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INSPECTION GUIDE FOR REINFORCED CONCRETE VESSELS

Volume 2 COMMENTARY

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Construction Technology Laboratories
A Division of the Portland Cement Association

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16. Abstract

This report provides background material on design and construction of reinforced concrete vessels. The material supplements the United States Coast Guard's "Inspection Guide for Reinforced Concrete Vessels." Topics covered include historical background; design and construction considerations; materials; batching and mixing concrete; placement of formwork, reinforcement, and embedments; transporting, and placing concrete; curing concrete; evaluation of concrete strength; post-tensioning and grouting; precast concrete; in-situ testing of hardened concrete; and guidelines for inspection.

The material is designed for use by the U.S. Coast Guard Marine Inspector. It provides basic information needed for inspection of concrete vessels.

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PREFACE

Work described in this report is part of a program to prepare U.S. Coast Guard Marine Inspectors for inspection of concrete vessels. Other materials developed under this program are an "Inspection Guide for Reinforced Concrete Vessels" and a course entitled "Concrete Technology and Inspection of Concrete Vessels - Training Course for U.S. Coast Guard Marine Inspectors." The project was sponsored by the U.S. Coast Guard under Contract No. DOT-CG-832171-A. Mr. J. S. Spencer served as Technical Representative for the U.S. Coast Guard.

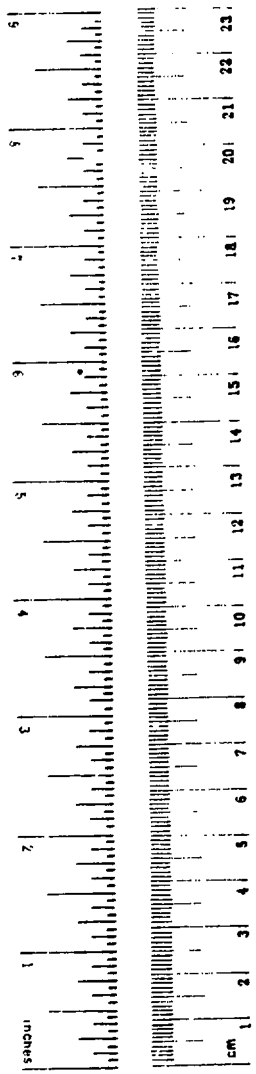
This report was prepared in the Engineering Development Division of the Portland Cement Association's Construction Technology Laboratories under the direction of Dr. W. G. Corley, Divisional Director. Dr. E. Hognestad, Director, Technical and Scientific Development, provided technical input and advice on overall conduct of the project. Mr. R. E. Wilson, Manager of Construction and Technology Education in the Portland Cement Association's Educational Services Department, made significant contributions to this work. Mr. L. S. Johal, Construction Engineer, assisted with preparation of the manuscript. Mrs. E. Ringquist provided editorial assistance. The manuscript was typed in the Word Processing Section.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

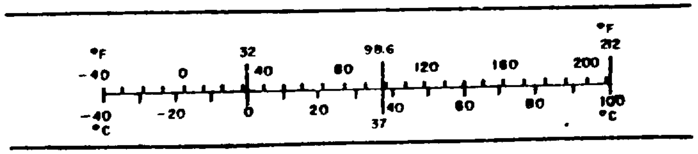
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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COMMENTARY ON INSPECTION GUIDE FOR

REINFORCED CONCRETE VESSELS

by

A. E. Fiorato*

1. HIGHLIGHTS

This report provides background material on design and construction of reinforced concrete vessels. The material supplements the United States Coast Guard's "Inspection Guide for Reinforced Concrete Vessels."** It is intended for use by Coast Guard Marine Inspectors who will be responsible for monitoring construction, in-service inspection, or repair of concrete vessels. A basic knowledge of concrete technology, and reinforced and prestressed concrete fundamentals is an essential prerequisite to use of material in this Commentary and the Inspection Guide. A brief review of reinforced and prestressed concrete principles is given in Appendix A.

Topics in the Guide and Commentary cover materials, construction procedures, testing, evaluation, and repair of concrete. Section 2 on "Historical Background" gives an overview of the history of concrete shipbuilding. It is included to orient the Marine Inspector who may not be familiar with concrete ships.

Section 3 entitled "Design and Construction Considerations" describes factors that are considered essential to use of concrete in marine environments. This material provides insight into reasons behind design and construction requirements that are unique to concrete vessels.

Sections 4 through 11 cover materials, construction procedures, testing, and repair of concrete for vessels. These sections are directly related to the Inspection Guide and reference corresponding sections in the Guide.

Finally, Section 12 gives general information on inspection of concrete construction.

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**Ferrocement vessels are outside the scope of the guide and commentary.

2. HISTORICAL BACKGROUND

Several excellent references are available on the history of concrete shipbuilding.[1-7]* Details will not be repeated here, but an overview will be given to provide historical perspective.

2.1 Early History

The first use of reinforced concrete in floating vessels is attributed to Lambot who, in 1848, constructed a boat by applying sand-cement mortar over a framework of iron bars and mesh.[8,9] This boat was not only the first concrete vessel, but it is also believed to be the earliest example of the use of reinforced concrete.

While numerous reinforced concrete barges and lighters were built after Lambot's early work, it was not until 1917 that the first self-propelled reinforced concrete ship was constructed.[1,10-13] This was the M.S. Namsenfjord built by N. K. Fougner in Norway. The vessel is shown in Fig. 1. It had a deadweight of 200 tons with an overall length of 84 ft, a beam of 20 ft, and a depth of 11.5 ft. Sections at midships, shown in Fig. 2, indicate the construction system and reinforcement arrangement. The hull was constructed using perforated metal lath instead of wood forms. Main steel was tied to the lath, and concrete was cast between two inside and outside layers of reinforcement. Interior and exterior faces were finished with a portland cement mortar.

Later in 1917, and in 1918, Fougner built several larger self-propelled reinforced concrete vessels.[1] These included the M.S. Stier, M.S. Patent, M.S. Askelad, and M.S. Concrete. The M.S. Patent and M.S. Concrete were classed by the Norwegian Veritas as Al "Experimental" under "Provisional Rules for Classification of Concrete Ships."[1]

In the United States, the first self-propelled concrete ship was the S.S. Faith, launched in 1918.[1,2,14] It was built in San Francisco and was, at that time, the largest concrete ship in the world with a design deadweight of 5,000 tons. It had an overall length of 320 ft, a beam of 44.5 ft, and a depth of 30 ft.[1] Primary reasons for construction of this vessel were dissatisfaction with use of green lumber for wooden ships and lack of a source of steel on the west coast.[2]

Although Fougner's pioneering efforts and construction of the S.S. Faith were significant events in the history of concrete shipbuilding, the principal

*Numbers in parentheses refer to references listed at the end of this report.

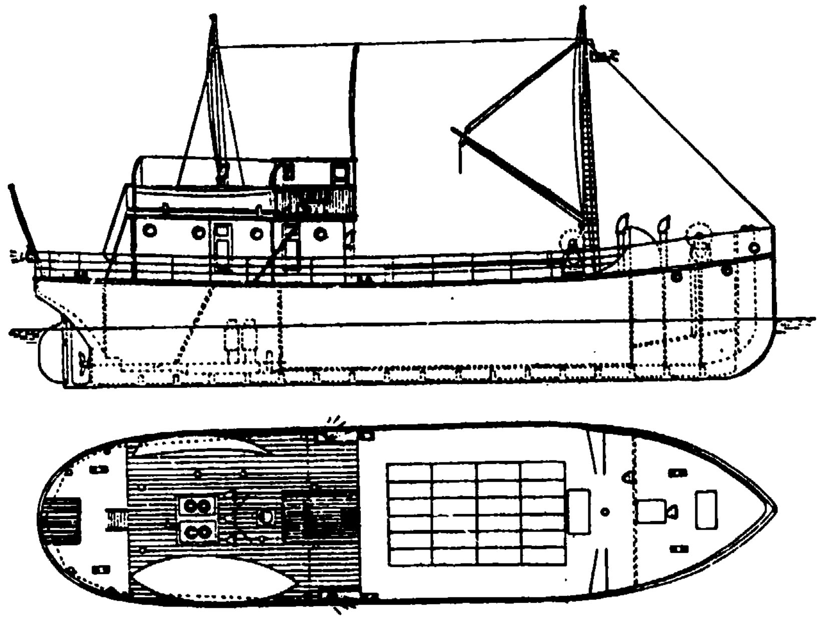
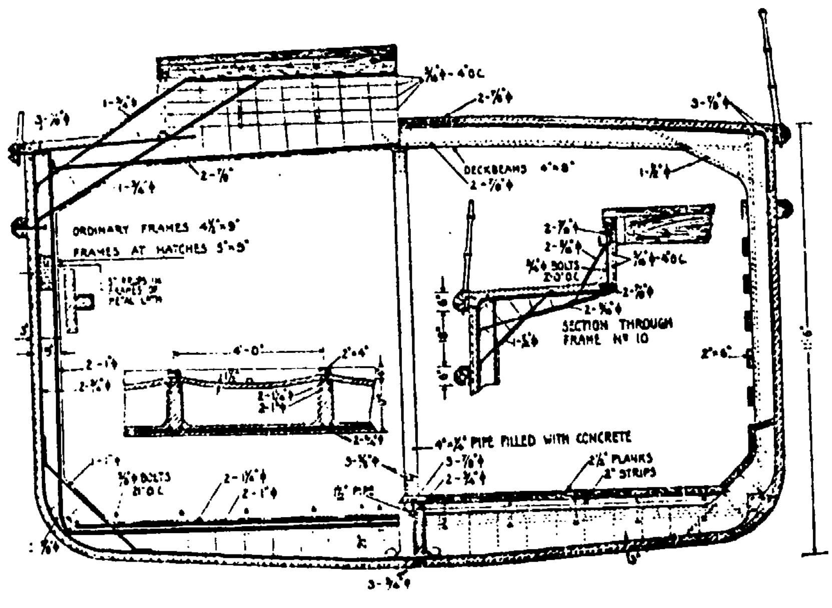


Fig. 1 M. S. Namsenfjord (1)



(a) Section Through Hatch (b) Section Through Deck

Fig. 2 Midship Sections of M. S. Namsenfjord (1) impetus to development of concrete vessels was the shortage of steel that occurred during World War I.[1-3,15-21]

2.2 Concrete Ship Program During World War I

In 1918 the United States Shipping Board Emergency Fleet Corporation instituted a program that resulted in construction and launching of 12 reinforced concrete vessels.[2] These are listed in Table 1. In addition to vessels in Table 1, two 7,500 ton cargo ships were started but never completed.[2]

Initially, the Atlantus and Polias "experimental vessels" were constructed under contract with private yards. Remaining vessels were constructed at yards owned by the Emergency Fleet Corporation. These yards were designed and built especially for concrete ship construction.

After construction of the experimental vessels, two 3,500 ton cargo ships were built by the Liberty Shipbuilding Company. Figures 3 and 4 show the general arrangement and details of these vessels.[16] Because of the need for larger capacity, all other vessels were 7,500 tons deadweight.

An interesting feature of the Emergency Fleet Corporation vessels was the extensive use of lightweight aggregate concrete.[2,16,22,23] Expanded clays and shales were developed to obtain 28-day compressive strengths in excess of 4000 psi with concrete having a unit weight of approximately 110 pcf. This weight is approximately 25% less than that of normal weight concrete. Obtaining the lower weight was a particularly significant achievement because at the start of the shipbuilding program development of lightweight aggregate concretes was only in the experimental stages.[22] Use of lightweight concrete permitted significant reductions in deadweight of the vessels.

None of the vessels constructed by the Emergency Fleet Corporation saw extensive service because they were completed too late to be used during the war. After the war, there was a surplus of shipping tonnage and concrete ships could not compete economically with conventional vessels. Several concrete vessels were eventually stripped of machinery and used as breakwaters or storage terminals.[2]

The S.S. Faith did see considerable service carrying commercial cargo until the end of 1921 when she could no longer compete with the oversupply of steel steamers.

TABLE 1 - CONCRETE SHIPS CONSTRUCTED UNDER U.S. SHIPPING BOARD EMERGENCY FLEET PROGRAM*

Vessel	Type	Launch Date	Deadweight (tons)	Contractor	Yard
Atlantus	Experimental	Dec. 1918	2,540	Liberty Shipbuilding Company	Brunswick, Georgia
Polias	Experimental	May 1919	2,460	Fougner Concrete Shipbuilding Co.	Flushing Bay, N.Y.
Cape Fear	Cargo	July 1919	3,500	Liberty Shipbuilding Company	Wilmington, N.C.
Sapona	Cargo	Oct. 1919	3,500	Liberty Shipbuilding Company	Wilmington, N.C.
Selma	Tanker	June 1919	7,500	Fred T. Ley and Company	Mobile, Alabama
Latham	Tanker	June 1919	7,500	Fred T. Ley and Company	Mobile, Alabama
Cuyamaca	Tanker	June 1920	7,500	Pacific Marine Construction Co.	San Diego, California
San Pasqual	Tanker	June 1920	7,500	Pacific Marine Construction Co.	San Diego, California
Palo Alto	Tanker	Aug. (?) 1920	7,500	San Francisco Shipbuilding Co.	Oakland, California
Peralta	Tanker	Oct. 1920	7,500	San Francisco Shipbuilding Co.	Oakland, California
Dinsmore	Tanker	June 1920	7,500	A. Bently and Sons Company	Jacksonville, Florida
Moffitt	Tanker	April 1921	7,500	A. Bently and Sons Company	Jacksonville, Florida

