

ACI 357.3R-14

Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures

Reported by ACI Committee 357



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Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures

Reported by ACI Committee 357

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Samuel X. Yao

Consulting Members
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James N. Reed

Steven W. G. Yee

*Deceased

Waterfront and coastal concrete marine structures are exposed to severe environmental conditions for which concrete is ideally suited. These conditions include wind; waves, including seiches and tsunamis; ice and ship impact; abrasion and impact from floating debris; passing vessel effects; and seismic events. As many of these structures are pile-supported, the seismic loading can be critical and, therefore, a discussion of piles and their installation is included in this guide. Also provided are the measures that can be taken to minimize the undesirable effects of these environmental factors and reduce the potential for serious problems.

This guide also defines waterfront and coastal concrete marine structures, discusses materials that can be used to construct them, describes potential durability issues and how to mitigate them, and presents sustainability and serviceability requirements. Design loads, analysis techniques, design methodology, and construction considerations are also presented. Other topics include quality control (QC), above-water and below-water inspection of these structures, and repair of damaged structures. The materials, processes, QC measures, and inspections described in this guide should be tested, monitored, or performed as applicable only by qualified individuals holding the appropriate ACI certifications or equivalent.

Keywords: construction procedures; durability; inspection; marine structures; materials, quality control; serviceability; sustainability; structural analysis; structural design.

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CHAPTER 1—GENERAL

1.1—Introduction

The use of properly designed, durable, and sustainable concrete is an economical approach to the design of marine structures. Except for some criteria in **ACI 357R** and specialized criteria in other ACI guides on durability, there are no comprehensive guidelines or standards that cover the application of concrete in the marine environment for coastal marine structures. Current building codes and ACI standards do not address the requirements unique to the design of these structures, with the exception of special applications or requirements for piles and concrete durability. This guide provides design guidance for the use of concrete for coastal marine structures, and is intended to complement other design manuals and guides used for this purpose.

1.2—Scope

This guide primarily covers marine structures used for berthing marine vessels in protected harbors, and for supporting the associated loads. Structures covered by this guide include pile-supported platforms, bulkheads, and gravity structures. It is not intended to cover marine structures such as gravity block walls, tunnels, breakwaters, floating structures, or offshore platforms. Emphasis is placed on special considerations for marine concrete and guidance for the design and construction of marine structures. Because of the severe nature of the marine environment and associated loading conditions, certain recommendations in this report are intended to complement the requirements of **ACI 318**.

Existing design guides are used for basic concepts, loadings, marine hardware, and other criteria that affect the use of concrete in marine structures. There are some comprehensive manuals that cover functional and structural guidelines for the design of coastal marine structures (**MIL-HDBK-1025 2006**; **BS 6349-1 to 8**; **Goda et al. 2009**; **EAU 2004**; **Ports, Customs and Free Zone Corporation 2007**; **Werner 1998**; **FEMA P-55 2011**).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

- D = dead loads
- E = earthquake loads
- EI = flexural stiffness
- E_s = modulus of elasticity of steel
- E_v = vertical seismic load

- F = loads due to weight and pressure of fluids with well-defined densities and controllable maximum heights
- F_a = flood load
- H = loads due to weight and pressure of soil, water in soil, or other materials
- I = moment of inertia of an uncracked reinforced concrete cross section
- L = live loads
- L_r = roof live load
- M = moment
- R = response modification factor, or rain load
- S = snow load
- T = cumulative effect of temperature, creep, shrinkage, differential and settlement
- W = wind load
- z_1 = distance between resultants of the internal compressive and tensile ties in strut-and-tie model

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/Tools/ConcreteTerminology.aspx>. The definitions provided herein compliment that resource.

air gap—distance from the underside of the structures deck to the datum high water level.

arctic structures—floating or fixed structures for exploration and production of oil and gas in ice-infested waters above the Arctic Circle.

B-region—a portion of a member where the plane section assumption of flexural theory can be applied.

barge-like structures—a floating vessel with vertical walls and a near-rectangular plan; the bow and stern may be raked or shaped as required.

batter action—the phenomenon that occurs if a horizontal load is applied to a pair of piles connected in an A-frame configuration; one that causes an axial compressive load in the batter pile and a vertical tension load in the vertical pile of the A-frame.

batter piles—piles with a receding upward slope of the outer surface of the pile.

berm—a narrow shelf or ledge typically at the bottom of a slope.

coastal structure—any facility built in close proximity to the ocean.

D-region—The portion of a member within a distance h from a force discontinuity or a geometric discontinuity.

earthquake-induced liquefaction—for soils, the process of making or becoming a liquid.

fixed offshore structures—structures that are founded on the seabed and obtain their stability from the vertical forces of gravity.

floating structures—structures that are temporally, intermittently, or continuously afloat.

graving dock—another term for dry dock, which is a relatively narrow, long basin, into which a vessel can be floated

and the water pumped out, leaving the vessel supported on blocks; used for building or repairing a vessel below the waterline.

gravity structures—see **fixed offshore structures**.

marine growth—a term applied to biofouling organisms that attach themselves to marine structures. The organisms are classified as hard or soft fouling types. Hard (Calcareous) fouling organisms include barnacles, encrusting bryozoans, mollusks, polychaete and other tube worms, and zebra mussels. Examples of soft (noncalcareous) fouling organisms are seaweed, hydroids, algae, and biofilm “slime.” Together, these organisms form a fouling community that increases the drag forces on the structure from waves and tides.

marine structure—any facility built to function in contact with a body of water.

mudline—the top of the soil surface underlying a body of water.

offshore concrete structures—fixed reinforced or prestressed concrete, or both reinforced and prestressed concrete structures, for service in deeper waters far from the shoreline.

offshore terminal—facility built far from the shoreline but connected to the shore by roadways or bridges.

p-delta analysis—analysis to quantify the changes in ground shear or overturning moment, or through axial force distribution at the base of a structural component, or all of the above, due to a lateral displacement.

p-y analysis—Analysis to characterize the lateral load behavior of a single embedded pile.

pier—a platform structure extending from the shore into the sea for use as a landing place or promenade or to protect or form a harbor.

pucher influence field charts—a series of contour plots of influence surfaces for various plate and loading geometries that can be used for deck design. For example, local moments in the deck slab due to wheel loads can be determined.

rip-rap—a loose assemblage of stones erected in water to prevent erosion of a shoreline or foundation.

scour—Erosive action of moving water that removes material, creates holes, or lowers the sea floor adjacent to structures.

slipway—a sloping surface leading down to water on which ships are built or repaired. Marine structures can be moved to and from the water. Also called a marine railway on where ships or vessels can be moved to and from the water.

tidal fluctuations—the rise and fall of the water surface from low tide to high tide levels

waterfront structure—any facility built along the edge of a shoreline.

wharf—a structure built along, or at an angle from, the shore for berthing ships to receive and discharge cargo and passengers.

CHAPTER 3—TYPES AND STRUCTURAL CONFIGURATIONS OF CONCRETE MARINE STRUCTURES

3.1—General definition

The term “marine structure” is usually applied to facilities constructed at or near a river or seashore to perform the functions associated with the activities such as transportation of cargo or people, shore protection, shipbuilding, fishing, recreational, and military and research installations. Detached structures, while physically not connected to the shore, retain close association with the shore in their basic functions. An example would be detached breakwaters. Consequently, detached structures are usually treated in the same way as shore-located or shore-connected facilities. With the growth and expansion of oil exploration and production on the continental shelf, structures erected in the sea for these purposes acquired the name “offshore structures.” A true offshore structure is a facility structurally detached from the shore (a pipeline is not a structural connection) and built to function independently from shore-related activities with complete autonomy.

