IN-LB	Inch-Pound Units
SI	International System of Units

An ACI Standard

Code Requirements for Environmental Engineering Concrete Structures (ACI 350-20) and Commentary (ACI 350R-20)

Reported by ACI Committee 350

ACI 350-20

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Reported by ACI Committee 350

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PREFACE

The "Code Requirements for Environmental Engineering Concrete Structures" (Code) portion of this document covers the structural design, materials selection, and construction of environmental engineering concrete structures. Such structures are used for conveying, storing, or treating water and wastewater, other liquids, and solid waste. The term "solid waste" as used in the Code encompasses the heterogeneous mass of disposed-of materials, as well as more homogeneous agricultural, industrial, and mineral wastes.

The Code also covers the evaluation of existing environmental engineering concrete structures.

Environmental engineering concrete structures are subject to uniquely different loadings and severe exposure conditions that require more restrictive serviceability requirements and may provide longer service lives than non-environmental structures.

Loadings include normal dead and live loads, earth pressure loads, hydrostatic and hydrodynamic loads, and vibrating equipment loads. Exposures include concentrated chemicals, alternate wetting and drying, high-velocity flowing liquids, and freezing and thawing of saturated concrete. Serviceability requirements include liquid-tightness, gas-tightness, and durability.

Proper design, materials, and construction of environmental engineering concrete structures are required to produce serviceable concrete that is dense, durable, nearly impermeable, and resistant to relevant chemicals, with limited deflections and cracking. This includes minimizing leakage and control over the infiltration of, or contamination to, the environment or groundwater.

The Code presents additional material as well as modified portions of the ACI 318-05, ACI 318-08, and ACI 318-11 building codes that are applicable to environmental engineering concrete structures.

The Commentary discusses some of the considerations of the committee in developing the ACI 350 Code, and its relationship with ACI 318. Emphasis is given to the explanation of provisions that may be unfamiliar to some users of the Code. References to much of the research data referred to in preparing the Code are given for those who wish to study certain requirements in greater detail.

The chapter and section numbering of the Code are followed throughout the Commentary.

Among the subjects covered are: drawings and specifications, inspections, materials, concrete quality, mixing and placing, forming, embedded pipes, joints, reinforcement details, analysis and design, strength and serviceability, flexural and axial loads, shear and torsion, development of reinforcement, slab systems, walls, footings, precast concrete, prestressed concrete, shell structures, folded plate members, provisions for seismic design, and an alternate design method in Appendix A.

The quality and testing of materials used in the construction are covered by reference to the appropriate standard specifications. Welding of reinforcement is covered by reference to the appropriate AWS standard. Criteria for liquid-tightness and gas-tightness testing may be found in ACI 350.1.

Keywords: chemical attack; coatings; concrete durability; concrete finishing (fresh concrete); concrete slabs, crack width and spacing; cracking (fracturing); environmental engineering; hydraulic structures; inspection; joints (junctions); joint sealers; liners; liquid; patching; permeability; pipe columns; pipes (tubes); prestressed concrete; prestressing steels; protective coatings; reservoirs; roofs; serviceability; sewerage; solid waste facilities; tanks (containers); temperature; torque; torsion; vibration; volume change; walls; wastewater treatment; water; water-cementitious materials ratio; water supply; water treatment.

INTRODUCTION

The Code and Commentary includes excerpts from ACI 318 that are pertinent to ACI 350. The Commentary discusses some of the considerations of ACI Committee 350 in developing this Code. Emphasis is given to the explanation of provisions that may be unfamiliar to users of the standard.

This Commentary is not intended to provide a complete historical background concerning the development of the Code, nor is it intended to provide a detailed summary of the studies and research data reviewed by the committee in formulating the provisions of the Code. However, references to some of the research data are provided for those who wish to study the background material in depth.

As the name implies, "Code Requirements for Environmental Engineering Concrete Structures" may be used as part of a legally adopted Code and, as such, must differ in form and substance from documents that provide detailed specifications, recommended practice, complete design procedures, or design aids.

