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NBS Technical Note 1247

Review of Nondestructive Evaluation Methods Applicable to Construction Materials and Structures

Robert G. Mathey and James R. Clifton

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PREFACE

This is the second compilation of nondestructive evaluation (NDE) methods for construction materials and structures prepared by the Center for Building Technology. Significant advances in NDE methods for construction materials and structures have been made since the first report was published in 1982 [1]. Readers, undoubtedly, are aware of NDE methods not included in the present compilation, which should be included in a future version. The authors welcome suggestions regarding additions to the compilation of NDE methods.

An extensive effort was required in the preparation of this report and if the anticipated growth in NDE occurs then preparation of a future version, in the same format, may become unwieldy. It is recommended, therefore, that starting with the present report the compilation be coded in an expert system form. This would facilitate the identification of appropriate NDE methods for specific materials and problems. Also, additions to the compilation could be easily introduced into the expert system program, thereby, reflecting the current state-of-the-art.

During the preparation of this report, it became obvious to the authors that an improved bases needs to be developed for interpreting the results of NDE inspections. At present, interpretation is frequently based on intuition and past experiences which are generally not recorded and, thus, are not of help to new inspectors. Without an adequate bases for interpretation, incorrect decisions could be made regarding the condition of building materials, components, or structures. Therefore, it is recommended that a standard practice, guide, or methodology be developed for interpreting the results of NDE tests.

ABSTRACT

Nondestructive evaluation (NDE) methods for evaluating in situ construction materials and for condition assessment of building components and systems were identified and are described. This report is intended to help inspectors and those involved in condition assessment choose appropriate NDE methods for specific building materials, components, and systems. Important properties of building materials along with important performance requirements for building components are listed, and appropriate NDE methods for determining these properties are recommended. In many cases the advantages and limitations of the NDE methods are presented. Potential NDE methods which may or may not require further research and development before they are ready for routine use were also identified and are briefly described. In addition, ASTM standards for NDE methods for concrete and other building materials and components were identified.

In a related aspect of the study, current Navy practices relative to the use of NDE methods in the construction and service cycle of buildings and other structures were reviewed. This review was based on Navy reports and documents provided by NCEL and NAVFAC, and on discussions with NAVFAC personnel involved with buildings and structures problems where NDE methods are used for diagnostic purposes. Navy Guide Specifications were examined for required tests, both NDE and destructive, of in situ building materials and components.

Key Words: Building components; building diagnostics; building materials; condition assessment; construction materials; in situ evaluation; nondestructive evaluation.

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1. INTRODUCTION

1.1 Background

Nondestructive evaluation (NDE) methods offer significant advantages over traditional laboratory and field methods for determining the properties of construction materials, especially in the making of in situ measurements of these materials. There are many NDE methods and they may be used in all phases of the construction and service cycle of buildings and other structures, beginning with the construction phase and continuing through the maintenance, repair, and rehabilitation phases. Currently used NDE methods and other methods based on emerging and advanced technology may be used in the maintenance, repair, and condition assessment of buildings and facilities. In addition, NDE methods may serve as an important tool in building diagnostics to assist in assessment of their condition because of construction deficiences and changes in occupancy or mission or materials properties.

The National Bureau of Standards (NBS) completed a study in 1982 for the U.S. Army Construction Engineering Research Laboratory (CERL) entitled, "In-Place Nondestructive Evaluation Methods for Quality Assurance of Building Materials" [1][1]. Since then, advances in the state-of-the-art of some NDE methods have taken place. The Naval Civil Engineering Laboratory (NCEL) and the Naval Facilities Engineering Command (NAVFAC) asked NBS to review current Navy NDE practices and to update the 1982 study [1]. This report is a revision of the earlier study and includes additions to the tables of NDE methods and to the text which describes the NDE methods. The list of ASTM standards for

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[1] Figures in brackets indicate references listed in Section 8.

NDE methods applicable to building materials is revised and updated. Based on reports and documents provided by NCEL and NAVFAC, a review of current Navy NDE practices is presented along with a brief summary of NDE studies.

1.2 Objective

The objectives of this study are: (1) to update the 1982 NBS study, "In-Place Nondestructive Evaluation Methods for Quality Assurance of Building Materials" [1] by identifying new NDE methods which can be used for condition assessment and to help to assure the quality and uniformity of in-place construction materials; and (2) to review current Navy practices relative to the use of NDE methods in the construction and service cycle of buildings and other structures.

1.3 Scope

Since completion of the 1982 NBS study [1], there have been advances in the state-of-the-art of some NDE methods. These advances in NDE methods for construction materials and condition assessment of buildings and structures have been included in this report. The information presented in this report was obtained from the literature and from those knowledgeable in the field. The 1982 NBS study [1] was the source for a considerable portion of the information. No laboratory research was performed during the course of this study. Discussions were held with members of technical committees which cover the selection and use of NDE methods and with researchers who have evaluated some NDE methods. ASTM standards were reviewed to identify those applicable for NDE methods which may be used for the in situ evaluation of construction materials and condition assessment of building components and structures.

Emerging NDE methods that have application to the diagnostic needs of the Navy were identified. These are considered to be methods which recently have been demonstrated to be sufficiently reliable to either be used in the field without further development or which need minimal further development. Promising advanced NDE methods which require further research and development before they are ready for routine use were also identified. Needed research in the area of NDE methods for construction applications of the Navy was addressed.

Current Navy practices relative to the use of NDE methods in the construction and condition assessment of buildings and other structures were reviewed. Information for this review was obtained from Navy reports and documents provided by NAVFAC and NCEL. The review of Navy practices regarding NDE methods included information from reports dealing with their use, evaluation, and research.

Over 200 Navy Guide Specifications were examined for required tests, both NDE and destructive, of in situ building materials and components. A list of the required NDE tests included in the Navy Guide Specifications was compiled.

2. REVIEW OF CURRENT NDE NAVY PRACTICES

2.1 Guide Specifications

NAVFAC provided NBS with 239 Guide Specifications for review with regard to NDE in situ tests (field tests) of building materials and components. The list of Guide Specifications and the corresponding required field tests, both NDE and destructive, are given in Appendix A. NDE tests were required in 29 of the reviewed Navy Guide Specifications. A list of these 29 Guide Specifications along with the in situ NDE tests are presented in Appendix B.

2.2 Summary of NDE Practices Obtained from Brief Discussions with NAVFAC Personnel

Discussions with NAVFAC personnel indicated that the Engineering and Design staff are involved with limited and special problems with buildings and structures where NDE methods are used. As an example, with regard to condition assessment of concrete, cover meters are used to determine rebar location and thickness of concrete cover. The penetration probe and rebound hammer are also used to assess concrete properties. Load tests of buildings and structures are conducted. In these tests American Concrete Institute (ACI) recommendations are followed for concrete structures. Strain gages and deflection gages are used for making measurements. It was reported that NCEL has equipment to detect vibrations in buildings that have been subjected to earthquakes and contain cracks in order to assist in the assessment of the condition of these buildings. In addition, NCEL has instrumented new buildings in order to obtain base line data of the properties of these buildings.

Leak detectors are used to detect leaks in pipe lines, including joints. Methods used have included ultrasonics and detection of gas. Welds are inspected by different methods including liquid penetrant inspection. It is desirable to determine the condition of underground pipe lines and to predict their service life. Included in the condition of underground pipes is the number of leaks (water, gas, steam, etc.) and the size and wall thickness of the pipes. It was reported that the Naval Research Laboratory (NRL) has developed methods for determining delamination of honeycomb panels using ultrasonic and acoustic emission techniques. It was also reported that NCEL has a device for determining locations where corrosion is occuring in precast and prestressed concrete piles. Underwater piles are difficult to inspect. The Navy's Chesapeake Division is involved in the evaluation of underwater structures.

NAVFAC has a program aimed at development of condition assessment standards for buildings, structures and utilities, such as PAVER (pavements) and ROOFER (roofs) in order to provide consistency in inspections. It is difficult to make usable technology available for condition assessment of these facilities. Pavement inspections are mostly visual but ultrasonic and radar techniques are used. These NDE methods are generally applicable at specific locations. Skid resistance measurements are made on runways.

2.3 Review of NDE Needed and Presently Used Methods Based on the Results of Responses to NCEL Questionnaires

In the fall of 1985 the NCEL sent questionnaires to Navy Public Works Centers regarding their needs and practices to assess nondestructively the quality of new construction and the condition of existing shore facilities. Eight of the responses that were received from Navy Public Works Centers were reviewed and a brief summary of the reported needs for inspections and assessment of the quality of new construction and the condition of existing facilities are presented along with presently used NDE methods.

2.3.1 List of Reported Needed NDE Methods

- early identification of problems with water front structures
- under-pier construction, methods for condition assessment and maintaining existing systems
- underwater inspection of wharves, piers, and underwater structures (currently divers must visually inspect pilings and sheet piles)
- underwater TV camera for inspection of piling underneath piers
- assessment of condition of underground heat distribution systems
- leak location detector for heating distribution systems
- extent of corrosion in piping, pumps and reservoirs
- location of underground piping
- detection of underground piping leaks
- remote monitoring of systems performance and condition of components of facilities
- condition of underground utility systems including leak detection (steam, electrical, natural gas, water, fuel)
- portable metering of utilities performance as a diagnostic tool in utilities management and maintenance
- moisture detection device for inspection of built-up roofs
- condition of cast iron piping and earthen dams
- inspection of underground storm drain and sewer lines
- methods for determining condition of underground storage tanks and for leak detection
- device to check for faults in power line insulation
- device to identify faults in pipe walls
- means for checking energy efficiency of building insulation (possible solution is the use of an infrared camera)
- infrared scanner to inspect insulated heating pipe
- early detection of minor trouble with large pieces of dynamic equipment

- pavement analysis equipment for early defect detection

- detection of worn or thin insulation on steam, chill water, and other pipelines

- determination of condition of transformers

- development of an exterior painting condition assessment computer program

- monitor condition of major transformers

- condition assessment for wood buildings including termite damage of wood components

- training program in diagnostics and condition assessment technology

2.3.2 List of Reported Presently Used NDE Methods

- location of underground piping leaks (methods used include injection of helium and SF_6 into compressed air systems to pinpoint leaks)

- leak location detector for heating distribution systems

- infrared scanning of polelines, switchgear, electrical equipment, electrical panels, and steam traps to identify anomalous sources of heat

- infrared scanning of building exteriors to identify heat leakage

- nuclear meter for detection of moisture in roof surveys

- electrical resistance probe for detecting moisture in walls, roofs, and slabs of buildings

- ultrasonic testing to determine the wall thickness of condensate pipe lines and their condition while the line is still in service

- ultrasonic testing to measure the wall thickness of metal pipes and thickness of fuel storage tank siding and floor

- examination of sewer lines with a TV camera to determine their condition (visual inspection with remote monitor)

- transformer condition can be judged from an analysis of its insulating fluid

- extent of wood decay and deterioration by puncturing with an ice pick and tapping with a hammer

- extent of termite damage using an audio scope.

2.4 Navy NDE Publications

Some Navy publications dealing with the inspection of buildings, design criteria, research, and relevant NDE methods which were provided by NCEL and NAVFAC were reviewed with regard to current Navy practices, evaluation methods, and recent research. The manual, "Inspection of Shore Facilities," Volume 2, NAVFAC MO-322, May 1978, provides maintenance inspection/service checklists for buildings, grounds, utility plants, utility and distribution systems, and components of Navy shore facilities. It provides a guide for developing and implementing an effective and efficient preventive inspection system. Only visual inspections are listed in this manual. Another Navy manual "Engineering and Design Criteria for Navy Facilities", NAVFAC P-34, August 1985, lists specifications and standards relative to Navy facilities which are issued by government agencies (public sector) and private sector organizations. This design manual refers to nondestructive evaluation of butt welds in crane and railroad rails.

Some NCEL Techdata Sheets containing information about NDE inspections or the use of NDE equipment which were provided by NCEL were reviewed. Techdata Sheets usually give a brief explanation of an NDE method or a brief description of NDE equipment and its use. In many cases the Techdata Sheets are based on a technical or research report which gives background data, research results, and details pertinent to the NDE methods or equipment. A list of the NCEL Techdata Sheets that were reviewed is given in Appendix C. The following examples are given regarding NDE methods contained in the Techdata Sheets:

- Inspection of painting
- Measuring water permeability of masonry walls
- Leak detection in pipelines
- Infrared thermometers for roofing inspections
- Use of penetration probe test system for strength evaluation of concrete in Naval construction
- Problems with underwater ultrasonic inspection
- Inspection methods for wood fender and bearing piles
- Locating and tracing buried metallic pipeline

Many different NDE methods are included in the Techdata Sheets. Most of the NDE methods are listed in the tables in Section 4 of this report and described in Section 5.

Some NCEL technical and research reports provided by NCEL and NAVFAC were reviewed with regard to NDE methods and equipment. These reviewed reports are also listed in Appendix C. They contain information about many types of NDE methods and in many cases research results, assessments of NDE methods, comparisons of NDE methods, the significance of the methods, their accuracy and reliability, and their use in the field are presented. Examples of the information regarding NDE methods in the technical and research reports include the following:

- Pulse echo ultrasonic testing has been investigated for measuring the corroded metal thickness of steel piles. Results of ultrasonic evaluations have been compared to resistance probing and coring for condition assessment of wooden waterftont structures.

- Information is available about instructions for inspection and testing of railroad and ground level trackage. NDE methods used are ultrasonic inspection, optical instrument surveying, electromechanical relative displacement measurements, inertial displacement measuring transducer, proximity sensors, and laser-based level devices.

- Assessment of cables and wire rope is carried out using alternating current to produce an electromagnetic field to detect loss of metallic areas in the wire rope. For smaller wire rope, a portable NDE device that employs an audible signal detected by a head set can indicate flaws.

- Moisture can be detected in roofing systems based on surveys using nuclear moisture meters, infrared thermography, and capacitance meters.

- With regard to underground utility lines, an NCEL state-of-the-art survey found no existing techniques capable of nondestructive condition assessment. Utility companies and water distribution agencies use sonic detectors for leak detection. It was reported that none of the six techniques investigated, acoustic emission, radiography, sonic,ultrasonic, eddy current, and magnetic flux, were suitable for Navy use on buried pipelines. Ground penetrating radar was investigated as a method for detecting underground utility lines.

- Extensive internal damage can be detected in underwater timber piles by an impact hammer sounding technique. The pile is struck with a hammer and damage is assessed from the acoustic response.

- Small portable infrared spectrophotometers that were introduced commercially for field analysis of gases and liquids were modified in order that organic solid materials could be identified and analyzed. This modified portable instrument showed promise that organic construction materials (paints, plastics, insulations, etc.) could be identified in the field. This could help provide for proper maintenance. It also could help ensure that specified materials were used by the contractor, and deterioration of protective coatings could be detected.

3. NDE METHODS

The NDE methods are listed in Tables 1 through 13 in Section 4 and descriptions of the NDE methods are given in Section 5. The tables and descriptions of the NDE methods have been updated from the previously mentioned 1982 NBS study [1]. A considerable portion of the information in the present report was taken from the previous study. It is noted that some in situ NDE tests may or may not cause minor damage to materials or buildings components. An example of an instrument that may cause minor damage is an electrical resistance probe to determine the moisture content of insulation.

The NDE tables in Section 4 list key properties of commonly used building materials and NDE methods for estimating the level of these properties or characterizing the materials. Operation, principles, and applications of the NDE methods are outlined in Table 13. These tables are intended to familiarize those personnel involved with quality assurance and condition assessment of building materials and components with NDE methods, and to help in the selection of appropriate methods. More detailed information about the NDE methods or descriptions of the methods are provided in Section 5. Appendix D lists standard test procedures which the American Society for Testing and Materials (ASTM) has issued for some NDE methods covered in this report.

To use the information in this report most effectively, begin with Tables 1 through 12. If, for example, the quality and uniformity of in-place concrete seem questionable, further inspection could be justified. The options for inspection of hardened concrete are given in Table 1. Concrete properties are given in the first column and appropriate NDE methods for each property are found in the second column. For the example given, four methods are listed for determining the general quality and uniformity of hardened concrete: (1) penetration probe, (2) rebound hammer, (3) ultrasonic pulse velocity, and (4) radiography (gamma). The methods are not ranked; the table simply provides a list of applicable methods. To help decide which of these methods would be appropriate for a specific application (considering factors such as equipment availability, cost, and information obtained), consult Table 13. For more information before selecting any of the four methods, refer to Section 5 which gives detailed information about the NDE methods.

The cross reference features of the tables can be used in the same way for information about other recommended NDE methods.

Note that the information in this report is not intended to supersede existing guide specifications. In cases of conflict, the guide specifications are to be followed.

4. NDE TABLES

4.1 Building Materials, Components, and Systems

Major building materials, their important properties, and NDE methods for estimating the value of these properties or for characterizing the materials are given in Tables 1 through 9. Materials considered are:

Table No.	Building Material
1	Concrete
2	Masonry materials
3	Wood and lumber
4	Metals
5	Roofing
6	Paints and coatings
7	Soils
8	Sealants
9	Thermal insulation

The following building components and systems are covered in Tables 10 through 12:

Table No.	Components and Systems
10	Building envelope
11	Pipe and drainage systems
12	Heating, ventilation, and air conditioning systems

In Tables 10-12, the main performance requirements are listed, and NDE methods intended for determining if these requirements are being met are also listed.

The selection of the building materials, components, and systems addressed in this report was largely based on considerations of: (1) the amount of their use; (2) the frequency and severity of problems caused by deficiencies in their quality, uniformity, or performance; and (3) the value of using NDE methods to inspect the material, component, or system. As an obvious example, NDE inspection is not necessary to determine that a glass window is broken, while locating reinforcing steel in concrete is more readily done by NDE inspection than by coring. Researchers from the NBS Center for Building Technology and from the NBS Office of Nondestructive Evaluation of the National Bureau of Standards, and personnel of the U.S. Army Corps of Engineers collaborated in the selection process in the earlier NBS study [1].

In Tables 1 through 12, the column headed "Currently Recommended NDE Methods" lists ways of testing various material properties. These tests are commonly used, and their limitations are well known. The column headed "Potential NDE Methods" lists NDE methods that may prove useful, but are still being assessed. In some cases, suitable NDE methods are not available, as an example, for the inspection of the bond between a sealant and its substrate (Table 8).

4.2 Survey of NDE Methods

The operation, principles, and applications of recommended NDE methods for inspecting building materials are outlined in Table 13. Self-explanatory NDE methods such as the use of rulers and visual inspection methods are not included in Tables 1 through 12.

Once construction inspectors and those involved in condition assessment become familiar with the advantages of using NDE, they may wish either to train people in their own organizations, or to obtain help from persons knowledgeable about NDE inspections. Comments on the expertise the user needs, equipment costs, and safety requirements are intended to help potential users decide which path to follow.

Table 1

NDE Methods for Inspecting Hardened Concrete

Property	Currently Recommended NDE Methods: Method	Location in Report[a]	Potential NDE Methods: Location in Report[a]	Method
Strength	Penetration Probe Rebound Hammer Cast-in-place pullout Maturity concept	5.21 5.28.2 5.7 5.13	5.30.1 5.20 5.23 5.6	Ultrasonic pulse velocity Point-load test Pull-off test Break-off method
General quality and uniformity	Penetration Probe Rebound Hammer Ultrasonic pulse velocity Radiography	5.21 5.28.2 5.30.1 5.25.1	5.30.2 5.14 5.24 5.5	Ultrasonic pulse echo Microwaves Radar Air permeability
Thickness			5.14 5.25.3 5.30 5.9.1 5.25.1	Microwaves (radar) Gamma radiography Ultrasonic pulse, velocity and echo Eddy current Radiography
Air content			5.17	Neutron density gage
Stiffness	Ultrasonic pulse velocity	5.30.1		
Surface texture	Visual	5.32	5.14	Microwaves
Density	Radiography Ultrasonic pulse velocity	5.25.3 5.30.1	5.17	Neutron density gage
Rebar depth and position	Cover meter Radiography	5.9.3 5.25.3	5.14 5.30.2 5.24	Microwaves (radar) Ultrasonic pulse echo Radar
Corrosion state of reinforcing steel	Visual Electrical potential measurement	5.32 5.8		
Presence of subsurface voids or delaminations	Acoustic impact Ultrasonic pulse echo Radiography Ultrasonic pulse velocity	5.2 5.30.2 5.25.3 5.30.1	5.29.1 5.24	Infrared thermography Radar
Moisture content and moisture penetration			5.14 5.16.3	Microwaves Nuclear
Cement content			5.16.3	Nuclear
Durability	Visual	5.32		
Steel fiber content			5.9.5	Electromagnetic method
Critical and rupture loads (crackability factor)			5.1 5.30.1	Acoustic emission Ultrasonic pulse velocity

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

Table 2

NDE Methods for Inspecting Masonry and Masonry Materials

Property	Currently Recommended NDE Methods: Method	Location in Report[a]	Potential NDE Methods: Location in Report[a]	NDE Method
Integrity of masonry	Acoustic impact Radiography Probe holes with fiberscope Ultrasonic pulse velocity	5.2 5.25.3 5.32.2 5.30.1	5.30.2 5.14 5.24	Ultrasonic pulse echo Microwaves Radar
Thickness of masonry	Probe holes	5.32	5.9.1 5.30.2 5.25.1	Eddy current Ultrasonic pulse echo Radiography
Reinforcing steel (location and size)	Cover meter Radiography	5.9.3 5.25.3	5.30.1 5.14 5.25.1	Ultrasonic pulse echo Microwaves Radiography
Presence of inner grout	Probe holes Radiography Acoustic impact Ultrasonic pulse velocity	5.32 5.25.3 5.2 5.30.1	5.30.2	Ultrasonic pulse echo
Moisture content and moisture penetration	Moisture meter-electrical resistance	5.16.1	5.14 5.16.3	Microwaves Moisture meter-nuclear
Presence of delaminations	Acoustic impact Radiography Ultrasonic pulse velocity	5.2 5.25.3 5.30.1	5.30.2 5.29.1 5.25.2	Ultrasonic pulse echo Thermal inspection (thermography) Radiography
Water permeability of coated masonry			5.33	Water permeability

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

Table 3

NDE Methods for Inspecting Wood and Lumber

Property	Currently Recommended NDE Methods: Method	Location in Report[a]	Potential NDE Methods: Location in Report[a]	Method
Integrity and general quality (including grade, mechanical properties, and assessment of insect, mechanical and decay damage*	Visual grading by certified grader* Proof loading	---- 5.22	5.1 5.30 5.25.1 --- 5.15 5.12	Acoustic emission Ultrasonic pulse velocity and echo Radiography Penetration hammer Middle ordinate method Longitudinal stress waves
Density	Ultasonic pulse velocity	5.30.1	--- 5.25.1 5.12	Penetration hammer Radiography Nuclear density meter
Moisture content	Electric resistance probe Capacitance instrument	5.16.1 5.16.2	5.16.3 --- ---	Nuclear moisture meter Surface hygrometers Microwaves absorption meter
Adhesive bond for laminated wood			5.2 5.29.1 5.25.1	Acoustic methods Thermal inspection (thermography) Radiography
Dimensions	Rulers, calipers, electronic measuring devices**	---		

[a] Numbers in this column refere to NDE Method Nos. described in Section 5 and listed in Table 13.

* Perform on lumber before use; this method not described in Table 13.
** Because of their simplicity, methods not described in Table 13.

Table 4

NDE Methods for Inspecting Metals

Property	Currently Recommended NDE Methods: Method	Location in Report[a]	Potential NDE Methods: Location in Report[a]	Method
A. Structural Metals				
Presence and location in other materials	Radiography	5.25.3	5.30.2	Ultrasonic pulse echo
	Magnetic devices	---		
	Cover meter	5.9.3		
	Eddy current devices	5.9.1		
	Probe holes with fiberscope	5.32.2		
Type of metal	Magnetic devices	---		
	Chemical spot testing*	---		
	Spark testing*	---		
	Color*	---		
	X-ray fluorescence analyzer	5.25.4		
	Electromagnetic methods	5.9		
Cracks, flaws	Radiography	5.25.3	5.10	Holography
	Ultrasonic pulse echo	5.30.2	5.14	Microwave
	Magnetic particle	5.9.4	5.29.1	Thermal inspection
	Liquid penetrant	5.32.3		
	Eddy current	5.9.1		
Corrosion condition	Electrical potential measurement	5.8	5.9.1	Eddy current
			5.30.2	Ultrasonic pulse echo
Loose bolts rivets and screws	Visual	5.32	5.2	Acoustic impact
B. Weld Defects				
Cracks	Ultrasonic pulse echo	5.30.2		
	Radiography	5.25.3		
	Magnetic particle	5.9.4		
	Liquid penetrant	5.32.3		
Lack of fusion	Ultrasonic pulse echo	5.30.2	5.9.4	Magnetic particle
	Radiography	5.25.3		
Slag inclusion	Radiography	5.25.3	5.30.2	Ultrasonic pulse echo
	Magnetic particle	5.9.4		
Porosity	Radiography	5.25.3	5.32.3	Liquid penetrant
			5.30.2	Ultrasonic pulse echo
Incomplete penetration	Radiography	5.25.3		
	Ultrasonic pulse echo	5.30.2		
C. Pipes and Tanks				
Type of metal	See Structural Metals, above			
Wall thickness	Eddy current	5.9.1		
	Ultrasonic pulse echo	5.30.2		
Leaks and continuity	Leak testing	5.11		
Corrosion condition	Electrical potential measurements	5.8	5.9.1	Eddy current
			5.30.2	Ultrasonic pulse echo

[a] Numbers in this Column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

* For more information on these methods see Reference [2].

Table 5

NDE Methods for Inspecting Roofing Systems

	Currently Recommended NDE Methods		Potential NDE Methods	
Property	Method	Location in Report[a]	Location in Report[a]	Method
Composition			---	Cores* -- laboratory analysis, specific gravity, solvent, odor, and chemical tests to distinguish between asphalt and coal tar pitch
Moisture content of insulation	Thermal inspection (thermography)	5.16.4	5.14	Microwaves
	Nuclear moisture meter	5.16.3		
	Capacitance	5.16.2		
	Electrical resistance probe	5.16.1		
Permeability of roofing system	Flood or pond water on roof followed by using methods to measure moisture content of insulation	---		
Seam integrity (single-ply)			5.29.1	Infrared thermography
			5.30.2	Ultrasonic pulse echo
Slope and drains			---	Flood or pond water on roof
Self supporting under design loads	Proof loading	5.22		
	Wind uplift test (can be destructive)	5.31		
Uplift resistance	Negative pressure	5.31		

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

*Destructive method

Table 6

NDE Methods for Inspecting Paints and Coatings

Property	Currently Recommended NDE Methods: Method	Currently Recommended NDE Methods: Location in Report[a]	Potential NDE Methods: Location in Report[a]	Potential NDE Methods: Method
Number and type of layers	Tooke Gage	5.18.1		
Dry film thickness				
Metal:	1. Magnetic pull-off gage	5.18.3.1		
	2. Magnetic flux gage	5.18.3.2		
	3. Eddy current	5.9.1		
	4. Tooke Gage	5.18.1		
Wood:	Tooke Gage	5.18.1		
Wet film thickness	1. Interchemical gage	5.18.4.1		
	2. Pfund gage	5.18.4.2		
	3. Notch gage	5.18.4.3		
Hardness	Pencil test	5.18.2		
Integrity (Pin holes)				
Metal:	Pin hole (holiday) detector	5.19		
Wood:	Field microscope	5.32.1		
Bond to subsurface			---	Adhesion tester
			---	Scratch adhesion test
			5.29.1	Thermal inspection (thermography)
Surface preparation			5.18.1	Tooke gage
			5.32.1	Field microscope
General quality color, reflectance, blistering, etc.			---	Photography -- comparison with standard
			---	Measurement of reflectivity
			5.29.1	Thermal inspection (thermography)

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

Table 7

NDE Methods for Inspecting Soils

Property	Currently Recommended NDE Methdos: Method	Currently Recommended NDE Methdos: Location in Report[a]	Potential NDE Methods: Location in Report[a]	Potential NDE Methods: Method
Adequate drainage	Visual check of grade and topography*	---		
Adequacy of backfill			5.14	Microwave to detect cavities in backfill
Density and compaction	Seismic testing (wave propagation) Nuclear density meter	5.26 5.17	5.27.2	Helical probes
Moisture contents	Nuclear moisture meter	5.16.3	5.16.1 5.16.4	Electrical resistance probe Infrared thermography
Stiffness			5.26	Seismic testing (wave propagation)
Permeability			5.16.4	Infrared thermography
Strength	Standard penetration test Cone penetration test	5.27.3 5.27.1	5.27.2	Helical probes
Detect cavities			5.14 5.26 5.29.1	Microwave Seismic testing (wave propagation) Infrared thermography

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

* Because of its simplicity, method not described in Table 13.

