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Field Evaluation of Concrete Pavement Consolidation

SHIRAZ D. TAYABJI AND DAVE WHITING

For long-term durability of concrete pavements, it is required that the concrete be adequately consolidated. Inadequate consolidation of concrete can result in weak concrete that may lead to premature failure or loss of serviceability of the pavement. Presented in this paper is the result of a comprehensive study on concrete pavement consolidation conducted by the Construction Technology Laboratories, Inc., and sponsored by the Federal Highway Administration. The scope of the work consisted of laboratory testing, evaluation of nuclear gauges, development of model acceptance plans for concrete consolidation, and field implementation of the acceptance plans. In laboratory tests, consolidation was found to have a strong influence on compressive strength, bond of concrete to reinforcing steel, and permeability of concrete. There was a lesser effect of consolidation on resistance to freezing and thawing. A loss of 30 percent was sustained in compressive strength for every 5 percent decrease in consolidation. A variety of nuclear density gauges was evaluated for use in monitoring consolidation of concrete. Information was obtained from literature sources and state highway agencies. Typical precision on field concrete ranges from 1 to 2 lb/ft^3 (16 to 32 kg/m^3) for most gauge types. A combination of techniques such as the consolidation monitoring device and commercial direct transmission gauges shows promise as means of monitoring consolidation during the paving process. A model acceptance sampling plan for concrete consolidation is proposed. The plan is of the inspection-by-variables type and requires a sample size of eight per lot. The plan provides for buyer's and seller's risks of 5 percent. Field trial of a model acceptance plan was carried out along a section of I-86 in Idaho. The field study indicates that it is practical and cost effective to monitor concrete consolidation in the field.

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Portland cement concrete (PCC) is a versatile, strong, and durable material for construction of highway pavements. However, the combination of traffic loading, wear, temperature stresses, freezing, and applications of deicing agents results in a

severe environment that requires the use of high-quality concrete materials and construction practices if the pavement is to perform as designed over its service life. Inadequate consolidation is an important factor that can lead to premature concrete deterioration requiring expensive rehabilitation or replacement. A knowledge of the effects of incomplete consolidation on concrete properties is needed so that the relationship between factors such as strength and degree of consolidation can be quantified and used by state highway agencies in preparation of quality control specifications.

Concrete must be adequately consolidated if its full strength and durability are to be realized. Fresh concrete, when initially placed, usually contains entrapped air. Consolidation, generally achieved through mechanical vibration, is needed to eliminate these voids that could result in a weak, porous, and nondurable material. There are many excellent publications that describe the technique and equipment needed to properly consolidate concrete. These include: an NCHRP synthesis *(1)*, the ACI Standard Practice for Consolidation of Concrete *(2)*, and other review articles *(3, 4)*. However, in these, detailed, quantitative information describing how concrete properties vary with degree of consolidation and how pavement service life may be affected is limited.

Finally, because a concrete pavement is a manufactured item, it is necessary to ensure that quality control is exercised at all critical phases of production. Presently, quality control specifications exist to assure a quality product through all phases, up to delivery of concrete at a site. However, there are no direct specifications available to routinely monitor concrete quality after the concrete is placed in front of the paver.

Recently, the Construction Technology Laboratories, Inc., conducted a comprehensive investigation on concrete consolidation. Results of this investigation, sponsored by the Federal Highway Administration (FHWA), are summarized in this paper.

OBJECTIVE AND SCOPE OF WORK

The objective of the research study was to develop information needed to support the introduction of consolidation measurements into pavement construction quality assurance programs. The scope of the work consisted of a literature review, laboratory testing, evaluation of the use of nuclear gauges, development of model acceptance plans for concrete consolidation, and field trials of the acceptance plans.

BACKGROUND

A brief background on concrete consolidation and its effect on pavement performance is presented.

Effect of Consolidation on Strength of Concrete

Perhaps the earliest and most widely used study is that of Glanville et al. *(5)*. These data indicate a drop of approximately 30 percent in strength [measured on 6-in. (150-mm) cube specimens] for a decrease in degree of consolidation from 100 to 95 percent. A decrease of 10 percent in degree of consolidation is accompanied by a decrease of almost 60 percent in strength. Results obtained by Kaplan *(6)* in a later study were similar.

Kaplan reported a flexural strength reduction of 24 percent at 5 percent decrease in consolidation and 45 percent for a 10 percent decrease; these values were somewhat less than corresponding reductions in compressive strength. Other studies include those of Stewart *(7)* and Talbot *(8)*, where similar results were obtained.

McBride *(9)* reported a loss of approximately 1,000 psi (6.9 MPa) in compressive strength of pavement cores for a reduction of 5 lb/ft^3 (80 kg/m^3) in density. Gerhardt *(10)* noted an average difference of compressive strength of approximately 400 psi (2.8 MPa) when cores were obtained from concrete directly in the path of paver-mounted vibrators as opposed to cores obtained from areas between the vibrators.

