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FINAL REPORT

EVALUATION OF A NUCLEAR GAGE FOR CONTROLLING THE CONSOLIDATION OF FRESH CONCRETE

by

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Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

Evaluated was an approach to controlling the consolidation of in-place portland cement concrete on the basis of densities obtained with a Troxler 3411 nuclear gage. The gage was used in the backscatter mode on low-slump concrete bridge deck overlays and in both the backscatter and the direct transmission modes on continuously reinforced concrete pavements. The nuclear gage readings were compared to rodded unit weight determinations by ASTM C138.

It was found that the nuclear readings compared favorably with the unit weight values. However, a petrographic examination of the cores taken from the deck and pavement indicated the presence of coarse voids in amounts exceeding those found in adequately consolidated concretes.

It is concluded that the variability in density resulting from acceptable variations in the grading and amounts of individual ingredients of concrete, including the air content, is of of the same order of magnitude or greater than the variability resulting from small but detrimental amounts of large air voids. Consequently, matching nuclear densities with densities obtained by weight per volume measurements does not assure the absence of small but detrimental excesses of large voids. However, the presence of an appreciable amount of honeycombing or excessive air entrainment would be detected by nuclear density measurements.

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PROBLEM STATEMENT

One requirement for good quality concrete is proper consolidation, a process through which fresh concrete is densified by removing entrapped air.(1) The benefits achieved from good consolidation include increased strength and abrasion resistance, enhanced resistance to freezing and thawing and aggressive fluids, reduced permeability, and improved bond to reinforcement or to hardened concrete.(2)

Density measurements are often used to determine the level of consolidation or proper batching of concrete.(2) In this report the terms "density" and "unit weight" are used interchangeably to refer to the weight of the concrete per unit volume, including the voids. Density, or unit weight, can be determined at the fresh stage using ASTM Standard Method C138 but this does not necessarily represent the density of in-place concrete. Another method for determining density is to run tests on cores from the hardened concrete. The drawbacks of the latter method are the variability in results, its destructive nature, and the delayed time of test.

It is desirable to determine the density of in-place concrete at the fresh stage, which is possible through the use of a nuclear gage, so that corrective measures can be taken if necessary. Considering the potential benefits that can be derived from the use of nuclear methods in Virginia, an evaluation of a nuclear gage was planned in the overlay of a bridge deck constructed in two courses and in continuously reinforced concrete pavements (CRCP).

BACKGROUND

Types of Voids

The voids of varying amounts and sizes in concrete affect its properties. Among other causes these voids result from intentionally entrained air, excess water, or entrapped air because of incomplete consolidation. The presence of voids, particularly in the large sizes, usually causes a reduction in strength. However, entrained air voids in specified amounts are necessary for resistance to freezing and thawing for concrete exposed to weathering and saturation. Water voids are present in concrete, but their amount and size can be minimized by proper proportioning. Excess water voids increase the permeability of concrete considerably and should be avoided. The remaining voids, the entrapped air voids, are undesirable and can be reduced by proper consolidation.

Adequate Consolidation

There is no generally accepted definition of "adequate consolidation". Several criteria can and have been used. For example, it could be defined in terms of (1) maximum density, (2) maximum strength, (3) resistance to chloride penetration, etc. But judging the adequacy of consolidation on the basis of maximum density or maximum strength is complicated by the fact that some voids classified as entrained air voids are removed by continued consolidation, and their removal reduces the total volume of voids and thus increases the density or strength such that no definitive end point can be identified.

Because the adequacy of consolidation is most desirably determined before the concrete hardens, recent research has been directed toward the in-place measurement of density by methods such as nuclear gages. In these studies the criteria for adequate consolidation have been based upon achieving sufficient consolidation to create resistance to chloride penetration. With this approach, which has been widely accepted nationwide, it is suggested that desired consolidation is achieved when the measured in-place density is at least 98% of the rodded unit weight.(3)

For the purposes of this project, adequate consolidation was defined in terms of definitions established by ACI Committee 116. That committee defines compaction, which is synonymous with consolidation, as

> The process whereby the volume of freshly placed mortar or concrete is reduced to the minimum practical space, usually by vibration, centrifugation, tamping, or some combination of these; to mold it within forms or molds and around embedded parts and reinforcement, and to eliminate voids other than entrained air.(4)

Its definition of entrapped air, stated below, indicates that these are voids other than entrained air.

> Entrapped Air — Air voids in concrete which are not purposely entrained and which are significantly larger and less useful than those of entrained air, 1 mm or larger in size.(4)

Thus, to be consistent with these definitions properly consolidated concrete would be judged on the basis of the amount of coarse voids larger than 1 mm present, which can be determined only at the hardened stage. At the Research Council, the linear traverse method is used on concrete specimens in accordance with ASTM C457 to determine void system parameters, including the total air content, specific surface, and the spacing factor of the bubbles. In addition, the voids are separated into two groups: those smaller and those larger than 1 mm (0.04 in.) maximum diameter on the lapped surface. Those larger than 1 mm are called coarse voids; they are entrapped air or water voids that result from a lack of consolidation or from excess water in the mixture. Experience at the Research Council indicates that in good quality concretes, coarse void contents are generally less than 2% in hardened concrete. This value relates well to the percentage of air in the matrix of non-air-entrained concretes reported by Powers,(5) which calculates to about 1.6% air in the low-slump concretes studied. Consequently, in this project concretes containing less than 2% of voids greater then 1 mm in the hardened stage were accepted as being properly consolidated. However, it is desired to establish a procedure for determining the degree of consolidation at the fresh stage. To this end, the widely used criterion of a nuclear gage reading exceeding 98% of the rodded unit weight was examined.