Table 8

NDE Methods for Inspecting Sealants

Property	Currently Recommended NDE Methods: Method	Currently Recommended NDE Methods: Location in Report[a]	Potential NDE Methods: Location in Report[a]	Potential NDE Methods: Method
Water permeability (infiltration)	Electrical resistance meter Capacitance instrument	5.16.1 5.16.2		
General quality and workmanship	Move water jet up the building wall (from bottom to top) and observe water infiltration -- use methods given for testing for water permeability	5.16.1 5.16.2		
Bond to substrate*				

[a] Numbers in this column refer to NDE Methods Nos. described in Section 5 and listed in Table 13.

* Destructive laboratory tests are available.

Table 9

NDE Methods for Inspecting Thermal Insulation

Property	Currently Recommended NDE Methods		Potential NDE Methods	
	Method	in Report[a]	in Report[a]	Method
Performance	Thermal inspection (infrared thermography)	5.29.1	5.29.5 5.29.3 5.29.4 5.29.2	Spot radiometer Heat flow meter Portable calorimeter Envelope thermal testing unit
Location	Thermal inspection (infrared thermography) Fiberscope	5.29.1 5.32.2	5.29.5 5.29.3	Spot radiometer Heat flow meter
Moisture contents			5.16.2 5.16.1 5.29	Capacitance instrument Electrical resistance meter Thermal inspection
Corrosiveness	Measure electrical potential of metals in contact with insulation	5.8		

[a] Numbers in this column refer to NDE Method Nos. described in Section 5 and listed in Table 13.

Table 10

NDE Methods for Inspecting the Building Envelope

Component or System	Main Performance Requirements	Currently Recommended NDE Methods: Method	Location in Report[a]	Potential NDE Methods: Location in Report[a]	Method
Walls and Ceilings	No penetration by rain water			5.16.2	Capacitance instrumentstion
				5.32.2	Fiber scope
				5.16.3	Nuclear meter
				5.16.1	Resistance probe
	Retard heat transmission	Thermal inspection	5.29	5.29.1	Thermal inspection (thermography)
				5.29.5	Spot radiometer
				5.29.3	Heat flow meter
				5.29.4	Portable calorimeter
				5.29.2	Envelope thermal testing unit
	Building envelope tightness	Air infiltration measurement	5.4	5.4.1	Tracer gas
				5.4.4	Smoke tracer
		Infrared thermography	5.29.1	5.4.3	Acoustic method
Foundation and Basement	Supports building				
	Prevents settlement	Visual crack survey	---		
		Level readings -- change with elapsed time*	---		
		Strain gage buttons on cracks*			
		Photographic recording of cracks with elapsed time*	---		
	Prevents upward movement of moisture	Mositure meter	5.16		
	Prevents basement slab movement	Visual and/or level readings - change with elapsed time*	5.32		
Roof	No penetration by rain water	Nuclear moisture meter	5.16.3	5.16.2	Capacitance instrument
		Thermal inspection (thermography)	5.16.4		
	Self-supporting under design loads	Proof loading	5.22		
	Retard heat transmitting	Thermal inspection (thermography)	5.16.4		
Floor	Levelness	Level readings -- change with elapsed time*	----		
		Carpenter's level*	----		
	Supports design service loads	Proof loading	5.22		
	Joining details and construction practices and materials			5.25.3	Radiography
				5.32.2	Fiberscope

[a] Numbers in this column refer to NDE Methods Nos. described in Section 5 and listed in Table 13.

* Self-explanatory; not described in Table 13.

Table 11

NDE Methods for Inspecting Pipe and Drainage Systems

Performance Requirements	Currently Recommended NDE Methods: Method	Currently Recommended NDE Methods: Location in Report[a]	Potential NDE Methods: Location in Report[a]	Potential NDE Methods: Method
Does not leak	Leak testing	5.11		
Proper flow rate	Measure volume of water flowing during time interval*	---	---	Flow meter connected to outlet
Proper flow pressure			---	Hydrostatic pressure gage
Dielectric joints between dissimilar metals	Measurement of electrical resistance across joint*	---	5.32.2	Inspection by fiberscope
Prevention of back flow of gases	Direct measurement of water in trap*	---	---	Determination of pressure of proper component

[a] Numbers in this column refer to NDE Methods Nos. described in Section 5 and listed in Table 13.

* Self-explanatory; not described in Table 13.

Table 12

NDE Methods for Inspecting Heating, Ventilation, and Air Conditioning Systems

Performance Requirements	Currently Recommended NDE Methods: Method	Currently Recommended NDE Methods: Location in Report[a]	Potential NDE Methods: Location in Report[a]	Potential NDE Methods: Method
Proper air flow level (ventilation)	Air flow measurement (tracer gas)	5.4.1	5.3.1	Pitot traverse
Air ducts properly sealed	Leak detection*	---	5.4.3 5.32.2 5.4.4	Sound Amplification Fiberscope Smoke tracer

[a] Numbers in this column refer to NDE Methods Nos. described in Section 5 and listed in Table 13.

* Self-explanatory; not described in Table 13.

Table 13

Operation, Principles, and Applications of Commonly Used and Potential NDE Methods for Inspection of Building Materials and Systems

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.1 Acoustic Emission	During crack growth or plastic deformation, the rapid release of strain energy produces acoustic (sound) waves thst can be detected by sensors attached to the surface of a test object.	Continuous monitoring of structure during service life to detect impending failure; monitoring performance of structure during proof testing.	$10,000 for single pick-up, up to $100,000 for multi-channel pickup.	Extensive knowledge required to plan test and to interpret results.	Monitors response of as-built structure to applied load; capable of detecting onset of failure; cspable of locating source of possible fsilure.	Requires means of loading structure; complex electronic equipment is required; access to surface is required.
5.2 Acoustic Impact (Hammer Test)	Surface of object is struck with a hammer (usually metallic). The frequency and damping characteristics of the "ringing" can indicate the presence of defects.	Detect delaminations or disbonds in composite systems; detect voids and cracks in materials, e.g., hammer technique to detect defective masonry units; "chain drag" method to detect delaminations in concrete pavements.	Neglible for manual techniques, $3000 for measuring devices.	Low level of expertise required to use, but experience needed for interpreting results.	Portable; easy to perform test; electronic device not needed for qualitative results.	Geometry and mass of test object influences results; poor discriminstion; reference standards required for electronic testing.
5.3 Air Flow Measurement	A traverse is made of the air velocity at a section in sn air duct.	Determination of average air velocity in an air duct.	-----	Should be performed by trained personnel.	Air velocity st a point in a air duct can be determined by a simple method using a pitot tube.	Measurements should not be made at locations where there is a disturbance in the airflow in the duct.
5.3.1 Pitot Traverse	The velocity in a duct is seldom uniform across any section; a traverse is made to determine average velocity; pitot tube and msnometer used to measure air velocity; traverse consists of at least 16 readings in the center of equal areas across the cross section of the duct.	Pitot tube traverse used to determine average air velocity in an air duct.	There are many forms of pitot tubes and manometers used for air velocity measurements.	Should be performed by trained personnel	Average air velocity in an air duct can be determined by a simple method.	For low air velocities a precision msnometer is essential; measurements should not be msde at locations of disturbance in air flow.
5.4 Air Infiltrstion Measurement	Air infiltration measurements can be made by tracer-gas decay method and by fan pressurization technique. Air infiltration sites can be found by acoustic method and smoke tracer systems.	Measurement of building air leakage and air exchange rate can be made using tracer gases. Building envelope tightness can be determined by fan pressurization technique.	-----	Should be performed by trained personnel.	Tightness of building can be determined and air leakage paths located.	Smoke should be used sparingly because of annoyance to building occupants and possible material damage.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.4.1 Tracer-Gas Decay Method	A tracer gas is injected into air handling system for the building. Measurements of tracer gas concentrations made at various locations and at different times.	Determination of differences in ventilation rates and localized air leakage.	-----	Should be performed by trained personnel	Versatile method; simplest of tracer-gas measurement systems; can be used for both short and long term measurements.	Difficult to obtain uniform concentration of tracer gas if building is large, divided into many rooms, or does not have air handling system.
5.4.2 Fan Pressurization technique	Building is pressurized by a fan and air flow rate measured. At a fixed pressure difference, the lower the air flow rate, the tighter the envelope.	Estimation of building envelop tightness.	-----	Should be performed by trained personnel	Simple method; direct comparison with other buildings and times of measurement; assess effectiveness of retrofit measures.	Very large fan or simultaneous use of a number of fans may be required.
5.4.3 Acoustic Method	Sound and air readily pass through openings in buildings. A sound source is placed on one side of wall and probing on other side to seek increases in sound levels.	Location of small openings through building envelope	-----	Low to moderate	Method is simple and low cost	May be difficult to detect leaks in lightweight walls and insulated walls; noisy environments cause problems in leak detection.
5.4.4 Smoke Tracer	A controlled smoke source is provided and a thin stream of smoke may be observed at air leakage sites.	Location of air leakage sites in building components and local areas of building envelope.	-----	Low to moderate	Locally used technique	Smoke source should be located close to suspected leakage site. No extensive use of smoke in building interior.
5.5 Air Permeability	A small diameter hole is drilled in concrete. The hole is plugged and vacuum pressure applied. Time for pressure to increase to a predetermined level is measured.	Research has concluded that this test (permeability) is an effective tool for evaluating durability and carbonation rate of aged concrete and for forcasting compressive strength of site concrete.	Small	Method considered as effective research tool. Knowledge of concrete and analysis of test results required.	As easy and inexpensive method.	Has not been established as a reliable NDE method to evaluate the quality of concrete.
5.6 Break-Off Method	A transverse force is applied to the top of small concrete cylinder which was formed by removing a plastic cylinder placed in fresh concrete or by drilling into hardened concrete.	Used to determine concrete strength at the site.	-----	Highly trained and experienced.	Simple, economical, and practical means to determine concrete strength at site.	Test results in slight damage to concrete. Method has not been established for use in the United States.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.7 Cast-in-Place Pullout	Measure the force required to pull out steel rod with enlarged head cast in concrete. Also, pullout device can be inserted in hole drilled in hardened concrete. Pullout forces produce tensile and shear stresses in concrete.	Estimation of compressive and tensile strengths of concrete.	$1000 to $5000.	Low, can be used by field concrete testers and inspectors.	Only NDE method which directly measures inplace strength of concrete. Appears to give good prediction of concrete strength.	Pullout devices must be inserted during construction, or inserted in hole drilled in hardened concrete. Cone of concrete may be pulled out, necessitsting minor repairs.
5.8 Electrical Potential Measurements	Electrical potential of steel reinforcement measured. Potential indicates probability of corrosion.	Determining condition of steel rebars in concrete and masonry.	$1000 to $2000.	Moderate. User must be able to recognize problems.	Portable equipment; field measurements readily made; appears to give reliable information.	Does not provide information on rate of corrosion. Requires access to reinforcing bars to make electrical contact.
5.9 Electro-Magnetic Methods	The following NDE Methods are included: eddy current, magneto-inductive methods (magnetic field testing) including cover meters, magnetic particle inspection, and determination of steel fiber content.	----	----	----	----	----
5.9.1 Eddy Current	An electrically excited coil induces eddy current flow and an associated eletromagnetic field in metal. Flaws alter induced electromagnetic field which in turn alters the impedance of the excitation coil. Change in coil impedance indicates presence of flaw or anomaly.	Inspection of metal parts for cracks, voids, inclusions, seams, and laps; measurement of thickness of nonmetallic coating on metals; detection of improper alloy composition.	Minimum of $3000.	Moderate	Extremely sensitive to change in properties and characteristics of metal; portable.	Requires calibration with standards; limited depth of penetration; only applicable to metals; sensitive to geometry of parts.
5.9.2 Magneto-Inductive Methods (Magnetic Field Testing)	An electrically energized primary coil is brought near test object. A voltage is induced in a secondary coil, and its magnitude is compared to a reference standard. Magnetic properties of test object affect induced voltages.	Distinguishing between steels based on differences in composition, hardness, heat treatment, or residual stresses; locating hidden magnetic parts; measuring thickness of nonmagnetic coatings or films.	$3000	Low to moderate, depending on application.	Portable; rapid tests; easily detects magnetic objects even if embedded in nonmagnetic material.	Applicable only to ferromagnetic alloys; reference standards and calibration may be required for some applications.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.9.3 Cover-Meter	Presence of steel affects the magnetic field of a probe. Closer probe is to steel, the greater the effect. Principle of operation is similar to eddy current method.	Determination of presence, location and depth of rebars in concrete and masonry.	\$800 to \$1500	Moderate, easy to operate, need some training to interpret results.	Portable equipment, good results if concrete is lightly reinforced.	Difficult to interpret results if concrete is heavily reinforced or if wire mesh is present.
5.9.4 Magnetic Particle Inspection	Presence of discontinuities in ferromagnetic material will cause leakage field to be formed at or above the discontinuity when the material is magnetized. The presence of the discontinuity is detected by use of finely divided ferromagnetic particles applied over the surface. These form an outline (termed indication) of the discontinuity.	Used most often to detect fatigue cracks in inservice metal components and inspection during production control. Applicable to inspecting welds.	Minimum of \$2000	Expertise required to plan nonroutine tests. Moderate expertise to perform test.	Capable of detecting subsurface cracks if they are larger than surface cracks; size and shape of component poses no limitation; portable equipment available.	Non-ferro magnetic metal cannot be inspected; coatings affect sensitivity; demagnetization may be required after testing.
5.9.5 Steel Fiber Content	The electromagnetic apparatus consists of a measuring device and coils for both excitation and induction of an electric current. The induced electric current increases with an increase in the steel fiber content of the specimen.	The steel fiber content in both hardened and fresh concrete can be determined from the level of the induced current.	-----	Moderate to high	Method shows promise as a research tool to measure steel fiber content in hardened and fresh concrete.	Has not been used extensively in the field. Further development work is required if it is to become a reliable NDE method.
5.10 Holography	A two step process creates a three-dimensional image of a diffusely reflecting object using visible light waves or ultrasonic waves. Deviations in shape or dimensions of an object can be observed and measured by comparing a regenerated three-dimensional image with the original image.	Deviations in the shape or dimensions of an object can be observed and measured by comparison of three-dimensional images recorded at different times.	-----	Skill required in developing holograms and in the interpretation of comparing holograms.	Changes in shape or dimensions of metal components and metal containing structures can be determined.	Method generally used in laboratory; complicated procedure.
5.11 Leak Testing	Telltale substances added to piping system under pressure reveal presence of leaks. Sound amplification to detect leak noise.	Detection of leaks in pipes carrying fluids.	Wide range depending on detection method. \$100 to \$5000	Low to high depending on application.	Can locate leaks too small to be found by any other NDE method.	Difficult to determine position of leaks in pipes hidden in wall or floor cavities.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.12 Longitudinal Stress Waves	The speed that longitudinal stress waves travel in wood are affected by many factors including moisture content, temperature, specific gravity, and grain orientation.	Stress waves show promise for rapid lumber grading and predicting mechanical properties of wood. Also stress-wave transmission has been investigated to determine extent and location of degradation of wood.	-----	High	A rapid method for possibly determining the quality of wood and wood members.	Additional research is needed to demonstrate the feasibility of using this method.
5.13 Maturity Concept	The early age strength development of concrete is related to the combined effect of temperature and time.	Prediction of the compressive strength of concrete during the construction phase.	Maturity meter costs around $2000.	Expertise required to develop maturity strength relationships.	Accounts for in-place temperature history. Field measurements simple to perform.	Calibration strength-maturity curve must be developed. No direct measure of in-place strength. Location of temperature sensors must be carefully selected.
5.14 Microwave Inspection	Microwaves are a form of electromagnetic radiation which have frequencies between 300 MHz and 300 GHz corresponding to wavelengths of 1 m to 1 mm. Because of their electromagnetic nature, microwaves can be reflected, diffracted and absorbed.	Microwaves are absorbed by water, thus a method was developed for determining the moisture content of concrete.	-----	High	Has potential for inspecting installed construction materials.	The feasibility of using microwaves for inspection of in situ materials has not been demonstrated.
5.15 Middle Ordinate Method	The middle ordinate instrument measures the perpendicular distance between the mid point of a chord and its arc. This distance or deflection is inversely related to stiffness of lumber.	Stiffness variations in lumber are detected over lengthwise regions of less than two feet.	-----	High	Provides a means of assessing in the laboratory the strength-reducing potential of defects in lumber.	Additional research is needed to demonstrate the feasbility of using this method to inspect lumber at the job site.
5.16 Moisture Detection Methods	There are four methods often used for moisture inspection measurements, the types of instruments or methods used include electrical resistance probes, capacitance instruments, nuclear meters, and infrared thermography.	-----	-----	-----	-----	-----
5.16.1 Electrical Resistance Probe	Electrical resistance between two probes inserted into test component is measured. The resistance decreases with increased moisture contents.	Measurement of moisture contents of timber, roofing materials, and soils. Can be used to map moisture migration patterns in masonry walls.	$300 to $1000.	Low	Equipment is inexpensive, simple to operate, and many measurements can be rapidly made.	Not reliable at high moisture contents; needs to be calibrated; precise results are not usually obtained.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.16.2 Capacitance Instruments	Water affects the dielectric constant and the dielectric loss factor of materials. Measurement of either property can be used to estimate moisture contents.	Measurement of moisture contents of timber, insulation, and roofing materials.	$1500	Low to use but experience needed to plan test.	Portable; simple to operate; effective over a range of moisture contents.	Measurement is only for limited depth; calibration required; results affected by roofing aggregates; many factors affect accuracy.
5.16.3 Nuclear Meter	Fast neutrons are slowed by interactions with hydrogen atoms. Back-scattered slowed neutrons are measured, the number of which is proportional to the number of hydrogen atoms present in a material.	Moisture content measurements of soil, insulation, and roofing materials. Can be used to map moisture migration patterns in masonry walls.	$4000 to $6000.	Must be operated by trained and licensed personnel.	Portable; moisture measurements can rapidly be made on in service materials.	Only mesures moisture content for limited depth (50 mm); dangerous radiation; hydrogen atoms of building materials are measured in addition to those of water.
5.16.4 Infrared Thermography	See Section 5.29.1	-----	-----	-----	-----	-----
5.17 Nuclear Density Meter	Gamma rays are used to measure mass density. The energy loss of the emitted gamma rays is proportional to the mass density of the material through which the rays pass.	Measurement of density of soils. Could be used for estimating density of concrete.	$4000 to $6000	Must be operated by trained and licensed personnel.	Portable; density measurements can be made without disturbing the material being tested.	Calibration necessary; dangerous radiation; only measures density of surface layers.
5.18 Paint Inspection Gages	Paint inspection gages are used for dry and wet film thickness and film hardness.	-----	-----	-----	-----	-----
5.18.1 Tooke Gage	A V-groove is cut into the coating, and an illuminated magnifier equipped with a reticle in the eyeplace is used to measure the number and thickness of the films.	Measurement of the number and thicknesses of paint layers.	$1300	Low.	Simple to operate; portable; measurement can be made with any type of substrate.	Small scratch is made in coating and the substrate is exposed.
5.18.2 Pencil Test	Pencil leads of known hardness are used to determine film hardness.	Determination of film hardness of an organic coating on a substrate.	Very small, the cost for a few pencils.	Knowledge of coatings required.	A rapid and inexpensive method.	Slight damage to coating.
5.18.3 Magnetic Thickness Gages	Magnetic thickness gages include magnetic pull-off gages and magnetic flux gages.	-----	-----	-----	-----	-----

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.18.3.1 Magnetic Pull-Off Gage	Spring tension required to overcome attraction of magnet to substrate.	Determination of thickness of dry nonmagnetic coating on a ferrous base.	$150	Knowledge of coatings required.	A rapid and inexpensive method.	Calibration required for use with each substrate.
5.18.3.2 Magnetic Flux Gage	Changes in magnetic flux used to measure coating thickness.	Determination of thickness of dry nonmagnetic coating on a ferrous base.	$300 to $500.	Knowledge of coatings required.	A rapid and relatively inexpensive method.	Calibration required for use with each substrate.
5.18.4 Wet Film Thickness Gages	Wet film thickness gages include interchemical, Pfung and notch gages.	-----	-----	-----	------	-----
5.18.4.1 Interchemical Gages	Eccentric center wheel supported by two concentric wheels.	Determination of thickness of wet coating.	-----	Knowledge of coatings required.	Rapid method for determining wet coating thickness.	Coating film needs repair at measurement locations.
5.18.4.2 Pfung Gage	Convex lens mounted in tube that slides freely in an outer tube.	Determination of thickness of wet coating.	-----	Knowledge of coatings required.	Rapid method for determining wet coating thickness.	Coating film needs repair at measurement locations.
5.18.4.3 Notch Gage	Rectangular or circular gages pushed or rolled into or across wet coating film.	Determination of thickness of wet coating.	-----	Knowledge of coatings required.	Useful in determining approximate wet film thickness when use of more precise methods not permitted.	Approximate wet film thickness determined. Coating film needs repair at measurement locations.
5.19 Pin Hole (Holiday) Detector	One electrode is connected to a conductive substrate, another electrode (a moisture sponge) is passed directly over a coating. An alarm is sounded when a pin hole (holiday) is encountered which completes the electrical circuit.	Determining the presence of pin holes in nonconductive coatings over metals.	$200	Low.	Simple to operate; portable.	Results are qualitative, e.g., there is no measure of the size of the pin hole.
5.20 Point-Load Test	Relatively small cores of plain of fibrous concretes are tested using a point load in a diametral test. The point load is applied at mid-length of the core along its diameter.	Test is intended to estimate the compressive and tensile strength of concrete.	-----	Moderate	A quick and inexpensive test; can be performed in the field on a simple and easily portable apparatus.	Additional research needed to demonstrate the feasibility of using this test; concrete needs to be repaired where cores are taken.
5.21 Probe Penetration Method	Probe fired into concrete and depth of penetration is measured. Surface and subsurface hardness measured.	Estimations of compressive strength, uniformity, and quality of concrete. Could be used for estimating the same properties of mortars.	$1000 plus cost of probes.	Low, can be operated by ordinary field personnel.	Equipment is simple and durable; good for determining quality of concrete.	Slightly damages small area. Does not give precise prediction of strength.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.22 Proof Loading	Structure or system is subjected to loads and response is measured.	Determining safe capacity and integrity of structures. Leak testing of pressure vessels and plumbing.	Wide, depending on application; often high.	Depends on nature of tests; can be high.	Entire structure can be tested in its "as-built" condition.	Can be very costly; instrumentation required to measure response; careful planning required; can damage structure.
5.23 Pull-Off Test	A circular steel probe is bonded to the surface of the concrete using epoxy resin. A tensile force is applied to the adhered probe until the concrete fails in tension. Compressive strength can be determined from calibration graphs.	Used to estimate the in situ strength of concrete.	-----	Moderate	A simple and inexpensive test which may be conducted on horizonal and vertical surfaces. Location of tests areas do not have to be planned in advance.	A standard test method has not been developed. Concrete needs to be repaired in areas where tests are conducted.
5.24 Radar	Radio frequency waves from a radar transmitter are directed into a dielectric material. The waves propagate through material until a boundary is intercepted, then part of the incident energy is reflected. The reflected (echo) wave is picked-up by a receiver. A boundary exists at discontinuities or at interfaces between materials of different dielectric properties.	Detection of interfaces, delaminations and voids in concrete and measurement of thickness of concrete pavements.	-----	High, requires an understanding of wave propagation in materials.	Large areas of concrete and other materials can be rapidly surveyed, internal construction details and defects can be identified.	Further research required to establish a technical basis for interpretation of test data. Interpretation of data may require use of computers.
5.25 Radioactive Methods	Radiography and radiometry are used to assess the properties of in situ concrete and other materials.	-----	-----	-----	-----	-----
5.25.1 Radiography	Radiography allows the internal structure of a test object be inspected by penetrating radiation which may be electromagnetic or radioactive.	-----	-----	-----	-----	-----
5.25.2 X-ray Rsdiography	Similar to gamma radiography, except X-rays are used.	To identify hidden construction features in wooden structures. Could be used for inspecting thin concrete components.	Field equipment is probably over $5000.	Should be operated by trained personnel because of radiation.	Portable equipment available; intensity of radiation can be varied.	Dangerous radiation; portable units have low intensities and field applications limited to wooden and thin components; opposite surfaces of component must be accessible.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.25.3 Gamma Radiography	Gamma radiation attenuates when passing through a building component. Extent of attenuation controlled by density, and thickness of materials of the building component. Photographic film record usually made, which is analyzed.	Locating internal cracks, voids and variations in density and composition of materials. Locating internal parts in a building component, e.g., reinforcing steel in concrete.	\$5000 to \$10,000	Must be operated by trained and licensed personnel.	Portable and relatively inexpensive compared to X-ray radiography; internal defects can be detected; applicable to a variety of materials.	Radiation intensity cannot be adjusted; long exposure times may be required; dangerous radiation; two opposite surfaces of component must be accessible.
5.25.4 X-ray Fluorescence Analyzer	Material is irradiated with a radioactive isotope and absorbed energy is re-emitted as X-rays characteristic of elements present in material.	Determination of the elements present in material.	\$7000 to \$20,000	Extensive knowledge of technique required for calibration; moderate to conduct field tests.	Rapid analysis; test can be performed on installed materials; portable.	Periodic calibration with reference standard required; not capable of detecting all elements; analysis of small region per test.
5.26 Seismic Testing	Integrity of material evaluated by analysis of shock wave transmission and effects. Shock wave induced by explosive charges and transmission detected by transducers.	Determination of soil densities and variation in densities. Also vibrational characteristics of buildings can be determined.	Wide, depending on amount of information desired.	Experience required to plan test and to interpret results.	Large area of soil and entire structure in its "as-built" condition can be tested.	If incorrectly placed, explosive charge could damage structure. Care must be exercised in handling explosives.
5.27 Soil Exploration	The cone penetration test and the standard penetration test are described in ASTM standards and are widely used in the U.S. and world wide in geotechnical engineering practice. Helical probes were found to be a practical and economical method for shallow depth soil exploration.	-----	-----	-----	-----	-----
5.27.1 Cone Penetration Test	Test is performed by pushing a cylinder having a conical tip into the ground.	Used for soil exploration.	-----	Should be operated by trained personnel.	Test has been correlated with many soil characteristics.	-----
5.27.2 Helical Probes	The probes consist of a helical screw connected to a 5-1/2 - 6 foot steel shaft. The probe is inserted into the ground in a clockwise direction using a torque meter. The magnitude of torque required to insert the probe into the soil is taken as a measure of resistance.	Soil exploration at shallow depth; and for compaction control.	\$400	Moderate; knowledge of soil properties needed.	A practical and economical method for shallow depth soil exploration.	Research should be continued for soils whose characteristics are well defined. A standard test method has not been developed.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.27.3 Standard Penetration Test	Test involves dropping a 63.5 kg hammer to drive a drillrod with soil sampler into the ground.	Used for soil exploration.	-----	Should be operated by trained personnel.	Test has been correlated with many soil characteristics.	-----
5.28 Surface Hardness Testing	Surface hardness methods are generally used to indicate the strength level or quality of a material rather than to detect flaws.	The most common applications are in testing metals and concrete.	-----	-----	-----	-----
5.28.1 Static Indentation	An indenter (small point) probe is mechanically forced into surface of a material, usually a metal, under a specific load. The depth of indentation is measured, and strength of material may be estimated.	Determination of effectiveness of heat treatment on hardness of metals. Estimating tensile strength of metals.	\$600 to \$4000.	Low.	Portable equipment available; fast and easy test to perform.	Conversion tables give only approximate tensile strengths; feasibility of testing limited by size and geometry of component.
5.28.2 Rebound Hammer	Spring-driven mass strikes surface of concrete and rebound distance is given in R-values. Surface hardness is measured.	Estimation of compressive strength, uniformity and quality of concrete.	\$250 to \$600	Low, can be readily operated by ordinary field personnel.	Inexpensive; large amount of data can be quickly obtained; good for determining uiformity of conrete.	Results affected by condition of concrete surface; does not give precise prediction of strength.
5.29 Thermal Inspection Methods	Heat sensing devices are used to detect irregular temperature distributions due to presence of flaws or inhomogenities in a material or component that has different impedances to heat flow. Contours of equal temperature (thermography) or temperatures (thermometry) are measured over the test surface with contact or non-contact detection devices. A common detection device is an infrared scanning camera.	Detection of heat loss through walls and roofs; detection of moisture in roofs; detection of delaminations in composite materials, including concrete and masonry walls.	\$30,000 for infrared scanning camera. Less expensive hand-held equipment.	Moderate to extensive depending on nature of tests.	Portable; permanent record can be made; testing can be done without direct access to surface and large areas can be rapidly inspected using infrared cameras.	Costly equipment; reference standards needed; means of producing thermal gradient in test component or material is required.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.29.1 Infrared Thermo-graphy	Differences in surface temperature can be detected. Changes in the temperature of a surface produce more than proportional changes in emitted energy.	Comparison of thermal resistances of roofs and walls; detection of entrapped moisture and heat loss in roofs and walls; detection of disbonds in laminated materials, deteriorated bridge decks, material density gradients, and anomalies in castings.	$30,000 for infrared scanning camera.	Moderate to extensive depending on testing.	Portable; permanent record can be made; direct access to surface not required; large areas can be rapidly inspected.	Equipment is costly, thermal gradient needed in test material or com-ponent; complexity of variables affecting surface temperature requires careful interpre-tation of test data.
5.29.2 Envelope Thermal Testing Unit	Unit consist of two blankets attached to opposite sides of walls through which the heat flux to opposite wall surfaces can be controlled.	To evaluate the in situ transient thermal per-formance of walls.	$5,000 to $10,000	Experience with this pro-cedure needed; understanding of funda-mentals of building heat transfer.	Measurements can be made of in situ transient thermal performance of walls.	Has been used only for research purposes not an established test method.
5.29.3 Heat Flow Meter	Consists of a thin flat wafer comprised of a series of pairs of thermocouples. Wafer contains an embedded thermopile which pro-duces a voltage pro-portional to the rate of heat flow passing through the wafer.	Thermal resistance of a building component at a representative location can be measured using a heat flow meter and temper-ature-sensing probes.	$100 to $200 for heat flow meter; $9,000 to $10,000 for instrument system for measurements at ten locations.	High; only qualified technicians.	When used with thermographic survey technique becomes viable tool for assessing thermal per-formance of building com-ponents	Used only during periods when there is no reversal in direction of heat flow; analysis of data complex for dynamic response.
5.29.4 Portable Calorimeter	Essentially guarded hot box; an insulated box having five sides, the open side sealed against building com-ponent. Temperature inside box is kept equal to indoor building temperature. Electrical energy supplied to box is essentially equal to heat transmission through metered area.	In situ measurement of heat transmission through building components.	$800 to $1000	High, only qualified technicians.	Provides a minimum disturbance to the measured heat trans-mission; large surface areas are metered.	Outdoor to indoor temperature difference greater than 10°F.
5.29.5 Radiometer	The device senses the total infrared radia-tion over a particular wave-length band emanating from the surface, including self-emitted surface radiation and reflected radiation.	Used to determine qualitatively whether a wall or other building component is insulated or if insulation voids or other thermal defects are present.	$300 to $1500.	Low	Gross thermal defects can be readily detected while quickly scanning the envelope of a building	Not accurate enough to permit detection of small differences in effectiveness of insulation.