*After Reference 2

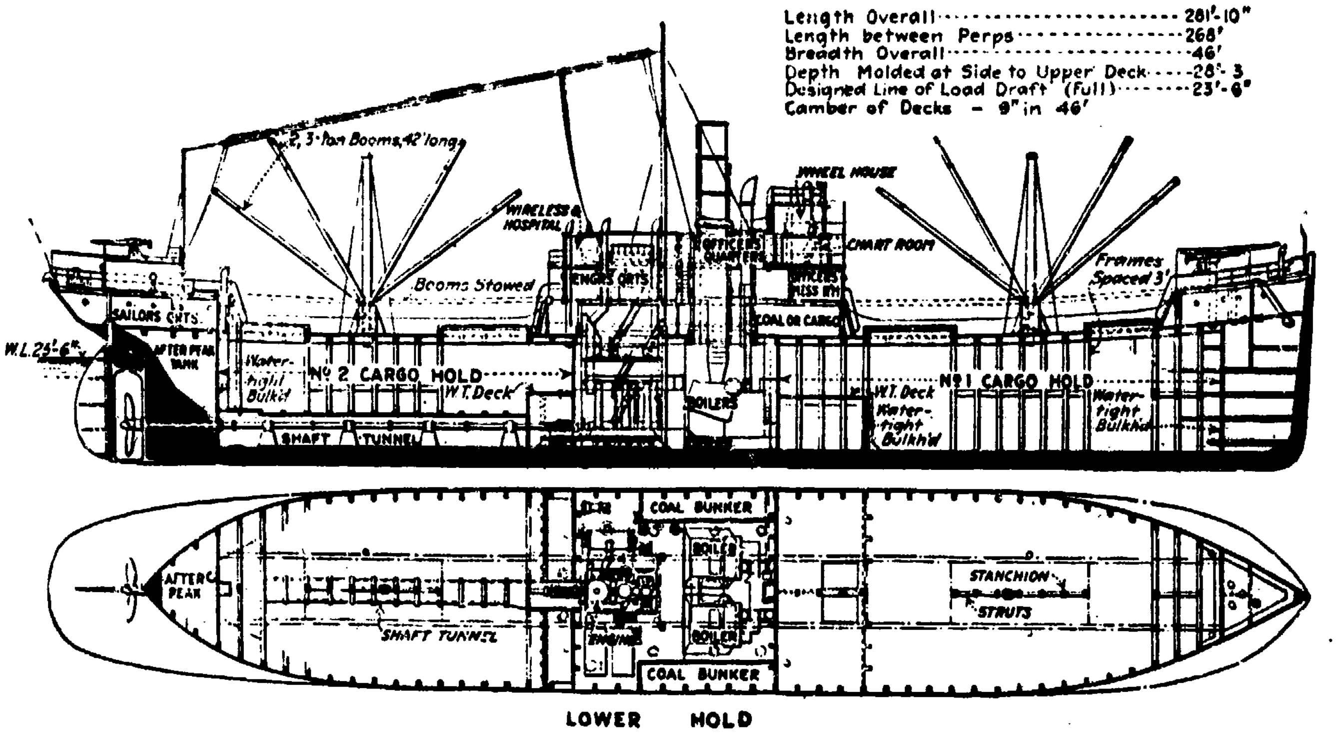
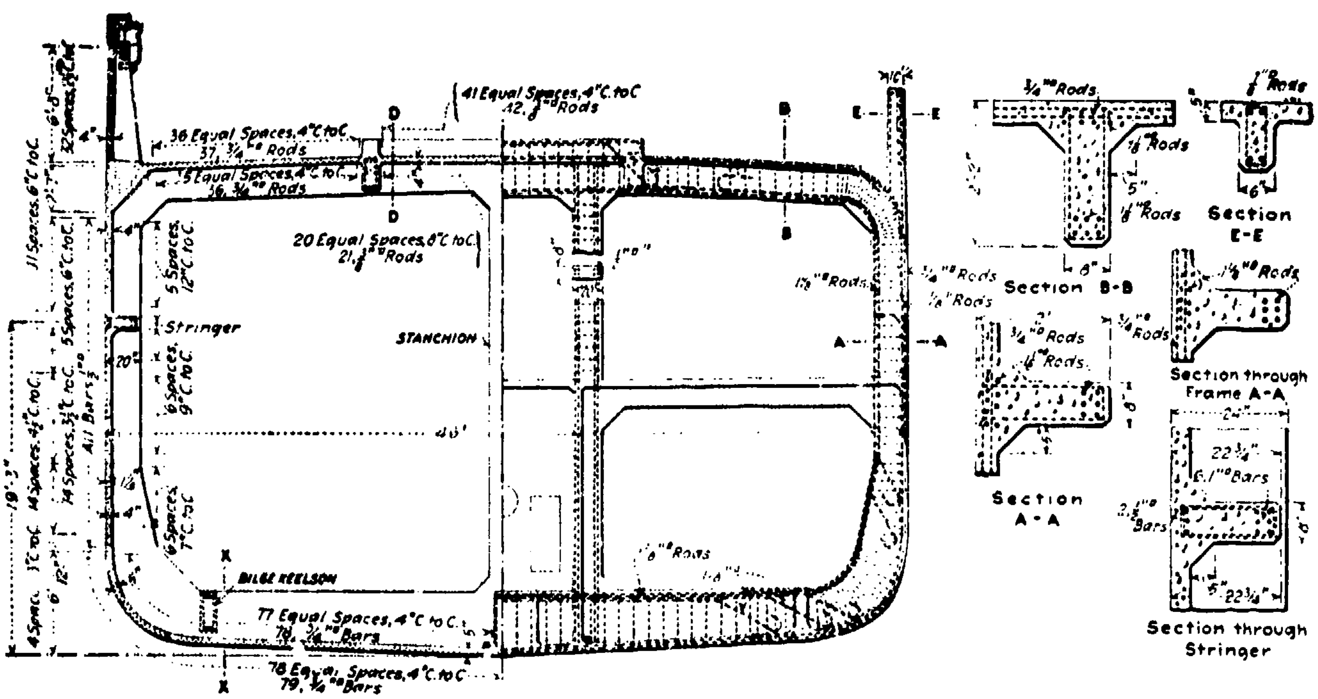


Fig. 3 U. S. Shipping Board 3500 Ton Cargo Ship (16)



(a) Shell Reinforcement (b) Frame Details (c) Sections

Fig. 4 U. S. Shipping Board 3500 Ton Cargo Ship Cross Section (16)

2.3 Concrete Ship Program During World War II

Although a few vessels were built after World War I, it was not until World War II that another major concrete ship program was undertaken.[2] This program was again prompted by a growing shortage of steel plate.[2,3,24] The U.S. Maritime Commission initiated the project in mid-1941, construction of facilities and hulls began in 1942, and delivery of vessels started in 1943.[24]

Table 2 is a summary of vessels constructed under the Maritime Commission program. Twenty of the 104 vessels built were self-propelled. One of the dry cargo barges is shown in Fig. 5.

As was the case for vessels constructed during World War I, lightweight aggregate concrete was used.[24,25] However, concrete strength requirements were increased from 4000 to 5000 psi at 28 days. Concrete made at different yards had fresh unit weights ranging from 108 to 128 pcf. Resulting 28-day compressive strengths ranged from 5085 to 6920 psi.[24]

None of the World War II vessels underwent extensive long-term service. However, all were used to some extent for transport of sugar, wheat, coffee, diesel oil, and gasoline.[2,3] The vessels were considered seaworthy and handled well. They were highly regarded for dry cargo storage because the interior of their hulls remained dry and did not sweat. Vessels used for oil storage showed no adverse reactions between the oil and concrete. Eventually, many of the vessels were used as breakwaters or storage barges.

2.4 Post-War Vessels

Since World War II, the primary interest in concrete for offshore structures has been for floating bridges, docks, pontoons, barges, and oil storage platforms.[3, 26-33]

Extensive use is being made of concrete barges for oil production and storage platforms along the Gulf Coast in Louisiana and Texas.[34,35] One type of barge, the Belden system, consists of an "egg crate" hull made up of precast reinforced conrete panels. The assembled panels are "wrapped" with welded wire fabric reinforcement and shotcrete is applied to the exterior. Various platform configurations can be constructed on top of the hull depending on intended use of the barge.[35]

TABLE 2 - CONCRETE SHIPS CONSTRUCTED UNDER U.S. MARITIME COMMISSION PROGRAM*

Vessel Designation	Type	No. Built	Displacement, tons	Contractor	Yard
B7A1	Oil Tanker-Barge	7	10,930	McEvoy Shipbuilding Corp.	Savannah, Georgia
B7A1	Oil Tanker-Barge	4	10,930	San Jacinto Shipbuilders Inc.	Houston, Texas
C1SD1	Dry Cargo-Self-Propelled	24	10,930	McCloskey and Company	Tampa, Florida
B7D1	Dry Cargo-Barge	20	10,930	Barrett and Hilp	San Francisco, California
B7A2	Oil Tanker-Barge	22	12,750	Concrete Ship Constructors	National City, California
B5BJ	Dry Cargo-Barge	27	4,000	Concrete Ship Constructors	National City, California

*After References 2, 3, and 24

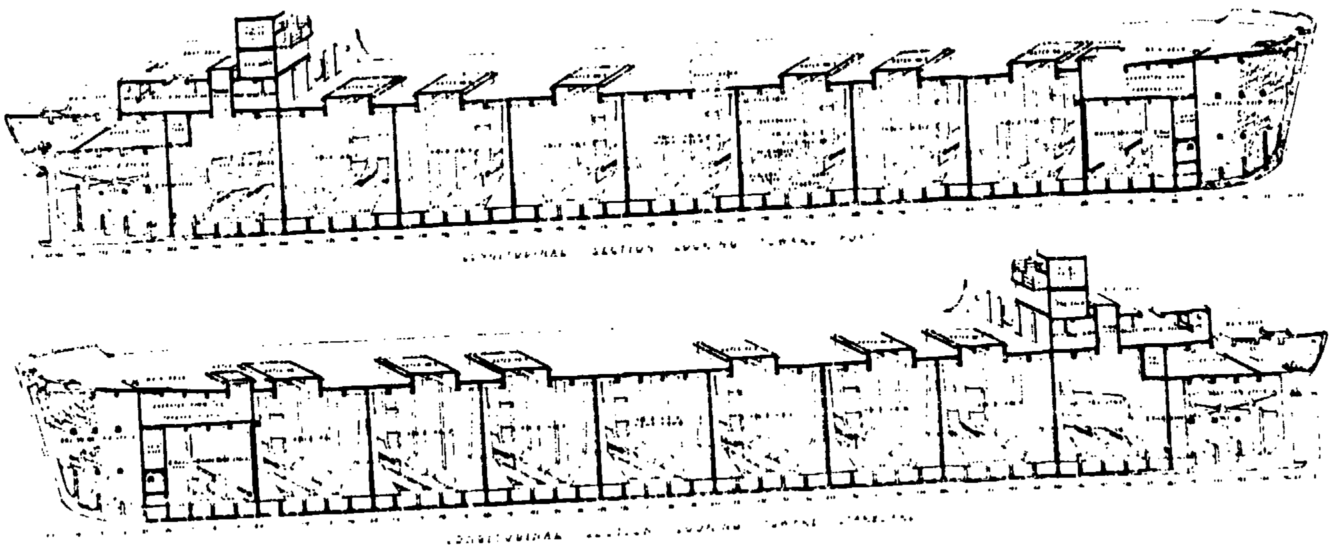


Fig. 5 Dry Cargo Barge B7D1 (24)

2.5 Prestressed Concrete Vessels

A significant development in construction of concrete floating structures that occurred after World War II is the use of prestressed concrete.[3,6] Prestressing "offsets" concrete's low tensile strength, and permits efficient use of materials which results in thinner sections. This reduces hull weight.

Prestressed concrete barges built in the Philippines have been in service since 1964.[36-37] Sixteen were built for general cargo and three were built for bulk petroleum transport. Deadweights ranged from 700 to 2,000 tons. A plan and section are shown in Fig. 6. The vessels have had considerable service including transport of ammunition, explosives, and petroleum products during the Vietnam war. Concrete in the smaller barges has resisted severe exposure from cargoes of industrial salts and fertilizers.

Another application of prestressed concrete for barges is the ARCO LPG terminal vessel, the Ardjuna Sakti.[38-39] This was designed as a post-tensioned segmental structure. Segments were individually cast and then post-tensioned together to form the hull. A cross section of the vessel is shown in Fig. 7. This vessel was towed from Tacoma, Washington, to Indonesia in 1976 where it is now in service for liquefaction and storage of petroleum gas.

Since construction of the Ardjuna Sakti, prestressed concrete vessels have been proposed for transporting liquefied natural gas - LNG[40-42] and for Offshore Thermal Energy Conversion (OTEC) plantships.[43] These vessels have not yet been constructed.

2.6 Summary

Experience with concrete vessels over the past 65 years has indicated a number of advantages and disadvantages. The most obvious disadvantage has been low deadweight-to-displacement ratio, which translates to less cargo carrying capacity.[5,6] Prestressing and high strength lightweight aggregate concretes can improve hull weights, but consideration must also be given to hull size and shape relative to intended function of the vessel. In addition to reduction in cargo capacity, overweight hulls require larger power plants to achieve operating speeds.

Advantages of concrete vessels have been:

(a) Low levels of vibration.

(b) Good cargo environment because of dry interiors without condensation.

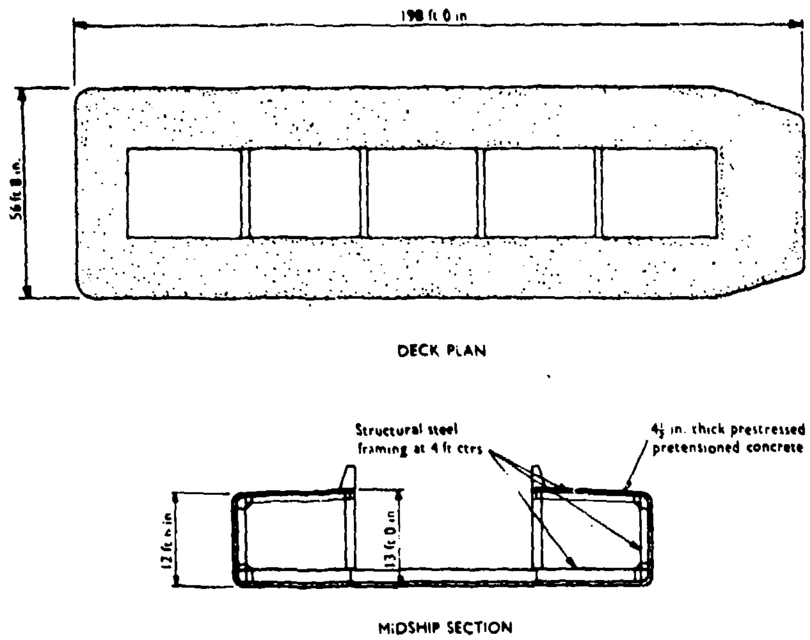


Fig. 6 General Cargo Barge Designed by A. A. Yee (37)

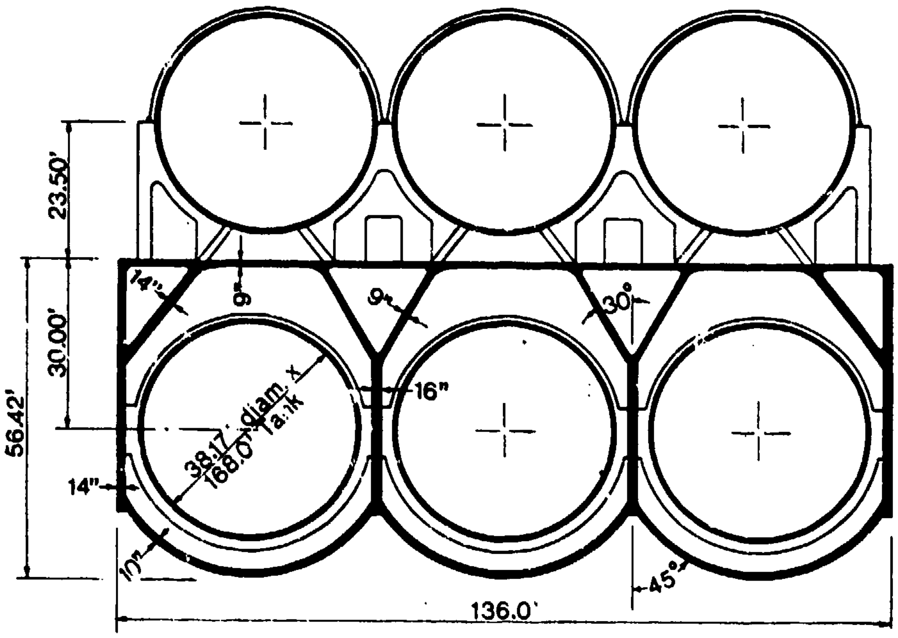


Fig. 7 Cross Section of Ardjuna Sakti (39)

(c) Adaptability to all cargo types including corrosive materials.