FHWA Survey on Nuclear Gages

To determine the level of consolidation, density (or unit weight), measurements are employed. If these measurements can be made on concrete at the fresh stage and the results found to be unsatisfactory, corrective measures could be taken to improve the consolidation. Nuclear gages have potential for measuring the densities of fresh concretes.

To determine the usefulness of these gages for monitoring the in-place density of fresh portland cement concrete, the Federal Highway Administration (FHWA) surveyed state highway departments in late 1977.(6) The issues considered in the survey included the extent of use of nuclear gages, the purposes for which they were used, the operating modes employed and the density standards and calibration methods used. It was found that 11 states were using the gages extensively and 16 others were evaluating or planning to evaluate them. Use of the gages for in-place density measurements was primarily on low-slump concrete overlays; however, full-depth bridge decks and pavements were also being monitored. The gages were being used in both the direct transmission mode, where the probe is immersed in concrete, and the backscatter mode, where the probe is held in the gage placed on the surface. In the backscatter mode it is also possible to use the gage raised above the surface to allow an air gap between the gage and the material being tested, but this method has limited use.

Both the direct transmission and the backscatter methods have been found to have drawbacks. In the direct transmission method, insertion of the probe is limited by the thickness of the overlay. A solution involves the placement of test wells at selected areas. Cleaning the probe after tests is another problem that requires attention.

The backscatter method is more sensitive than the direct transmission mode to the chemical composition of aggregate and both may require use of a correction factor. Several states have indicated, however, that they have experienced difficulty in obtaining valid correction factors. There is also concern about the response of the gage if it is placed above a reinforcing bar, especially when the bar is close to the surface. One other problem with backscatter measurements has been the need to account for the roughness of the surface on which the gage is seated in taking measurements. However, the newer gages, such as the Troxler 3411, are designed to be less sensitive to surface roughness.

Besides choosing the operating mode, it is necessary to select a density standard and percentage compaction requirement . Most of the states determine the rodded unit weight as the density standard, but difficulties are encountered in fully consolidating the unit weight bucket.(6) Some states have tried vibrated and theoretical unit weights, but a satisfactory solution has not been found.

The most commonly used percentage compaction requirement is that the minimum nuclear gage reading be 98% of the rodded unit weight. This percentage is based on the results of a study that concluded consolidation was not adequate to provide resistance to penetration of chloride in bridge decks, unless the in-place density equalled or exceeded this percentage of the rodded unit weight.(3)

TESTS WITH NUCLEAR GAGE

Procedure

The nuclear gage used in this study was a Troxler 3411 model. Before readings were taken, the nuclear gage was warmed up and a count was taken on a reference standard.[7] The standard count was checked against a value furnished by the manufacturer, and if the reading was within 2% of the given value it was assumed to be satisfactory.

After the standard was checked (all standard counts made in the study were within the 2% tolerance), the gage was placed on a container filled with fresh concrete from the project and a count taken to determine a correction factor for the effect of the materials on the gage readings. The nuclear gage used contained a full data processor that provided a direct display of the density measurement. The difference between the gage reading and the ratio of the measured weight of the concrete to the volume of the container was taken as the correction factor.

The gage was then placed on the bridge deck or the pavement to be tested and 1-minute readings were taken and corrected by the above factor.

Precision

To determine the precision of the nuclear gage, it was placed on low-slump concrete having gravel as the coarse aggregate and a water-cement ratio of 0.345. Thirteen 1-minute readings were taken without moving the gage. The coefficient of variation of these 13 readings was 0.4%. The precision was also checked in the laboratory on a concrete with crushed stone as the coarse aggregate, a cement content of 635 lb. (288 kg), and a water-cement ratio of 0.47. The 15 readings taken at one location on this concrete had a coefficient of variation of 0.5%.

Numbers of Tests

As can be seen in Table 1, 324 nuclear gage readings were taken in the backscatter mode and 122 readings in the direct transmission mode for determining the correction factors and the in-place readings. Eleven correction factors for the gage readings in the backscatter mode were obtained on the bridge deck and four on the CRCP. Four were also determined on the CRCP in the direct transmission mode.

TABLE 1

Tests Conducted and Number of Measurements Made

Test	No. of Measurements
Nuclear Gage Density Readings:	
Backscatter mode	324
Direct transmission	122
Unit Weight (ASTM C138)	15
Air Content:	
Fresh Concrete (ASTM C231)	15
Hardened Concrete (Linear Traverse)	8
Absorption	10

Mode of Tests

The nuclear gage was used in the backscatter mode on overlays of low-slump portland cement concrete (PCC) on a bridge deck at Port Royal and in both the backscatter and the direct transmission modes on CRCP's around Richmond. These deck overlays were studied as part of an evaluation of the use of low-slump concretes in bridge decks, the results of which are given in another report.(8)

Percentage of Rodded Unit Weight

Unit weights of fresh concretes were determined in accordance with ASTM C138 utilizing rodding and vibration. Air contents were measured and the unit weights were then corrected to the average specified air for the project.

The ratio of the corrected in-place nuclear gage density to the corrected unit weight of fresh concrete multiplied by 100 is called the percentage of rodded unit weight and was to be 98% or more for adequate consolidation. The procedure for determining the percentage of rodded unit weight with the nuclear gage is summarized in Table 2.

TABLE 2

Determination of the Percentage Rodded Weight with Nuclear Gage

Correction Factor (C)	=	$\frac{w}{v}$ container - gage density reading
Corrected in-place gage density	=	in-place gage density + C
Corrected unit weight	=	unit weight (ASTM C138) $\frac{(1\text{-air specified})}{(1\text{-air measured})}$
Percentage of rodded unit weight	=	$\frac{\text{corrected in-place gage density}}{\text{corrected unit weight}} \times 100$

OVERALL TESTING PROGRAM

Bridge Deck Overlay

The bridge deck at Port Royal was constructed using two-course construction; the overlay on the northbound lanes (NBLs) was placed in late 1978, and that on the southbound lanes (SBLs) in 1979. Both overlays consisted of 2 in. (50 mm) thick low-slump concrete. They contained gravel coarse aggregate and siliceous sand, and the cement content was 823 lb. (374 kg). Low-slump concrete has a very stiff consistency and requires a special vibrating screed for consolidation.

