EVALUATION OF BITUMINOUS COMPACTION PROCEDURES USING NUCLEAR GAGES

Richard L. Grey, Bureau of Materials, Testing and Research, Pennsylvania Department of Transportation

A study was conducted by using nuclear gages to evaluate present bituminous construction procedures. Specifically, nuclear density tests were taken both during roller operations and after compaction had been completed. The density data were analyzed to study the feasibility of using nuclear gages to establish optimum rolling patterns for several different types of bituminous pavement materials for the rollers encountered. After final compaction, continued nuclear tests were taken in a study of any density variations in the compacted pavement. Density tests were taken transversely, on joints, along the pavement edges, along the longitudinal wheelpath areas, and in random locations along the pavement. Areas of low density appeared to be predominantly the joints and pavement edges. A separate study was conducted with 2 commercially available nuclear density gages to evaluate the effective depth of measurement. Both backscatter and air-gap techniques were analyzed. The air-gap density test was shown to be dependent on only the top 1¾ in. of material tested using the test method described.

•THE USE of nuclear gages for the determination of density and moisture has gained widespread acceptance in the past several years. Recent samplings show that nearly all states now use nuclear gages for specification control or are at least investigating the technique seriously prior to specification adoption. Early reluctance to accept nuclear devices revolved about the unwillingness to set aside techniques that had been in existence since the evolution of compaction control. Significant studies by Ballard and Gardner (1) evaluated nuclear gage techniques, and minimization of inherent errors has been accomplished as reported by McDougall, Dunn, and Gardner (7). Nuclear gages can no longer be questioned as to validity.

With the acceptance of nuclear gages for the determination of soil density and moisture, it was only natural that the technique be extended to bituminous compaction control. Because the theory of the nuclear gage on soil is completely analogous to bituminous materials, with only the temperature of the material being different, the techniques are readily applicable to compaction control of bituminous concrete construction. The advantage of nondestructively testing the compaction of hot bituminous material in situ is obvious.

Previous methods of determining bituminous concrete density usually consisted of removing cores or slabs of the finished bituminous mat after completion of compactive effort. These samples were then removed to the laboratory and tested by volumeter methods to ascertain their density and compare this to preestablished minimum control figures of optimum compaction. Inherent problems were that the samples left areas of the pavement to be patched; expensive equipment and trained crews were required for obtaining the samples; and, most significantly, samples were taken after pavement rolling had been completed. Thus, a lack of compaction as may have been shown by testing these samples could not be corrected because the pavement was already cooled and additional rolling usually accomplished nothing. The final result,

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nonetheless, was a bituminous concrete base course or pavement that was neither properly nor uniformly compacted, which often resulted in pavement degradation or failure after several years.

An additional problem prior to the advent of nondestructive testing was in the compactive effort itself, that is, the optimum number of passes to be made by the rollers approved for the job of compacting the hot mix to its optimum density. The number of passes to be made by a particular roller was usually decided by the roller operator who had developed a "feel" for compaction through years of experience. Operator judgment may have been surprisingly good in many cases, but compaction nevertheless was a hit-and-miss proposition dependent on the experience and "feel" of the equipment operator.

Because nuclear gages can rapidly test the hot mix nondestructively after each pass of the roller in operation, it was the intent of this project to evaluate current compaction procedures as to uniformity and overall effectiveness on hot bituminous materials and to investigate the validity of compaction control by nuclear density gages while the job is in progress.

FIELD-TESTING PROCEDURE

The primary objectives of this project were an evaluation of existing compaction techniques and the development of testing techniques by nuclear gages to control bituminous concrete compaction while the job is in progress.

Previous reports have shown the validity of nuclear testing applied to bituminous construction. An excellent list of references pertaining to the use of nuclear testing devices on bituminous materials is included in a report by Metcalfe, Averitt, and Larue (2). A recent study by Worona (3) entailed the use of several gage designs on various thicknesses and grades of bituminous mixes over several base courses. The final analysis consisted of thousands of tests by nuclear gages compared to 1,200 cores and 300 slab tests. Results showed that nuclear tests were compatible with conventional tests for the materials tested.