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.30 Ultrasonic Pulse Methods	Ultrasonic inspection is based on two principles: 1) the velocity of acoustic waves in a material is a function of the material's elastic constants and density; and 2) when an acoustic wave encounters an interface between dissimilar materials, a portion of the wave is reflected.	-----	-----	-----	-----	-----
5.30.1 Ultrasonic Pulse Velocity	Based on measuring the transit time of an induced pulsed compressional wave propagating through a material.	Estimation of the quality and uniformity of concrete.	$4000 to $6000.	Low level required to make measurements. Expertise needed to interpret results.	Excellent for determining the quality and uniformity of concrete. Can rapidly survey large areas and thick members.	Does not provide precise estimate of strength; skill required in analysis of results; moisture variations and presence of metal reinforcement can affect results.
5.30.2 Ultrasonic Pulse Echo	Pulsed compressional waves are induced in materials, and those reflected back are detected. Both the transmitting and receiving transducers usually are contained in the same probe.	Inspecting metals for internal discontinuities. Some work has been performed on the use of the pulse echo method to inspect concrete for delaminations and cracks.	Minimum of $5000	High level of expertise required to interpret results.	Portable; internal discontinuities can be located and their sizes estimated.	Good coupling between transducer and test substrate critical; interpretation of results can be difficult; calibration standards required.
5.31 Uplift Resistance	A controlled negative pressure is created on top of the roof surface using a chamber fitted with a vacuum pump and a pressure measuring device.	Determination of the resistance of built-up roofing systems to uplift pressure.	$2500	Should be operated by personnel with expertise in the performance of roofing systems.	Portable equipment available for field tests of new and weathered built-up roofs.	Skill required to conduct tests to prevent roof damage and to evaluate test results. Tests should not be conducted during high wind.
5.32 Visual Inspection	Surface defects often can be detected visually using methods to improve ordinary observations. Methods used to improve visual inspection are optical magnification and liquid penetration inspection. The inside of a cavity can be observed using a fiberscope inserted through a small access hole into the cavity.	-----	-----	-----	-----	

Table 13. Continued

Method	Principle	Main Applications	Approximate Equipment Cost	User Expertise	Advantages	Limitations
5.32.1 Optical Magnification	Available magnifying instruments range from simple, inexpensive glasses to expensive microscopes.	A useful tool for field inspection is a pocket magnifier with a built-in viewing scale for measurement of flaw dimensions.	-----	Low to moderate depending on type of measurement or observation.	Flaw dimensions can be readily measured in the field.	With a small field of view it difficult to examine large surface areas. Instruments need to be calibrated.
5.32.2 Fiberscope (Endoscope)	Bundle of flexible, optical fibers with lens and illuminating systems is inserted into small bore holes thus enabling view of interior of cavities.	Check condition of materials in cavity, such as thermal insulation, pipes, and electrical wiring installed in wall cavities; check for unfilled cores in reinforced masonry construction; check for voids along grouted stressed tendons.	$3000 to $6000.	Low.	Direct visual inspection of otherwise inaccessible parts is possible.	Probe holes usually must be drilled; probe holes must connect to a cavity.
5.32.3 Liquid Penetrant Inspection	Surface is covered with a liquid dye which is drawn into surface cracks and voids. Developer is applied to reveal presence and location of flaws.	Detection of surface cracks and flaws. Usually used to inspect metals.	$50 to $250 per 100 linear feet of inspection.	Low.	Inexpensive; easy to use; can be applied to complex parts; results are easy to interpet.	Detects only surface flaws; false indications possible on rough or porous materials; surface requires cleaning prior to testing.
5.33 Water Permeability	The transmission of water through coated masonry walls is proportional to the number of "pin holes" in the coating.	A properly coated masonry surface will have a limited water transmssion rate.	-----	Moderate	Water transmission rate through coated masonry can be measured in the field.	Care required during test not to allow excessive water to enter wall which may have damaging effects.
5.34 Combinations of Nondestructive Evaluation Methods	No single NDE method may be entirely satisfactory for predicting the strength or quality of material; combinations of methods may give more definite information.	-----	-----	-----	-----	-----

5. DESCRIPTION OF NDE METHODS

The descriptions of the NDE methods generally include information about the methods, descriptions of the methods, applications of the methods, and the advantages and limitations in using the methods. In some cases, other information about the NDE methods is presented such as reliability of a method and calibration of NDE equipment. In other cases, however, because information was not available in the literature some information such as advantages and limitations of the NDE methods may not be included in this section of the report.

5.1 Acoustic Emission Method

In this method, stress waves originating within the test object are detected by surface transducers [2]. The acoustic waves result from the sudden release of stored strain energy when either pre-existing or newly created flaws propagate under the action of an applied stress field. The types of flaw propagation that can be detected include dislocation movement in metals and microcrack growth in metals or brittle solids such as concrete. Thus, acoustic emission can indicate the start of mechanical failure -- i.e., yielding or fracture. The test object must undergo stress so that flaws will appear or propagate; static flaws are not detected by acoustic emission.

Description of Method

Acoustic emission testing is a passive technique; only an acoustic wave detection instrument is required. The acoustic waves, which may have a frequency range from audible to ultrasonic, are detected by piezoelectric transducers attached to the surface of the test object. The existence of flaw growth can be detected by a transducer anywhere on the test object (provided that there is enough wave amplitude to be detected). Thus, the location of transducers relative to pre-existing flaws is not critical in this method unless it is required to locate the flaw. The transducers generally detect waves in the frequency range of 50 kHz to 10 MHz [2]. Detected signals are amplified; the amount of necessary amplification depends on the source of the acoustic emission. Signals from dislocation movement require greater amplification than signals from microcrack propagation. After amplification, the acoustic emission activity is processed and displayed. The most useful displays are the rate of acoustic emission events (detected signals), or the cumulative number of events plotted as a function of a pertinent parameter, such as time, applied load, or number of load cycles. Growth of microcacks as small as 10^{-5} in. (2.5×10^{-4} mm) can be detected, while the minimum static flaw detectable by ultrasonic or radiographic methods is about 0.001 in. (0.025 mm).

Applications

The method has been used to monitor the in-service behavior of pressure vessels (including nuclear reactors), to detect the onset of rapid crack propagation under fatigue loading or caused by stress corrosion, and to monitor the response of systems to proof-load tests. Because acoustic emissions give forewarning of ultimate failure, the technique can be used to signal when loads should be reduced to prevent total failure. By using both multiple pickup of acoustic signals with transducers at different locations and electronic data processing, regions of high acoustic emission activity can be pinpointed, and a critical "weak link" in the system located.

Advantages

The most significant advantage of the acoustic emission method is that it gives the response of the total structure or system (in "as-built" condition) to applied loads. By observing the acoustic emission activity as loads are applied, one can find the extent of internal material degradation (yielding or fracture) as a function of load. Generally, the stage of incipient failure can be determined because this is usually accompanied by a rise in the acoustic emission rate and a rapid increase in the cumulative number of emissions.

Limitations

A major difficulty in interpreting acoustic emission results is the separation of signals caused by the loading system or by microscopic slippage at joints in the test object from the signals produced by flaw propagation in the material. Users of the technique must be aware of all the possible extraneous acoustic signals that may be detected by the transducers, and must be careful not to confuse them with signals due to flaw growth. Some background noise may be eliminated by using low frequency filters, but elimination of other noise may require more complicated methods. A high level of skill is required to properly plan an acoustic emission inspection program. Equipment costs vary from moderate ($10,000) to very expensive, depending on whether a single- or multiple-pickup system is required for the particular application.

5.2 Acoustic Impact Method

Description of Method

Acoustic impact is the oldest and simplest form of acoustic inspection. In this method, audible stress waves are set up in a test object by mechanical impact; the frequency and damping characteristics of the vibrations can be used to infer the integrity of the test object [3]. In its most unsophisticated form, the test object is struck with a hammer, and the operator listens to the "ringing" caused by the resonant vibration of the object. In a more sophisticated form, a transducer is attached to the test object, and an amplifier and display unit are used to produce a visual display of the frequency and damping characteristics of the "ringing." By comparing the output with a standard representing acceptable quality, a decision is made regarding the integrity of the object.

Applications

This method can be used to detect hollow zones and delaminations in concrete and masonry structures, or it may be used to find studs behind wall-board. It also has been used to detect delaminations in laminar and composite materials.

Advantages

The equipment required to carry out the test is relatively inexpensive, and the test can be done easily.

Limitations

Because the "ringing" can be affected by the mass and geometry of the test object, an experienced operator may be needed to correctly interpret the results.

5.3 Air Flow

5.3.1 Pitot Traverse

Principle and Applications

Air velocity at a point in an air duct can be determined by a simple method using a pitot tube in conjunction with a suitable manometer. The velocity in a duct is seldom uniform across any section, thus a traverse is usually made to determine average velocity since a pitot tube reading indicates velocity at only one location. In general, air velocity is greatest near the center and lowest near the edges or corners. The ASHRAE Handbook indicates that in round ducts, at least 20 readings should be taken along two diameters of equal areas. In rectangular ducts, take readings in the center of equal areas across the cross section of the duct. The number of spaces should be at least 16, and need not exceed 64 [4]. To determine average velocity in the duct from the readings obtained, average the calculated individual velocities or the square roots of the velocity heads.

If there is a disturbance in the air flow in the duct, the pitot tube should be located at least 7.5 diameters downstream from the disturbance. The type of manometer used with a pitot tube depends upon the velocity pressure being measured and the desired accuracy. A draft gage of appropriate range is usually satisfactory for velocities greater than 1500 fpm. For low air velocities, a precision manometer is essential. There are many forms of pitot tubes that have been used to make air velocity measurements.

5.4 Air Infiltration Measurements

Principle and Applications

Air leakage is the uncontrolled entry of outdoor air into a building. Air leakage tests are performed to determine the tightness of buildings and to determine whether overall building ventilation is adequate. With regard to building tightness, air leakage tests provide data to determine primarily the natural air leakage rates occurring in the building under various climatic conditions and use patterns, tightness of the building compared with other buildings and with itself after corrective measures have been completed, location of leakage paths in the building, and the magnitude of each leakage path.

Measurements of both building air leakage and air exchange rate can be made using tracer gases. The rate of decay of concentrations of these gases which are introduced in the air in buildings is the technique used. Another way to measure building envelope tightness is the fan pressurization technique.

5.4.1 Tracer-Gas Decay Method

The tracer-gas decay method is very versatile and is reported to be the simplest of the tracer-gas measurement systems [5]. It can be used for both short and long term measurements. The air measuring equipment may be located on site or the air samples may be collected into air bags and analyzed off site. Injection of the tracer gas and measurements of the concentrations can be made manually or automatically to study the dependence of air exchange rates as weather changes over time.

A single injection of tracer gas is sufficient for each measurement and complicated apparatus is not required to control the concentration or automatically inject gas, although several automated techniques have been developed. As much time as necessary may be allowed for mixing of the tracer gas with the air. A fan may be used initially to mix thoroughly the tracer gas with the air, or the fan may be run throughout the entire measurement procedure. It is convenient to inject tracer gas into the air handling system for the building. In this case, air is sampled at the return air ducts. If the building is large or divided into many rooms and does not have a mechanical air handling system, it may be difficult to obtain a uniform concentration of tracer gas throughout the building. It is possible that even if a uniform distribution of tracer gas exists initially, concentrations may decay at different rates at different locations in the building. The measurements will reveal the extent of the nonuniformities such as differences in ventilation rates and localized air leakage.

5.4.2 Fan Pressurization Technique

A building may be pressurized by a fan and the air flow rate measured to estimate building envelope tightness. At a fixed pressure difference, the lower the air flow rate, the tighter the envelope. In order to obtain measureable air flow rates, large pressure differences are usually introduced in order to overcome any natural pressure differences. For even medium size buildings this may require the use of a very large fan or simultaneous use of a number of fans. Measurement of isolated wall and roof areas may avoid the necessity for using large fans. This stepwise method also provides information about permeability of individual building envelope components. Buildings can be compared directly by expressing the induced air leakage at a standardized pressure difference, usually 50 Pa [5].

The fan pressurization method has the advantage of simplicity, direct comparability with other buildings and times of measurement, intrinsic meaningfulness without reference to temperature and wind conditions, usefulness in locating leakage openings when used in conjunction with infrared thermography, and the ability to assess the effectiveness of retrofit measures applied one at a time.

5.4.3 Acoustic Method

Principle and Applications

This method is based on the principle that sound and air readily pass through openings in buildings. The method is simple, low cost, and can be used with minimum of training. Small openings through building structures serve as paths for both air infiltration and sound. Even very small openings in walls can significantly increase acoustic transmission compared to the case where the openings are sealed. A sound source is placed on one side of a wall and probing is carried out on the other side seeking local increases in sound levels. Almost any sound source of sufficient loudness can be used; however, preferred sources are steady and broad-band noise containing many frequencies and a saw-tooth warble tone that sweeps in frequency from 50 to 8000 Hz about three times per second. The broad band sound could be produced by a vacuum cleaner. Both sounds could be produced using a cassette tape and portable tape recorder. The warble tone works better because it is easily discernable. If the sound source is placed outside the building, the steady and broad-band sound is preferred because it is less annoying.

Sound can be detected near the surface and over a small area using a mechanic's stethoscope, airline plastic headset, Type I and Type II sound level meters, and low-cost sound meters consisting of a battery-powered microphone and headphones.

Limitations

Lightweight walls (barriers) will only reduce sound levels slightly making it difficult to detect leaks from normal sound transmission. Insulation in walls may greatly reduce the sound transmission, especially through an air passage that is not straight through, thus making it difficult to detect the leak. Noisy environments can also cause problems in the application of this method.

5.4.4 Smoke Tracer

Principle and Applications

Some of the commercial smoke tracer systems include guns, pencils, and sticks. These systems provide a controlled smoke source so that at leakage sites a thin stream of smoke may be observed. Pressurizing the interior and thereby causing the smoke to flow outward through any openings is the preferred method. The controlled smoke source should be located close to the suspected leakage site.

Limitations

Knowledge of suspected leakage sites is necessary in order to limit leak detection efforts. This will enable the controlled smoke source to be located near the leak site. The smoke must be used sparingly because of annoyance to building occupants and possible material damage. This is a locally used technique and therefore no extensive use of smoke is recommended in the building interior.

5.5 Air Permeability

Research results suggest that the measurement of the air permeability of concrete is effective in forecasting the carbonation rate and compressive strength of site concrete.

Description of Method

This test method provides an estimate of air permeability of concrete in situ. The test method involves boring a small diameter hole about 2 in. (50 mm) in depth in the concrete. The hole is plugged and sealed at the surface of the concrete. A hypodermic needle is pushed through the plug and a vacuum pressure is applied to the needle. The time for the pressure to increase to a predetermined level is taken as a measure of permeability. Research has concluded that the air permeability test is an effective tool for evaluating the durability and carbonation rate of aged concrete and for forecasting the compressive strength of site concrete [6].

Limitations

The feasibility of using the air permeability methods for inspecting concrete has not been demonstrated. Further development work is required if the air permeability method is to become a reliable NDE method to evaluate the quality of concrete.

5.6 Break-Off Method

The break-off test is used to determine concrete strength at the site.

Description of Method

A circular slit about 2 in. (50 mm) in diameter and 3 in. (75 mm) in depth is formed in the concrete either by placing plastic cylinder forms in fresh concrete and removing them after curing, or by drilling into hardened concrete [7,8]. A transverse force is applied, using a hydraulic testing device, to the top portion of the concrete cylinder to fracture the resulting core in the concrete. Fracture or break-off of the core generally occurs along the embedded end (depth) of the circular slit in the concrete due to the transverse force. The measured transverse force can be correlated with the compressive strength by using calibration charts.

Advantages

This in situ test has proven to be a suitable method for in-situ monitoring the quality of concrete. It has been accepted world-wide and has been approved as a test method in a number of national codes and standards including those in Norway and Sweden [7]. The test is a simple, economical, and practical means to determine concrete strength at the site. Further tests can be conducted immediately if the results suggest this to be necessary.

Limitations

The concrete needs to be repaired at locations where the cores were broken off from the concrete.

5.7 Cast-in-Place Pullout

The pullout test measures the force required to pull out a steel insert, with an enlarged end, which has been cast in the concrete. A pull-out device may also be inserted into a hole drilled in hardened concrete. The concrete is subjected to complex stresses by the pullout force, and a cone of concrete is removed at failure. The pullout forces are usually related to the compressive strength of the concrete, with the ratio of pullout strength (force divided by surface area of the conic frustum) to compressive strength being in the range of 0.1 to 0.3. Correlation graphs are used to relate pullout force to compressive strength. There are several commercially available test apparatuses for measuring the pullout resistance of concrete.

Description of Method

ASTM has issued a standard test method, C 900, which describes in detail the pullout assembly and gives allowable dimensions [9]. The pullout insert is cast in place during the placing of fresh concrete. As noted, a pull-out device may also be inserted into a hole drilled in hardened concrete. The insert is either pulled completely out of the concrete, or pulled until maximum load is reached, with a manually operated hollow tension ram exerting pressure through a steel reaction ring. Testing and calculation procedures are also given in ASTM C 900. Techniques have been developed so that the inserts can be embedded deep in concrete, thereby permitting testing of the interior concrete.

Because the pullout insert is usually cast in place during placing of the fresh concrete, these tests must be planned in advance. Alternatively, hardened concrete can be drilled to receive the pullout insert. This necessitates drilling through the bottom or backside of a concrete slab, for example, to the proper depth and width to permit the insertion of the enlarged head. A smaller hole, permitting insertion of the steel shaft, is drilled through the remaining portion of the concrete slab. The insert is placed through the bottom or backside, and the test is performed.

Reliability of Method

Malhotra [10] and Richards [11] have shown that the pullout method can reliably estimate the compressive strength of concrete. Malhotra [10] found that the coefficients of variation for pullout test results were in the same range as obtained from testing standard cylinders in compression. Correlation coefficients of 0.97 to 0.99 have been obtained for normal weight concrete from curve fitting of pullout and compression test results.

Advantages and Disadvantages

The pullout technique is a nondestructive test method which directly measures a strength property of concrete in place. The measured strength is generally thought to be a combination of tensile and shear strengths. The major disadvantage of the pullout test is that a cone of concrete is sometimes pulled out, necessitating minor repairs. However, if the pullout force is quickly released just when failure begins, the concrete cone will not be torn loose, and no repairs will be required. Another disadvantage is the need to plan where inserts are to be located and to make provisions for them before placing concrete. The feasibility of drilling holes into hardened concrete and of inserting pullout devices was explored [12]. This would eliminate the need to install the inserts prior to placing concrete.

5.8 Electrical Potential Measurements

Information on the corrosion state of metals can be obtained from measuring the electrical potential difference of the metal using a standard reference electrode and a voltmeter. If the metal has a certain difference in electrical potential, active corrosion is very likely.

Measurements on Steel in Concrete

The electrical potential method is commonly used to assess the corrosion condition of steel reinforcement in concrete. The electrical potential differences of steel reinforcement are measured by making an electrical connection from a voltmeter to the reinforcement, and a second electrical connection from the voltmeter to a reference cell in physical contact with the surface of the concrete. Dry concrete must be moistened before electrical measurements are made. A saturated copper-copper sulfate electrode is commonly used as the reference cell. The electrical potential difference of the reinforcement below the location of the reference cell is measured.

If the electrical potential difference of the steel reinforcement is more negative than -0.35 volts versus the copper sulfate electrode, active corrosion is probably taking place. Values in the range of -0.30 to -0.35 volts seem to suggest that corrosive conditions are developing within the concrete, while values less negative than -0.30 volts indicate that the steel is probably passive -- i.e., not corroding [13].

An electrical potential difference diagram of a concrete slab can be constructed in which areas of similar potential differences are outlined. This diagram can be used to identify areas where the reinforcement may be corroding.

Advantages

The equipment is inexpensive, and only a moderate amount of skill is needed to make the measurements. Measurements of the electrical potential differences of steel reinforcement provide information concerning the probability of corrosion.

Limitations

Information on either the rate or the extent of corrosion is not obtained. In addition, a direct electrical connection must be made to the reinforcing steel. If the steel is not exposed, then some concrete covering must be removed.

5.9 Electromagnetic Methods

The presence of flaws or changes in composition of metals will affect their electrical and magnetic properties. Therefore, it is possible to infer the presence of anomalies by making measurements which rely on the electrical and magnetic properties of metals. The following NDE methods can be used: eddy current testing, magneto-inductive testing, and magnetic particle testing. Also, a method has been proposed for in situ measurement of steel fiber content of steel fiber reinforced concrete.

5.9.1 Eddy Current Inspection

Eddy current inspection is a versatile NDE method based on the principles of electromagnetic induction; it is applicable to inspection of metals [2] and to the measurement of the thickness of nonconductive coatings on a conductive metal [14].

Description of Method

A coil carrying an alternating electric current will have an associated alternating magnetic field which acts to oppose the flow of current into the coil. When the coil is brought near a conductive material, the alternating magnetic field will induce in the material a closed loop current flow known as eddy current. The eddy currents will also be alternating, and, therefore, a secondary magnetic field is associated with them. The secondary magnetic field will oppose the magnetic field of the coil. When the energized coil is brought near a metal surface, there will be a change in the current flow in the coil. Measuring the changes in the current flow (or the coil impedance) is the basis of eddy current inspection.

The magnitude of the changes in the coil current will depend on the intensity of the eddy currents induced in the metal. Factors which influence the intensity of eddy current flow include:

1. the frequency and magnitude of the coil current
2. the electrical conductivity of the metal
3. the magnetic permeability of the metal
4. the size and shape of the test object
5. the proximity of the coil to the test object
6. the presence of discontinuities or inhomogeneities in the metal [15].

The electrical and magnetic properties of the metal are controlled by alloy composition, microstructure, and residual stress [2].

Eddy Current Inspection Systems

The principal elements of an eddy current inspection system include the inspection coil, and oscillator to provide coil excitation, a detector to monitor changes in coil impedance, and an output device to display the test results. Various coil geometries are available, depending on the specific application. An important principle when inspecting for discontinuities is that the maximum signal is obtained when the eddy current flow is transverse to the flaw. Thus, the user needs to understand the relationships between coil configuration, eddy current flow and type of flaw to be detected.

The frequency of the excitation current affects the depth of the eddy currents and the sensitivity of flaw detection. The coil frequency can be increased to detect small, near-surface flaws; penetration is reduced, but sensitivity is increased. If sub-surface flaws are to be detected, a lower frequency should be used; however, the minimum size of flaws that can be detected is increased. Thus, there is a trade-off between penetrating ability and sensitivity; this is also common to other inspection methods. The range of frequencies is from 200 Hz to 6 MHz, with the lower frequencies used primarily for inspecting ferromagnetic metals [2].

The detector circuit can also take many forms, depending on the application of the instrument. In any case, the changes in coil impedance that occur during inspection are small; bridge circuitry, similar to that used to monitor electrical resistance strain gages, is used to detect these changes. In making a measurement, the impedance bridge is first balanced by using an internal adjustment or placing the coil on a reference object of acceptable quality; then the coil is placed on the test object. Any difference between test object and reference object will result in an imbalance of the bridge which is indicated on the output device. There are many output devices; audible alarms, meters, X-Y plotters, strip-chart recorders, magnetic tape, storage oscilloscopes, and computers.

Instrument Calibration

Because many factors may affect the coil impedance when a test is performed, the object used to calibrate the instrument must be carefully chosen. For example, to detect cracks, the reference object must have the same electrical and magnetic properties as the test object; otherwise, differences in alloy composition could be interpreted as a crack. Therefore, a user must be knowledgeable about operating an eddy current device in order to calibrate it properly and to interpret test results.

Applications

Eddy current inspection has many uses, including the detection of flaws such as cracks, porosity, or inclusions in metals; detection of changes in alloy composition or microstructure; and the measurement of the thickness of nonconductive coatings on a metal.

Limitations

One important limitation of eddy current inspection is the volume of material examined. The inspection depth depends on the penetration depth of eddy currents, the intensity of which decreases exponentially with depth. The strength of the signal due to a particular defect will depend on the nearness of the coil to the surface of the test object. As this distance called "lift-off" increases, the signal strength diminishes. The "lift-off" effect is so strong that it may mask signal changes due to defects. Therefore, care must be taken to ensure uniform contact between coil and test object; it may be difficult to test objects with rough or irregular surfaces. The "lift-off" effect may be used to measure the thickness of nonconductive coatings on conductive metals, or non-magnetic metal coatings on magnetic metals. Proper calibration samples are required in order to use an eddy current instrument as a thickness gage.

5.9.2 Magneto-Inductive Methods (Magnetic Field Testing)

This technique is only applicable to ferromagnetic metals and is primarily used to distinguish between steels of different alloy composition and different heat treatments. The principle involved is electromagnetic induction. The equipment circuitry resembles a simple transformer in which the test object acts as the core [2]. There is a primary coil connected to a power supply delivering a low frequency (10 to 50 Hz) alternating current, and a secondary coil feeding into an amplifier circuit. In the absence of a test object, the primary coil induces a small voltage in the secondary coil, but when a ferromagnetic object is introduced, a much higher secondary voltage is induced. The nature of the induced signal in the secondary coil is a function of the magnetization characteristics of the object. Changes in these characteristics are used to distinguish between samples of different properties. As in the case of eddy current inspection, this method can only be used for quantitative measurement if proper calibration is performed.

