Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions

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Current methods available for evaluating physical properties of concrete in existing structures to determine its capability of performing satisfactorily under service conditions are identified and discussed. Although general knowledge of the structural design criteria used for the principal structures of a project is essential to determine satisfactory procedures and locations for evaluation of the concrete physical properties, analysis for the purpose of determining structural capability is not within the scope of this report. The report recommends project design, operation, and maintenance records and in-service inspection data to be reviewed. Existing methods of making condition surveys and nondestructive tests are reviewed; destructive phenomena are identified; methods for evaluation of tests and survey data are presented; and finally, preparation of the final report is discussed.

Keywords: alkali-aggregate reaction; alkali-carbonate reaction; cavitation; cements; chemical analysis; concrete cores; concrete dams; concrete durability; cracking (fracturing); elastic properties; erosion; evaluation; extensometers; impact tests; inspection; laboratories; maintenance; mass concrete; nondestructive tests; nuclear power plants; post-tensioning; pozzolans; resurfacing; sampling; seepage; serviceability; spalling; static tests; stresses; surveys; x-ray diffraction.

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ACI 207.3R-94 supersedes ACI 207.3R-79 (Revised 1985) and became effective July 1, 1994.

CHAPTER 1—INTRODUCTION

Deteriorating infrastructure continues to be a growing concern. Accurate information on the condition of concrete in a massive structure is critical to evaluating its safety and serviceability. This information is required by decision makers to determine if repair or replacement is necessary and to select optimum repair techniques where conditions require.

The guidelines for evaluating the serviceability of concrete described herein apply to massive concrete structures such as dams or other hydraulic structures, bridge foundations and piers, building and reactor foundations, and other applications that qualify to be considered mass concrete. Mass concrete is defined in ACI 116R as "any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change to minimize cracking." The practices described pertain to concrete placed either by conventional means or by roller compaction.

In addition to this report, other documents such as ACI 201.1R, ACI 201.2R, ACI 224.1R, ACI 228.1R, ACI 437R, and ASTM C 823 provide good tools for those evaluating concrete in existing massive structures.

1.1—Scope

This report focuses on practices used to evaluate concrete in existing massive structures. Design considerations, evaluation of existing operating records and past inspection reports, condition surveys, maintenance reports, determination of in-situ conditions, instrumentation, identification of damage, and final evaluation of concrete are principal subjects that are covered.

1.2—Objective

The objective of this report is twofold: (a) to present current methods available for evaluating the capability of mass concrete to meet design criteria under service conditions; and (b) to present procedures to detect the change in physical properties of concrete that could affect the capability of the concrete to meet performance requirements in the future.

1.3—Report

The prepared report should identify and evaluate properties of the concrete as they relate to the design criteria of the project structures, but should not preempt the structural engineer's responsibility for determining if the structures of the project are meeting design requirements. Photographic and graphic presentation of investigation data should be used to a maximum practical extent. The report is an essential tool for those charged with the final responsibility of determining the structural adequacy and safety of the project.

CHAPTER 2—PRE-INSPECTION AND IN-SERVICE INSPECTION

Arrangements prior to an inspection should be made to obtain or have access to all available records and data pertaining to the structure. Pertinent engineering data to be reviewed include design criteria and memoranda, construction progress reports, instrumentation records, operation and maintenance records, and to the extent available, preconstruction data. Information on adjacent projects, additions, or modifications that may affect a change in the original design conditions should also be reviewed.

2.1—Preconstruction evaluation

Engineering data relating to design criteria, design site conditions, purpose of project, and construction planning and procedure should be collected and arranged for ease of information retrieval. Documents that are readily available can be assembled first. Data that are missing but deemed necessary for evaluation should be identified. A suggested list of data to be reviewed is as follows:

2.1.1 *Project description documents*

2.1.1.1 For a hydroelectric plant, the Federal Energy Regulatory Commission (FERC) licensed application

2.1.1.2 For a nuclear plant: the Preliminary Safety Analysis Report (PSAR)

2.1.1.3 All formal and final completion reports

2.1.2 *Contract documents*

2.1.2.1 Contract documents: technical specifications and drawings including modifications or addendums

2.1.2.2 As-built drawings

2.1.2.3 Original issue drawings

2.1.3 *Regional data*

2.1.3.1 Land use map showing location of structure and its relationship to surrounding localities

2.1.3.2 Topographic map of site and drainage area

2.1.3.3 Geologic plans and sections

2.1.3.4 Seismic data

2.1.3.5 Reservoir volume versus elevation curve

2.1.4 *Site subsurface data*

2.1.4.1 Logs of borings

2.1.4.2 Geological maps, profiles, and cross sections

2.1.4.3 Soils investigation, availability of test results

2.1.4.4 Foundation treatment reports

2.1.4.5 Water table elevation

2.1.4.6 Geohydrologic data

2.1.5 *Site surface data*

2.1.5.1 Control elevations

2.1.5.1.a For buildings: finished grade, basement, floors, roof, etc.

2.1.5.1.b For dams and spillways: Crest, maximum and minimum reservoir surface, outlet works, maximum and minimum tailwater, etc.

2.1.6 *Drainage*

2.1.6.1 Detail of drains in structure and foundation

2.1.7 *Environmental*

2.1.7.1 Temperatures: Maximum, minimum, and mean daily

2.1.7.2 Precipitation, maximum, and mean annual

2.1.7.3 Average humidity and range

2.1.7.4 Number of sunny days

2.1.7.5 Exposure: To sulfates; to organic acids; to deleterious atmospheric gases

2.2—Design criteria

2.2.1 *Design memorandum or report*

2.2.2 *Values of static and intermittent loadings, wind, temperature, impact, loads*

2.2.3 *For hydraulic structures: hydrostatic and hydrodynamic loads*

2.2.4 *Type of analysis: static, dynamic*

2.3—Concrete laboratory records

2.3.1 *Materials used*

2.3.1.1 Cement

2.3.1.1.a Certified mill test records including fineness moduli

2.3.1.1.b Additional physical and chemical properties tests

2.3.1.2 Pozzolan

2.3.1.2.a Certified test records

2.3.1.2.b Physical and chemical properties

2.3.1.3 Aggregates

2.3.1.3.a Type and source(s)

2.3.1.3.b Gradation

2.3.1.3.c Summary of physical and chemical properties as specified in ASTM C 33

2.3.1.3.d Results of tests for potential reactivity

2.3.1.3.e Report of petrographic examination

2.3.1.4 Mixing water quality tests

2.3.2 *Concrete records*

2.3.2.1 Mix proportions

2.3.2.2 Water-cement ratio

2.3.2.3 Slump or, for roller-compacted concrete, Vebe time

2.3.2.4 Unit weight or, for roller-compacted concrete, compacted density measurements

2.3.2.5 Temperature records including complete thermal history, if available

2.3.2.6 Records of strength tests

2.3.2.7 Admixtures including air-entraining agents used, percent air entrained.

2.4—Batch plant and field inspection records

2.4.1 *Storage and processing of aggregates*

2.4.1.1 Stockpiles

2.4.1.2 Rinsing and finish screens for coarse aggregate

2.4.1.3 Bins or silos

2.4.2 *Cement, pozzolan, and admixture storage and handling*

2.4.3 *Forms*

2.4.3.1 Type and bracing, tightness of joints

2.4.3.2 Time interval for stripping

2.4.3.3 Method of finish or cleanup of unformed surfaces

2.4.4 *Preparation and condition of construction joints*

2.4.5 *Mixing operation*

2.4.5.1 Type of batch plant

2.4.5.2 Type of mixing equipment and mixing time

2.4.5.3 Condition of equipment

2.4.5.4 Monitoring and control practices

2.4.5.5 Any unscheduled interruptions due to plant breakdown or weather

2.4.5.6 Any scheduled seasonal interruption

2.4.6 *Method of transporting concrete: Pumps, chutes, conveyor belts, trucks, buckets, etc.*