Based on this definition, offshore terminals, which are sometimes built far from the shoreline to extend mooring and berthing operations into deeper water, cannot be considered as true offshore structures because they are connected to the shore by roadways or bridges. Historically, offshore construction is a relatively recent development; the term “marine structure” was applied to any facility built to function in contact with the seawater. With the appearance of offshore structures as a distinctly different group, the term “marine structure” was retained in engineering practice for the remaining types of marine facilities. In this sense, marine structures can be very broadly defined as “any structure built to function in contact with the seawater, except offshore structures.” The term “waterfront and coastal concrete marine structure” is used in this guide to help differentiate the difference from offshore marine structures. This guide will primarily cover maritime structures used for berthing ships and supporting uniform and transit loads. It is not intended to cover all types of marine structures, including gravity block walls, jetties, breakwaters, and other shore protection structures. Refer to the Coastal Engineering Manual of the Engineer Research and Development Department (ERDC 2002) of the U.S. Army Corps of Engineers for shore protection structures.

3.2—Functional classification

Most frequently, marine structures are defined by their basic function. This classification comes naturally for all types of structures because they are designed and constructed for certain purposes. Marine structures built for nonmilitary applications include seven general groups that can be most readily identified in Table 3.2.

Table 3.2—Functional classification of marine structures

Berthing and mooring facilities	a) General cargo wharves and piers b) Bulk cargo wharves and piers c) Container terminals d) Oil and liquid gas terminals e) Roll-on, roll-off wharves f) Passenger and ferry terminals g) Mooring and turning dolphins h) Single-point moorings* i) Small craft slips
Wave protection	a) Breakwaters* b) Wave deflection walls*
Ship-building and ship repairs	a) Graving docks* b) Floating dry docks* c) Slips d) Travelifts e) Piers f) Outfitting berths
Shore protection	a) Armored slopes* b) Embankments* c) Groins* d) Tidal barriers* e) Concrete-filled slope protection
Seawater crossings and canals	a) Bridges over waterways* b) Underwater tunnels* c) Locks*
Navigation	a) Light towers
Special structures	a) Tidal and wave power generation b) Recreational piers c) Fishing piers d) Floating plants and pump stations* e) Intakes and outfalls f) Structures and reclaimed areas for extension of land-based operations (for example, airports, recreational sports facilities, and residential)

*Not covered in this report.

3.3—Layout and operational terminology

Many important features of marine structures that may affect their operational and design parameters are associated with the facility layout. Structures built along the shore with continuous parallel waterfront and rear land operational areas are called wharves. The terms “quay”, “quaywall”, seawall”, and “dock” are also used to describe berthing/mooring facilities constructed parallel to the shore, although the term “wharf” is widely preferred by American marine structural engineers.

Structures that extend into the seawater at some angle to the shoreline are called piers. Narrow piers for roadways, walkways, and pipe support are frequently referred to as jetties. Large reclaimed areas that extended from the shoreline and have marginal wharves along the remaining three waterfront sides are usually referred to as wide piers. In some major ports, the term “berth” is used to describe a portion of the waterfront allocated for handling of a single ship, while the word “wharf” is reserved for a larger continuous section of the waterfront constructed at a certain period of time. A wharf may consist of several berths.

3.4—Structural configurations

All the terms for description of the functional and operational features of marine structures and their layout as described in this guide can be used in the design documents for a project. However, the content and flow of information in the design documents should be defined on the basis of structural classification. For example, a project task may be described as the design of a passenger pier or an oil terminal. However, the design procedure used to perform this task will be either for a piled platform, sheet pile wall, or gravity structure, depending on the structural configuration chosen for the facility to be designed. A review of existing practice shows that, on the most basic level, there are five structural concepts used for design of marine structures (Fig 3.4):

- 1) Piled platforms
- 2) Bulkheads
- 3) Gravity structures
- 4) Rubble mounds
- 5) Floating structures

These five general groups can be used to create a substantial number of specific structural configurations by combining several structural concepts. For example, sheet pile cells are gravity structures where the fill (providing the gravity-generated stability) is retained by bulkheads; relieving piled platforms are placed behind frontal gravity or bulkhead structures to reduce the lateral pressure from the deck surcharge or crane loads; and bulkheads and rubble-mound dikes are used to retain the fill at the rear of open piled wharves. The design manual cannot address all possible varieties of structural types and configurations, but it can be made useful and relatively concise if the design procedures for the five basic concepts are considered.

3.5—Application of concrete in marine structures

Concrete is widely used in the design of all functional types of marine structures, as well as in all structural concepts described in the previous sections. While steel structures and steel components are also widely used in marine construction, the general industry trend is to limit the application of steel where possible due to the higher durability of concrete in the marine environment. Concrete is used for marine design in all of its traditional forms: cast-in-place, precast, prestressed, pretensioned, post-tensioned, and in combinations of these. A recent design of a large pier included cylinder concrete piles consisting of pretensioned, prestressed sections assembled by post-tensioning, and pile caps that included precast and cast-in-place sections. The composite deck included pretensioned, prestressed planks that served as the forms for cast-in-place topping. At the same time, the prestressed planks were incorporated into the structural design of the deck to create composite action in bending.

Some of the major components of marine structures can be made of steel. The most typical examples of the combined application of concrete and steel are concrete decks on steel-pile wharves, or steel-sheet pile bulkheads with a concrete cap. Gravity structures, with the exception of sheet-pile cells, are made of concrete. Concrete is almost exclusively

used for armor units of rubble mound breakwaters, slope protection, and wharf and pier deck structures.

3.6—Concrete marine structures in contemporary design practice

The application of concrete for marine construction began more than 100 years ago. During this period, a large variety of structural configurations were created by marine designers. At some stages of this process, certain concepts were preferred over others. For example, concrete gravity structures dominated in European design practice prior to World War II, with most of the wharves built of concrete blocks or of large caissons. The development of prestressed concrete pile technology generated considerable growth in the number of piled wharves. There appeared also a distinct difference in the basic approach between designers of American and European schools. In Europe, the traditional approach, based on the idea that the main goal of design is to achieve the most efficient use of structural materials, is still very much alive. Because the design of marine structures is greatly affected by the geotechnical conditions of the site, this approach invariably leads to customizing or tailoring of the design to better suit existing conditions. As a result, a greater variety of structural configurations are created.

In contemporary American practice, the main goal almost universally is to simplify the construction and to minimize construction labor and equipment costs. Consequently, fewer structural types are used and considerable effort is made to increase the application of precast or modular components. The open wharf on concrete piles is emerging as the most popular type of concrete marine structure in the United States. Precast concrete sheet pile bulkheads are widely used as well.

CHAPTER 4—MATERIALS

4.1—General

This chapter discusses the materials used in waterfront and coastal concrete structures. Selected references and experience are included for background information. For a more extensive discussion of concrete durability, refer to [ACI 201.2R](#).