Northbound Lanes

Slump, Air Content, and Unit Weight of Fresh Concrete

The low-slump concretes in the overlay on the NBLs were tested for slump, air content, and unit weight. A container made of 3/4 in. (19 mm) plywood and measuring 21 x 27 x 5 in. (530 x 690 x 130 mm) was used to determine the correction factor for the gage readings. The specimens were consolidated by (1) rodding and tapping, or (2) rodding, tapping, and using an external vibration consisting of a vibrating table at a frequency of 3,300 cycles per minute, or (3) rodding, tapping, and using external vibration with a surcharge of 50 lb./ft.^{2} (2.39 kPa). The results of slump, air content, and unit weight by method of consolidation are given in Table 3.

The nuclear gage readings on the container, the unit weights of the container, correction factors, and the unit weights determined by ASTM C138 corrected for a specified air content of 5.5% are given in Table 4. For the NBLs, the factor used in correcting the in-place nuclear gage readings was obtained by averaging the factors from the first 5 batches for a w/c of 0.328 and from batches 6-8 for a w/c

TABLE 3

Properties of Fresh Low-Slump Concretes for NBLs
(The method of consolidation is indicated as R for rodding, and tapping, E for external vibration, and S for application of a surcharge.)

Batch	W/C	Slump, in.	Air, %	Unit Weight, lb./ft.^{3}	Method of Consolidation
1	0.328	3/4	14.0	137.3	R
2	0.328	1/4	4.9	147.0	R
3	0.328	1/4	5.8	148.6	R
4	0.328	1/4	6.2	144.2	R + E
5	0.328	1/4	7.2	142.7	R + E
6	0.345	1/8	5.8	145.8	R
7	0.345	5/8	7.0	144.2	R + E + S
8	0.345	3/4	7.4	142.2	R + E

Note: 1 in. = 25.4 mm

1 lb./ft.^{3} = 16.01 kg/m^3

1 psi = 6.89 kPa

TABLE 4

Nuclear Gage Correction Factors and Corrected Unit Weights for NBLs in lb./ft.^{3}

Batch	Gage Readings on Containers: No.	Wet Density	Std. Dev.	Container Unit Weight	Correction Factor	Corrected Unit Weight
1	3	129.7	0.4	132.0	2.3	150.9
2	3	149.4	0.5	147.6	- 1.8	146.1
3	3	148.5	0.6	148.3	- 0.2	149.1
4	3	147.7	0.5	146.3	- 1.4	145.3
5	3	148.8	1.1	144.8	- 4.0	145.3
6	3	144.3	0.3	150.1	5.8	146.3
7	3	147.6	0.6	144.7	- 2.9	146.5
8	3	142.0	0.7	143.5	1.5	145.1

Note: 1 lb./ft.^{3} = 16.01 kg/m^3

of 0.345, as depicted in Table 5. Table 5 also includes the average unit weight and the average corrected unit weight values for two water-cement ratios. The first batch had an unacceptably high air content. Therefore, in obtaining the average unit weight it was excluded from the calculations. However, in determining the corrected unit weight it was included since it is corrected for the proper amount of air.

TABLE 5

Summary of Data for Correction Factors and Unit Weights for NBLs in lb./ft.^{3}

		Correction Factor		Unit Wt.		Corrected Unit Wt.	
Batches	w/c	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
1-5	0.328	- 1.0	2.3	145.6*	2.7	147.3	2.5
6-8	0.345	1.5	4.4	144.1	1.8	146.0	0.8

* First batch excluded.

Note: 1 lb./ft.^{3} = 16.01 kg/m^3

In-place Density Measurements on Fresh Concrete

Nuclear gage measurements in the backscatter mode were made on the bridge deck overlay from a work bridge located behind the screed. The width of the overlay was approximately 17 ft. (5.2 m), and 3 gage readings were obtained along a direction transverse to the centerline; 1 in the middle and 1 about 3 ft. (0.9 m) from each end.

The first 3 readings were taken on an area with a w/c of 0.328. The span was the first to be overlaid and the first batch of concrete tested had an air content of 14% as was shown in Table 3. After the nuclear gage readings were taken, the screed broke down, causing removal of the overlay concrete. The corrected in-place gage readings were 134.4, 134.1, and 137.4 lb./ft.^{3} (2152, 2147, 2200 kg/m^3), and the percentages of rodded unit weight were 0.91, 0.91, and 0.93, respectively.

Afterwards, 114 gage reading measurements were taken on 7 spans; 69 of the readings were on areas with a w/c of 0.328 and 45 on areas with a w/c of 0.345. The average corrected in-place nuclear density value for 69 readings was 148.1 lb./ft.^{3} (2371 kg/m^3), with a coefficient of variation of 1.4%; that for 45 readings was 146.6 lb./ft.^{3} (2347 kg/m^3), with a coefficient of variation of 1.2%. The percentage of rodded unit weight was determined utilizing the correction factors and the corrected unit weights given in Table 5. Figures 1 and 2 are histograms showing the number of gage readings the percentages of rodded density for two water-cement ratios. For a w/c of 0.328, only 2 out of 69 values exhibited percentages of rodded density lower than 98%, the assumed minimum level acceptable, and for a w/c of 0.345 only 1 out of 45 values was below 98%.