2.4.7 *Method of placing concrete*

2.4.7.1 Where vibrated: lift heights, vibrator types and number

2.4.7.2 Where roller-compacted: layer thickness, roller type

2.4.8 *Concrete protection*

2.4.8.1 Curing methods: Water ponding or spray; curing compounds; shading; starting time and duration

2.4.8.2 Hot weather protection

2.4.8.3 Cold weather protection

2.5—Operation and maintenance records

2.5.1 *Operation records*

2.5.1.1 Instrumentation data

2.5.1.2 Seepage: amount with time, type and location of measuring device

2.5.1.3 Unusual loading conditions

2.5.1.3.a Earthquake

2.5.1.3.b Floods

2.5.1.3.c Extreme temperatures (temporary and prolonged)

2.5.1.3.d Operational failure

2.5.1.4 Change in operating procedures

2.5.1.5 Shutdown of all or parts of the system

2.5.1.6 Increased loads or loadings

2.5.2 *Maintenance records*

2.5.2.1 Location and extent

2.5.2.2 Type of maintenance

2.5.2.3 Dates of repair

2.5.2.4 Repair materials

2.5.2.5 Performance of repaired work

2.6—In-service inspections

2.6.1 *General*—Most organizations monitor the performance of completed structures to ensure that they function safely and in accordance with the design. The monitoring may be part of the owner's operation and maintenance program or may be required by law.[1,2] Service records are generally more complete for recently constructed structures than for older structures as the concern for public safety has increased in recent years. The scope of surveillance can vary widely between organizations and may depend to an even greater extent on the size and nature of the project or structure and potential hazards it may present.

To properly compare and evaluate the existing condition of concrete in massive structures, it is essential to review these in-service records, which may also include routine and periodic inspections.

2.6.2 *Routine inspections*—Routine inspection by various organizations are generally made at a frequency of 6 months to 2 years. They commonly consist of a visual examination of the condition of the exposed and accessible concrete in various components of a structure or project. Submerged structures or portions thereof may be visually examined by a diver or by a remotely-operated vehicle (ROV) with an on-board video camera. In some cases, visual examination may be supplemented by nondestructive tests as described in Chapter 3 to indicate certain properties and conditions of the in-situ concrete at that particular time, such as compressive strength, modulus of elasticity, and presence of voids and cracking. Data from instrumentation embedded in the concrete may also be available. A comparison of the concrete properties, conditions, and instrumentation at each inspection interval are useful analysis tools and may reveal abnormal changes.

Immediately after placing the structure in service, frequent inspections are made so that performance can be assessed and, if necessary, modifications made to the design and operating practices. Inspections made thereafter are directed at identifying any changes in condition of the concrete or concrete properties that may affect the integrity of the structure and its future serviceability. Inspections may be performed by trained technicians or qualified engineers, depending on the program established. A report describing the findings of each routine inspection generally notes any changed conditions, contains photographs of the conditions and recommends corrective action. Further in-depth investigations may be initiated if for any reason problems are suspected. Documentation of the inspection and any action taken are generally filed with the owner.

2.6.3 *Periodic inspections*—Periodic inspections are generally conducted at a frequency of 2 to 10 years and are the same in nature or objective as routine inspections. However, periodic inspections entail a more detailed study. Periodic inspections are generally associated with higher-risk structures or projects and supplement the routine inspections. However, it should be emphasized that, unless changes in the appearance or performance of the concrete or concrete structures are noted, extensive periodic inspections may not be necessary.

Periodic inspections may include considerable preparation such as dewatering or arranging means for inspecting submerged portions of a structure, or excavating inspection trenches. Also, a comprehensive review of instrumentation data, and design and operating criteria, may be required for a complete evaluation. In addition the periodic inspection may include sampling of seepage and reservoir waters, nondestructive testing, and determination of stress conditions. The amount of investigative work necessary usually depends on the condition of the concrete. It should yield sufficient detailed information to provide practical guidance for the selection of the best method of repair or maintenance work. In some cases, the actual maintenance work may be accomplished at the same time as the periodic inspection. The scope of the inspection should also include identification of causes of deterioration. Methods and techniques for performing investigative work in connection with periodic inspections are discussed in detail in Chapters 2 and 3.

2.6.4 *Inspection reports and records*—The in-service inspection reports and records previously descried are in essence a history of the project or structure from which future performance can be predicted. In addition to a qualitative description, the information presented may supply actual values that can be used in structural analysis and comparison with the original design.

Documentation of the inspections should be on file with the owner or responsible authority.

CHAPTER 3—IN-SITU CONDITION SURVEYS AND TESTING

A condition survey includes a visual examination of exposed concrete to identify and define areas of distress and examination of interior concrete. Conditions are described in common terminology for further investigation. The appendix to ACI 201.1R presents terms associated with the durability of concrete and a series of photographs typical of these conditions. ACI 201.1R should be reviewed before making a condition survey. ASTM C 823 contains additional information useful in conducting a condition survey. The inspection should include a checklist of items of concern identified in previous inspections and additional items based on the inspector(s)' experience and state-of-the-art advancements on evaluation techniques.

Testing is conducted to determine conditions of stress and strain; concrete properties, homogeneity, and integrity; loads on the structure; and structural movement.

The investigator should also consider a review of design computations to identify areas that may be more highly stressed and susceptible to cracking. It is considered good practice to sample concrete in such areas. The adequacy of the foundation, capacity of hydraulic structures, and such factors as uplift, horizontal and vertical movement, and seepage and erosion are considered only as they affect the durability, cracking, and strength of concrete.

Although the objective of this report is to evaluate the material properties, and not the structural adequacy of the concrete, it is important to review design requirements and criteria used for the structures of the project prior to undertaking materials investigations. This review permits realistic planning of investigations. For example, strength, elastic properties, and the condition of the boundary concrete, particularly at the abutments, are important in arch dams. However, in gravity dams, strength may not be as important, but cracking, leakage, and foundation uplift pressures will be of prime importance. Durability of the concrete is important in both types of structures.

Careful review of any instrumentation data and a visual inspection of the concrete in all accessible parts of the structures by experienced engineers are important parts of the evaluation of the concrete. Past photographs, which could reveal changes in the condition of the concrete, should be reviewed when available. As many operating features should be used as feasible during the inspection so that the concrete can be observed under a variety of loadings.

3.1—Surface damage surveys

Surface damage may be caused by cavitation, impact, abrasion, wet-dry cycles, freeze-thaw deterioration, and chemical attack. A survey of such damage should provide information on the area affected, depth, and its nature. Sections and profiles using surveying techniques are valuable in evaluating the extent and depth of erosion. Notation of evidence in the areas of damage commonly provide keys to diagnosing the cause. Such evidence may be loose, semi-detached fragments, D-cracking, rock and debris piles, offsets or protrusions, coloration, and overall condition of the damaged area and of the surrounding concrete. These observations should be recorded.