4.2—Cementitious materials

4.2.1 Portland cement—Portland cements of Types I, II, and III corresponding to [ASTM C150/C150M](#) are considered satisfactory for use in a marine environment. Blended hydraulic cements conforming to [ASTM C595/C595M](#) are also considered suitable by some authorities for use in marine concrete. Other types of cement, such as [ASTM C1157/C1157M](#), are also in use in areas where other ASTM cements are not available. These other cements should have demonstrated performance in waterfront and coastal marine structures and be approved by the owner. The tricalcium aluminate (C_3A) content in cement is important to protect against sulfate attack and chloride-induced corrosion of reinforcement. Higher C_3A contents result in increased reinforcement corrosion by bonding with chloride entering

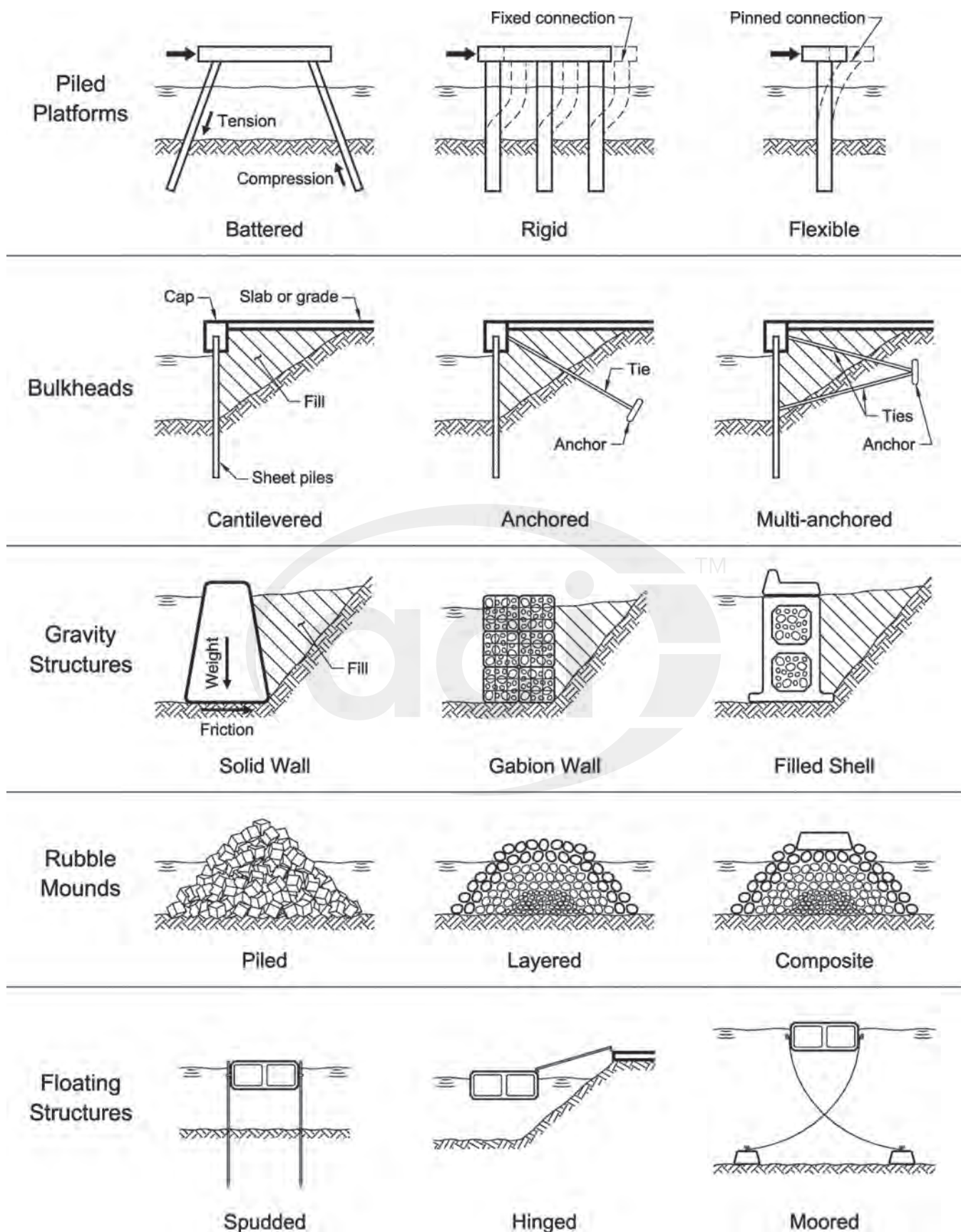


Fig. 3.4—Typical sections of different marine structures.

the concrete. Lower C_3A contents help protect the concrete against sulfate attack. Cement with a C_3A content of 5 to 8 percent is typically recommended in a marine environment to reduce steel corrosion (ACI 201.2R). Because sulfate attack on marine structures is not common compared to chloride ion attack, Type V portland cement generally is not recommended for concrete in a marine environment because of its low C_3A content.

4.2.2 Mineral admixtures—Reductions in the permeability of concrete, alkali-silica reactivity, and sulfate chemical attack may be achieved by the use of fly ash (ACI 232.2R), slag cement (ACI 233R), or silica fume (ACI 234R) as part of the cementitious materials (Mehta and Monteiro 2006; Malhotra and Mehta 2004). The use of fly ash or slag cement can assist in the reduction of heat development in large placements during hydration, reducing the risk of thermal cracking. The use of fly ash (Malhotra and Ramezaniapour 1994) or silica fume (Holland 2005) can also mitigate the effects of alkali-aggregate reactivity (AAR) and can be verified using ASTM C441/C441M and ASTM C311.

Fly ash is available as both Type F and Type C, depending on the type of coal that it originated from; both types have been used in waterfront and coastal concrete structures. Type F fly ash is generally preferred because of durability benefits in concrete in a marine environment. It is shown to have more resistance to alkali-aggregate reactions and sulfate attack than Type C fly ash (Malhotra and Ramezaniapour 1994).

Fly ash and other pozzolans should conform to ASTM C618 and may be used in amounts recommended by ACI 211.4R. Slag is covered by ASTM C989/C989M. Silica fume is used in concrete as a partial replacement or in addition to cement and should conform to ASTM C1240.

4.3—Aggregates

Aggregates for marine structures should conform to ASTM C33/C33M or ASTM C330/C330M. Both standards cover fine and coarse aggregates. Lightweight aggregates (ASTM C330/C330M) are often used in floating concrete structures or to reduce dead load in structures. Use care selecting an aggregate with an appropriate modulus and ultimate strain capacity. The crushing strength, abrasion resistance, and elastic modulus of aggregates are interrelated properties that are greatly influenced by porosity. Aggregates from natural sources are generally dense and strong and, therefore, are seldom a limiting factor to the strength and elastic properties of concrete. With sedimentary rocks, the porosity varies over a wide range, as will the crushing strength and related characteristics. Additional guidance on aggregates and their use can be found in ACI 221R.

The use of reactive aggregates should be avoided. The potential for adverse alkalis in the cement or seawater and silica in the aggregates should be evaluated (ACI 201.2R). Marine sand and aggregates typically should not be used in reinforced concrete. However, in regions where they are the only aggregates available, such as in the Middle East, they can be repeatedly washed to remove deleterious materials. Additional information on aggregates is given in ACI 221R.

4.4—Water

It is preferable to use fresh, clean, potable water in reinforced concrete for marine structures. However, seawater has been used in concrete that does not contain any carbon steel reinforcement or other metallic items. Water used for curing, washing aggregates, and as mixing water should conform to ASTM C1602/C1602M. ASTM C1602/C1602M allows the use of potable water without testing and includes methods for qualifying nonpotable sources of water with consideration of effects on setting time and strength. Testing frequencies are established to ensure continued monitoring of water quality. ASTM C1602/C1602M includes optional limits for chlorides, sulfates, alkalis, and solids in mixing water that can be invoked if appropriate.

4.5—Chemical admixtures

4.5.1 General requirements—Chemical admixtures for concrete may be used for concrete workability or to impart special properties. All admixtures should be compatible with selected concrete materials and other admixtures. Storing, handling, and dispensing admixtures should follow manufacturer's recommendations. Detailed information on chemical admixtures for use in concrete can be found in ACI 212.3R, Mailvaganam and Rixom (1999), Ramachandran (2011), and Spiratos et al. (2003).

