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These Digests are issued in the interest of providing an early awareness of the research results emanating from projects in the NCHRP. By making these results known as they are developed and prior to publication of the project report in the regular NCHRP series, it is hoped that the potential users of the research findings will be encouraged toward their early implementation in operating practices. Persons wanting to pursue the project subject matter in greater depth may obtain, on a loan basis, an uncorrected draft copy of the agency's report by request to the NCHRP Program Director, Highway Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418

Moisture Measurement Instrumentation
Review of Literature and Existing Technology

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 21-1, "Instrumentation for Moisture Measurement," by L. F. Ballard, Research Triangle Institute, Research Triangle Park, N. C.

THE PROBLEM AND ITS SOLUTION

Water in its various states, when insufficient or in excess in the components of a highway system, adversely affects the service behavior. Despite recognition of the importance of the relationship between the presence of water and service behavior, the engineer has been hampered in his effort to provide predictable performance by the lack of instrumentation and techniques for adequate water or moisture measurement. The economic significance of the problem in highway construction and maintenance is particularly evidenced by the large financial investment aimed at removal of excess water that causes loss of supporting capacity of subgrade soils and aggregate bases, embankment instability, and deterioration of pavements.

The Research Triangle Institute staff conducted an extensive literature review on the subject of moisture measurement within the highway field and other disciplines and evaluated the suitability of existing moisture measurement instrumentation for highway applications, identified the techniques that appear to be applicable to highway problems but need further field evaluation, and determined the specific areas for which the development of new instrumentation is needed to adequately measure the amount and state of water in highway components. Information was categorized into three subject areas: (1) highway moisture measurement problems, (2) currently applicable moisture measurement techniques, and (3) general performance characteristics for each method of moisture measurement.

The study findings -- in the form of a concise compilation of performance characteristics for all known methods of moisture measurement applicable to highway problems -- will be of immediate value to engineers in the selection of instruments for specific measurement problems. In addition, the effort provides a sound basis for the development of a research program aimed at much more comprehensive resolution of moisture measurement needs in the highway field.

The most suitable techniques currently available for use in highway problems are the nuclear and gravimetric methods. For nondestructive surface or near-surface measurements, the nuclear method appears to be unexcelled. Where samples can be removed for analysis, gravimetric methods are most suitable. Oven drying is the most commonly used gravimetric method and is normally the standard for calibration of other methods. For field use, chemical extraction techniques are also popular. All techniques have some limitation; however, many can be of significant value in certain applications.

FINDINGS

The majority of acceptance procedures for the construction control of highway embankments, subgrades, and base courses require the determination of moisture content of the material being compacted. Moisture measurement problems are also associated with the storage and use of plant-processed materials such as aggregates used in paving materials. Both the design and the performance of pavements are influenced by the moisture content of the substructure components. Other problems for which information on moisture content is of value to highway engineers are migration in embankments and slopes, soils susceptible to volume change, buildup immediately below pavements, groundwater fluctuations, research and performance of cemented pavement components, frost action and long-term performance studies.

The ultimate need is for a very small, inexpensive device for measuring moisture that may be remotely monitored and that will rapidly and accurately indicate the amount and state of the water in the surrounding material. No such instrument was identified during this study; however, a number of instruments are available that are suitable for application to some of the current moisture measurement problems.

The various moisture measurement techniques identified during this study are listed in the accompanying table with descriptions of the performance characteristics as determined from the literature review. Further details on the principle of operation for each method are included in the full report.

Future research needs pertaining to instrumentation for moisture measurement in highway components can be grouped into the following categories:

1. Measurement of moisture in bases, subgrades, and earth materials.

2. Measurement of moisture in cemented pavement materials.

3. Measurement of pore pressure in granular and earth materials.

APPLICATIONS

A systematic approach was developed during this study for choosing an appropriate method or instrument for any given moisture measurement problem. The approach includes the following steps:

1. Define the problem in terms of the relative importance of each of the instrument performance characteristics.

2. Review available data on potential methods.

3. Conduct preliminary evaluation to select candidate methods.

4. Conduct laboratory evaluation of candidate methods.

5. Conduct field evaluation of methods that perform satisfactorily in the laboratory.

A linear model, $V_j = W_i P_{ij}$, is used for the preliminary evaluation (Step 3) to provide an estimate of the best available instrument for a particular moisture measurement problem. This estimate is based on the relative importance of several performance characteristics and the probability as determined by previous experience and available data that one instrument is better than another for a particular characteristic. In the model, V_j is the performance value for instrument or measurement method j, W_i is the weighting factor or probability that performance characteristic i is the most significant for the particular measurement problem, and P_{ij} is the probability that method j is best for the measurement problem for performance characteristic i. The method that yields the highest performance value, V, should be the most appropriate method for the specific measurement problem, subject to further laboratory and field evaluation if deemed necessary. As indicated in Table 7, there is a lack of reliable data with regard to the performance of many of the potential measurement methods. At the present time, it will be necessary to rely heavily on personal experience and engineering judgment for W_i and P_{ij} values.