Petrographic Examination and Absorption of Cores

Cores of the overlay concrete from the NBLs were subjected to petrographic examination and absorption tests. The petrographic examination consisted of a linear traverse analysis and microscopic observations to determine the uniformity of the void system and the nature of the larger voids. As can be seen in Table 6, the linear traverse results showed an average coarse void content of 3%, which exceeds the desired amount of 2.0% or less for good quality concretes. In these low-slump concretes, the coarse voids are attributed to a lack of consolidation because of the stiffness of the mixtures. The microscopic examination of these and other concrete specimens from the study verified the linear traverse results.(6)

TABLE 6

Linear Traverse Analysis of Cores

Sample	w/c	Voids, %			Specific Surface, in.$^{-1}$	Spacing Factor, in.
		>1 mm	<1 mm	Total		
1, 2, 3	0.328	3.3	4.6	7.9	633	0.0060
3A	0.328	2.9	5.2	8.1	606	0.0061
13	0.345	2.6	3.7	6.3	550	0.0084
18	0.345	3.0	4.3	7.3	517	0.0084

Note: 1 in. = 25.4 mm

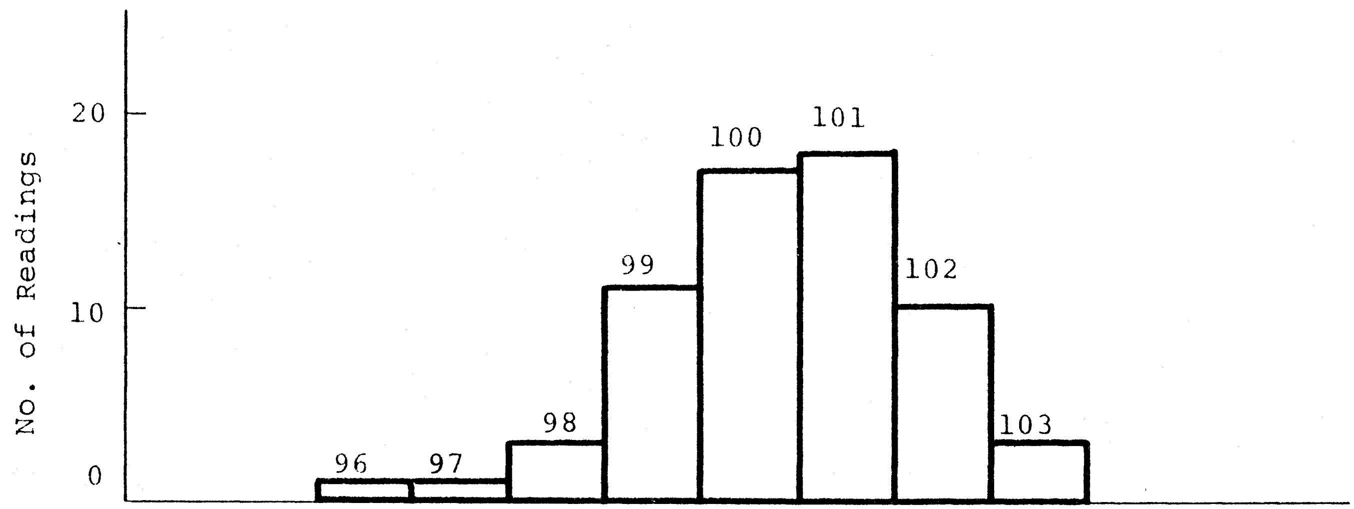

Figure 1. Percentages of rodded weight for 69 readings on low-slump concrete, for NBLs with a w/c of 0.328.

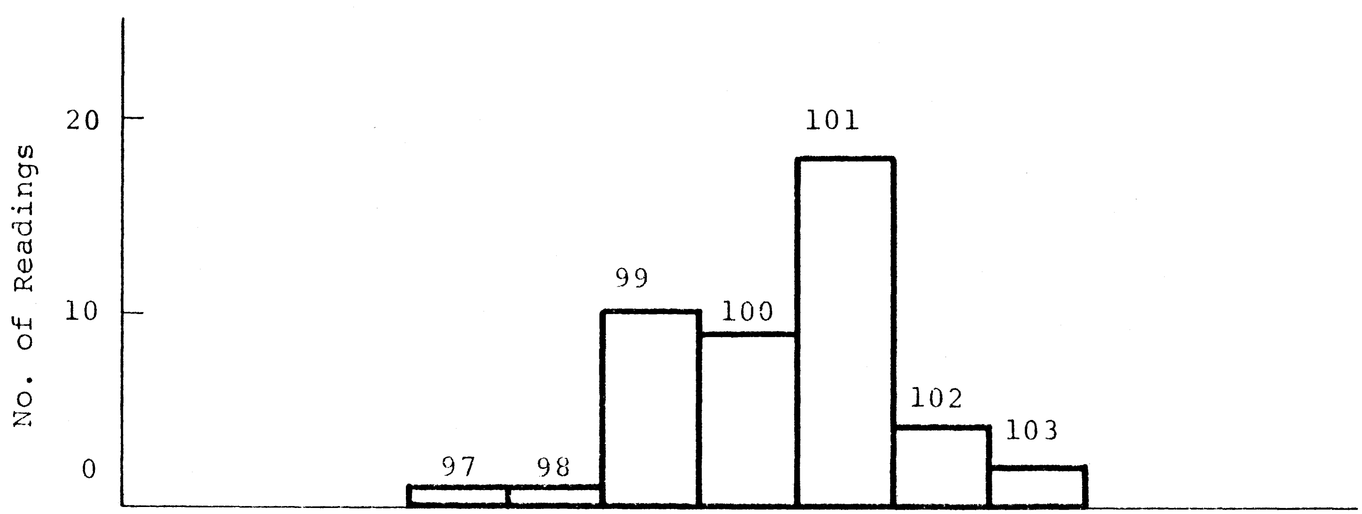

Figure 2. Percentages of rodded weight for 45 readings on low-slump concrete, for NBLs with a w/c of 0.345.