Effect of Consolidation on Bond of Concrete to Reinforcing Steel

There is very little quantitative information relating to the effects of consolidation on bond of concrete to reinforcement. While studies on revibration *(11)* indicate that a reduction in void space between reinforcement and concrete (which is a major benefit of revibration) is indeed beneficial to obtain bond, this additional consolidation is normally applied a number of hours after the concrete is placed; the effects, therefore, may not be the same as when degrees of consolidation of concrete vibrated immediately after placement are compared.

An indication of the effects of consolidation on bond may be inferred from the work of Hognestad and Siess *(12)*. In these studies, an increase of 1 percent in air content resulted in a decrease in 10 percent in bond.

Effect of Consolidation on Freeze-Thaw Durability of Concrete

Most studies dealing with the effects of consolidation on freeze-thaw durability have been concerned with the effects of overconsolidation; that is, how prolonged vibration influences durability. The consensus on this issue, as demonstrated in studies by Tynes *(13)* and Backstrom et al. *(14)*, is that while vibration may remove some of the entrained air from concrete, it is mostly the larger sizes of voids that are displaced from the concrete. The remaining void system, while having lower total air content, generally exhibits spacing factors within acceptable limits. In these studies, freeze-thaw durability was generally adequate even after extended periods of vibration.

Effect of Consolidation on Structural Response of Concrete Pavements

Inadequate consolidation of concrete may affect concrete pavement structural response and resulting performance as follows:

1. Reduced service life due to lower strength.
2. Poor performance at doweled joints.

3. Shorter crack spacing and reduced service life of continuously reinforced concrete pavements.

Concrete strength directly affects pavement thickness requirements. For equal design traffic, a pavement with lower strength concrete requires a thicker pavement. Conversely, if the as-built concrete strength is lower than that required by design because of poor consolidation, then the pavement service life can be expected to be significantly lower. Using the procedures given in AASHTO's guide for design of pavement structures *(15)* the projected service life of pavement sections can be shown to range from 20 yr for a concrete flexural strength of 600 psi (4.1 MPa) to approximately 6 yr for a concrete flexural strength of 400 psi (2.8 MPa).

Inadequate consolidation of concrete may result in poor performance of doweled joints. Load transfer across a doweled joint is greatly influenced by the quality of concrete surrounding the dowels. If it has voids or is not stiff enough, then the dowels may not be as effective in transferring load across a joint. This deficiency may ultimately result in faulting and pumping at joints, as well as surface or bottom spalling at joints.

For continuously reinforced concrete pavement (CRCP), concrete strength also affects crack spacing. Lower concrete tensile strengths result in shorter crack spacing. While shorter crack spacing results in cracks being tightly closed, there is a limit to how short the crack spacing can be in CRCP. Normally, crack spacing in CRCP pavements ranges from 4 to 6 ft. A minimum concrete-to-steel bond strength of about 300 psi (2.1 MPa) is required for an average CRCP pavement.

LABORATORY STUDY OF CONCRETE CONSOLIDATION

As part of the reported investigation, a laboratory program was conducted to determine the influence of consolidation on properties of concrete.

Concrete specimens were prepared at different degrees of consolidation varying from 100 to 85 percent. Additionally, concrete specimens were intentionally overvibrated to the point of incipient segregation. Concrete mixtures were typical of those used for pavement construction, with cement factors ranging from 520 to 610 lb/yd^3 and air contents ranging from 5 to 9 percent. Coarse aggregates used were a crushed subangular dolomitic limestone and a partially crushed, rounded siliceous river gravel.

Test specimens were prepared for determination of compressive strength, bond of reinforcing steel to concrete, permeability of concrete to chloride ions, and resistance of concrete to freezing and thawing in water. Test details are given by Whiting et al. *(16)*.

Results show that compressive strength was reduced by about 30 percent for each 5 percent decrease in degree of consolidation. Bond strength was reduced even more, suffering a loss of approximately 50 percent for 5 percent reduction in degree of consolidation. Overconsolidation had little effect on compressive strength and may increase bond strength by virtue of displacement of air in air-entrained concrete.

Permeability to chloride ions increased as degrees of consolidation decreased, especially when aggregate with higher water demand (limestone) was used and where high air contents were employed. In most cases, resistance to freezing and thawing in water was not appreciably affected within the range of variables studied.

USE OF NUCLEAR DENSITY GAUGES

The measurement of in-place density of a variety of construction materials has been greatly facilitated through the application of nuclear gauge technology. The release of gamma rays or photons during decay of certain radioactive nuclei forms the basis for the technique; gamma rays are chargeless electromagnetic radiation having zero mass that travel at the speed of light. Gamma radiation of the type used in commercial nuclear gauges interacts with matter primarily by photoelectric absorption and compton scattering. The compton scattering is most sensitive to the density of the sample, while photoelectric absorption is heavily dependent on the chemical composition of the sample. Both direct transmission and backscatter density gauges are designed to maximize use of the compton scattering process and to minimize the influence of photoelectric absorption.

