and/or tests on materials from previous lots. If subsequent maximum density data indicates that a substandard lot was actually acceptable, it should be accepted on the basis of the upgraded information. Once a lot is accepted, however, the Contractor should be relieved from any liability indicated by the new test maximum density results.

TransLab is currently attempting to develop a test procedure, that can be used on the job site, to provide test maximum density data within an hour.

4. **"Rollers Used for Compaction**

   a. **Manufacturer & Model**
   b. **Settings (Vibratory)**
   c. **Number of Coverages"**

The rollers used for compacting the AC on these projects were the same rollers that are allowed under the method specifications. In several cases the application of these rollers did differ from the procedures specified in the standard specifications.

5. **"What, if any, adjustments did the contractor make in his procedures because of the relative compaction values determined by Test 375? (Equipment, coverages, batching temperature, time between placement and compaction, etc.)"**

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Some Contractors found it necessary to increase the compactive effort by increasing the number of coverages and/or the number of rollers to achieve the required relative compaction. One RE reported that the roller operator had no established pattern for rolling when the job started. Failing tests forced the Contractor to establish an acceptable pattern which resulted in relative compaction results in the range of 95 to 97 percent.

Several REs reported, that as a result of this specification the Contractor became more conscious of the need to compact AC while it is hot. This was accomplished by an increased effort to keep the rollers working closer to the paver. One Contractor found it necessary to increase the temperature in his mixer. On that project there was some question regarding whether the original temperature was actually high enough to meet the requirements of the existing method specifications.

There were other cases where the Contractor was able to reduce the compactive effort and/or the mix temperature and still achieve the desired degree of compaction.

The responses to this question indicate that one of the primary purposes of the end-result compaction specification is being fulfilled; that is, to allow the Contractor to make appropriate adjustments to the compaction effort, provided the required density is achieved.

6. **"In what ways did the use of the end-result specification impact the overall project?**

   a. **Caltrans' operation**
   b. **Contractor's operations"**

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There was a broad range in the response to this question. While a few pointed out that the time required to watch the rolling operation and monitor the mix temperature was reduced significantly, the majority complained that the testing required at least one additional full-time inspector and/or overtime. A part of the increase in inspection needs apparently stemmed from a reluctance to assign responsibility for achieving compaction to the Contractor. The comments of one RE were interpreted as resentment because the Contractor was able to achieve the required density with only 2 or 3 coverages with a single vibratory roller and no intermediate pneumatic roller. In actuality, the rollers and procedures used by the Contractor complied with the current method specifications.

Two REs indicated that application of this end-result specification required increased traffic control because of delays in opening the road to traffic. As mentioned earlier, on some projects it may be necessary for the tester to be available at all times so that individual sites can be tested immediately after the finish rolling is completed.

One RE reported, "From start to finish of operation using final product requires more time, i.e., waiting for correct temperature to do finish rolling, which requires more traffic control, which reflects up the entire operational chain." This response was difficult to interpret. Since the purpose of finish rolling is to iron out roller marks and improve the surface finish, it is often necessary to delay this operation until the pavement has cooled sufficiently to allow the final rolling without causing new marks. If roller marks persist, the AC is probably too hot to open to traffic regardless of which specification is used for acceptance.

Another RE reported that the test results had apparently been affected when testing was attempted on hot pavement. This has not been a normal problem since all of the gages purchased by Caltrans

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are tested for heat sensitivity prior to acceptance. The possibility of an increase in gage heat sensitivity after a period of time should be investigated.

7. **"Do you believe that the end-result compaction requirement provided adequate control over the AC paving?"**

The majority of the responses to this question were positive. Some, in fact, were very emphatic that this method of acceptance should be applied on all projects. There were a few that expressed objections, or at least reservation, regarding the specification and test method as they are now written. One concern was that the specification addresses only compaction and no provision is made to assure proper paving. As a result, the Contractor was more concerned about compaction than about ride quality. To address this concern, it has been suggested that a Profile Index or Ride Score be included as a part of the end-result pavement specification. Also, because of the shortage of construction personnel, it was not possible to properly inspect other aspects of the paving operation.

A few also believed that, even though the Contractor was achieving specified densities, the product was suffering because of the lack of control over mix temperature and roller operation.

The question of gage reliability was raised on a couple of projects. Of primary concern was the fact that the density determinations appeared to be erratic and did not agree with values determined with a second gage. On one project, inconsistent results were traced to excessive wear in the source rod positioning mechanism. When the handle was moved into position, the latch would not hold, thus allowing the rod containing the nuclear source to slide closer to the pavement surface. The effect was an increase in the nuclear count and a corresponding apparent decrease in density. Similar problems could be encountered on other projects if the gages are not properly maintained and used.

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Many Caltrans employees shared a concern over the wording of the specification wherein 95% relative compaction was required but no penalty would be imposed until the relative compaction fell below 93%. Two primary reasons for concern were expressed. One was that there was no incentive for the Contractor to change his procedures as long as the relative compaction was at least 93%. The second was that the Contractor might back-off on his compactive effort to achieve no more density than necessary to avoid penalties. Each of these concerns is justified and requires clarification.

Specifying 95% relative compaction, but applying a penalty only when the relative compaction is below 93%, was selected as a means of allow for test repeatability. Previous TransLab studies(1)(5) have shown that the backscatter nuclear gage is accurate within ±0.04 g/cc 95% of the time. Assuming that most AC mixtures in California have an in-place density greater than 2.10 g/cc, the relative compaction determinations should be accurate within 1.9%. With this in mind, the intent of the specification was to require a reasonable effort to achieve 95% relative compaction but, at the same time to avoid penalizing a Contractor due to test repeatability. To actually reduce the specified relative compaction to 93% would not only lower densities, but would open the door to Contractor claims based on gage accuracy if penalties were assessed for all test results below 93%.

It is doubtful that a Contractor could intentionally aim for 93% relative compaction without subjecting himself to almost certain penalties. Test data which will be presented later in this report shows that the range in relative compaction of individual test lots is at least 1% above and below the average for the project. On most projects this range was even greater.

Some also questioned whether the penalty is sufficient to encourage the Contractor to make an honest effort to improve his procedures. At a price of $30.00 per ton the penalty on a 2,000 ton lot that was

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compacted to 92.9% would be only $120 (2000 tons x $30 x .998 = $59,880). Although this small penalty will not guarantee an effort to improve, it should alert the Contractor that unless some improvement is made, subsequent testing could result in a much larger penalty. For example, at 92.5% relative compaction, the penalty would be $720 (2000 x $30 x .988 = $59,280). At 1.0% below, it would be $1800 (2000 x $30 x .970 = $58,200). The key to the success of the specification is the RE's willingness to impose the specified penalties.

8. **"Please describe any problems you encountered in enforcing the end-result specification."**

The availability of qualified testing personnel was the most common problem. While this is a major issue, and a primary factor in the success of an end-result compaction requirement for AC pavements, resolution is beyond the scope of this study.

Lag time in establishing maximum density turned out to be a concern on some projects. As discussed in Item 3 of this section, it is of utmost importance to make an immediate decision on the acceptability of the pavement.

9. **"Please add any other comments you wish to make regarding the specification, test method, quality of pavement, reaction of Contractor, etc."**

Some very good comments, suggestions and questions were submitted in response to this last question. There were also some statements which indicated that there may be misconceptions regarding the application of both the end-result compaction specification and the current method specification.

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The majority of those responding indicated that they believed that the end-result compaction specification is the better method for assuring that AC pavements are properly compacted. Several would like to see this specification included in all AC paving projects. Some questioned if the increased quality justified the increased cost. Caltrans has not correlated the degree of compaction with pavement service life, but other agencies, such as the Oregon DOT, have determined from their studies (6) that pavement life is directly related to compaction. If, as the studies by Oregon DOT indicate, the service life is decreased by 10% with each 1% increase in air voids, then the savings in maintenance and repair costs are significantly greater than the increase in initial construction and inspection costs.

Most of the comments received concerning gage reliability, delays in receiving laboratory density data, and additional personnel requirements, have been discussed in other sections. Suggestions for improving the test method and/or specifications will be incorporated as deemed appropriate.

A few references were made to difficulties in achieving compaction in miscellaneous areas. The following situations point out the importance of exercising engineering judgement even when applying the end-result compaction specification. On one project, the RE correctly concluded that the specified relative compaction was not appropriate in narrow gutter areas with steep cross slopes. On another project, the Contractor was using a standard width roller to compact a 2-foot strip of AC base being added to widen the traffic lane. Because of the extremely poor relative compaction results, the RE insisted that other methods be used. As a result, the Contractor was able to develop a procedure to achieve the specified relative compaction.

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A few of the responses to this questionnaire were disturbing in that they indicated a lack of understanding or a misinterpretation of both the existing standard specifications and the new end-result specification. One RE complained that he had no control over the number or type of rollers and, as a result, the Contractor eliminated the pneumatic roller and used only one vibratory roller for breakdown. This is not a justified criticism of the end-result specification, especially since this reduction in rollers has been permitted under the method specifications in the Standard Specifications since 1975.

Another RE expressed concern over applying penalties when the nuclear gage used for determining density may not be accurate within 2%. He also indicated that deductions had been made for two lots which had relative compactions of 92.6% and 91.3%. If these two lots had been placed and compacted under the same conditions that existed for the approved lots, there might be some reason for concern. However, his closing statement was "the only significant difference between these two tests and other tests was that the AC material laid in the window for quite a long time before it was spread. Temperatures at times of spreading was (sic) 180° average." Two conclusions can be drawn from this:

1) The test method does expose areas deficient in compaction and,
2) The Contractor should have been elated that he was allowed to use material that would not have complied with the method specifications.

One inspector complained that the Contractor did not accept the responsibility for establishing rolling patterns that would enable him to attain the required compaction. In this case, the Contractor maintained that State forces should help them establish that procedure. The paving inspector was correct in that the purpose of the end-result specification is to turn over to the Contractor the

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responsibility for achieving the specified relative compaction in exchange for allowing him to make what he considers to be appropriate adjustments in the compactive effort and/or mix temperature. Since this approach to compaction control is new to AC pavements in California, many of the Contractors do not have the equipment nor the experience to make those decisions on their own. There is an advantage in cooperating with the Contractor by evaluating the effects of different rolling patterns. Once it has been established that the specified relative compaction can be achieved, he no longer has an excuse for failure.

B. Contractor Response

A brief questionnaire was also submitted to the Contractor for each project included in this study. Only three were returned and two of these were from the same company. The questions and responses are restated below.

1. **"Did you encounter any difficulty in achieving the specified relative compaction? ____None ____Slight ____Severe"**

   Two responses indicated no difficulties. The third indicated slight difficulty due to the lack of experience of the lab technicians and lack of cooperation. This same Contractor responded to question Number 7 below by stating that the lab technician "must be available to the Contractor full-time to establish and control rolling patterns and temperatures." Although this was not the intent of the specification, there may be some advantage in Caltrans cooperating with the Contractor on a limited basis during the initial transition from procedural to end-result specifications. This was discussed briefly in the responses to Question 9 of the Construction Personnel questionnaire.

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2. **"Were you able to improve the relative compaction by changing equipment or procedures? ____Yes ____No"**

   Two responded positively and the third said that it was not necessary.