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The absorption data indicated accessible pore spaces and thus are related to the level of permeability and consolidation. As shown in Table 7, cores from the NBLs had absorption values averaging 5%. Good quality concretes are generally expected to have absorption values around 4%.(8)

The unit weights of cores were also determined after immersion (ASTM C642) and were found to range from 146.0 to 146.6 lb./ft.^{3} (2337 or 2347 kg/m^3), as given in Table 7.

TABLE 7

Absorption and the Unit Weight of Cores
After Immersion (ASTM C642)

w/c	Absorption, %	Unit Wt. lb./ft.^{3}
0.328	4.7	146.6
0.345	5.2	146.0
0.345	5.0	146.6
0.345	4.6	146.0
0.345	5.6	146.6
0.345	5.2	146.6

Note: 1 lb./ft.^{3} = 16.01 kg/m^3

Summary and Results

Most of the nuclear gage readings on fresh overlay concrete were above 98% of rodded unit weights, a value established as indicating satisfactory levels of consolidation. In fact, the average corrected in-place gage readings for water-cement ratios of 0.328 and 0.345 were 0.5% and 0.4%, respectively, higher than the average corrected unit weight measurements. However, the petrographic examination and the absorption values for cores from the hardened overlay showed undesirable amounts of coarse voids. The in-place overlay concrete and field specimens consolidated by mechanical vibration generally exhibited a higher amount of coarse voids than the manually prepared, vigorously tapped specimens.(8) However, the difference was within one or two percentage points. While the unit weights of the specimens prepared by vigorously tapping the unit weight bucket are expected to exhibit higher densities than the in-place overlay concrete, the nuclear densities were slightly higher than the corrected unit weights. This difference could be attributed to the difficulties in achieving satisfactory correction factors for the nuclear density measurements and to the deviation of the average field air content from that of the specified value. The above findings introduce a question of whether or not the criterion established on the basis of density values provides assurance in all cases that satisfactory compaction has been attained.

Considerable variations were encountered in the determination of correction factors and the unit weights on low-slump concretes. An attempt was made to calculate the percentage of rodded unit weight based on a theoretical unit weight rather than the corrected unit weight which employs a unit weight bucket. The theoretical unit weight for a w/c of 0.328 was 144.2 lb./ft.^{3} (2309 kg/m^3) and that for a w/c of 0.345 was 143.4 lb./ft.^{3} (2296 kg/m^3). These unit weights are smaller than the corrected unit weights, which would lead to slightly higher percentages of rodded unit weight values, and would still indicate that the percentage of rodded weight values are satisfactory even though undesirable amounts of coarse voids are present.

Southbound Lanes

For the overlays on SBLs placed a year later the NBLs, the correction factors were determined using a metal container, which had a better dimensional stability, rather than the wooden container used earlier. The metal container, depicted in Figure 3, was 22.5 in. (570 mm) in diameter and 5 in. (130 mm) deep. The gage was placed at four locations on the container rotated at 90^o apart, and 3 readings were taken at each location. For the three batches of fresh concrete tested for the SBL, the results of slump, air content, and unit weight and the method of consolidation are given in Table 8. The correction factors and the corrected unit weights are shown in Table 9. The average correction factor was -1.7 lb./ft.^{3} (-27 kg/m^3), average unit weight 147.3 lb./ft.^{3} (2358 kg/m^3), and the average corrected unit weight 146.0 lb./ft.^{3} (2337 kg/m^3).

For these overlays, 9 in-place nuclear readings gave an average corrected density reading of 148.0 lb./ft.^{3} (2370 kg/m^3), with a coefficient of variation of 0.9%. This reading is 1.4% higher than the average corrected unit weight reading. Two of the readings attained percentages of rodded unit weight of 100, another 101, and the remaining seven 102, all of which were better than the desired 98% value. Cores were not taken from the SBLs.

Paving Concrete

The nuclear gage was used on CRCP placed by slip form paver around Richmond in the summer of 1979. A direct transmission mode in which the probe was immersed 2 in. (51 mm) into concrete and the backscatter mode were employed. The cement content of the concrete was 564 lb. (256 kg), a maximum w/c of 0.49 was specified, and crushed stone coarse aggregate was used.

In-place Density Measurements

Correction factors for the gage in both modes were determined on four batches of concrete using the metal container and procedures used for the SBLs at Port Royal, which included 12 readings on the container. The nuclear readings on the container and the correction