An extensive study of the use of nuclear gauges to monitor concrete consolidation was done by the Mississippi Highway Department *(17)*. Direct transmission gauges were used at depths of 2 in. (51 mm) and 6 in. (152 mm). These were compared with unit weight tests of the plastic concrete (AASHTO-T121). Density measurements were made with the nuclear device and the readings were within ±2.5 pcf (40.4 kg/m^3) of that of conventional unit weight tests. Federal Highway Administration studies *(18)* also used direct transmission gauges to monitor consolidation of fresh concrete with good results in laboratory investigations.

Work done by the Colorado Division of Highways *(19, 20)* confirmed the value of nuclear density devices for indicating consolidation of fresh concrete immediately behind a slipform paver. In these tests, nuclear readings averaged 0.37 pcf (5.9 kg/m^3) lower than the average of other density tests.

Direct Transmission Gauges

One of the two designs used for static density measurements of concrete in highway construction is the direct transmission gauge. The transmission gauge is characterized by the placement of the source of radiation and the radiation detector so that the portion of the concrete to be measured is between the source and the detector. The source of radiation is actually inserted in the concrete while the detector remains in the gauge case seated on the concrete surface. As the density of the concrete increases (the spacing between source and detector must be held constant), the radiation intensity detected decreases.

Precisions quoted (as standard deviations) by manufacturers *(21)* for direct transmission gauges range from 0.12 pcf (1.92 kg/m^3) to 0.48 pcf (7.68 kg/m^3) at a density of 120 pcf (1922 kg/m^3). The lower (more precise) values are associated with longer count times, of the order of 4 min or longer.

Backscatter Gauges

Both direct transmission and backscatter capabilities are contained within a single instrument, only the mode of operation is different. To operate as a backscatter gauge, the source is lowered from the shielded position to the bottom of the instrument just above the specimen surface. Both source and detector remain inside the gauge case seated on the concrete surface. Only scatter radiation from the specimen is detected. The radiation detected bears a complex relationship to the density of the specimen.

Because of many potentially interfering factors, precision of backscatter gauges is typically not as good as that of direct transmission gauges. Quoted precisions range from 0.26 pcf (4.16 kg/m^3) to 1.04 pcf (16.6 kg/m^3) at a density of 120 pcf (1922 kg/m^3). Backscatter gauges find their greatest application for density measurements on thin overlays of 2-in. (50-mm) thickness or less, where use of direct transmission gauges would be impractical.

Consolidation Monitoring Device

Measurements using commercially available, static nuclear gauges suffer from a number of drawbacks, including inability to keep up with rapidly moving paving trains, need to make a large number of measurements in order to obtain representative values, and inaccessibility of pavement immediately after passage of the paving train. A more promising approach is use of a continuous gauge. Such a device, termed a consolidation monitoring device (CMD), was developed under a previous contract to FHWA *(22–25)*.

The gauge utilizes a 500 millicurie (1.8×10^{10}Bq) Cs-137 source mounted in tandem with a NAI(T*l*) scintillation detector and positioned on a slipform paver by a traversing mechanism. The source and detector are collimated so that only multiple scattered photons can reach the detector. The unit rolls back and forth transversely along a horizontal guide beam as the paver moves forward. The amount of gamma radiation scattered by the concrete back into the detector is proportional to the concrete density.

Since the CMD is constantly moving over a new volume of the specimen, a different readout than that done for the static devices is necessary. The continuous gauge uses a ratemeter rather than a scaler and the information is most often presented as a strip chart recording.

Precision testing on the first generation CMD (uncompensated for air gap) indicated standard deviation of the difference between CMD readings and conventional densities (vibrated unit weight, weighed density, and core density) to average from 1 to 1.5 pcf (15–25 kg/m^3).

Twin-Probe Technique

Both backscatter and direct transmission techniques suffer from the limitation that data on variability of density with depth are not well defined. In the case of backscatter gauges, approximately 80 to 85 percent of the response reflects the density of the top 2 in. (50 mm) of concrete. While direct transmission gauges will include a contribution from all concrete located between the source and detector, the density represents only an average value through the thickness being measured. These limitations can be overcome by use of a twin-probe source and detector system. Distance between the source and detector is generally set at 12 in. (305 mm).

Current State Experiences with Nuclear Gauges

A large number of state agencies have used nuclear gauge technology in controlling consolidation of concrete. Some use nuclear density gauges on a routine basis, others have included their use in certain limited situations or on experimental projects. The information discussed in this section relates primarily to application of commercially available nuclear density gauges.

In 1977 FHWA conducted a survey of state highway agencies on the use of nuclear density gauges on concrete. Results of this survey were reported to the Transportation Research Board (TRB) by Mitchell *(26)*. At that time, 29 states had used or were using nuclear gauges to varying extents on portland cement concrete. Of these states, 11 used the gauges on a routine basis for consolidation monitoring, primarily on low slump, dense concrete (LSDC) bridge deck overlays. Use on full-depth deck and pavement placements was limited.