4.5.2 Admixtures for water reduction and setting time modification—These admixtures should conform to ASTM C494/C494M. Admixtures for use in producing flowing concrete should conform to ASTM C1017/C1017M. The various classifications for these types of admixtures are as follows:

- a) Type A—water-reducing admixtures
- b) Type B—retarding admixtures
- c) Type C—accelerating admixtures
- d) Type D—water-reducing and retarding admixtures
- e) Type E—water-reducing and accelerator admixtures
- f) Type F—high-range water-reducing admixtures
- g) Type G—high-range, water-reducing, and retarding admixtures

4.5.3 Air-entraining admixtures—Concrete exposed to freezing and thawing conditions should be air entrained. ACI 201.2R gives recommended air contents for frost-resistant concrete. Air-entraining admixtures should conform to ASTM C260/C260M.

4.5.4 Miscellaneous admixtures—There are a large number of other chemical admixtures that can be used in concrete. They include the following:

- a) Gas-forming admixtures
- b) Grouting admixtures
- c) Extended set-control admixtures
- d) Bonding admixtures
- e) Pumping aids
- f) Pigments
- g) Flocculating admixtures
- h) Fungicidal, germicidal, and insecticidal admixtures
- i) Permeability-reducing admixtures
- j) Chemical admixtures to reduce AAR expansion
- k) Corrosion-inhibiting admixtures

- l) Anti-washout admixtures
- m) Freeze-resistant admixtures
- n) Hydration stabilizers

More detailed information on these admixtures can be found in [ACI 212.3R](#). Most of these miscellaneous admixtures are only used for special situations in waterfront and coastal marine concrete structures. Of this list, the more common applications include the use of corrosion-inhibiting admixtures, chemical admixtures to reduce AAR, and permeability-reducing admixtures.

4.5.5 Nonstandard admixtures—Admixtures to be used in concrete that do not conform to [4.5.1](#) and [4.5.2](#) should be evaluated prior to use and approved by the project owner.

4.5.6 Admixture compatibility—If two or more admixtures are used in concrete, their compatibility should be checked and documented in accordance with [ASTM C1679](#).

4.5.7 Chloride-containing admixtures—Calcium chloride or admixtures containing chloride from sources other than impurities in admixture ingredients should not be used in reinforced concrete, prestressed concrete, in concrete containing embedded aluminum, or in concrete cast against stay-in-place galvanized steel forms.

4.6—Concrete

Concrete should be proportioned in accordance with [ACI 211.1](#), [ACI 211.2](#), [ACI 211.3R](#), [ACI 211.4R](#), and [ACI 211.5R](#). The recommended minimum 28-day cylinder compressive strength is 5000 psi (35 MPa), although many marine structures are constructed with concrete strengths that exceed this value.

4.7—Fibers

4.7.1 Introduction—The use of fiber-reinforced concrete or fiber-reinforced shotcrete may be permitted on some construction projects. These fibers are typically steel or polypropylene, but other polymeric type fibers are also available. A standard specification for fiber-reinforced concrete is [ASTM C1116/C1116M](#).

4.7.2 Steel fibers—Steel fibers can be used in concrete to improve certain properties (refer to [ACI 544.3R](#) and [ACI 544.4R](#)), including:

- a) Compressive ductility
- b) Tensile strength and ductility/toughness
- c) Shear strength and ductility
- d) Crack control
- e) Fatigue resistance

Actual properties will depend on the amount and type of fiber used as described in [ACI 544.1R](#). Steel fiber types are defined by [ASTM A820/A820M](#).

4.7.3 Polypropylene fibers—Polypropylene or other synthetic fibers have been used to improve early crack resistance to drying shrinkage. They can also improve the resistance to spalling of concrete in fire that can occur in facilities used in the loading and unloading of hydrocarbon products ([Hoff et al. 1997](#); [Hoff 1998](#)). Documented evidence of satisfactory performance in a temperature range to which the concrete will be exposed in service should be requested

from the producer of the fibers. Documented evidence can be provided by laboratory testing.

Not all types of polymer fiber provide the same level of protection against spalling in fire. Discrete fibers are more effective than fibrillated fibers ([ACI 544.1R](#)). Some research has shown that the proportion of fiber required to prevent spalling is greater in prestressed concrete than normally reinforced concrete, and that the proportion increases with the level of prestress.

4.8—Deformed reinforcement

4.8.1 Carbon steel bars—Deformed carbon steel reinforcing bars should conform to the requirements of [ASTM A615/A615M](#). This specification covers deformed and plain carbon-steel bars for concrete reinforcements in cut lengths and coils. Bars are of four minimum yield strength levels: namely, 40,000, 60,000, 75,000, and 80,000 psi (280, 420, 520, and 550 MPa), designated as Grade 40, 60, 75, and 80 (Grade 280, 420, 520, and 550), respectively. Steel bars containing alloy additions can be permitted if the resulting product meets all other requirements of this specification. The standard sizes and dimensions of deformed bars and their number designations are given in [ASTM A615/A615M](#). Steel specimens should undergo tensile tests and conform to required values of tensile strength, yield strength, and elongation. Steel samples should also undergo deformation, tension, and bend tests.

Welding of [ASTM A615/A615M](#) reinforcement should be approached with caution because no specific provisions have been included to enhance its weldability. As the carbon percentage content of steel rises, steel has the ability to become harder and stronger through heat treating. The steel, however, becomes less ductile through heat treating. Regardless of the heat treatment, higher carbon content reduces weldability. If steel is to be welded, a welding procedure suitable for the chemical composition and intended use or service should be used. The use of [AWS D1.4/D1.4M](#) is recommended, which describes the proper selection of filler metals and preheat/interpass temperatures, as well as performance and procedure qualification requirements.

4.8.2 Low-carbon chromium bars—Low-carbon chromium bars have been used in waterfront and coastal structures where long-term service life was specified. The composition of these bars is such that corrosion is reduced.

These bars are covered by [ASTM A1035/A1035M](#). This specification covers low-carbon chromium steel bars, deformed and plain, for concrete reinforcement in cut lengths and coils. The standard sizes and dimensions of these bars and their number designations are given in [ASTM A1035/A1035M](#). Bars are of two minimum yield strength levels: 100,000 and 120,000 psi (690 and 830 MPa), designated as Grade 100 and 120 (Grade 690 and 830), respectively.

Designers should be aware that typical design standards limit the design strength to 80,000 psi (550 MPa), except for prestressing steel and spiral transverse reinforcement. Members reinforced with bars with yield strengths that are considerably above 80,000 psi (550 MPa) may exhibit behavior that differs from that expected of conventional rein-

forced concrete members, or may require special detailing to ensure adequate performance at service and factored loads. The stress-strain behavior of these bars is different from the **ASTM A615/A615M** bars in that there is no distinct yield stress, although methods of defining it have been developed. Information on the use of these bars in design can be found in **ACI ITG-6R** for Grade 100 bars.

Welding of **ASTM A1035/A1035M** reinforcement should be approached with caution because no specific provisions have been included to enhance its weldability. If this steel is to be welded, a welding procedure suitable for the chemical composition and intended use or service should be used.

4.8.3 Low-alloy bars—ASTM **A706/A706M** for low-alloy bars may be specified if restrictive mechanical properties and chemical composition are required for compatibility with controlled tensile property applications or to enhance weldability.