5.9.3 Cover Meters

Cover meters are portable, battery-operated magnetic devices that are primarily used to estimate the depth that reinforcing steel (bars and tendons) is embedded in concrete, and to locate its position. In addition, some information can be obtained regarding the dimensions of the reinforcement [10].

Principle and Applications

Cover meters are based on the magneto-inductive principle. A magnetic field is induced between the two faces of the probe (which houses a magnetic core) by an alternating current passing through a coil. If the magnetic field passes through concrete containing reinforcement, the induced secondary current is controlled by the reinforcement. The magnitude of this change in inductance is measured by a meter. For a given probe, the magnitude of the induced current is largely controlled by the distance between the steel reinforcement and the probe.

The relationship between the induced current and the distance from probe to the reinforcement is nonlinear, largely because the magnetic flux intensity of a magnetic material decreases with the square of the distance. In addition, the magnetic permeability of the concrete, even though it is low, will have some effect on the reading. Therefore, the calibrated scales on the meters of commercial equipment are nonlinear. Also, a meter must be readjusted if a different probe is attached.

The probe is highly directional -- i.e., sharp maximum in induced current is observed when the long axis of the probe and reinforcement are aligned, and when the probe is directly above the reinforcement.

Some commercial cover meters can measure concrete cover over reinforcement up to 8 in. (200 mm). By using spacers of known thickness, the size of reinforcing between 3/8 and 2 in. (10 to 50 mm) can be estimated.

Another possible application of the cover meter is to estimate the thickness of slabs which are accessible from both sides. If a steel plate is aligned on one side with the probe on the other side, the measured induced current will indicate the thickness of the slab. For this application, a series of calibration tests must be performed first. British Standard BS 4408 gives guidance for the use of cover meters.

Advantages

Cover meters are portable, inexpensive instruments that can be easily used. They are useful when reinforced concrete has only one layer of widely separated reinforcing bars.

Limitations

In highly reinforced concrete, the presence of secondary reinforcement makes it difficult to determine satisfactorily the depth of concrete cover. Furthermore, reinforcing bars running parallel to that being measured influence the induced current if the distance between bars is less than two or three times the cover distance [10].

5.9.4 Magnetic Particle Inspection

Principle of Method

This inspection method relies on the tendency of cracks to alter the flow of a magnetic field within a metal so that fine magnetic powder will be attracted to the crack zone, allowing cracks to be identified [2,16,17]. For example, consider a bar magnet in which the magnetic field flows through the magnet from south to north poles. If ferromagnetic particles are sprinkled over the middle surface of a crack-free magnet, there will be no attraction because the magnetic field lies wholly within the magnet. Now consider a cracked magnet; the two sides of the crack acts as north and south poles, and the magnetic field bridges the gap. However, some of the magnetic field will leak out of the magnet into the air, and ferromagnetic powder would be attracted by the leakage field. Therefore, the attraction of the powder indicates a crack. A subsurface crack would also produce a leakage field, but the response would be weaker than for a surface crack.

Application of Method

In using the magnet particle method, it is necessary to magnetize the object being inspected, apply ferromagnetic particles, and then inspect for cracks. Two general types of magnetic fields may be induced in the test object: circular and longitudinal. A circular field is produced by passing an electric current through the test object: the magnetic field then would be concentric with the direction of current flow. A longitudinal field could be created by placing the test object inside a coil carrying electric current: the magnetic field then would be parallel to the longitudinal axis of the coil. The direction of the magnetic field relative to the test object controls which cracks will be detected. Strong leakage fields are produced by cracks which intersect the magnetic lines of force at an angle; no leakage fields are produced by cracks parallel to the magnetic lines of force. Therefore, complete inspection should include rotation of the test object with respect to the magnetic field to make sure that all existing cracks intersect the magnetic field lines.

In field inspections, it usually is not practical to pass a current through the entire part or surround the part with a coil. Portable units are available that permit inspection of small portions of the test object at a time. For example, prods can introduce a flow of current between two contact points on the object. In this case, a circular magnetic field is induced. A yoke -- a U-shaped electromagnet in which the poles are brought into contact with the test object -- can also be used. With a yoke, a longitudinal magnetic field is set up in the object, and the lines of force in the electromagnet run from one pole to the other. With either portable method, only a small portion of a large test object can be inspected at one time; 12 in. (300 mm) is a practical limit for spacing between prod contacts [2].

The choice of current used to magnetize the test object is important. If subsurface cracks are to be detected, direct current should be used because alternating current will only produce a magnetic field near the surface. The direct current may be from a constant or pulsating source, though the pulsating type is preferred because it imparts greater mobility to the ferromagnetic powder. The current supply is low voltage and very high amperage for user safety, but still permits strong magnetization of the test object.

Inspection is usually carried out with the current on, but if the metal has high retentivity (permanent magnetism), the current may be turned off before the powder is applied.

The powder used to indicate the leakage fields may be dry or suspended in a liquid. Dry powders are preferred for the best sensitivity to subsurface cracks and should be used with direct current. Wet powders are superior for detecting very fine surface cracks. To improve visibility, powders are available in various colors, providing high contrast with the background. In addition, fluorescent particles are available for increased visibility.

Advantages

The magnetic particle inspection method has several advantages over other crack detection systems [2]. Portable equipment is available that can be readily taken to the inspection site. This equipment is inexpensive and simple to operate; positive crack indications are produced directly on the part and no electronic equipment is needed. Any part that is accessible can be inspected.

Limitations

This method will only work with ferromagnetic metals. For complete inspection, each area needs to be inspected more than once using different magnetic field directions; very large currents are needed to inspect large areas at once. Experience and skill are needed to interpret properly the particle indications and to recognize patterns which do not indicate cracks. Demagnetization may be required after inspecting steels with high magnetic retentivity. The maximum depth of the flaw detection is about 0.5 in. (13 mm), and the detectable flaw size increases as flaw depth increases.

Portable equipment is limited with regard to the current available for the inspection. For detection of deep lying discontinuities and for coverage of large areas with one prod contact, a larger machine, such as a mobile unit or stationary unit with higher-amperage output is required.

5.9.5 Steel Fiber Content

Description of Method

The electromagnetic apparatus for measuring steel fiber content of steel fiber reinforced concrete consists of a measuring device and several attachments having circular or square openings in the center into which the test specimens are inserted [18]. In the attachments there are coils for both excitation and induction of an electric current. With an increase in steel fiber content of the specimen in the attachment, the induced electric current increases. Based on this principle, the steel fiber content can be determined from a reading of the induced current. This method can be used for both hardened and fresh concrete. For fresh fiber reinforced concrete, it must be placed in molds that do not contribute to the induced electric current.

Limitations

This electromagnetic method for in situ measurement of steel fiber content in hardened and fresh concrete shows promise as a research tool. The method has not been used extensively in the field. Further development work is required it if is to become a reliable NDE method.

5.10 Holography

Description of Method

Two methods available for nondestructive inspection are optical holography, using visible light waves, and acoustical holography, using ultrasonic waves.

In these methods, a two step process creates a three-dimensional image of a diffusely reflecting object [14]. The first step involves recording both the amplitude and phase of any type of coherent wave motion emanating from the object. The recording of this information in a suitable medium is called a hologram. At a later time, the wave motion can be reconstructed from the hologram to regenerate a three-dimensional image having the shape of the object. The nondestructive inspection of an object is accomplished by using the regenerated three-dimensional image as a template against which any deviations in the shape or dimensions of the object can be observed and measured [14].

Limitations

Skill is required in developing holograms (three-dimensional images) and in the interpretation of comparing holograms in order to measure deviations that have occurred in the shape or dimensions of the object that is inspected.

5.11 Leak Testing Method

Principle of Method

Leakage testing is the detection and sizing of holes in pipes and tanks which permit the escape of liquids or gases [19]. There are many different methods of leak testing, but they can be generally classified into two categories. In the first, the leaking system is monitored under normal operating conditions. This includes the use of pressure meters, the application of a soap solution, or the use of audio or amplified listening devices. In the second category, a particular substance is added into the system flow to provide special indications of leakage. This includes additives such as colored dyes, Freon 12 and helium gas, radioactive tracers, and odorous indicators.

Applications

Many leak detection methods are suitable for field application. Liquid storage vessels and above ground piping can usually be checked visually for leakage under normal operating conditions with no special equipment. Gas-carrying systems usually can be checked best in the field with a soap solution or (with freon gas added to the system) a propane torch. These systems have no special power requirements, and none of the equipment involved weighs more than 5 lb (2 kg).

Advantages

Leak detection methods can locate flaws too small to be found by any other NDE technique. Leaks with rates as small 10^{-12} cc/sec can be detected with radioactive tracers and radiation monitoring devices, while a soapy water solution can locate leaks with rates as low as 10^{-3} cc/sec [19].

Limitations

Flaws can be detected only if they penetrate through a structure that can be held at pressure conditions exceeding those of the surrounding atmosphere.

5.12 Longitudinal Stress Waves

Description of Method

The speed that longitudinal (parallel to the grain) stress waves travel in wood has been measured by resonant frequency, impact, and by ultrasonic stress-wave devices [20]. Stress wave-speed (speed of sound) of waves that travel in the longitudinal direction is affected by several factors such as moisture content, temperature, knots, specific gravity, and orientation of grain in the wood (grain angle). The type of longitudinal stress wave induced in wood does not have a significant effect on stress wave-speed. Stress waves show promise for rapid lumber grading and predicting mechanical properties of wood [20].

Development of an effective in situ test method to evaluate the soundness of wood subject to deterioration would be useful in appraising its service life. Wood members under some environmental exposures may lose some structural integrity through decay or chemical degradation. Stress-wave transmission has been investigated to determine nondestructively the extent and location of degradation in wood [21].

Limitations

Additional research is needed to demonstrate the feasibility of using longitudinal stress waves to assess the mechanical properties of wood and for rapidly determining the quality of wood members.

5.13 Maturity Concept

Principle and Application of Method

The maturity concept has been proposed as a method for predicting early age strength development of hardening concrete. It relates the combined effect of temperature and hydration time of concrete to its strength [22]. Maturity (M) is usually expressed as:

$$M = \Sigma\ (T-T_o)\Delta t$$

where T = temperature of the concrete

T_o = the highest temperature below which the strength of hardening concrete does not change

Δt = the increment of time for each temperature.

According to the maturity concept, the strength of a given concrete mix is a single-valued function of maturity, independent of the actual temperature history [22].

To apply this method, one first experimentally determines the strength-maturity relation of the concrete mix to be used in building the structure. This is done by making and curing standard specimens in a laboratory, monitoring the actual concrete temperature, and testing strength at various ages. From the temperature record, the corresponding maturity value at each test age is calculated, and strength versus maturity data are generated. Various equations for the strength-maturity relation have been proposed, and can be used in analysis of the data [23-25]. During construction, the in-place concrete temperature is recorded, from which maturity values at any age can be determined. The previously determined strength-maturity calibration curve is used to predict the strength of the in-place concrete. The maturity method is identified in ACI Committee Report 306R-78 as a viable means of predicting the in situ strength of concrete [26].

Maturity can be calculated using temperature records from continuous strip-chart recorders or from digital data-loggers, which print out the temperature at regular time intervals. As an alternative, commercial "maturity meters" are available; these monitor the in-place temperature and automatically compute the cumulative maturity. Such instruments cost about $3000. Multi-channel maturity meters have been developed to allow monitoring maturity at many locations with a single instrument. In addition, single-use, disposable meters have been produced, although their reliability has not been tested. Finally, one may use programmable data-loggers as maturity meters.

Advantages

Because in-place temperatures are measured, the maturity method accounts for one of the major factors affecting early-age strength development of concrete.

Limitations

Since only temperature and time are measured, another method is needed to verify that the in-place concrete has the correct mix proportions. Otherwise, the user has no way of knowing if the strength-maturity calibration curve is appropriate. Accelerated curing tests of samples taken from the concrete batch, or other in-place tests discussed in this report may be used. Because of the nonuniform temperature distribution in the structure, the temperature probes must be carefully located to avoid overestimating maturity development in the critical strength regions. In addition, there is a question about whether the equation given earlier in this Section (5.13) is the best temperature-time function for computing maturity. Carino discussed this problem and suggested alternative methods [25]. Finally, the maturity method is only applicable for strength prediction in new construction and cannot be used to estimate the strength of concrete in existing structures.

5.14 Microwave Inspection

Microwaves (or radar waves) are a form of electromagnetic radiation which have frequencies between 300 MHz and 300 GHz corresponding to wavelengths of 1 m to 1 mm. Microwaves are generated in special vacuum tubes called klystrons and transported in a curcuit by waveguides. Diodes are commonly used to detect microwaves.

Applications

Because of their electromagnetic nature, microwaves can be reflected, diffracted, and absorbed. These waves are absorbed by water and this has led to development of a method for determining the moisture content of concrete. The use of microwaves to estimate the moisture contents of concrete and roofing materials has been explored [10,27,28]. Similar to capacitance instruments (see Section 5.16.2), changes in the dielectric properties of materials are detected. Since moisture affects the dielectric properties of a material, changes in moisture content in the material can be detected. Boot and Watson report that the microwave technique only estimates the moisture content of concrete within 12 to 30 percent of its mean value [29]. The low accuracy of micowave inspection is largely attributed to the heterogeneity of concrete, and the internal scattering and diffraction it causes.

Limitations

The feasibility of using microwaves for inspecting installed construction materials has not been demonstrated. Further development work is required if the microwave method is to become a reliable field NDE method.

5.15 Middle Ordinate Method

Description of Method

In this method a laboratory instrument is used that is capable of detecting stiffness variations within boards (lumber) over lengthwise regions of less than two feet [30]. A bending moment is applied to each end of the board under test. Stiffness calculations are based upon the assumption that short segments of a board undergoing bending approximate arcs of circles with varying radii. The middle ordinate instrument measures, either on a continous basis or in discrete steps, the perpendicular distance between the midpoint of a chord and its arc. This distance or deflection is inversely related to stiffness. The instrument provides a means of assessing in the laboratory the strength-reducing potential of defects in lumber.

Limitations

This research method has not been used in the field. Additional research and field use are needed to demonstrate the feasibility of using the middle ordinate method as a reliable NDE method to inspect lumber at the job site.

5.16 Moisture Detection Methods

Many of the problems encountered in a building are caused by moisture. Visual inspection can reveal obvious surface moisture, but even if a surface is dry, subsurface moisture can be present. Four NDE methods are often used for moisture inspection measurements. The types of instruments or methods used include electrical resistance probes, capacitance instruments, nuclear meters, and infrared thermography [27,28,31].

5.16.1 Electrical Resistance Probe

Principle and Applications

The resistance probe method involves measuring the electrical resistance of a material, which decreases as the moisture content increases. Most instruments consist of two closely spaced probes and a meter-battery assembly which are enclosed in one housing or in two attached assemblies. The probes are usually insulated except at the tips so that the region being measured lies between the tips of the probes. The probe can penetrate soft materials, such as roofing membranes, so that moisture at various distances below the surface can be detected. Operation of a resistance probe is very simple. A voltage is impressed between the probes and the resistance measured.

Probe instruments have been used for moisture detection in plaster, brick, concrete, and roofing materials. Similar procedures have been used for determining the electrical resistance of soils, except a four probe system is used.

Calibration

The electrical resistance probe and other moisture measuring instruments are usually calibrated by obtaining relationships between their response and the moisture content of materials similar to those being inspected. The moisture contents of the reference specimens are gravimetrically determined -- i.e., specimens are weighed before and after oven drying with the differences in weight considered to be their moisture contents.

Advantages

The simple, inexpensive instruments, while giving only an approximation of the extent of wetness, are useful in identifying wet areas and for determining moisture migration patterns. More sophisticated instruments appear to be capable of giving semi-quantitative information if they are properly calibrated.

Limitations

Electrical resistance probe instruments do not determine moisture contents precisely. When used on roofing membranes the test method is considered to be destructive.

5.16.2 Capacitance Instruments

Principle and Applications

Capacitance instruments used to detect moisture are based on the principle that moisture can affect the dielectric properties of a material [31]. The dielectric constant, K, of a material is a relative measure of the ability of a material to store electrical energy and is given by:

$$K = C/C_o$$

where C is the capacitance of a material and C_o is the capacitance of a vacuum.

The dielectric constants for many dry building materials are usually low; e.g., for dry roofing materials, K ranges from 1 to 5, while water has a K of approximately 80 [28]. The value of K for a moist material will theoretically increase linearly as the volume fraction of water increases. Capacitance-radio frequency instruments have been used to measure the moisture contents of paper products, wallboard, and roofing materials. Commercial capacitance instruments have various electrode configurations. The electrodes are attached to a constant frequency alternating current source and establish an electrical field in the material to be tested. Current flow or power loss -- indicating moisture content -- is then measured. Most instruments operate in the radio frequency region (1 to 30 MHz).

Advantages

Capacitance instruments are portable and measurements can be taken rapidly.

Limitations

Capacitance meters have extreme sensitivity to surface moisture; because of this it is essential that the roof surface be dry when capacitance surveys are made [32]. An investigation by Knab et al. suggests that capacitance instruments may not give reliable quantitative measurements of the moisture contents of roofing systems beyond the "threshold" moisture content [31].

5.16.3 Nuclear Meter

Principle of Method

Fast neutrons, emitted during the decay of radioactive isotopes, are used in making moisture content measurements [28,29]. Fast neutrons from the isotope source enter the material and are both scattered and slowed by collisions with the nuclei of the atoms composing the material. Nuclei of all materials slow down the neutrons by momentum exchange, but the speed reduction is greatest for collisions with hydrogen nuclei, which have about the same mass as the neutrons. Some of the slow or thermal neutrons are scattered so that they reach the slow neutron detector in the instrument and are counted for a specific period of time. The thermal neutrons reaching the detector are much more likely to have collided with hydrogen nuclei than with other atomic nuclei because the scattering cross-section of hydrogen is greater than for other atoms likely to be present. The detector measures primarily the backscattering of slow neutrons which have collided with hydrogen nuclei in the surface region of materials. For example, the depth of measurement is limited to 2 to 8 in. (51 to 203 mm) in soils.

Commercial Meters and Applications

Nuclear meters are used to measure both moisture content and density of soils, portland-cement concrete, asphaltic concrete, and roofing materials [10,27,28]. These meters consist of a shielded radioactive isotope source, a detector or counting device, and readout equipment. In commercial meters, the isotopes used are radium 226-beryllium, and americium 241-beryllium. Both americium and radium are alpha particle emitters. These particles interact with the nucleus of beryllium, resulting in the emittance of fast neutrons.

In addition to neutron sources, most commercial nuclear moisture meters also have gamma ray sources. The gamma rays are used to determine the density of materials. See Section 5.25 about Radioactive Methods for an explanation of the principle.

Advantages

Nuclear meters are portable, and moisture measurements can rapidly be made on materials.

Limitations

The hydrogen atoms of building materials in addition to those of water will contribute to the number of detected thermal neutrons. For example, asphalt in a roofing membrane may contribute to a reading because it contains bonded hydrogen atoms. For hydrogen-containing materials, the meter must be calibrated with samples identical to those expected during field inspection. Also, a license must be obtained from the Nuclear Regulatory Commission to use the radioactive isotopes in the neutron source of the neutron moisture meters. Transportation of meters may be difficult because of restrictions.

5.16.4 Infrared Thermography

In addition to locating heat loss, infrared thermography can be used to detect moisture in building materials if heat is flowing through them. The presence of moisture will affect the heat transfer properties of materials; this permits the identification of wet areas by thermography. The principles involved in making thermography scans are discussed under Thermal Inspection Methods (Section 5.29). The infrared thermography method is being used in making aerial scans of roofs. Large roof areas and many buildings can be scanned in a relatively short time [27,28]. Handheld infrared cameras also are being used to measure heat losses and to detect moisture in roofing systems [32,33]. Additional applications of infrared thermography are given in Section 5.29. In using thermography to detect moisture in roof systems, it is necessary to assume that temperature gradients are caused by moisture and are not associated with differences in roofing composition or thickness. Because construction and thickness variations can be present, results from thermographic inspections should be interpreted carefully.

Limitations

Some destructive testing may be necessary to verify roofing composition and thickness.

5.17 Nuclear Density Meter

See Section 5.16.3.

5.18 Paint Inspection Gages

5.18.1 Tooke Gage

Principles and Applications

The Tooke Gage measures dry paint film thickness by the microscopic observation of a small v-groove cut into the paint film. In addition, the number of paint layers and their individual thicknesses can be determined. The thickness of dry coating applied to any type of surface can be measured -- e.g., to wood, metal, glass, or plastic. The Tooke Gage is easily portable, with overall dimensions of 4.5 x 3.5 x 1 in. (114 x 89 x 25 mm); and it weighs 26 oz (0.7 kg). Three cutting tips are furnished; these permit measurements of film thicknesses up to 50 mil (0.13 mm).

Limitations

A disadvantage of this method is that a cut is made in the paint film which may have to be repaired, depending on the substrate and the severity of the environment.

5.18.2 Pencil Test

Principle and Applications

This rapid and inexpensive method can be used to determine film hardness of an organic coating on a substrate using pencil leads of known hardness. Testing is started with the hardest pencil lead and continued down the scale of hardness to either of two end points: (1) the pencil that will not cut into or gouge the film, or (2) the pencil that will not scratch the film.

Advantages

The method causes only slight damage to the coating.

5.18.3 Magnetic Thickness Gages

5.18.3.1 Magnetic Pull-Off Gage

Principle and Applications

These instruments measure thickness by using a spring calibrated to determine the force required to pull a permanent magnet from a ferrous base coated with a nonmagnetic film. The instrument is placed directly on the coating surface to take a reading. The attractive force of the magnet to the substrate varies inversely with the thickness of the applied film. The spring tension required to overcome the attraction of the magnet to the substrate is shown on the instrument scale as the distance between the magnet and the substrate.

5.18.3.2 Magnetic Flux Gage

Principle and Applications

These instruments measure coating thickness by changes in the magnetic flux within the instrument probe or the instrument itself. The instrument probe must remain in direct contact with the coating at all times during measurement. The magnitude of flux changes as an inverse (nonlinear) function of the distance between the probe and the ferrous substrate. The testing apparatus is mechanically or electrically operated. The mechanically operated instruments house an integral horseshoe magnet, the contacts of which are placed directly on the coated substrate. The electrically operated gages utilize a separate instrument probe that houses the magnet and the gages must be placed directly on the coated surface. In both types, the coating thickness is shown on the instrument scale or meter.

The methods for nondestructive measurement of dry film thickness of nonmagnetic coatings applied to a ferrous base are described in ASTM Standard D 1186 (Appendix D). In addition, the method for nondestructive measurement of film thickness of pipeline coatings on steel is described in ASTM Standard G 12 (Appendix D).

5.18.4 Wet Film Thickness

Measurements of wet film thicknesses of organic coatings using the Interchemical Wet Film Thickness Gage and the Pfung Gage are described in ASTM Standard D 1212 (Appendix D). Wet film thickness measurements using Notch Gages are described in ASTM Standard D 4414 (Appendix D).

5.18.4.1 Interchemical Wet Film Thickness Gage

The gage consists of an eccentric center wheel supported by two concentric wheels so as to provide two scales that are bilaterally symmetrical. The gage is rolled on the wet film; as it rotates there is a change in clearance between the wet film and the eccentric wheel. The point at which the film first touches the eccentric center wheel is a measure of the thickness of the paint film. The gage is available in a variety of ranges and can measure wet film thickness up to 60 mils on the English scale and up to 700 μm on the metric scale.

Limitations

At locations where thickness measurements are made, the coating film may have to be repaired.

5.18.4.2 Pfung Gage

Principle and Applications

The gage consists of a convex lens that is mounted in a short tube that slides freely in an outer tube. The lower surface of the convex lens has a radius of curvature of 250 mm. Compression springs keep the convex surface out of contact with the wet film until pressure is applied to the top of the short tube forcing the lens down through the film to the substrate. After the pressure is released, an oversized circular spot is retained on the lens. The diameter of the circular spot retained on the lens is a measure of the wet film thickness.

Limitations

At locations where thickness measurements are made, the coating film may have to be repaired.

5.18.4.3 Notch Gage

Principle and Applications

Square or rectangular, and circular, notch rigid metal gages are used to measure film thicknesses ranging from 0.5 to 80 mils (13 to 2000 μm) for square or rectangular gages and from 1 to 100 mils (25 to 2500 μm) for circular gages. These gages are used on coatings on flat substrates. Notched gage measurements are neither accurate nor sensitive, but they are useful in determining approximate wet film thickness of coatings where sizes and shapes of coated objects prohibit the use of the more precise methods given in ASTM Standard D 1212. The square or rectangular gages are pushed perpendicular into the film and the circular gages are rolled perpendicularly across the film. Thickness is determined from tabs and notches wetted by the film.

Limitations

At locations where thickness measurement are made, the coating film may have to be repaired.

5.19 Pin Hole Dectector

Principle and Applications

This type of device is used to find pin holes (holidays) in nonconductive coatings applied to metals. Pinhole and holiday detectors are of three general types; low voltage wet sponge, direct current high voltage, and alternating current electrostatic types [34]. Most low voltage commercial instruments consist of a probe or electrode, which makes contact with the coating through a moist sponge, and an earth lead, such as alligator clip, which is attached to an area of bare metal. When the moist sponge passes over a pin hole, an electrical circuit is completed and an alarm sounds. Most high voltage detectors use in general a direct current power source in the range of 500 to 1500 volts [35]. High voltage detectors basically function on the same operating principle as the low voltage detectors except that a sponge is not used. The alternating current electrostatic type detector is used for testing conductive linings applied over steel substrates.

Limitations

There are several problems in using the detectors to inspect for pin holes. If a metallic object is completely coated, part of the coating must be removed so that the earth lead can make contact with the metal. The voltage must be carefully selected to match the coating thickness because too high a voltage would break through a thin film even if pin holes were not present. The results are qualitative since no information on the size of a pin hole is given.

5.20 Point-Load Test

This test is intended to estimate the compressive and tensile strength of concrete using small cores.

Description of Method

Relatively small cores of plain or fibrous concretes about 2.7 in. (68 mm) in diameter and 4 in. (100 mm) in length are tested using a point load in a diametral test [36]. Cores have to be drilled and extracted from the concrete for which strength determinations are to be made. The apparatus for the point-load test is a portable testing machine consisting of a loading system and load measuring capability. A truncated steel cone is used to apply the point load at mid-length of the core along its diameter until failure occurs. The point-load test is essentially an indirect tensile test and will give a maximum tensile stress which differs from the actual direct tensile stress because of high compressive stress under the load. The compressive strength can be related to the tensile strength through empirical formulae.

Advantages

This test is quick to carry out, is relatively inexpensive, and can be performed in the field on a simple and easily portable apparatus. A total of six point-load tests may be expected to provide a realistic estimate of concrete strength.

Limitations

Additional research is needed to demonstrate the reliability of using the point-load test to assess the strength of concrete and for this test to become a reliable in situ NDE method. The concrete needs to be repaired where cores are taken.

5.21 Probe Penetration Method

Principle of Method

The probe penetration method involves measuring the exposed length of a cylindrical steel probe driven into concrete by a powder charge. This method is useful for assessing the quality and uniformity of concrete in situ, and for delineating areas of poor quality or deteriorated concrete in structures.

Probe penetration results have also been used to estimate the compressive strength of concrete by using correlation graphs. The graphs are constructed by plotting the exposed lengths of probes versus experimentally measured compressive strengths. This can be done by performing penetration tests on a concrete slab and taking core samples for compression testing.

Probe Equipment and Its Use

The Windsor Probe is the most commonly selected, and possibly the only, commercially available apparatus for measuring the penetration resistance of concrete. It consists of a special driving gun which uses a 32 caliber blank with a precise quantity of powder to fire a high-strength steel probe into the concrete. A series of three measurements is made in each test area. The length of a probe extending from the surface of the concrete can be measured with a simple device.

Operating procedures for the Windsor Probe are given by the manufacturer. In addition, testing procedures are given in ASTM Standard C 803 (Appendix D). The probe can be easily operated by concrete inspectors, and is readily portable.

The manfacturer supplies a set of five calibration curves, each corresponding to a specific Moh's hardness for the coarse aggregate used in the concrete. With these curves, probe measurements can be converted to compressive strength values. However, Arni observed that use of the manufacturer's calibration curves often resulted in grossly incorrect estimates of the compressive strength of concretes [37]. Therefore, the Windsor Probe should be calibrated by the individual user, and should be recalibrated whenever the type of aggregate or mix design is changed.