The Code is intended to cover environmental engineering concrete structures but is not intended to supersede ASTM standards for precast structures.

Requirements more stringent than Code provisions may be desirable for unusual structures. The Code and Commentary cannot replace sound engineering knowledge, experience, and judgment.

A code for design and construction states the minimum requirements necessary to provide for public health and safety. ACI 350 is based on this principle. For any structure, the owner or the structural designer may require the quality of materials and construction to be higher than the minimum requirements necessary to provide serviceability and to protect the public as stated in the Code. Lower standards, however, are not permitted.

ACI 350 has no legal status unless adopted by government bodies having the power to regulate building design and construction. Where the Code has been adopted, it cannot present background details or suggestions for carrying out its requirements or intent. It is the function of the Commentary to fill this need. Where the Code has not been adopted, it may serve as a reference to good practice.

The Code provides a means of establishing minimum standards for acceptance of design and construction by a legally appointed building official or designated representatives. The Code and Commentary are not intended for use in settling disputes between the owner, engineer, architect, contractor, or their agents, subcontractors, material suppliers, or testing agencies. Therefore, the Code cannot define the contractual responsibility of the involved parties. General references requiring compliance with ACI 350 in the job specifications should be avoided, as the contractor is rarely in the position of accepting responsibility for architectural and engineering design details. Generally, the drawings, specifications, and contract documents should contain all the necessary requirements to ensure compliance with the Code. In part, this can be accomplished by reference to specific code sections in the job specifications. Other ACI publications, such as ACI 350.5, "Specifications for Environmental Concrete Structures," are written specifically for use as part of the contract documents for construction.

ACI Committee 350 recognizes the desirability of standards of performance for individual parties involved in the contract documents. Available for this purpose are the certification programs of the American Concrete Institute, plant certification programs of the Precast/Prestressed Concrete Institute and the National Ready Mixed Concrete Association, and qualification standards of the American Society of Concrete Contractors. Also available are "Standard Specification for Agencies Engaged in Construction Inspection and/or Testing" (ASTM E329) and "Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation" (ASTM C1077).

Design aids (general concrete design aids are listed in ACI 318-11):

"Rectangular Concrete Tanks," Portland Cement Association, Skokie, IL, 1998, 182 pp. (Presents data for design of rectangular tanks.)

"Circular Concrete Tanks Without Prestressing," Portland Cement Association, Skokie, IL, 1993, 54 pp. (Presents design data for circular concrete tanks built in or on ground. Walls may be free or restrained at the top. Wall bases may be fixed, hinged, or have intermediate degrees of restraint. Various layouts for circular roofs are presented.)

Concrete Manual, U.S. Department of Interior, Bureau of Reclamation, eighth edition, 1981, 627 pp. (Presents technical information for the control of concrete construction, including linings for tunnels, impoundments, and canals.)

"Design of Liquid-Containing Concrete Structures for Earthquake Forces," Portland Cement Association, Skokie, IL, 2002, 60 pp. (Presents design examples for designing for hydrodynamic forces.)

"Moments and Reactions for Rectangular Plates" Engineering Monograph No. 27, United States Department of the Interior, Bureau of Reclamation, 1990, 100 pp. (Presents design aids for rectangular plates.)

GENERAL COMMENTARY

Environmental engineering concrete structures are subject to stringent service conditions and should be designed for extended service life expectancy and detailed with care. The quality of concrete is important, and rigorous quality control must be maintained during construction to obtain dense, durable concrete suitable for the expected service conditions.

Environmental engineering concrete structures for the containment, treatment, or transmission of liquid such as water and wastewater as well as solid waste disposal facilities, should be designed and constructed to be liquid-tight, and where required, gas-tight, with minimal leakage under normal service conditions.