Bars are of two minimum yield strength levels: 60,000 and 80,000 psi (420 and 550 MPa), designated as Grade 60 and 80 (Grade 420 and 550), respectively. Plain bars, in sizes up to and including 2-1/2 in. (63.5 mm) in diameter can be furnished in cut lengths under this specification. Reinforcing bars up to and including 0.75 in. (19 mm) can be ordered in coils.

ASTM A706/A706M limits the mechanical properties to provide the desired yield/tensile properties for controlled tensile property applications. This specification also limits the chemical composition and carbon equivalent to enhance the weldability of the material. If ASTM A706/A706M steel is to be welded, a welding procedure suitable for the chemical composition and intended use or service should be used. The use of the latest edition of **AWS D1.4/D1.4M** is recommended. This document describes the proper selection of the filler metals, preheat/interpass temperatures, as well as performance and procedure qualification requirements.

4.8.4 Other corrosion-resistant bars

4.8.4.1 Types of corrosion-resistant bars—A number of other types of reinforcing bars that have had limited use for corrosion resistance in waterfront and coastal concrete structures are:

- a) Epoxy-coated
- b) Glass fiber-reinforced polymer (FRP)
- c) Solid stainless steel
- d) Stainless-clad
- e) Hot-dip galvanized

4.8.4.2 Epoxy-coated bars—Epoxy coated bars are covered by **ASTM A775/A775M** or **ASTM A934/A934M**. These specifications cover both deformed and plain steel reinforcing bars. The steel is blast-cleaned and coated with a protective fusion-bonded epoxy coating by electrostatic spray or other suitable method. Steel specimens typically undergo deformation tests, holiday checks, bending tests, and cathodic disbondment test. The specifications include required values of coating thickness, continuity, flexibility, and adhesion.

ASTM A934/A934M is applied to prefabricated reinforcing bar elements that have been prebent or shaped. If the construction project requires epoxy-coated steel reinforcing

bars that should be able to sustain field bending or rebending, the use of coated bars conforming to ASTM A775/A775M may be considered. However, issues about using these bars have occurred as indicated in 4.5.7. Suggested project specifications provisions for epoxy-coated reinforcing bars are presented by **Gustafson (1999)**. Other organic coatings may be used, provided they meet the requirements of these specifications.

4.8.4.3 Solid stainless steel bars—Solid stainless steel bars are covered by **ASTM A1022/A1022M** and **ASTM A276**. These specifications cover stainless steel wire and welded-wire reinforcement produced from hot-rolled stainless steel rod. The stainless steel wire is cold-worked, drawn or rolled, plain (nondeformed), deformed, or a combination of deformed and plain. It is used as concrete reinforcement for applications requiring resistance to corrosion, controlled magnetic permeability, or both. Common wire sizes and dimensions are found in these specifications.

The chemical composition of the steel (stainless grade) should be selected for suitability to the application involved by agreement between the manufacturer and the purchaser. Use ASTM A276 for chemical requirements.

Only austenitic and duplex stainless steels are usually recommended for use as reinforcement in concrete because of their high corrosion resistance. Austenitic stainless steels have good general corrosion resistance, strength characteristics which can be improved by cold working, good toughness and ductility properties at low temperatures, and low magnetic permeability. Duplex stainless steels generally have a corrosion resistance greater than that of most austenitic steels and are magnetic. Other stainless steels with different chemical compositions than the series and types mentioned previously may be used for less-restrictive applications.

The Unified Numbering System (UNS), which is an alloy designation system, is to be included with the type number and noted in brackets—that is, austenitic stainless steels as Type 304 (S30400), 304L (S30403), 316 (S31600), 316L (S31603), 316N (S31651), 316LN (S31653), and duplex stainless steel Types 2205 (S32205) and 329 (S32900).

4.8.4.4 Glass FRP bars—The performance of glass FRP bars is typically defined by their longitudinal tensile strength and elongation. From a tension test, a variety of data are acquired that are needed for design purposes. Material-related factors that influence the tensile response of bars, and that should therefore be reported, include the following: constituent materials; void content; volume percent reinforcement; methods of fabrication; and fiber reinforcement architecture. Much of this information can be obtained from the manufacturer of the bars. Additional information is available in **ACI 440.6**.

ASTM D7205/D7205M test method determines the quasi-static longitudinal tensile strength and elongation properties of FRP matrix composite bars commonly used as tensile elements in reinforced, prestressed, or post-tensioned concrete. Properties, in the test direction, that may be obtained from this test method include

- a) Ultimate tensile strength

- b) Ultimate tensile strain
- c) Tensile chord modulus of elasticity
- d) Stress-strain curve

The strength values provided by this method are short-term static strengths that do not account for sustained static or fatigue loading. Additional material characterization may be required, especially for bars that are to be used under high levels of sustained or repeated loading.

4.8.4.5 Galvanized reinforcement—Galvanized reinforcing bars are produced by hot-dip galvanizing in a bath of molten zinc. The molten zinc reacts with the steel surface of the bars to form stratified zinc-iron alloy layers that are metallurgically bonded to the steel. Galvanized reinforcing bars have been used for more than 50 years and are the standard method of protecting reinforcing steel in many countries.

Individual galvanized reinforcing bars are covered by **ASTM A767/A767M**. Fabricated reinforcing steel bar assemblies are covered by **ASTM A123/A123M**. ASTM A123/A123M also covers the standard requirements for hot-dip galvanized zinc coatings on iron and steel products made from rolled pressed and forged shapes, castings, plates, bars, and strips that can also be used in waterfront and coastal structures. ASTM A767/A767M requires post-treatment of the galvanized bar with a chromate solution, whereas ASTM A123/A123M does not. Where ASTM A767/A767M is specified, ASTM A123/A123M-certified material should not be substituted without prior written approval from the specifier.

Design codes treat carbon steel and galvanized steel the same. The zinc coating on a galvanized piece of steel will add 5 to 7 percent to the original weight. The after-galvanizing weight should be considered when scheduling transportation of galvanized material to avoid over-loading trucks.

4.8.4.6 Stainless-clad bars—**AASHTO M329M/M329** is a standard specification for these types of bars. Additional information and data for specifying these bars can be obtained from the bar supplier and manufacturer.

4.8.4.7 Zinc and epoxy dual-coated steel reinforcing bars—**ASTM A1055/A1055M** covers deformed and plain steel reinforcing bars with a dual coating of zinc alloy and an epoxy coating. The zinc alloy layer is applied by a thermal spray coating method that is followed by an epoxy coating.

4.9—Prestressing systems

4.9.1 Introduction and definitions—Prestressing systems can be either pretensioned or post-tensioned. Both systems are used in waterfront and coastal structures. In a pretensioned structural element, the prestressing strands or bars are tensioned prior to casting the section. Pretensioning is normally performed at precasting plants. Post-tensioning is defined as when the prestressing tendons are tensioned after the concrete has been cast and has achieved a required level of strength. Prestressed reinforcement used in waterfront and coastal structures can include single strands and wires, multistrand tendons, and bars. The materials used in these systems are similar and are described in the following sections. Prestressing systems have been developed by competitive companies and, although they may have

different approaches and different preferences for some of the materials, the end-results should comply with the project specifications. More detailed information can be found in the Prestressed Concrete Institute (PCI) *Design Handbook* (PCI 2010), **ACI 423.7**, and **PTI M50.3-12**.

4.9.2 Single strands—**ASTM A421/A421M** covers two types of uncoated, stress-relieved, round, high-carbon steel wire commonly used in prestressed linear concrete construction. Type BA wire is used for applications in which cold-end deformation is used for anchoring purposes (button anchorage). Type WA wire is used for application in which the ends are anchored by wedges and no cold-end deformation of the wire is involved (wedge anchorage). Additional information on unbonded single-strand tendons is found in **PTI M10.2-00**.