As part of the present research study, a second survey of nuclear gauge users was undertaken. Thirty-two states were included in the 1985 survey; of these, 7 reported no use of nuclear gauges. Three others were believed to be using, or had used, nuclear gauges, but did not supply any additional information. This left a total of 22 states that supplied information on gauge applications.

Pertinent information obtained from the current survey is summarized by Whiting and Tayabji *(27)*. The predominant application of nuclear gauges is still in monitoring consolidation of LSDC overlays. Seven states reported use on other types of structures (bridge deck pours and pavements). Of the six states having experience with their use on pavements, three have used the gauges only once on experimental projects.

Capabilities and Potential Applications of Nuclear Density Gauges

The four basic types of nuclear density gauges, while similar in principle, differ sufficiently in their operations so that their application to various phases of construction carry certain advantages and disadvantages for each gauge type. In order to properly select a gauge for a certain application, a knowledge of these limitations is essential. To offer the reader a ready reference, these advantages and disadvantages have seen summarized in Table 1.

Nuclear density gauges should prove a useful tool in acceptance testing as well as monitoring gross changes in concrete quality such as air content. Currently, provided that thickness specifications are met and the pavement is not obviously honeycombed or defective, no tests are routinely performed that assure the owner that proper consolidation has been achieved. While many other variables may contribute to the ultimate

TABLE 1 RELATIVE ADVANTAGES AND DISADVANTAGES OF NUCLEAR DENSITY GAUGE TYPES

Gauge Type	Advantages	Disadvantages
Direct transmission	Includes full concrete thickness in measurement. Little chemical interference. Widely used in other areas, commercially available. Fairly easy to calibrate, precision is good. Can avoid steel by proper gauge positioning.	Disturbance of concrete; only measures small volume of concrete placed. Relatively slow measurement. Difficult to clean gauge completely. May be difficult to use where reinforcement is congested. Radiation monitoring required.
Backscatter	Easy to perform. Minimal disturbance of concrete. Widely used in other areas, commercially available. Satisfactory precision. Useful on thin overlays (more sensitive to surface layers). Facilitates cleanup.	Insensitive to deep layers. Volume of influence ill-defined. Sensitive to chemical effects. Reinforcing steel and underlying concrete may interfere. Radiation monitoring required.
Twin-probe	Depth localization of density. Long path length included in measurement. Sensitive to small voids. Little chemical effect. Small radiation source. Good precision.	Increased disturbance of concrete. Slow measurement. Difficult to operate Equipment not commercially available. Radiation monitoring required.
CMD	Large volume of concrete included in measurement. Adaptable to process control. No disturbance of concrete. Satisfactory precision.	Sensitive to surface layers only. Measurement value represents average of volume scanned. Sensitive to chemical effects. Difficult to calibrate. Awkward to handle. Increased radiation hazard. Needs custom installation for each paver type. Measurements near pavement edges restricted. Radiation monitoring required.

quality and performance of concrete construction, if the consolidation is poor, strength will suffer and the service life will most likely be shortened.

QUALITY CONTROL PROCEDURE DEVELOPMENT

Acceptance sampling is a systematic procedure for deciding, for a given level of risks, whether to accept or reject the product inspected. A good sampling plan forces the supplier to control the quality of his product. A very strict acceptance sampling plan can be unfair to the supplier and may result in an unnecessarily higher price for the product. Thus, a balance has to be maintained between acceptable levels of quality and price of the product.

Existing Specifications for Paving Concrete

Existing specifications for paving concrete can be classified into two broad categories. The first category relates to the strength of hardened concrete, and the second to the properties of the plastic concrete delivered to the site. In addition to specifying the quality of concrete, specifications are also used to ensure the quality of the finished pavement by specifying tolerances for pavement thickness and the finished surface characteristics.

Specifications Based on Strength

Acceptance of concrete based on strength is a common and accepted procedure. Strength may be defined in terms of compressive or flexural strength. Many highway agencies prefer to use compressive strength even though concrete pavement design is usually based on flexural strength. Many agencies, however, do not specify a minimum strength. These agencies attempt to control the quality of concrete by specifying the mix design and the quality of the concrete-making materials.

A major problem with controlling the quality of concrete by specifying a minimum strength is that test results are not available until 28 days after concrete placement. In addition, because the specimens used for strength tests are molded, the quality of these specimens is not necessarily representative of the quality of in-place concrete that is greatly influenced by the degree of consolidation.

When concrete strength is specified, it is usually specified as follows:

> Concrete represented by a strength test of at least 95% of the required 28-day compressive strength will be acceptable for cast-in-place and precast concrete. *(28)*

or

> The average of any *n* consecutive strength tests, tested at the end of 28 days, shall have an average strength equal to or greater than the specified strength. *(29)*

Highway agencies as a rule have not used pay schedules for concrete strength, although pay schedules are widely used for pavement thickness. The Federal Aviation Administration (FAA) provides for acceptance of concrete based on a pay schedule for each lot of concrete *(30)*. Weed has suggested use of pay schedules for concrete used for highway paving *(31–34)*. Weed suggests using pay schedules for withholding

sufficient payment at the time of construction to cover the extra cost anticipated in the future as the result of deficient-quality work *(32)*.