For this investigation several nuclear gages were used to gather data. These gages had previously been used in the study mentioned earlier so that no new gage variables or designs were introduced.

Data were gathered over a period of 2 construction seasons from 70 projects. Each job was designated by a code, and information was obtained for classifying the location of the project; the test dates; the model, manufacturer, and weight of rollers and weight ballast with each; the paver model; the base course; the material used for base and wearing course; and the design density and asphalt content of the design mix. All data were recorded on computer format forms for direct conversion to punch cards for analysis by computer.

On any individual project, a 2-phase study of compaction was carried out. First, readings of bituminous density were taken after placement of material by the paver but prior to any roller compactive effort and after each individual pass of any roller used on the job. The speed of the paver and each roller used and the temperature at the beginning and end of each roller phase were recorded. Gages were properly standardized and calibrated at the start of each day prior to testing, and all final density readings were corrected for photoelectric absorption effect by the air-gap technique after final compaction (4). A detailed explanation of the theory governing the determination of density, moisture, and asphalt content by nuclear methods may be found in another report (1). No attempt was made to control compaction by use of the gages; rather, compaction was left to the discretion of the roller operator and inspector and to the nuclear gages used to observe results of the methods of compaction employed. Each gage was initially outlined with talcum powder on the bituminous concrete so that it was placed in the same spot after each roller pass to minimize surface roughness errors and lateral positioning errors. Also, during testing, each gage was placed parallel to the direction of paving. This placement technique alleviated problems of seating the gage properly during the rubber-tire rolling.

Throughout this report, a roller pass means one traverse over a given spot in one direction.

After all rollers had made the number of passes deemed necessary based on the material temperature and the judgment of the roller operator and inspector, the area was considered to have reached final compaction. The second phase of the compaction study using nuclear gages was then carried out. This phase entailed a detailed study of the uniformity of compaction and sought to locate any cyclical variations in density if these proved apparent. Density tests conducted during this phase consisted of the following:

Test	Location
Transverse	From right edge to left edge of pavement in 1-ft increments
Right edge	Along right edge of pavement, usually about 1 ft in from edge, at 2-ft increments longitudinally for at least 100 ft
Left edge	Along left edge of pavement, usually about 1 ft in from edge, at 2-ft increments longitudinally for at least 100 ft
Longitudinal right lane	In middle of right lane at 2-ft increments for at least 100 ft
Longitudinal left lane	In middle of left lane at 2-ft increments for at least 100 ft
Longitudinal center joint	Along longitudinal center joint at 2-ft increments for at least 100 ft
Random	At locations decided by table of random x- and y-coordinates. Coordinates were measured by a 100-ft tape, and tests were taken at each coordinate position. Fifty random tests were taken in a 500-ft section.

Data for 4 of the largest jobs encountered are given in Table 1. Many thousands of additional tests were taken on approximately 70 separate construction projects. These four are representative of the whole in compaction trends and variation. Each reading given in Table 1 is an average of approximately 200 individual readings at selected stations.

Although overall tests were very near or above compaction requirements, many of the individuai tests fell far below an acceptable density figure. This appeared much more prevalent on the longitudinal center joint and on the left and right edges of the pavement where, it seems, roller compactive effort is neglected most as was visually noted in the many projects observed.

Poorest compaction was realized along the edges of the pavement. In many cases it was noticed that only one pass was made with each roller in these areas. Samples taken