4.9.3 Multistrand tendons—**ASTM A416/A416M** and **ASTM A882/A882M** are both applicable to multistrand tendons.

ASTM A416/A416M covers two types and two grades of seven-wire, uncoated steel strand for use in pretensioned and post-tensioned prestressed concrete construction. The two types of strand are low-relaxation and stress-relieved (normal-relaxation). Low-relaxation strand should be regarded as the standard type. Stress-relieved (normal-relaxation) strand will not be furnished unless specifically ordered, or by arrangement between purchaser and supplier. Grades 1725 and 1860 (Grades 250 and 270) have minimum ultimate strengths of 250 and 270 ksi (1725 and 1860 MPa), respectively, based on the nominal area of the strand.

ASTM A882/A882M specification covers filled epoxy-coated seven-wire prestressing steel strands. This specification also covers relaxation loss limits for filled epoxy-coated strands. It covers ASTM A416/A416M low-relaxation Grade 250 and Grade 270 seven-wire prestressing steel strand with protective fusion-bonded epoxy coating applied by the electrostatic deposition method, or other method that will meet the coating requirements of the specification so that the interstices of the seven wires are filled with epoxy to minimize migration of corrosive media, either by capillary action or other hydrostatic forces.

4.9.4 Prestressing bars—**ASTM A722/A722M** covers uncoated high-strength steel bars intended for use in pretensioned and post-tensioned prestressed concrete construction or in prestressed ground anchors. Bars are of a minimum ultimate tensile strength level of 150 ksi (1035 MPa). Two types of bars are included: Type I bar has a plain surface and Type II bar has surface deformations.

4.10—Prestressing anchorages

For post-tensioned concrete, those parts of prestressing anchorages—the wedge plate and anchor head—that transfer the prestress load during service should be fabricated from alloy steels or ductile iron that comply with project ductility requirements as applicable for the service temperature. Other materials—for example, cast iron—can be used for parts of prestressing anchorages if performance satisfactory to the designer is demonstrated by means of appropriate tests.

Typically, once the prestressing ducts have been grouted, the end-anchorage could be redundant.

4.11—Prestressing ducts

4.11.1 General—Ducts for grouted tendons should be mortar-tight and nonreactive with concrete, prestressing steel, grout, and corrosion inhibitor. Prestressing ducts can be rigid or flexible and made of ferrous metal or polymeric material. The choice of duct system is an important factor in the durability of a post-tensioned tendon. Allowable duct types should be stipulated in the contract specifications.

Some contract specifications require that the duct enclosures for prestressing steel be rigid ferrous metal, galvanized, and mortar-tight; however, other rigid ducts as described in this guide are also suitable. The rigid duct is used to take advantage of the low tendon-to-duct friction inherent with rigid duct. The rigid duct is stiff enough to eliminate horizontal wobble, but flexible enough to bend and meet the required tendon profiles.

Ducts are generally described as:

- a) Corrugated steel
- b) Smooth, rigid steel pipe
- c) Polymeric ducts

4.11.1.1 Corrugated steel—Ducts are spirally wound to the necessary diameter from strip steel with a minimum wall thickness of 26-gauge (0.45 mm) for ducts less than 2-5/8 in. (66 mm) diameter or 24-gauge (0.6 mm) for ducts of greater diameter. The strip steel should be galvanized to **ASTM A653** with a coating weight of G90. Ducts should be manufactured with welded or interlocking seams with sufficient rigidity to maintain the correct profile between supports during concrete placement. Ducts should also be able to flex without crimping or flattening. Joints between sections of duct and between ducts and anchor components should be made with positive, metallic connections that provide a smooth interior alignment with no lips or abrupt angle changes.

4.11.1.2 Smooth, rigid steel pipe—Smooth steel pipes should conform to **ASTM A53/A53M**, Grade B Schedule 40. When required for curved tendon alignments—for example, deviation saddles and similar—the pipe should be prefabricated to the required radius.

4.11.1.3 Polymeric ducts—Polymeric ducts for post-tensioning are corrosion-resistant. The plastic encapsulation of the prestressing steel acts as a seamless, water-tight barrier to corrosive substances and extends the life of the post-tensioning. With special details, some duct systems can provide electric isolation of the tendon. Polymeric ducts are available in high-density polyethylene (HDPE) and polypropylene. These plastics have lower friction than standard metal ducts. The lower friction may result in savings of post-tensioning strands. In elements subjected to fatigue loading—for example, from waves or other sources—plastic duct improves the fatigue life of the tendon because the plastic duct is a better friction partner than a steel duct. Ducts can be round, oval, or flat. In smaller diameters, round ducts can come in long coils, reducing the number of duct splice locations. In larger diameters, round ducts come in

straight, shippable lengths of 15 to 40 ft (4.5 to 12 m). Oval ducts are available to facilitated installation in thin elements such as webs of precast girders. Flat ducts, which accommodate a single layer of two to five strands, are frequently used in thin elements such as slabs because this maximizes the available tendon eccentricity. The choice of HDPE or polypropylene will depend on installation temperatures. One material handles better at low temperatures, while the other handles better at high temperatures.

Plastic ducts made for post-tensioning are distinctly different than the regular corrugated plastic pipe available at the local hardware store. Tendon profiles usually include curves. The stands will push against the duct toward the inside of the curves. Post-tensioning ducts should have sufficient wall thickness and flat sections between corrugations so that the strands will not rub through the duct during post-tensioning. With regular corrugated plastic pipe, strand can rub through the duct at high points of the corrugation at the inside of tendon curves, resulting in loss of encapsulation and in higher friction if the strand starts rubbing the concrete. Occasionally, smooth-walled plastic pipe is used when bonding the prestressing steel to the concrete is not required. For most applications, bonded tendons are required. In this case, the profile of the corrugations and the wall thickness of the post-tensioning duct should be such that there is mechanical overlap of the grout in the corrugation rib and the concrete on the outside to achieve mechanical bond. Ducts can be spliced by a variety of methods, including: fusion welding, mechanical couplers incorporating one or more gaskets to ensure that the ducts do not leak, heat-shrink sleeves, threaded connectors, or a bell-and-spigot detail that is made secure and watertight with duct tape. Plastic duct, which should be well-supported, may require a half-shell saddle at support locations to prevent local denting of the duct.

Corrugated plastic duct to be completely embedded in concrete should be constructed from either polyethylene or polypropylene. Polyvinyl chloride (PVC) is generally not permitted for use in concrete structures due to the potential for long-term breakdown of the PVC and associated release of chlorides over the service life of the structure. The minimum acceptable radius of curvature should be established by the duct supplier according to standard test methods. Polyethylene duct should be fabricated from resins meeting or exceeding the requirements of **ASTM D3350** with a cell classification of 344434C. Polypropylene duct should be fabricated from resins meeting or exceeding the requirements of **ASTM D4101** with a cell classification range of PP0340B44544 to PP0340B65884. The duct should have a minimum material thickness of 0.079 in. + 0.010 in. (2.0 mm + 0.25 mm). Ducts should have a white coating on the outside or be of white material with ultraviolet stabilizers added.

High-density polyethylene ducts have been used with external tendons. As HDPE does not corrode in a chloride environment, it is well suited for waterfront and coastal concrete structures. High-density polyethylene duct is available in different diameters, wall thickness, and phys-

ical and chemical properties. There is significant variability in commonly available materials. It is essential that it has satisfactory properties for handling, storage, installation, and durability for the application. The color is normally black from a small amount of carbon in the material that protects against degradation from ultraviolet light. The wall thickness, diameter, and physical strength should be sufficient to initially withstand grouting pressures. In the long term, it should not deteriorate or split. Requirements should be in accordance with **AASHTO HB-17**.