Effect of Consolidation on Pavement Service Life

Laboratory test data summarized earlier indicate that the degree of consolidation has a significant effect on compressive strength. Test results show that compressive strength is reduced by about 30 percent for each 5 percent decrease in degree of consolidation. The general relationship between percent consolidation and compressive strength is

$$f_{cx} = 10^{2-[A_1(100-x)]} \quad (1)$$

where

f_{cx} = $f_{c,x}/f_{c,100}$,
$f_{c,x}$ = compressive strength at x percent consolidation,
$f_{c,100}$ = compressive strength at 100 percent consolidation, and
A_1 = regression constant.

Since pavement analysis and design procedures generally use flexural strength (modulus of rupture), the consolidation-compressive strength relationship was used to establish the relationship between flexural strength and degree of consolidation.

The flexural strength, f_r, is generally estimated from the compressive strength, f_c, using the following relationship:

$$f_r = K(f_c)^n \quad (2)$$

where k = a constant and n = 0.5.

Substituting Equation 2 into Equation 1, the following is obtained:

$$f_{rx} = 10^{2-[0.5A_1(100-x)]} \quad (3)$$

where

f_{rx} = $f_{r,x}/f_{r,100}$,
$f_{r,x}$ = flexural strength at x percent consolidation, and
$f_{r,100}$ = flexural strength at 100 percent consolidation.

The value of A_1 when all the data for the 6 mixes were combined equals 0.0364 with a standard error of estimate of 0.0602 applicable to the logarithmic form of Equation 1, which has a coefficient of correlation of 0.965. The equation for the combined data can be written as follows:

$$f_{rx} = 10^{2+0.5\,[-A_1(100-x)\pm Z(0.0602)]} \quad (4)$$

where Z = standard deviate associated with a given level of confidence limits = 1.96 for 95 percent confidence limits.

Equation 4 is tabulated in Table 2. The effect of degree of consolidation on projected service life of a concrete pavement can be estimated using Equation 4 and the procedures given in AASHTO's *Guide for Design Pavement Structures (15)*. The AASHTO design guide contains an equation that predicts the number of equivalent 18-kip single-axle loads (SAL) that a concrete pavement can sustain as a function of several design parameters such as concrete flexural strength and pavement thickness.

TABLE 2 EFFECT OF CONSOLIDATION ON CONCRETE FLEXURAL STRENGTH

Percent Consolidation, x	$f_{r,x}/f_{r,100}$ Lower Limit	Average	Upper Limit
80	0.38	0.44	0.49
82	0.41	0.47	0.54
84	0.45	0.51	0.59
86	0.49	0.56	0.64
88	0.53	0.61	0.69
90	0.57	0.66	0.75
92	0.62	0.71	0.82
94	0.68	0.78	0.89
96	0.74	0.85	0.97
98	0.81	0.92	1.05
100	0.87	1.00	1.15

NOTE: Based on Equation 4. Upper and lower limits refer to the 95 percent confidence limits. $f_{r,x}$ = flexural strength at x percent consolidation. $f_{r,100}$ = flexural strength at 100 percent consolidation.

The projected service life of a concrete pavement was determined as a function of degree of consolidation using Equation 4 and the AASHTO design equation. The projected service life is given in Table 3. It is seen that concrete consolidation can have a significant effect on pavement service life. At 90 percent consolidation, projected pavement service life is only 5.4 yr.

As discussed in the preceding sections, methods exist to relate the effect of degree of consolidation to pavement service life based only on the strength characteristics. Thus, in the development of acceptance plans for concrete consolidation, only the effect of consolidation on strength and thereby on expected pavement service life is considered. It is assumed that if the strength-based acceptance criteria are satisfied, then there will be sufficient assurance that the other characteristics such as steel-concrete bond strength and permeability to chloride ions would be acceptable.

TABLE 3 EFFECT OF CONSOLIDATION ON PROJECTED SERVICE LIFE

Percent Consolidation	Projected Service Life (yr)
100	20.0
99	17.6
98	15.4
97	13.5
96	11.9
95	10.4
94	9.1
93	8.0
92	7.0
91	6.2
90	5.4

NOTE: Straight-line projection for traffic growth assumed. Design concrete flexural strength (at 100 percent consolidation) = 600 psi (4.1 MPa). Projected service life is independent of design pavement thickness.

Development of Acceptance Plan Based on Consolidation

The development of an acceptance plan requires consideration of at least the following items:

1. Risks involved for the buyer and the seller.
2. Quality levels—the acceptable quality level (AQL) and the rejectable quality level (RQL).
3. Operating characteristic curves.
4. Lot size and sample size.