(d) Good durability.

(e) Good fire resistance.

(f) Low maintenance.

(g) Ease of repair.

(h) Locally obtainable materials.

(i) Good insulation characteristics.

Concrete is a proven shipbuilding material. Future development of concrete ships will depend on needs of the industry and economic conditions.[44-48]

Perhaps the most significant factor that has been apparent throughout the history of concrete ship construction is the need for high quality materials and workmanship as well as good design.

3. DESIGN AND CONSTRUCTION CONSIDERATIONS

This Section is a preface to more detailed material given in Sections 4 through 12. Design and construction of seagoing concrete vessels requires consideration of factors unique to this type of structure and to use of concrete in seawater. It will be helpful to the Marine Inspector to understand these factors because they are a basis for requirements stipulated in construction specifications for concrete vessels.

Basic properties of concrete that need to be considered in design and construction of vessels have been recognized for many years.[1,16,18] They include workability, strength, weight, watertightness, durability, and corrosion resistance. These properties are insured by proper inspection of materials and construction procedures, as well as by good design.

3.1 The Design Process

Detailed discussion of design of reinforced and prestressed concrete vessels is outside the scope of this Commentary. However, general background information will be useful to the inspector. Additional data can be obtained in References 49 through 64.

As with any structure, design of a concrete vessel is an iterative process. Initially a hull configuration is selected with preliminary dimensions determined from functional and structural considerations. This preliminary vessel is analyzed for various loading conditions to determine magnitude and distribution of critical forces. Once critical forces are known, structural dimensions and reinforcement arrangements are selected. This may require changes in the preliminary configuration of the hull. If so, the vessel is reanalyzed to insure that critical forces have not changed. The procedure is repeated until the design is refined to satisfy requirements of safety, function, and economy. Requirements related to safety are defined by U.S. Coast Guard regulations and Classification Society Rules.

Vessels are designed for a variety of loading conditions.[50-53] Included are dead, live, environmental, deformation, and accidental loads. Dead loads are permanent static loads such as the weight of the structure and fixed equipment. Live loads are either static or dynamic and vary in location and magnitude. They include fuel and stores, cargo, moveable equipment, mooring and docking forces, and forces generated by operation of equipment. Environmental loads result from natural phenomena such as waves, wind, current, ice or snow. Deformation loads include forces generated by temperatures, prestressing, creep and shrinkage, and absorption. Accidental loads are caused by accident or negligence. They include impact from dropped objects, collisions, explosions, fire, and grounding.

As part of the design process, the vessel is analyzed for the various loads acting either individually or simultaneously. This defines the critical forces that the structure must resist. The analysis accounts for dynamic as well as static loading conditions. It is at this point that final dimensions of the structure, design strengths of concrete and steel, and amount and location of reinforcement are determined. Various recommendations are used for guidance in determination of structural resistances.[50-60]

A primary objective of quality assurance is to insure that the structure is built in accordance with the design. This includes final dimensions, material strengths, reinforcement locations, and reinforcement details.

3.2 Strength/Weight Ratio of Concrete

Unit weight of concrete is a major consideration in design of floating structures. Concrete can be produced at unit weights ranging from about 15 to 400 pounds per cubic foot (pcf). Generally, strength is a function of unit weight with heavier concretes having higher compressive strengths. However, at a particular weight, a wide range of strengths can be obtained. For example, normal weight concrete has a unit weight of 145 pcf and is commonly produced at strengths from 2500 to 8000 psi depending on job requirements. The strength obtained is primarily dependent on water-cement ratio. High-strength normal weight concretes have been produced in the field at strengths up to 12,000 psi.

Because of the need to minimize hull weight, lightweight concrete has long been recognized for use in concrete vessels.[1,16,18,24,65,66] Lightweight concretes can be produced with unit weights from 15 to 120 pcf.[67,68] Those with unit weights ranging from 15 to 50 pcf are classified as insulating concretes. Compressive strengths for these materials range from 100 to 800 psi. They are primarily used for their thermal insulating characteristics.

Lightweight aggregate concretes with unit weights ranging from 50 to 85 pcf are classified as fill concretes. Concretes in this range have not had widespread use. This is because their strengths are low and their insulating characteristics are not as good as lower density concretes. However, recent research on lightweight concrete for OTEC cold water pipes has resulted in development of a mix with an air dry unit weight of 75 pcf and a strength of 4500 psi.[69] This concrete is applicable to ship structures.

Lightweight aggregate concretes with unit weights ranging from 85 to 120 pcf are classified as structural concrete. For this classification 28-day compressive strengths must exceed 2500 psi.[67] Strengths commonly achieved range from 2500 to 6000 psi.[67,68] However, it is possible to achieve compressive strengths of 6000 to 12,000 psi with concretes having unit weights of 105 to 125 pcf.[68,70]

Table 3 is a summary of compressive strength-to-unit weight ratios that are representative of concretes at different unit weights. Strength/weight ratios vary from 10 to 85 psi/pcf. For ship structures, high-strength concretes offer considerable advantages to the designer.[69,70] Although most experience with lightweight concrete ships relates to expanded clay and shale aggregates, new materials are constantly being developed.[71-73] Application of these to vessels will need to be evaluated in terms of cost as well as physical properties.

Marine applications of lightweight concrete have been covered in several reports.[74-76] In this Commentary, differences in construction practices between lightweight and normal weight concretes will be noted where they are significant.

Although weight and strength are basic parameters, another essential factor that must be considered during design and construction is durability.

3.3 Durability of Concrete

Durability of concrete relates to its ability to resist weathering, chemical attack, abrasion or other deterioration processes.[77] For concrete structures in marine environments, durability is a function of the zone of exposure.[50,55,77,78]

Three zones are defined:

(a) Submerged Zone: In this zone concrete is continuously covered by seawater.

(b) Splash Zone: In this zone concrete is subject to repeated wetting and drying.

(c) Atmospheric Zone: In this zone concrete is not directly exposed to seawater, but is exposed to ocean air and winds carrying sea salts.

TABLE 3 - STRENGTH/WEIGHT RATIOS OF CONCRETE

Type	Unit Weight (pcf)	Compressive Strength (psi)	Strength/Weight Ratio (psi/pcf)
Insulating Concrete	30	300	10
Fill Concrete	75	1,500	20
OTEC Concrete	75	4,500	60
Structural Lightweight	115	5,000	45
High-Strength Lightweight	125	10,000	80
Normal Weight	145	5,000	35
High-Strength Normal Weight	145	12,000	85

For vessels, the splash zone is considered the most critical with regard to durability.[55,79]

Types of durability problems that must be considered for concrete vessels include:

(a) Chemical Attack

(b) Freeze-Thaw Damage

(c) Corrosion of Reinforcement

(d) Abrasion

(e) Marine Organism Attack

Although these problems will be discussed separately, they can occur simultaneously.

3.4 Chemical Attack

The most important type of chemical attack on concrete in seawater is related to presence of sulfates.[77-82] Complex chemical reactions between naturally occurring sulfates in seawater and constituents of hydrated portland cement can result in expansive compounds that cause progressive disintegration of concrete.[78,82-85] The rate of chemical attack is more rapid in warmer waters.[81]

Because of potential sulfate reaction with cement, most provisions for concrete sea structures limit the maximum amount of tricalcium aluminate compound (C_3A) that can be present in the cement.[50-53] Cements with low percentages of this compound have been found to be resistant to sulfate attack.[77-86] However, some researchers have found that even concretes made with high C_3A cement are durable if permeability of the concrete is low.[78,85]

Although seawater can have a relatively high sulfate content, experience has shown that it is only moderately aggressive to concrete.[77,82] It is believed that chlorides in seawater help mitigate the action of sulfates.

Protection against chemical attack is obtained by using high quality concrete with a low water-cement ratio and a low in-place permeability, a portland cement with the required C_3A content, and high quality nonreactive aggregates.[77-84] There is also evidence that addition of pozzolans* will improve durability of concrete against sulfate attack.[77,78,79,85,87]

3.5 Freeze-Thaw Damage

Exposure of damp concrete to cycles of freezing and thawing can result in severe deterioration if in situ** concrete quality is not satisfactory.[77] Although the actual mechanism is quite complicated, freeze-thaw damage is basically caused by expansion and diffusion of freezing water in the void system of cement paste and aggregates.[77,83,84] Alternating freeze-thaw cycles cause progressive deterioration as a result of continued expansive pressures from excess water that freezes in the concrete. Since freeze-thaw deterioration requires presence of absorbed water that can be frozen, areas within the splash zone are most susceptible to damage.

Laboratory tests indicate that the rate of freeze-thaw deterioration is more severe in seawater than in fresh water.[81,88] However, even in seawater deterioration of high quality concrete is very slow.[81]

Resistance to freeze-thaw damage is obtained by using concrete having low in-place permeability, a low water-cement ratio, air entrainment, and sound aggregates.[77,79,80,81,84,88] Concrete with low permeability does not absorb as much water which can later freeze.

Air entrainment results in a significant improvement in freeze-thaw resistance. Air entrained concrete contains small air bubbles that are uniformly distributed throughout the cement paste. These air bubbles are distinct from accidentally entrapped air, which is found in all concrete, in that entrapped air voids are larger. Air entrainment is obtained using air-entraining cement or air-entraining admixtures. The uniformly distributed intentionally entrained air bubbles relieve hydraulic pressures developed during freezing of cement paste. Thus, resistance to freeze-thaw

*Pozzolans are siliceous or siliceous and aluminous materials, which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Naturally occurring materials such as diatomaceous earth, opaline cherts, calcined shales and pumicites, and some artificial materials such as fly ash are used as pozzolans.

**In this report, the terms "in situ" and "in place" are used interchangeably. Both terms refer to material properties existing in their final position in the vessel.

damage is significantly improved. Concrete vessels that may see service in cold climates should be built with air-entrained concrete.

3.6 Corrosion of Reinforcement

Potential corrosion of reinforcing and prestressing steel is a major consideration in design and construction of concrete vessels. Concrete normally provides a high degree of corrosion protection for embedded reinforcement.[77,81,89] This protection occurs because high alkalinity of the concrete provides a passive environment for the steel. In addition, air dry concrete provides a relatively high electrical resistivity which helps to resist corrosion.[77] However, in marine environments, there are a number of factors that contribute to depassivation of the concrete.

Reinforcement corrosion in marine structures is considered to be an electrochemical process.[77,79,83,89] Electrochemical corrosion occurs from flow of electrical current and accompanying chemical reactions. Flow of electrical current can be caused by:

(a) Stray electrical currents.

(b) Contact between different metals in the concrete.

(c) Corrosion cells within the concrete.

Incidents of corrosion resulting from stray electric currents are rare.[89] However, laboratory tests have confirmed that stray currents can produce corrosion in prestressed concrete.[90] Therefore, on vessels housing electrical generating equipment, consideration must be given to effects of stray currents. In addition, impressed current cathodic protection systems should only be used after evaluation of potential corrosion risks.[90]

Contact between dissimilar metals embedded in moist concrete produces electrical potential differences that can result in corrosion.[77,89] It is for this reason that construction specifications should require electrical isolation between reinforcement and metallic embedments or inserts.

The principal type of electrochemical corrosion in concrete marine structures occurs as a result of corrosion cells that develop within the concrete and steel.[77,79,89] Normally corrosion is prevented because a passive iron oxide film forms on the surface of the steel. This occurs with the presence of moisture, oxygen, and water soluble alkaline products formed during hydration of cement.[89] However, the passive film is destroyed if the alkaline environment of the concrete is lost. Reduction in alkalinity can occur by carbonation of the hydrated portland cement or by ingress of chloride ions in the presence of oxygen.[77,89] For marine structures, the most critical effect is penetration of chloride ions which are naturally present in seawater.[81,91]

The effect of chloride penetration is illustrated in Fig. 8.[79] Penetration of oxygen and chloride ions through low-quality porous concrete results in a corrosion cell. An anode is formed along the steel reinforcement because of differences in potential resulting from differences in moisture content, oxygen concentration, and electrolyte concentration.[77] Corrosion is initiated at the anode.

Since products of corrosion ("rust") take up a larger volume than the original steel, expansive forces are eventually generated as corrosion becomes severe. These forces can cause cracking and spalling. Spalling refers to loss of concrete fragments from the surface of a member. Severe corrosion can also cause structural damage because reinforcing steel area, and thus tensile strength, is reduced. Effects on structural capacity are more critical in prestressed concrete because corrosion of small diameter highly stressed prestressing wires has a greater potential for catastrophic damage.[77,79]

Primary elements essential for electrochemical corrosion in reinforced concrete are:

(a) Presence of moisture.

(b) Presence of chloride ions (salts)

(c) Presence of oxygen.

Moisture and chloride ions form an electrolyte capable of conducting a "corrosion current".

