The test results for the andesite aggregate are shown in Figure 2. Again, each curve shown represents the average of three specimens. The tests demonstrate that both coating treatments tested were effective in preventing freezing and thawing damage. The control (untreated) specimen failed in six cycles of freezing and thawing.

CONCLUSIONS

Epoxy and linseed oil emulsion coatings and epoxy, methyl methacrylate, boiled linseed oil, and polyethylene glycol impregnants were all found to be eminently successful in upgrading highly frost-susceptible aggregates. Even sulfur, the only impregnant that did not meet the failure criterion, improved the frost resistance of these aggregates by a factor of five. The high degree of success in preventing freeze-thaw damage is considered to be a matter of no small consequence. Frost susceptibility is generally considered to be the most common characteristic limiting the use of aggregate materials in PCC. In addition, the results suggest that there exists a wide range of coating or impregnation materials that are capable of eliminating the frost susceptibility of aggregates.

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State of the Art in Use of Nuclear Density Gages on Portland Cement Concrete

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Proper consolidation during construction improves all of the important properties of portland cement concrete. The state of the art in state highway department use of commercially available, static nuclear density gages to monitor concrete consolidation is discussed based on the results of a 1977 Federal Highway Administration survey of state highway departments. The survey showed rapidly growing use of the gages for controlling the density of thin bridge-deck overlays, particularly of low-water-cement-ratio (0.32), low-slump (Iowa) concretes. Some use during construction of full-depth bridge decks and of pavements was also reported. A discussion of the problems involved in the use of nuclear gages—e.g., the effect of reinforcing steel on gage response and the selection of appropriate density standards—is also included.

Late in 1977, the Federal Highway Administration (FHWA) surveyed state highway departments regarding their use of nuclear gages to monitor the in-place density of fresh (plastic) portland cement concrete (PCC). This paper summarizes the responses to the survey and discusses various procedures and recommendations for future research. Portions of individual state responses are given in Table 1.

CURRENT STATE USE OF NUCLEAR GAGES

Eleven states reported extensive use of nuclear gages at the time of the survey, and another 16 reported current evaluation studies or plans for such studies in the immediate future. The responses showed that attention is being focused on use of the gages to control the density of thin bridge-deck overlays, particularly of concretes with low water-cement (w/c) ratio and low slump (Iowa concretes). Some use of nuclear procedures during construction of full-depth bridge decks and of pavements was also reported.

CONSTRUCTION OF BRIDGE-DECK OVERLAYS

Mode of Gage Operation

The first step in the development of a procedure for monitoring overlay densities is the choice of the operating mode for the nuclear gage--either direct transmission or backscatter. The states that use the gages extensively on thin overlays are divided almost evenly between the two modes. Neither method is clearly superior, and each shows certain disadvantages.

Direct Transmission

In direct transmission, the probe containing the radioisotope source is immersed in the concrete. The commercial gages normally allow the probe to be inserted to set depths that vary from 50 to as much as 300 mm (2-12 in). Use of the 50-mm setting on

Table 1. Responses to survey of state highway departments.

FHWA Region	State	Extent of Use				Application			Operating Mode			State Test Method Available	Density Standard				Calibration		
		A	B	C	D	E	F	G	H	I	J		K	L	M	N	O	P	Q
1	New Hampshire			X		X				X			X				X		X
	New York				X	X			X			X	X				X		X
3	Pennsylvania	X																	
	Virginia			X		X		X		X								X	
	West Virginia			X		X	X		X				X				X		X
4	Alabama		X					X	X			X	X					X	X
	Georgia	X							X					X				X	
	Kentucky				X	X					X	X			X			X	
	Mississippi	X						X	X				X					X	
	North Carolina			X		X				X		X	X					X	X
	Tennessee			X		X			X	X			X					X	
5	Illinois			X		X				X		X		X			X		X
	Indiana				X	X		X		X		X	X					X	X
	Michigan				X	X			X			X				X		X	X
	Minnesota			X		X	X		X		X		X						X
	Ohio				X	X				X						X		X	
	Wisconsin			X		X		X			X	X	X					X	X
6	Louisiana			X		X		X	X	X			X					X	
	New Mexico			X		X		X			X		X					X	
	Oklahoma				X	X				X		X	X				X	X	
7	Iowa				X	X	X		X			X	X					X	
	Kansas				X	X	X	X	X	X		X	X				X		X
	Missouri			X		X			X			X	X						X
	Nebraska				X	X			X			X	X					X	X
8	Colorado				X	X	X	X	X	X		X	X	X	X			X	X
	Montana			X		X			X				X						
	Wyoming		X			X													
9	California	X					X			X			X					X	
	Nevada				X	X			X			X	X				X		X
10	Idaho			X		X			X	X		X	X					X	X
	Oregon			X		X		X	X			X		X			X		X
	Total number	4	2	14	11	26	6	10	18	13	4	17	22	4	2	2	8	19	17