An illustrative preliminary evaluation involving two moisture measurement method and two performance characteristics is shown in the following:

Performance Characteristic	Weighting Factor, W_i (%)	Method 1		Method 2	
		P_{ij}	$W_i\ P_{ij}$	P_{ij}	$W_i\ P_{ij}$
Accuracy	40	0.67	0.268	0.33	0.132
Portability	60	0.25	0.150	0.75	0.450
Total performance, V			0.418		0.582

Method 1 is judged to be twice as accurate and one-third as portable as Method 2. Portability is considered to be of greater importance than accuracy for this particular measurement problem. As indicated, the weighting factor (W_i) should total 100%, and the sum of P_{ij} for each performance characteristic should be 1.0.

TABLE 7

COMPARISON MATRIX OF METHODS FOR MEASUREMENT OF MOISTURE

METHOD	AVAILABILITY	PORTABILITY	SAMPLE SIZE	EFFECT ON SAMPLE	ACCURACY (PRECISION, INTERFERENCE)	SPEED OF MEASUREMENT
GRAVIMETRIC, OVEN DRY	General use	Could be made portable, but normally is not	As required	Destructive	As precise as the technique for extracting the sample; volatile materials interfere	Many hours
GRAVIMETRIC, ALCOHOL BURNING	General use	Portable design	0.5–2 lb	Destructive	Similar to oven drying	Typically 5 min
GRAVIMETRIC, CALCIUM CARBIDE	General use	Portable design	13–26 grams	Destructive	Similar to oven drying; operator care and cleanliness also affect precision	Typically 1–5 min
NUCLEAR NEUTRON SCATTER	Units designed for highway use	Portable units in use	2–12 in., depending on moisture content	Nondestructive	Precision $\geq 0.1\%$ (dry), depending on counting time; interferences are density, neutron absorbers, and hydrogenous materials	Typically 1–5 min; 20 measurements in time of 1 gravimetric measurement
TENSIOMETRIC	Primarily for agricultural use, occasionally in highway use	Small, but not necessarily portable	Determined by region of moisture equilibrium	Requires installation in sample	Inadequate for many applications	A few minutes with small cavity and solid-state pressure transducer; others are much longer
CONDUCTIMETRIC, ELECTRICAL RESISTANCE	In limited use in R/D	Small, but not necessarily portable	Broadly defined by electrode position, but exact size is unpredictable	Nondestructive	Accuracy is poor for a variety of materials; salts interfere; 2 measurements give precision of one gravimetric	Real-time response except where electrodes are covered with fiberglass or other absorbent material
THERMAL CONDUCTIVITY	In limited use in R/D	Small but not necessarily portable	Small	Requires installation in sample	Thermal contact, density, and pore size are influential	Limited by time to install; non-equilibrium conditions can be used
HYGROMETRIC RESISTANCE	R/D units for concrete; primarily used in areas unrelated to highway engineering	Small but not necessarily portable	Region of vapor equilibrium	Normally requires installation in sample	Poor for ionic or hygromaterials or those containing volatile substances; hysteresis occurs	Limited by time to install and time to reach equilibrium with sample
MICROWAVE	Laboratory prototype	None available, but size not a major limitation	Depends on moisture content and frequency	Nondestructive	Less accurate than oven drying	Real-time measurement

[a] Depending on sensor type.

MOISTURE TYPE	DURABILITY	RELIABILITY	STABILITY	HAZARDS	TEMPERATURE EFFECTS	LIFE	REMOTE MONITORING
Free or partially bound	Rugged	Little chance of failure	No unstable components	Thermal; electrical	Depends on oven temperature (~105° C)	>10 years	No
Free or partially bound	Rugged	Little chance of failure	No unstable components	Thermal; chemical	Very small	>10 years	No
Surface water	Rugged	Little chance of failure	No unstable components	Thermal; chemical	Corrections applied to calculations	>10 years	No
Primarily responds to hydrogen	Adequate except for extreme conditions	Proven electronic system	Electronic system requires occasional recalibration	Nuclear; electrical	Slight temperature dependence between 0–32° C determined by electronic system and detector	>5 years	Type 1
Free	Rugged	Air entry causes failure	Air entry changes calibration	Electrical	Strong temperature dependence	>6 months	Type 3
Free or partially bound	Generally rugged; electrical contact must be maintained	Good except in severe thermal or chemical environment	Contact is difficult to keep constant	Electrical	~3% resistance/°C	1 mo to 1 yr [a]	Type 2 or 3
Free or partially bound	Generally rugged; electrical contact must be maintained	Electrical system is very simple	Thermal contact must be maintained	Electrical	Very small	>1 year	Type 3
Evaporable water at ambient temperature	Generally rugged; electrical contact must be maintained	Sensor failure depends on environment	Sensor aging occurs; this is improved by polystyrene insulation or moisture-permeable membranes	Electrical	Most have a strong negative temperature coefficient	1 mo to 2 yr [a]	Type 2 or 3
Free or partially bound	Adequate except for extreme conditions	Proven electronic system	Electronic stability required	Electrical	Sensitive to temperature	>5 years	Type 1