The liquid-tightness and gas-tightness of a structure will be reasonably assured if:

a) The concrete mixture is properly proportioned, mixed, placed, consolidated, finished, and cured.

b) Crack widths and depths are minimized.

c) Joints are properly spaced, sized, designed, waterstopped, and constructed.

d) Adequate reinforcing steel is provided, properly detailed, fabricated, and placed.

e) Impervious protective coatings or barriers are used where required.

Usually it is more economical and dependable to resist liquid or gas permeation through the use of quality concrete, proper design of joint details, and adequate reinforcement, rather than by means of an impervious protective barrier or coating. Liquid-tightness or gas-tightness can also be obtained by appropriate use of shrinkage-compensating concrete. However, the engineer must recognize and account for the limitations, characteristics, and properties of shrinkage-compensating concrete as described in ACI 223 and ACI 224.2R.

Reduced permeability of the concrete is obtained by lowering the water-cementitious materials ratio as low as possible, without sacrificing acceptable workability and consolidation. Permeability decreases dramatically with extended periods of moist curing. In some cases, surface treatments can be an alternative to moist curing. Reduced permeability of the concrete surface can be achieved through the use of smooth forms or by troweling.

Air entrainment increases consolidation, reduces segregation and bleeding, increases workability, and provides resistance to the effect of freezing-and-thawing cycles. Other admixtures, such as water reducers, are useful, as they increase workability and improve consolidation while lowering the water-cementitious materials ratio (w/cm), which can increase strength characteristics. Use of some supplementary cementitious materials can also provide similar benefits. In addition, supplementary cementitious materials can also reduce permeability, increase durability, and extend service life.

Joint design should also account for movement resulting from thermal dimensional changes, differential settlements, and shrinkage strains induced by placement sequencing. Joints that form a barrier to the passage of liquids and gases are required to include waterstops in complete, closed circuits. Proper rate of concrete placement operations, adequate consolidation, and proper curing are also essential to control of cracking in environmental engineering concrete structures. Additional information on cracking is contained in ACI 224R and ACI 224.2R.

The design of the entire environmental engineering concrete structure as well as all individual members should be in accordance with the Code, which has been adapted from ACI 318. When all relevant loading conditions are considered, the design should provide adequate safety and serviceability, with a service life significantly greater than the service life expected if these structures were designed following the provisions of ACI 318. Some components of the structure, such as jointing materials, have a shorter life expectancy and will require maintenance or replacement.

The size of elements and amount of reinforcement should be selected on the basis of the serviceability and stress limits to promote long service life.

CONTENTS

CHAPTER 17—PRECAST CONCRETE, p. 369

CHAPTER 18—COMPOSITE CONCRETE FLEXURAL MEMBERS, p. 377

CHAPTER 19—PRESTRESSED CONCRETE, p. 381

CHAPTER 20—SHELLS AND FOLDED PLATE MEMBERS, p. 413

CHAPTER 21—LIQUID-CONTAINING GROUND-SUPPORTED SLABS, p. 423

CHAPTER 22—STRENGTH EVALUATION AND CONDITION ASSESSMENT OF STRUCTURES, p. 429

APPENDIX A—ALTERNATE DESIGN METHOD, p. 437

APPENDIX B—STRUT-AND-TIE MODELS, p. 447

APPENDIX C—ALTERNATIVE PROVISIONS FOR REINFORCED AND PRESTRESSED CONCRETE FLEXURAL AND COMPRESSION MEMBERS, p. 463

APPENDIX D—ALTERNATIVE LOAD FACTORS, STRENGTH REDUCTION FACTORS, AND DISTRIBUTION OF FLEXURAL REINFORCEMENT, p. 471

CODE

CHAPTER 1—GENERAL REQUIREMENTS

1.1—Scope

1.1.1 Except for primary containment of hazardous materials, this Code, where adopted under the requirements of the legally adopted building code, provides minimum requirements for the design and construction of reinforced concrete elements of environmental engineering concrete structures. In areas without a legally adopted building code, this Code defines minimum acceptable standards for materials, design, and construction practice. This Code also covers the strength

COMMENTARY

CHAPTER R1—GENERAL REQUIREMENTS

R1.1—Scope

The American Concrete Institute **"Code Requirements for Environmental Engineering Concrete Structures (ACI 350-20),"** hereinafter referred to as this Code, provides minimum requirements for environmental engineering concrete design and construction practices.