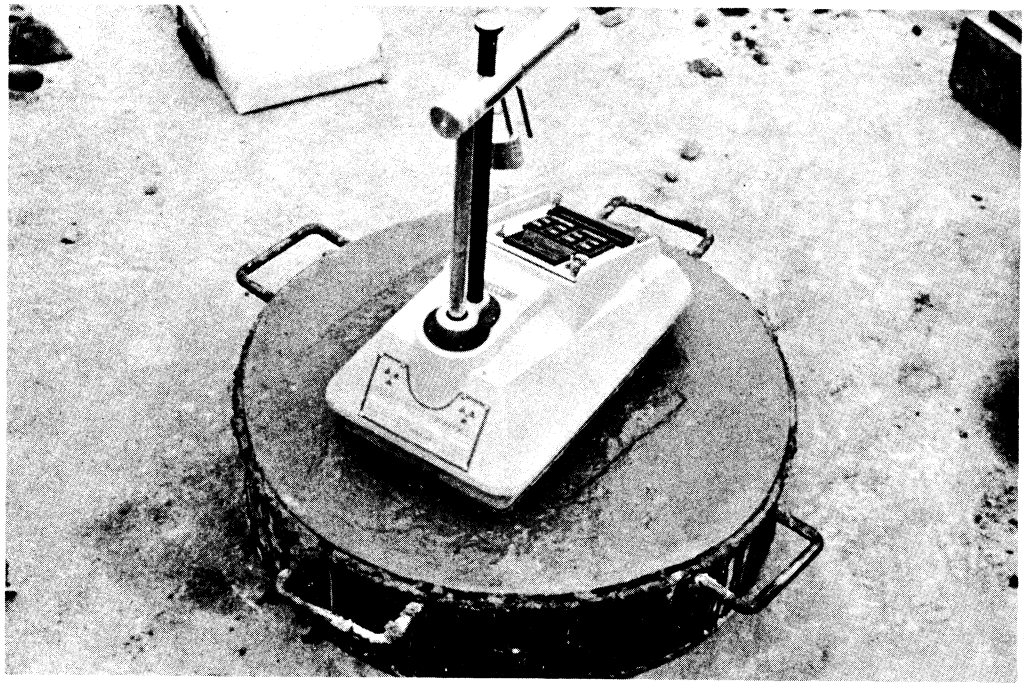

Figure 3. Nuclear gage and metal container used to determine correction factors.

TABLE 8

Properties of Fresh Low-Slump Concrete for SBLs

Batch	w/c	Slump, in.	Air, %	Unit Weight, lb./ft.^{3}	Method of Consolidation
9	0.345	1 1/4	5.0	147.0	R
10	0.345	1 1/8	4.6	147.0	R
11	0.345	1/4	4.4	148.0	R

NOTE: 1 in. = 25.4 mm

1 lb./ft.^{3} = 16.01 kg/m^3

1 psi = 6.89 kPa

TABLE 9

Nuclear Gage Correction Factors and Corrected Unit Weights for SBLs in lb./ft.^{3}

Batch	Gage Reading on Containers			Container Unit Weight	Correction Factor	Corrected Unit Weight
	No.	Wet Density	Std. Dev.			
9	12	150.2	1.3	149.6	- 0.6	146.2
10	12	150.2	1.7	148.8	- 1.4	145.6
11	12	150.0	0.8	148.8	- 3.2	146.3

NOTE: 1 lb./ft.^{3} = 16.01 kg/m^3

factors are shown in Table 10. The average correction factor in the backscatter mode was -0.3 lb./ft.^{3} (-5 kg/m^3), with a standard deviation of 1.9 lb./ft.^{3} (30 kg/m^3), and that in the direct transmission mode was 6.0 lb./ft.^{3} (96 kg/m^3), with a standard deviation of 0.5 lb./ft.^{3} (8 kg/m^3). The spread in correction factor values was lower in the direct transmission mode.

The air content, slump, unit weight, and the corrected unit weight are given in Table 11. The average unit weight was 140.4 lb./ft.^{3} (2248 kg/m^3), with a coefficient of variation of 0.5%, and the corrected unit weight of 141.7 lb./ft.^{3} (2269 kg/m^3), with a coefficient of variation of 0.3%.

At the project, concrete was placed in 24 ft. (7 m) wide sections. Three nuclear gage measurements were taken along a direction transverse to the centerline; one at the middle and one 4 ft. (1.2 m) from each end of a work bridge behind the unit of the paving train that consolidates and screeds. The 74 measurements taken in the backscatter mode yielded an average corrected density value of 146.3 lb./ft.^{3} (2342 kg/m^3) and exhibited a coefficient of variation of 1.4%. The 74 obtained in the direct transmission mode averaged 147.5 lb./ft.^{3} (2361 kg/m^3), with a coefficient of variation of 1.8%. The percentages of rodded weight values are presented in histograms for the backscatter and the direct transmission modes in Figures 4 and 5, respectively. In the backscatter mode, all the values were above the 98% level and in the direct transmission all but one were above 98%.

Petrographic Examination and Absorption Data

Four cores were obtained from the section of pavement on which readings were taken. The cores were subjected to linear traverse analysis, microstructural examination, and absorption tests. The void structure determined from the linear traverse analysis, as reflected in the data in Table 12, included a large amount of coarse voids averaging 2.8%. The visual examination of these cores indicated a deficiency in consolidation.

The percent absorption for the cores, given in Table 11, averaged 4.7%, which is considered to be marginal or on the high side for a satisfactory level of permeability. The unit weight measurements on the cores (ASTM C642) shown in Table 13 averaged 146.5 lb./ft.^{3} (2345 kg/m^3).

TABLE 10

Density Readings on the Container and Correction Factors for CRCP, lb./ft.^{3}

Batch	Backscatter Wet Density	Backscatter Std. Dev.	Direct Transmission Wet Density	Direct Transmission Std. Dev.	Unit Weight Container	Correction Factors Backscatter	Correction Factors Direct Transmission
1	142.6	0.7	138.4	1.4	144.3	1.7	5.9
2	139.7	0.6	133.8	1.4	140.4	0.7	6.6
3	146.1	0.6	137.5	1.8	143.5	- 2.6	6.0
4	145.1	1.4	138.8	1.9	144.2	- 0.9	5.4

NOTE: 1 lb./ft.^{3} = 16.01 k/m^3

TABLE 11

Air Content, Unit Weight (ASTM C138), and Corrected Unit Weight for CRCP

Batch	Air, %	Slump, in.	Unit Weight lb./ft.^{3}	Corrected Unit Weight, lb./ft.^{3}
1	6.5	2.5	140.7	141.5
2	7.2	2.7	139.4	141.3
3	6.7	2.7	141.0	142.0
4	7.0	2.0	140.5	142.0