Because the three primary elements required for corrosion are most abundant in the splash zone, parts of the structure in this zone are most susceptible to damage. This has been confirmed by field surveys.[79,83,91,92] In the splash zone, chloride concentrations build up because of alternate wetting and drying. Therefore, more chloride ions are available to penetrate the concrete than in submerged zones where the concentration is limited to chloride content of seawater.[79] In addition, more oxygen is available in the splash zone than in the submerged zone.[79]

The most significant measure that can be taken to minimize potential corrosion is to use high-quality impermeable concrete.[77,79,92,93] This is

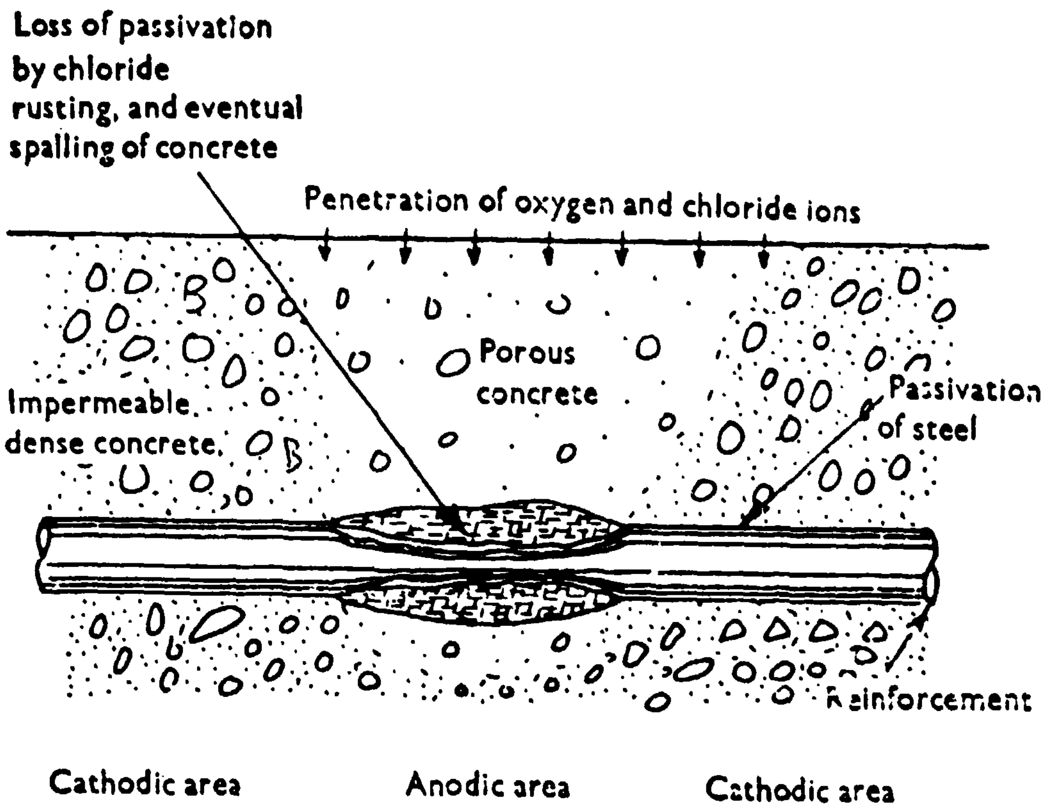


Fig. 8 Development of Corrosion Cell (79)

done by designing a workable mix with a low water-cement ratio, adequate cement content, and well graded, sound aggregates.[77,79,93]

It is also important to insure that concrete mix materials do not contain soluble chlorides that can promote corrosion. Chlorides may be present in aggregates, mixing water, and admixtures. While it is not practical to specify zero chloride content, many specifications set a limit on total chlorides.[77] This is particularly evident in specifications for prestressed concrete.

It is not sufficient to limit corrosion protection to the concrete mix design because it is in-place quality that is important. Proper placement, consolidation, and curing practices must also be followed.[77,79,93]

In conjunction with low permeability concrete, adequate concrete cover must be provided over reinforcing steel.[77,89] Adequate concrete cover inhibits penetration of oxygen and chloride ions. Although two to three inches of concrete cover are generally specified for marine exposures, there are examples of concrete vessels where considerably less cover has given satisfactory performance.[22,23,80] In such cases, concrete around the reinforcement was a uniformly distributed well consolidated mix of low permeability.[23,80]

Penetration of chloride ions can also occur through cracks in concrete. However, correlation between cracking in hardened concrete and onset of corrosion is not well defined.[80,82,92-95] It is generally believed that crack widths less than about 0.01 in. are not large enough to induce corrosion.[80,82,93]

In addition to provisions for low permeability concrete, special protective measures have been, and are being, developed to protect concrete marine structures from corrosion. Typically, these are only considered for extra protection in the splash zone where potential for corrosion is greatest.[79,81,91] Special corrosion protection measures include concrete surface coatings, concrete sealers (epoxy or wax impregnation), reinforcement coatings (zinc or epoxy), corrosion inhibiting admixtures, and cathodic protection.[79,91,96]

Bituminous or epoxy coatings provide a membrane against seawater and oxygen penetration.[77,81,91,97] However, they must be carefully applied and maintained because defects in the coating can result in "wet and dry" areas within the concrete that will promote formation of corrosion cells.

Concrete sealing methods such as epoxy or wax impregnation are relatively new.[77,98] Although they have been used for bridge decks in field trials, their use in concrete vessels may not be cost effective.

Both zinc (galvanized) and epoxy coated reinforcement are being used, with mixed success, for protection of steel in severe environments.[77,91,92,99-101] As is the case for concrete coatings, care must be exercised when using coated reinforcement. Damaged coatings can result in local corrosion cells.[91,101] Chromate treatment of galvanized steel or chromate admixtures have been suggested to reduce corrosion potential of zinc coated reinforcement.[100]

Corrosion inhibiting admixtures are relatively new and long-term field experience with their use is lacking.[91,102,103] These admixtures are added to fresh concrete to inhibit electrochemical activity. Although they may find application in the splash zone of concrete vessels, they should be used with caution until performance data become available.[91]

Cathodic protection can be used to prevent corrosion of reinforcement.[91,104-106] The basic principle of cathodic protection is to arrest electrochemical corrosion by making the steel reinforcement a cathode.[104] Cathodic protection can be obtained using impressed current or sacrificial anodes.[104,105] Because of problems with stray currents, systems using sacrificial anodes are preferred.[90,105]

While special methods of corrosion protection are available, they should not be used as a trade-off for high-quality low-permeability concrete, nor should they be used to cover up low-quality permeable concrete.[77,79,93,97,105]

3.7 Abrasion

Abrasion resistance is the ability of concrete to resist surface damage from rubbing or friction.[77,84] For concrete vessels, waterborne particles act as an abrasion medium.

Abrasion resistance of concrete is a function of compressive strength, aggregate properties, and finishing and curing methods.[77,80,84] Compressive strengths in excess of 4000 psi are considered adequate for abrasion resistance unless severe scouring is anticipated.[77] Strengths in excess of 5000 psi are commonly specified for marine structures.[50] Coarse aggregates should be hard and sound.[77,80,84]

Finishing and curing are also important because they affect hardness of concrete at the surface.[77,80] Finishing procedures should not bring excess water to the surface that will weaken the concrete. Curing should start immediately after finishing. For concrete vessels, surfaces exposed to abrasion will generally be cast against forms. This will minimize finishing and curing problems.

3.8 Marine Organisims

Although incidents of severe damage to concrete by marine organisms are not widespread, there are species of shipworms that can attack concrete.[107] Stone borers, Pholadidae, will drill into weak, porous, or soft concrete in the same way that they attack timber.[80,107] Boring clams, Lithophaga, deposit acids that can dissolve cement paste.[80,108] Provisions for a hard impermeable concrete surface will effectively protect against damage from borers.

Marine organisms, such as barnacles, mussels, and "seaweed," will grow on concrete structures in cold or temperate seas as well as in warm tropical water.[96,109,110] Fouling on concrete surfaces is no greater than for steel.[49] Although marine growths increase hull weight and frictional resistance, there is no indication that they adversely affect concrete.[109] They can be removed by scraping and brushing, or by high velocity water jets.[49,109] Sandblasting can also be used to remove marine growths. However, air pressures and abrasives used for blasting should be selected to avoid excessive etching of concrete surfaces. Antifouling coatings are also available.[80,110] Antifouling admixtures for concrete are being developed for possible use in OTEC cold water pipes.[110] These may eventually find application in concrete hulls.

3.9 Requirements for Durable Concrete

Essential elements of durable concrete have been recognized since the earliest days of concrete shipbulding.[1,18,24,111] Basically, these consist of providing a workable high-quality mix designed to facilitate placement so that in-place concrete is uniform, watertight, and of adequate strength. Factors important to obtaining durable concrete include:

(a) Materials Selection

- Cement Composition Meeting Specifications
- Sound, Hard, Nonreactive Aggregates
- Potable Water Low in Chlorides and Sulfates
- Compatible Admixtures Low in Chlorides

- Reinforcing Materials Meeting Specifications

(b) Concrete Mix Proportions

- Low Water-Cement Ratio
- Adequate Cement Content
- Workable Mix
- Adequate Design Strength
- Low Chloride Content
- Adequate Air Entrainment

(c) Construction Procedures

- Accurate Batching and Thorough Uniform Mixing
- Clean, Tight, Accurately Placed Formwork
- Clean, Secure, Accurately Placed Reinforcement and Inserts
- Proper Tolerances on Spacing and Cover of Reinforcement and Inserts
- Transporting and Placing to Avoid Segregation
- Complete Consolidation of Concrete
- Proper Finishing
- Complete Curing
- Carefully Applied Coatings if Specified

These factors are deceptively simple. Because concrete is "field produced," there are innumerable occurrences that can disrupt operations. Therefore, quality assurance procedures for regular monitoring at each stage of operations is important to obtaining a high-quality durable product.

3.10 Importance of Permeability

In-place permeabilty is the most important factor influencing durability of concrete in marine environments.[78,79,112] Permeability to liquids such as seawater is a measure of the rate at which a liquid will penetrate concrete.[84] Concretes with high permeability are susceptible to more rapid penetration. Since ingress of seawater has a major effect on chemical attack, freeze-thaw damage, and reinforcement corrosion, it is important to obtain low permeability. In addition, low permeability is required to obtain a watertight hull. This section describes basic factors that affect permeability of concrete.

Permeability is not a simple function of porosity.[84,113] Porosity is a measure of the total volume of voids, but permeabilty is a funcion of size, distribution, and continuity of the voids as well as total volume. Movement of liquid through concrete requires an interconnected system of voids. For example, a mature portland cement paste made with a water-cement ratio of 0.4 has approximately the same permeabilty as unflawed dense trap rock. However, porosity of cement paste is at least 30% while that of trap rock is about 1/2 to 2%.(113) The paste has a relatively high porosity, but low permeability because the void system is not interconnected.

Permeability of concrete is a function of mix proportions, placement, and curing conditions because these factors affect void structure of the hardened concrete. Discussion of details on formation of voids in portland cement paste is beyond the scope of this Commentary, but is available elsewhere.(84,112-115)

On a somewhat simplistic basis, permeability of paste can be considered to be primarily a function of capillary pores that are left after hydration of cement. The volume of capillary pores left in hardened paste is a function of the initial water-cement ratio of the mix and the degree of hydration. If the water-cement ratio is high, a large volume of capillary pores are created by space originally occupied with mix water. A sufficient volume of products of cement hydration will not be available to fill and block capillary pores. Even though remaining capillary pores are submicroscopic, with diameters ranging from 8×10^{-6} to 13×10^{-3} mm, they are large enough to permit flow of seawater. Figure 9 illustrates the drastic effect that water-cement ratio has on permeability.(115) Concretes for marine structures are generally required to have water-cement ratios between 0.40 and 0.45 by weight. These are capable of providing low permeability.

Table 4 shows the effect of cement hydration on permeability of paste.(115) Again, this is directly related to "sealing off" capillary pores. As more cement hydrates, large volumes of hydration products are formed to fill capillary pores. With regard to field practice, it is essential to provide proper curing conditions so that cement hydration can take place. Although the greatest reduction in permeability occurs within the first week of curing, hydration and corresponding reductions in permeability continue with time.(116) This is shown in Fig. 10.

Permeability of concrete is also affected by aggregate permeability. Generally, the influence of aggregate permeability is not great.(84,112,114) As shown in Table 5, natural rock materials have permeabilities of the same order of magnitude as portland cement paste. Since aggregate particles in

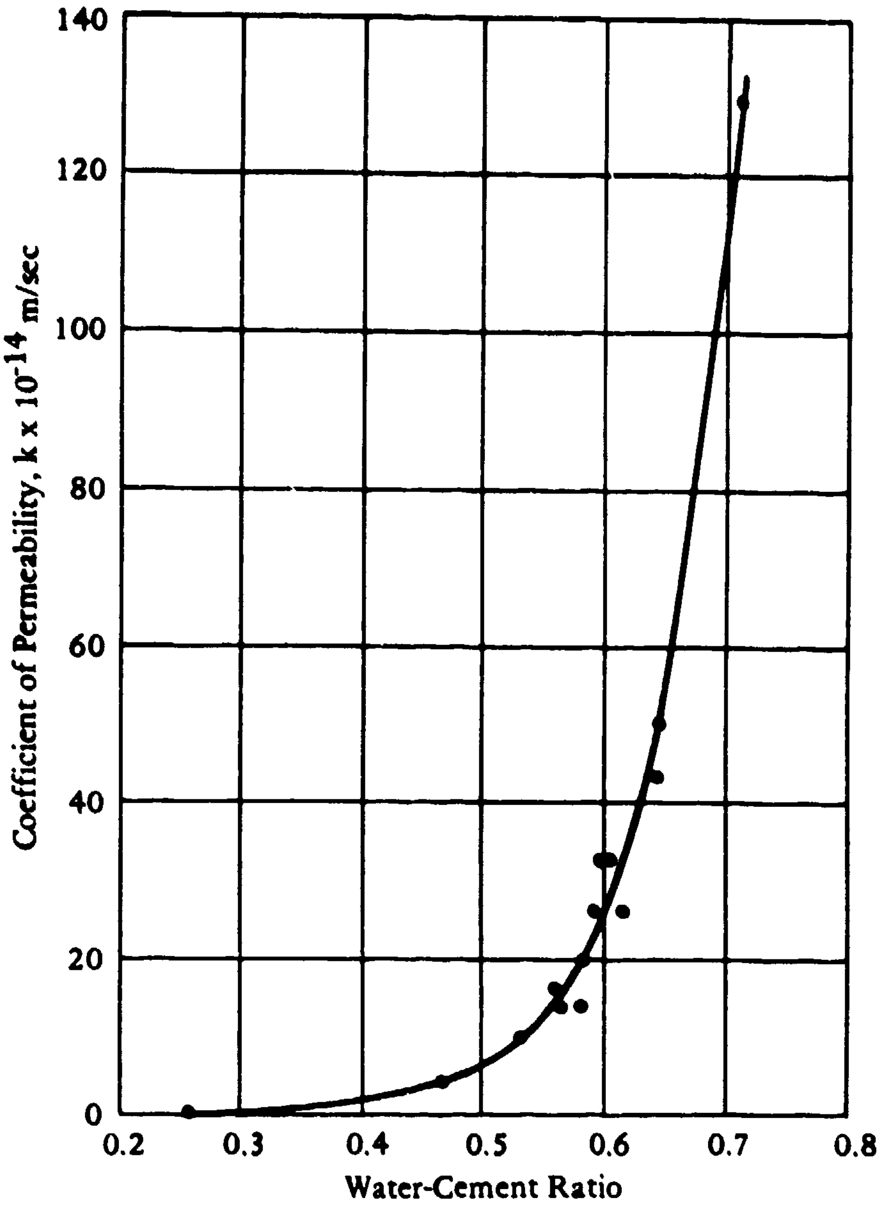


Fig. 9 Effect of Water-Cement Ratio on Permeability (112,115)