3. **"Were you able to use equipment, or follow procedures, which would not have been permitted by the procedural requirements in the Standard Specifications? ____Yes ____No"**

   None of the responding Contractors indicated that they had made any changes in equipment or procedures.

4. **"What changes in equipment or procedures were made during the contract that affected the relative compaction of the AC."**

   On two projects, an extra roller was added for "insurance."

5. **"Would you hesitate to bid on another job which included end-result compaction requirements for AC pavement? ____Yes ____No"**

   All three replied "No."

6. **"What general affect, if any, do you feel the use of an end-result specification will have on bid prices for AC?"**

   One responded with "no change." The other two implied that the time waiting for test results and the need of an extra roller could have an effect.

7. **"Please add any comments you would like to express regarding the adoption of this specification on future projects."**

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As discussed in Item 1 above, one Contractor believed that Caltrans should provide a technician to help establish a rolling pattern and appropriate temperature. The other two stated that more timely testing and issuing of test results was needed.

In addition to the responses stated above, a few comments by Contractors were reported by Caltrans personnel. In the opinion of the author of this report, the Contractor's acceptance of this method of determining contract compliance may well be directly related to his attitude prior to starting the project.

C. Effect on Bid Prices

An effort was made to compare the bid prices for asphalt concrete placed on contracts which incorporated the end-result compaction specifications with the bid prices on contracts where compaction compliance was evaluated by the method specifications. This task turned out to be more difficult, and probably less accurate, than originally anticipated.

The greatest problem was the number of factors that can affect the cost. Availability and cost of producing acceptable aggregate, haul distance, traffic control, quantity of material, and the number of interested contractors (bidders) are but a few of the obvious variables.

The annual Contract Item Cost Data Summaries were of very little value because they contain average bid prices of all projects regardless of size or circumstances. As a result, the average bid prices were unreasonably high in most cases.

During the period of time that these projects with end-result compaction requirements were being processed and let to contract, the bid sheets were accumulated from other projects. No special effort was made to obtain the bid sheets from all projects but as bid sheets were received by TransLab, they were reviewed and those that included more than two thousand tons of asphalt concrete pavement were set aside for inclusion in this comparison.

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During the 1984-85 and 1985-86 fiscal years, bid sheets were collected from 178 contracts representing 3.7 million tons of AC. The price of AC on these projects varied from $19 to $50/ton. The highest and lowest prices paid on these projects are tabulated in Table 1 along with the average costs in each district. It should be pointed out that the costs included in this summary were the prices submitted by the low bidder for the contract but often they were not the lowest price submitted for that particular item. In an effort to minimize the effect that quantity has on bid prices, the average costs were calculated on a weighted average basis. The weighted average cost for all 178 projects was $28.16/ton.

The cost of AC is also listed separately for each of the 18 projects that incorporated the end-result compaction specifications. In two districts (01 and 09), the highest of the recorded prices were on the end-result projects. It must also be pointed out, however, that the lowest prices in Districts 01, 05, 08, 10, and 11 were on projects with end-result compaction specifications.

As shown in Table 1, the total weighted average price per ton of AC was less when the end-result specifications were used than when the standard specification requirements were applied. This was probably due in part to the fact that three of the end-result projects were very large, with over 100,000 tons in each, which resulted in relatively low unit prices. Also, the project in District 08 included special cost incentives because of the use of recycled AC materials. The increased problems associated with maintaining traffic through a downtown construction area was probably the primary reason for the extremely high costs on one of the District 01 projects.

In only a few instances was it possible to compare prices on projects that were equal in all respects other than the compaction specifications. Two adjacent overlay projects in District 05 were done by the same Contractor less than a year apart. The first, which included 22,900 tons, was compacted using the end-result specification and was bid at $26.78/ton. The second, which was bid ten months later and included 37,000 tons compacted

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TABLE 1

SUMMARY OF ASPHALT CONCRETE BID PRICES
(Compiled from partial list of projects let to bid during fiscal years 1984/85 and 1985/86)

District	No. of Projects	Price/Ton on Awarded Contract			
		Low	High	Weighted Average	End-Result Projects
01	8	30.90	50.00	36.45	50.00 30.90
02	12	19.00	46.00	27.50	26.75
03	13	23.05	38.00	28.77	
04	40	24.00	42.00	29.35	40.10 30.81
05	8	26.78	39.00	30.64	26.78
06	11	22.00	35.00	25.82	24.00 27.70 29.00
07	30	26.10	41.00	29.85	27.20
08	7	19.92	30.00	22.63	19.92
09	9	22.00	40.00	27.08	40.00 27.36
10	20	21.00	45.00	27.25	21.00 24.15
11	20	22.00	39.00	26.21	36.00 31.00 22.00
Total	178				
Weighted Average				28.16	26.01

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under the method specifications, was bid at $27.97. Two other nearly adjacent and similar projects were also constructed by the same Contractor in District 06. The AC on the project that included end-result specifications was bid at $27.70/ton and the project constructed by the method specifications was bid at $24.00/ton.

Because of the multiple factors that affect the cost of placing AC pavements, it was not possible to draw any specific conclusions regarding the effect of the end-result compaction specification on construction bid prices. It does not appear that there was any significant difference in the prices of the contracts included in this study.

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D. Summary of Test Data

Data from the sixteen selected projects are summarized in Table 2. This summary includes the number of lots tested on each project, the average relative compaction and the standard deviation for each project, and the percentage of the test lots that met or exceeded each increment of relative compaction.

With the exception of Projects 2 and 4, the relative compaction values are plotted in Figures 1 through 14. Data from Projects 2 and 4 were not plotted because of the limited number of tests performed during construction.

It is obvious from the test data that there are significant differences in the relative compaction values determined on the different projects. The greatest difference occurs between Projects 2, 8, 10 and 16. Where 2 and 8 reported all of the pavement as being compacted to less than 95% relative compaction, 93% and 94% of the pavement placed on Projects 10 and 16 was compacted to 95% relative compaction or greater. An attempt will be made in the following pages to present the authors explanation of some of these differences.

It should also be pointed out at this time that the majority of the pavement on each job was compacted sufficiently to be out of the penalty range. To achieve this on Project 13, it was necessary to retest some areas after the Contractor had applied additional compactive effort. This leads to the conclusion that 93% relative compaction was not an unreasonable requirement for any of the projects.

The summary data also indicate that contractors whose pavements showed the greatest variability in relative compaction were most likely to produce pavements with relative compaction in the penalty range (below 93% relative compaction). This point is demonstrated in Table 3 by arranging the data in order of relative compaction variability as indicated by the standard deviation of the project compaction tests.

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TABLE 2

SUMMARY OF RELATIVE COMPACTION TEST RESULTS

Project	No. Lots	Avg RC	Std Dev	% Equal to or Greater										
				100	99	98	97	96	95	94	93	92	91	90
1	24	94.7	0.85				0	4	45	79	100			
2	4	94.4	0.47						0	75	100			
3	14	94.3	0.50					0	7	86	100			
4	6	96.1	1.03				33	50	83	100				
5	14	95.5	1.39			0	14	43	71	79	100			
6	14	95.5	0.82				0	14	86	93	100			
7	25	95.5	1.28			0	4	48	72	92	96	96	100	
8	9	93.6	1.10						0	55	78	89	100	
9	15	93.7	0.79					0	7	27	93	100		
10	364	96.0	0.84		0	1	11	55	94	97	100			
11	122	94.7	1.21			0	1	10	40	84	93	94	97	99
12	35	94.2	1.10						23	51	94	97	100	
13	14	92.3	1.17			0	7	7	7	7	43	43	79	93
13 with retests		94.0	2.43		0	7	21	29	36	71	71	86	100	
14	51	94.8	1.70		0	4	14	27	47	61	86	98	100	
15	73	95.6	1.70	0	3	8	23	48	67	81	92	99	100	
16	14	96.0	0.89				21	43	93	100				
				0	.2	.8	8	20	47	75	93	94	99	

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TABLE 3

SUMMARY OF RELATIVE COMPACTION TEST RESULTS

Project	No. Lots	Avg RC	Std Dev	% Equal to or Greater										
				100	99	98	97	96	95	94	93	92	91	90
2	4	94.4	0.47						0	75	100			
3	14	94.3	0.50					0	7	86	100			
9	15	93.7	0.79					0	7	27	93	100		
6	14	95.5	0.82				0	14	86	93	100			
10	364	96.0	0.82		0	1	11	55	94	97	100			
1	24	94.7	0.85				0	4	46	79	100			
16	14	96.0	0.89			0	21	43	93	100				
4	6	96.1	1.03			0	33	50	83	100				
8	9	93.6	1.10						0	55	78	89	100	
12	35	94.2	1.10					0	23	51	94	97	100	
11	122	94.7	1.21			0	1	10	40	84	93	94	97	99
7	25	95.5	1.28			0	4	48	72	92	96	96	100	
5	14	95.5	1.39			0	14	43	71	79	100			
14	51	94.8	1.70		0	4	14	27	47	61	86	98	100	
15	73	95.6	1.70	0	3	8	23	48	67	81	92	99	100	
13	14	94.0	2.43		0	7	21	29	36	71	71	86	100	

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The compaction tests for the first eight projects listed in Table 3 had standard deviations of 1.03 or less. Only one of the 455 lots tested on these projects had a relative compaction of less than 93%. On the remaining eight projects, the standard deviations were 1.10 and above. Of these, only one project did not have materials in the penalty range. It is believed that most of this variability in relative compaction test results is due primarily to inconsistent and/or improper construction practices and controls on the part of the Contractor.

The projects in this study included some new construction but the majority were overlays. The thickness of the overlays varied from 0.15 ft to 0.35 ft. They were placed on both PCC and AC pavements. Several also included "reinforcing" fabric. The thickness of the individual AC layers that were tested varied from 0.15 ft to 0.25 ft. An attempt was made to correlate these construction variables to differences in relative compaction and uniformity. No correlation could be identified.

The following brief synopsis of the projects included in this study are based on information reported to TransLab by personnel directly involved in the projects, along with personal observations of the author during brief visits to some of the projects. Although the information does not provide qualitative evidence, it does provide some insight into the authors reasoning in developing some of his conclusions.

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PROJECT 1

DESCRIPTION: 0.15 ft AC overlay on 2 lane mountain road

LENGTH: 14 miles

AMOUNT OF AC PLACED: 27,000 tons

NUMBER OF TEST LOTS: 24

RELATIVE COMPACTION:
AVERAGE: 94.7% RANGE: 93.1 to 96.1%

COMPACTION EQUIPMENT: Caltrans-approved 11-ton vibratory roller and 8- to 10-ton static steel drum roller.

OBSERVATIONS: Although acceptance of this roller was based on it being operated in the high amplitude setting, the operator insisted that it should be operated at low amplitude in order to prevent tearing of the pavement surface. Early in the project, the author worked with the roller operator to help him establish a suitable rolling pattern. During this time, it was shown that a relative compaction of 95% or above could be achieved when the roller was operated at high amplitude and the mix was sufficiently hot. It was also shown that lower densities could be expected when the roller was operated at low amplitude. This demonstration obviously had little effect on the operator since he continued to operate the roller at low amplitude. There was also some evidence that the temperature of the AC at the time of compaction did not always meet the requirement of the procedural specifications.