NOTE: 1 lb./ft.^{3} = 16.01 kg/m^3

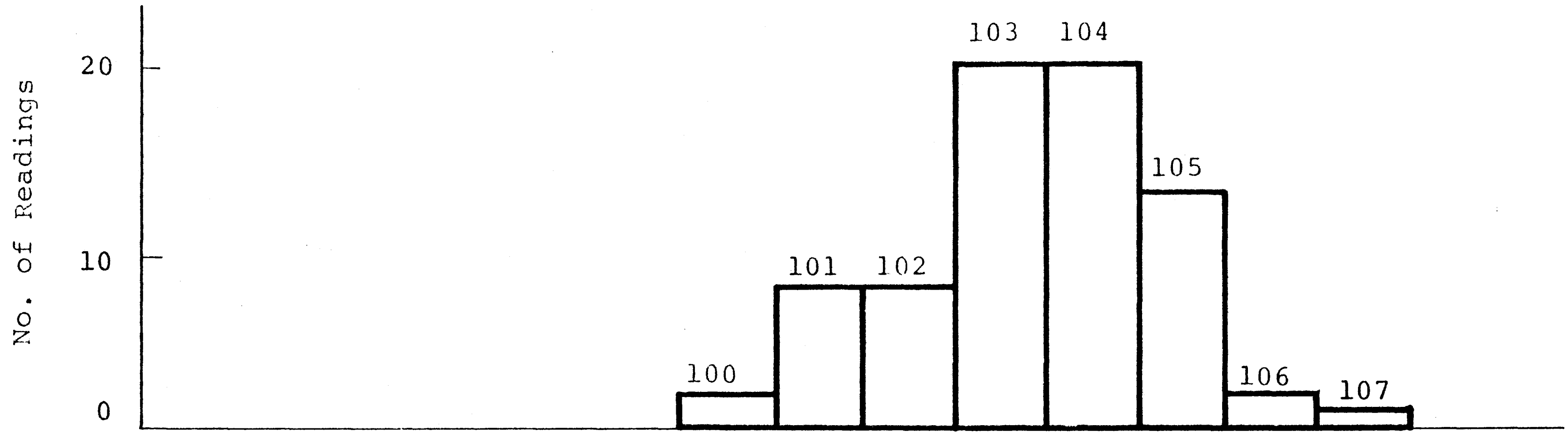

Figure 4. Percentages of rodded weight for paving concrete, 74 readings, backscatter mode.

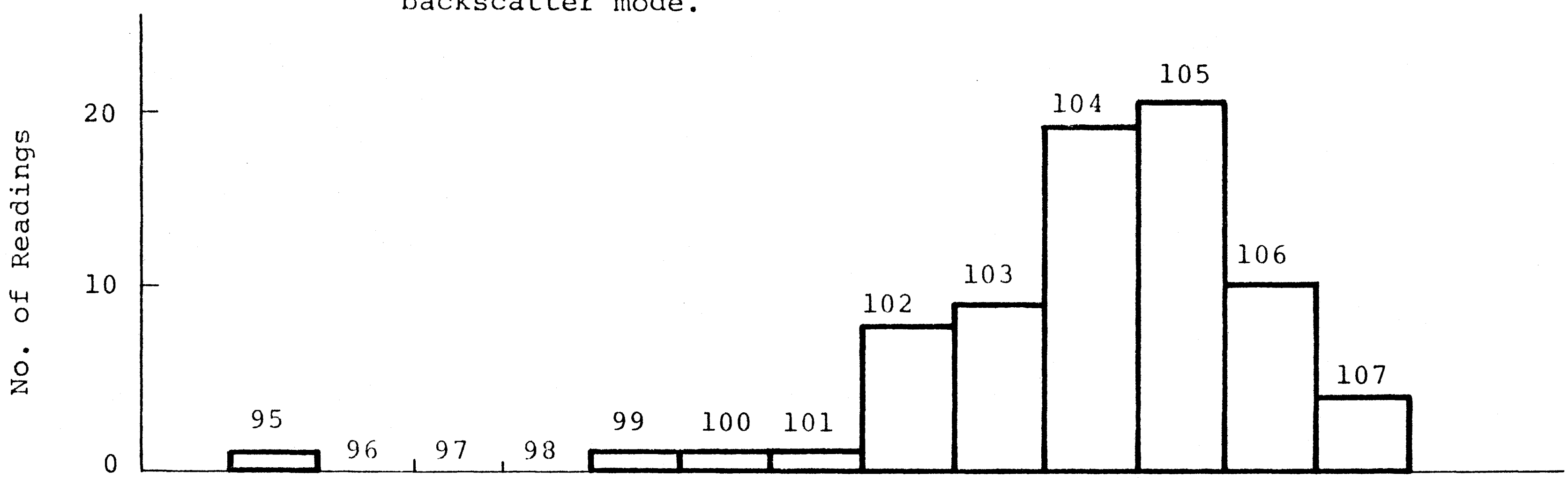

Figure 5. Percentages of rodded weight for paving concrete, 74 readings, transmission mode.

TABLE 12

Linear Traverse Analyses of Cores from Paving Concrete

Sample	w/c	Voids, %			Specific Surface, $in.^{-1}$	Spacing Factor, $in.^{-1}$
		>1 mm	<1 mm	Total		
1	0.49	2.7	6.9	9.6	426	0.0060
2	0.49	2.4	4.3	6.7	389	0.0103
3	0.49	3.7	6.1	9.8	359	0.0071
4	0.49	2.3	7.0	9.3	472	0.0055

NOTE: 1 in. = 25.4 mm

TABLE 13

Absorption and the Unit Weight after Immersion (ASTM C642), Cores from Paving Concrete

w/c	Absorption, %	Unit Weight, $lb./ft.^3$
0.49	4.6	146.6
0.49	5.0	143.5
0.49	4.4	148.5
0.49	4.8	147.3

NOTE: 1 $lb./ft.^3$ = 16.01 kg/m^3

Summary and Results

The average corrected in-place nuclear density readings for the paving concrete were higher than the average corrected unit weights by 3.1% in the backscatter mode and by 3.9% in the direct transmission mode. The theoretical unit weight of the concretes was 142.1 lb./ft.^{3} (2275 kg/m^3), which is about 1% higher than the average unit weight (ASTM C138). The nuclear readings resulted in percentages of rodded unit weight values above the 98% level in all cases in the backscatter mode and 99% of the cases in the direct transmission mode (only 1 value out of 74 was below the 98% level). However, the petrographic examination of the concrete cores revealed the presence of clearly visible large voids and showed the concretes to be of marginal quality. This finding again indicates that the criterion applied did not assure the complete elimination of consolidation problems.