Unless otherwise specified, nominal internal area of the duct for grouted tendons should be a minimum of 2-1/4 times the prestressing strand and 2-1/2 times for tendons placed by the pull-through method. For tendons made up of a single wire, bar, or strand, the duct diameter should be at least 1/4 in. (6.35 mm) larger than the nominal diameter of the wire, bar, or strand (**ACI 301**). Duct vents are usually required on very long ducts and are typically located within 6 ft (1.8 m) of a high point in the duct profile. Vent holes may also be placed at positions recommended by the post-tensioning supplier.

4.12—Grout for bonded prestressing tendons

4.12.1 Types of grouts and general requirements—Grout provides bond between the post-tensioning strands, tendons, or bars and the concrete and also provides corrosion protection for them.

The minimum compressive strength of the grout, as measured by cubes, should be 125 percent of the design concrete compressive strength, as measured by cylinders in order to have the grout strength match the concrete strength. Guidance on grouts can be found in the Post-Tensioning Institute (PTI) Grouting Specification **PTI M55.1-12**.

Grout should consist of portland cement and water; portland cement, sand, and water; or a 100 percent solids, two-component epoxy resin system. Epoxy grout has been used in limited applications. Grout properties should be reviewed, including differences in the coefficient of thermal expansion and heat generation.

4.12.2 Portland-cement grout—Cement for grouting operations should be Type I or Type II in accordance with **ASTM C150/C150M**. Cement used in the work should be the same as that on which selection of grout proportions was based. Past success with grout for bonded tendons has been with portland cement. A blanket endorsement of all cementitious material (as defined in 4.2) for use with this grout may not be appropriate because of a lack of experience or tests with cementitious materials other than portland cement, as well as concern that some cementitious materials might introduce chemicals listed as harmful to tendons.

4.12.3 Water—Water should conform to 4.4.

4.12.4 Sand—Only large ducts with large void areas should consider using finely graded sand in the grout. Sand, if used, should conform to **ASTM C144** except that gradation should be permitted to be modified as necessary to obtain satisfactory workability.

4.12.5 Admixtures—Admixtures are generally used to increase grout workability, reduce bleeding and shrinkage,

or provide expansion. This is especially desirable for grouting of vertical tendons. Substances known to be harmful to prestressing tendons, grout, or concrete are chlorides, fluorides, sulfites, and nitrates. Aluminum powder or other expansive admixtures should produce an unconfined expansion of 5 to 10 percent. Admixtures conforming to 3.5 and known to have no injurious effects on grout, steel, or concrete should be permitted. The limitations on admixtures in 3.5 also apply to grout. Calcium chloride should not be used.

4.12.6 Epoxy grout—Epoxy grout should be moisture insensitive and have a low exotherm to prevent overheating of the epoxy.

CHAPTER 5—DURABILITY

5.1—General

Durability of concrete relates to its ability to resist weathering, freezing and thawing, chemical attack, reinforcement corrosion, abrasion, or other deterioration processes. Good concrete durability is essential for the improved sustainability of the structure. For a more extensive discussion of concrete durability, refer to **ACI 201.2R**.

5.2—Exposure zones

For concrete structures in marine environments, durability is generally considered to be a function of the zone of exposure. Four zones are commonly defined as in the following.

5.2.1 Submerged zone—Concrete is continuously covered by seawater. It is typically defined as any element, or portion thereof, that is located below mean lower low water (MLLW). In areas with minimal tides, it is defined as that portion of the element below mean sea level (MSL).

5.2.2 Tidal zone—Concrete is regularly wetted by tides. This is typically any element, or portion thereof, that is located between MLLW and mean higher high water (MHHW). In areas with minimal tides, this would be defined as the area located between MSL and mean high water (MHW).

5.2.3 Splash zone—Concrete is predominantly dry, but is likely wetted by wave action and wind-driven spray.

5.2.4 Atmospheric zone—Concrete is not directly exposed to seawater, but is exposed to ocean air and winds carrying sea salts. The atmospheric zone is any portion of the waterfront structure above the splash zone.

For waterfront and coastal concrete structures, the most critical corrosion problem is due to penetration of chloride ions that are naturally present in seawater. Because the three primary elements required for corrosion (chlorides, water, and oxygen) are most abundant in the tidal and splash zones, parts of the structure in these zones are most susceptible to damage. This has been confirmed by field surveys. In the tidal and splash zones, chloride concentrations build up because of alternating cycles of wetting and drying. Therefore, more chloride ions are available to penetrate the concrete than in submerged zones where concentration is limited to the chloride content of seawater. In addition, more oxygen is available in the tidal and splash zones than in submerged zones.

submerged zone. The tidal and splash zones are considered the most critical with regard to concrete durability.

5.3—Marine durability problems

Major types of durability problems that should be considered for coastal marine concrete structures include:

- a) Chemical attack
- b) Freezing-and-thawing damage
- c) Corrosion of reinforcement
- d) Abrasion

5.3.1 Chemical attack

5.3.1.1 Sulfate attack—Sulfate attack can occur on concrete in seawater due to the presence of sulfates in seawater. Those sulfates can occur naturally in the seawater, can come from industrial sources dumping into the sea, or if concrete structures are placed on reclaimed coastal areas with foundations below saline groundwater level. In the latter case, capillary suction and evaporation may cause super-saturation and crystallization in the concrete above ground. Another potential source of chemical attack is at-bulk handling facilities. Sulfate attack has occurred in piles in a marine environment.

Although a low C_3A content is usually recommended to reduce sulfate attack, Type V cement is not recommended for concrete in a typical marine environment. The principal chemical attack on concrete in seawater comes from the chloride ions and these can be captured, to some degree, by the C_3A . The reduced C_3A content of Type V cement works against mitigating the influence of chloride ions penetrating the concrete. Where the waterfront and coastal concrete structures are in areas where there is industrial pollution that significantly increases the sulfate content of the seawater and adjoining soils, the use of ASTM Type I, II, or III cements combined with Class F fly ash, slag cement, or silica fume will adequately protect against sulfate attack and provide some protection against chloride in a marine environment. Concrete containing silica fume and Type I cement has been shown to be equivalent to Type V cement in sulfate environments (Rasheeduzzafar et al. 1990).

Delayed ettringite formation (DEF) is also a form of chemical sulfate attack if the source of the sulfate ions is internal (within the concrete) rather than external (in the seawater) (Mehta and Monteiro 2006; Collepardi 1999). Some instances of DEF in waterfront and coastal concrete structures have been reported. It is known to occur if either a gypsum-contaminated aggregate or cement containing unusually high sulfate content has been used in the concrete production. Some researchers believe that the problem occurs principally in steam-cured concrete elements or if the concrete internal temperature exceeds 175°F (80°C). These higher temperatures can occur in large caissons cast with low water-cement ratio (w/c) contents. ACI 301 recommends that the maximum temperature in mass concrete after placement should not exceed 158°F (70°C).

The best protection against sulfate attack is a high-quality, low-permeability concrete. Factors leading to low permeability are high cementitious content, use of supplementary cementitious materials (fly ash, silica fume, ground blast-

furnace slag), low w/c, proper consolidation, and adequate curing (Mehta and Monteiro 2006).