Note: A = past, B = planned, C = current experimental, D = extensive; E = overlays, F = full-depth decks, G = pavements; H = direct transmission, I = backscatter, J = backscatter air gap; K = rodded unit weight, L = vibrated unit weight, M = theoretical unit weight, N = vibrated unit weight in box; O = use gage manufacturer's curves, P = use own calibration blocks, Q = correction with concrete on each project.

50-mm overlays is marginal, and on thinner overlays it is impossible unless special procedures are adopted. Gages have been modified by some users to create depth positions of 38 mm (1.5 in) and smaller, but the resulting data are susceptible to a variety of errors, and therefore such modifications should not be introduced without careful study.

Currently, the best direct-transmission procedure is to place test wells in the underlying concrete by removing material 25-50 mm (1-2 in) down over a small area before placing the overlay. It is then possible to use the 50-mm setting on the nuclear gage and properly run a direct-transmission test. This method has the disadvantage of identifying the test site prior to placement of the overlay.

Keeping gages clean is also a problem with the repeated insertion of the probe into the fresh concrete. This problem will be addressed later in this paper.

Backscatter

Effect of Existing Deck

In the backscatter mode, the source remains inside the main body of the nuclear gage, which in turn is seated on the concrete surface. On thin overlays, the principal problem is the effect of the underlying concrete--i.e., the existing deck--on gage response to the overlay density. Backscatter gages typically register 70 percent of their response from the top 38 mm (1.5 in) of a sample and 80-85 percent from the top 50 mm (2 in). With this sensitivity profile, if 38 mm of a 2560-kg/m^3 (160-lb/ft^3) overlay is placed and fully consolidated on an existing 2320-kg/m^3 (145-lb/ft^3) deck, a backscatter nuclear gage would read less than 2500 kg/m^3 (156 lb/ft^3).

Current state practices for correcting the density reading for the underlying material range from ignoring the effect to using correction factor tables based on nuclear readings on both the original and the overlaid deck and on the thickness of the overlay. At least one gage manufacturer has published an application note that outlines a correction procedure for his latest gage model (1). Because of the potential impact of this effect when the overlay and existing densities differ significantly, users of the backscatter procedures need to consider correcting gage results on a project-by-project basis.

Effect of Chemical Composition of Aggregate

Backscatter methods generally have a higher sensitivity to the chemical composition of the sample than do direct-transmission methods. Thus, two concretes, one containing siliceous aggregate and the other calcareous aggregate, can give different nuclear-gage readings even though they are consolidated to the same density. These differences have been reduced considerably in the latest generation of nuclear gages and are also not a problem in the few states that use air-gap procedures. (Air-gap procedures require two nuclear readings, one with the gage on the surface and the other with a small gap between the gage and the concrete. The ratio of these two counts is insensitive to the chemical composition of the sample.)

In general, the state users do not have problems with chemical composition errors because their test procedures require development of a correction factor for their gages on each project. The correction factors are developed from comparisons of nuclear gage densities with densities established by weighing a fixed volume of concrete, typically in a 600x600x150-mm (24x24x6-in) box. The difference between the nuclear and weighed densities is then applied to all future nuclear readings on the same project. (Some states use a similar procedure to correct transmission-mode measurements.)

The validity of such correction procedures depends on the accuracy of the weighed-density determination and the uniformity of consolidation in the box. An accurate weighed-density determination depends, in turn, on an accurate measurement of the volume of the concrete. Several states reported problems with the procedures for developing correction factors, and at least one--Iowa--has eliminated the plastic concrete correction because of the difficulty of obtaining satisfactory correction factors in the field (and because of the lack of significant variation in chemical composition of the state's aggregate supplies). However, based on user experience, the establishment of a correction factor on each project is recommended.