TABLE 1

COMPACTION FOR FOUR REPRESENTATIVE JOBS

Test	Density (pcf)				Standard Deviation (pcf)				Compaction (percent)			
	Job 1	Job 2	Job 3	Job 4	Job 1	Job 2	Job 3	Job 4	Job 1	Job 2	Job 3	Job 4
Transverse	136.8	138.4	149.3	141.0	5.0	5.3	3.9	3.6	100.3	97.0	98.5	94.4
Longitudinal center joint	130.4	141.6	148.8	140.5	4.4	4.7	4.1	2.0	95.6	99.2	98.2	94.4
Left edge	129.1	129.0	144.2	137.2	3.1	3.7	2.9	3.2	94.6	90.4	95.1	91.8
Right edge	134.8	133.9	144.8	137.2	2.7	2.9	2.9	3.1	98.8	93.8	95.5	91.8
Longitudinal left lane	135.5	141.3	151.3	141.7	3.6	4.5	3.1	3.0	99.3	99.0	99.8	94.8
Longitudinal right lane	141.0	141.7	148.5	144.4	3.7	4.2	4.2	3.5	103.4	98.9	98.0	96.6
Random	138.2	138.3	149.0	141.2	5.5	5.3	4.2	4.2	101.3	96.9	98.3	94.5

Notes: Material for jobs 1, 2, and 3—ID2 wearing, 2 in. thick over ID2 binder; for job 4—bituminous concrete base course, 2 in. thick over base course. Marshall design density for job 1—136.4 pcf, 95 percent or 129.6 pcf required; for job 2—142.7 pcf, 95 percent or 135.6 pcf required; for job 3—151.6 pcf, 95 percent or 144.0 pcf required; for job 4—149.4 pcf, 90 percent or 134.5 pcf required.

TABLE 2

ROLLING PATTERNS

Job	Station	Breakdown Roller		Rubber-Tire Roller		Finish Roller		Temperature of Mat (deg F)		Final Density (lb/ft^3)
		Passes	Speed (mph)	Passes	Speed (mph)	Passes	Speed (mph)	Behind Paver	After Compative Effort	
1	035008	6	2.3	5	5.8	2	4.9	277	169	136.6
	035009	3	1.8	3	4.3	7	5.4	294	188	140.1
	103008	2	1.8	2	5.4	1	5.5	253	154	136.7
	103009	1	3.0	6	4.1	3	4.3	291	144	134.1
	121008	2	2.6	4	5.5	5	3.9	288	136	142.0
	121009	3	1.9	6	4.6	1	2.8	267	122	135.3
2	171008	2	1.0	4	5.5	2	1.4	260	180	151.0
	084209	2	4.0	3	6.0	—	—	290	110	144.0
	171009	3	3.6	5	4.5	3	3.9	285	191	152.2
	086108	1	2.2	4	5.5	5	4.0	272	170	147.3
	077308	3	3.0	3	3.9	6	3.5	254	168	141.8
	077309	5	4.1	—	—	1	5.1	293	132	142.8
	093408	2	2.6	5	5.3	5	4.8	287	148	151.4

as cores or slabs for compaction acceptance, however, are usually taken from the wheelpath area of the pavement (longitudinal left or right lane), which would indicate acceptable densities. This, of course, is not representative of actual compaction near the pavement edges. With nuclear testing, however, many more tests may be taken while a project is still progressing to indicate areas of low density so that the condition may be rectified by additional rolling.

As mentioned previously, no attempt was made to control the rolling operations on any of the projects. Data were taken, however, for densities versus the number of passes of each roller, including the speed of the roller and temperature of the mix at the time of each pass.

Data are given in Table 2 for two of the projects described earlier. Each set of data was taken at a different station on the pavement. The last digit of each station number, 8 or 9, indicates the right or left lane respectively. There was little, if any, methodology to rolling patterns. Speeds remained somewhat constant for a given roller, and the limited speed ranges are too narrow to attempt any analysis of roller speed versus compactive effort.

In many cases, there was a definite time lag before rolling operations proceeded after placement of the uncompacted mat and an even greater time gap between different rollers. During most of the jobs encountered, the ambient temperature was in the 70 to 90 F range. With cooler ambient temperatures such as the 40 F required minimum, such time lags would undoubtedly hamper compactive effort because rapid material temperature drop between successive rollers.

Because of the large variation in actual passes by each roller, it would be extremely difficult to set forth suggestions as to optimum number of passes for each roller. Also, each individual type of material requires a different roller pattern for optimum density. The only way to set forth optimum rolling patterns is to establish them at the beginning of each job on a given bituminous material. As long as the material remains resonably constant, the pattern set forth at the beginning should yield optimum compaction for the entire project.