Exposed surfaces are generally surveyed during routine inspections only. However, for periodic inspections or for special observations deemed necessary during routine inspections, surfaces flooded, under water, or backfilled and underground should be checked for surface damage by various methods. The method selected may depend on the size and depth of concrete of the area to be surveyed, conditions in the area, including water depth, and whether maintenance work will be done at the time of the inspection. Usual methods used include excavation, dewatering the structure, observation by submerged video camera mounted on a remotely-operated vehicle (ROV), diver inspection, and sounding. Dewatering or excavation are usually the most expensive and, therefore, are generally done only when there is concern about safety of the structure.

Failure to properly identify and correct surface damage can result in excessive wear or cavitation. This may cause loss of the design hydraulic characteristics, mechanical equipment malfunction and, in extreme cases, the loss of structural stability.

3.1.1 *Surface mapping*

3.1.1.1 *Scope*—Surface mapping may consist of detailed drawings produced from hand mapping, still photographic or video mapping, or a combination of these and similar techniques. Surface maps become a permanent record of the condition of the concrete at the time each survey is made and are an integral part of the report. Items most often identified and mapped include: cracking, spalling, scaling, popouts, honeycombing, exudation, distortion, unusual discoloration, erosion, cavitation, seepage, conditions of joints and joint materials, corrosion of reinforcement (if exposed), and soundness of surface concrete.

3.1.1.2 *Procedure*—A list of items recommended for surface mapping is as follows:

a) Structure drawings, if available
b) Clipboard and paper or field book
c) Tape measure, 50 to 100 ft (15 to 30 m)
d) Ruler graduated in 1/16 in. (1 mm)
e) Feeler gauge
f) Pocket comparator or hand microscope
g) Knife
h) Hammer—2 lb (1 kg)
i) Fine wire (not too flexile)
j) String
k) Flashlight or lantern
l) Camera with flash and assortment of lenses
m) Assortment of film—color and high speed
n) Marking pens or paint
o) Thermometer

Mapping should begin at one end of the structure and proceed in a systematic manner until all surfaces are mapped. Both external and internal surfaces should be mapped if accessible. Use of three-dimensional isometric drawings is occasionally desirable showing offsets or distortion of structural features.

It is important to describe each condition mapped in clear, concise detail and avoid generalizations unless it is common to other areas previously detailed. Profiles are advantageous for showing the depth of erosion. Areas of significant distress should be photographed for later reference. A familiar object or scale should be placed in the area to show the relative size of the area included.

3.1.2 *Crack surveys*

3.1.2.1 *Scope*—A crack survey is an examination of a concrete structure to locate, mark, and measure cracks, and to determine the relationship of cracks with destructive phenomena such as surface deterioration, alkali-aggregate reactions, impact loading, structural tensile stresses, and volume changes due to shrinkage or temperature changes. In most cases, cracking is the first symptom of concrete distress. Hence, a crack survey is significant in evaluating the future serviceability of the structure. Some cracks may appear at an early age and may not be progressive; others may appear at later ages and increase in extent with time; and some may appear following some unusual event.

Judgment must be used in determining which cracks are to be mapped. It is easy to be overwhelmed by this task if non-critical cracking is not eliminated. A technician can accomplish this task with appropriate guidance from a structural or materials engineer.

3.1.2.2 *Procedure*—The initial step in making a crack survey is to locate and mark the cracking and define it by type. According to ACI 201.1R, cracks are classified by direction, width, and depth using the following adjectives: longitudinal, transverse, vertical, diagonal, and random. The three width ranges suggested are: fine—generally less than 0.04 in. (1 mm); medium—between 0.04 and 0.08 in. (1 and 2 mm); and wide—over 0.08 in. (2 mm). Width and depth can normally be determined using an average of feeler gauge readings or by readings from a suitable measure or pocket comparator. Highly accurate crack width measurements can be made with a commercially available hand-held illuminated microscope with internal scale divisions of 0.0008 in. (0.02 mm). When a series of measurements are to be made over a period of weeks or months, the measurement point location should be marked and the sharp edges of the crack protected by a thin coat of clear epoxy to avoid breakage. If possible, the depth should be determined by observing edges or inserting a fine wire or feeler gauge; however, in most situations, the actual depth may be indeterminable without drilling or use of other detection techniques such as the pulse velocity described in Section 3.9.2.3.

The nature of the cracking should be defined in common terminology, which can be visualized by others less familiar with the structure. These terms include such visual cracking terminology as pattern cracking, surface checking, hairline cracking, and D-cracking, foundation-related displacement cracking, and thermal cracking. An offset of the concrete surface at either side of the crack should be noted.

Conditions that may be associated with the cracking, either over portions of the length or for the entire length, should be noted. These conditions may include seepage through the cracks, deposits from leaching or other sources, carbonation of surfaces adjacent to cracks, spalling of edges, and differential movement. Chemical analyses of the seepage water and the deposits may be desirable.

It may be worthwhile to repeat the survey under seasonal or other loading conditions when a change in crack width is suspected. Furthermore, tapping of surfaces with a hammer may detect shallow cracking beneath and parallel to the surface. A hollow sound generally indicates that such cracking is likely even though it cannot be seen.

Photographs of "typical" cracks or patterns will visually document conditions for comparison with future or past inspections. Vellum overlays on photographs of surfaces with a few large cracks will assist in highlighting cracks for structural evaluation.

3.2—Joint surveys

Joints in massive structures should be examined to ensure they are in good condition and functioning as designed. Information on joints and joint materials can be found in ACI 504R and ACI 224.1R. Location and type of each joint, whether expansion, contraction, or construction, should be noted together with a description of its existing condition. Joint openings should be measured under seasonal or other loading conditions if appropriate. The joints should be carefully examined for spalling or D-cracking, absence or presence and condition of joint fillers, and evidence of seepage, emission of solids or chemical attack. Measurements should also be taken of surface offsets on either side of the joints or other irregularities. Joint construction details should be recorded and mapped if drawings are not available.

3.3—Vibration load testing

The integrity of a structure can be estimated by exciting the structure with forces and observing the resulting motion.[3] The vibration characteristics of a sound structure will differ from those of a distressed structure. The vibratory loading is accomplished in the field using either forced (artificial) or ambient vibration. In the forced vibration technique, the mass is vibrated at known frequencies and mode shapes. Response spectra (amplitudes, frequencies, and damping effects) are measured at various locations in a structure. Similar observations are also made using natural vibrations induced by wind, wave action, and micro-seismic loading. One of the advantages of this type of testing is that the global integrity of the structure, including the foundation and supports, can be assessed. Field observations can be compared with finite element calculations of expected vibratory motions to determine the degree of deterioration of complex structures.

3.4—In-situ stress determinations

In evaluating the effects of observed distress due to materials deterioration, excessive dynamic or static loading, and other causes, determination of existing stress conditions may be necessary. In-situ stress determinations have been primarily limited to arch dams where stress analysis may be complex. In some instances, structural movements in service change the pattern and distribution of stress assumed in the original design. Stress conditions determined can be compared with design parameters and with existing strength levels. One method that has been successfully used to investigate in-situ stress conditions is the "Over Coring Stress Relief" Method.