Effect of Reinforcing Steel

Colorado and California both provided data showing that reinforcing steel has a significant effect on gage response in the backscatter mode if the device is placed directly over a steel bar. The depth of concrete cover at which this effect becomes significant depends on the gage model and the source position. Colorado (2) reported that some gage models showed no influence of the reinforcing steel with only 38 mm (1.5 in) of cover whereas others showed significant effects when the steel had 64 mm (2.5 in) of cover. In the field, then, this effect may be significant on overlay decks because the reinforcing steel may be at or near the surface of the original (underlying) deck concrete.

As an example of the size of the steel effect, California reported that concrete that gave a nuclear-gage reading of 2395 kg/m^3 (149.5 lb/ft^3) with 100 mm (4 in) of cover over reinforcing steel gave readings of 2419 and 2480 kg/m^3 (151 and 154.8 lb/ft^3) when the cover decreased to 64 and 38 mm (2.5 and 1.5 in), respectively. Taking a backscatter reading directly over the reinforcing steel can thus produce a misleadingly high density value and indicate adequate consolidation when that is not the case.

Density Standards and Percentage Compaction Requirements

The second major choices the user faces in developing a procedure for monitoring overlay densities are the selection of a test method for establishing the density standard and the selection of a percentage compaction requirement based on that standard.

The test method should be a reproducible and accurate procedure for determining the maximum density the concrete can be expected to attain in place. More than 70 percent of the users rely on rodded unit weight (AASHTO T121) as the density standard, but several expressed dissatisfaction with the method, particularly when it is used on low-w/c-ratio (Iowa) mixes. The problem is that samples are not always fully consolidated in the unit weight bucket, and low densities are obtained. As a result, reports from the field showing relative compactions from 100 to as much as 115 percent are common. Vibrated and theoretical unit weights have also been considered as standards by a few states, but the suitability of either has not been demonstrated.

In addition to selecting the method for establishing the density standard, the user must set a compaction requirement as a percentage of the standard. The most common requirement is that the nuclear-gage reading be a minimum of 98 percent of the rodded unit weight. This value is apparently based on corrosion studies (3) that indicate that Iowa overlays (w/c ratio of 0.32) consolidated to 98 percent show very low permeabilities to chloride ions in long-term ponding studies. At 92-93 percent compaction, on the other hand, Iowa-type concretes proved to be very permeable. The validity of the 98 percent requirement obviously depends on obtaining an accurate rodded unit weight. Research is still needed to find a reproducible, foolproof, and reliable procedure for establishing the density standard and then to find what percentage of that standard is required in order to ensure an impermeable and durable overlay.

CONSTRUCTION OF FULL-DEPTH BRIDGE DECKS AND PAVEMENTS

According to the questionnaire responses, only a few states are currently using nuclear gages to monitor the densities of full-depth bridge decks and pavements. A recent slide package (4), prepared jointly by FHWA and the Colorado Department of Transportation, offers a good introduction to nuclear testing for density control of concrete pavement. For the future, the consolidation monitoring device, a nuclear backscatter gage that is mounted on a slipform paver, offers the possibility of monitoring the density of large volumes of new concrete during paving (5).

Much of the discussion in the previous section on overlays is relevant to the application of nuclear gages to full-depth slabs and decks. The user is faced with the same questions--e.g., direct transmission versus backscatter and choice of density standard--and many of the same options. The only additional problem is that of the effect of reinforcing steel on direct-transmission operations. Colorado is the only state that currently has a nuclear-gage-based specification for pavements. That state uses direct-transmission measurements to enforce a requirement that the concrete be vibrated to not less than 96 percent of the maximum theoretical field density. This percentage was established from a research study (6) that showed that cores from pavements with poor abrasion records had densities less than 97 percent of rodded unit weight.

The direct-transmission mode is easier to apply to full-depth slabs than to thin overlays. However, care must be taken to avoid interference with the gage response from the reinforcing steel. The critical distance from reinforcing mesh or rod has not been established. As a result most state procedures include a general directive to establish the test location "to avoid being near the steel". FHWA Rapid-Test Procedure RT-13 (7) recommends that the center of the test site be 200 mm (8 in) laterally from any steel unless the concrete cover is greater than the depth of the source probe. The 200-mm lateral distance was based primarily on the results of a 1973 California study (8) on how close nuclear-gage readings can be taken to adjacent structures. The instruction manual for the Troxler 3400 series gages says that "the back of the instrument (should be) no closer than 150 mm (6 in) to an obstruction" (9). A recent study (10) suggests that the source probe may be placed up against dowel bars without affecting the gage response as long as the steel does not lie in the sensitive ellipsoidal volume between the source and the detector.