CONCLUSIONS: Although the average relative compaction for the project was 94.7%, and none of the test lots were in the penalty range, it is believed that inconsistencies in temperature and rolling patterns were responsible for the variations in the measured density. It is also believed that the Contractor could have consistently achieved relative compactions above 94% with very little additional effort.

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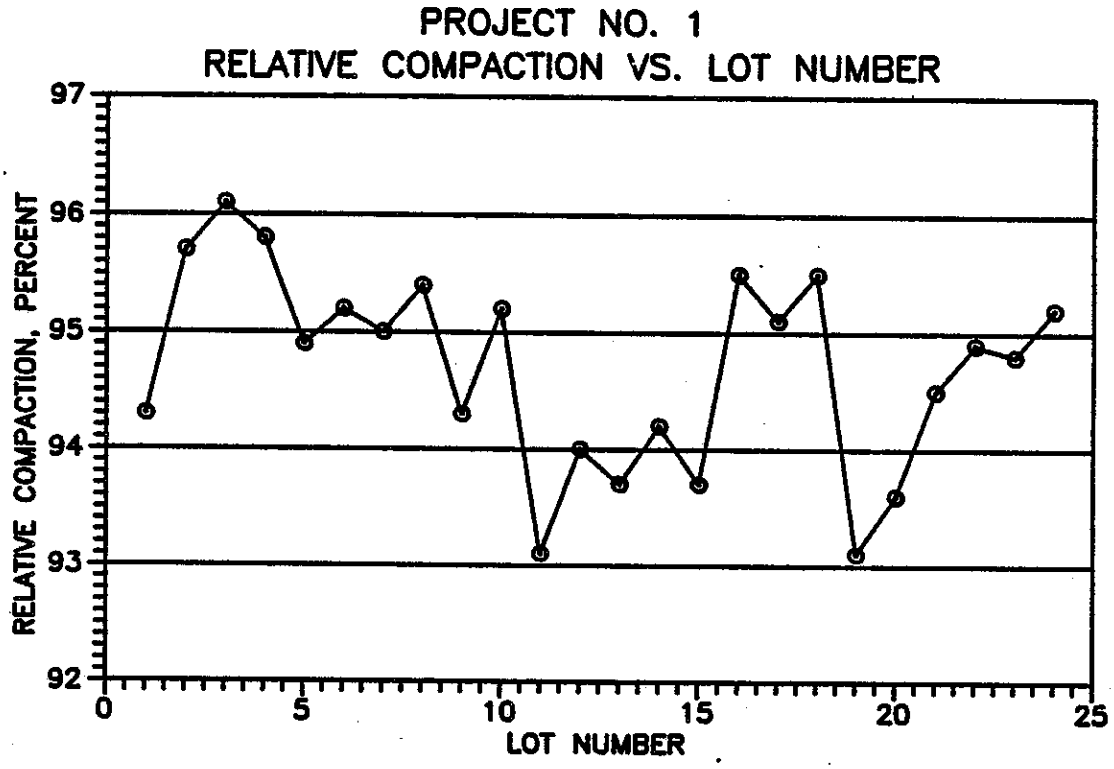
FIGURE 1



SUMMARY:

1. AVERAGE RELATIVE COMPACTION = 94.7%
2. STANDARD DEVIATION = 0.85
3. PERCENT EQUAL TO OR GREATER THAN 97.....0
   96.....4
   95.....46
   94.....79
   93.....100

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PROJECT 2

DESCRIPTION: 0.25 ft AC overlay

LENGTH: 0.9 mile

AMOUNT OF AC PLACED: 7,300 tons

NUMBER OF TEST LOTS: 4

RELATIVE COMPACTION:
AVERAGE: 94.4% RANGE: 93.8 to 94.9%

COMPACTION EQUIPMENT: Caltrans-approved 11-ton vibratory and 8- to 10-ton finish roller.

OBSERVATIONS: Because of the size of the project and the limited number of tests, very little information was contributed.

CONCLUSIONS: It appears that 94% relative compaction was easily achieved.

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PROJECT 3

DESCRIPTION: 0.35 ft AC overlay with pavement reinforcing fabric over existing four lane PCC freeway.

LENGTH: 6.8 miles

AMOUNT OF AC PLACED: The project included 85,000 tons of AC; however, only the top 0.15 ft layer could be tested because of the specified minimum layer thickness requirement for end-result density determinations.

NUMBER OF TEST LOTS: 14

RELATIVE COMPACTION:
AVERAGE: 94.3% RANGE: 93.6 to 95.5%

COMPACTION EQUIPMENT: Caltrans-approved 16-ton vibratory roller and finish roller.

OBSERVATIONS: The densities reported are relatively uniform with all but three of the fourteen test lots having relative compactions between 94.0% and 94.8%. Of the three lots that were outside this range, the data sheets for two included notes which point out probable causes. A note on the data sheet for Lot No. 2 indicated that the roller vibrators were not on during the initial pass of the roller. A note on the data sheet for Lot No. 6 indicated that this lot was not tested until after being exposed to traffic over the weekend.

It was also noted that the Contractor's normal operation of the vibratory roller included vibration only during the initial coverage. Use of this roller under the current procedural specification requires two coverages with the vibrators functioning.

CONCLUSIONS: Ninety four percent relative compaction was easily achieved. Based on the reduction from normally required compactive effort, and the apparent increase in density by traffic, it is assumed that an even higher density could have been easily achieved with very little additional effort on the part of the Contractor.

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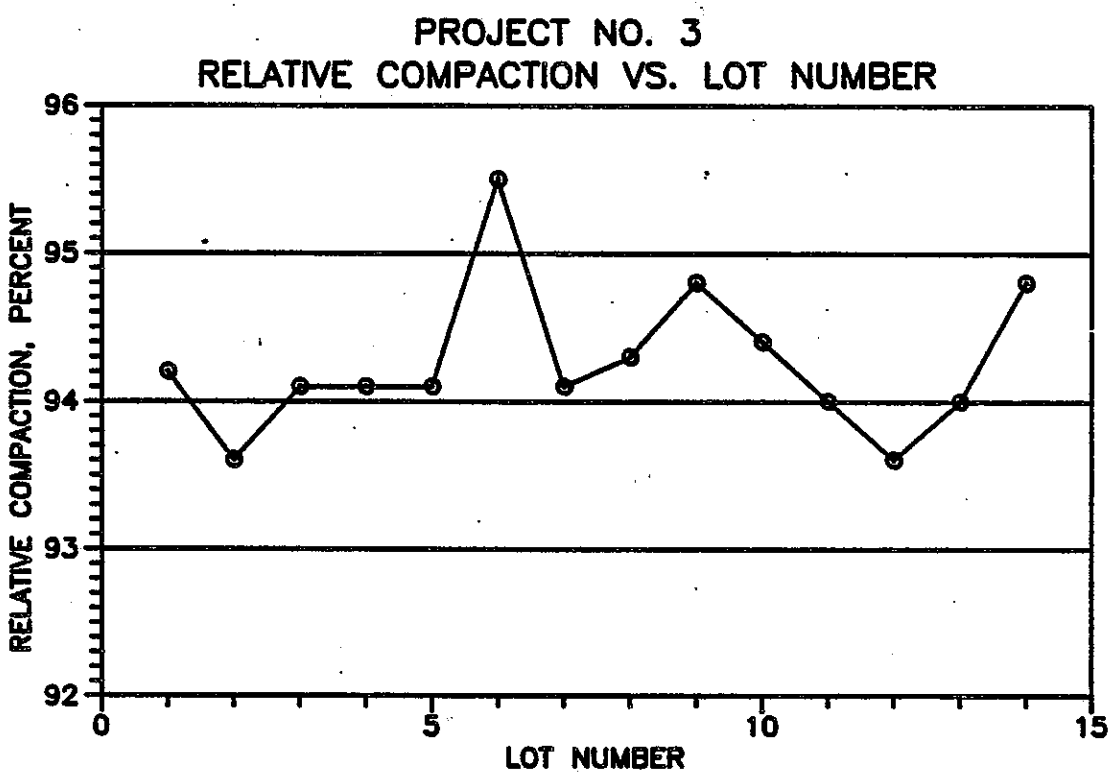
FIGURE 2



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 94.3%
2. STANDARD DEVIATION = 0.50
3. PERCENT EQUAL TO OR GREATER THAN 96.....0
95.....7
94.....86
93.....100

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PROJECT 4

DESCRIPTION: 0.20 ft AC overlay on 64 ft wide parkway with center divider

LENGTH: 0.5 mile

AMOUNT OF AC PLACED: 2,800 tons

NUMBER OF TEST LOTS: 6

RELATIVE COMPACTION:
AVERAGE: 96.1% RANGE: 94.7 to 97.1%

COMPACTION EQUIPMENT: Not reported.

OBSERVATIONS: Five of the six lots had relative compactions greater than 95%. The sixth was 94.7%. It must be pointed out, however, that there were problems with the nuclear gages used on this project. It was noted that, when originally tested using a different nuclear gage, densities of the first two lots were much lower. No reason was found for this discrepancy between the gages.

The biggest problem encountered on this project was in completing the testing so that the new pavement could be opened to traffic. It was reported that lane closures had to be extended by approximately 1/2 hour to allow time for completing the testing.

CONCLUSIONS: A relative compaction of 95% was apparently readily achieved; however, the discrepancies between gages cast some doubt on the validity of the data.

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PROJECT 5

DESCRIPTION: 0.25 ft AC overlay on two-lane mountain road.

LENGTH: 5 miles

AMOUNT OF AC PLACED: 17,000 tons. Only the top 0.15 ft layer was tested.

NUMBER OF TEST LOTS: 16

RELATIVE COMPACTION:
AVERAGE: 95.5% RANGE: 93.3 to 97.5%

COMPACTION EQUIPMENT: Two Caltrans approved vibratory rollers weighing 10 tons and 7 tons, and an 8 ton finish roller.

OBSERVATIONS: On the first day of paving the surface course, only the 10-ton vibratory roller was used with the finish roller. A relative compaction of 93.5% was measured. Thereafter, the Contractor used both vibratory rollers along with the finish roller. The breakdown coverage was normally done with the 10-ton roller which was followed up with the 7-ton roller. With the exception of the first and last days paving, the relative compaction was consistently greater than 94.5%. Although the use of the single vibratory roller may account for the lower densities on the first day, no explanation was noted for the lower densities recorded on the last day.

It should be noted that the nuclear gage that was first used on this project indicated densities that were significantly below the readings shown in Figure 3. It was quickly determined that this gage had not been properly recalibrated after being repaired. All of the data shown in Figure 3 were from gages that had been calibrated as specified in California Test 375.

CONCLUSIONS: The combination of rollers and rolling patterns used by the Contractor was very successful at achieving 95% relative compaction.

It is also obvious that the successful application of the end-result compaction specification is highly dependent upon the proper maintenance and calibration of the nuclear gages.