3.4.1 *Overcoring*—The over coring technique was originally developed in the study of rock mechanics. However, in the last 20 years it has also been applied to investigate the in-situ stress in concrete structures. The U.S. Bureau of Reclamation used the overcoring stress relief method to investigate three arch dams located near Phoenix, Ariz.[4,5] The procedure involved drilling an EX size hole (1-13/16 in. (45 mm) nominal diameter), inserting the probe-type gauge, overcoring the EX hole with a 6 in. (152 mm) core barrel and recording the strain at 60-degree intervals around the circumference of the gauge. Drilling three horizontal holes, which intersected near the center of the structure and at an angle of 22.5 degrees with each other, produced accurate determinations of in-situ maximum and minimum stress conditions. The results further showed that in arch dams, a single drill hole drilled approximately normal to the principal stresses in the vertical-tangential plane was adequate for maximum/minimum stress determinations. Accuracy of the results also depends, to a large extent, on good drilling equipment and techniques and experienced crews. The borehole gauge used was developed by the U.S. Bureau of Mines and was later modified for water tightness and ease of maintenance. Modulus of elasticity at each measurement point was determined in the field using the 6 in. (152 mm) donut-shaped core taken from each location. A special apparatus was used to hydraulically load the core section in a chamber with a borehole gauge inserted in the EX hole. The thick wall cylinder formula was used to compute the modulus of elasticity. The 6 in. (152 mm) overcore recovered was also tested for triaxial shear, compressive strength, tensile strength, modulus of elasticity, Poisson's ratio, specific gravity, absorption, alkali-aggregate reaction, and used for petrographic examinations.

3.4.2 *Other methods*—Two other methods of determining the in-situ properties have been widely used in rock mechanics[6] and have been applied to concrete. These include the flatjack and the velocity propagation methods. The flatjack method involves cutting a slot in the concrete, inserting the flatjack, pressurizing the flatjack, and measuring the change in slot width. The width across the slot location must also be measured before and after cutting the slot. The method provides a measure of actual stress in the surface plane. However, this method is restricted to near-surface measurements because of the difficulty of cutting deep flatjack slots.

The velocity propagation method uses measurement of stress waves passed between two points. Accordingly, two or more boreholes enable crosshole wave measurements, which provide, besides qualitative assessments from crest to base, correlation with extracted core tests to determine quantitative measurements used in structural analyses.

3.5—Supplemental instrumentation

Supplemental instrumentation may be required when unusual behavior or changing conditions are detected during inspection of the structure. Conditions may relate to movement of the structure, movement within monoliths of the structure along joints, or movement within monoliths at cracks. Other instrumentation may include equipment for measuring hydrostatic pressures in cracks and joints and under the structure (uplift). Instrumentation that has been found most valuable in evaluating existing structures is described in the subsequent subsections.

3.5.1 *Extensometer points*—An arrangement of three embedded plugs—two on one side of a crack or joint and the third on the other—will provide a measurement of relative shear movement as well as crack width change. A mechanical strain gauge or equivalent is used to measure the change in length between plugs.

3.5.2 *Borehole extensometers*—Primarily intended for measuring consolidation of weaker layers within rock, but can be used to detect internal movement at structural cracks.

3.5.3 *Joint meter*—The joint meters are attached across joints or cracks to measure the opening and closing. Measurements can be taken at some remote location by connecting cable. Joint meters are commercially available from firms specializing in instruments for embedment in soil and concrete.[7]

3.5.4 *Electrolevel*—This is a highly-refined bubble level, with the position of the bubble determined by means of electrodes. Changes in slope of 0.0005 in. per in. (500 millionths) can be measured, remotely if desired. A portable level may be used where access allows it to be placed on scribed lines of a permanently installed stainless steel plate. Unless encased in epoxy, some permanently installed levels have been vulnerable to corrosion.

3.5.5 *Cased inclinometer*—These are accelerometers housed in a wheeled probe that is passed through a grooved casing. Inclination from vertical is determined at selected elevations, with a sensitivity of one part in 10,000. This is a more precise version of the slope indicator equipment originally developed for monitoring subsurface movements in soils.

3.5.6 *Tilt-measuring instruments*—A portable sensor mounted on a metal plate, placed on reference plugs or plate embedded in the structure, senses changes in rotation of the order of 10 seconds of arc. This is comparable to the electrolevel precision.

3.5.7 *Observation wells*—These are simply open holes into the structure or foundation in which water level measurements can be taken to determine uplift pressure at that location.

3.5.8 *Piezometer*—An instrument for measuring pressure head. Generally, the piezometer consists of a pressure cell installed in a drill hole in the foundation.

3.5.9 *Vertical and horizontal control*—Survey points for line and level measurements are established at various locations on the structure for the purpose of measuring differential movements with time. History plots of data, covering months or years, may be necessary to differentiate between normal and extreme or critical movements. Data may reveal cycles associated with temperature or applied loading. Whenever possible, estimated values of deformation or displacement should be developed, based on theoretical analyses using the best available data on materials, properties, and parameters. Observed values may indicate distress when the expected or normal movements are exceeded.

Electronic distance-measuring instruments are capable of accuracies from 5 to 10 mm over distances up to 9 km, with adequate reflector targets, atmospheric corrections, and proper techniques. They are most useful for monitoring structure displacements.

3.5.10 *Weir/flume*—A device used to monitor seepage and water flow.

3.5.11 *Thermocouple/resistance thermometer*—Attached to a surface or placed within a drilled hole to monitor temperatures and their effect on instrumentation readings or physical observations.

3.5.12 *Plumb bob*—Either a conventional plumb bob with a weighted pointer at the bottom of a freely suspended line indicating the relative movement at the top of the line compared to a scale at the bottom of the line, or an inverted plumb bob with the pointer located on a float in a fluid at the top of the line.

3.6—Geophysical logging

Several geophysical drill-hole logging techniques often used in the oil industry are available and may be used to provide supplemental data on the physical properties and condition of in-situ concrete.[8] Geophysical logging consists of lowering various instruments into an open drill-hole; the type of instrument dependent on the type of measurement (log) to be developed. As the instrument is lowered to or withdrawn from the bottom of the hole, an automatic recorder traces the log on graph paper. The recorder paper on which the log is traced moves on a vertical scale with the instrument and measurements received from the instrument are plotted on the horizontal scale. In general, porosity and density are the most common parameters derived from geophysical logs. Porosity may be determined from several logs including Sonic, Density, and Neutron Logs. Density can be directly obtained from the Density Log. Also, the previously mentioned logs together with Resistivity and

Caliper Logs provide a graphic record of the uniformity of concrete throughout the depths examined. When drill-hole core recovery is poor or is not practical, geophysical logging can provide a method of locating cracks, voids, contacts, and other discontinuities of significance. Logging of drill holes and interpretation of logs should be done by firms that specialize in this exploration technique.

3.7—Down-hole video camera

The condition of interior concrete and foundation rock can be examined directly, and video-taped if desired, by the use of small video cameras. These instruments are successors to the Corps of Engineers borehole camera, which is no longer generally available. Video cameras range in size down to 1 in. (25 mm) diameter probes, with directional control of lenses and no lighting necessary. The transmitted picture is continuously displayed on a scanner screen, and can be supplemented by video recording for a permanent record. The camera assembly will resist hydrostatic heads up to 1300 ft (400 m) and the focusing capability will permit estimating the size of caverns or cavities encountered. Turbidity of the water must be controlled for best results. Both the Bureau of Reclamation and Corps of Engineers have used this technique with satisfactory results.[9]

3.8—Seepage monitoring

Seepage is the movement of water or other fluids through pores or interstices. Some structures may include design features to control seepage such as waterstops, sealed joints, drain holes, cut-off walls, grout curtains, granular drains, and drainage galleries. These features should be checked to assure they are functioning as designed. Seepage can be important with respect to durability, can indicate failure of the structure to function monolithically and may also indicate operating problems in water retention structures. Seepage occasionally occurs through horizontal or vertical construction joints; around waterstops or sealants in expansion, contraction or control joints; along cracks; along the interface between concrete and some other material such as foundation interfaces, form bolt or tie holes, or other embedded items; or through areas of porous low-quality concrete.