However, decompaction can occur because of overrolling the bituminous mat. This occurs when too many passes are made, particularly with the breakdown roller, and the material is pushed out from under the roller, resulting in a thin mat of widely separated aggregate. Thus, care must be taken not only to establish an optimum minimum number of passes but also to see that decompaction does not result from too many roller passes. Either extreme is undesirable but may be excluded by taking nuclear density tests after each roller pass.

It appears further that much closer control is required so that rolling begins immediately after placement of the bituminous mat and progresses so that large time lags do not occur between start and finish of rolling over a given area as indicated by the rather large temperature differentials given in Table 2.

Wearing courses offering good gage seating predominated throughout the project because the variable intended to be studied was compaction as a function of compactive effort. Approximately 15 jobs were, however, coarse-graded mixes ranging from binder materials to bituminous concrete base courses. These usually had 100 percent passing the 1½- or 2-in. sieve compared with 75 to 100 percent passing the ⅜-in. sieve for the fine-graded wearing courses.

No serious problems of seating the nuclear gages on the course-graded bituminous mixes occurred as originally expected because of the open-surface texture. When the hot material was placed, the gage was easily seated. The soft nature of the material resulted in intimate gage-surface contact.

DEPTH OF PENETRATION STUDY

The depth of penetration of the nuclear gages was investigated at this time. Manufacturers of gages designed specifically for use on bituminous materials had usually claimed that the devices considered only the top 2½ in. of material, which is about the maximum to be expected in wearing course construction of bituminous pavement.

Tests were performed by inverting the nuclear gages—a nuclear Chicago asphalt density gage, model 5846, and a Troxler Electronics, Inc., asphalt density gage, model A-240F—and placing a 4-sided wooden box, which form-fitted the gage bottom area, directly over the gage bottom. This allowed material to be poured into the box so that the gage effectively "saw" only the material admitted to the box. Glass beads normally used for the reflectorization of traffic paint were then poured into the molds at ½-in. increments, and counts were taken after each successive layer. The glass beads had a density of approximately 98 lb/ft^3. Although this is much less than will be encountered in bituminous construction, uniformity of the sample was excellent and provided a clean material very easy to handle.

Both gages experienced a maximum count differential at 1½ in. (count at some depth minus count at immediately preceding depth), and both further exhibited 50 percent of final count achieved at very nearly 1 in. This is about ½ in. less than studies on soil density-moisture gages as shown previously by Weber (5).

On this low-density material, both gages further exhibited that 90 percent of the final count was due to approximately the first 3 in. of material. Use of a material of greater density, more closely approximating bituminous pavement material, would probably have decreased this depth to the 2½-in. range that was claimed by the manufacturers. Because most wearing courses are placed over a binder of similar properties and density as the top course, the sphere of influence of the asphalt density gages tested appeared satisfactory. If a thinner wearing surface is placed over a more dense base course such as concrete, however, allowances will have to be made for the scattering of gammas by the dense base resulting in erroneous density readings if the gage is used only in the Compton backscatter surface mode.

A "worst case" was included in the study to check the mechanics of such an occurrence and to examine the effect of an exaggeratedly dense base course. Glass beads were again placed in ½-in. increments, but now a ½-in. thick block of aluminum, approximately 170 lb/ft^3, was placed on top of each successive layer of beads. In this case, 62 percent of the final count achieved was due to the top 1-in. layer of beads compared to 50 percent found previously without the aluminum base. Also, 96 percent of the final count was due to 3 in. of beads now, rather than 90 percent found previously. A definite effect was produced by a heavier base material, even under 3 in. of material.

Thus, care must be taken to ensure that corrections are applied if thin wearing surfaces are tested over dense base courses by using only surface count readings. If one looks at only the minimum count method proposed by Virginia (6), this correction is unnecessary because the thickness of wearing course and the density of the base are constant.