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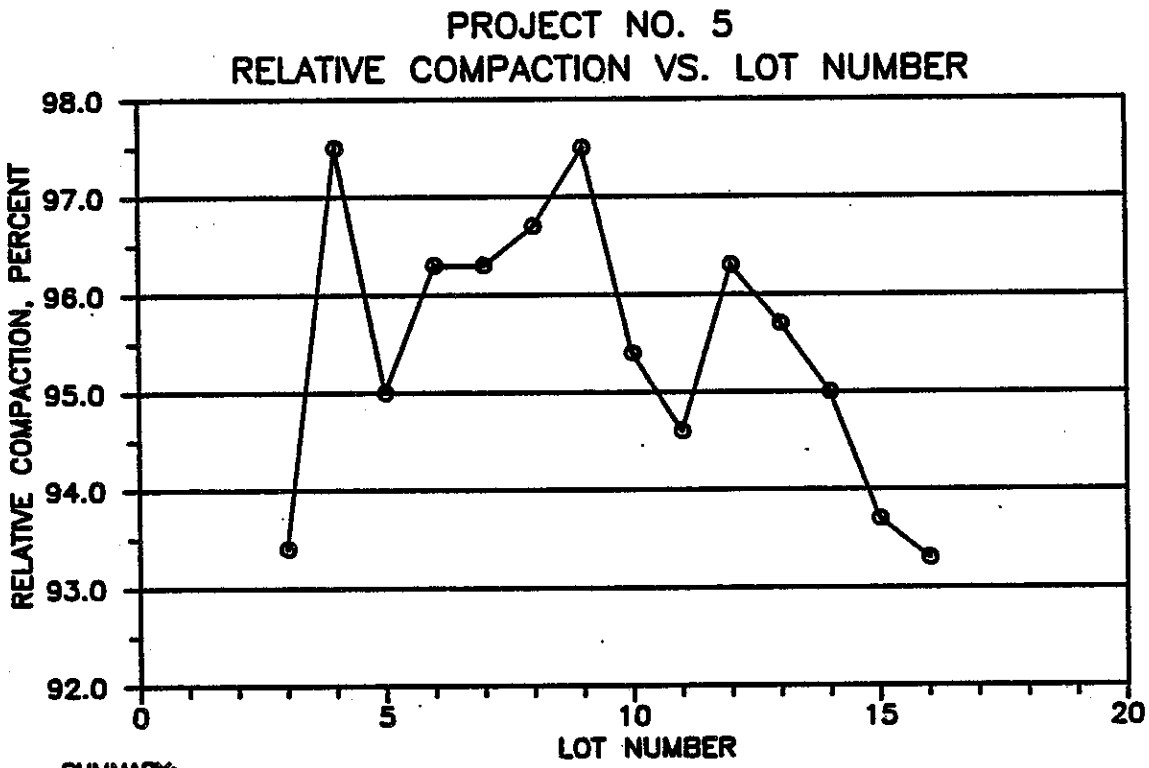
FIGURE 3



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 95.5%
2. STANDARD DEVIATION = 1.39

3. PERCENT EQUAL TO OR GREATER THAN:

98.0.....0	•	95.0.....71
97.0.....14	•	94.0.....79
96.0.....43	•	93.0.....100

NOTE: Gage used on lots 1 and 2 was not correctly calibrated prior to testing. Lot 3 is a retest of lot 2 using a calibrated gage.

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PROJECT 6

DESCRIPTION: 0.35 ft AC overlay with pavement reinforcing fabric over one side of an existing four-lane divided PCC freeway.

LENGTH: 5 miles

AMOUNT OF AC PLACED: 29,000 tons. Only the top 0.15 ft layer could be tested because of specified minimum layer thickness requirement.

NUMBER OF TEST LOTS: 14

RELATIVE COMPACTION:

AVERAGE: 95.5% RANGE: 93.5 to 96.7%

COMPACTION EQUIPMENT: Not reported.

OBSERVATIONS: Only two of the fourteen test lots had relative compactions of less than 95%. Very little information, other than the test record sheets, was submitted from this project. It is suspected that ambient temperatures may have had some effect on the densities. Paving was done during the last few days of October and the first few days of November. Although the average relative compaction of Lot 12 was 95.3%, the relative compaction recorded for three individual test sites in this lot were 90.2, 93.9 and 92.1%. A footnote on the test record sheet stated that, in the area of the three low test results, rolling was not as extensive because of the rush to finish before dark.

The test record sheet for Lot 14 also included a note indicating that the last five test sites could not be tested until the following day due to darkness.

CONCLUSIONS: Ninety-five percent relative compaction was obviously readily attainable on this project. The occasional lower test results are assumed to be due to rapid temperature losses normal during late afternoon at this season of the year.

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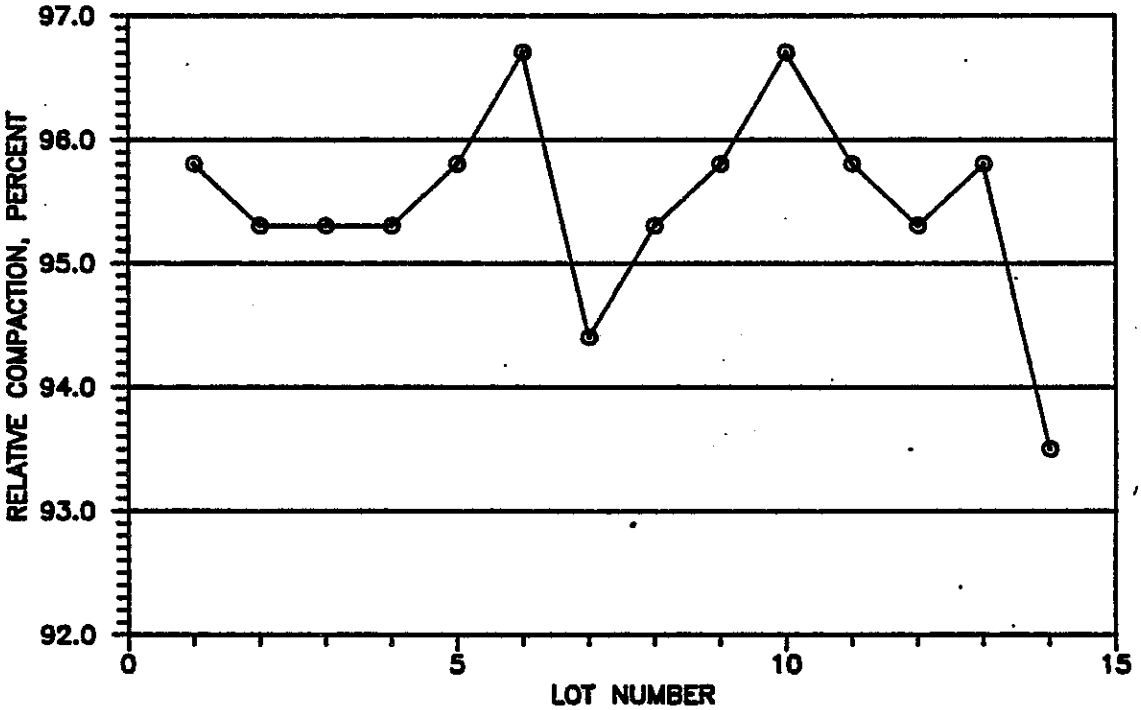
FIGURE 4

PROJECT NO. 6

RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 95.5%
2. STANDARD DEVIATION = 0.82
3. PERCENT GREATER THAN 96.....14
95.....86
94.....93
93.....100

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PROJECT 7

DESCRIPTION: This project consisted of reconstruction and overlays of existing ramps and frontage roads over a 73-mile section of freeway. Overlays were a minimum of 0.15 ft thick. Reconstructed areas included digouts with full depth AC replacement to thicknesses of up to 0.85 ft.

LENGTH: Indeterminable

AMOUNT OF AC PLACED: 24,000 tons

NUMBER OF TEST LOTS: 25

RELATIVE COMPACTION:
AVERAGE: 95.5% RANGE: 91.5 to 97.1%

COMPACTION EQUIPMENT: Various types and sizes including several brands of vibratory rollers and a pneumatic roller.

OBSERVATIONS: The Contractor included the use of the pneumatic roller for intermediate compaction which is not required under the procedural specifications when vibratory rollers are used for breakdown compaction. It was indicated by construction personnel that the Contractor also heated the mix to a higher temperature on this project than he would have done on a routine project. No specific temperatures were indicated in the project data.

During the authors brief visit to the project two noteworthy events occurred. During the compaction of Lot No. 2, the vibrators on the 11 1/2 ton vibratory roller were not functioning. Although the relative compaction for this area was 94.5%, it was noticeably lower than that for the majority of test lots. Lot No. 3 represented the first 0.25 ft layer of AC placed in a digout area. The paving inspector did not believe that as much effort had gone into this layer as into previous areas and there was also an indication that the subgrade may have been resilient enough

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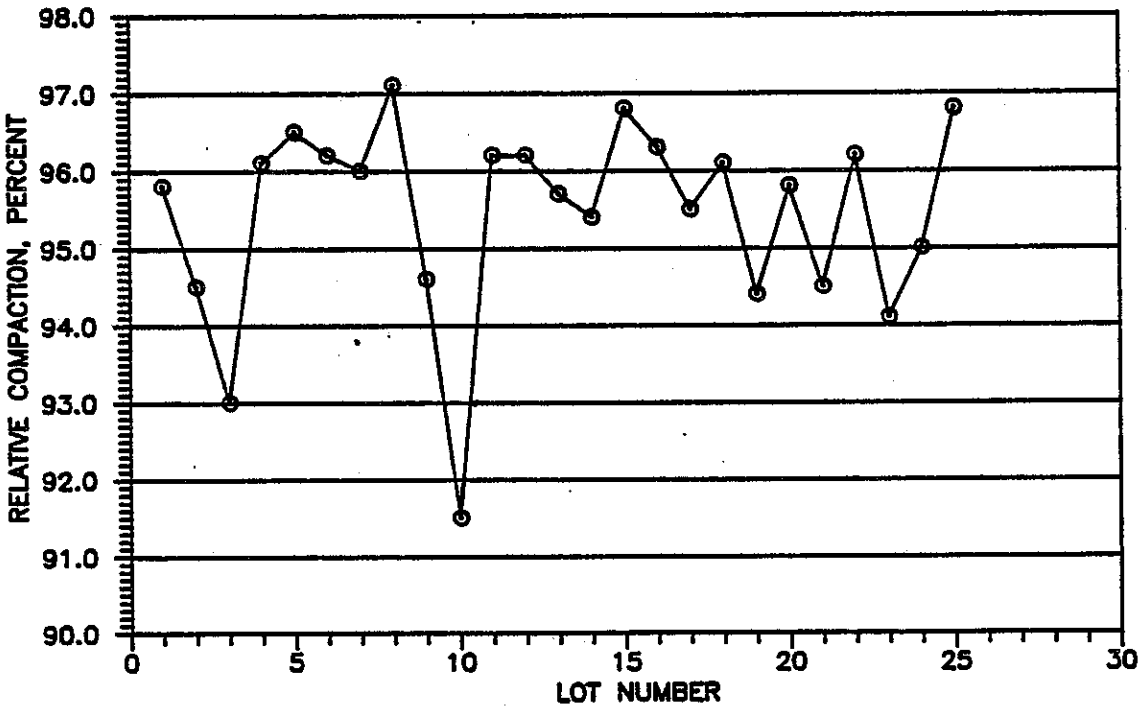
to hinder compaction. Because of the low relative compaction (93.0%) of this lot, the paving foreman increased the compactive effort applied to the subsequent lots and the relative compaction immediately went up to 96% or more. The data record sheets did not include any information reflecting on conditions that may have contributed to the low relative compaction reported for Lot No. 10.