Several types of equipment are available for measurement of seepage. Weirs and flumes are the most commonly used equipment for open channel flow measurements. Weirs, generally of rectangular, v-notch, or Cipolletti configuration, require water to be ponded, forming a stable backwater condition. Flumes, available in Parshall, Plamer Bowlus, or trapezoidal configurations, provide less impedance to flow and are less susceptible to blockage by debris. Sophisticated instrumentation is available for use with these devices to monitor and record water depths and other parameters.

Water from seepage may result in the development of excessive hydrostatic heads on portions of the structure, may attack the concrete chemically, provide excess moisture to produce mechanical failure during freeze-thaw cycles, or may transport undesirable particles from the concrete or foundations. Analysis of seepage water can be used to evaluate chemical activity. Caution must be used when evaluating seepage water. Inappropriate conclusions can result if the evaluation does not consider how the water may have been altered as it passed through the structure or became exposed to air at the surface. Also, a very minor amount of local deposit that drops into a small sample when it is obtained can drastically affect the chemical quantities and types reported by a laboratory that analyzes the sample. The appearance of seepage water, if cloudy, will indicate the presence of transported sediments. Determination should also be made of the extent and the quantity of seepage water if measurable.

Frequently, it is important to know the source and velocity of seepage. The source can sometimes be obtained by simple measurements such as comparing the temperature of seepage with groundwater or reservoir temperatures. Dye tests can be made using commercial dyes such as Rhodamine B (red) or Fluorescein (green). The dye is introduced into water at some location near the upstream face, in drill holes, or other appropriate accessible points. The location and time of reappearance will indicate the source of various seeps and will provide the velocity of dye movement. Federal, state, and local environmental agencies should be consulted to determine if dye compounds are permissible under local regulations.

3.9—Nondestructive testing

3.9.1 *General*—The purpose of nondestructive testing is to determine the various properties of the concrete such as strength, modulus of elasticity, homogeneity, integrity, as well as conditions of strain and stress without damaging the structure. Selection of the most applicable method or methods of testing will require good judgment based on the information needed, size and nature of the project, and the seriousness of observed conditions.[10,11] In-situ testing, if required, normally should follow a condition survey. Generally, determination of the concrete properties is only necessary to further evaluate the effects of observed distress on the safety or serviceability of the structure. In-situ testing will provide parameters for structural analysis by current analytical techniques for comparison with the present-day design requirements. Care should be taken in interpreting results of instruments such as the Schmidt Hammer and Windsor Probe, which only measure the quality of near-surface concrete. Because of surface weathering, leaching, carbonation or other conditions, surface tests may not reflect the properties of interior concrete.

3.9.2 *Surveying techniques*—Although compressive strength and modulus of elasticity, depending on the method used, can be estimated from the survey techniques described in the following subsections, the accuracy of these estimations are usually considered to be only relative based on the many factors that can influence the various measurements. The accuracy of strength estimations may be greatly improved if they are correlated with test results on drilled core specimens from the same structure. The techniques described are valuable survey tools in that results provide comparative values. When surveys are made at different times, changed conditions can be detected and monitored.

3.9.2.1 *Rebound hammer*—The rebound hammer, also referred to as a Swiss, rebound, or impact hammer, is a lightweight portable instrument used for qualitative measurement of in-place concrete strength. The greatest value of the hammer is for comparison of indicated strength between different areas, thereby detecting areas of potentially low strength. The indicated strength is recorded on a built-in scale that measures the rebound of a spring-driven plunger after it strikes the concrete surface. Rebound is a measure of surface compressive strength and is affected by many factors such as the mixture composition, aggregate properties, surface texture and curvature, moisture content, and mass of the concrete tested. Calibration by statistical correlation with the strength of cores drilled from the structure will indicate the degree of reliance that can be placed on strength estimated from rebound readings. Calibration on concrete test cylinders is helpful in estimating strength or relative differences in strength, but such estimates must be used with care. Published calibration data should not be used to estimate strength from rebound surveys. However, the rebound hammer is an excellent tool for quickly determining the uniformity of in-place concrete. The method of testing concrete by the rebound hammer is described in ASTM C 805. No correlation has been found between rebound readings and modulus of elasticity.

3.9.2.2 *Probe penetration*—The probe penetration method of test consists of driving a precision probe into concrete using a "gun" that produces a specific energy. Generally, three probes are driven into the concrete at each location in a triangular pattern, controlled by template. The protruding ends of the probes are measured. The probe penetration system has been found comparable with the rebound hammer. On concrete 40 to 50 years old, the probe system may yield higher strength than actually exists. Limited information suggests that the cause of higher indicated values may relate to microcracking between the aggregate and paste, which are indicated by test cylinder results but not by the probe readings. Interpretation of test results based on other known factors is necessary to effectively use this equipment. The probe penetration test procedure is described in ASTM C 803.

3.9.2.3 *Pulse velocity*—Pulse velocity testing involves measurement of the velocity of compression waves through concrete. The method provides an overall indication of the uniformity of in-place concrete and can detect general areas of deterioration.[12] The extent to which cracks can be accurately located and described is influenced by conditions such as whether the cracks are open or closed and the degree to which they may be filled with sediments, chemical deposits, or water. The test method is described in ASTM C 597, "Standard Test Method for Pulse Velocity through Concrete."

The equipment used is very portable, consisting only of a lightweight instrument housing a pulse generator and receiver and high-speed electronic clock, transmitting and receiving transducers, and cable connectors. Velocity is determined by dividing the measured wave travel time by the shortest direct distance or path length between transducers. When a signal cannot be received it usually indicates one of the following conditions: an open crack, insufficient consolidation, or the energy was absorbed between the transducers. Accordingly, pulse velocity equipment may be used in determining crack depth. Available equipment is effective up to a path length of approximately 50 ft. It is important that a high degree of accuracy is needed in determining both travel time and path length because small errors in either measurement may produce significant changes in the indicated pulse velocity.

Velocity measurements are usually made between exposed surfaces with one transducer stationary while the other transducer is moved from point to point within an effective area. Measurements can also be made from inspection or drainage galleries within the structure if available and accessible. Pulse velocity surveys have had relatively wide usage as one of the techniques for investigation of existing concrete dams and other concrete structures.

3.9.2.4 *Acoustic echo techniques*—Two very useful acoustic techniques have been applied to the nondestructive evaluation of concrete structures. Both techniques, referred to as "echo" methods, can detect cracking, delaminations, voids, reinforcing bars, and other inclusions in concrete. As with pulse velocity, the extent to which these conditions can be accurately described depends on their orientation and condition, that is, open versus closed cracks, accumulations of debris or chemical deposits, and presence of water. Acoustic energy originates from a piezoelectric crystal or hammer and propagates through the material, reflecting from any object or free surface that produces a change in acoustic impedance. This reflection, or echo, then returns to the surface where it is recorded by a receiver. A distinct advantage of these systems over through-transmission pulse velocity technique is that the only one accessible surface is required.