TABLE 4 - EFFECT OF CEMENT HYDRATION ON PERMEABILITY[115]

Age (days)*	Permeability Coefficient (m/sec)
fresh	$2,000,000 \times 10^{-12}$
5	400×10^{-12}
6	100×10^{-12}
8	40×10^{-12}
13	5×10^{-12}
24	1×10^{-12}

*Cement paste with 0.7 water-cement ratio by weight

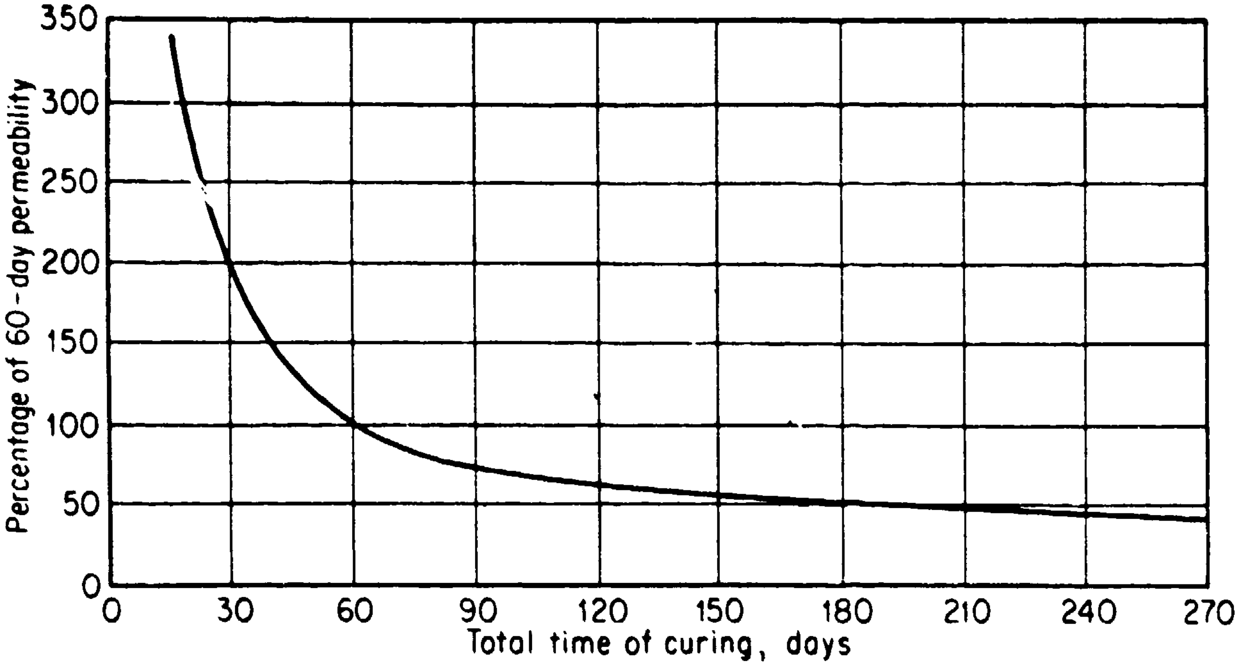


Fig. 10 Effect of Duration of Curing on Permeability (116)

TABLE 5 - PERMEABILITIES OF ROCKS AND MATURE PORTLAND CEMENT PASTES[113]

Kind of Rock	Permeability of Rock, (m/sec)	Water-Cement Ratio of Paste for Same Permeability
dense trap	0.000345×10^{-11}	0.38
quartz dioriate	0.00115×10^{-11}	0.42
marble	0.00334×10^{-11}	0.48
marble	0.0805×10^{-11}	0.66
granite	0.748×10^{-11}	0.70
sandstone	1.72×10^{-11}	0.71
granite	2.18×10^{-11}	0.71

consolidated concrete are coated with cement paste, the paste has the greatest effect on permeability.(84,93) This has also been confirmed for concretes with lightweight aggregates which have a higher volume of voids than normal weight aggregates.(74-76,112) Use of a workable mix with a low water-cement ratio provides a rich paste to "seal" aggregate particles. There is also some indication that lightweight aggregate fines have pozzolanic properties that reduce permeability.(74,75)

Another constituent of the concrete mix that influences permeability is air entrainment. While it would appear that intentionally entrained air should increase permeability, this is not necessarily the case. Air entrainment reduces segregation and bleeding, and improves workability of the mix. This permits use of a lower water-cement ratio which reduces permeability.(84)

Throughout the discussion of durability, emphasis has been on <u>in-place</u> concrete quality. Permeability is affected by consolidation. This is illustrated in Fig. 11.(116) Data in Fig. 11 indicate that water flow (permeability) decreases with increasing cement content, and that to obtain the same permeability level, higher cement contents are required for concrete placed by hand. Concretes used to obtain these data were of a similar consistency, with slumps* ranging from 2 to 4 in. Thus, for concretes having the same workability and same water-cement ratio, mechanical vibration results in a much lower permeability. Incomplete consolidation can cause large variations in in-place permeability.(117)

Tests of concrete spheres submerged in seawater over a five-year period have indicated that there is a significant decrease in permeability rate with time.(112,118,119) It is hypothesized that this decrease is caused by chemical reactions between seawater and hydrated cement that produce compounds which fill pores in the concrete.(112) Similar decreases have not been observed for concrete in fresh water.(112) These data are of interest for the submerged portion of concrete hulls. They support most observations that conditions in the submerged zone are more favorable than those in the splash zone.(79)

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*Slump is a measure of consistency of freshly mixed concrete. It is measured as the subsidence of a molded truncated cone of concrete immediately after removal of the slump cone mold.

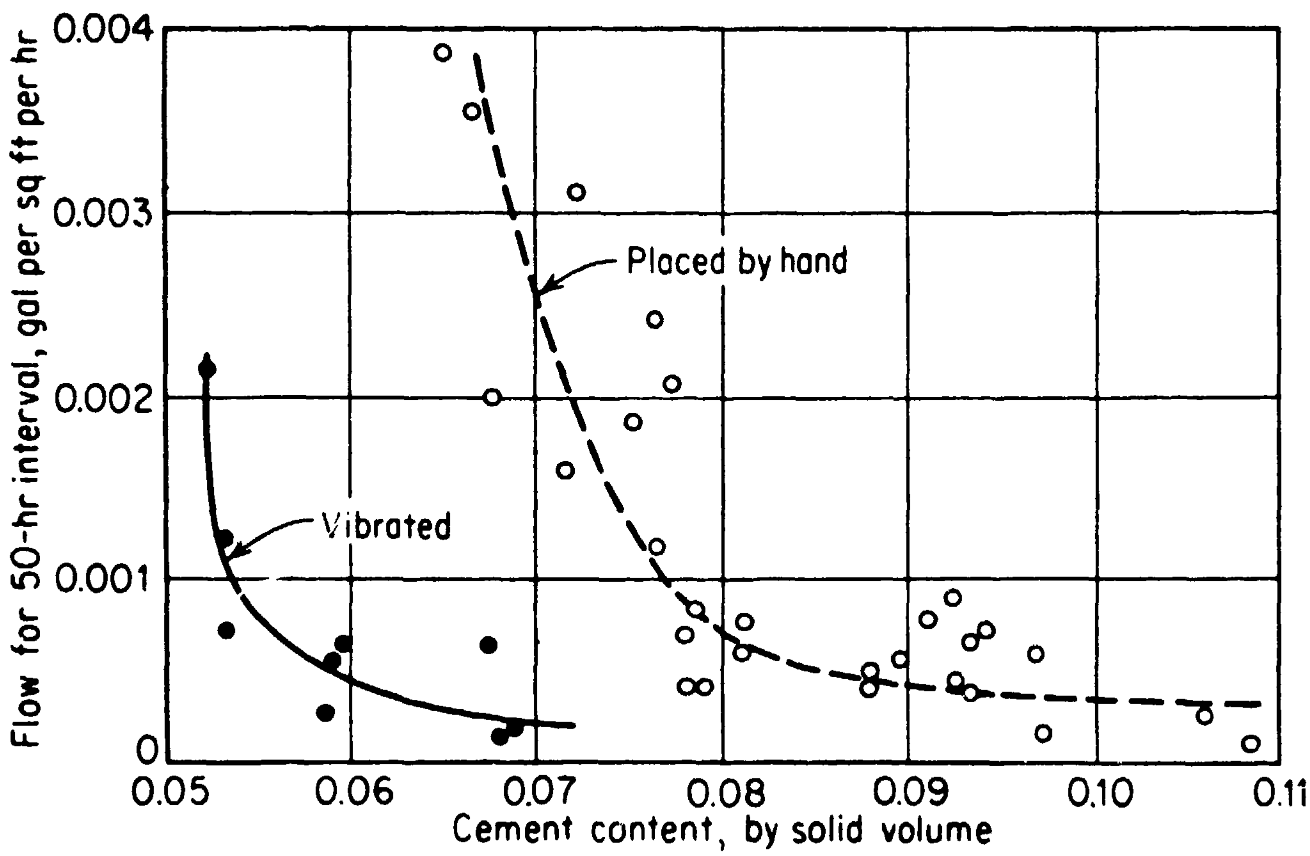


Fig. 11 Effect of Cement Content and Compaction on Permeability (116)

4. MATERIALS

Section 3 of this Commentary has dealt with considerations for design and construction. Particular emphasis was placed on aspects of concrete technology relevant to durability in seawater. This Section covers specific requirements for materials to be used in concrete vessels. In general, materials should have documentation that demonstrates prior satisfactory performance under similar conditions or their use should be verified by sufficient test data.(50)

4.1 Cement

Type I, II, and III cements corresponding to ASTM Designation: C150, "Standard Specification for Portland Cement" are satisfactory for use in marine environments, including concrete vessels.(50-53) Type I is a general-purpose cement that is usually suitable unless special properties of other types are required. Type II is used where precautions against moderate sulfate attack or where moderate heat of hydration are required. Type III is used when high early strength is required.

Chemical and physical requirements for these cement types are given in ASTM Standard C150. Tests specified include chemical analysis (ASTM Designation: C114), fineness (ASTM Designation: C115 or C204), autoclave expansion (ASTM Designation: C151), time of setting (ASTM Designation: C191 or C266), air content of mortar (ASTM Designation: C185), and compressive strength (ASTM Designation: C109). Optional tests include false set (ASTM Designation: C451) and heat of hydration (ASTM Designation: C186). The significance of these tests is discussed elsewhere.(84,120) Since some chemical and physical requirements of ASTM Standard C150 are optional, construction specifications should be consulted for specific tests required. For large projects, incoming cement may be sampled and tested to verify supplier's certifications. Procedures for sampling and testing should be included in the construction specifications.

Blended hydraulic cements conforming to ASTM Designation: C595 "Standard Specification for Blended Hydraulic Cements" are also considered suitable for use in marine concrete.(50-53) This ASTM specification covers portland blast-furnace slag, portland-pozzolan, slag, and pozzolan-modified portland cements. Use of blended blast-furnace slag or pozzolan portland cements has been found to reduce permeability, and therefore improve durability, of concrete.[78,85,87] Research is in progress to further evaluate marine durability of concretes made with blended cements.[121]

To insure durability of concrete against sulfate attack, the tricalcium aluminate content (C_3A) of cement is usually limited to a maximum value. The amount of C_3A, which is one of the principal chemical compounds of cement, can be obtained from certified mill test reports for the particular cement being used.

There is some difference of opinion over the maximum limit on C_3A content. Table 6 shows suggested values from several sources. The reason for differences in suggested maximum limits is that results of research data have given conflicting evidence on effects of C_3A on durability.[79] If a high-quality low-permeability paste is used, durable concrete can be obtained even with C_3A contents of 12 to 17%.[78] However, if permeability is high, use of low C_3A content cement becomes more important.[81,86] Type I cements have approximate C_3A contents ranging from 5 to 14% with a mean of 12%.[84] The corresponding range for Type II cements is 4 to 8% with a mean of 6%.[84] Thus, maximum C_3A limits can be met with many Type I cements and all Type II cements.

As shown in Table 7, limits on minimum C_3A content have also been suggested. These limits are intended to insure durability against corrosion. They are based on research that indicates improvement in corrosion resistance with higher C_3A contents.[86] As was the case for maximum C_3A content, there are differences in opinion regarding effects of C_3A on corrosion resistance.[78] These differences need to be resolved by further research. However, for practical purposes, it is possible to meet suggested minimum C_3A limits with most cements.

Cement is commonly shipped in bulk by rail, truck, or barge. All incoming cement, whether delivered in bulk or in bags, should be marked to indicate type of cement, name and brand of manufacturer, and weight. Date of receipt should be recorded to insure that cement is used in chronological order. This is particularly important for cement stored in bags because they can easily be mixed. Incoming bags should be inspected for tears or other damage.

Since portland cement is moisture sensitive, it must be kept dry to maintain quality. Cement that has been stored in contact with moisture will set more slowly and gain less strength than cement that has been kept dry.[120]

TABLE 6 - RECOMMENDED LIMITS ON MAXIMUM C_3A CONTENT OF CEMENT

Source	Exposure Zone		
	Submerged	Splash	Atmospheric
ACI 357 (50)	10%	10%	10%
DNV (51,53)	10%	10%	10%
FIP (52)	12%	12%	12%
Gerwick (49,97)	8%	8%	8%
Browne and Domone (79)	8%	8%	8%
Gjorv (81)	8%	8%	8%

TABLE 7 - RECOMMENDED LIMITS ON MINIMUM C_3A CONTENT OF CEMENT

Source	Exposure Zone		
	Submerged	Splash	Atmospheric
ACI 357 (50)	4%	4%	4%
DNV (51,53)	5%	5%	5%
FIP (52)	-	-	-
Gerwick (49,97)	4%	4%	4%

Therefore, provisions must be taken to insure that cement is protected from weather and kept dry during shipment and storage.

On large jobs, or on jobs where cement is to be stored for long periods, construction specifications may require that cement in storage be sampled and tested periodically. As cement is being used it should be inspected for contamination and lumps.[120,122] If evidence of contaminants or lumps are found, cement should be sampled and tested.

4.2 Aggregates

Aggregates for concrete vessels should conform to ASTM Designation: C33, "Standard Specification for Concrete Aggregates" or ASTM Designation: C330, "Lightweight Aggregates for Structural Concrete."[50] Both standards cover fine and coarse aggregate. They include tests for aggregate gradation, strength, soundness, abrasion resistance, freeze-thaw resistance, particle shape and texture, unit weight, specific gravity, absorption and moisture content, chloride content, and reactivity. Applicable test methods are summarized in Tables 8 and 9. Detailed discussion of the significance of these tests is given elsewhere.[84,120] Specific tests required for individual jobs should be given in the construction specifications.