CONCLUSIONS: Ninety-five percent relative compaction was achievable on this project. The variety of rollers, the different thicknesses of AC and the number of areas where the work was done may have contributed to variations in relative compaction.

FIGURE 5

PROJECT NO. 7

RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 95.5%
2. STANDARD DEVIATION = 1.28
3. PERCENT GREATER THAN 96.....48
94.....92
92.....96
90.....100

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PROJECT 8

DESCRIPTION: Cold planing various freeway ramps and resurfacing with 0.15 ft of AC with pavement reinforcing fabric or with 0.40 ft of AC.

LENGTH: Indeterminable

AMOUNT OF AC PLACED: 9,500 tons

NUMBER OF TEST LOTS: 9

RELATIVE COMPACTION:
AVERAGE: 93.6% RANGE: 91.5 to 94.9%

COMPACTION EQUIPMENT: Various types and sizes including several brands of vibratory rollers and a pneumatic roller.

OBSERVATIONS: This project was done by the same Contractor, using materials from the same source as Project 7. Some of the testing was done with the same gage that was used on Project 7. Despite these similarities, the relative compaction of the AC was significantly less than on the previous project. No explanation is available other than that Project 7 was done in June and July and Project 8 was done in October and November.

CONCLUSIONS: Ninety-five percent relative compaction did not appear to be attainable on this project. Weather and the accompanying increased rate of heat loss may have been a contributing factor.

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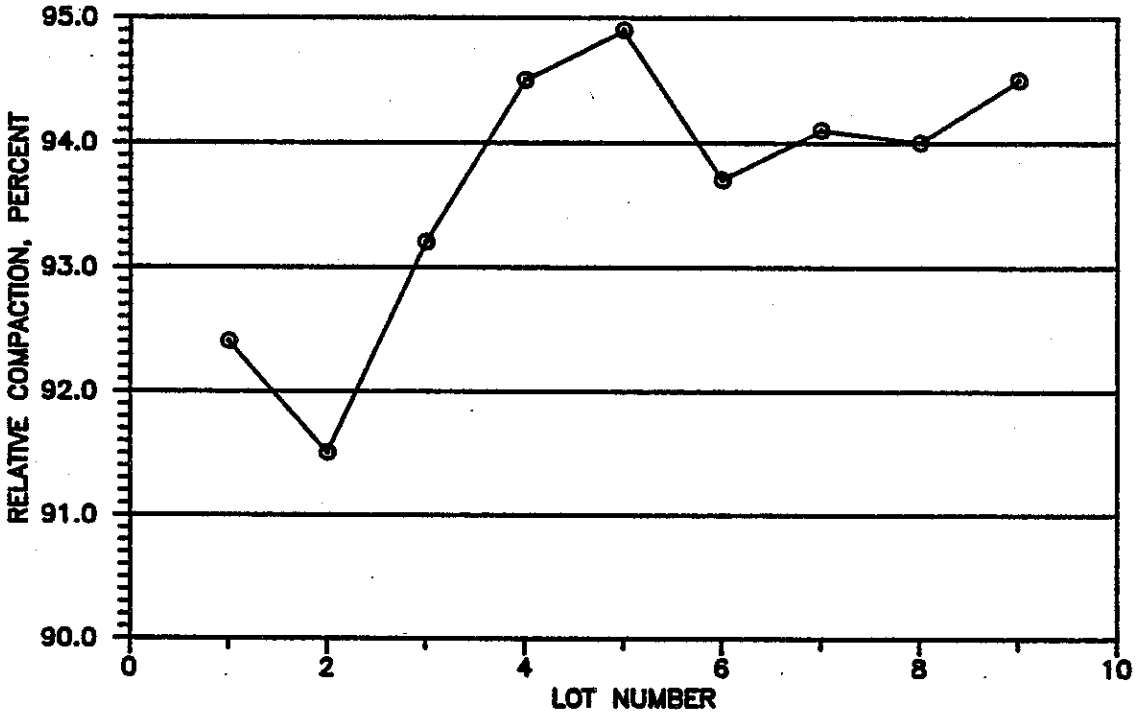
FIGURE 6

PROJECT NO. 8

RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 93.6%
2. STANDARD DEVIATION = 1.10
3. PERCENT GREATER THAN 94.....55
93.....78
92.....89
91.....100

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PROJECT 9

DESCRIPTION: Widening with new construction consisting of 0.40 ft AC over 1.40 ft AB and overlaying existing 24 ft wide road with 0.20 ft AC.

LENGTH: 2.3 miles

AMOUNT OF AC PLACED: 12,500 tons

NUMBER OF TEST LOTS: 15

RELATIVE COMPACTION:
AVERAGE: 93.7% RANGE: 92.2 to 95.3%

COMPACTION EQUIPMENT: Caltrans-approved 11.4-ton vibratory roller with offsetting drums and a 12-ton finish roller.

OBSERVATIONS: On the first day of placing AC, the Contractor operated the vibratory roller with the drums in the offset position. Because of the low relative compaction achieved, this procedure was changed so that the roller was operated with the drums in line for the remainder of the job. The Contractor also made a greater effort to reduce the delay between spreading and compacting. Although the majority of the test lots had relative compactions of less than 94%, the few that were near 95% indicate that 95% may have been attainable with a little more effort. This project was also constructed during October so weather may have had some effect.

The reported average relative compaction of Lot No. 4 was 90.9%. A review of the data sheets indicated that, one of the 5 tests in this lot was in error, or there was a total lack of compaction at one test site where a relative compaction of only 84% was measured. Because of the improbability of such a low density, the author assumed that there had been an error in taking the nuclear gage reading. By deleting this one reading, the average for the test lot was increased to 93.1%.

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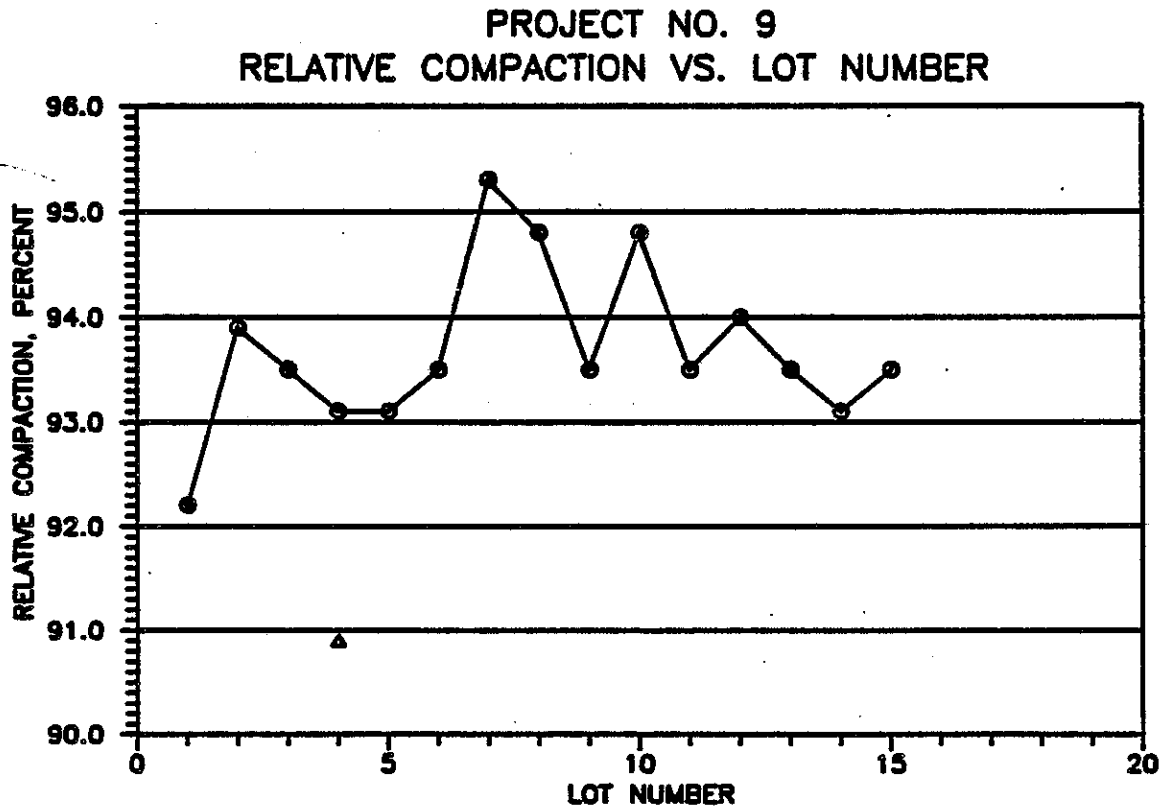
The RE on this project expressed concern that the testing required the time of a person that could have been performing other tasks along with watching the rolling. It should be pointed out that the expense of performing these tests was not a wasted effort. The test data sheets indicate that the AC was placed over a period of six days. If a penalty was assessed on Lot No. 1 according to the schedule in the specification, it would have more than covered inspectors time for the entire paving operation. An even greater saving should be realized by the extended service life resulting from the improved densities that occurred because of the change in the way the roller was being used.

CONCLUSIONS: The relative compaction on this project probably could have been increased with very little additional effort.

FIGURE 7



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 93.7%
2. STANDARD DEVIATION = 0.79

3. PERCENT EQUAL TO OR GREATER THAN:

96.0.....0	93.0.....93
95.0.....7	92.0.....100
94.0.....27	

▲ Represents eroneous reading from original calculation.

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PROJECT 10

DESCRIPTION: Constructing or reconstructing ramps, frontage roads, shoulders and additional lanes, and overlaying an existing six-lane freeway. New AC pavements and overlays varied from 0.25 to 0.50 ft thick.

LENGTH: 4.9 centerline miles

AMOUNT OF AC PLACED: 81,000 tons

NUMBER OF TEST LOTS: 364

RELATIVE COMPACTION:
AVERAGE: 96.0% RANGE: 93.9 to 97.8%

COMPACTION EQUIPMENT: Caltrans-approved 10-ton vibratory rollers and a finish roller.

OBSERVATIONS: Because of the large number of individual test lots, only the daily averages are plotted in Figure 8. The statistical values are very similar whether calculated by lot or daily averages. Obviously this Contractor had no problem meeting the 95% relative compaction requirement. Only 20 of the 364 lots had relative compactions of less than 95%. Two primary factors contributed to the outstanding success of attaining the desired relative compaction on this project. The first was the Contractor's confidence that he could achieve it and the second was the concern of the paving inspector to see that he did. Even prior to beginning any of the paving, the Contractor stated that he would not have any problem since he had worked under similar specifications on airport projects and knew that properly heating the AC and then compacting immediately after placement were the keys to success. The inspector was quick to determine the density of the finished pavement and to inform the Contractor when the results of his efforts were insufficient.