Steel interferences can be significant: As in the case of backscatter measurements, they can produce high-density readings even though adequate consolidation has not been achieved. For example, Colorado (2) reported that 50 mm (2 in) direct transmission measurements through concrete with reinforcing steel at 38 mm (1.5 in) depth showed errors in density determinations of 106 kg/m³ (6.6 lb/ft³). Until more specific data on critical distances from reinforcing steel are obtained, a 150 to 200-mm (6- to 8-in) separation between the center of the test site and the nearest steel appears sufficiently conservative (when the cover over the steel is less than the depth of the source probe). In heavily reinforced decks where such separations are not possible, care should be taken to keep the steel out of the sensitive volume between the source and the detector.

OTHER CONSIDERATIONS

Accuracy

There are few data in the literature on the accuracy of nuclear density measurements on concrete (accuracy is defined here as how closely the nuclear-gage-determined density matches the true density). Finding a suitable standard of comparison--i.e., the "true" density--is a problem; for example, core densities, a common standard, are based on different volumes of concrete than nuclear gage densities established at the same physical locations. When core densities were used as the basis for comparisons, one study (5) reported the standard error for backscatter-mode measurements to be ±30 kg/m³ (±1.9 lb/ft³); that is, there is a 95 percent probability that a nuclear-gage-determined density is within ±60 kg/m³ (±3.8 lb/ft³) of a core density at that location. In another pavement study (11), Colorado researchers compared direct-transmission test results with the densities of the same areas established from averages of core samples, beam samples, and the nuclear results. They reported the overall standard error to be ±21 kg/m³ (±1.3 lb/ft³).

Because concrete is relatively homogeneous compared with soils and soil-aggregates and because surface roughness errors on plastic concrete are minimal, the user can expect the accuracy of nuclear density determinations on concrete to be at least as good as, and probably better than, the accuracy expected on soil materials.

Calibration

Making absolute density determinations on concrete requires a calibration curve of nuclear gage count versus density. Most state agencies now have standards in their central and/or district laboratories for establishing their own calibration curves. In addition, the questionnaire responses showed that, on concrete, most states use a correction factor developed on each project. As discussed previously, nuclear gage readings are taken on a box of plastic, well-consolidated concrete (sizes range from 300x450x100 mm to 600x600x150 mm (12x18x4 in to 24x24x6 in), and the nuclear gage density is then determined from the standard calibration curves. The true density is also established by dividing the weight of the concrete-filled box by its previously established volume. The difference between the nuclear gage density and the true density becomes a correction factor that is applied to all subsequent nuclear gage readings on the same project. The Iowa Department of Transportation originally used this technique but now establishes the correction factor only on standard blocks of granite or hardened concrete. This approach eliminates errors in establishing the true density on each project but may introduce slight additional chemical-composition errors if project materials differ significantly from the standard block.

A few states rely on their standard calibration curves without project-by-project corrections. However, if the true, weighed density is carefully established, development and use of a correction factor on each project should provide the most accurate density determinations. (It should be noted that several states reported problems with volume changes in the calibration box when it was filled with concrete.)

Radiation Safety

Safety practice for the use of nuclear gages on concrete is, with one exception, the same as that for their use on soils, soil aggregates, and bituminous pavements. The one additional problem is caused by the adherence of mortar to the probe in the direct-transmission mode: Repeated retraction of the probe tends to clog the wiper ring and critical parts on the bottom of the gage. Gage manufacturers state that the wiper ring is adequate to remove most of the mortar but recommend that the other easily accessible parts on the gage bottom be cleaned at the end of each day.

Most of the agencies that use direct-transmission measurements responded that their procedures include a wiping of the probe after each test. The dose rate at 10 mm (0.4 in) from an 8-millicurie cesium-137 source in a typical probe is 25 rem/h; one hundred 15-s wipings of the probe per week at this radiation level would yield a total exposure of about 500 millirem to the operator's hands. This is approximately one-third of the currently allowable dose to the hands. However, such an exposure is unnecessary and should be avoided. Most of the state test procedures prohibit direct hand contact with the probe but are unclear as to the actual wiping procedure allowed. Use of a squirt bottle and/or a sponge or rag held in a pair of tongs should minimize the operator's dose. Two states reported trying copper and plastic tubing to protect the probe while it is in the concrete, but results of those trials are not available.

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