Because all final readings were corrected for photoelectric absorption by the air-gap method, tests on depth of penetration were also conducted by incorporating an air-gap between the gages and the box. Material was then placed as before in ½-in. increments, and counts were taken at each depth interval. The air-gap space induced was that recommended by the manufacturer. Similar results were obtained for both gages. Inducing an air-gap resulted in 50 percent of the final count being due to approximately the first $\frac{1}{2}$ in. of material, while 90 percent of the final count was due to the first $1\frac{3}{4}$ in. of material. These depths would probably drop with the use of a more dense material. The finding is particularly significant because the inclusion of an air-gap test to obtain the final densities is now more heavily dependent on the wearing course and practically independent of the base course density for surface materials more than $1\frac{1}{2}$ in. thick.

CONCLUSIONS

Although only 4 major bituminous construction projects are listed in this report, similar data were taken on approximately 70 projects. The results listed are indicative of the majority of findings on all projects. Based on the results of this study, the following conclusions can be stated.

1. Present methods of compaction result in a lack of uniformity because rolling patterns are usually left to the discretion of the roller operators.
2. Nuclear devices can readily establish optimum rolling patterns while the job is in progress, and tests may be made at any time to check compaction.
3. Densities at edges are often lower than those for the rest of the roadway, indicating poor compaction control at edges.
4. Very large time lags are often prevalent between the times rolling begins and ends and between successive rollers. In many instances, rollers continued to attempt compaction when the material was so cool that any number of additional passes did not increase compaction. Greater control is necessary to see that rollers advance so that optimum compaction occurs.
5. Nuclear tests point out that there is a trend in transverse compaction.
6. No obvious cyclical trends appeared in any of the longitudinal density studies.
7. For the several different nuclear gages used in the study, the high temperatures had no effect on results, and no major gage malfunctions occurred so long as the batteries in the systems were maintained at proper charge level and the bottom surface kept clean.
8. From the similarity of standard deviations of density results as found by the nuclear gages, the method appears satisfactorily reliable and repeatable for compaction control on bituminous concrete construction projects.
9. Because the bituminous materials, when hot, allowed very good nuclear gage-material surface contact, no serious surface texture errors were prevalent in the use of nuclear gages on hot mixes of widely different gradations.
10. From the results of the compactive effort studies, it would appear that the best method of compaction control on bituminous construction is to establish optimum rolling patterns by the use of nuclear gages, to maintain this compactive effort for a given project with close inspection to see that the pattern is followed on all areas of the roadway at proper temperatures, and to take periodic tests of compaction results while the project is in progress to ensure that optimum compaction is being achieved.
11. Inclusion of an air-gap test to compensate for chemical effects results in density readings dependent more on the wearing surface and minimizes results due to backscatter from dense base courses. At wearing course depths greater than $1\frac{1}{2}$ in., corrections do not have to be applied for dense base effect.

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REFERENCES

1. Ballard, L. F., and Gardner, R. P. Density and Moisture Content Measurements by Nuclear Methods—Interim Report. NCHRP Rept. 14, 1965.
2. Metcalfe, T. B., Averitt, W. K., and Larue, F. L. Asphalt Content by Nuclear Devices. Dept. of Chemical Engineering, Univ. of Southeastern Louisiana, Lafayette, Research Bull., 1968.
3. Worona, V. Evaluation of Nuclear Bituminous Density Gauges. Pennsylvania Department of Highways, Research Proj. 64-15, March 1969.
4. Kuhn, S. H. Effects of Type of Material on Nuclear Density Measurements. Highway Research Record 66, 1965, pp. 1-14.
5. Weber, W. G. Laboratory and Field Evaluation of Nuclear Surface Gages for Determining Soil Moisture and Density. Highway Research Record 66, 1965, pp. 51-70.
6. Hughes, C. S., and Anday, M. C. Compaction Control of Granular Base Material by Use of Nuclear Devices and the Control Strip Technique. Virginia Highway Research Council, Dec. 1966.
7. McDougall, F. H., Dunn, W. L., and Gardner, R. P. Report on Nuclear Soil Gauge Calibration Workshop Symposium. North Carolina State Univ., April 1969.