Basically, aggregates for marine concrete should be clean, hard, strong, and durable. They should be free of organic matter, clay, salt, silt, fine dust, sulfates, soft particles, and potentially reactive matter. Long flat particles or particles that are easily split (friable), should not be used. Aggregates should be well graded as this effects workability of the concrete. A description of aggregate classifications, excavation, grading, and testing is given in References 120 and 122. If aggregates are obtained from different souces, required tests should be made on samples from each source.

Marine aggregates are considered satisfactory for use in concrete.[50,52] However, these aggregates should conform to ASTM Designation: C33. In addition, they should not have chloride and sulfate contents that will result in a concrete mix that exceeds specified chloride and sulfate limits. Aggregates can be washed with fresh water to remove excess salts.[50,84] Washed aggregates should be sampled and tested to insure compliance with specifications.

Aggregates should be handled and stored to prevent intermingling of different gradations, contamination by organic or other foreign material, and to minimize segregation.[120,122,123] Recommended practices are available

TABLE 8 - CHARACTERISTICS AND TESTS OF AGGREGATES(120)

Characteristic	Significance	ASTM Test Designation	Requirement or Item Reported
Resistance to abrasion	Index of aggregate quality; wear resistance	C131 C295 C535	Maximum percentage of weight loss
Resistance to freezing and thawing	Surface scaling, roughness, loss of section, and unsightliness	C295 C666 C682	Maximum number of cycles or period of frost immunity; durability factor
Resistance to disintegration by sulfates	Soundness against weathering action	C88	Weight loss, particles exhibiting distress
Particle shape and surface texture	Workability of fresh concrete	C295 D3398	Maximum percentage of flat and elongated pieces
Grad[illegible]	Workability of fresh concrete; economy	C117 C136	Minimum and maximum percentage passing standard sieves
Bulk unit weight or density	Mix design calculations; classification	C29	Compact weight and loose weight
Specific gravity	Mix design calculations	C127, fine aggregate C128, coarse aggregate C29, slag	--
Absorption and surface moisture	Control of concrete quality	C70 C127 C128 C566	--
Compressive and flexural strength	[illegible]ptability of fine [illegible]gregate failing other tests	C39 C78	Strength to exceed 95% of strength achieved with purified sand
Definitions of constituents	Clear understanding and communication	C125 C294	--

TABLE 9 - TESTS FOR DELETERIOUS MATERIALS IN AGGREGATES (120)

Substances	Effect on Concrete	ASTM Test Designation
Organic impurities	Affect setting and hardening, may cause deterioration	C40 C87
Materials finer than No. 200 sieve	Affect bond, increase water requirement	C117
Coal, lignite, or other lightweight materials	Affect durability, may cause stains and popouts	C123
Soft particles	Affect durability	C851, C235
Clay lumps and friable particles	Affect workability and durability, may cause popouts	C142
Chert of less than 2.40 specific gravity	Affects durability, may cause popouts	C123 C295
Alkali-reactive aggregates	Abnormal expansion, map cracking, popouts	C227 C289 C295 C342 C586

for guidance.[67,123] Figure 12 illustrates recommended methods of handling and storing aggregates.[123]

Control of moisture content in aggregates is important to insure uniform consistent mixes. Provisions should be made to obtain uniform and stable moisture content of aggregates as batched. Excess free water should be permitted to drain prior to use of aggregates.[123] Batch proportions must be adjusted to compensate for moisture content measured on aggregates just prior to their introduction into the mix.[123]

Procedures for obtaining uniform moisture content of lightweight aggregates should be given special attention. Some lightweight aggregates require prewetting to insure consistent batch control.[67] Lightweight aggregates can absorb water during mixing. This can result in slump loss and reduced workability, and is particularly important if concrete is to be pumped.[67]

4.3 Mixing Water

It is preferable to use fresh, clean, potable mix water in concrete for marine structures.[52,108] Most public water supplies are satisfactory.[120,124]

General building code requirements permit use of unpotable water under the following conditions. Unpotable water may be used for making concrete if mortar cubes made with the water have 7- and 28-day compressive strengths equal to at least 90% of companion specimens made with potable water.[125-127] Mortar cubes should be prepared and tested in accordance with ASTM Designation: C109, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm cube specimens.)" This criterion should be satisfactory for marine structures as long as limits on chemical composition of mixing water are met.

Chloride and sulfate contents of mixing water for concrete or grout should be limited to insure durability against chemical attack and corrosion. ACI Committee 357 suggests a maximum chloride limit of 0.07% $C\ell$ by weight of cement and a sulfate limit of 0.09% sulfates as SO_4.[50] For prestressed concrete, the chloride limit is reduced to 0.04%. Chloride and sulfate contents are obtained from tests in accordance with ASTM Designation: D512 "Standard Test Methods for Chloride Ion in Water and Waste Water" and ASTM Designation: D516, "Standard Test Methods for Sulfate Ion in Water and Waste Water."[120]

Although satisfactory concrete can be made with seawater, there may be an increased risk of corrosion with seawater in the mix.[84,87,120] Therefore,

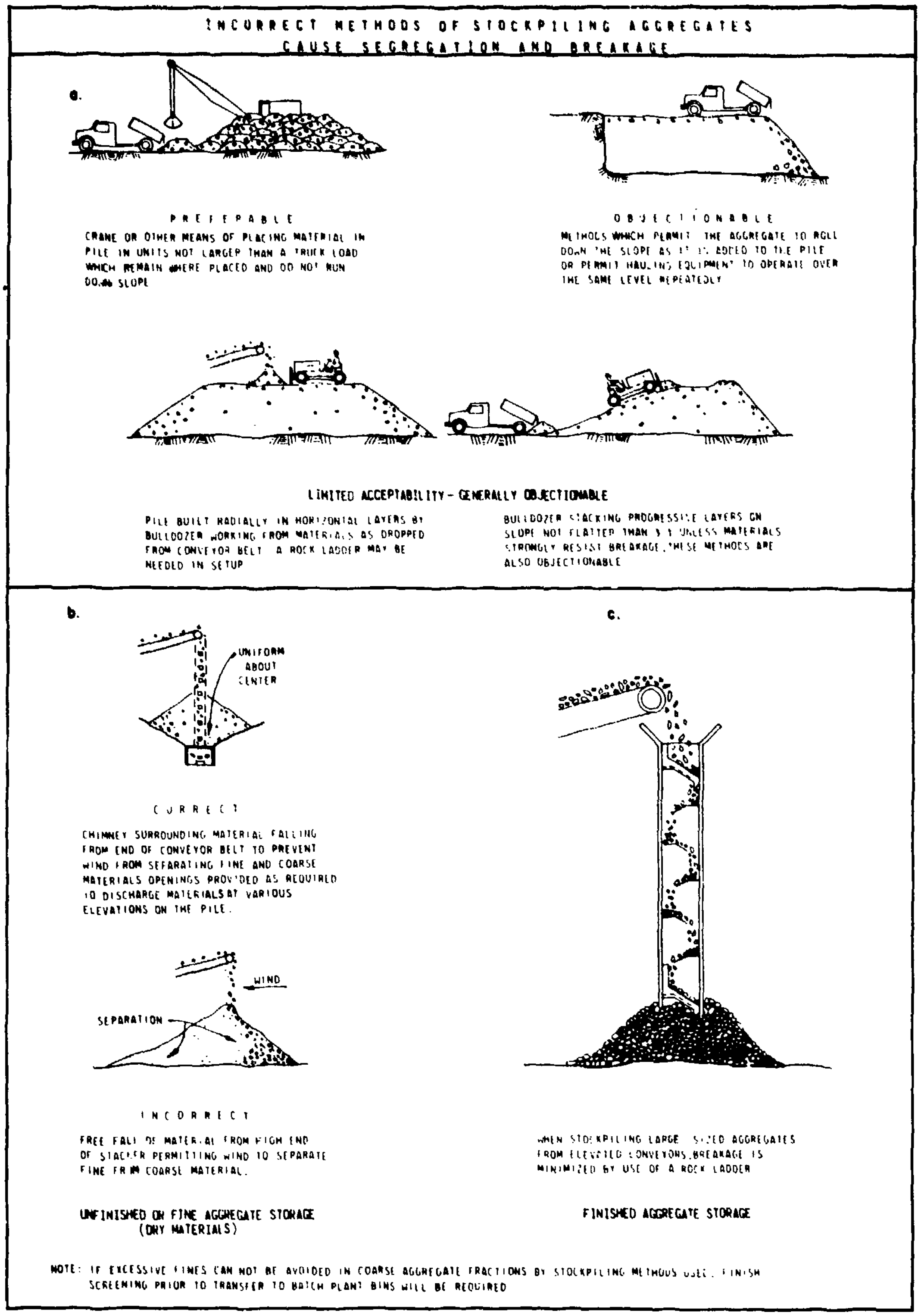


Fig. 12 Correct and Incorrect Methods of Handling and Storing Aggregates (123)

seawater should be prohibited as mixing water unless there is adequate documentation to justify its use. Since effects of corrosion are more critical in prestressed concrete, seawater should not be used to make prestressed vessels.

4.4 Admixtures

Admixtures include any material added to the concrete mix other than portland cement, water, and aggregates.[120,128] Table 10 gives a general classification of admixtures and relevant ASTM standards.[120] Included are:

(a) Air-Entraining Admixtures

(b) Water-Reducing Admixtures

(c) Retarding Admixtures

(d) Accelerating Admixtures

(e) Pozzolans

(f) Workability Agents

(g) Miscellaneous Agents (Pumping Aids, Gas Formers, Dampproofing Agents, Waterproofing Agents, Air Detrainers).

All admixtures used in concrete vessels should be tested and documented to insure compatibility with selected concrete mix materials and with other admixtures being used.[50-53] Admixtures should not be used as a substitute for a high-quality low-permeability concrete mix. Admixtures should conform to appropriate ASTM Standards.[50,120]

Air-entraining admixtures are covered by ASTM Designation: C260, "Standard Specification for Air-Entraining Admixtures for Concrete." Water-reducing, retarding, accelerating, water-reducing and retarding, and water-reducing and accelerating admixtures are covered by ASTM Designation: C494, "Standard Specification for Chemical Admixtures for Concrete." Pozzolans are covered by ASTM Designation: C618, "Standard Specification for Fly Ash and Raw or Calcinated Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete."

Det Norske Veritas requires the following information to be provided prior to use of an admixture:[51,53]

(a) Trade Name

(b) Manufacturer and Supplier

(c) Main Function of the Admixture

(d) Side Effects of the Admixture (Favourable or Unfavourable)

(e) Physical State

TABLE 10 - CLASSIFICATION OF ADMIXTURES(120)

Desired Effect	Type of Admixture (ASTM Designation)	Material
Improve durability	Air-entraining (C260)	Salts of wood resins Some synthetic detergents Salts of sulfonated lignin Salts of petroleum acids Salts of proteinaceous material Fatty and resinous acids and their salts Alkylbenzene sulfonates
Reduce water required for given consistency	Water reducer (C494, Type A)	Lignosulfonates Hydroxylated carboxylic acids (Also tend to retard set so accelerator is added)
Retard setting time	Retarder (C494, Type B)	Lignin Borax Sugars Tartaric acid and salts
Accelerate setting and early-strength development	Accelerator (C494, Type C)	Calcium chloride (ASTM D98) Triethanolamine
Reduce water and retard set	Water reducer and retarder (C494, Type D)	(See water reducer, Type A, above)
Reduce water and accelerate set	Water reducer and accelerator (C494, Type E)	(See water reducer, Type A, above. More accelerator is added)
Improve workability and plasticity	Pozzolan (C618)	Natural pozzolans (Class N) Fly ash (Class F and G) Other materials (Class S)
Cause expansion on setting	Gas former	Aluminum powder Resin soap and vegetable or animal glue Saponin Hydrolized protein
Decrease permeability	Dampproofing and waterproofing agents	Stearate of calcium, aluminum, ammonium, or butyl Petroleum greases or oils Soluble chlorides
Improve pumpability	Pumping aids	Pozzolans Organic polymers
Decrease air content	Air detrainer	Tributyl phosphate
High flow	Superplasticizers	Sulfonated melamine formaldehyde condensates Sulfonated naphthalene formaldehyde condensates

(f) Composition

(g) Identification of Main Active Constituents of the Admixture and Other Constituents that May Form

(h) Conditions of Storage, Preparation, and Procedure for Introducing the Product into the Mix

(i) Recommended Proportion by Weight of Cement (Include Type of Cement, Cement Content of Mortar or Concrete, and the Consistency of the Mix)

(j) Maximum Permissible Dosage and Influence of Overdose

(k) Possible Incompatibility With Certain Types of Cements or With Other Admixtures

(l) Packing Methods, Storage Conditions, Maximum Storage Time Before Use and Date of Manufacture

(m) Information Confirming Effects Claimed by the Manufacturer (Verification Tests Done by an Independent Laboratory).

ACI Committee 212 also provides guidance for use of admixtures in concrete.[129]

ACI Committee 357 recommends that admixtures containing chlorides should not increase total chloride ions limit for the concrete mix as given in the construction specifications.[50] Calcium chloride, an accelerator, is not recommended for prestressed concrete marine structures.[50-53]

Storage, handling, and dispensing of admixtures should follow manufacturers' recommendations and standard good practices such as those given by ACI Committee 212.[129]

4.5 Reinforcing and Prestressing Steel

Reinforcing and prestressing steel for concrete vessels is the same as that used for general building construction.[50,126] Ordinary deformed reinforcement* and prestressing tendons are manufactured in accordance with ASTM specifications summarized in Table 11. Elements such as inserts, anchor bolts, or plain bars for dowels at joints are not normally considered to be reinforcement under provisions of the ACI Building Code.[126] Except for steel used in spirals or in prestressing tendons, deformed reinforcement is required by building codes for concrete structures. Deformed reinforcement includes deformed bars, bar and rod mats, deformed wire, welded smooth wire fabric and

*Deformed reinforcing bars are manufactured with surface deformations that provide mechanical bond with surrounding concrete.

TABLE 11 - REINFORCING AND PRESTRESSING STEEL

ASTM Designation	Standard Specification for	Grade on Type	Product Form
A615	Deformed and Plain Billet/Steel Bars for Concrete Reinforcement	40, 60	Deformed Bar
A616	Rail-Steel Deformed and Plain Bars for Concrete Reinforcement	50, 60	Deformed Bar
A617	Axle-Steel Deformed and Plain Bars for Concrete Reinforcement	40, 60	Deformed Bar
A706	Low-Alloy Steel Deformed Bars for Concrete Reinforcement	60	Deformed Bar
A82	Cold-Drawn Steel Wire for Concrete Reinforcement	60, 70 (yield)	Plain Wire
A496	Deformed Steel Wire for Concrete Reinforcement	70, 75 (yield)	Deformed Wire
A185	Welded Steel Wire Fabric for Concrete Reinforcement	55, 65 (yield)	Welded Smooth Wire Fabric
A497	Welded Deformed Steel Wire Fabric for Concrete Reinforcement	70 (yield)	Welded Deformed Wire Fabric
A184	Fabricated Deformed Steel Bar Mats for Concrete Reinforcement	40, 60	Deformed Bar Mats
A416	Uncoated Seven-Wire Stress-Relieved Strand for Prestressed Concrete	250, 270	Strand
A421	Uncoated Stress-Relieved Wire for Prestressed Concrete	BA, WA	Wire
A722	Uncoated High-Strength Steel Bar for Prestressing Concrete	150	Deformed or Plain Bars

welded deformed wire fabric.[125] General information on use of reinforcement in concrete structures is available in a number of references.[130-134]

Standards for reinforcing bars are included in ASTM Designations: A615, A616, A617, and A706 as shown in Table 11. These standards cover bars made from billet steel, rail steel, axle steel, and low alloy steel, respectively. The ASTM standards cover chemical requirements, requirements for deformations, tensile requirements, bar sizes, and bar identification. Most reinforcement in general use corresponds to ASTM Designation: A615 for new billet steel.