Consideration of Buyer's and Seller's Risks

When a sampling plan is used, a decision has to be made to accept or reject the material in question. Two types of risks are involved with each decision. These risks are usually termed the buyer's risk and the seller's risk. The buyer's risk, denoted as β, is the risk of erroneously accepting unsatisfactory material. The seller's risk, denoted as α, is the risk of erroneously rejecting satisfactory material. For the purpose of development of the model acceptance sampling plans, the following risks were selected:

Buyer's risk = 5 percent
Seller's risk = 5 percent

These risk levels are commonly used in highway construction.

Acceptance Plan for Inspection by Variables

Acceptance plans for inspection by variables are used when the characteristics of the product being inspected can be measured. Variable plans are more statistically efficient than attribute plans and provide greater discriminating power for a given sample size. A variable plan requires computation of the mean and the standard deviation for a given lot and requires selection of a sample size per lot.

In developing a variable acceptance plan for concrete consolidation, procedures outlined in the *Interim Recommended Practice for Acceptance Sampling Plans for Highway Construction* (AASHTO Designation: R9-85), *(35)* were followed. The use of a variable acceptance plan requires that the population being sampled is normally distributed. Data on in-place densities of concrete in highway paving indicate that the assumption of normality of density measurements is reasonably valid. A detailed discussion of the acceptance plan development is given in a report by Whiting and Tayabji *(27)*.

Sufficient data are not available from field projects to enable reliable estimation for the population mean, $\bar{X}$, and the population standard deviation, σ. Also, in many instances when in-place density data are available, data on the reference unit weight are not available. Thus, in such cases it is not possible to calculate the degree of consolidation. However, the limited data that are available indicate that on well-constructed projects it is possible to achieve mean degree of consolidation of at least 98 percent of the rodded unit weight. These data indicate that the average overall standard deviation obtained when consolidation is measured using a nuclear gauge is about 2.0 pcf (32 kg/m^3) or about 1.4 percent of the rodded (reference) unit weight.

In practice, an estimate of the population mean can be obtained by averaging the mean of the degree of consolidation measured from several projects. Similarly, a reliable estimate of the population standard deviation can be obtained by calculating the pooled standard deviation from data obtained from several projects.

For the purpose of development of a model sampling plan based on consolidation, the following criteria are used:

- Achievable standard deviation for the population of degree of consolidation measurements = 1.5 percent
- Lower acceptance limit for degree of consolidation measurements = 97 percent.

Operating Characteristics Curves

Operating characteristic (OC) curves were developed for acceptable quality level of 10 percent. The AQL is that level of lot percent defective at or below which the work is considered to be completely acceptable. The OC curves were selected to ensure that the seller's risk was about 5 percent. Thus, the probability of accepting a lot with an AQL of 10 percent is 95 percent.

Operating characteristic curves for sample sizes of 5, 10, and 15 were developed *(35)*. Use of OC curves requires knowledge of the quality index, Q_L, and the acceptance constant. The relationship between Q_L and k is

$$Q_L = \frac{\bar{X}-L}{S} \geq k \tag{5}$$

where

$\bar{X}$ = sample mean,
S = sample standard deviation,
L = lower specification limit outside of which the material is defined to be defective.

The three OC curves developed satisfy the requirement that the probability of accepting a lot that is 10 percent defective (AQL) is 95 percent. The primary difference in the three curves is that as the sample size is reduced, the probability of accepting a defective lot increases. Thus, if the rejectable quality level (RQL) of percent lot defective was set at 50 percent, then the probability of accepting at RQL would be 16, 2, and 0 percent for sample size of 5, 10, and 15. If the probability of accepting at the level RQL is to be as low as possible, a sampling plan using a sample size of 10 would be regarded as satisfactory. If the probability of accepting at the RQL level is set at 5 percent, then a sampling plan using a sample size of 8 would be regarded as satisfactory. The OC curve of sample size of 8 is similar to that for sample size of 10.

When sample size of 8 is used, the following condition would need to be satisfied:

$$Q_L = \frac{\bar{X}-L}{S} \geq k = 0.66 \tag{6}$$

The application of a sampling plan to inspection of consolidation can now be considered. For the model acceptance plan,

the lower limit for acceptance of degree of consolidation is established at 97 percent. Then, if a sample size of 8 is used with a corresponding k-value of 0.66, the following sample mean would be required as a minimum for the lot to be considered acceptable:

Sample Standard Deviation, S, Percent	*Sample Mean, $\bar{X}$, Percent*
1.0	97.7
1.5	98.0
2.0	98.3

The maximum allowable estimated percent lot defective, M, associated with sample size of 8 and k of 0.66 is 26.

Model Acceptance Plan

The model acceptance plan presented in this section is applicable when use is made of portable nuclear density gauges. The application of the CMD to evaluation of the degree of consolidation is discussed later in this paper. The model acceptance plan for degree of consolidation is based on $\alpha = \beta = 0.05$ and can be stated as follows:

Take $n = 8$ randomly located measurements to determine the degree of concrete consolidation. Compute the sample mean, $\bar{X}$, and the sample standard deviation S. Then, use $\bar{X}$ and S to compute the Q_L value as follows:

$$Q_L = \frac{\bar{X} - 97}{S} \tag{7}$$

For the lot to be judged acceptable, Q_L should be equal to or greater than $k = 0.66$.