The Windsor Probe can be used for assessing the quality and uniformity of concrete because physical differences in a concrete will affect its resistance to penetration. A probe will penetrate deeper as the density, subsurface hardness, and strength of the concrete decrease. Areas of poor concrete can be delineated by making a series of penetration tests at regularly spaced locations.

The Windsor Probe has been used to estimate the compressive strength of concrete. However, the relationship between the depth of penetration of the probe and the compressive strength can only be obtained empirically because the penetration of the probe depends on a complex mixture of tensile, shear, frictional, and compressive forces [37]. The estimation of compressive strengths with the Windsor Probe, therefore, must be made using a correlation diagram with appropriate confidence limits.

The probe technique appears to be gaining acceptance as a practical NDE method for estimating the compressive strength of concrete. Improved correlations between probe results and in-place strength can be obtained by keeping the curing conditions of the test specimens close to those expected for in-place concrete, and by making sure that the test concrete is representative of the in-place concrete. If the Windsor Probe is calibrated using concrete specimens taken from an early construction stage, the calibration chart could be used to estimate the strength of concrete placed during later stages (assuming that the concrete design is the same).

Advantages

The Windsor Probe equipment is simple, durable, requires little maintenance, and can be used by inspectors in the field with little training. The probe test is very useful in assessing the general quality and relative strength of concrete in different parts of a structure.

Limitations

Care must be exercised, however, because a projectile is fired; safety glasses should be worn. (Note: The gun can only be fired when it is pushed against the spacer plate.) The Windsor Probe primarily measures surface and subsurface hardness; it does not yield precise measurements of the in situ strength of concrete. However, useful estimates of the compressive strength of concrete may be obtained if the probe is properly calibrated.

The Windsor Probe test does damage the concrete, leaving a hole of about 0.32 in. (8 mm) in diameter for the depth of the probe, and may cause minor cracking and some surface spalling. Minor repairs of exposed surfaces will be necessary.

5.22 Proof Load Testing

Principle of Method

Proof load testing is based on the concept that a structure capable of surviving the stresses of a severe overloading should be serviceable under normal operating conditions [19]. Proof loading requires overloading a structure in a load pattern similar to operating conditions (e.g., high pressure in a pipeline).

Applications

Proof load testing can be used with leak testing (see Section 5.11) in pressure vessels and pipelines inspection to increase the sensitivity of leak detection. This method is generally used as a last resort to determine the adequacy of a structural system.

Advantages

An entire structure can be tested in its "as-built" condition.

Limitations

The test may cause the premature failure or the destruction of a structure. Proof load testing requires extensive planning and preparation, and is usually expensive.

5.23 Pull-Off Test

The pull-off test is used to estimate the in situ strength of concrete.

Description of Method

The pull-off test, used as a means of predicting the compressive strength of concrete, involves bonding a circular steel probe, 2 in. (50 mm) in diameter, to the surface of the concrete to be tested [38]. The concrete surface should be properly prepared and epoxy resin used to bond the probe to the concrete. A tensile force is applied to the adhered probe using a portable mechanical system; the force is increased until the concrete fails in tension. From the tensile force at failure, the compressive strength of the concrete can be determined from calibration graphs based on data from a large number of pull-off tests and corresponding cylinder compressive strength tests. Since the tensile strength of the bonded area is greater than the concrete, the concrete will eventually fail in tension. The amount of overbreak is usually small so that the area of failure can be taken as being equal to that of the probe.

Advantages

The procedure is simple, inexpensive, and does not require a highly skilled operator to make the measurements. Tests can be conducted on horizontal and vertical surfaces. The stress at failure is a direct measure of the tensile strength. Inspection of the probe after test will indicate if failure occurred in the concrete, thus unsatisfactory failures can be discounted. It is not necessary to plan the location of the test areas in advance of placing the concrete; as is the case for some other partially destructive tests. The internal concrete strength can be estimated by partial coring to the desired depth and conducting the test on the cored area.

Limitations

Although considerable testing has been done and the tests gave consistent and reliable results, a standard test such as an ASTM test has not been developed. The concrete needs to be repaired in areas where the test was conducted.

5.24 Radar

Radar is capable of rapid nondestructive assessment of materials such as asphalt, concrete, soil, and rock by penetrating them to varying depths to indicate material changes, separations, voids, and other discontinuities [39]. Radar may also be used to estimate material quality.

Description of Method

Radar techniques are based on the principle that electromagnetic waves are reflected by concrete and other materials. Radar wavelengths can be longer than those associated with NDE microwave inspections. Portable equipment is available commercially for application to assessment of concrete, but the method has yet to be standardized. The radar technique has been used with success in New York and New Jersey to evaluate concrete pavements and bridge decks [40]. An attractive feature of this technique is the speed, approximately 17 km/h, at which pavements can be scanned. It is noted that great planning and skill are needed to evaluate the data.

The frequencies of the electromagnetic energy selected for radar NDE inspections range from 100 to 1200 MHz depending on penetration depth and resolution desired. The resolution or ability to differentiate closely spaced objects is a function of the signal frequency and bandwidth. Very small changes over short distances require a higher frequency and wider bandwidth. With lower frequency and narrower bandwidth, the ability to see small changes is lessened but the depth of penetration is greater. The energy travels through different materials at a specific speed for each material depending on the material's dieletric properties. As an example, at a frequency of 1200 MHz and in 1 nanosecond, the radar wave will travel 6 in. (152 mm) in air, 2.5 in. (64 mm) in concrete, and 3 in. (76 mm) in asphalt. When a change in material dieletric occurs such as at an interface of air to asphalt or asphalt to concrete it is indicated by a change in wave shape.

Low frequency radar is used for macro-studies, such as soil mapping and location of material changes in the subsurface. In micro-studies, higher frequency radar is used for locations of voids or delaminations in thin sections such as roadways and bridge decks.

Advantages

Radar can rapidly scan pavements and bridge decks. The data can be stored and compared with perodic scans to determine changes which occur with time.

Limitations

Skill is required in interpretation of data to determine with a reasonable degree of confidence the condition of materials with regard to voids, cracks, and delamination. Further development work is required if the radar method is to become a reliable field NDE method.

5.25 Radioactive Methods

There are two types of radioactive NDE methods, radiography and radiometry, used to assess the properties of in situ concrete and other materials. The radiography method uses a radioactive source in order to take a graphic picture of the interior of building components. The radiometry method involves detecting the intensity of the emerging radiation which passed through a building component. Prior calibration charts can be used to determine in situ density of building components and their thickness. Internal defects and location of internal parts in building components can be determined using both radiography and radiometry methods. A British standard (BS 4408, Part 3, 1970) outlines testing procedures with regard to gamma radiography.

5.25.1 Radiography

Radiography allows the internal structure of a test object to be inspected by penetrating radiation, which may be electromagnetic (X-ray, gamma rays, etc.) or particulate (neutrons) [2,41,42]. The object is exposed to a radiation beam, and the intensity of the radiation passing through is reduced according to the object's variations in thickness, density, and absorption characteristics. The quantity of radiation passing through the object is measured and used to deduce internal structure. X-rays and gamma rays have been most widely used.

5.25.2 X-ray Radiography

X-rays are produced by bombarding a target material with fast moving, high energy electrons. The high energy electrons collide with electrons in the target, which are promoted to higher energy levels. As the promoted electrons return to their ordinary energy levels, their excess energy results in the emission of X-rays. X-rays are generated in an evacuated chamber (X-ray tube) in which high energy electrons are generated by applying a very high voltage between an incandescent filament (the electron source) and the target material. By varying the voltage, X-rays with different penetrating abilities can be generated. For example, for routine inspections using exposures of several minutes duration and with medium speed film, 200 kV X-rays are capable of penetrating about 1 in. (25 mm) of steel, while 400 kV X-rays can penetrate up to 2 in. (51 mm) of steel [25], which is generally about the maximum radiation emitted with portable equipment. Recent developments, such as linear accelerators can speed up and increase the penetrating power of field radiographic methods [14]. In general, the penetrating ability of X-rays of a given energy level decreases as the thickness or the density of the object increases.

5.25.3 Gamma Radiography

Gamma rays are physically indistinguishable from X-rays; they differ only in the manner in which they are produced [14]. Gamma rays are the result of radioactive decay of unstable isotopes. Thus, there are some basic differences between gamma ray and X-ray radiography. Because gamma rays are produced by nuclear disintegrations, a gamma ray source will lose its intensity with time. In addition, each source produces rays of fixed penetrating ability. Isotopes of thulium, iridium, cesium, radium and cobalt have been used for radiography. Thulium has a penetrating ability of 0.5 in. (13 mm) of steel, while cobalt produces gamma rays capable of penetrating up to 9 in. (230 mm) of steel. The gamma sources usually used for inspecting concrete are given in Table 14. Note that the relative penetration abilities of the gamma rays are controlled by their energies.

Table 14

Gamma Ray Sources [41]

Radioactive Source	Gamma Energy (MeV)	Half-life ($t_{1/2}$)	Optimum Working Thickness of Concrete (mm)	Dose Rate*
Iridium 192	0.296 and 0.613	70 days	30-200	0.55
Cesium 137	0.66	33 years	100-300	0.39
Cobalt 60	1.17 and 1.33	5.3 years	150-450	1.35

* Roentgens per hour per curie at 1 m. One curie is equal to 3.7×10^{10} disintegrations per second.

Portable gamma radiography units are available for field inspections. Using iridium-192 or cobalt-60 in these units enables short exposure times and good image sharpness in field applications.

Principles and Applications

Gamma and X-ray radiation is attenuated (reduced) when passing through materials. The extent of attenuation depends on the density and thickness of the material, and on the energy of gamma rays. In radiography, differences in radiation attenuation produced by variations in the density and thickness of a material are recorded on photographic film. For example, when reinforced concrete is radiographically inspected, steel reinforcement attenuates the radiation more than concrete and appears as a lighter area in the film. Voids and cracks in the concrete appear as darker areas on the film because the incident radiation is attenuated little.

In practice, penetrating rays generated by a suitable source are allowed to pass through materials, with the emerging radiation being recorded on X-ray film held in a light-tight cassette. Some of the applications of gamma radiography are inspecting concrete to locate reinforcing bars, and to determine if excess microscopic porosity or macroscopic voids are present [43]; inspecting welds for cracks, voids, and slag inclusion; and inspecting masonry walls for the presence of reinforcement or grout.

Advantages

Radiography provides a method for readily characterizing the internal features of an in-place material or building component. This method is applicable to a variety of materials.

Limitations

The most important drawback of radiography is the health hazard associated with the penetrating radiation. The relatively high cost is another limiting factor in the use of gamma radiography. A radiographic inspection program should be planned and carried out by trained individuals who are qualified to perform such inspection. All personnel involved in radiographic inspection must carry devices that monitor the radiation dosage to which they have been subjected, and must be protected so that the dosage rate does not exceed Federal limits. Gamma ray sources are inherently hazardous because they emit rays continuously, and high energy sources have extremely high penetrating ability. As a result, gamma ray sources require large amounts of shielding material; this limits the portability of gamma radiography equipment. The use of gamma-producing isotopes is closely controlled by the Nuclear Regulatory Commission; users must have a license.

5.25.4 X-ray Fluorescence Analyzer

Principle and Applications

This method is generally carried out in the laboratory but there has been some limited use in the field. The basis of the x-ray fluorescence technique lies in the relationship between the atomic number and the wavelength of the x-ray photons emitted by the sample element. Although almost any high energy particle can be used to excite characteristic radiation from a specimen in the laboratory, application of an x-ray source offers a reasonable compromise between efficiency, stability and cost. Almost all commercial laboratory x-ray spectrometers use an x-ray source. "Since primary (source) x-ray photons are used to excite secondary (specimen) radiation, the technique is referred to as x-ray fluorescence spectrometry" [44].

In the potential NDE field method, the material is irradiated with a radioactive isotope and absorbed energy is re-emitted as x-rays characteristic of elements present in the material. The method is used for determination of the elements present in a material.

Advantages

The potential NDE field method provides for a rapid analysis to determine elements present in installed materials. The analyzer is portable and can be used in the field and the laboratory.

Limitations

Field analysis is limited to small regions of material per test and the technique is not capable of detecting all elements. The field apparatus requires periodic calibration with reference standards.

5.26 Seismic Testing

Principle of Method

Seismic testing is the evaluation of material integrity by analysis of shock wave transmission rates and effects [19]. An array of sensing devices around an explosive charge of known energy (the most common shock load input system) is used to record shock wave transmission rates. These rates can be related to material densities. Vibrational patterns induced from shock loading can be used to determine resonant frequencies in structures.

Applications

Seismic testing can measure soil densities and locate density variation boundaries. Soil density values can then be related to load bearing capacities and foundation preparation requirements. Seismic testing can also be used to check structures for possible resonant frequencies that could cause failure under operating dynamic loads.

Advantages

All components of some seismic test systems are portable.

Limitations

Seismic testing is applicable only to monitoring soil conditions and structural vibrations. Multi-channel recording systems, power cables, and many sensing devices are needed. The hazards of explosives are also involved in the testing.

5.27 Soil Exploration

5.27.1 Cone Penetration Test

Principle and Applications

The Cone Penetration test is described in ASTM Standard D 3441. It is widely used in European practice and is gaining increasing popularity in the United States [45]. The test is performed by pushing a cylinder having a conical tip into the ground. The cylinder can be described as having a 1.55 in.^{2} (1000 mm^2) cross sectional area, a 23.25 in.^{2} (15,000 mm^2) surface area, and the conical tip has a 60 degree apex angle. The soil resistance is measured by the resistance to the penetration of the conical tip into the ground and the frictional forces exerted on the surface of the cylinder which are measured separately. The cone penetration test has been correlated both empirically and theoretically with the bearing capacity of deep and shallow foundations, and with the shear strength, density, stiffness and compressibility of soils.

5.27.2 Helical Probes

Principle and Applications

Helical probes have been found to be a practical and economic method for exploring soils at a shallow depth [45]. Test results correlated well with traditional in situ exploration methods and the probes were also found to be applicable for compaction control. The probes can be inserted into the soil to a depth of 6 feet (1.8 m). The magnitude of the torque required to insert the helix into the soil is taken as a measure of soil resistance. The probes can be operated with ease by one person. A probe could also be coupled with drillrods and used at a greater soil depth.

The probes consist of a helical screw connected to a 5-1/2 to 6 foot (1.7 - 1.8 m) long steel shaft. A hexagonal nut at the upper end of the shaft is used for applying the torque. The probe is inserted into the ground by turning it in a clockwise direction using a torquemeter. The torquemeter has a dial gage to read the torque needed to insert the probe into the soil. Torque readings are generally taken at 6 in. (15 cm) penetration levels, however, it is possible to also continuously monitor the torque. The rate of advance of the probe during a torque reading is kept to correspond to approximately 4s for a 180 degree turn of the torquemeter. The average torque rather than the peak value is recorded. Upon completion of the in situ soils test, the probe is withdrawn by turning it in a counter clockwise direction.

Limitations

Although extensive testing indicated that the probe test results correlated well with traditional in situ exploration methods, it was recommended that research be continued [45]. Additional data are needed for controlled conditions and for soils whose characteristics are well defined. There is also a need for more data for clays and for compacted fills.

5.27.3 Standard Penetration Test

Principle and Application

The Standard Penetration test is described in ASTM Standard D 1586. It was developed in 1927 and is the most widely used soil exploration test in the United States and in worldwide geotechnical engineering practice [45]. The test involves dropping a 140 lbm (63.5 kg) hammer from a height of

30 in. (0.76 m) to drive a drillrod with a standard split-tube sampler into the ground. The number of blows to achieve a 1 ft (0.30 m) penetration by the split-tube sampler, is used as a measure of soil resistance. The Standard Penetration test has been empirically correlated with many soil characteristics, including allowable bearing capacity of foundations, in situ shear strength, density, stiffness and compressibility, and liquefaction potential during earthquakes.

5.28 Surface Hardness Testing

Surface hardness methods are generally used to indicate the strength level or quality of a material rather than to detect flaws. Hardness in these tests refers to the resistance a material offers to indentation by an object. Indentation is produced under static or impact loading conditions. The most common applications are in testing metals and concrete.

5.28.1 Static Indentation Tests

Static indentation tests are primarily used in testing metals. They usually involve indenting the surface with an indenter of fixed geometry under specified loads [2]. The indenter has a small point and thus at the point of contact produces stresses high enough to cause the metal to yield. A permanent indentation results. The magnitude of the indentation will depend on the hardness of the metal, the applied load, and the geometry of the indenter. Therefore, by measuring the size of the indentation under a given set of conditions, one can get an approximate measure of the hardness. For some metals such as hardened and tempered steel, the hardness value can be used to predict with resonable accuracy the tensile strength, impact resistance, and endurance limit [2]. Portable hardness testers are available for in-place testing of metal structures.

Standard Methods

There are three widely used methods for hardness testing of metals. The Brinell method involves applying a constant load (500, 1500, or 3000 kg) on a 0.4 in. (10 mm)-diameter hardened steel ball-type indenter, and measuring the diameter of the indentation with a microscope. A hardness number is determined by substituting the values of the applied load, ball diameter, and indentation diameter into a standard formula. An example of a Brinell test result would be 400 HB; 400 is the number calculated from the standard formula, "H" stands for hardness, and "B" for Brinell. For softer metals, one would use a smaller load to cause the indentation.

The Vickers method is similar to the Brinell method, except that a square-based, pyramidal diamond indenter is used, and the applied loads are much smaller. The diagonal of the square indentation is measured, and its value and the applied load are substituted into a standard equation to calculate the Vickers hardness number (HV).

The most common method is the Rockwell hardness test, which measures the depth of additional permanent indentation that occurs as the load is increased from a small load to the test load. The test instrument measures the depth automatically, and the hardness number is read directly from a scale on the instrument. The Rockwell test can be performed much faster than the previously described methods. There are 15 Rockwell hardness scales -- five different indenters and three different loads. A hardness number of 60 on the Rockwell

C scale would be designated 60 HRC. The variety of scales permits testing a wide range of metals from very soft to very hard.

Usefulness of the Hardness Number

Tables are available that permit conversion of the hardness number from one test method to the equivalent number of another test method, for example, see ASTM Standard E 140 (Appendix D). There are also tables which give the approximate tensile strengths of metals corresponding to the different hardness numbers. Care must be taken in using the strength tables because each applies to only certain types of metals.

5.28.2 Rebound Hammer Method

The rebound method is based on the rebound theories of Shore [46]. He developed the Shore Scleroscope method in which the height of rebound of a steel hammer dropped on a metal test specimen is measured. The only commercially available instrument based on the rebound principle for testing concrete is the Schmidt Rebound Hammer [47].

The technique has gained wide acceptance by researchers and concrete inspectors. It is one of the most universally used nondestructive test methods for determining the in-place quality of concrete, and for deciding when forms may be removed. According to Clifton, standards have been drafted in Poland and Romania for the rebound hammer [48]. The British Standards Institution has issued Building Standard 440 which covers non-destructive test methods for concrete, and includes the rebound hammer method in part 4 of the Standard [48]. The ASTM has issued Standard C 805, which gives procedures for the use of the rebound hammer (Appendix D).

Description of Method

The Schmidt Rebound Hammer consists of a steel weight and a tension spring in a tubular frame. When the plunger of the hammer is pushed against the surface of the concrete, the steel weight is retracted against the force of the spring. When the weight is completely retracted, the spring is automatically released, the weight is driven against the plunger, and it rebounds. The rebound distance is indicated by a pointer on a scale that is usually graduated from zero to 100; the rebound readings are termed R-values. The R-values indicate the hardness of the concrete; the values increase with the hardness of the concrete.

Each hammer has a calibration chart, showing the relationship between compressive strength of concrete and rebound readings. However, rather than placing too much confidence in the calibration chart, users should develop their own calibration for each concrete mix and each rebound hammer.

Applications

Numerous investigators have shown that there is some correlation between the compressive strength of concrete and the hammer rebound number [49-51]. There is, however, extensive disagreement about the accuracy of the strength estimates from rebound measurements [52,53]. Mitchel and Hoagland found that the coefficient of variation for estimated compressive strength, for a wide variety of specimens from the same concrete, averaged 18.8 percent [54]. Arni found that the rebound hammer gave a less reliable estimate of compressive strength than the Windsor Probe [37]. Some investigators have attempted to establish correlations between the flexural strength of concrete and the hammer rebound number. Relationships similar to those for compressive strengths were obtained, except that the statistical variations were even greater [53,55]

Mitchel and Hoagland attempted to correlate rebound numbers with the modulus of specimens [54]. They concluded that no valid correlations could be made. Peterson and Stoll, and Klieger have developed some empirical relations between the dynamic modulus of elasticity and hammer rebound [49,56].

Advantages

The Schmidt Rebound Hammer is a simple and quick method for the nondestructive testing of concrete in place. The equipment is inexpensive, coating less than $1000, and can be operated by field personnel with a limited amount of instruction.

The rebound hammer, like the Windsor Probe, is very useful in assessing the general quality of concrete and for locating areas of poor quality concrete. A large number of measurements can be rapidly taken so that large exposed areas of concrete can be mapped within a few hours.

Limitations

The Schmidt Rebound Hammer, however, has recognized limitations. The rebound measurements on in situ concrete are affected by:

1. Smoothness of the concrete surface
2. Moisture content of concrete
3. Type of coarse aggregate
4. Size, shape, and rigidity of specimen, e.g., a thick wall or beam
5. Carbonation of the concrete surface [10,53,57].

The rebound method is a rather imprecise test and does not provide a reliable prediction of the strength of concrete.

5.29 Thermal Inspection Methods

Thermal inspection includes methods in which heat-sensing devices or substances are used to detect irregular temperatures. Thermal inspection of objects can be used to detect flaws and to detect undesirable distribution of heat during service [14]. There are several methods for carrying out thermal inspections and many types of temperature measuring devices and substances. The two main types of thermal inspection are thermography and thermometry. Thermography involves mapping of isotherms, or contours of equal temperature, over a test surface; while thermometry is the measurement of temperature. Both of these methods can be conducted by means of contact and noncontact inspections. The most commonly used materials or substances for contact thermographic inspections are heat-sensitive paints, heat-sensitive papers, thermal phosphors, and liquid crystals. Infrared detectors are used for noncontact thermographic inspections. There are several basic thermal detectors used for contact thermometric inspection and they include bolometers, thermistors, thermocouples, and thermopiles. Surface temperature can be measured by noncontact thermometric inspections using radiometers and pyrometers or infrared thermometers.

The presence of discontinuities in an object, such as cracks, voids, or inclusions, will change the heat transfer characteristics of the object. Thus, if there is a transient heat flow condition, there will be nonuniform surface temperatures. The pattern of the surface temperatures can be used as an indirect indicator of subsurface anomalies [2]. Thermal inspection can also detect anomalous operating characteristics of a system, such as overloaded electrical wiring or heat loss through walls and roofs of buildings. The following discussion addresses primarily the application of thermal inspection to detect anomalies in the internal structure of test objects such as structural metallic components and roofing systems.

Principle of Thermal Inspection

To establish the condition for thermal inspections, a temperature gradient must exist or be created in the test object. If necessary, this can be done by applying a temporary heat source to the front or back surface of the test object. The flow of heat from the warm to the cold surface will be affected by the material's thermal diffusivity, which is a function of the material's thermal conductivity, density, and specific heat. If there are discontinuities which have thermal diffusivities different from that of the bulk material, local "hot" or "cold" spots will exist on the surfaces directly over the location of the voids. Therefore, by measuring the pattern of surface temperatures under heat flow conditions, subsurface flaws can be detected.

As stated above, surface temperatures can be determined by contact or noncontact inspection methods. With contact methods, the surface is covered with a temperature-sensitive material, and differences in surface temperature are recorded as a pattern on the coating material. Examples of coatings developed for this application are: heat sensitive paints and papers; phosphor coatings for which the fluorescence, under ultraviolet light, is affected by temperature; melting point coatings which melt when a specific temperature is reached; and liquid crystals which change color as their temperatures vary. Contact methods are generally not very sensitive, have relatively long response times, and require an application procedure before thermal inspection. Noncontact methods permit remote sensing of the thermal patterns, and are the more popular thermal inspection methods.

5.29.1 Infrared Thermography

Principle of Method

An object having a temperature above absolute zero will radiate electromagnetic waves. The wavelengths of the radiation fall within certain bands, depending on the temperature. For example, at room temperature, the wavelengths are typically from 4 to 40 micrometers, with a peak wavelength of about 10 micrometers [2]. At very high temperatures, the wavelengths of the emitted radiation are reduced to less than 1 micrometer and fall within the visible spectrum, which explains why some metals give off a red color when heated to high temperatures. The longer wavelength radiation associated with room temperature is not visible to the eye. This is infrared radiation. By using instruments that can detect infrared radiation, differences in surface temperatures can be "seen." This is the basis of the thermal inspection method known as infrared thermography.

The rate of radiant energy emission per unit area of surface (W) is given by the Stefan-Boltzmann Law:

$$W = e\alpha T^4$$

where: T = the absolute temperature
e = the emissivity
α = the Stefan-Boltzmann constant (5.67×10^{-12} watt/cm^2/°K^4).

Thus, changes in the temperature of a surface produce more than proportional changes in emitted energy, and this allows the testing equipment to detect temperature differences as small as 0.2°C. Emissivity refers to the efficiency of energy radiation by the surface. The maximum radiation efficiency occurs in a "black body," and this is given an emissivity value of 1. All real surfaces have an emissivity less than 1; polished metallic surfaces have low emissivity, while roughly textured nonmetals have high emissivity. Since detection methods are based on the intensity of emitted radiation, a change in emissivity at various points on the surface may be incorrectly interpreted as a change in temperature. Surfaces with nonuniform or low emissivity can be painted with high emissivity coatings.

Remote Inspection

Infrared thermography permits remote inspection of the test object. This is possible because air is practically transparent to the infrared wavelengths associated with conditions near room temperature [28]. However, high water content will reduce the transmission of infrared radiation through air, so problems may arise when the weather is humid. Semiconductor crystals are most often used to detect infrared radiation. Their electrical properties are altered by incident infrared radiation. For best sensitivity, the crystals should be kept cold with liquid nitrogen. This places some limitations on the portability of the detection systems. Dewar flasks are needed to hold the liquid nitrogen, and the nitrogen needs to be replaced as it evaporates.

Infrared Scanners and Display

Operating on a scanning principle similar to television, infrared scanners allow the user to view a picture of the test object's surface. Through a system of special mirrors, the surface is scanned, a small spot at a time; the intensity of radiation is measured by the detector and is displayed on a cathode ray tube. The horizontal and vertical scans occur so quickly that a picture (thermogram) of the surface is reconstructed on the cathode ray tube. The picture is presented as shades of gray corresponding to variations in surface temperatures of the viewed object. A calibration strip is also shown so that the shades can be converted to absolute temperatures if desired. It is also possible to have a color display showing different temperatures in different colors.

Applications

Thermal inspection methods have been applied for detecting disbonds in laminated materials, entrapped moisture, material density gradients, and anomalies in castings [2]. In the construction area, infrared thermography has been applied to compare thermal resistances of roofs, to detect water penetration into built-up roofs, to detect heat loss through walls and roofs of buildings, and to detect overloaded electrical circuits [28]. Infrared thermography has also been used to detect deteriorated regions in bridge decks [58].

Advantages

Thermal inspection equipment is generally portable, and a permanent record (photograph) can be made of the inspection results. By using infrared thermography, inspections can be performed without direct contact with the surface, and large areas can be rapidly inspected.

Limitations

In determing the size and location of detectable flaws, it should be recognized that under heat flow conditions the surface temperature patterns will be a function of the type and size of the discontinuity, its distance from the surface, the heat intensity applied or flowing to the surface of the object, and the observation time [2]. The sensitivity of infrared thermography in detecting internal flaws is a complex function of these variables. Therefore, the results of such inspections should be carefully interpreted.

5.29.2 Envelope Thermal Testing Unit

Principle and Applications

The envelope thermal testing unit consists of two blankets which are attached to opposite sides of walls and through which the heat flux to opposite wall surfaces can be controlled [5]. This testing unit was developed by the Lawrence Berkeley Laboratory in order to evaluate the in situ transient thermal performance of walls. It was designed to overcome some of the difficulties in using heat flow meters and calorimeters for the in situ evaluation of building components. The difference between the envelope thermal testing unit and these techniques is that the heat flow is controlled and not the temperature.