Low alloy steel deformed bars, made in accordance with ASTM Designation: A706, are a relatively recent development. These bars are intended for special applications where welding, bending, or both, are of importance.[126] ASTM specifications for low alloy steel deformed bars include stricter requirements on steel chemistry than is required for billet steel, rail steel and axle steel bars.

A review of physical requirements for ASTM reinforcing bars and a general discussion of standard practice in the reinforcing steel industry is included in the "Manual of Standard Practice" published by the Concrete Reinforcing Steel Institute[130].

Two exceptions to ASTM standards for new billet, rail steel and axle steel are prescribed in the ACI Building Code.[125,126] The first exception requires that tensile yield stress be determined by tests on full-size bars. This provision is made because tests indicate that reduced section specimens show higher strength than tests on full-size bars.[126] To meet this provision of the code, a test can be run on full-size bars or on standardized small-size turned down specimens. If standardized small specimens are used, results must be correlated by statistical analysis with tests on full-size bars. In either case, yield stress is based on the nominal area of the bar.

The second exception to the ASTM specifications for billet steel, rail steel, and axle steel concerns bend test requirements for the bars. The ACI Building Code requires that smaller pin diameters be used in the bend test.[125,126] This is because diameters specified in the ASTM Standard are larger than the minimum bend diameter allowed for fabrication of reinforcement. Bend test requirements given in the ACI Building Code are shown in Table 12. Low alloy steel bars manufactured in accordance with ASTM Designation: A706 satisfy both exceptions.

TABLE 12 - ACI 318 BEND TEST REQUIREMENTS FOR BILLET, RAIL AND AXLE STEEL REINFORCING BARS[125]

Bar Designation[1]	Pin Diameter for a Bend Test[2]
#3, #4, and #5	3-1/2 bar diameters
#6, #7, and #8	5 bar diameters
#9, #10, and #11	7 bar diameters
#9, #10, and #11 (of Grade 40)	5 bar diameters

(1) If #14 or #18 bars are to be bent, full-size bar specimens shall be bend tested 90 degrees, at a minimum temperature of 60 F around a nine-bar diameter pin without cracking of the bar. However, if #14 and #18 bars as used in the structure are required to have bends exceeding 90 degrees, specimens shall be bend tested to 180 degrees with the other criteria the same as for 90 degrees.

(2) 180 degree bend.

Reinforcing bars meeting ASTM specifications listed in Table 11 can also be obtained with zinc or epoxy coating. As mentioned previously, these coatings have been developed to protect steel from corrosion in severe environments. Zinc coated (galvanized) bars are covered by ASTM Designation: A767, "Standard Specification for Zinc Coated (galvanized) Bars for Concrete Reinforcement." A corresponding ASTM Standard for epoxy coated bars is under development. Currently, manufacturers' recommended specifications are available.(135)

ACI Committee 357 recommends that weldable reinforcement be used in the splash zone of marine concrete structures to facilitate future repairs that may be necessary.(50) Welding of reinforcing steel is covered by the "Reinforcing Steel Welding Code (AWS D 12.1)" of the American Welding Society.(136) This code includes provisions to insure that welding procedures and steel properties are compatible. Chemical requirements included in ASTM Standards for billet, rail and axle steel must be supplemented to cover special requirements of welding. This should be done in the contract specifications.(126) Low alloy steel reinforcing bars covered by ASTM Designation A706 were developed specifically for welding. This steel has a controlled chemistry and a specified maximum carbon equivalent which eliminates the need for supplementary requirements.(126)

Welded wire fabric for concrete reinforcement is covered by two ASTM Standards. ASTM Designation: A185, "Standard Specification for Welded Steel Wire Fabric for Concrete Reinforcement," covers welded smooth wire fabric. This fabric is made by welding together square or rectangular grids of cold drawn wire.(131) Each wire intersection is electrically resistance welded by a continuous automatic welder. Wire for smooth welded wire fabric must conform to ASTM Designation: A82, "Standard Specification for Cold Drawn Steel Wire for Concrete Reinforcement." For wire fabric, this reinforcement has a yield stress of 60,000 psi

Welded deformed wire fabric must conform with ASTM Designation: A497, "Standard Specification for Welded Deformed Steel Wire Fabric for Concrete Reinforcement." Wire used in deformed wire fabric is governed by ASTM Designation: A496, "Standard Specification for Deformed Steel Wire for Concrete Reinforcement." This wire has a minimum yield stress of 70,000 psi when used in wire fabric.

The ACI Building Code requires that welded intersections in smooth wire fabric have a maximum spacing of 12 inches in the direction of primary structural reinforcement. For deformed wire fabric, welded intersections should not be spaced farther apart than 16 inches in the direction of primary flexural reinforcement.[125]

Reinforcement for concrete structures may also take the form of bar or rod mats. These mats consist of an assembly of steel reinforcement composed of two or more layers of bars placed at angles to each other. They are fastened together by welding or by tie wires. The ACI Building Codes provides for bar and rod mats conforming to ASTM Designation: A184, "Specification for Fabricated Deformed Steel Bar Mats for Concrete Reinforcement." Although this standard includes both welded and clipped intersections, ACI Committee 301 recommends that the clip type be used.[127]

To provide an adequate factor of safety between yield strength and ultimate strength of the member, it is necessary to limit the strain at which the yield stress is defined. For bars, wire, or wire fabric with a specified yield stress exceeding 60,000 psi, the ACI Building Code requires that the yield stress correspond to a strain of 0.35 percent. This requirement is made because the calculated flexural strength of members is based on the assumption of an elasto-plastic stress-strain relationship for reinforcement.

Wire, strands, and bars used in prestressed concrete are covered by ASTM Designations: A421, A416, and A722, respectively.[50,125] These standards include requirements for yield stress, breaking strength, elongation, dimensions, and inspection. ASTM Standards for strand and wire contain supplementary requirements for low relaxation materials. If low relaxation strand or wire are required, the supplement to ASTM Designation: A416 or A421 should be referenced in the construction specifications. Relaxation is tested in accordance with ASTM Designation: E328, "Recommended Practice for Stress Relaxation Test for Materials and Structures."

Anchorage components and couplings for prestressing tendons are a part of the load bearing system. For pretensioned members, tendon systems are tested automatically when the unit is fabricated. However, when used for post-tensioned construction, tendon assemblies can be proof tested under static and dymanic conditions in accordance with guide specifications of the Post-Tensioning Institute.[132] These specifications are intended to insure that the entire tendon assembly is capable of developing the required design strength, and that anchorages and couplings are not "weak links" in the system. Generally, post-tensioned systems are marketed as a complete package including anchorage components and couplings. Therefore, performance data on tendon assemblies are available through manufacturers. For large jobs, verification of performance tests may be required by the construction specifications.

All reinforcing materials should be shipped and stored so as to maintain their identification with regard to heat number, manufacturer, size, type, and grade. Extra precautions should be taken to insure that prestressing tendons are protected from corrosion. Tendon assemblies should be shipped and stored in weather tight enclosures. Corrosion can have a significant effect on strength, deformation capacity, and fatigue of tendons.[137] It is also important that tendons be kept clean and free of grease, oil, salts or any other materials that can affect bond or durability.

Welding, flame cutting or similar operations should be carried out far enough away from stored prestressing tendons to insure that temperature of the stored tendons is not raised sufficiently to affect material properties of the steel.[137]

4.6 Post-Tensioning Ducts

ACI Committee 357 recommends that post-tensioning ducts be semi-rigid and watertight with at least 1 mm of wall thickness.[50] This provision is consistent with FIP recommendations for design and construction of concrete sea structures.[52] The provision is intended to insure that ducts will remain aligned without excessive "wobble" and that ducts will not be susceptible to intrusion of mortar. Thicker walled ducts are more rigid but are also more difficult to ship and handle.[137]

Ducts are commonly manufactured from bright or galvanized steel strips that are spirally wound and longitudinally seamed.[132] ACI Committee 357 recommends that galvanized metal ducts be passivated by a chromate wash. Chromate passivation is recommended because of concerns about the possibility of free hydrogen being liberated from chemical reactions between cement and zinc. It is suspected that this could result in hydrogen embrittlement of tendons. However, direct laboratory or field evidence of such embrittlement has not been definitely established.[137]

ACI Committee 357 recommends against the use of plastic duct material.[50] Although plastic conduit has been used in post-tensioned structures, problems have been encountered with curved tendons because the tendons bite into the walls of the plastic conduit when they are being stressed. Thus, friction factors may become excessive, which would reduce the effective level of prestress.[137]

ACI Committee 357 recommends that bell and spigot joints be used for connecting duct segments. It is important that joints in ducts be clean, and free of burrs and dents. This is necessary to prevent problems at later stages of construction when tendons are placed. Proper jointing will minimize obstructions to tendons as they are pulled through the ducts.

Guide specifications of the Post-Tensioning Institute require that for tendons made up of a single wire, bar, or strand the duct diameter should be at least 1/4-in. larger than the nominal diameter of the wire, bar or strand.[132] For tendons made up of multiple wires, bars, or strands, the duct area should be at least twice the net area of the prestressing steel.

4.7 Grout for Bonded Tendons

Injection of cement grout is the most widely used method of encasing prestressing tendons in ducts.[137] Grout provides bond between the post-tensioning tendons and concrete, and also provides corrosion protection for the tendons.[126,137] Guide specificatons for grouting of post-tensioned prestressed concrete are provided by the Post-Tensioning Institute.[132] ACI Committee 357 recommends that grout for bonded tendons in offshore concrete structures conform to the ACI Building Code.[50,125] In addition, for marine structures it is necessary that limits for tricalcium aluminate content of cement, and chloride and sulfate contents of mixing water and admixtures also be met. This is to insure durability. It is also important that total chloride content of the grout be limited to values stated in the construction specifications.[50-55]

Mix proportions for grout are based on either results of tests of fresh and hardened grout prior to start of grouting operations, or on the basis of prior documented experience with similar materials and equipment.[125,132] The ACI Building Code and PTI guide specifications limit the maximum water-cement ratio of the grout to 0.45 by weight.[125,132] It is also recommended that the water content be the minimum necessary for proper placement. Use of these guidelines should provide grout with a 7-day compressive strength on standard 2-in. cubes in excess of 2500 psi and 28-day strengths of about

4000 psi.[125,126,132] The guide specifications for grout are used for the range of concrete strengths commonly specified for post-tensioned members.

Sand is not commonly used in grout, however, it may be advantageous for tendons with large void areas.[132] ACI Committee 301 recommends that fine sand may be used in grout mixes when the gross inside cross-sectional area of the duct exceeds four times the tendon cross-sectional area.[127] Sand should meet the requirements of ASTM Designation: C144, "Standard Specifications for Aggregate for Masonry Mortars."

Type I, II, or III cement corresponding to ASTM Designation: C150, "Standard Specification for Portland Cement" are satisfactory for use in grout.[50-53,132] Normally, Type III cement is only used for cold weather grouting.[132] Cement used should satisfy limits for tricalcium aluminate content as specified in the construction specification. Generally, these limits would be established at the same level as for cement to be used in concrete for the vessel.

Admixtures for grout are defined as any material that is added to the grout other than portland cement, sand, and water.[132] Commonly, admixtures are added to improve flowability, minimize bleeding, and reduce shrinkage. Admixtures should only be used after sufficient testing to indicate that their use would be beneficial.[50] They should be essentially free of chlorides or any other material that has been shown to be detrimental to steel or grout.[50]

Shrinkage compensating admixtures result in expansion of grout during hydration of cement. Most specifictions require that unrestrained expansion of grout be limited to 10% by volume.[51,53,132,137]

Because grout must be fluid, it is necessary to take precautions against excessive bleeding. The term "bleeding" refers to the separation of water from the solid materials in the grout. It can be caused by the settlement of solid materials and is particularly troublesome when vertical or long inclined sections of tendons must be grouted. PTI guide specifications provide criteria for evaluating bleeding characteristics of grout.[132] Thixotropic admixtures* have also been developed to reduce bleeding in grout.[137]

*Thixotropic materials acquire a lower viscosity when mechanically agitated, but stiffen in a short period on standing. Thixotropic admixtures increase grout flowability without requiring additional water which may lead to bleeding.

4.8 Inserts and Embedments

Embedment plates, conduits, pipes and sleeves to be cast into concrete for vessels should be made of materials that are not reactive.

The ACI Building Code prohibits use of aluminum in structural concrete unless it is coated.[125,126] Aluminum reacts with concrete and, in the presence of chloride ions, may also act electrolytically with steel. This can result in cracking or spalling of concrete. Aluminum electrical conduits present an additional problem because of effects of stray electric currents.[126]

ACI Committee 357 recommends that reinforcing bars which are to be welded to embedment plates be of weldable grade steel.[50] It is also recommended that full penetration welds conforming to AWS D12.1 be used for bars welded to embedment plates.[50] Reinforcement which meets the chemical analysis requirements of ASTM Designation: A706 is considered weldable.[50,126]

4.9 Concrete

In general, recommendations for concrete in marine structures include limitations on the following characteristics

(a) Maximum water-cement ratio

(b) Minimum compressive strength

(c) Minimum cement content

(d) Minimum and maximum entrained air content

(e) Maximum chloride content.

All of these items are specified to obtain workable, impermeable, and durable concrete. Table 13 lists concrete properties from a number of different sources in which recommendations for marine structures are given. Although different values are given depending on the source, all sources address basic properties listed above. Construction specifications for specific projects should contain limits on concrete properties that fall within the range of values shown in Table 13.