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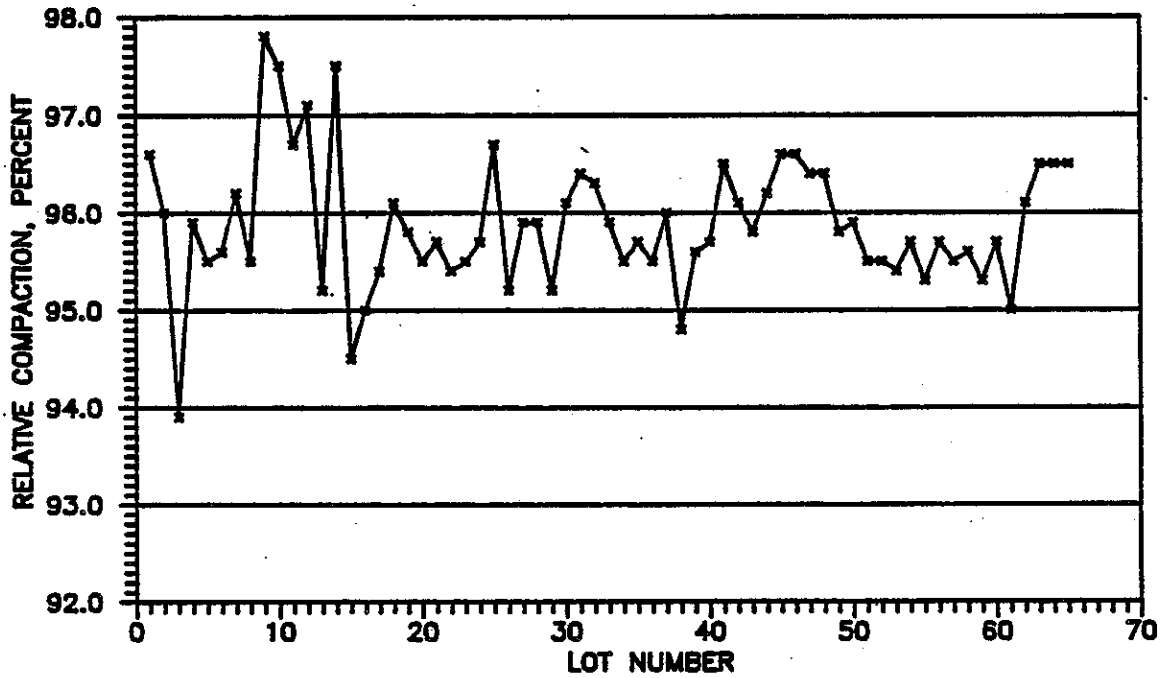
In order to provide immediate test results, the inspector turned to the use of the moving average of previous test maximum densities rather than wait on results from tests on the current test lot.

CONCLUSIONS: Ninety-five percent relative compaction is attainable when the Contractor and the inspector see the specification as a realistic goal.

FIGURE 8

PROJECT NO. 10

RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 95.9%
2. STANDARD DEVIATION = 0.68
3. PERCENT GREATER THAN 97.....6
96.....35
95.....94
94.....98
93.....100

NOTE: VALUES FOR RELATIVE COMPACTION REPRESENT DAILY AVERAGES.

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PROJECT 11

DESCRIPTION: Remove and replace the upper portion of AC on an existing six-lane freeway. AC reclaimed from the existing pavement was recycled by blending with new aggregate in a hot plant to provide 0.15 ft of additional thickness to the entire roadway including shoulders.

LENGTH: 3.2 centerline miles

AMOUNT OF AC PLACED: 46,500 tons

NUMBER OF TEST LOTS: 122

RELATIVE COMPACTION:
AVERAGE: 94.7% RANGE: 89.6 to 97.0%

COMPACTION EQUIPMENT: Caltrans-approved 15-ton and 11-ton vibratory rollers. The 11-ton roller was used without the vibrators for finish rolling.

OBSERVATIONS: During the early phases of this project, test lots were 2,000 ft long and were tested every 200 ft. As a result, as many as 10 lots were tested in a single day. During the first two days of paving, nearly half of the test lots were in the penalty range. To correct this problem, the Contractor increased both the compactive effort and the temperature of the mix. Thereafter, the average relative compaction remained near 95% while only a few lots tested below 94%.

Although not confirmed, the author suspects that the temperature of the mix during the first two days of paving was largely responsible for the low densities. During a visit to the project, on the sixth day of paving, he was told that the Contractor had increased the temperature of the mix from 270°F± to over 300°F. At that time the plant gauge did indicate a temperature of over 300°F, but when checked at the discharge of the drum, and also on the street, the temperature was consistently

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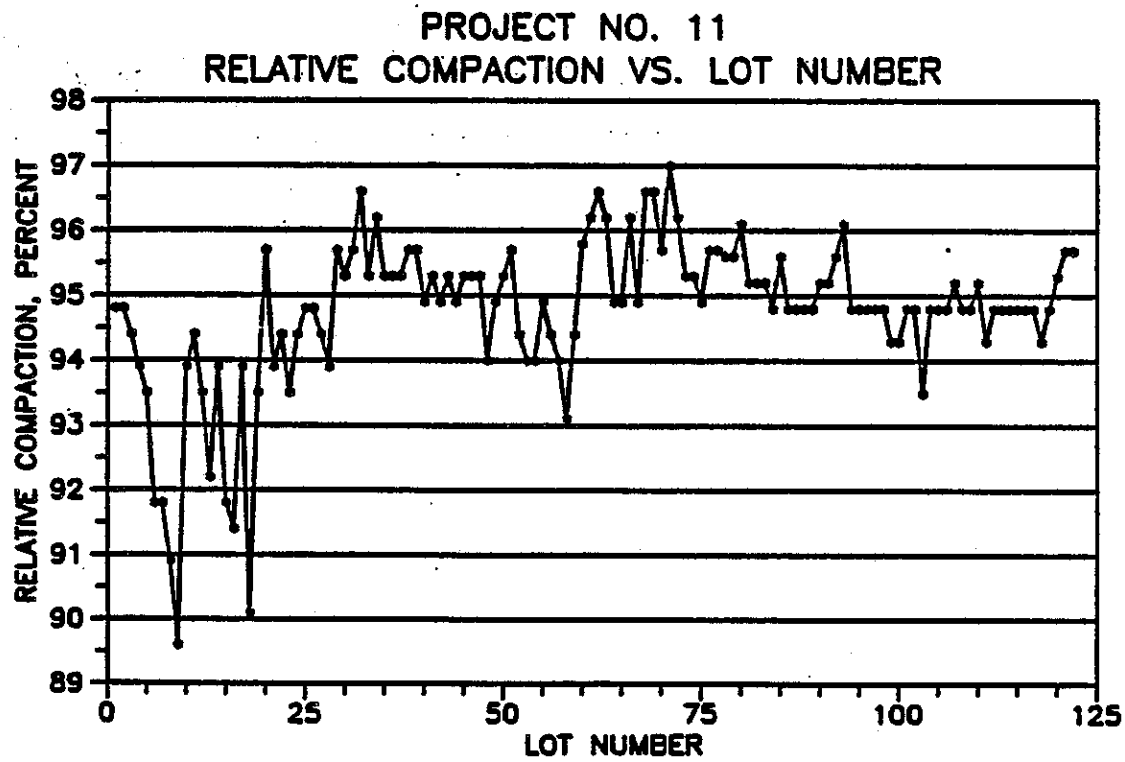
between 270 and 280°F. If this same discrepancy existed earlier, then it is highly probable that the AC was being delivered at a temperature below 250°F. If further compounded by delays in compaction, the mix could well have been too cold to achieve the required density.

It should also be mentioned that the amount of new asphalt being added to the mix had been increased from 2.0% at the start of the project up to 2.4% by the sixth day and was further increased to 2.6% after that. This low asphalt content at the beginning of the job also may have had some effect on the compactability of the AC.

CONCLUSIONS: Ninety-five percent relative compaction was achievable on this project. The temperature of the AC at the time of compaction was the most likely hindrance to achieving the desired density.

FIGURE 9



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 94.7%
2. STANDARD DEVIATION = 1.21

3. PERCENT EQUAL TO OR GREATER THAN:

98.....0	•	93.....93
97.....1	•	92.....94
96.....10	•	91.....97
95.....40	•	90.....99
94.....84	•	89.....100

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PROJECT 12

DESCRIPTION: Construct additional lanes with 0.50 ft AC over AB and shoulder with 0.30 or 0.40 ft of AC over AB. Overlay existing pavement with 0.15 or 0.20 ft of AC.

LENGTH: 2.9 centerline miles

AMOUNT OF AC PLACED: 27,500 tons

NUMBER OF TEST LOTS: 35

RELATIVE COMPACTION:
AVERAGE: 94.2% RANGE: 91.2 to 96.1%

COMPACTION EQUIPMENT: Caltrans-approved 15-ton vibratory roller, 10-ton pneumatic roller and an 11-ton vibratory roller, operated without the vibrators, for finish rolling.

OBSERVATIONS: The RE reported that the Contractor used the pneumatic roller for intermediate rolling which would not have been required under the procedural specifications. He also indicated that the Contractor attempted to keep the temperature at 275°F or higher. The variability in relative compaction (normally between 93.0 and 96.0%) indicates that there must have been some variation in at least one of the factors that affect compaction. The two lots that had relative compactions below 93% were known to have been compacted at temperatures as low as 180°F. These were discussed in an earlier section of this report.

CONCLUSIONS: The fact that 23% of the test lots had relative compaction above 95% indicates that 95% is achievable. In order to consistently meet this goal, it would first be necessary to identify and eliminate the causes of the lower values.

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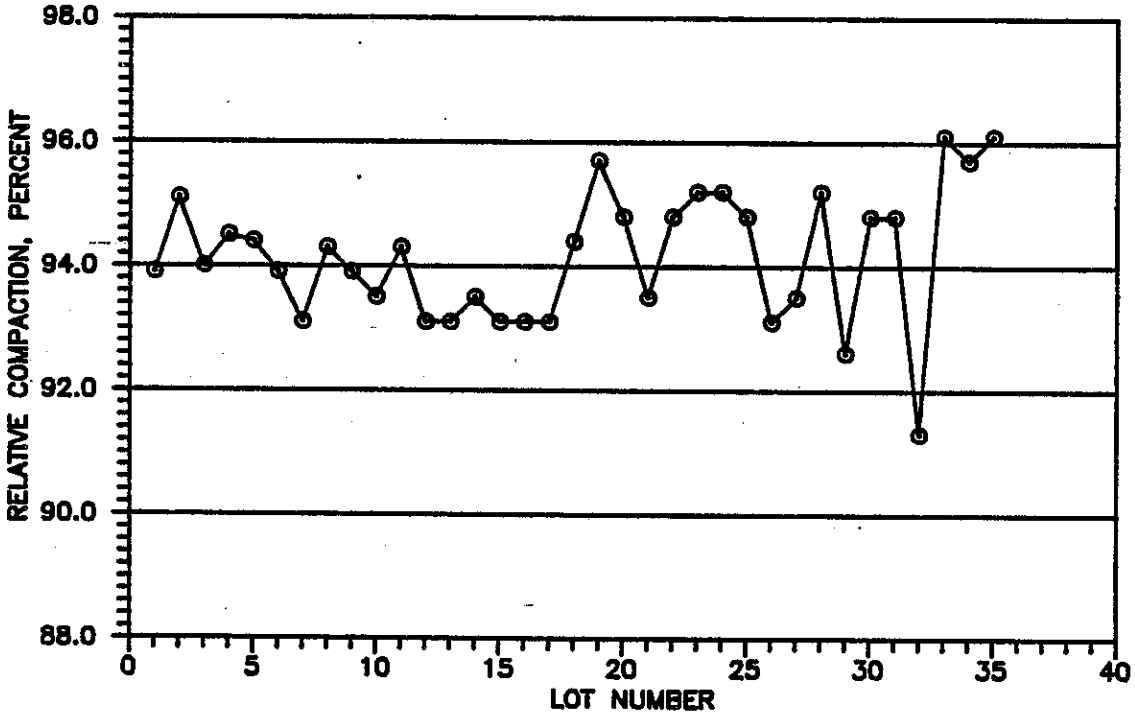
FIGURE 10

PROJECT NO. 12

RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:

1. AVERAGE RELATIVE COMPACTION = 94.2%
2. STANDARD DEVIATION = 1.10
3. PERCENT GREATER THAN 95.....23
   94.....51
   93.....94
   92.....97
   91.....100

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PROJECT 13

DESCRIPTION: Add passing lane and resurface entire roadway with minimum of 0.15 ft AC on a high mountain road.