The 2020 edition of this Code revised the previous code, ACI 350-06. This Code includes in one document the requirements for all reinforced concrete used for environmental engineering structures. This covers the spectrum of concrete containing nonprestressed reinforcement, prestressing steel, or composite steel shapes, pipe, or tubing.

Prestressed concrete is included under the definition of reinforced concrete. Provisions of this Code apply to prestressed concrete except those that are specifically stated to apply to nonprestressed concrete.

Chapter 13 of this Code contains provisions for design and detailing of earthquake-resistant structures. Refer to 1.1.9.

Appendix A of this Code contains provisions for an alternate method of design for nonprestressed reinforced concrete members using service loads (without load factors) and permissible service load stresses. The strength design method of this Code is intended to give design results similar to the Alternate Design Method.

Appendix B of this Code contains provisions for the design of regions near geometrical discontinuities, or abrupt changes in loadings.

Appendix C of this Code contains provisions for reinforcement limits based on $\mathbf{0.75}\rho_b$, determination of the strength reduction factor ϕ, and moment redistribution that have been in the ACI 318 codes for many years, including ACI 318-99. The provisions are applicable to reinforced and prestressed concrete members. When used, the provisions of Appendix C are to be used in their entirety.

Appendix D of this Code permits the use of load, environmental durability, strength reduction factors, and flexural reinforcement distribution provisions similar to those in Chapters 9 and 10 of ACI 350-01. Designs made using the provisions of Appendix D are equally acceptable as those based on the body of this Code, provided the provisions of Appendix D are used in their entirety.

Appendix E of this Code contains provisions for anchoring to concrete.

R1.1.1 A hazardous material may be defined as a liquid, solid, gas, or sludge waste that contains properties that are dangerous or potentially harmful to human health or the environment. The Environmental Protection Agency (EPA) listed wastes are organized into three categories under the Resource Conservation and Recovery Act (RCRA): source-specific wastes, generic wastes, and commercial chemical products. Source-specific wastes include sludges and waste-

CODE

evaluation and condition assessment of environmental engineering concrete structures.

In this Code, the term "concrete" shall also include shotcrete except where specifically indicated otherwise.

The specified concrete compressive strength shall not be less than 4000 psi. No maximum specified compressive strength shall apply unless restricted by a specific Code provision.

1.1.1.1 Environmental engineering concrete structures are defined as concrete structures intended for conveying, storing, or treating water, wastewater, or other liquids and non-hazardous materials such as solid waste, and for secondary containment of hazardous liquids. For ancillary structures for which liquid-tightness, gas-tightness, or enhanced durability are essential, design considerations shall also conform to requirements of environmental engineering concrete structures.

1.1.2 Precast concrete environmental structures designed and constructed in accordance with ASTM standards are not covered in this Code.

1.1.3 This Code supplements the general building code and shall govern in all matters pertaining to design and construction of reinforced concrete elements of environmental engineering concrete structures, except wherever this Code is in conflict with requirements in legally adopted codes addressing environmental engineering concrete structures.

COMMENTARY

waters from treatment and production processes in specific industries such as petroleum refining and wood preserving. The list of generic wastes includes wastes from common manufacturing and industrial processes such as solvents used in degreasing operations. The third list contains specific chemical products such as benzene, creosote, mercury, and various pesticides.

Shotcrete is pneumatically placed whereas other types of concrete are typically placed by gravity or pumped.