The slightly flexible blankets made to conform to slight irregularties in wall surfaces are placed in direct thermal contact with the wall, thus eliminating complications associated with air film and considerably reducing the bulk of the unit. Each blanket consists of two large area electric heaters separated by a low-thermal-mass insulating layer. An array of temperature sensors is embedded in each heat layer. The electric heaters are designed to provide heat output that is uniform over the entire area and the heat output is controlled by adjusting the voltage applied to the heaters. In calculating the thermal resistance of a wall, the data are analyzed in the manner as the data obtained from heat flow meters and calorimeters.

Limitations

The envelope thermal testing unit has been used only for research purposes and is considered as being under development. Only qualified technicians experienced with this procedure and also having an understanding of the fundamentals of building heat transfer should carry out this procedure.

5.29.3 Heat Flow Meter

Principle and Applications

A heat flow meter consists of a thin flat wafer, either circular or rectangular in shape, that is comprised of a series of pairs of thermocouple junctions [59]. The wafer contains an embedded thermopile which produces a voltage (millivolt) signal that is proportional to the rate of heat flow passing through the wafer. The sensitivity of a heat flow meter (millivolts per Btu/h ft^2) is a function of its average temperature. "In selecting a heat flow meter for a particular application, it is important that the heat flow meter provide a signal sufficiently large for measurement and resolution by the readout device at the lowest expected heat flow rate [5].

The thermal resistance of a building component can be measured by using a heat flow meter spot-glued to a representative location on the interior surface of the component, and temperature-sensing probes attached to the inside and outside surfaces at the same location. After the heat flow meter is bonded to the surface, it should be covered with the same or similar coating used on other parts of the surface, so that the radiative exchange between the monitored location and other surfaces in the room will be comparable. The measured thermal resistance of the component is determined by dividing the average difference in surface temperature, for a sufficient period of time, by the average heat flow measured during the same time interval. For accurately calibrated heat flow meters, this technique has been shown to be accurate to within 6 percent [5]. The thermal resistance measurement is applicable only to the particular spot where the heat flow meter is attached to the building component. However, when used with a thermographic survey this technique becomes an effective tool for assessing the thermal performance of building components.

Limitations

This technique can only be used during periods when there is no reversal in direction of heat flow. Only qualified technicians should carry out this procedure. They should be experienced with techniques for making proper low-level electrical measurements and also have an understanding of the fundamentals of building heat transfer. If the thermal dynamic response of the building component is to be determined, graduate level training in mathematics is needed.

5.29.4 Portable Calorimeter

Principle and Applications

The portable calorimeter is essentially a guarded hot box and is used for measuring in situ heat transmission through building components. It was developed by the Building Research Division of the National Research Council of Canada [5]. The calorimeter is an insulated box having five sides; the open side is sealed against the inside surface of the building envelope component for which heat transmission tests are to be performed. The temperature inside the box is kept equal to the indoor temperature of the building enclosure by means of a thermostatically controlled electric heater. The electric energy supplied to the electric heater is essentially equal to the heat transmission through the metered area since the reverse heat loss through the box and edge loss where the box edge contacts the metered surface are essentially nulled to zero [5]. This technique has the advantages that it provides a minimum disturbance to the measured heat transmission and a sufficiently large surface area is metered so that the measurements are representative of the performance of a building component. It is reported that the accuracy of the technique is about 5 percent [5].

Limitations

Calorimeter measurements should be conducted only during periods when the outdoor to indoor temperature difference (ΔT) is greater than 10°F. Solar heating of walls in the winter season may frequently produce ΔT less than 10°F. During the measurement of heat transmission through building components, the indoor temperature must be thermostatically controlled at a constant level in order to minimize differences in temperature between the calorimeter and the room. Also, solar radiation into the building and conditioned air from a warm air supply must not be permitted to strike the calorimeter. Only qualified technicians experienced with this technique and also having an understanding of the fundamentals of building heat transfer should carry out this procedure.

5.29.5 Spot Radiometer

Description of Method

Spot radiometers can be used to determine qualitatively whether a wall or other building component is insulated or if insulation voids or other thermal defects are present. They are hand-held devices used to radiometrically measure the equivalent blackbody temperature of a relatively small area of a surface [5]. Spot radiometers are generally small, light weight, and most are gun-shaped. They are calibrated by pointing them at a surface of known temperature and adjusting a meter so that the device radiometrically determines the correct temperature of the reference surface. Manufacturers often provide reference surfaces having approximately black body characteristics (i.e., reflecting little radiation from surrounding surfaces) for calibration purposes. Interior surfaces of buildings generally have emittances which range from about 0.80 to 0.95. Since the emittance of an interior wall surface to be measured may differ from the reference surface, the apparent surface temperature determined using a spot radiometer may differ from the actual surface temperature by a small amount [5].

In using the spot radiometer, it is pointed at the surface for which temperature is to be measured and the on-off trigger is depressed. The device senses the total infrared radiation over a particular wavelength band emanating from the surface, including both the self-emitted surface radiation and reflected radiation from surrounding surfaces. The device is calibrated to read the apparent radiance temperature on either a digital or meter display. The apparent radiance temperature is defined as the temperature of a perfectly black surface (emittance = 1) which would radiate the same amount of thermal radiation as the self-emitted and reflected radiation emanating from the real surface at its actual temperature and having a surface emittance different from unity. The devices generally have their principal spectral response in the range of 10 microns, and a response time less than 2 seconds. Contact with the surfaces to be measured is not necessary with these devices. Operation close to a wall or building component will indicate apparent surface temperature of a small region, while operation at a distance will indicate apparent surface temperature for a larger region. Spot radiometers may be equipped with an audio device that will produce a change in audible tone when a thermal anomaly such as an air infiltration path or missing insulation is found while scanning a wall or building component. Gross thermal defects can be readily detected while quickly scanning the envelope of a building.

Limitations

This technique is not sensitive enough to permit detection of small diffrences in effectiveness of insulation such as to distinguish an R-13 wall from an R-15 wall.

5.30 Ultrasonic Pulse Methods

In the ultrasonic pulse methods, sound waves which are beyond the audible range are induced in a test object by a piezoelectric transducer, and either reflected waves or those passing through the object are detected by a similar type of transducer [2,10,60-63]. When reflected waves are detected, the technique is called "pulse-echo," and the transmitting transducer may also act as the receiver. Waves passing through the object are detected with a second transducer, i.e., a receiving transducer.

Ultrasonic inspection is based on two principles: (1) the velocity of the acoustic waves in a material is a function of that material's elastic constants and density; and (2) when an acoustic wave encounters an interface between dissimilar materials, a portion of the wave is reflected. The amount of reflection depends on the mismatch in acoustic impedance (product of wave velocity and density) of the materials, with the amount of reflection increasing with the mismatch.

5.30.1 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity method is one of the most universally used NDE methods for assessing the quality of concrete.

Principle of Method

The ultrasonic pulse velocity method measures the travel time of an ultrasonic pulse passing through a material. The pulse generated by an electroacoustic transducer is picked up by a receiver transducer and in some cases the pulse may be amplified. The time of travel of the pulse is measured electronically [63].

When a mechanical pulse is applied to a material by an electroacoustic transducer, waves are induced in the material. Longitudinal waves are used most often in testing concrete. These waves are transmitted by particles vibrating parallel to the direction of propagation. The waves' velocity, controlled by the elastic properties and the density of the material, is virtually independent of the geometry of the object being tested.

If a longitudinal wave encounters a discontinuity such as crack or void, it may "bend," i.e., be diffracted around the discontinuity. This increases the internal distance the wave must pass between the transmitting and pickup transducers, and consequently its travel time increases. The travel time of a longitudinal wave will also be affected by changes in density and elastic properties of a given concrete along the travel path.

Several ultrasonic pulse velocity units are commercially available for testing concrete; these cost about $4000. Some models can be used to test concrete as thick as 75 ft (30 m).

Application for Assessment of Condition of Concrete

The ultrasonic pulse velocity method is best for nondestructive evaluation of the uniformity of in-place concrete. (ASTM Standard C 597 gives the standard test procedure, see Appendix D). For example, velocity measurements have been successfully used to detect deteriorated regions in concrete bridges and to check the uniformity of concrete in walls. In general, if substantial variations in pulse velocities are found in a structure, without any apparent reason (such as intentional changes in materials, concrete mix, or construction procedures), this indicates that the concrete is unsound.

A general rating which has been proposed to assess the relative quality of concrete is presented in Table 15 [64]. These criteria should be used with caution because differences in the qualities of concrete cannot be as sharply delineated as indicated in Table 15. In addition, velocity is affected by the density and amount of aggregate in the concrete. A crude assessment of the quality of similar types of concrete can be made, however, using these criteria. For example, if one concrete has a pulse velocity of 15,000 ft/sec (4570 m/sec), while another concrete with a similar composition has a velocity below 10,000 ft/sec (3050 m/sec), then there is clearly a significant difference in their qualities.

Table 15

Pulse Velocities in Concrete [64]

Feet per Second	(Meters per Second)	General Condition
Above 15,000	(4570)	Excellent
12,000-15,000	(3660-4570)	Good
10,000-12,000	(3050-4570)	Questionable
7,000-10,000	(2130-3050)	Poor
Below 7,000	(2130)	Very Poor

Estimation of Strength Properties of Concrete

Many investigations have attempted to correlate compressive and flexural strengths of concrete with pulse velocity [63]. Some correlations have been obtained in laboratory studies, provided that mix proportions, the cement, types of aggregate, and curing conditions were not varied. If these factors were altered, however, no usable correlations were obtained. For example, Parker [65] compared pulse velocities and compressive strengths for concretes made from only one type of aggregate, but containing different cements from different sources and a variety of admixtures. His analysis of the data indicates that at the 95 percent confidence level the estimated strength of 4440 psi (30.7 MPa) concrete ranged from about 2100 to 6000 psi (14.5 to 41.8 MPa). Obviously, the ultrasonic pulse method cannot be used to obtain reliable estimates of compressive strength when the composition of concrete in a structure is unknown.

Jones has offered these concluding remarks regarding strength prediction from wave propagation methods: "In spite of some of the promising results of the early investigations, it must be concluded that no general relation has been found between the dynamic modulus of elasticity and its flexural or compressive strength" [66]. This statement still holds if one substitutes "pulse velocity" for "dynamic modulus of elasticity."

Extraneous Effects on Velocity Measurements

The measurement of the pulse velocity of concrete is affected by several factors which are not intrinsic properties of concrete, and, therefore, are not a function of the quality or strength of concrete [10]. These factors include:

1. Smoothness of concrete at transducer contact area. Good acoustical contact between the transducers and concrete is required. In addition, a coupling agent such as an oil or a jelly must be used.

2. Concrete temperatures outside the range between 41° and 86°F (5° and 30°C) affect the measured pulse velocity. Below this temperature range, the velocity is increased, and above, the velocity is decreased.

3. Moisture condition of concrete. Pulse velocity generally increases as the moisture content of concrete increases, while compressive strength decreases as moisture content increases.

4. Presence of reinforcing steel. The pulse velocity in steel is 1.2 to 1.9 times the velocity in concrete. Measurements made near steel reinforcing bars, therefore, may not be representative of the concrete. If possible, measurements should be made perpendicular to the longitudinal axis of the bars. If measurements must be made parallel to the longitudinal axis of the steel bars, crude correction factors are available.

5.30.2 Ultrasonic Pulse Echo

Principle of Method

In the ultrasonic pulse echo method, waves which are reflected off discontinuities (e.g., cracks and voids) and from interfaces (e.g., those between concrete and steel or between concrete and air) are recorded. Both the transmitting and receiving transducers are contained in the same probe; thus, only waves which are reflected back at nearly 180 degrees are detected. The penetrating ability of the ultrasonic pulse and the minimum size of detectable flaws are influenced by the frequency of the generated waves. High frequency results in less penetration but better sensitivity than low frequency.

Applications

Echo techniques have been extensively used to identify and locate discontinuities and defects in metals and welds [2,60-62]. The echo technique is one of the most versatile and accepted NDE methods for metals. However, it has not been used often with concrete -- largely because the extensive pore system, the presence of cracking, and the heterogeneous nature of concrete cause multiple reflections when very high frequency pulses are used. Therefore, the reflected waves are significantly attenuated and the interpretation of the observations complicated. As noted, the heterogeneous nature of concrete poses problems not encountered in pulse-echo evaluation of metals, thus, progress in this area of concrete nondestructive testing has been slow. A review of research indicates that the pulse-echo method has been used successfully to detect flaws within concrete, however, standardized methods do not currently exist for pulse-echo evaluation of concrete structures [67]. Pulse-echo methods have been used for detection of very large cracks in dams, for integrity testing of piles and other slender concrete structures, and for measuring the thickness of slabs and pavement. In addition, it may be possible to combine the echo method with acoustic impact (see Acoustic Impact Method, Section 5.2) so that low frequency waves are generated. These would be insensitive to microscopic flaws but could be used to detect large discontinuities [68]. Commercial equipment is not yet available for such testing.

Advantages

Ultrasonic pulse-echo inspection offers several advantages over other NDE methods -- such as gamma radiography -- capable of detecting internal flaws in a test object [2]. For example, acoustic waves have excellent penetrating ability, and with proper instrument selection, thick sections of 30 ft (10 m) or more can be inspected. Very small flaws may be detected, and their location and geometry estimated with reasonable accuracy. In addition, test results are immediately available and the equipment is lightweight and portable.

Limitations

Because of the indirect nature of flaw detection by ultrasonic pulse-echo inspection, personnel with a high level of expertise are needed to plan an inspection program. A thorough understanding of the nature of the interactions between the acoustic waves and different discontinuities is required in order to interpret test results properly. The physical testing, on the other hand, may be performed by technicians after proper training. Before ultrasonic inspection equipment can be used, calibration and referencing with standards must be performed; otherwise, test results have no meaning. The nature of the calibrations will depend on the particular inspection program.

5.31 Uplift Resistance

Description of Method

The resistance of built-up roofing systems to uplift pressure can be determined using the ASTM Standard E 907 test method (Appendix D). A controlled negative pressure is created on top of the roof surface using a chamber, 5 x 5 ft (1.5 x 1.5 m) in area, fitted with a vacuum pump and a pressure measuring device. Provisions must be made to provide a smooth surface along the roof to allow the edges of the chamber to be in complete contact with the roof surface so that a negative pressure can be applied inside the chamber. For roofs containing mineral aggregate surfacing, the loose surfacing should be removed by sweeping a path about 12 in. (300 mm) wide and applying a heavy pouring of hot asphalt over the swept area. When the asphalt cools it will provide the smooth surface necessary for contact with the chamber. The bottom flanges of the chamber are equipped with a foam strip to seal the chamber to the roof surface. The chamber is oriented on the roof so that the edges are parallel with the direction of the structural framing of the building.

The negative pressure is applied in increments and the deflection is continuously monitored during the test for sudden or variable rates of movement. The predetermined increments of pressure are held for 1 minute and further increments are applied until a preselected negative pressure is reached or failure (adhesion or cohesion) occurs. Most roof systems subjected to a negative pressure will exhibit an upward deflection that will increase with an increase in negative pressure. Poorly adhered roofing systems will exhibit relatively large increases in upward defections with relatively small increases in applied pressure. For well adhered roofing systems the increase in deflection will be gradual and at a relatively constant rate up to a point at or near failure.

5.32 Visual Inspection

Surface defects often can be detected visually using methods to improve ordinary observations. Optical magnification or other techniques which can be used to increase the apparent size of surface cracks are covered in this section.

5.32.1 Optical Magnification

Available magnifying instruments range from simple, inexpensive glasses to expensive microscopes. Some fundamental principles about the operating characteristics of magnification instruments should be understood before a system is chosen for a particular application. For example, the focal length decreases as the magnification power increases. This means that when high magnification is desired, the primary lens must be placed close to the test object. The field of view (the portion of the object that can be seen at any instant) also decreases as magnification power increases. A small field of view means that it will be tedious to examine a large surface area. Another important characteristic is the depth of field -- the elevation difference of rough textured surfaces that can be viewed in focus simultaneously; the depth of field decreases as the magnification power of the instrument increases. Therefore, to inspect a rough-textured surface, a magnification power should be selected that gives a large enough depth of field so that the "hills" and "valleys" are simultaneously in focus. Finally, the illumination intensity required to clearly see surface flaws will increase as the magnification power increases. High magnification may require a light source to supplement the available lighting.

A useful tool for field inspection is a pocket magnifier with a built-in viewing scale, which allows measurement of flaw dimensions. A stereomicroscope is very useful when a three-dimensional view of the surface is required. With this instrument, one can determine whether a wide crack is shallow or extends deep into the object. If calibrated, a stereomicroscope can also be used as a depth gage to measure the approximate height of surface irregularities.

5.32.2 Fiberscope

Another useful instrument is the fiberscope, which is composed of a bundle of flexible optical fibers and lens systems. The fiberscope can be inserted through a small access hole so that the inside of a cavity can be seen. Some of the fibers in the bundle carry light into the cavity and illuminate the field of view. The viewing head can be rotated so that a wide viewing angle is possible from a single access hole. A fiberscope, because of the discrete nature of light transmission of the fibers, may not have as good resolution as a borescope, which is straight, rigid tube using a lens system for viewing. The best resolution is obtained with an instrument having small-diameter fibers in which the fiber density per unit area is high. To use a fiberscope, one must drill access holes if natural channels are not present, and the hole must intercept cavities. The acoustic impact technique (Section 5.2) can be used to locate hollow spots for subsequent fiberscope inspection.

5.32.3 Liquid Penetrant Inspection

In this method a highly visible dye is used to coat the surface to be inspected [2,69]. Any cracks open to the surface will soak up the dye because of low surface tension and capillary effects. After application of the dye, the surface is cleaned. However, the dye which penetrated into cracks remains and reveals the presence of cracks. The method is one of the most inexpensive inspection tools, but it only permits detection of open flaws on the surface of the test object.

Description of Method

Dye penetrant inspection involves the following steps: (1) cleaning the surface, (2) applying the dye, (3) removing excess dye from the surface, (4) applying a developer, and (5) interpreting the results.

The objective of the cleaning is to remove foreign matter from cracks so that the dye can penetrate. The specific procedures depend on the condition of the surface. Care must be taken to ensure that the cleaning process does not smear the cracks or fill them with residues. For example, sandblasting a soft metal may "hammer" the surface so much that cracks become closed and undetectable.

The dye may be applied to the surface by spraying, painting, or dipping. Two types of dye are available: one is for viewing under ordinary light and is usually a brilliant red color, the other is fluorescent and viewed under ultraviolet light. Fluorescent dyes offer the best sensitivity for detecting small cracks. The dye is allowed to remain on the surface from 10 to 30 minutes (dwell time) before the excess is removed.

Cleaning can be done by flushing the surface with water or by wiping with a rag dampened with solvent. An emulsifying agent is needed so that the dye can be completely removed with water. The agent is either already included in the dye, or it is added to the coated surface before washing. This phase is very important; all excess dye must be removed, otherwise some indications of cracks will be false. If the surface is very porous, inspection by this method may be difficult; if dye is not removed from the pores, there will be a loss of contrast because the surface will take on a color that is a light shade of the dye. If the dye is removed from all pores, it probably will be removed from some of the cracks as well.

After cleaning, the surface is allowed to dry, and a developer is added. Developer is a fine powder which: (1) provides a uniform, colored background to increase contrast, and (2) has a blotting effect, thereby drawing up the dye from the cracks. The blotting action increases the apparent width of the cracks so that they are clearly visible. Developer can be applied as a dry powder or as a paint. The thickness of the developer layer is important; if it is too thin, there will not be good contrast, and if it is too thick, it may mask the cracks.

Finally, the prepared surface is inspected. If the application was done correctly, the cracks will be clearly shown.

However, the inspector needs to be familiar with the patterns associated with "irrelevant indications," i.e., patterns not from cracks but from other sources, such as improper cleaning.

Applications and Limitations

Although dye penetrant inspection relies on simple principles, a certain amount of skill is necessary to carry out do the process correctly. The operator needs to recognize what materials to use for a particular application, and to understand how the materials respond to different temperature conditions. Portable kits are available with the various chemicals in aerosol cans, thus making field inspection possible. The technology is now geared primarily toward inspection of metals. The applicability of the procedures to masonry or concrete structures having surfaces of high porosity has not been demonstrated.

5.33 Water Permeability of Coated Masonry Walls

Principle and Applications

The transmission of water through coated masonry walls is proportional to the number of "pin holes" in the coating. The exterior coating and its application are the most significant variables in preventing excessive permeation into the masonry. A reservoir, about 7 in^3 (12×10^4 mm^3), with an open face is sealed to the masonry and kept pressed against the wall by a spring which is stretched between two hooks that are secured to the masonry wall. The reservoir is filled with water and the water is allowed to permeate the wall for 15 minutes or the time required to absorb 25 ml of water. The water absorbed by the wall is determined from a burette connected to the reservoir. From a measurement of the diameter of the reservoir, the rate of water absorption can be expressed in gallons per square foot per hour. When the rate of water disappearance from the reservoir is less than 1 gal/ft^2/h there are no damaging effects. In order to provide a margin of safety, a limit of 1/2 gal/ft^2/h was established [70]. A properly coated masonry surface will have a water transmission rate of about one-tenth that amount.

5.34 Combinations of Nondestructive Evaluation Methods

While no single NDE method may be entirely satisfactory for predicting the strength or quality of material, combinations of methods which respond to different factors may give more definite information. The combined NDE approach has been developed mainly for evaluating concrete; therefore, only applications to concrete will be described.

The results of two methods can be combined in a linear equation of the form:

$$f'_c = A(NDE_1) + B(NDE_2) + C$$

where f'_c is the estimated compressive strength from the combined method, NDE_1 and NDE_2 are the results of the individual methods, and A, B, and C are empirically determined constants.

Two combinations often used are the ultrasonic pulse velocity method and the measurement of the damping constant of concrete [71], and the ultrasonic pulse velocity and pulse attenuation methods [72]. These combinations are essentially laboratory research techniques and therefore will not be discussed further.

The most popular combination has been the ultrasonic pulse velocity method and the rebound hammer [73]. This combination has been used primarily in Europe, with the most exhaustive studies being carried out by Facaoaru [74-77]. In this combined approach, measurements of ultrasonic pulse velocity and rebound number are made on in situ concrete. The pulse velocity and rebound number are substituted into a previously derived regression equation to predict compressive strength. It is generally believed that the multiple regression equation should give a more accurate estimate of compressive strength than either of the individual measurements alone.

For standard concrete mixes, Facaoaru has developed calibration charts from which the compressive strengths can be estimated when the pulse velocities and rebound numbers are known [74]. Correction factors have also been developed to be used in the case of nonstandard concrete mixes. This combined method has been used often in Romania to estimate the compressive strength of in situ concrete [74,76]. Based on his experiences, Facaoaru contends that the combined method offers the following accuracy in predictions of compressive strengths:

1. When composition is known and test specimens or cores are available for calibration purposes, accuracy is within 10 to 15 percent.

2. When only the composition of the concrete is known, accuracy is within 15 to 20 percent.

3. When neither the composition is known nor test specimens or cores are available, accuracy is within 20 to 30 percent [76].

This suggests that for case 3, the combined method gives no better prediction of the compressive strength than can be obtained by measuring only the ultrasonic pulse velocity or only the rebound number; in case 2, the improvement is marginal.

Therefore, only when the concrete is well characterized is this combined method better than the individual nondestructive methods.

6. SUMMARY

Nondestructive evaluation (NDE) methods for evaluating in situ construction materials and condition assessment of building components and systems were identified and described. This report is intended to help inspectors and those involved in condition assessment choose appropriate NDE methods for specific building materials, components, and systems. Important properties of building materials along with important performance requirements for building components are listed, and appropriate NDE methods for determining these properties are recommended. In many cases the advantages and limitations for the NDE methods are presented. Potential NDE methods which may or may not require further research and development before they are ready for routine use were also identified and briefly described. In addition, ASTM standards for NDE methods for concrete and other building materials and components were identified.

In a related aspect of the study, current Navy practices relative to the use of NDE methods in the construction and service cycle of buildings and other structures were reviewed. This review was based on Navy reports and documents provided by the Naval Civil Engineering Laboratory (NCEL) and the Naval Facilities Engineering Command (NAVFAC), and on discussions with NAVFAC personnel involved with buildings and structures problems where NDE methods are used for diagnostic purposes. Navy Guide Specifications were examined for required tests, both NDE and destructive, of in situ building materials and components. Twenty nine of the 239 Guide Specifications reviewed contained required NDE tests.

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APPENDIX A. REVIEW OF NAVY GUIDE SPECIFICATIONS

The Navy Guide Specifications that were reviewed with regard to NDE in situ tests of building materials and components are listed in Table A. Twenty nine of the 239 Navy Guide Specifications listed in this table contained required NDE tests. The twenty-nine Guide Specifications along with the NDE tests required for each specification are given in Appendix B.

The tests included in the Guide Specifications are listed for each specification and they include field tests, laboratory tests, and NDE tests. Some of the field tests and laboratory tests are of the destructive type.