The correction factor values obtained in the direct transmission mode showed less of a variation than those in the backscatter mode. The average in-place readings in the former were higher than those in the latter by 1.2 lb./ft.^{3} (19 kg/m^3). This difference could be related to the variations in the determination of the correction factors or, possibly, the variations in density throughout the depth as shown by the related standard deviation values. The backscatter mode is affected more by the portion of the concretes closer to the surface than is the direct transmission mode.

SUMMARY AND CONCLUSIONS

1. The average corrected in-place nuclear gage density readings in the backscatter mode on the overlay were higher than the average corrected unit weight measurements by 1.4% or less. On the CRCP, the in-place nuclear readings in the backscatter mode were higher by 3.1% and in the direct transmission mode and 3.9% higher than the average corrected unit weight values.

   Thus the nuclear densities obtained on in-place concrete were higher than the average corrected unit weights. However, the opposite would be expected, since the average corrected unit weight measurements included some on specimens subjected to vigorous tapping that had better consolidation than the concretes compacted by the vibratory screed. This anomaly may have resulted from difficulties in achieving a correction factor for the in-place nuclear gage readings and also from the deviation of the average field air content from that of a specified value.

2. The variations of the in-place nuclear readings in the backscatter mode as measured by the coefficient of variation were

   1.4% for 69 readings on the NBLs with a w/c of 0.328
   1.2% for 45 readings on the NBLs with a w/c of 0.345
   0.9% for 9 readings on the SBLs with a w/c of 0.345, and
   1.4% for 74 readings on the CRCP with a w/c of 0.49.

   In the direct transmission mode the coefficient of variation was 1.8% for 75 readings on paving concrete.

3. Correction factors determined as the difference between standard density measurements (weight/volume) and the nuclear gage readings on the same container indicated considerable variation in the backscatter mode as measured by standard deviation values. In the direct transmission mode the standard deviation for correction factors was smaller than that in the backscatter mode.

4. In the low-slump concretes the unit weight measurements (ASTM C138) showed considerable variation. The coefficient of variation was 1.6% for 5 readings on the NBLs with a w/c of 0.328, and 3.0% for 3 readings on the NBLs with a w/c of 0.345. In the SBLs, the standard deviation was 0.9% for 3 readings.

   Despite indications of satisfactory consolidation by in-place density measurements equal to or greater than 98% of the corrected unit weight, the cores obtained from the NBLs and the paving concrete exhibited higher than desirable amounts of coarse voids attributed to a deficiency in consolidation. Also, absorption values were higher than would be expected for a well-consolidated concrete.

5. The above results indicate that the nuclear gage is capable of measuring the density of concrete within the precision and accuracy normally expected for measurements by other means. However, the criterion that satisfactory compaction has been attained when density measurements with the nuclear gage are equal to 98% of the rodded unit weight of the plastic concrete is shown by these data not to be applicable in all cases. Even though the nuclear gage measurements agreed well with the unit weight measurements and showed percentages of rodded unit weight values equal to or greater than 98%, all of the cores examined had undesirable amounts of coarse voids. The absorption values of the cores were generally higher than would be expected for a well proportioned, consolidated, and cured concrete having a low w/c. This difference in indications from the readings and other tests is not related to the accuracy and sensitivity of the nuclear gage, but rather to the variations in the density of concrete that can occur because of the variability of its constituents, including air contents within acceptable ranges. Consequently, density measurements per se are not of sufficient sensitivity to establish the absences of small but detrimental amounts of coarse voids in all cases.

6. The nuclear gage does have sufficient accuracy and precision to detect large variations in air contents such as might result from gross honeycombing or excessive amounts of air-entraining agents.

RECOMMENDATION

Nuclear gages can be employed to detect large differences in density that could generally occur as a result of gross honeycombing or entrained air in amounts significantly above the specification limits. If all needed corrections are made, the gages give accurate density readings on concrete. In some circumstances, however, variations in the actual density of the concrete due to within specification variability of its components can lead the user to wrong conclusions about the degree of consolidation. Based on the rarity of honeycombing problems in Virginia and on the variations in density encountered in otherwise acceptable concrete, the use of nuclear gages or other means of measuring the density of in-place concrete to monitor consolidation is not recommended at this time.

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REFERENCES

1. Recommended Practice for Consolidation of Concrete, ACI Standard 309-72, American Concrete Institute, Detroit, Michigan.

2. Consolidation of Concrete for Pavements, Bridge Decks, and Overlays, NCHRP 44, National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C. 1977.

3. Clear, K. C., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Vol. 3, Performance after 830 Daily Salt Applications", FHWA-RD-76-70, Federal Highway Administration, Washington, D. C., 1976.

4. ACI Committee Report, Cement and Concrete Terminology, ACI Committee 116, Publication SP-19(78), American Concrete Institute, Detroit, Michigan.

5. Powers, T. C., Properties of Fresh Concrete, John Wiley & Sons, Inc., New York.

6. Mitchell, T. M., "State of the Art in Use of Nuclear Density Gages on Portland Cement Concrete", Presented at the 59th Annual Meeting of the Transportation Research Board, Washington, D. C., January 1980.

7. 3400 Series Instruction Manual, Surface Moisture-Density Gages, Troxler Electronics Laboratories, Inc., North Carolina.

8. Ozyildirim, H. C., "Placement of Low-Slump Concrete", VHTRC-81-R33, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, January 1981.

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