A lower limit for the degree of consolidation of 97 percent was used for the model plan. This lower limit should be as high as is achievable in the field. It is expected that as more experience is gained with acceptance sampling based on degree of consolidation, a better estimate for the lower limit would be established.

Lot Size

An essential requirement in selecting the lot size is that it represent uniformity in terms of source of concrete and the placement procedure used. In selecting a lot size for performing density tests, the lot size should be such that the required number of tests can be performed without disrupting the concrete placement or finishing operations.

Assuming that a single reading with a 1-min time period is used with the nuclear density gauge and that another 5 min are required for set up and clean up, then the minimum lot size for a sample size of 8 is obtained as follows:

Paver Speed ft/min (m/min)	*Lot Size (length), ft (m)*
5 (1.5)	240 (75)
10 (3)	480 (150)
15 (5)	720 (225)

As more experience is obtained in the field with routine use of nuclear gauges, the lot size can be appropriately selected so that the testing poses no delay to the paving operation.

Test Locations

The eight test locations per lot should be selected randomly. A simple method of doing this is to divide the lot into 8 sublots. The test would then be performed at a randomly located point at midlength of the sublot. The test point is randomly selected by dividing the paving width in 1-ft (0.3-m) increments not counting the 1-ft (0.3-m) width at each edge. These increments are numbered sequentially starting with 1 from the first increment near the shoulder (outside edge). Thus, for a 24-ft (7.3-m) paving width there will be 22 increments. A random number generator (calculator or tabular) is then used to select the increment number for the test location. The outlined procedure allows forward progress at a uniform rate. However, any other statistically reliable procedure can be used for selecting test locations.

Test Procedure

It is recommended that density measurement be performed according to ASTM Designation: C1040-85-Standard Test Methods for Density of Unhardened and Hardened Concrete in Place by Nuclear Methods.

For each lot being tested, a test should be performed to determine the reference unit weight at 100 percent consolidation. The reference unit weight can be determined using the procedures of ASTM Designation: C138-Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete. The procedure allows use of rodding or internal vibration for consolidating concrete having a slump of 1 to 3 in. (25 to 76 mm). Care should be exercised during consolidation to ensure that concrete is fully (100 percent) consolidated.

The degree of consolidation is then determined simply by dividing the measured in-place density by the reference unit weight.

Application to the Consolidation Monitoring Device

The consolidation monitoring device is a nuclear backscatter device used to continuously and automatically monitor the degree of consolidation of plastic concrete. Since the CMD is constantly moving progressively over concrete, it provides an average reading of the density over a large volume of concrete. The CMD currently provides the density information in the form of a strip chart from which densities can be read to the nearest 0.5 lb/ft^3 (8 kg/m^3).

CMD as a Monitoring Device

The CMD can be used primarily as a device to monitor concrete consolidation. In this case a benchmark (lower-limit) value of degree of consolidation (density) is established, such as 97 percent degree of consolidation. The benchmark value is

identified on the strip chart. When more than 5 percent of the readings fall below the benchmark level, the contractor is notified and requested to make appropriate changes in his paving operation to ensure compliance with the requirements of consolidation.

CMD for Acceptance Sampling

The CMD can also be used directly for acceptance sampling of concrete consolidation. However, to make efficient use of the CMD, it would be essential that a digitized form of the density information also be available, possibly on the basis of a time interval, and that a capability exist to automatically provide the mean and the standard deviation for a group of the digitized readings. A procedure for acceptance sampling similar to that described earlier can then be used. With the CMD there is greater flexibility in establishing the sample size or the lot size, or both, and the seller's risk can be greatly reduced while maintaining the same buyer's risk.

A great advantage of the CMD is that lot size can be as small as can be handled administratively and full use would be made of all the digitized density data that are obtained. The rate for digitizing can be related to the lot size so that the number of measurements digitized per lot equals the selected sample size.

FIELD TRIAL OF ACCEPTANCE PLAN

During the 1986 construction season, a field trial using the conventional nuclear gauge was carried out at a site along Interstate 86 in the state of Idaho.

Project Details

An 11-mile section of Interstate 86 in Idaho was constructed during the summer of 1986 between Raft River and the Rockland junction west of American Falls. The pavement design prepared by the Idaho Department of Transportation (DOT) required a 10-in.-thick plain concrete pavement to be placed over an existing asphalt-treated base. The pavement was 38 ft wide and incorporated an 8.5-ft-wide tied outside concrete shoulder and a 3.5-ft inside concrete shoulder. Joints were spaced at 13, 15, 16, and 14 ft. A Gunther and Zimmerman slipform paver was used to place the 38-ft width of concrete. Spud vibrators on the paver were spaced at about 18 in. An automatic dowel bar inserter supplied by Gomaco was used to insert 1¼-in.-diameter and 18-in.-long dowel bars spaced at 12 in. The inserter unit followed the slipform paver.