Below-grade structures, such as pump stations and pipe galleries, which are part of treatment facilities and which may be exposed to external groundwater pressures, generally are designed as environmental engineering concrete structures. Above-grade building structures that are not directly exposed to liquids, solid wastes, corrosive chemicals, corrosive gases, or high humidity associated with treatment facilities generally may be designed in accordance with the general building code or applicable industry standards. Nevertheless, consideration of corrosive effects on such structures may still be advisable.

R1.1.1.1 Environmental engineering concrete structures include but are not limited to tanks, reservoirs, clarifiers, separators, lagoon liners, and secondary containment structures. Also included are hydraulic structures associated with flood control and water supply projects such as stilling basins, channels, portions of power houses, spillway piers, spray walls, training walls, flood walls, intake and outlet structures, flood control tunnels and shafts, energy-dissipating structures such as impact basins, lock walls, guide and guard walls, canal linings, and reinforced sections of concrete gravity dams.

R1.1.2 Although precast environmental concrete structures designed and constructed in accordance with ASTM standards are not included in the scope of this Code, the licensed design professional should evaluate whether additional requirements may be necessary to minimize deterioration and to achieve the desired durability and service life of the structure. For example, ASTM C478 allows a maximum *w/cm* of 0.53 and the standard has no criteria that will permit addressing service conditions where the concrete may be exposed to freezing and thawing, harmful chemicals and gases, or harmful sulfates, all of which could accelerate deterioration and reduce durability of the structure and the expected service life.

R1.1.3 The American Concrete Institute recommends that this Code be adopted in its entirety; however, it is recognized that when this Code is made a part of a legally adopted general building code, that general building code may modify some provisions of this Code.

CODE

1.1.4 This Code shall apply in all matters pertaining to design, construction, and material properties wherever this Code is in conflict with requirements contained in other standards referenced in this Code.

1.1.5 The provisions of this Code shall govern for tanks, reservoirs, and other reinforced concrete elements of environmental engineering concrete structures. For special structures such as arches, bins and silos, blast-resistant structures, and chimneys, provisions of this Code shall govern where applicable. When an environmental concrete structure may be considered a building structure then it shall be designed to the requirements of this Code.

COMMENTARY

R1.1.5 Environmental engineering projects can contain several types of structures. For example, a treatment plant can contain environmental engineering concrete structures such as tanks and reservoirs, as well as an administration building. The ACI 350 Code would apply to the environmental structures, while ACI 318 could apply to the administration building. Also, the following ACI publications could apply to other structures.

"Code Requirements for Reinforced Concrete Chimneys (ACI 307-08) and Commentary" by ACI Committee 307. This standard prescribes material, construction, and design requirements for circular cast-in-place reinforced chimneys. It sets forth minimum loadings for the design of reinforced concrete chimneys and contains methods for determining the stresses in the concrete and reinforcement required as a result of these loadings.

"Design Specification for Concrete Silos and Stacking Tubes for Storing Granular Materials (ACI 313-16) and Commentary" reported by ACI Committee 313. This specification provides material, design, and construction requirements for reinforced concrete bins, silos, and bunkers and stave silos for storing granular materials. It includes recommended design and construction criteria based on experimental and analytical studies plus worldwide experience in silo design and construction.

Bins, silos, and bunkers are special structures, posing special problems not encountered in normal building design. While ACI 313 refers to **"Building Code Requirements for Structural Concrete (ACI 318)"** for many applicable requirements, it provides supplemental detail requirements and ways of considering the unique problems of static and dynamic loading of silo structures. Much of the criteria are empirical, but this specification does not preclude the use of more sophisticated methods that give equivalent or better safety and reliability.

ACI 313 sets forth recommended loadings and methods for determining the stresses in the concrete and reinforcement resulting from these loadings. Methods are recommended for determining the thermal effects resulting from stored material and for determining crack width in concrete walls due to pressure exerted by the stored material. Appendixes provide recommended minimum values of overpressure and impact factors.

"Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-06) and Commentary" reported by ACI Committee 349. This standard provides minimum requirements for design and construction of concrete structures that form part of a nuclear power plant and that have nuclear safety-related functions. This stan-