Thornton and Alexander developed the Ultrasonic Pulse-Echo Technique, which measures the time of arrival of echoes from inclusions in concrete.[13] The incident acoustic wave is produced by a piezoelectric crystal. The resulting echo is recorded by a second transducer, and the time of arrival is determined. Digital signal processing techniques can be used to extract from the echo signal information that is otherwise hidden, such as the presence of microcracking. A disadvantage of this technique is that the depth of penetration is currently limited to 12 to 18 in. Current research is intended to increase the depth of penetration to tens of feet.

Tests have shown that the system is capable of identifying sound concrete, concrete of questionable quality, and deteriorated concrete as well as delaminations, voids, reinforcing steel, and other inclusions within concrete.[14,15] The system will work on both horizontal or vertical surfaces as well as above or below the water surface. The present system requires an experienced operator to use the system and interpret the reflected signals.

Carino and Sansalone have developed the Impact Echo System, which uses a hammer to induce a sonic wave in the structure.[16] A surface receiver measures the displacements caused by the reflecting stress waves. Information on the condition of the concrete is determined by analyzing the reflections. Small-diameter steel ball bearings and spring-loaded, spherically-tipped impactors have been used successfully to induce the incident energy. Impact-echo methods have been used to detect a variety of defects, including cracks and voids in concrete, freezing-and-thawing damage, depth of surface-opening cracks, voids in prestressing ducts, honeycombed concrete, and delaminatons.[16-18]

3.9.2.5 *Radar*—Certain types of radar have been used to evaluate the condition of concrete up to 30 in. in depth.[19-21] Radar can differentiate between sound concrete and deteriorated concrete. The deterioration can be in the form of delaminations, microcracks, and structural cracks. Radar has also been shown to be capable of detecting changes in materials and to locate where these changes occur.[20] In addition, radar has been used to locate misaligned dowel bars and areas of high chloride concentration.[21] Short-pulse radar has been used successfully to survey the condition of concrete revetments along the banks of the Mississippi River.[22] In limited applications, radar has been used to detect voids underneath pavements.

Underwater topography is commonly surveyed by soundings using an acoustical transducer or an array of transducers mounted to the underside of a boat.[22] Such surveys are very effective in mapping contours in stilling basins and river bottoms. Depending on the equipment, the survey can be accurate to within 0.1 ft (0.03 m). Because data are collected in a Cartesian coordinate format (x, y, z), excellent graphical presentations and detailed analyses are possible.

CHAPTER 4—SAMPLING AND LABORATORY TESTING

4.1—Core drilling and testing

Core drilling is presently the most accepted method of obtaining information on concrete within the structure in areas that otherwise can not be observed. However, core drilling to substantial depths is expensive and should only be considered when sampling and testing of interior concrete is necessary.

The presence of abnormal conditions of the concrete at exposed surfaces only suggests questionable quality or a change in the physical or chemical properties of the concrete. These conditions may include scaling, leaching, pattern cracking, and freeze-thaw weathering, to name the most common. When such observations are made, core drilling to examine and sample the hardened concrete may be necessary. The minimum depth of sampling concrete in massive structures should be 2 ft (0.6 m) in accordance with ASTM C 823. However, under some conditions core drilling of the entire thickness may be required to obtain representative samples of a monolith. Occasionally, this drilling can be coordinated with foundation inspection. Core drill holes may also be used for nondestructive testing of the mass structure as described in Section 3.9 and for installation of inclinometers.

The diameter of core holes will depend on the testing anticipated. For compressive strength, modulus of elasticity, or similar laboratory tests, the diameter of the core should be between 2.5 to 3.0 times the maximum size of aggregate. However 8 or 10 in. (200 or 250 mm) diameter cores are generally extracted for concrete with 6 in. (150 mm) nominal maximum size aggregate because of the higher cost and handling problems of larger-diameter cores.

Cores obtained from drill-holes should be logged by methods similar to those used for geological subsurface exploration. Logs should show, in addition to general information on the hole, conditions at the surface, depth of obvious deterioration, fractures and conditions on fractured or unbonded surfaces, unusual deposits, coloring or staining, distribution and size of voids, locations of observed construction joints, and contact with the foundation or other surfaces. Lift joints that are known to have been broken during drilling or core extraction should be noted. See Section 4.2 for additional instructions on the examination of cores.

Cores recovered from drilling operations should be immediately marked for identification, including location, depth, and notation of the top and bottom, and should be placed in protective core boxes or preferably sealed to prevent drying. They should then be stored in safe areas protected from the weather, especially freezing when the cores are still moist. Metal boxes should be used when the cores will be stored in areas of termite infestation.

4.1.1 *Strength and elastic property determination*—The following test procedures are appropriate for evaluation of drilled cores:

4.1.1.1 *Standard tests*—The following ASTM test procedures should be used for determining physical properties of drilled concrete cores:

C 42—Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete for compressive strength and tensile strength

C 215—Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens for dynamic modulus of elasticity (Young's Modulus)

C 469—Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression for static modulus of elasticity and Poisson's ratio

4.1.1.2 *Other tests*

4.1.1.2.a *Dynamic loading*—This generally refers to a load application time, or a complete tension-compression loading and unloading cycle, which is a fraction of that normally used or experienced in conventional static beam or cylinder testing. Examples might be the forces generated by blasts, explosions, or earthquakes. Tests have indicated concrete shear strengths are 50% and 80% greater under single pulse dynamic loading rates equivalent to 7 Hz and 300 Hz, respectively, than under static load rates.[23,24] Little data exist on the magnitude of possible tensile strength increases for comparable loading times.

4.1.1.2.b *Seismic loading*—Earthquake or seismic loading is at the lower end of the dynamic range, or a total tension-compression cycle period between 1 Hz and 10 Hz. This is equivalent to single-mode load application rates from 0.25 to 0.025 seconds. Dynamic tensile and compressive tests often exhibit little difference in strength whether specimens are tested in a dry or wet state. However, static tensile and compressive tests on specimens in a wet state usually result in lower strengths than dry specimens. Hence, when comparing dynamic and static test results, the moisture condition of the specimen will determine if dynamic tests will produce an increase in strength over static tests. Direct tensile tests at these rates have indicated no increase in concrete strengths above static rate levels for dry concrete, but a 30% increase for moist concrete.[25] Other tests show an increase in compressive strength of from 30 to 50% with an increasing loading rate within the seismic range.[26] Still others[27] have shown up to an average increase of 66% in direct tension and 45% from splitting tensile tests on mass concrete cores taken from existing concrete dams.

4.2—Petrographic analysis

The petrographic analysis of concrete should be made by a person qualified by education and experience to operate the equipment used in the analysis and to record and interpret the results obtained. The petrographer should be consulted before samples are taken in the field and should be furnished with preconstruction, construction, and condition reports described in Chapters 2 and 3.

4.2.1 *Sampling*—Taking of samples of concrete for laboratory testing and analysis presents great problems of judgment in order that the samples are truly representative of the conditions to be studied. The surveys made under Chapters 2 and 3 should furnish information on the location and number of samples required. The most useful samples for petrographic examination of concrete are diamond-drilled cores with a diameter of at least twice, and preferably three times, the maximum size of the coarse aggregate in the concrete. If 6 in. (150 mm) aggregate was used, a core 8 to 10 in. (200 to 250 mm) in diameter has been found to be satisfactory and is commonly taken in practice to avoid the high cost and handling difficulty of 12 to 18 in. (310 to 460 mm) cores.