Table A. Review of Navy Guide Specifications

Guide Spec. No & Date	Guide Spec. Title
1. TS-T18 a (July 1965)	Specification for Timber Harvesting

No tests specified

2. NFGS-02050 (March 1984)	Demolition and Removal

No tests specified

3. NFGS-02102 (August 1982)	Clearing and Grubbing

No tests specified

4. TS-02200 Amendment-1 (November 1980)	Earthwork

Field Tests	NDE Tests
• gradation of fill or backfill material • liquid limit and plasticity of fill or backfill material • moisture density relationship of fill or backfill material • density of in place material • moisture content of in place soil material (ASTM D 3017)	None specified

5. NFGS-02247 (March 1983)	Portland Cement Stabilized [Base] [or] [Subbase] Course for Airfields, Roads and Streets

Tests	NDE Tests
• aggregate or existing soil aggregate materials -sieve analysis of combined material -liquid limit -plasticity index • compressive strength of cement treated materials • smoothness of paved area • thickness of base or subbase course	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
• field density • laboratory tests -optimum moisture content and maximum density -moisture-density relationship of existing soils (for site preparation)	
6. NFGS-02250 (June 1981)	Soil Treatment for Subterranean Termite Control
No tests specified	
7. NFGS-02361 (July 1983)	Round Timber Piles
Tests	NDE Tests
• load test of piles	None specified
8. TS-02362.3 (October 1980)	Auger-Placed Grout Piles
Tests	NDE Tests
• load tests of piles • grout consistency (flow cone test) • grout compressive strength	None Specified
9. NFGS-02363 (August 1981)	Cast-in-Place Concrete Piling, Steel Casing
Tests	NDE Tests
• load tests of piles • concrete testing	None specified
10. NFGS-02367 (August 1981)	Prestressed Concrete Piling
Tests	NDE Tests
• load tests of piles • concrete testing (aggregates, compressive strength of concrete)	None specified

Table 4. (Continued)

Guide Spec. No & Date	Guide Spec. Title
11. TS-02360.1 (October 1980)	Round Timber-Concrete Composite Piles
Tests	NDE Tests
• load tests of piles	None specified
12. TS-02368 (January)	Steel H-Piles
Tests	NDE Tests
• load tests of piles	None specified
13. NFGS-02369 (March 1984)	Pressure-Injected Footings
Tests	NDE Tests
• load tests of footings, measure deflection or settlement	None specified
14. NFGS-02369.1 (September 1983)	Sheet Steel Piles
No tests specified	
15. NFGS-02452 (September 1984)	Railroad Trackwork
Tests	NDE Tests
• verify gauge, alignment, and surface elevation of track	• ultrasonic inspection of welded rail joints
16. NFGS-02485 (December 1982)	Turf
No tests specified	
17. NFGS-02490 (November 1982)	Trees, Plants, and Ground Cover
No tests specified	

Table 4. (Continued)

Guide Spec. No & Date	Guide Spec. Title
18. TS-02513.1 (September 1979)	Asphalt Concrete Base Course (Central Plant Hot Mix)
Tests of Pavement Course	NDE Tests
• density using cores • thickness • straightedge of compacted surface	None specified
19. NFGS-02559 (October 1983)	Portland Cement Concrete Pavement for Roads and Air Fields
Tests at job site	NDE Tests
• slump • air content • temperature of plastic concrete in-place • surface smoothness • pavement thickness (core samples); note, cores can also be used to evaluate condition of the concrete • flexural strength (from job site beam specimens)	None specified
20. NFGS-02573 (March 1984)	Bituminous Hot Mix Pavement
Tests	NDE Tests
• density using cores • thickness of binder and wearing courses • smoothness of compacted surfaces • finish grades of each course placed	None specified
21. NFGS-02576 September 1981	Asphalt Slurry Seal
Tests	NDE Tests
• slurry mixture water content residual asphalt content gradation of extracted aggregate calculate percent of emulsified asphalt	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
• trial application (demonstrate ability to apply slurry seal)	
22. TS-02577 (July 1980)	Pavement Markings (Airfields and Roads
Field Testing	NDE Tests
None specified	None specified
23. NFGS-02578 (August 1982)	Rubber and Paint Removal from Airfield Pavements
Field Testing	NDE Tests
• demonstrate rubber and paint removal on 50 ft. long test area • recommended friction and texture testing after removal work	None specified
24. TS-02581 (September 1978)	Rotary Drilled Water Well
Tests	NDE Tests
• measure flow and drawdown	None specified
25. TS-02614 (January 1978)	Joints, Reinforcement and Mooring Eyes in Concrete Pavements
No tests specified	
26. TS-02616 (October 1979)	Resealing of Joints in Rigid Pavement
No tests specified	
27. NFGS-02622.1	Fiberglass Reinforced Plastic (FRP) Piping (for Petroleum Products)
Field Tests	NDE Tests
• initial pneumatic test at a pressure of 15 psig • second pneumatic test at a pressure of 50 psig	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
• hydrostatic pressure test • hydrostatic cycle test of system • operational test of system • backfill density	
28. TS-02671 (September 1980)	Bituminous Tack Coat
No tests specified	
29. TS-02672 (September 1980)	Bituminous Prime Coat
Tests	NDE Tests
• sulfonation index test for tar • spot test for asphalt	None specified
30. TS-02673 (September 1980)	Bituminous Seal Coat, Spray Application
Tests	NDE Tests
• stripping test • spot test	None specified
31. TS-02675 (March 1979)	Coal Tar Seal Coat with Unvulanized Rubber
Field Tests	NDE Tests
None specified	None specified
32. NFGS-02676 (February 1982)	Fog Seal
No tests specified	
33. TS-02677 (August 1980)	Bituminous Surface Treatment
No tests specified	

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
34. TS-02685 (October 1980)	Select-Material Base Course for Rigid Pavement
Field Tests	NDE Tests
• aggregate gradation • smoothness of top layer • density of each layer of base course • thickness of base course	None specified
35. TS-02686 (October 1980)	Graded Aggregate Base Course for Flexible Pavement
Field Tests	NDE Tests
• aggregate gradation • smoothness of top layer • density of each layer of base material • thickness of base course	None specified
36. NFGS-02696 (November 1981)	Selected-Material Subbase Course for Flexible Pavement
Field Tests	NDE Tests
• aggregate gradation • smoothness of top layer • density of each layer • thickness of subbase course	None specified
37. NFGS-02714 (July 1982)	Exterior Steam Distribution
Field Tests	NDE Tests
• test system to demonstrate compliance with contract • before insulation is applied, hydrostatically test each piping system	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
38. TS-02722 (July 1980)	Exterior Sanitary Sewer System

Field Tests

- straightness of pipelines and gross deficiences
- leakage
- deflection of plastic pipelines
- pressure test of the system
- field tests for concrete (Section 03300, "Cast-in-Place Concrete")
  - slump
  - compressive strength (from job-site cylinders)
  - temperature tests

NDE Tests

None specified

Guide Spec. No & Date	Guide Spec. Title
39. NFGS-02734 (March 1984)	Rotary-Drilled Water Well

Field Tests

- measure flow and drawdown (pump test)
- well plumbness and alignment

NDE Tests

None specified

Guide Spec. No & Date	Guide Spec. Title
40. NFGS-02854 (March 1983)	Railroad Track Work

Field Tests

- (visual) inspect new rail fittings thoroughly (bolted joints and welds)
- verify gage, alignment and surface elevation of track

NDE Tests

None specified

Guide Spec. No & Date	Guide Spec. Title
41. NFGS-02881 (November 1981)	Dredging

No tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
42. TS-02886 (August 1980)	Wood Marine Piling
Field Test	NDE Tests
• load tests on piles	None specified
43. NFGS-02891 (March 1982)	Pier Timberwork
No tests specified	
44. NFGS-02910 (November 1982)	Welding Crane and Railroad Rail-Thermite Method
Tests	NDE Tests
• visual inspection of each welded joint • ultrasonic inspection of each welded joint • hardness of the weld 6 in. on each side of joint (Brinell Hardness Number)	• ultrasonic inspection of each welded joints • hardness of the weld (6 in. on each side of the joint)
45. TS-03300 (June 1980) Amendment-3 (February 1984)	Cast-In-Place Concrete
Field Tests of Concrete	NDE Tests
• slump • ball penetration • compressive strength or flexural strength (from job site cylinders) • yield (when challenged by contracting officer) • temperature • aggregate sampling and testing for specified requirements	None specified

Table A. (Continued)

Guide Spec. No. & Date	Guide Spec. Title

46. NFGS-03302
(April 1981)

Cast-In-Place Concrete
(Minor Building Construction)

Amendment-1 (February 1984)

No tests specified

47. NFGS-03361
(April 1985)

Shotcrete

Field Tests

- visual inspection
- make test panel
- compressive and flexural strength (cores and beams)
- durability factor (from core)
- air content

NDE Tests

None specified

48. TS-03410
(December 1978)

Precast Structural Concrete
(Non-Prestressed)

Testing at Casting Site

- slump
- air content
- unit weight for lightweight concrete
- compressive strength (cylinders made at casting site, core testing required if compressive strength fails to meet requirements)

Other Requirements

- tolerances of finished products
- finished appearance

NDE Tests

None specified

49. NFGS-03411
(August 1981)

Precast Concrete Wall Panels

Testing at batch plant

- aggregate tests (mechanical analysis, including specific gravity) from samples
- slump
- compressive strength (cylinders made at plant)

Table A. (Continued)

Guide Spec. No. & Date	Guide Spec. Title
Other Requirements	NDE Tests
• tolerances of finished panels and in installation • finished appearances	None specified
50. TS-03420 (December 1978)	Precast Prestressed Concrete
Testing at Casting site	NDE Tests
• slump • air content • unit weight of lightweight concrete • compressive strength (cylinders made at casting site)	None specified
Other Requirements	
• tolerances of finished products • finished appearances • measurement of cracks in precast-prestressed concrete • camber	
51. TS-03501 (March 1979)	Insulating Concrete Roof Deck System
Field Tests (test specimens taken at job site)	NDE Tests
• compressive strength • oven dry density • coefficient of heat transmission	None specified
52. NFGS-04200 (November 1983)	Unit Masonry

No field tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
53. NFGS-04230 (July 1984)	Reinforcing Masonry
Tests at Job-Site	NDE Tests
• compressive strength of mortar and grout • compressive strength of masonry prims • efflorescence (masonry units and for mortar)	None specified
54. NFGS-04250 (November 1982)	[ceramic Glazed Structural Clay Facing Tile] [AND] [Prefaced Concrete Masonry Units]
No field tests specified	
55. NFGS-05120 (August 1981)	Structural Steel
Tests	NDE Tests
• visual inspection of welds • test for embrittlement of welds	• radiographic • ultrasonic • magnetic particle • dye penetrant
56. NFGS-05210 (December 1983)	Steel Joists
No tests specified	
57. NFGS-05311 (May 1983)	Steel Roof Decking
Field Tests	NDE Tests
• inspect decking top surface for flatness (straight edge)	None specified
58. TS-05321 (September 1979)	Steel Floor Deck
Field Tests	NDE Tests
• visual inspection of welds	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
59. NFGS-05400 (August 1983)	Cold-Formed Metal Framing

No field tests specified

Guide Spec. No & Date	Guide Spec. Title
60. TS-05500 (November 1980)	Metal Fabrications

No field tests specified

Guide Spec. No & Date	Guide Spec. Title
61. NFGS-07110 (April 1983)	Membrane Waterproofing
Field Tests	**NDE Tests**
• sample bulk liquid asphalt (conformance with specification requirements) • watertightness (cover membrane waterpoofing horizontal surfaces with ponded water for 24 hours)	None specified
62. TS-07111 (September 1980)	Elastomeric Waterproofing Sheet Applied
Field Tests	**NDE Tests**
• watertightness of horizontal surfaces of elastomeric waterproofing (cover with ponded water for 24 hours)	None specified

NDE Tests

None specified

Guide Spec. No & Date	Guide Spec. Title
63. TS-07120 (June 1980)	Elastomeric Waterproofing System, Fluid Applied
Field Tests	**NDE Tests**
• prior to application of fluid-applied waterproofing, check moisture content of substrate using a moisture meter • check wet film thickness • watertightness, cover waterproofing with ponded water for 24 hours	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
64. TS-07130 (December 1980)	Bentonite Waterproofing
No field tests specified	
65. NFGS-07140 (February 1983)	Metallic Oxide Waterproofing
No field tests specified	
Guide Spec. No & Date	Guide Spec. Title
66. NFGS-07160 (April 1983)	Bituminous Dampproofing
No field tests specified	
67. NFGS-07211 (July 1981)	Loose Fill (Cellulosic and Mineral Fiber) Insulation
No field tests specified	
68. TS-07220 (March 1980)	Roof Insulation
No field tests specified	
69. NFGS-07221 (November 1982)	Masonry Wall Insulation
No field tests specified	
70. NFGS-07222 (December 1982)	Tapered Roof Insulation
No field tests specified	
71. NFGS-07232 (September 1981)	Ceiling, Wall, and Floor Insulation
No field tests specified	

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
72. NFGS-07250 (February 1984)	Sprayed-on Fireproofing
Field Tests	NDE Tests
• thickness • density	None specified
73. NFGS-07310 (August 1983)	Asphalt Shingles
No field tests specified	
74. NFGS-07410 (May 1983)	Preformed Metal [Roofing] [and] [Siding]
Factory tests to be conducted by manufacturer	
• salt spray • formability • accelerated weathering • chalking resistance • color change	• abrasion resistance for color coating • humidity test • fire hazard • specular gloss
Field Tests	NDE Tests
None specified	None specified
75. NFGS-07511 (June 1981)	Aggregate Surfaced Bituminous Built-Up Roofing
Field Tests	NDE Tests
• fastener resistance to pullout • watertightness of roofing system (24 hour ponded water)	None specified
76. NFGS-07512 (July 1981)	Smooth Surfaced Bituminous Built-Up Roofing
Field Tests	NDE Tests
• fastener resistance to pullout • watertightness of roofing system (24 hour ponded water)	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
77. NFGS-07520 (February 1984)	Prepared Roll Roofing
Field Tests	NDE Tests
• fastener resistance to pullout	None specified
78. NFGS-07540 (August 1979) Amendment-1 (June 1984)	Silicone Rubber Roof Coating
Pages missing [only pages 1, 1.1, 4, and 8 f guide spec. are given)	
79. NFGS-07545 (July 1984)	Sprayed Polyurethane Foam (PUF) for Roofing Systems
Field Tests	NDE Tests
None specified	None specified
80. TS-07600 (September 1978) Amendment-1 (June 1981)	Flashing and Sheet Metal
[only Amendment-1 given]	
81. NFGS-07920 (August 1981)	Sealants and Calkings
No field tests specified	
82. NFFGS-08110 (November 1981)	Hollow Metal Doors and Frames
No field tests specified	
83. NFGS-08120 (February 1984)	Aluminum Doors and Frames
No field tests specified	
84. NFGS-08129 (July 1982)	Aluminum Storm Doors
No field tests specified	

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
85. TS-08210 (February 1980)	Wood Doors

No field tests specified

86. NFGS-08301 (November 1982)	Steel Sliding Hanger Doors
Field Tests	NDE Tests
• complete operating test of doors	None specified
87. NFGS-08310 (March 1983)	Sliding Fire Doors

No field tests specified

88. NFGS-08320 (March 1983)	Metal-Clad (Kalamein) Doors and Frames

No field tests specified

89. NFGS-08331 (March 1983)	Overhead Coiling Doors

No field tests specified

90. NFGS-08360 (July 1982)	Overhead Metal Doors
Field Tests	NDE Tests
• demonstrate proper installation, and proper functioning of operators, safety features, and controls	None specified
91. NFGS-08367 (July 1982)	Vertical Lift Metal Doors

No field tests specified

92. NFGS-08371 (July 1983)	Aluminum Sliding Glass Doors

No field tests specified

Table A. (Continued)

Guide Spec. No & Date		Guide Spec. Title
93. TS-08510 (January 1980)		Steel Windows
Field Tests		NDE Tests
• steel windows to comply with specified feeler gage tests		None specified
94. NFGS-08520 (June 1982)		Aluminum Windows
	No field tests specified	
95. TS-08525 (June 1978)		Storm Windows and Storm Doors
	No field tests specified	
96. NFGS-08529 (July 1982)		Aluminum Storm Windows
	No field tests specified	
97. TS-08610 (April 1980)		Wood Windows
	No field tests specified	
98. NFGS-08710 (March 1985)		Finish Hardware
	No field tests specified	
99. NFGS-08800 (December 1983)		Glazing
	No field tests specified	
100. NFGS-09100 (February 1984)		Metal Support Systems
	No field tests specified	

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
101. NFGS-09110 (August 1982)	Lathing
No field tests specified	
102. NFGS-09150 (April 1981)	Plastering and Stuccoing
No field tests specified	
103. TS-09215 (August 1979)	Veneer Plaster
No field tests specified	
104. NFGS-09250 (March 1985)	Gypsum Board
No field tests specified	
105. NFGS-09310 (March 1984)	Ceramic Tile, Quarry Tile, and Paver Tile
No field tests specified	
106. NFGS-09331 (October 1983)	Chemical-Resistant Quarry Tile Flooring
Field Tests	**NDE Tests**
• chemical resistance of mortar and grout • water absorption of mortar • hardness of mortar • before tile is applied test structural floor for levelness and uniformity of slope	None specified
107. NFGS-09411 (September 1983)	Terrazzo, Bonded to Concrete
No field tests specified	

Table A. (Continued)

Guide Spec. No & Date		Guide Spec. Title
108. NFGS-09561 (March 1984)		Gymnasium-Type Hardwood Strip Flooring Systems
	No field tests specified	
109. NFGS-09563 (July 1982)		Portable (Demountable) Wood Flooring
	No field tests specified	
110. NFGS-09570 (August 1983)		Wood Parquet Flooring
	No field tests specified	
111. NFGS-09595 (July 1983)		Wood Block Industrial Flooring
	No field tests specified	
112. TS-09661 (September 1980)		Vinyl Composition Tile on Concrete
	No field tests specified	
113. NFGS-09666 (February 1982)		Institutional Sheet Vinyl Flooring
Tests		NDE Tests
• stain resistance of flooring material • moisture test for concrete subfloor		None specified
114. TS-09670 (January 1980)		Fluid Applied Resilient (Resinous) Flooring
Field Tests		NDE Tests
• None specified		None specified
115. NFGS-09682 (January 1983)		Carpet
Field Tests		NDE Tests
None specified		None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
116. NFGS-09690 (July 1981)	Carpet Tile
Field Tests	NDE Tests
None specified	None specified
117. NFGS-09785 (April 1984)	Metallic Type Conductive and Spark Resistant Concrete Floor Finish
Field Tests	NDE Tests
• ground resistance of studs, rods, and interconnecting ground wire • conductivity of finished floor surface • spark resistance of finished floor surface	None specified
118. TS-09804 (January 1978)	Linseed Oil Protection of Concrete Surfaces
No field tests specified	
119. TS-09805.1 (September 1979)	Coating Systems (Coal-Tar for Sheet Piling and Other Steel Waterfront Structures
Field Tests	NDE Tests
• thickness of coatings • holidays and pin holes in coatings • visual inspection of coatings	• holidays, pin holes and other defects/electrical flaw detector
120. TS-09805.2 (May 1980)	Coating Systems (Vinyl and Epoxy) for Sheet-Steel Piling and Other Steel Waterfront Structures
Field Tests	NDE Tests
• thickness of coatings • holidays, pin holes, and other defects in coatings • visual inspection of coatings	• holidays, pin holes and other defects/electrical flaw detector

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
121. NFGS-09815 (April 1981)	High-Build Glaze Coatings
Field Tests	NDE Tests
• dry film thickness/Tooke gage	None specified
122. NFGS-09809 (September 1981)	Protection of Buried Steel Piping and Steel Bulkhead Tie Rods
Field Tests	NDE Tests
• test protective system for holes, voids, cracks, and other damage, visually	• test with an electrical flaw detector
123. NFGS-09910 (September 1981)	Painting of Buildings (Field Painting)
Field Tests	NDE Tests
None specified	None specified
124. NFGS-09951 (August 1982)	Vinyl-Coated Wall Covering
Field Tests	NDE Tests
• Test walls for moisture content with an electric moisture meter	None specified
125. TS-10152 (April 1980)	Hospital Cubicle Track
Field Tests	NDE Tests
None specified	None specified
126. NFGS-10162 (November 1982)	Toilet Partitions
Field Tests	NDE Tests
None specified	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
127. NFGS-10201 (January 1983)	Metal [Wall] [And] [Door] Louvers
Field Tests	NDE Tests
None specified	None specified
128. NFGS-10270 (July 1983)	Access Flooring
Field Tests	NDE Tests
• floor system electrical resistance	None specified
129. NFGS-10440 (March 1981)	Signs
Field Tests	NDE Tests
None specified	None specified
130. TS-10623 (September 1979)	Accordion Folding
Field Tests	NDE Tests
• Visual tests for light leakage	None specified
131. NFGS-10800 (October)	Toilet and Bath Accessories
Field Tests	NDE Tests
None specified	None specified
132. TS-11162 (November 1980)	Fixed Type Industrial Dockboard
Field Tests	NDE Tests
• visual inspection of welds • proof-load dockboard • drop tests on dockboard • low temperature environmental test of loading ramp • visual inspection of dockboard • roll over load test of dockboard	• welds dye penetrant examined • welds magnetic particle tested

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
133. TS-11171 (October 1978)	Incinerators, Packaged, Controlled-Air Type
Field Tests	**NDE Tests**
• hydrostatic pressure of oil piping systems (using oil) • pneumatical test of gas piping systems; soap bubbles to verify tightness of system • performance test of incinerator including controls • shell temperature (outer shell) of incinerator	None specified (other than pneumatic test)
134. TS-11301 (April 1980)	Packed, Gravity Oil/Water Separator
Field Tests	**NDE Tests**
• hydrostatic test of piping • performance test of separator • test for contaminants in effluent	None specified
135. NFGS-11334 (August 1982)	Comminutor
Field Tests	**NDE Tests**
• performance test of comminutor	None specified
136. TS-11361.1 (September 1980)	Rectangular Clarifier Equipment
Field Tests	**NDE Tests**
• performance test of rectangular clarifier mechanism	None specified
137. TS-11361.2 (September 1980)	Circular Clarifier Equipment
Field Tests	**NDE Tests**
• performance test of circular clarifier mechanism	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
138. NFGS-11371 (December 1982)	Trickling Filter
Field Tests	NDE Tests
• performance test of distributor mechanism	None specified
139. NFGS-11700 (April 1984)	General Requirements for Medical Equipment
Field Tests	NDE Tests
• performance test of installed equipment	None specified
140. NFGS-11701 (June 1981)	Casework, Metal and Wood Medical and Dental
No field tests specified	
141. TS-11702 (July 1980)	Medical Equipment, Miscellaneous
Field Tests	NDE Tests
• performance test of equipment	None specified
142. NFGS-11704 (April 1985)	[Casework, Movable and Modular for Laboratory and Pharmacies] [And] [Materials Handling Units] for Medical Facilities
No field tests specified	
143. TS-11720 (September 1980)	Stills and Associated Equipment
Field Tests	NDE Tests
• performance test of water distilling apparatus	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
144. TS-11722 (September 1980)	Sterilizers and Associated Equipment
Field Tests	NDE Tests
• performance test of equipment	None specified
145. TS-11730 (September 1980)	Washing Equipment
Field Tests	NDE Tests
• performance test of equipment	None specified
146. TS-11744 (August 1980)	Dental Equipment
Field Tests	NDE Tests
• performance test of equipment	None specified
147. NFGS-11757 (August 1981)	Radiographic Darkroom Equipment
Field Tests	NDE Tests
• performance test of equipment	None specified
148. TS-11770 (August 1980)	Government-Furnished and Contractor - Installed Existing Medical Equipment
Field Tests	NDE Tests
• insure equipment is operational	None specified
149. NFGS-12322 (August 1982)	Wardrobes
Field Tests	NDE Tests
None specified	None specified
150. NFGS-12331 (March 1985)	Prefabricated Vanities

No field tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
151. NFGS-12332 (March 1985)	Wardrobe Storage Cabinets

No field tests specified

152. TS-12391 (January 1981)	Kitchen Cabinets [and Vanity Cabinets]

No field tests specified

153. NFGS-12510 (April 1981)	Blinds, Venetian (and Audio Visual)
Field Tests	NDE Tests
• test for light intensity	None specified
154. NFGS-12540 (July 1984)	Draperies

No field tests specified

155. NFGS-12711 (February 1984)	Theater Seating

No field tests specified

156. TS-13092	X-Ray Sheilding
Field Tests	NDE Tests
• Visual inspection	None specified
157. NFGS-13121 (October 1983)	Pre-engineered Metal Buildings Rigid Frame)
Field Tests	NDE Tests
• sample panels tested for conformance to specified requirements [salt spray, accelerated weathering, flexibility, adhesion (film)]	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
158. NFGS-13411 (June 1981)	Water Storage Tanks

No field tests specified

159. NFGS-13625 (February 1982)	Flow Measuring Equipment (Sewage Treatment Plant)
Field Tests	**NDE Tests**
• test in-place the flow measuring equipment to demonstrate it meets the accuracy requirements	None specified
160. NFGS-13657 (March 1983)	Cleaning Petroleum Storage Tanks
Field Tests	**NDE Tests**
• lead-in-air tests (after cleaning)	None specified
161. NFGS-13661 (August 1981)	Fiberglass Reinforced Plastic Lining System for Bottoms of Steel Tanks (for Petroleum Fuel Storage)
Field Tests	**NDE Tests**
• test panels, steel plate, for sand blast for use as standard of comparison • air inhibition test (for evidence of undercure of lining) • fill test (for leakage of tank)	• holiday detector test of lining
162. TS-13765 (April 1979)	Radio Frequency Shielded Enclosures, Demountable Type
Field Tests	**NDE Tests**
• door sag test • attentuation testing (RF shielded enclosures) • door static load test	• seam leak detector testing (shielding), "sniffer"

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
163. TS-13766 (April 1979)	Radio Frequency Shielded Enclosures, Welded Type

Field Tests

- swinging door static load test
- swinging door sag test
- sliding and swinging door closure test
- attenuation testing
- visual inspection of welds

NDE Tests

- seam leak detector testing of welds, "sniffer"

Guide Spec. No & Date	Guide Spec. Title
164. NFGS-13947 (August 1983)	Energy Monitoring and Control System (EMCS) Large System Configuration

No field tests specified

Guide Spec. No & Date	Guide Spec. Title
165. NFGS-13948 (August 1983)	Energy Monitoring and Control System (EMCS) Medium System Configuration

No field tests specified

Guide Spec. No & Date	Guide Spec. Title
166. NFGS-13950 (August 1983)	Energy Monitoring and Control System (EMCS) Micro System Configuration

No field tests specified

Guide Spec. No & Date	Guide Spec. Title
167. TS-13981.1 (March 1980)	Solar Energy Systems Flat Plate Collectors (Liquid Type)

Field Tests

- hydrostatic testing
- pneumatic testing
- start-up and operational tests

NDE Tests

None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
168. TS-14200 (May 1980)	Electric [Passenger] [Freight] Elevator
Field Tests	NDE Tests
• operational tests • speed load tests • temperature rise tests (motor, etc) • car leveling tests • brake test • insulation (electrical) resistance tests • buffer tests	None specified
169. NFGS-14214 (February 1984)	Hydraulic [Passenger] [Freight] Elevator
Field Tests	NDE Tests
• operational tests • speed load tests • car leveling tests • stop test • pressure test (pump and cylinder head) • insulation (electrical) resistance tests	None specified
170. NFGS-14304 (January 1984)	Portal Crane Track Installation
Field Tests	NDE Tests
• grout compressive strength • visual inspection (fittings, bolted joints, welds) • as-built survey • load test of trackage and curve • throw mechanism operational test	• ultrasonic inspection of welded rail joints

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
171. TS-14305 (February 1980)	Fabricated Portal Crane Track Switches and Frogs
Field Tests	NDE Tests
• operational tests • tolerances (vertical movement) • joint mismatch tolerances (vertical, horizontal) • joint gap tolerance	None specified
172. NFGS-14334 (March 1983)	Monorails with Manual Hoist
Field Tests	NDE Tests
• operational inspection and tests	None specified
173. NFGS-14335 (April 1982)	Monorails with Air Motor Powered Hoist
Field Tests	NDE Tests
• operational inspection and tests	None specified
174. NFGS-14336 (January 1982)	Cranes, Overhead Electric, Overrunning Type
Field Tests	NDE Tests
• operational inspection and tests	None specified
175. NFGS-14637 (July 1984)	Cranes, Overhead Electric, Underrunning (Under 20,000 pounds)
Field Tests	NDE Tests
• operational inspection and tests	None specified
176. NFGS-15011 (February 1981)	Mechanical General Requirements

No field tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
177. NFGS-15116 (July 1982)	Welding Pressure Piping
Field Tests	NDE Tests
• Visual inspection of welds	• NDE personnel shall be certified as qualified • radiographic examination of welds • liquid penetrant examination of welds • magnetic particle examination of welds • ultrasonic examination of welds
178. TS-15200 (September 1979)	Noise, Vibration, and [Seismic] Control
Field Tests	NDE Tests
• check for vibration and noise transmission through connections, piping duct work, foundations, and walls • vibration tests for conformance with criteria • sound level tests for conformance with criteria	None specified
179. NFGS-15251 (January 1984)	Insulation for Exterior Piped Utilities
Field Tests	NDE Tests
None specified	None specified
180. TS-15301 (December 1978)	Exterior Sanitary Sewer and Drainage System Piping
Field Tests	NDE Tests
• leakage tests • alignment of pipeline	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
181. TS-15355 (October 1980)	Fuel Gas Piping
Field Tests	NDE Tests
• metal welding or brazing inspection • PE Fusion welding inspection • pressure test piping system • operational tests for conformance with criteria	None specified
182. NFGS-15361 (January 1984)	Carbon Dioxide Fire Extinguishing Systems (High Pressure)
Field Tests	NDE Tests
• acceptance tests • pneumatic test (leakage)	None specified
183. NFGS-15362 (January 1984)	Carbon Dioxide Fire Extinguishing Systems (Low Pressure)
Field Tests	NDE Tests
• pneumatic test (leakage) • acceptance tests (conformance with specified requirements)	None specified
184. NFGS-15365 (February 1984)	Halon 1301 Fire Extinguishing System
Field Tests	NDE Tests
• pneumatic test (leakage of system) • acceptance and opeational tests of system	None specified
185. TS-15388 (October 1973)	Screening Equipment (Sewage)
No field tests specified	
186. TS-15390 (May 1972)	Aeration Equipment (Sewage)
No field tests specified	

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
187. TS-15395 (October 1973)	Sludge Digestion Equipment

No field tests specified

188. TS-15399 (March 1979)	Package Rotating Biological Contractor Wastewater Treatment Unit
Field Tests	NDE Tests
• cathodic protection inspection • pressure test each pipeline • acceptance and operational tests of system for conformance to specified requirements	None specified
189. NFGS-15400 Amendment-1 (September 1983)	Plumbing

No field tests specified

190. NFGS-15403 (March 1981)	Nonflammable Medical Gas Systems
Field Tests	NDE Tests
• leak tests of systems • equipment pressure tests of joints • vacuum tests	None specified
191. NFGS-15411 (July 1983)	Compressed Air Systems (Non-Breathing Air Type)
Field Tests	NDE Tests
• visual inspection of welds • destructive tests of welds • hydrostatic and leak tightness tests of system • operational tests	• NDE personnel shall be certified • radiographic (for welds) • liquid penetrant (for welds) • magnetic particle (for welds)