Field Trial Details

Field trial of the model acceptance plan was carried out along the westbound lanes of I-86 on August 27 and 28, 1986. The following items of work were accomplished:

1. Eight lots were tested for consolidation.
2. The nuclear density gauge was calibrated for the concrete used at the project.
3. A study was conducted to establish correlation between direct transmission and backscatter measurements.
4. The practicality of consolidation monitoring was evaluated.

A nuclear density gauge (Model MC-1) manufactured by Campbell Pacific Nuclear Corporation, Pacheco, California, was used. The gauge was operated by an Idaho DOT technician. The procedures of ASTM Designation: C1040-Density of Unhardened and Hardened Concrete in Place by Nuclear Methods were generally followed.

Testing Plan

The pavement to be tested was divided into lots. Eight readings, as required by the proposed plan, were obtained per lot. Test locations were randomly selected across the width of the pavement and were spaced at about 42 ft longitudinally. A platform (walking bridge) that was part of the Gomaco dowel inserter unit was used to facilitate the testing. The inserter unit stopped at every joint location and remained stationary for about 12 to 13 sec while the dowels were being inserted into the plastic concrete. A density test was conducted at every third stop of the inserter unit, at approximately every 42 ft.

In order not to disturb the paving operation, direct transmission readings were obtained using a 15-sec count period. An 8-in. probe depth was used.

The nuclear gauge was calibrated for the I-86 concrete using a box 18 in. square and 10 in. deep. The smaller size box was used because of the limitation of the weight scale in field (maximum of 350 lb). The calibration test indicated that a correction factor of 1.026 should be applied to the manufacturer-supplied calibration tables.

Test Results

Results of the consolidation monitoring for the eight lots tested are given in Table 4. It can be seen from Table 4 that the concrete for the eight lots tested was well consolidated and meets the acceptance criteria for the value of Q_L.

Notes on Field Trial

Some of the highlights of the field trial are discussed next. A detailed discussion is given by Whiting and Tayabji *(27)*.

1. Field monitoring of concrete consolidation is considered practical and, if properly planned, will not interfere with the contractor's paving operation.
2. Ideally, a separate platform (bridge) should be used to facilitate the testing. The deck of the platform should not be more than 1 ft over the pavement surface to facilitate repeated placement of the "heavy" gauge on the pavement surface. On large paving projects, a similar platform is used to measure pavement thickness.
3. Lot size can be adjusted in the field to correspond with the speed of paving.
4. Frequent tests should be conducted to obtain the refer-

TABLE 4 RESULTS OF FIELD TRIAL

Lots	Number of Tests	Average Measured Density (pcf)	Reference Density (pcf)	Average Consolidation (%)	Standard Deviation (%)	Q_L
A	8	142.3	143.9	98.9	0.5	3.8
B	8	142.0	143.9	98.7	1.3	1.3
C	8	143.5	143.9	99.7	0.8	3.4
D	8	143.0	143.9	99.4	1.1	2.2
E	8	144.1	143.9	100.2	1.3	2.5
F	8	143.5	143.6	99.9	0.9	3.2
G	8	143.0	143.6	99.6	0.8	3.3
H	8	143.6	143.6	100.0	0.9	3.3

NOTE: Reference density is average of rodded unit weight measured at the time of concrete quality assurance testing. $Q_L = \frac{\bar{X}-97}{S} \geq 0.66$ (for acceptance) (lower limit for acceptance of consolidation is 97 percent).

ence unit weight of the plastic concrete. In addition, a carefully controlled calibration check should be made for each nuclear gauge using the project concrete at the start of the paving project following the procedures of ASTM C1040. The weight scales used in the field should be regularly calibrated.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In this study the importance of achieving proper consolidation of concrete has been demonstrated. Failure to achieve full consolidation can result in significant loss in strength, bond to reinforcing steel, and large increases in permeability of concrete. Compressive strength may be reduced as much as 30 percent for a 5 percent reduction in degree of consolidation. Bond to reinforcing steel is even more dramatically reduced due to inadequate consolidation.

A concrete pavement is a manufactured item. It is therefore necessary to ensure that quality control is exercised at all phases of production. Presently quality control specifications exist to assure a quality product through all phases of construction, up to delivery of concrete at a site. However, there are no direct procedures available to monitor concrete quality after concrete is placed in front of the paver. Monitoring of concrete consolidation offers highway agencies a procedure to exercise timely control over in-place concrete.

Nuclear density gauges offer a rapid means for controlling densities in the field. Many of these devices are commercially available, and can be used to determine density of surface layers as well as to obtain information on density through the full thickness of the slab.

Study results demonstrated that concrete consolidation is an important property of concrete and is critical to satisfactory performance of concrete pavements. Use of nuclear density gauges or the CMD for inspection of in-place density should be considered to be a practical necessity.

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