Sampling should be done with complete objectivity, so that the suite of samples is not weighted with either the unusually poor or unsound materials. In securing samples, care should be taken to avoid disturbance or contamination of the materials to assure that laboratory tests and analyses are truly representative. Coring is preferable to sampling by other means because the concrete is disturbed the least. Use of sledges or air hammers may induce internal fracturing or may so disrupt the concrete as to make it difficult or impossible to describe its structure accurately and in detail.

The sampling should include both near-surface concrete and concrete at depth, because they may differ substantially in development of cracking, deterioration of the cement paste, progress of cement-aggregate reactions, and other features. The samples should be sufficient in size and number to permit all necessary laboratory tests. The petrographic examination should be performed on concrete that has not already been subjected to a compression test or some other test.

4.2.2 *Visual examination*—Visual inspection with the unaided eye, a hand lens, and a stereoscopic microscope can provide valuable information when applied to original exterior surfaces, surfaces of fractures and voids, surfaces of fresh fractures, and through the cement paste and aggregate. From this examination, the following features can be studied and descried:

- Condition of the aggregate
- Pronounced cement-aggregate reactions
- Denseness of cement paste
- Homogeneity of the concrete
- Occurrence of settlement and bleeding of fresh concrete
- Depth and extent of carbonation
- Occurrence and distribution of fractures
- Characteristics and distribution of voids
- Presence of contaminating substances

As part of the visual examination, noteworthy portions of the concrete, secondary deposits, or particles of aggregate are separated for more detailed microscopic study or for chemical, x-ray diffraction or other types of analyses.

4.2.3 *Petrographic microscopy*—Petrographic thin sections permit thorough examination of concrete because details of texture and structure are preserved. Such sections are slices of concrete that are cemented to a small glass plate and then are ground thin enough to readily transmit light. When so prepared, the sections can be examined under the petrographic microscope at magnifications up to about 1000 diameters, or with oil immersion objectives to about 2000 diameters. From the examination of thin sections, the following features can be studied and descried:

- Composition of fine and coarse aggregates
- Evidence of cement-aggregate reaction
- Proportion of unhydrated granules of cement
- Presence of mineral admixtures

Sawed and finely ground surfaces of concrete are used in microscopical analysis of concrete to determine the air content and various parameters of the air void system in accordance with ASTM C 457. This method can also be used to analyze the concrete for the volumetric proportions of aggregate, cement paste, and air voids.

4.2.4 *Other petrographic methods*—In some instances, petrographic methods other than microscopy, such as x-ray diffraction and differential thermal analysis, may be required or might serve to rapidly identify fine-grained materials.

4.3—Chemical analysis

Although hardened concrete may be subjected to chemical analysis for any of many reasons, the most common is for determination of the proportion of cement used in the mixture. The ASTM C 1084 method and variants of this are usually employed for this purpose.

Dependable quantitative chemical methods for detection of organic admixtures in hardened concrete have not been developed. Calcium chloride is the only commonly used admixture that can be quantitatively determined by chemical methods. Substances formed by degradation of lignosulfonate in portland cement mixtures can be detected by characteristic fluorescence of water solutions produced by acid extractions of hardened concrete at ages up to 2 years. The method, although not quantitative, is sufficiently sensitive to indicate the presence of lignosulfonate in amounts equivalent to less than 0.1% by weight of the cement. No generally applicable methods are available for detection of the many other organic admixtures used in concrete.

Concrete may contain any of a wide variety of organic or inorganic substances, either as contaminants in the concrete-making materials or the fresh concrete, or because they were absorbed into the hardened concrete. Inorganic chemicals can be determined by classical analytical methods, but the results may be difficult to interpret when they are similar to chemicals that were deliberately included in the concrete. Organic substances are particularly difficult to identify. Evidence available at the job site might suggest the solution to problems of attack of aggressive chemicals upon the hardened concrete.

4.4—Physical tests

Freeze-thaw resistance (Procedure A; freezing and thawing in water) or frost resistance (Procedure B; freezing in air and thawing in water) can be determined by ASTM C 666. Furthermore, results of the freeze-thaw tests may be useful in predicting the relative rate at which deterioration of concrete in the structure may occur and service life of the structure.

4.5—Report

Laboratory testing should be concluded by the preparation of a laboratory report that includes the items listed below.

4.5.1 *Location, elevation, and orientation of cores tested*

4.5.2 *List of physical and chemical tests and their results*

4.5.3 *Photographs of cores as received, photographs and photomicrographs of features of interest, and photomicrographs of thin sections*

4.5.4 *Conclusions based on test results of condition of concrete*

CHAPTER 5—DAMAGE

5.1—Origin of distress

When evaluating the condition of mass concrete structures, the distress or damage may have more than one origin. It is necessary to determine the cause or causes of such distress in order to evaluate the structural integrity of the structure, estimate the length of service remaining, and select the appropriate repair. The following sections describe the origins of distress most commonly encountered.

5.1.1 *Temperature and shrinkage surface cracks*—Cracks of this type are characterized by the fineness and absence of any indication of movement. They are usually shallow, a few inches in depth, and are not detected by sonic procedure. However, temperature cracks can extend full depth through unreinforced concrete. Where reinforcing steel exists near the surface, the cracks provide an access for water, which may result in the formation of rust and subsequent discoloration or spalling, especially if carbonation of concrete occurs in the location of the steel. ACI 222R contains a thorough report on corrosion of metals in concrete. Steep temperature gradients during construction are often responsible for excessive tensile strains at the surface. Drying during and subsequent to the curing period can produce the same result. The surface shrinkage crack pattern is typically orthogonal or blocky. This surface cracking should not be confused with thermally-induced deeper cracking occurring when dimensional change is restrained in newly placed concrete by rigid foundations or hardened lifts of concrete. Because all of the cracking described in this section is likely the result of construction conditions, this basic cause cannot be eliminated.

5.1.2 *Structural cracking*—Causes of this type of cracking are either excessive stress (which may be due to loading or stress pattern different from that expected by the designer) or inadequate concrete strength. The validity of the first possibility may be established by a review of the original design computations or a re-analysis of the structural design. Crack openings originating from structural action may tend to increase as a result of continuous loading and creep of the concrete. Laboratory testing of cores or in-situ testing should reveal any deficiencies in concrete strength or unusual elastic modulus. These results should be compared with reliable and adequate construction records, if available.

5.1.3 *Cavitation erosion and abrasion*—Cavitation distress of concrete surfaces can be very severe at high water velocities but can also occur at low water velocities. ACI 210R discusses erosion of concrete in hydraulic structures. The process of cavitation is associated with the creation and sudden collapse of negative pressure resulting in the extraction of solid pieces of aggregate or mortar. Abrupt projections, uneven surfaces and changes in direction of flow can cause cavitation conditions to develop.

Erosion is caused by suspended solids generally fine and hard, which wear away the relatively soft cement paste or mortar. Characteristics of erosion damage are sharp ridges remaining on the harder portions of the exposed materials. Erosion of this type is less jagged and more undulating than damage by cavitation. Abrasion is the result of large and hard materials, such as aggregate, debris, ice, cobbles, or reinforcing steel, being entrapped and churned around on a relatively small concrete surface area. With time, these materials will wear away the concrete to form a hole, and the abrading action will continue until the cavity extends completely through the concrete mass. Impact of large debris at higher velocities can accelerate the rate of abrasion.