5.3.1.2 Alkali-aggregate reactivity—Alkali-aggregate reactivity (AAR) is the reaction of alkalis from cement or seawater with reactive siliceous aggregates. The resulting reaction leads to expansion and cracking of the concrete, which leads to reduced strength. Popouts and exudation of a viscous alkali-silicate fluid are other manifestations of the phenomena. The most important factors influencing the phenomena are as follows (Mehta and Monteiro 2006):

- a) The alkali content of the cement and the cement content of the concrete;
- b) The alkali-ion contribution from sources other than portland cement, such as admixtures, salt-contaminated aggregates, and penetration of seawater into the concrete;
- c) The amount, size, and reactivity of the alkali-reactive constituent present in the aggregate;
- d) The availability of moisture to the concrete structure;
- e) The ambient temperature.

For waterfront and coastal structures, there is little control of items d) and e) in the previous list. The other three items—a), b) and c)—can be addressed in the project specifications as follows:

- a) Use low-alkali portland cement (less than 0.6 percent equivalent Na_2O);
- b) If a low-alkali portland cement is not available or if the cement content is high where the total amount of alkalis in the concrete is elevated, replace a portion of the cement with supplementary cementing materials (fly ash, silica fume, and ground blast-furnace slag).

If beach sand or sea-dredged sand and gravel are to be used, they should be washed, repeatedly if necessary, with potable water to ensure that the total alkali content is less than 5 lb/yd³ (3 kg/m³). Aggregates under consideration for the concrete should be evaluated in accordance with ASTM C1293. This test method is intended to evaluate the potential of an aggregate or combination of an aggregate with pozzolan or slag to expand deleteriously due to any form of AAR. The test duration is 1 year and evaluations of potential aggregate sources should begin while the project is in the planning stage. ASTM C1260 is often specified to determine the reactivity of proposed aggregates but has been shown to be overly conservative for a number of aggregate types (Ideker et al. 2012). It is also very useful to visually examine comparable in-service concrete made with the proposed aggregate for indications of AAR distress. Preferably, that concrete should be at least 5 years old.

5.3.2 Freezing-and-thawing damage—Deterioration of concrete exposed to freezing conditions can occur if there is sufficient internal moisture present that can freeze at the given exposure conditions. Moisture can be from either an internal or external source. Internal water is water that is already in the pores of concrete that can be redistributed by thermodynamic conditions to provide a high enough degree of saturation at the point of freezing to cause damage. External water is water entering the concrete from an external source such as rainfall, water from maintenance activities, or from the seawater, and spray from wave action on or near the struc-

ture. Dry concrete, generally below approximately 75 to 80 percent internal relative humidity (RH), is normally immune to damage from freezing.

Resistance to freezing and thawing of a concrete mixture is substantially improved by incorporating entrained air voids into the concrete (5.5.3). Additional guidance is provided in [ACI 201.2R](#).

5.3.3 Corrosion of reinforcement—Concrete provides protection against corrosion of embedded steel because of the highly alkaline environment provided by the portland-cement paste. Adequacy of protection depends on the amount of concrete cover, concrete quality, construction details, degree of exposure to chlorides (from concrete component materials and the environment), and the service environment. Refer to Section 5.5, [ACI 222R](#), and [ACI 201.2R](#) for comprehensive treatment.

5.3.4 Abrasion resistance—The abrasion resistance of concrete is typically defined as the ability of a surface to resist being eroded by rubbing and friction. Erosion (attrition and scraping) of concrete in waterfront and coastal marine structures can occur due to the action of abrasive materials, including ice and floating debris carried by or within the seawater, and wear on concrete deck surfaces caused by heavy-duty industrial vehicular traffic. Refer to [Section 5.6](#), [ACI 210R](#), and [ACI 201.2R](#) for comprehensive treatment.

5.4—Concrete mixture design considerations

To obtain workable and durable concrete for waterfront and coastal concrete structures, pay attention to the following characteristics of the concrete:

- a) Water-cementitious materials ratio (w/cm)
- b) Cement type
- c) Air entrainment
- d) Chloride content

5.4.1 Water-cementitious materials ratio—Because most high-performance concrete mixtures that should be used in waterfront and coastal concrete structures contain other cementitious materials, a w/cm calculation should be considered in place of the traditional water-cement ratio (w/c) ([ACI 211.4R](#)). The w/cm , like the w/c , should be calculated on a mass basis. The mass of water in a high-range water-reducing admixture (HRWRA) should be included in the w/cm . The relationship between w/cm and compressive strength, which has been identified in normal-strength concrete, is valid for high-performance concrete as well. The use of chemical admixtures and other cementitious materials has been proven generally essential to producing workable concrete with a low w/cm .

5.4.2 Portland cement—Type I, II, or III portland cements ([ASTM C150/C150M](#)) or blended cements ([ASTM C595/C595M](#)) should be used for marine concrete structures. Most references no longer recommend minimum cement content, but rather recommend cement type, minimum compressive strength, maximum w/cm , and the addition of chemical admixture, mineral admixtures, or both, to achieve low permeability and provide high-durability concrete.

5.4.3 Air entrainment—Entrained air provides for resistance to freezing and thawing. Freezing-and-thawing damage

is caused by the development of pressure gradients of the expansion from freezing water in the void system of cement paste and aggregate. The amount of entrained air required is shown in [ACI 201.2R](#) and varies with the maximum aggregate size specified for the mixture. It is important to consider that resistance to freezing and thawing is not only dependent on the absolute amount of entrained air, but also on the pore size distribution and spacing. These are given in terms of a calculated spacing factor, which can be evaluated based on a petrographic analysis of the hardened concrete ([ASTM C856](#)).

5.4.4 Chloride content—Chloride is a naturally occurring chemical that can occur in aggregates, water, and admixtures. Keeping the chloride content at zero in a concrete mixture is nearly impossible. However, caution is advised in selecting mixture materials. Do not intentionally add chloride to the concrete mixture in the form of admixtures or mixing water. Recommended maximum acid-soluble chloride content for corrosion protection of a concrete mixture is found in [ACI 222R](#). Depending on a number of parameters associated with the concrete quality, materials, and environment, the threshold value of chloride (Cl^-) by mass of cement for corrosion initiation has been reported to be 1.0 to 1.5 lb/yd³ (0.6 to 0.9 kg/m³). The average content of water-soluble chloride in concrete is approximately 75 to 80 percent of the acid-soluble chloride content in the same concrete. Issues regarding limits on the allowable amounts of chloride ion in concrete is one still under active debate.

5.5—Protection against corrosion of reinforcement

5.5.1 General—Corrosion of reinforcing and prestressing steel is a major consideration in design and construction of waterfront and coastal marine structures. Concrete normally provides a high degree of corrosion protection for embedded reinforcement. Refer to [ACI 222R](#), [ACI 222.2R](#), [ACI 222.3R](#), and [PTI M50.3-12](#) for a full description of the corrosion process and methods for controlling it.

Measures that can be taken in reinforced concrete construction to protect reinforcing steel against corrosion can be divided into three categories ([ACI 222R](#)):

1. Design and construction practices that maximize the protection afforded by portland-cement concrete;
2. Treatments that penetrate, or are applied on the surface of, the reinforced concrete member to slow the entry of chloride ions into the concrete;
3. Techniques that prevent corrosion of the steel reinforcement directly.

In Item 3, two approaches are possible—to use corrosion-resistant reinforcing steel or to nullify the effects of chloride ions on unprotected reinforcement.

5.5.2 Durability design—With careful design and good construction practices, the protection provided by portland-cement concrete to embedded reinforcing steel can be optimized. It is the detailing, not the technical sophistication of structural design, that determines the durability of a reinforced concrete member in a corrosive environment. The provision of adequate drainage and a method of returning drainage water from the structure are particularly important