LENGTH: 1 mile

AMOUNT OF AC PLACED: 6,000 tons

NUMBER OF TEST LOTS: 14

RELATIVE COMPACTION:
AVERAGE: 92.3% RANGE: 89.9 to 97.1%

COMPACTION EQUIPMENT: Caltrans-approved vibratory rollers weighing 15 and 9 tons were used at different times. The 9-ton roller with the vibrators turned off was used for finish rolling.

OBSERVATIONS: The first five lots were placed in October after the weather had turned very cold and a major snowstorm had occurred. On the day that the author visited the project, Lot No. 4 was being placed. On that day, it was nearly impossible to find any phase of construction that was going right. As a result of the cold weather, the asphalt emulsion had partially separated in the distributor truck and major delays in paving were caused while trying to apply a tack coat to the existing surface. Because of a 90-minute haul time from the plant and a several hour wait at the job site, the temperature of the AC varied from 305 to 165°F as it was dumped from the trucks. At a preestablished review point, the first pass with the roller was not made until 15 minutes after the AC had been spread. A portion of the spread at this point was not rolled for the first time until 35 minutes after it was placed and the surface temperature, as determined by an infrared thermometer, was 170°F. Following paving of this area, which was essential to carrying traffic through the winter, the project was suspended until the following summer.

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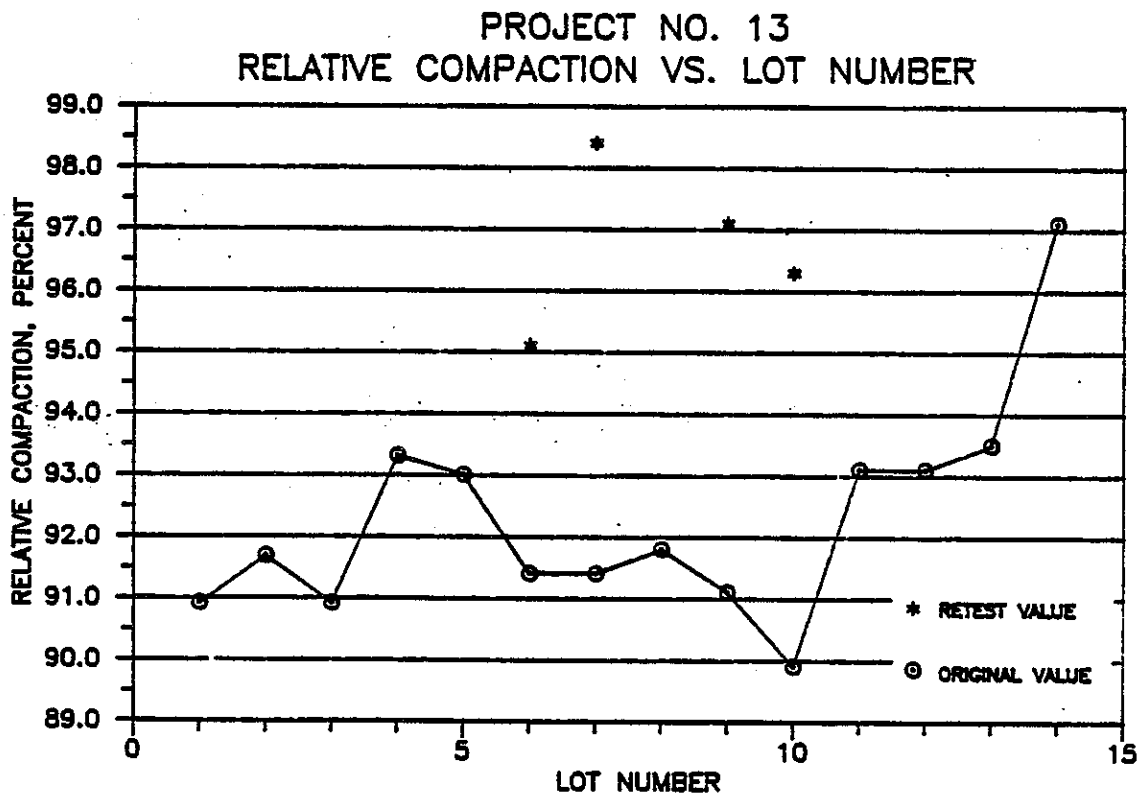
When the Contractor resumed work, he also resumed his inadequate approach to compaction. Because the densities were being measured and made available immediately, the Contractor was able to apply additional compactive effort to several lots. The beneficial effect of these early test results, and the additional rolling, are immediately obvious in the "retest" results plotted in Figure 11. In each instance, the Contractor was able to increase the relative compaction to well above the specified minimum. Although their efforts obviously paid off with much improved densities, field personnel questioned whether they should be responsible for helping the Contractor establish methods and procedures necessary for him to do his job.

CONCLUSIONS: Ninety-five percent relative compaction was attainable on this project when appropriate construction procedures were applied.

FIGURE 11



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 92.3%
2. STANDARD DEVIATION = 1.77
3. PERCENT EQUAL TO OR GREATER THAN:

98.0.....0	91.0.....79
97.0.....7	90.0.....93
93.0.....43	89.0.....100
92.0.....43	

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PROJECT 14

DESCRIPTION: 0.35 ft AC overlay with pavement reinforcing fabric over existing four-lane PCC freeway.

LENGTH: Portions with a 30 mile overall distance.

AMOUNT OF AC PLACED: 102,000 tons

NUMBER OF TEST LOTS: 51

RELATIVE COMPACTION:
AVERAGE: 94.8% RANGE: 91.1 to 98.8%

COMPACTION EQUIPMENT: Caltrans-approved 15-ton vibratory roller and finish roller.

OBSERVATIONS: Although the average relative compaction was good, the range in test results was extremely large. Several factors may have contributed to this variation. The RE reported that the relative compaction dropped off as production increased. An unconfirmed report also indicated that the AC was being windrowed over a mile ahead of the paving machine. In addition, the Contractor was pulling material from two plants which were producing from two aggregate sources.

A major potential problem observed by the author was that the Contractor was using only one breakdown roller working behind two paving machines working in echelon to place a 20 ft width of pavement in the No. 2 lane and outside shoulder. A close review of rolling patterns revealed extreme differences in time, temperature and compactive effort applied across the width of the roadway. It was also observed that the roller vibrators were not always functioning.

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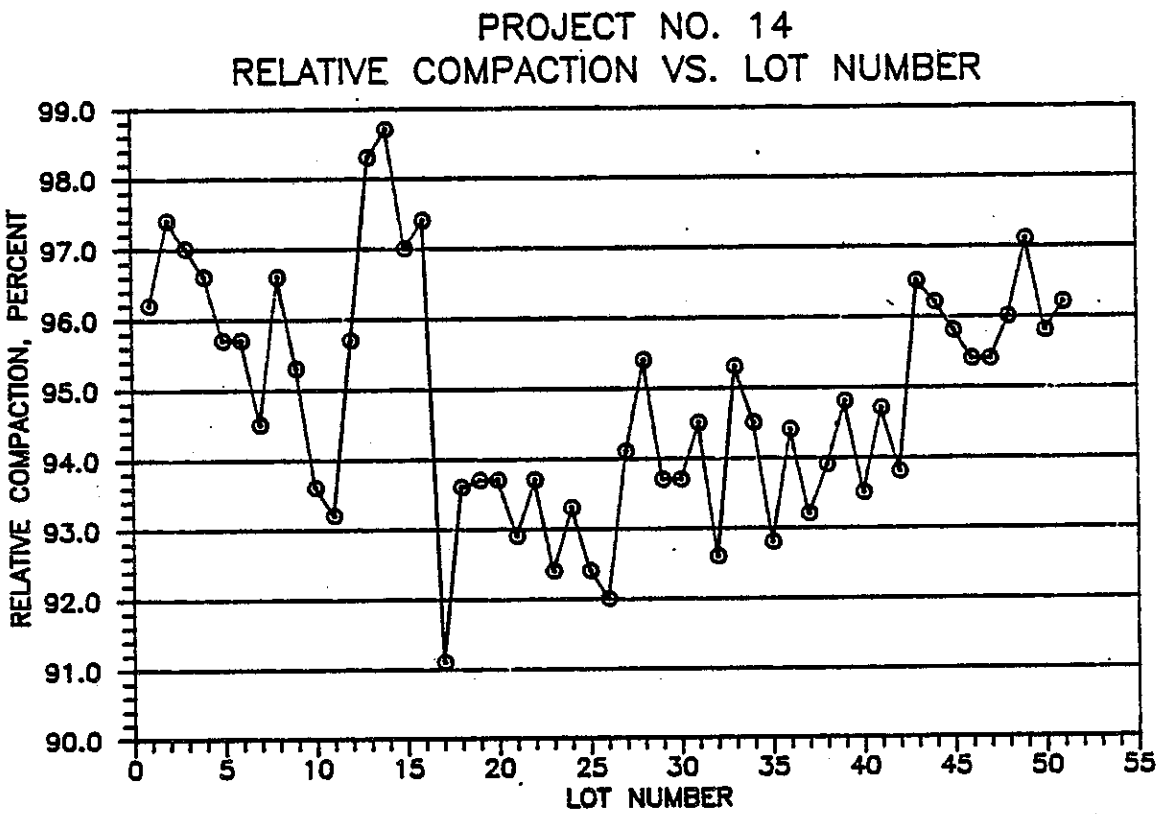
CONCLUSIONS: The broad range in relative compaction was due primarily to inconsistent compactive effort. The 95% relative compaction could have been met more consistently if the Contractor had applied appropriate compactive effort. Under the procedural specification, a breakdown roller would have been required for each paving machine in use.

FIGURE 12



SUMMARY:
1. AVERAGE RELATIVE COMPACTION = 94.8%
2. STANDARD DEVIATION = 1.70

3. PERCENT EQUAL TO OR GREATER THAN:

99.0.....0	94.0.....61	
98.0.....4	93.0.....86	
97.0.....14	92.0.....98	
96.0.....27	91.0.....100	
95.0.....47		

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PROJECT 15

DESCRIPTION: 0.35 ft AC overlay with reinforcing fabric over existing four-lane PCC freeway.

LENGTH: 15.8 miles

AMOUNT OF AC PLACED: 101,000 tons. Only the top 0.15 ft layer could be tested because of the specified minimum layer thickness requirement for end-result determinations.