5.1.4 *Cement-aggregate reaction*—ACI 201.1R and ACI 221R contain in-depth discussions of alkali reactivity. Both the alkali-silica and alkali-carbonate reactions are characterized by reaction rims surrounding individual pieces of aggregate.[28,29] The effect in either instance is an expansion of the concrete due to the increased volume of the reaction products. The intensity and magnitude of such reactions will depend on the mineralogical composition of the aggregate, the alkali content of the cementing material, availability of moisture, and the age of the structure. Expansion and corresponding cracking is most pronounced on surfaces and in thin structures or those not rigidly confined in three directions. Only a very approximate estimate can be made of the rate of future expansion and the length of satisfactory service life remaining. A method of determining future expansion used with some success is to compare the expansion of identical specimens subjected to distilled water and high-alkali solution. Certain maintenance procedures have been effective, to a limited extent, in slowing the expansion and regression of concrete strength and elastic properties. Filling of cracks with grout or other suitable sealants, and waterproofing exposed surfaces, generally inhibit the entrance of moisture required in the reaction process. In some instances, it may be necessary to provide additional structural support.

5.1.5 *Environmental distress*—Aggressive chemicals in soils or water, above various minimum concentrations, may be evidenced by discoloration around pattern cracking, disintegration of the mortar, or excessive expansion. The most common cause is likely a sodium, calcium, or magnesium sulfate occurring in the soil, in rivers, and in salt water. The effects of many acids, salts, and other materials are described in ACI 201.1R.

Leaching of lime from an inundated concrete surface such as the upstream face of a dam can result in up to 50% loss in strength. Generally, only depths less than 1/4 in. (6 mm) are affected. The leaching potential increases with increases in purity of the water and decrease in temperature. Lime has the peculiar property of being more soluble in cold water than in warm water.

Virtually all mass concrete placed in recent years has included entrained air. While this has substantially reduced deterioration due to freeze-thaw actions, such distress still can occur under some circumstances. Inadequate air content, or an aggregate that is itself vulnerable to freeze-thaw deterioration, coupled with near-complete saturation, are examples of such conditions. Closely spaced, fine, parallel cracks near edges or joints may indicate that freeze-thaw expansions are occurring. Entrance of water into the cracks and subsequent freezing further aggravates the condition.

5.1.6 *Physical and thermal properties*—Structural analyses of existing structures, either to determine stress magnitude and direction or to establish stability of the entire structure, require definite values of tensile strength, compressive strength, and elastic modulus. These data can be developed most reliably from drilled cores taken from the structure. When the structural analysis will require a knowledge of creep, the related parameters can likely be estimated from existing literature. Similarly, the coefficient of thermal expansion (with consideration of aggregate type and moisture conditions) and Poisson's ratio may be estimated. If necessary, these properties can also be determined by tests on cores.

5.2—Considerations for repair and rehabilitation

Following completion of damage surveys, recommendations for repair should be made. The objective of the recommendations is to present optimum alternatives for arresting deterioration, restoring deficient concrete, preventing leakage, and re-establishing structural stability where such is deemed necessary by the structural engineer.

5.2.1 *Estimated service life*—Based upon the rate at which the surface concrete is deteriorating or disintegrating, an estimate of the useful life of the structure is generally possible, assuming no repairs and continued exposure to the cause of the distress.

5.2.2 *Eliminating the cause*—Where the cause of deterioration can realistically be controlled (for example, by eliminating the use or presence of aggressive chemicals), such practices should be identified and the potential benefits, in terms of extended service life and reduced maintenance, presented. Where natural causes such as sulfate soils, river water contamination, or freeze-thaw conditions are responsible, this should be so indicated.

5.2.3 *Surface protection*—Thin surface coatings are effective only in mildly distressed circumstances. Overlays of several inches of thickness require removal of all concrete of doubtful quality and replacement by a superior material. Surface protection of tunnels, concrete subjected to aggressive chemicals, and entire dam faces subjected to freeze-thaw and ice loads has been successfully accomplished for over 10 years using unbonded polyvinyl chloride sheet protection. This is especially common in the European Alps. In-place polymerized concrete or mortar, epoxy mortar, or very low water-cement ratio concrete are alternative materials potentially capable of resisting mechanical abrasion or ingress of chemicals or water.[30-32]

5.2.4 *Restoring structural integrity*—Obvious indications of doubtful structural stability are cracks of substantial width, cracks that change in width with load changes or temperature cycles, or significant leakage. If the crack movement and the hydrostatic head is not high, leakage can be eliminated by routing out the crack and injecting an elastomeric filler or a rigid epoxy mortar, depending upon the probability of crack movement. In cases of high hydrostatic pressure, leakage may have to be controlled by drainage systems. When structural analyses indicate a fundamental deficiency in stability, post-tensioning between structural components or between components and foundation rock should be considered. An adequate cover of grout or mortar around the steel strands is a necessity to avoid corrosion.

CHAPTER 6—REPORT

6.1—General

A formal report describing the condition of the concrete in the various structures of the project should be submitted to the owner or regulatory agency or engineering organization requesting the evaluation. Hazardous conditions found during the evaluation should be reported to appropriate operating officials of the project without delay prior to preparation of the formal report.

The report should give an evaluation of the adequacy of the concrete based on current design and service conditions. If appropriate, recommendations for repair and maintenance required to assure future longevity and serviceability of the structures of the project should be given.

6.2—Contents of report

6.2.1 *Description of the project*—Regional vicinity maps for the project, plans, elevations, sections of the structures, and geologic maps when applicable should be shown. General purpose and operating requirements of the project and safety hazards and economic impacts involved in case of structural failure should be described.

6.2.2 *Pertinent design criteria for structures of project*—Significant structural design criteria upon which evaluation of the concrete was made and analyses, test methods, data, and investigations pertinent to the evaluation should be described.

6.2.3 *Summary of data collected*

6.2.3.1 *Existing records*

6.2.3.2 *Visual inspection of concrete*

6.2.3.3 *Analysis of existing instrumentation, investigations, inspections, and test records*

6.2.3.4 *Results and analyses of new investigations and test data*

6.2.4 *Summary evaluation of concrete*

6.2.4.1 *Evaluation of portions of structures not requiring immediate repair*

6.2.4.2 *Evaluation of portions of structures requiring immediate repair*

6.2.4.3 *Alternative methods of repair*

CHAPTER 7—REFERENCES

7.1—Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below.

American Concrete Institute

116R	Cement and Concrete Terminology
201.1R	Guide for Making a Condition Survey of Concrete in Service
201.2R	Guide to Durable Concrete
210R	Erosion of Concrete in Hydraulic Structures
221R	Guide for Use of Normal Weight Aggregates in Concrete
222R	Corrosion of Metals in Concrete
224.1R	Causes, Evaluation, and Repair of Cracks in Concrete Structures
228.1R	In-Place Methods for Determination of Strength of Concrete
437R	Strength Evaluation of Existing Concrete Buildings
504R	Guide to Sealing Joints in Concrete Structures

ASTM International

C 33	Specifications for Concrete Aggregates
C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 215	Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens
C 457	Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete
C 469	Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 597	Test Method for Pulse Velocity Through Concrete
C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 803	Test Method for Penetration Resistance of Hardened Concrete
C 805	Test for Rebound Number of Hardened Concrete
C 823	Practice of Examination and Sampling of Hardened Concrete in Constructions
C 1084	Standard Test Method for Portland-Cement Content of Hardened Hydraulic-Cement Concrete

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, Pa. 19428-2959

7.2—Cited references

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