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
192. NFGS-15460 (July 1984)	Hospital Plumbing Fixtures
Field Tests	NDE Tests
• operational and acceptance tests	None specified
193. TS-15502 (October 1980)	Fire Extinguishing Sprinkler Systems (Dry Pipe)
Field Tests	NDE Tests
• hydrostatic pressure test of system • acceptance and operational tests	None specified
194. NFGS-15540 (February 1982)	Fire Pumps
Field Tests	NDE Tests
• hydrostatic pressure tests • acceptance and operational tests	None specified
195. TS-15609 (April 1978)	Aviation Fuel Distribution Systems
Field Tests	NDE Tests
• hydrostatic pressure tests of piping systems • acceptance and operational tests	None specified
196. NFGS-15612 (April 1984)	Gas Distribution System
Field Tests	NDE Tests
• visual inspection of welds • piping strength and tightness (pressure test)	• electrical holiday detector for discontinuities in pipe coatings

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title

197. NFGS-15631 (September 1981) — Steam Boilers and Equipment 500,000 - 18,000,000 Btu/h)

Field Tests	NDE Tests
• acceptance and operational tests for compliance with contract requirements • strength and tightness (hydrostatic test) • pneumatic tests (air casing and ducts) • combustion tests • capacity and efficiency tests	None specified

198. NFGS-15632 (September 1981) — Steam Boilers and Equipment 18,000,000 - 60,000,000 Btu/Hr Input)

Field Tests	NDE Tests
• acceptance and operational tests for compliance with contract requirements • strength and tightness (hydrostatic test) • pneumatic tests (air casing and ducts) • combustion tests • capacity and efficiency tests • steam tests	None specified

199. NFGS-15651 (January 1983) — Refrigerant, Chilled Water, Condenser Water, Hot and Cold Water (Dual Service) Piping

Field Tests	NDE Tests
• tightness of system • pressure test (refrigerant system) • operational tests	None specified

200. TS-15652 Amendment-1 (July 1982) — Central Refrigeration System for Air Conditioning

No field tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
201. NFGS-15653 (June 1984)	Unitary Air Conditioning Systems
Field Tests	NDE Tests
• operational tests • sound tests	• leak testing (electronic type detectors)
202. NFGS-15707 (September 1981)	[Factory Insulated] Glass Fiber Reinforced Plastic (FRP) Pipe Coondensate Return System
Field Tests	NDE Tests
• hydrostatic pressure test of system • operational test • moisture-density test of backfill • in-place compaction test	None specified
203. NFGS-15711 (March 1981)	Hot Water Heating System
Field Tests	NDE Tests
• strength and tightness (hydrostatic test) for boiler and piping system • combustion test • operational test • capacity and efficiency test	None specified
204. NFGS-15721 (March 1981)	Steam System and Terminal Units
Field Tests	NDE Tests
• hydrostatic pressure test of piping system • operational test	None specified
205. TS-15802 (November 1972)	Air Supply Systems

Note: The last part of this specification was missing

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
206. TS-15813 (October 1980)	Warm Air Heating Systems
Field Tests	NDE Tests
• operational test • fire test • duct test	None specified
207. TS-15820 (September 1980)	Air Handling and Distribution Equipment
Field Tests	NDE Tests
• operational test	None specified
208. TS-15822 (October 1980)	Evaporative Cooling System
Field Tests	NDE Tests
• operational test	None specified
209. NFGS-15840 (November 1982)	Ductwork and Accessories
Field Tests	NDE Tests
• operational test • pressure tests for air leakage (ducts, plenums, and casings)	None specified
210. TS-15852.2 (May 1980)	Duct Collector, Electrostatic Precipitation Type (Flue Gas Particulates)
Field Tests	NDE Tests
• operational test	None specified
211. NFGS-15852.3 (January 1983)	Duct Collector, Fabric Filter Type (Fly Ash Particles in Flue Gas)
Field Tests	NDE Tests
• operational test	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
212. TS-15901 (August 1980)	Space Temperature Control Systems
Field Tests	NDE Tests
• operational test	None specified
213. TS-16011 (November 1978)	General Requirements, Electrical
No field tests specified	
214. NFGS-16113 (February 1984)	Underfloor Raceway System
Field Tests	NDE Tests
• electrical continuity test	None specified
215. NFGS-16202 (October 1981)	Power Generating Plants, Diesel Electric (Design 1) 500 to 2500 kW Continuous Duty Units
Field Tests	NDE Tests
• hydrostatic test of piping • operational tests and acceptance tests	None specified
216. NFGS-16203 (October 1981)	Power Generating Plants, Diesel Electric (Design 2) 2,501 kW and Larger Continuous Duty Units
Field Tests	NDE Tests
• hydrostatic test of piping • electrical insulation resistance tests • operational and acceptance tests	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
217. NFGS-16204 (November 1981)	Power Generating Plants, Diesel Electric (Design 3) 300 to 1,000 kW Standby Duty Units
Field Tests	NDE Tests
• hydrostatic test of piping • electrical insulation resistance tests • operational and acceptance tests	None specified
218. NFGS-16205 (September 1981)	Power Generating Plants, Diesel Electric (Design 4) 1,001 kW and Larger Standby Duty Units
Field Tests	NDE Tests
• hydrostatic test of piping • electrical insulation resistance tests • operational and acceptance tests	None specified
219. NFGS-16207 (November 1981)	Power Generating Plants, Diesel Electric (Design 6) 1,001 kW and Larger Emergency Duty Units
Field Tests	NDE Tests
• hydrostatic test of piping • electrical insulation resistance tests • operational and acceptance tests	None specified
220. NFGS-16208 (July 1982)	Diesel Engine-Generator Set (25-250 kW
Field Tests	NDE Tests
• operational test	None specified
221. TS-16262 (November 1982)	Automatic Transfer Switches

No field tests specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
222. NFGS-16301 (April 1984)	Underground Electrical Work
Field Tests	NDE Tests
• test 600 volt conductors for short circuits or accidental grounds • test high voltage cables • test ground rods for ground resistance value	None specified
223. NFGS-16302 (February 1984)	Overhead Electrical Work
Field Tests	NDE Tests
• test ground rods for ground resistance value • operational test • test transformer secondary voltages	None specified
224. NFGS-16304 Amendment -1 (July 1982)	Pier, Electrical Distribution for Naval Stations
No field tests specified	
225. NFGS-16335 (September 1981)	Transformers, Substations and Switchgear, Exterior
Field Tests	NDE Tests
• acceptance tests • test transformer secondary voltages • dielectric tests (low voltage switchgear)	None specified
226. NFGS-16402 (February 1983)	Interior Wiring Systems
Field Tests	NDE Tests
• operational and acceptance tests • test 600-volt wiring (no short circuits or accidential grounds) • grounding system test	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
227. TS-16475 (August 1979)	Interior Transformers
Field Tests	NDE Tests
• operational and acceptance tests • ground resistance tests	None specified
228. NFGS-16462 (July 1981)	Pad Mounted Transformers
Field Tests	NDE Tests
• operational and acceptance tests • ground resistance of ground rods	None specified
229. NFGS-16465 (March 1983)	Interior Substations
Field Tests	NDE Tests
• operational and acceptance tests • relay testing • transformer tests • field dielectric tests • ground resistance tests	None specified
230. TS-16475 (August 1979)	Interior Switchgear
Field Tests	NDE Tests
• operational and acceptance tests • ground resistance tests	None specified
231. NFGS-16492 (January 1983)	Motor-Generator Sets, 400 Hertz
Field Tests	NDE Tests
• operational and acceptance tests • voltage and frequency transiet tests • ground resistance tests	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
232. NFGS-16530 (March 1985)	Exterior Lighting
Field Tests	NDE Tests
• operational tests • insulation resistance test • ground resistance tests	None specified
233. NFGS-16560 (June 1982)	Airfield Lighting
Field Tests	NDE Tests
• operational tests • electromagnetic interference • test 600-volt class conductors (no short circuits or accidental grounds) • counterpoise and ground rod tests • progress testing for series airfield lighting circuits • electrical acceptance tests for series and multiple airfield lighting circuits • low voltage continuity, ground, and insulation resistance tests • high voltage insulation resistance test • electric tests	None specified
234. TS-16641 (March 1979)	Cathodic Protection by Galvanic Anodes
Field Tests	NDE Test
• static pull test of anode with lead wires • operational test	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
235. TS-16642 (March 1979)	Cathodic Protection by Impressed Current
Field Tests	NDE Tests
• static pull test of anode with lead wires • wire for power service (free from short circuits and grounds) • operational test	None specified
236. NFGS-16650 (June 1983)	Radio Frequency Interference Power Line Filters
Field Tests	NDE Tests
• operational and acceptance tests	None specified
237. NFGS-16721 (December 1972)	Exterior Fire Alarm System
Field Tests	NDE Tests
• ground resistance • dielectric strength and insulation resistance • operational tests (power supply, alarm, box and transmitter, signal transmission and recording, trouble line operation, manual-set transmitter test)	None specified
238. TS-16722 (October 1978)	Fire Alarm and Fire Detecting System (Local)
Field Tests	NDE Tests
• operational and functional tests • ground resistance • dielectric strength and insulation resistance	None specified

Table A. (Continued)

Guide Spec. No & Date	Guide Spec. Title
239. NFGS-16723 (October 1981)	Fire Alarm System Radio Type
Field Tests	NDE Tests
• acceptance test • ground resistance	None specified

APPENDIX B. REVIEWED NAVY GUIDE SPECIFICATIONS HAVING NDE TESTS

The Navy Guide Specifications that contain required NDE tests are listed in Table B along with the corresponding NDE tests. Of the 239 Guide Specifications reviewed (see Appendix A), 29 contained required NDE tests. Some of the tests included under NDE tests in Table B were listed as field tests in the specifications. Those tests listed as field tests in the specifications are denoted with a footnote.

Table B. Reviewed Navy Guide Specifications that Contain Required NDE Tests

Guide Spec. No & Date	Guide Spec. Title	NDE Tests
NFGS-02452 (September 1984)	Railroad Trackwork	• Ultrasonic inspection of welded rail joints
NFGS-02854 (March 1983)	Railroad Track Work	• Ultrasonic inspection rail joints (MIL-STD-1699)
NFGS-02910 (November 1982)	Welding Crane and Railroad Rail - Thermite Method	• Ultrasonic inspection of each welded joint
		• Hardness of the weld (6 in. on each side of the joint)
NFGS-05120 (August 1981)	Structural Steel (some papers were missing from this spec.)	• Nondestructive evaluation of welds
NFGS-07110 (April 1983)	Membrane Waterproofing	*• Watertightness (ponded water for 24 hours)
TS-0711 (September 1980)	Elastomeric Waterproofing Sheet Applied	*• Watertightness (ponded water for 24 hours)
TS-07120 (June 1980)	Elastomeric Waterproofing System, Fluid Applied	*• Prior to waterproofing application, check moisture content of substrate using a moisture meter
		*• Watertightness (ponded water for 24 hours)
NFGS-07511 (June 1981)	Aggregate Surfaced Bituminous Built-Up Roofing	*• Watertightness (ponded water for 24 hours)
NFGS-07512 (July 1981)	Smooth Surfaced Bituminous Built-Up Roofing	*• Watertightness (ponded water for 24 hours)
NFGS-09666 (February 1982)	Institutional Sheet Vinyl Flooring	*• Moisture test for concrete subfloor

* Listed as field tests in specifications.

Table B. (Continued)

Guide Spec. No & Date	Guide Spec. Title	NDE Tests
NFGS-09785 (April 1984)	Metallic Type Conductive and Spark Resistant Concrete Floor Finish	*• Ground resistance of studs, rods, and interconnecting ground wire *• Conductivity of finished floor surface *• Spark resistance of finished floor surface
TS-09805.1 (September 1979)	Coating Systems (Coal-Tar) for Sheet Piling and Other Steel Waterfront Structures	*• Thickness of coatings • Holidays, pin holes and other defects/ electrical flaw detector
TS-09805.2 (May 1980)	Coating Systems (Vinyl and Epoxy) for Sheet-Steel Piling and Other Steel Waterfront Structures	*• Thickness of coating • Holidays, pin holes and other defects/ electrical flaw detector
NFGS-09815 (April 1981)	High-Build Glaze Coatings	*• Dry film thickness/ Tooke Gage
NFGS-09809 (September 1981)	Protection of Buried Steel Piping and Steel Bulkhead Tie Rods	*• Visual inspection of protective systems for holes, voids, cracks, and damage • Test with an electrical flaw detector
NFGS-09951 (August 1982)	Vinyl-Coated Wall Covering	*• Test walls for moisture content/eletric moisture meter
NFGS-10270 (July 1983)	Access Flooring	*• Floor system electrical resistance

* Listed as field tests in specification.

Table B. (Continued)

Guide Spec. No & Date	Guide Spec. Title	NDE Tests
TS-11162 (November 1980)	Fixed Type Industrial Dockboard	*• Visual inspection of dockboard and welds *• Proof-load dockboard • Welds, dye penetrant examined • Welds, magnetic patricle tested
TS-11171 (October 1978)	Incinerators, Packaged, Controlled-Air Type	• Pneumatical test of gas piping systems; soap bubbles to verify tightness of system *• Hydrostatic pressure of oil piping systems (using oil)
TS-11301 (April 1980)	Packaged, Gravity Oil/ Water Separator	• Hydrostatic test of piping
NFGS-13661 (August 1981)	Fiberglass Reinforced Plastic Lining System for Bottoms of Steel Tanks (for Petroleum Fuel Storage)	• Holiday detector test of lining
TS-13765 (April 1979)	Radio Frequency Shielded Enclosures, Demountable Type	• Seam leak detector testing (shielding), "sniffer"
TS-13766 (April 1979)	Radio Frequency Shielded Enclosures, Welded Type	• Seam leak detector testing of welds, "sniffer"
NFGS-14304 (January 1984)	Portal Crane Track Installation	• Ultrasonic inspection of welded rail joints

* Listed as field test in specification.

Table B. (Continued)

Guide Spec. No & Date	Guide Spec. Title	NDE Tests
NFGS-15116 (July 1982)	Welding Pressure Piping	*• Visual inspection of welds • NDE personnel shall be certified as qualified-radiographic, liquid penetrant, magnetic particle, ultrasonic-examination of welds conform to "ASME Boiler and Pressure Vessel Code, Section V."
NFGS-15403 (March 1981)	Nonflammable Medical Gas Systems	*• Leak tests of systems
NFGS-15411 (July 1983)	Compressed Air Systems (Non-Breathing Air Type)	*• Visual inspection of welds • NDE personnel shall be certified-radiographic, liquid penetrant, magnetic particle-for welds
NFGS-15612 (April 1984)	Gas Distribution System	*• Visual inspection of welds • Electrical holiday detector for discontinuities in pipe coatings
NFGS-15653 (June 1984)	Unitary Air Conditioning Systems	• Leak testing (electronic type leak detector)

* Listed as field test in specification

APPENDIX C. LISTS OF REVIEWED NCEL TECHDATA SHEETS AND NCEL TECHNICAL AND RESEARCH REPORTS THAT CONTAIN NDE METHODS

The Navy publications provided by NCEL and NAVFAC which were reviewed are listed in this appendix. Section 2.4 provides information about these types of reports. Table C1 contains a list of reviewed NCEL Techdata Sheets and Table C2 contains a list of reviewed NCEL technical and research reports.

Table Cl. List of Reviewed NCEL Techdata Sheets that Contain NDE Methods

NCEL Techdata Sheet 79-09, "Inspection of Painting," Port Hueneme, CA, September 1979.

NCEL Techdata 75-31, "Measuring Water Permeability of Masonry Walls," Port Hueneme, CA, December 1985.

NCEL Techdata Sheet 82-13, "Leak Detection in Pipelines," Port Hueneme, CA, September 1982.

NCEL Techdata Sheet 84-05, "Infrared Thermometers for Roofing Inspectors," Port Hueneme, Ca, March 1984.

NCEL Techdata Sheet 77-20, "Use of Windsor Probe Test System for Strength Evaluation of Concrete in Naval Construction," Port Hueneme, CA, December 1977.

NCEL Techdata Sheet 80-12, "Problems with Underwater Ultrasonic Inspection," Port Hueneme, CA, October 1980.

NCEl Techdata Sheet 76-13, Inspection Methods for Wood Fender and Bearing Piles," Port Hueneme, CA, September 1976.

NCEL Techdata Sheet 82-14, "Locating and Tracing Buried Metallic Pipelines," Port Hueneme, CA, September 1982.

Table C2. List of Reviewed NCEL Technical and Research Reports that Contain NDE Methods

NCEL Technical Memorandum M-43-81-07, "An Evaluation of Pulse Echo Ultrasonic Techniques for Underwater Inspection of Steel Waterfront Structures," R. L. Brackett and L. W. Tucker, Port Hueneme, CA, May 1981.

NCEL Technical Memorandum M-43-81-08, "Ultrasonic Inspection of Wooden Waterfront Structures," C. A. Keeney, Port Hueneme, CA, May 1981.

NCEL Technical Memorandum M-51-81-11, "Concepts for Detecting Weak Spots in Pavement-Encased Trackage on Waterfront Facilities," G. E. Warren, Port Hueneme, CA, August 1981.

NCEL Technical Note N-1594, "Nondestructive Test Equipment for Wire Rope," H. H. Haynes and L. D. Underbakke, Port Hueneme, CA, October 1980.

NCEL Technical Memorandum M-52-80-10, "Specialized Roof Moisture Inspection," Robert L. Alumbaugh and John R. Keeton, Port Hueneme, CA, September 1980.

NCEL Technical Memorandum M-52-81-06, "Inspection of POL Supply Facilities," Thorndyke Roe, Jr., Port Hueneme, CA, September 1981.

NCEL Technical Memorandum M-55-81-04, "Inspection of Underground Utility Lines-Milestone Zero Report," S. S. Wang, Port Hueneme, CA, July 1981.

NCEL Technical Memorandum M-55-81-06, "Inspection of Underground Utility Lines," S. S. Wang and S. J. Oppedisano, Port Hueneme, CA, November 1981.

NCEL Technical Memorandum M-43-78-09, "Underwater Inspection and Nondestructive Testing of Waterfront Structures: A State of the Art Assessment," R. L. Brackett, Port Hueneme, CA, June 1978.

NCEL Technical Memorandum M-51-80-27, "Noncontact Displacement Measurement as an Inspection Tool for Naval Shipyard Trackage," G. E. Warren, Port Hueneme, CA, December 1980.

NCEL Technical Memorandum M-52-77-3, "Roofing Survey of Naval Shore Bases," J. R. Keeton and R. L. Alumbaugh, Port Hueneme, CA, March 1977.

NCEL Technical Note N-1624, "Underwater Inspection of Waterfront Facilities: Inspection Requirements Analysis and Nondestructive Testing Technique Assessment," R. L. Brackett, W. J. Nordell, and R. D. Rail, Port Hueneme, CA, March 1982.

NCEL Technical Note N-1632, "Evaluation of NDT Equipment for Specialized Inspection," G. Warren, Port Hueneme, CA, June 1982.

NCEL Technical Report R-903, "Pulse Echo Ultrasonic Techniques for Underwater Inspection of Steel Waterfront Structure," R. L. Brackett, L. W. Tucker, and R. Erich, Port Hueneme, CA, June 1983.

Table C2. (Continued)

NCEL Technical Note N-1233, "Calibration of Windsor Probe Test System for Evaluation of Concrete in Naval Structures," J. R. Keeton and V. Hernandez, Port Hueneme, CA, June 1972.

NCEL Technical Note N-1703, "Evaluation of Nondestructive Underwater Timber Inspection Techniques," C. A. Keeney and S. E. Pollio, Port Hueneme, CA, August 1984.

NCEL Technical Memorandum M-43-84-01, "Evaluation and Comparison of Commerical Ultransonic and Visual Inspections of Timber Piles," A. P. Smith, Port Hueneme, CA, December 1983.

Technical Memorandum M-53-85-03, "Detection of Underground Utilities and Obstacles with Ground Penetration Radars - An Initiation Decision Report," M. C. Hironaka and G. D. Cline, Port Hueneme, CA, January 1985.

Technical Memorandum M-53-82-02, "Dectection of Underground Utilities and Obstacles - An Initiation Decision Report," M. C. Hironaka, Port Hueneme, CA, September 1982 .

Technical Memorandum M-53-84-5, "Ground Probing Radars and Hand-Held Detectors for Locating Underground Utility Lines and Other Objects," M. C. Hironaka and G. D. Cline, Port Hueneme, Ca, August 1984.

NCEL Technical Memorandum M-43-81-07, "An Evaluation of Pulse Echo Ultrasonic Techniques for Underwater Inspection of Steel Waterfront Structures," R. L. Brackett and L. W. Tucker, Port Hueneme, CA, May 1981.

NCEL Technical Memorandum M-43-78-09, "Underwater Inspection and Nondestructive Testing of Waterfront Structures: A State-of-the-Art Assessment Report," R. L. Brackett, Port Hueneme, CA, February 1984.

NCEL Technical Memorandum tm no: 52-84-04, "Design and Development of a Portable Infrared Spectrophotometer for NDT Analysis of Coatings," T. Novinson, Port Hueneme, CA, November 1983.

NCEL Technical Memorandum tm no: 52-83-03, "Laboratory Prototype of a Portable Infrared Spectrophotometer for NDT Field Analysis of Coatings and Other Organic Materials," T. Novinson and D. S. Kyser, Port Hueneme, CA, November 1982.

NCEL Technical Note N-1179, "Measuring Water Permeability of Masonry Walls," H. Hochmam, Port Hueneme, CA, August 1971.

NCEL Technical Memorandum M-55-82-01, "Leak Detection in Underground Utility Lines-Status Report," S. S. Wang and S. J. Oppendisano, Port Hueneme, CA, May 1982.

APPENDIX D. ASTM STANDARDS FOR NDE METHODS FOR CONSTRUCTION MATERIALS AND BUILDING COMPONENTS

ASTM has recognized the need for standards covering nondestructive evaluation methods for a variety of materials and applications. Consequently, a number of ASTM standards for NDE procedures have been issued. ASTM standards for NDE methods for concrete are listed in Table D1. Some ASTM standards for other common NDE methods are listed in Table D2. As new ASTM standards for NDE appear, they can be located by reviewing the index to ASTM standards which is published annually.

Table D1. ASTM Standards for NDE Methods for Concrete

NDE Method	ASTM Standard and Designation
Rebound Hammer	Test for rebound number of hardened concrete: C 805
Penetration Probe	Test for penetration resistance of hardened concrete: C 803
Ultrasonic Pulse Velocity	Test for pulse velocity through concrete: C 597
Nuclear Moisture Meter	Test for moisture content of soil and soil-aggregate in place by nuclear methods (shallow depth): D 3017
Cast-in-place Pullout	Test for pullout strength of hardened concrete: C 900
Visual	Practice for examination of hardened concrete in constructions: C 823
Corrosion of Rebars	Test for half cell potentials of reinforcing steel in concrete: C 876
Mechanical Properties	Test for fundamental transverse, longitudinal, and torsional frequencies of concrete specimens: C 215 (laboratory method)

Table D2. ASTM Standards for NDE Methods for Construction Materials and Building Components

NDE Method	ASTM Standard and Designation
Acoustic Emission	Practice for acoustic emission monitoring during continuous welding: E 749
	Practice for acoustic emission monitoring of structures during controlled stimulation: E 569
	Practice for acoustic emission examination of reinforced thermosetting resin pipe: E 1118
Air Leakage	Method for Determining Air Leakage Rate by Tracer Dilution: E 741
	Method for Determining Air Leakage Rate by Fan Pressurization: E 779
Coating Thickness Testing	Practice for measuring coating thickness by magnetic-field or eddy-current (electromagnetic) test methods: E 376
	Measurement of thickness of anodic coatings on aluminum and of other nonconductive coatings on non-magnetic basis metals with eddy-current instruments: B 244
	Measurement of dry film thickness of nonmagnetic coatings applied to a ferrous base: D 1186
	Measurement of dry film thickness of nonconductive coatings applied to a nonferrous metal base: D 1400
	Measurement of film thickness of pipeline coatings on steel: G 12
	Measurement of dry film thickness of protective coating systems by destructive means: D 4138 (Tooke gage)
	Practice for measurement of wet film thickness by notch gages: D 4414
	Measurement of wet film thickness of organic coatings: D 1212

Table D2 (Continued)

NDE Method	ASTM Standard and Description
Eddy Current Method	Test for electrical conductivity by use of eddy current: B 342
	Practice for in situ electromagnetic (eddy-current) examination of nonmagnetic heat exchanger tubes: E 690
	Practice for electromagnetic (eddy-current) testing of seamless copper and copper alloy tubes: E 243
Hardness Testing	Hardness conversion tables for metals (relationship between Brinell hardness, Vickers hardness, Rockwell hardness, Rockwell superficial hardness, and Knoop hardness): E 140
	Test for Brinell hardness of metallic materials: E 10
	Test for Vickers hardness of metallic materials: E 92
	Test for indentation hardness of metallic materials by portable hardness testers: E 110
	Rapid indentation hardness testing of metallic materials: E 103
	Test for Rockwell hardness and Rockwell superficial hardness of metallic materials: E 18
	Test for film hardness by pencil test: D 3363
Magnetic Particle	Practice for magnetic particle examination: E 709
	Specification for magnetic particle inspection of large crankshaft forgings: A 456

Table D2 (Continued)

NDE Method	ASTM Standard and Description
Magnetic Particle (Continued)	Reference photographs for magnetic particle indications on castings: E 125
	Method for magnetic particle examination of steel forgings: A 275
	Terminology of symbols and definitions relating to magnetic testing: A 340
Penetrant Testing	Practice for liquid penetrant inspection method: E 165
	Reference photographs for liquid penetrant inspection: 433
Radiographic Testing	Reference radiographs for steel coatings up to 2 in. (51 mm) in thickness: E 446
	Reference radiographs for heavy-walled (2 to 4-1/2 inch) steel castings: E 186
	Reference radiographs for steel fusion welds: E 390
	Method for controlling quality of radiographic testing: E 142
	Practice for radiographic testing: E 94
Soils Inspection	Method for density of soil in place by the sand-cone method: D 1556
	Methods for density of soil and soil-aggregate in place by nuclear methods (shallow depth): D 2922
	Methods for moisture-density relations of soils and soil-aggregate mixtures, using 5.5-lb (2.49 kg) rammer and 12-in. (305 mm) drop: D 698
	Method for penetration test and split-barrel sampling of soils: D 1586

Table D2 (Continued)

NDE Method	ASTM Standard and Description
Soil Inspection (Continued)	Classification of soils for engineering purposes: D 2487 Method for deep, quasi-static cone and friction-cone penetration tests of soil: D 3441
Ultrasonic Testing	Practice for measuring thickness by manual ultrasonic pulse-echo contact method: E 797 Practice for ultrasonic pulse-echo straight-beam testing by the contact method: E 114 Practice for ultrasonic contact examination of weldments: E 164 Practice for ultrasonic examination of heavy steel forgings: A 388 Straight-beam ultrasonic examination of steel plates: A 435 Practice for ultrasonic inspection of metal pipe and tubing: E 213 Practice for measuring ultrasonic velocity in materials: E 494 Testing for leaks using ultrasonics: E 1002 Practice for ultrasonic examination of longitudinal welded pipe and tubing: E 273
Uplift Testing	Field testing uplift resistance of roofing systems employing steel deck rigid insulation and bituminous built-up roofing: E 907
Window Testing	Method for strucutural performance of glass in windows, curtain walls, and doors under the influence of uniform static loads by nondestructive method: E 998

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Robert G. Mathey and James R. Clifton

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Nondestructive evaluation (NDE) methods for evaluating in situ construction materials and for condition assessment of building components and systems were identified and are described. This report is intended to help inspectors and those involved in condition assessment choose appropriate NDE methods for specific building materials, components, and systems. Important properties of building materials along with important performance requirements for building components are listed, and appropriate NDE methods for determining these properties are recommended. In many cases the advantages and limitations of the NDE methods are presented. Potential NDE methods which may or may not require further research and development before they are ready for routine use were also identified and are briefly described. In addition, ASTM standards for NDE methods for concrete and other building materials and components were identified.

In a related aspect of the study, current Navy practices relative to the use of NDE methods in the construction and service cycle of buildings and other structures were reviewed. This review was based on Navy reports and documents provided by NCEL and NAVFAC, and on discussions with NAVFAC personnel involved with buildings and structures problems where NDE methods are used for diagnostic purposes. Navy Guide Specifications were examined for required tests, both NDE and destructive, of in situ building materials and components.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

building components; building diagnostics; building materials; condition assessment; construction materials; in situ evaluation; nondestructive evaluation

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