NUMBER OF TEST LOTS: 73

RELATIVE COMPACTION:

AVERAGE: 95.6% RANGE: 91.9 to 99.5%

COMPACTION EQUIPMENT: Not reported.

OBSERVATIONS: The only information provided by construction personnel was copies of the test data sheets. It can be seen from the data plotted in Figure 13 that there were major problems at the beginning of the project. One of these was a nuclear gage that had not been properly calibrated. It is also obvious that the Contractor was able to make adjustments in his procedures that resulted in significant increases in the relative compaction. As the project progressed, it appears that there was a relaxation in effort. The gradual, steady decline in relative compaction seems to indicate that an effort was being made to meet the minimum requirement with the least amount of effort.

CONCLUSION: Ninety-five percent relative compaction was easily attainable on this project.

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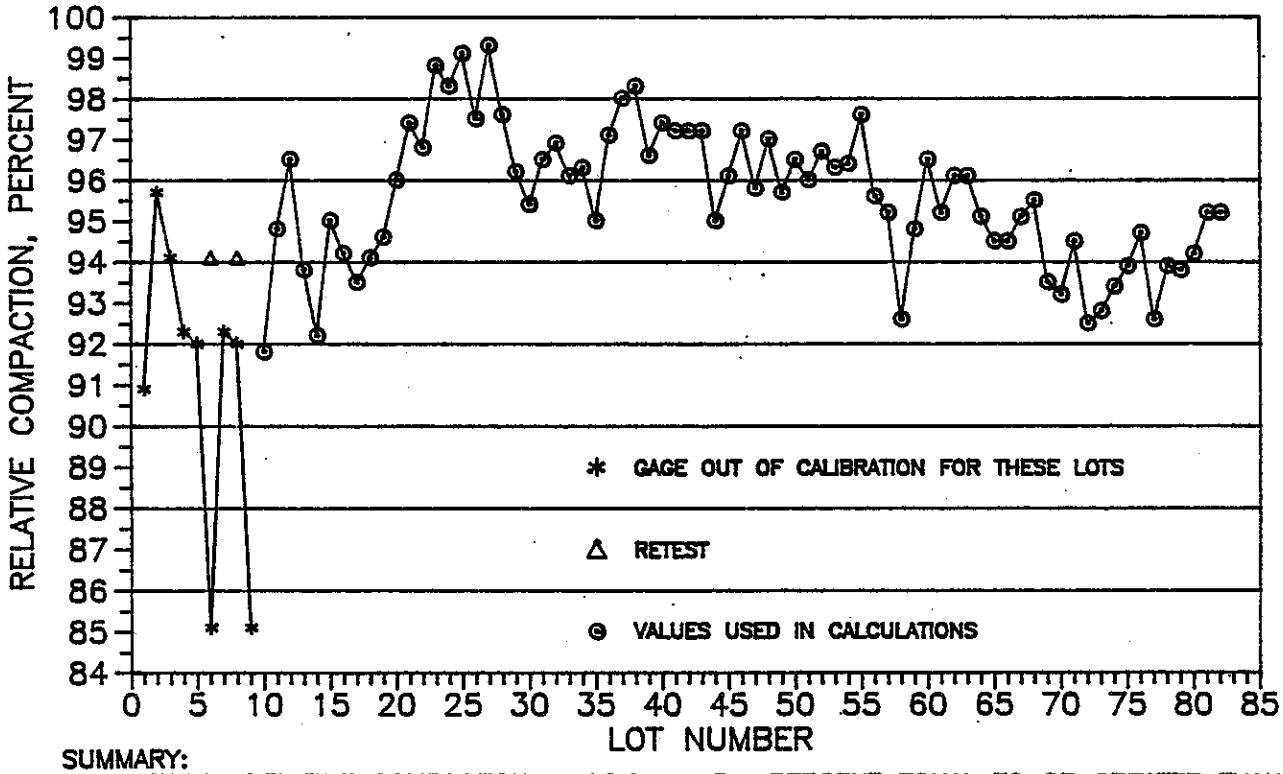
FIGURE 13

PROJECT NO. 15
RELATIVE COMPACTION VS. LOT NUMBER



SUMMARY:

1. AVERAGE RELATIVE COMPACTION = 95.6%
2. STANDARD DEVIATION = 1.70
3. PERCENT EQUAL TO OR GREATER THAN:

100.....0	*	95.....67
99.....3	*	94.....81
98.....23	*	93.....92
97.....23	*	91.....100
96.....48	*	

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PROJECT 16

DESCRIPTION: Reconstruct portions of existing roadway, widen and overlay with a minimum of 0.23 ft AC and pavement reinforcing fabric.

LENGTH: 4 centerline miles

AMOUNT OF AC PLACED: 21,000 tons

NUMBER OF TEST LOTS: 14

RELATIVE COMPACTION:
AVERAGE: 96.0% RANGE: 94.8 to 97.8%

COMPACTION EQUIPMENT: Two Caltrans approved 12.5 ton vibratory rollers and an 8 to 10 ton finish roller. When both vibratory rollers were used at the same time, one was used as a finish roller.

OBSERVATIONS: Even though the relative compaction was consistently above 95%, the RE did not believe that the end-result specification provided adequate control. He reported that compaction was achieved with one roller and that the pavement surface was full of cracks or checking.

CONCLUSION: Compaction was easily achieved on this project. Reported cracking may have been the result of too much compactive effort.

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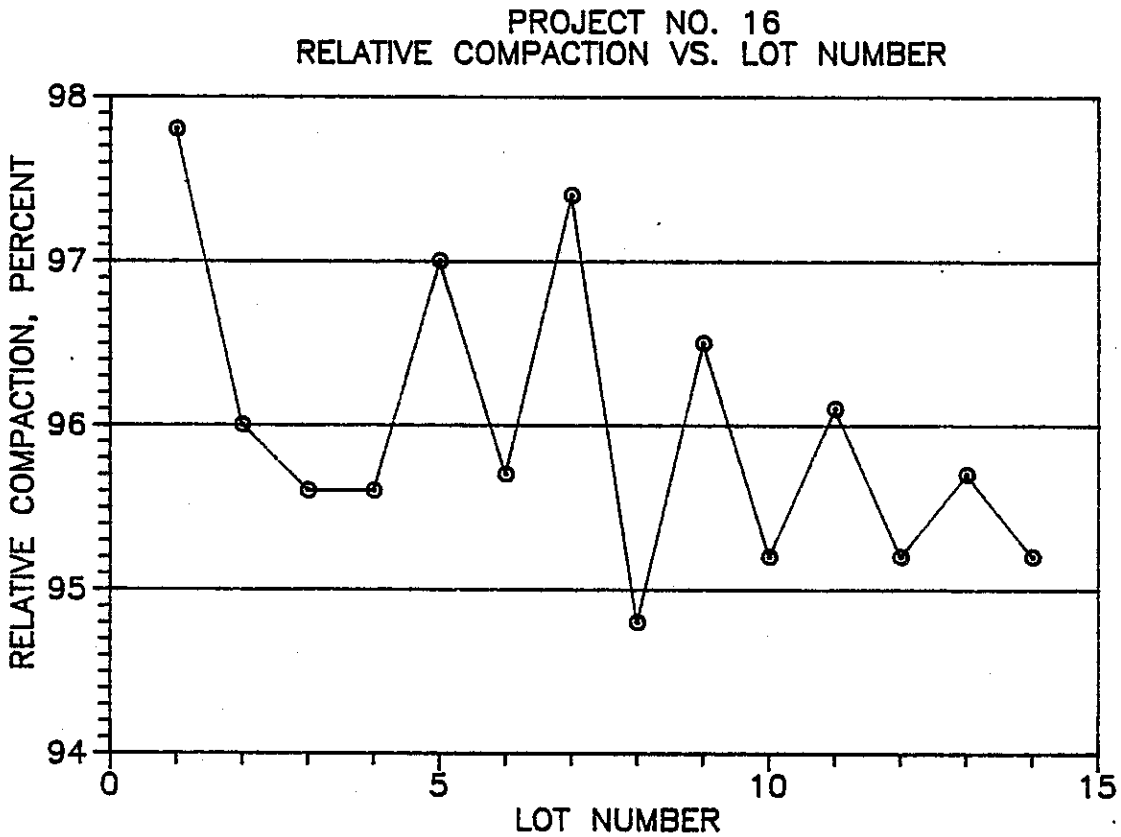
FIGURE 14



SUMMARY:

1. AVERAGE RELATIVE COMPACTION = 96.0%
2. STANDARD DEVIATION = 0.89
3. PERCENT EQUAL TO OR GREATER THAN:

98	0	95	93
97	21	94	100
96	43		

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REFERENCES

1. Alexander, M. L., "Control of AC Compaction Using An End-Result Specification," State of California, Department of Transportation, Transportation Laboratory, Report No. FHWA/CA/TL-85/08, March 1985.

2. California Standard Special Provision 39.03, State of California, Department of Transportation, January 2, 1984.

3. California Test 375, "Determining the In-Place Density and Relative Compaction of AC Pavement," State of California, Department of Transportation, Transportation Laboratory Manual of Test, January 1985.

4. Standard Specifications Section 39-6, State of California, Department of Transportation, July 1984.

5. Bensen, P. E., Kuhl, D. J., "Precision of the Relative Compaction Test Using Nuclear Gages," State of California, Department of Transportation, Transportation Laboratory, December 1976.

6. Hicks, R. G.; Wilson, James E.; Bell, C. A., "Impact of Variation in Material Properties on Asphalt Pavement Life - Final Report," Oregon Department of Transportation, May 1982.

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DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
Office of Transportation Laboratory
P.O. Box 19128
Sacramento, CA 95819

California Test 375
January, 1985

APPENDIX A

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 conditions 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.)

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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	.159	.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

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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.

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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
.788	.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
.068	.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
.882	.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	.486	.629	.663	.619	.007	.295	.456
.630	.673	.665	.666	.399	.592	.441	.649	.270	.612
.804	.112	.331	.606	.551	.928	.830	.841	.602	.183
.360	.193	.181	.399	.564	.772	.890	.062	.919	.875
.183	.651	.157	.150	.500	.875	.205	.446	.648	.685

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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 text 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 acording to the procedures for making stabilometer test speciments 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 by following the procedures in California Test 308, Method A.
   d. Calcuate the TMD by averaging the densities of the five briquettes to the nearest 0.01 g/cc.

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 vertification 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. 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. Calcuate the relative compaction (RC) of the lot to the nearest 0.1 percent.

$$RC = \frac{\text{Average In-place Density}}{\text{TMD}} \times 100$$

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

REFERENCES

A California Method
End of Text 5 Pages on 375

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APPENDIX B

California Standard Special Provision 39.03
(Caltrans' End-Result Specification for Compacting
AC Pavements)

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

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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		

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APPENDIX C

California Standard Special Provision 39.01
(Caltrans Supplemental Specification to Control
The Thickness of AC Layers)

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

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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

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APPENDIX D

Standard Specifications

STATE OF CALIFORNIA

DEPARTMENT OF TRANSPORTATION

JULY, 1984

Selected Portions of

SECTION 39

ASPHALT CONCRETE

(Caltrans'Method Specification for Placing and Compacting AC Pavement)

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

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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-

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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.

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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.

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(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."

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