As can be seen in Table 13, most recommendations for marine concrete structures specify quality of concrete on the basis of water-cement ratio and cement content as well as concrete strength. This is done because it has been found that the volume of cement paste is important to insure durability. It is also important that the concrete mix be designed for workability. If water-cement ratio is lowered without regard for workability, the resulting

TABLE 13 - RECOMMENDED CONCRETE PROPERTIES FOR MARINE APPLICATIONS

Source	Property	Exposure Zone		
		Submerged	Splash	Atmospheric
ACI 357[50]	Max. water-cement ratio (by weight)	0.45	0.40	0.40
	Min. 28-day cyl. compressive strength (psi)	5000	5000	5000
		(6000 in areas subject to abrasion)		
	Min. cement content (lb/cu yd)	600	600	600
	Max. cement content (lb/cu yd)*	700	700	700
	Air entrainment (%)**	--	5.5 to 7.5	5.5 to 7.5
	Total Cℓ content (% by wt. of cement)	0.10 for reinforced concrete		
		0.06 for prestressed concrete		
DNV[51,53]	Max. water-cement ratio (by weight)	0.45 (≤ 0.40 preferred)		
	Min. 28-day cyl. compressive strength (psi)	--	--	--
	Min. cement content (lb/cu yd)	500	675	500
	Max. cement content (lb/cu yd)*	--	--	--
	Air entrainment (%)**	--	3 to 5	3 to 5
	Total Cℓ content (% by wt. of cement)	0.1	0.1	0.1
FIP[52]	Max. water-cement ratio (by weight)	0.45 (≤ 0.40 preferred)		
	Min. 28-day cyl. compressive strength (psi)	5000	5000	5000
		(6000 in areas subject to abrasion)		
	Min. cement content (lb/cu yd)	540 to 600	675	540 to 600
	Max. cement content (lb/cu yd)*	840	840	840
	Air entrainment (%)**	--	4 to 7	4 to 7
	Total Cℓ content (% by wt. of cement)	(Chloride content should be minimized)		
Gerwick[49,97]	Max. water-cement ratio (by weight)	0.45 (≤ 0.40 preferred)		
	Min. 28-day cyl. compressive strength (psi)	--	--	--
	Min. cement content (lb/cu yd)	650	650	650
	Max. cement content (lb/cu yd)*	--	--	--
	Air entrainment (%)**	--	4 to 6	4 to 6
	Total Cℓ content (% by wt. of cement)	(Limits given for mix constituents)		
Browne and Domone[79]	Max. water-cement ratio (by weight)	0.45	0.45	0.45
	Min. 28-day cyl. compressive strength (psi)	--	--	--
	Min. cement content (lb/cu yd)	550 to 675	550 to 675	550 to 675
	Max. cement content (lb/cu yd)*	--	--	--
	Air entrainment (%)**	--	4 to 6	4 to 6
	Total Cℓ content (% by wt. of cement)	(Chloride content should be minimized)		

*For cement contents above this level, precautions should be taken to prevent excessive thermal stresses from developing.

**When freeze-thaw durability is required. Required air content varies with maximum aggregate size.

concrete mix may be difficult to place. This will result in poor in-situ concrete quality.[79,93]

If a high cement content is used in a relatively thick section, precautions must be taken to prevent severe temperature stress gradients that may result as concrete temperature rises when cement hydrates.[50,52] This may require the selection of cements that have a low heat of hydration, use of set retarding admixtures, use of reduced rates of placement, precooling of aggregates, or use of pozzolans.[50]

When freeze-thaw durability is required, concrete should be made with entrained air. The amount of entrained air required varies with the maximum aggregate size specified for the mix.[77] It is important to consider that freeze-thaw durability is not only dependent upon the absolute amount of entrained air, but it also depends upon pore size distribution.

DNV rules for marine concrete include recommendations for pore size distribution and spacing.[51,53] These are given in terms of a calculated spacing factor which must be evaluated based on a petrographic analysis of the hardened concrete.

Both ACI Committee 357 and DNV set specific limits on the maximum total chloride content of the concrete.[50,51,53] These limits are to minimize the possibility of corrosion.

ACI Committee 357 and FIP recommendations include requirements for increased concrete strengths where severe scouring action can occur.[50,52] These requirements are based on data that indicate abrasion resistance increases with increasing concrete strength.[77]

5. BATCHING AND MIXING CONCRETE

General procedures for batching and mixing concrete to be used in marine structures do not differ from procedures used for concrete in land based structures. The basic objectives are to produce concrete that is thoroughly mixed and uniform in quality. Therefore, ingredients must be accurately measured for each batch and must be completely mixed to insure that all surfaces of aggregate particles are coated with cement paste and the entire mass uniformly blended.[84,120] ACI Committee 304, in its "Recommended Practice for Measuring, Mixing, Transporting and Placing Concrete", provides detailed information on batching and mixing procedures.[123]

5.1 Ready Mixed Concrete

Provisions for batching and mixing ready mixed concrete are covered under ASTM Designation: C94, "Standard Specification for Ready Mixed Concrete". This ASTM specification covers ready mixed concrete manufactured and delivered to the jobsite in a freshly mixed and unhardened state. In addition, the National Ready Mixed Concrete Association has produced a "Check List for Certification of Ready Mixed Concrete Production Facilities" which describes a system for establishing that production facilities in ready mixed concrete plants are satisfactory.[138] This checklist covers material storage and handling, batching equipment, mixing equipment, delivery equipment, and documentation and inspection. Truck mixer and agitator standards are also available through the Truck Mixer Manufacturers Bureau.[139]

5.2 Site Mixed Concrete

ACI Committee 304 provides recommendations for mixing concrete at the jobsite.[123] Specifications generally require that materials be measured in individual batches within the following percentages of accuracy:

(a) Cement ± 1%

(b) Aggregates ± 2%

(c) Water ± 1%

(d) Admixtures ± 3%

These tolerances are typical of most specifications.[120,123,127] Specifications also require that accuracy of batching equipment be checked periodically.

Concrete mixing time is based upon the ability of the mixer to produce uniform concrete throughout the batch, and from batch to batch.[123] If concrete has been adequately mixed, samples taken from different portions of a batch will have essentially the same unit weight, air content, slump, and coarse aggregate content.[120,123]

5.3 Control of Admixtures

Generally chemical admixtures are added to the mix as solutions with the liquid being considered as part of the mixing water.[120,123,127] Admixtures that cannot be added in solution are either weighed or measured by volume as directed by the manufacturer.[120,127] Dispensing equipment for admixtures should be checked frequently because errors in batching can lead to serious problems in both fresh and hardened concrete.[120] Batching and dispensing equipment used should be readily capable of calibration and should contain visual check tubes.[123] Some specifications require that if two or more admixtures are used in the concrete they should be added separately to avoid possible deleterious interaction.[127] If a single dispenser is used for different admixtures, it is important that the unit be cleaned between changes in admixtures.[138] Specific batching recommendations for different types of admixtures are given by ACI Committee 212.[129]

5.4 Control of Mix Temperature

Batch-to-batch uniformity of concrete is dependent upon consistency of concrete temperature.[123] Therefore, it is important that maximum and minimum concrete temperatures be controlled throughout all seasons of the year.

During hot weather it is common practice to cool mixing water with ice prior to its introduction into the mix.[120] Ice used for such purposes should be finely crushed, shaved, or chipped, so that it is completely melted at the completion of mixing.[120,127]

During cold weather, mixing water is the easiest and most practical component of the mix to heat.[120] However, in some cases aggregates are also heated prior to their introduction into the mix. Most specifications require that cement should not be added to mixes when the temperature of water and aggregate exceeds 100°F.[127] This recommendation is intended to prevent the possibility of a quick or flash set of the concrete.[120] It is also necessary in cold weather to take adequate measures to insure that aggregates do not contain frozen clumps, ice, or snow when they are introduced into the mixer.[120] Additionally, precautions should be taken to insure that deleterious salts or chemicals are not used to lower the freezing point of the mixing water.

General recommendations for hot weather and cold weather concreting are given by ACI Committees 305 and 306, respectively.[140,141]

5.5 Lightweight Aggregates

Lightweight aggregate concrete can be mixed the same way as normal weight concrete when the aggregates have less than 10% total absorption by weight, or if they have been shown to absorb less than 2% by weight during the first hour after immersion in water.[120,127] Concrete made with lightweight aggregates that do not conform to these absorption limits can be made in accordance with procedures recommended by ACI Committees 213 and 301.[67,127] The aggregate manufacturer should also be consulted on procedures for batching and mixing. Highly absorptive lightweight aggregates require either prewetting to a uniform moisture content or premixing with water prior to addition of other ingredients of the concrete.[67]

6. INSPECTION BEFORE CONCRETING

Prior to placement of concrete it is essential that reinforcement, prestressing tendons, formwork and embedments, and construction joints be inspected. This inspection is intended to insure that all reinforcement and embedded items are properly placed and secured in position, and that formwork is correctly positioned to obtain final dimensions within tolerance limitations of the construction specifications. Once concrete is cast it is extremely difficult to correct deficiencies that may have occurred during fabrication and placing of reinforcement, embedments, and formwork.

6.1 Reinforcement

Provisions for surface condition of reinforcement are included in most codes and specifications.[50-53,125-127] These provisions generally state that, at the time of concrete placement, reinforcement should be free of mud, loose rust, grease, oil, deposits of salts, ice, snow, or any other materials that may adversely affect bond or durability. Specific limits on the amount of rust or loose mill scale are based on tests of bond characteristics of reinforcing steel.[142] Research has shown that a normal amount of rust increases bond and that normal handling of reinforcement is generally sufficient to remove rust that is loose enough to injure bond between concrete and reinforcement.[126] ASTM specifications for reinforcement contain provisions for evaluating the point at which rust or mill scale can be considered excessive.

General recommended practices for placement of reinforcing bars have been developed by the Concrete Reinforcing Steel Institute.[134]

Standard hooks at ends of bars and minimum bend diameters for fabrication of reinforcement are specified in the ACI Building Code.[125] General procedures for meeting these requirements are given in industry standards.[130,131,134] Codes and specifications for reinforced concrete require that all reinforcement be cold bent unless otherwise permitted by the project engineer.[50,51,125,127] This requirement is intended to avoid changes in reinforcing bar material properties that can occur if sections of bars are overheated.

Tolerances for fabrication of reinforcement are included in specifications for structural concrete for buildings and in industry standards.[127,130,131)

Field bending of reinforcement partially embedded in hardened concrete is prohibited unless approved by the project engineer.(125-127) This provision is intended to avoid damage to bars that can occur by reworking. Field bends should only be made under controlled conditions with careful supervision.(126,143) If preheated, limits on maximum temperatures should be observed.(126,143)

Reinforcement to be welded should be indicated on the construction drawings and welding procedures to be used should also be specified.(125) Steel should not be welded without regard to steel weldability and proper welding procedures.(126) The specified welding procedure and the steel to be welded should be compatible. The "Reinforcing Steel Welding Code" of the American Welding Society provides recommended welding practices. When welding is needed, contract specifications should specifically require that chemical analysis of reinforcement be provided in addition to standard ASTM requirements.(126) Analysis is not needed for low-alloy reinforcement conforming to ASTM Designation: A706 because this standard contains provisions to define steel weldability.

Most codes for reinforced concrete require that reinforcement be protected against weld splatter and arcs due to strikes or current drainage.(50,125,127) Similarly, welding of crossing bars ("tack" welding) is prohibited in most codes.(50,125,127) These provisions are made because tack welding can seriously weaken a bar at the weld point by creating a metallurgical notch effect.(126) Under controlled conditions, as specified in the AWS code, tack welds can be performed safely.(136) However, this should only be done under special circumstances and with authorization of the project engineer.(125-127,136) Test results have shown that careless tack welding of stirrups can reduce fatigue life of longitudinal bars at a given stress range by 75%.(144)

In the structural design of a concrete vessel, it is assumed that the structure behaves as a continuous unit. However, it is not feasible to provide full-length continuous reinforcing bars in any sizeable structure. Most reinforcement is rolled in standard lengths of 60 ft., although special arrangements can be made to obtain longer length bars.(130,145) Therefore, splices of reinforcement are unavoidable. Reinforcement can be spliced by lapping bars, by welding, or by use of mechanical couplers.(145) Because splices represent potential "weak links" in the structure, care must be taken to insure that they are located and fabricated in accordance with the construction drawings and specifications. Generally, design of the structure will be such as to locate splices away from regions where critical stresses can occur.[126] Therefore, the location of splices should not be changed during construction without specific approval of the project engineer.

Provisions for lap splice lengths are given in codes to provide guidance for the designer.[125,126] ACI Committee 357 recommends that lap splices be avoided in areas of fatigue, but permits the designer to use lap splices in such areas if their development length, calculated in accordance with the ACI Building Code, is doubled.[50] Lap lengths for splices should be shown on the construction drawings, as should anchorage lengths for embedded reinforcement.

If welded splices are used, all welding of reinforcing steel should conform to the American Welding Society "Reinforcing Steel Welding Code".[50,125,136] If mechanical splices are used, they should conform to the construction specifications. Criteria for mechanical splices are given in the ACI Building Code.[125]

If bundled bars are to be used in the vessel, they should conform to requirements of the ACI Building Code unless otherwise stated in the construction specifications. Bundled bars are groups of four or fewer reinforcing bars that are placed in contact with each other, enclosed in stirrups or ties, and used as a reinforcing element. Provisions for use of bundled bars are based on insuring that bond and crack control criteria are met.[126]

All reinforcement for concrete vessels should be correctly positioned and rigidly fixed so as to prevent displacement during concreting.[50,125,127] Recommendations for bar supports, chairs, and spacers are given in industry standards.[130,131,134] Tolerances on the location and spacing of reinforcement are given in the ACI Building Code.[125,126] Construction specifications should also be consulted for reinforcement placement tolerances.

For marine concrete structures it is particularly important that tolerances on concrete cover over reinforcement be met. Table 14 summarizes recommended limits on concrete cover from several sources. Laboratory and field tests have established that increases in concrete cover increase corrosion protection.[146] Concrete cover over reinforcing and prestressing steel also improves fire resistance.

TABLE 14 - RECOMMENDED LIMITS ON CONCRETE COVER

Source	Limitations	Cover Over Reinforcing Steel, in.			Cover Over Prestressing Duct, in.		
		Submerged	Splash*	Atmospheric**	Submerged	Splash*	Atmospheric**
ACI 357 (50)	<20 in. Thick Sections	2.0	2.5	2.0	3.0	3.5	3.0
		(Stirrups 0.5 in. less)					
	≥20 in. Thick Sections	1.5 times max. aggregate or 1.5 times max. bar dia. or 0.75 in., whichever is greater			0.5 in. less than cover for reinforcing steel		
DNV (51)	--	2.0	2.0	1.5	4.0	4.0	3.0
		(Not less than 1.5 max aggregate)					
DNV (53)	Can Be Drydocked	1.0	1.0	1.0	2.0	2.0	2.0
	Cannot Be Drydocked	1.5	1.5	1.0	3.0	3.0	2.0
		(But not less than larger of bar dia., duct dia., or max. aggregate + 0.20 in.)					
FIP (52)	<20 in. Thick Sections	2.5	3.0	See 20 in. Thick Sections	3.0	4.0	See 20 in. Thick Sections
	≥20 in. Thick Sections	1.5 times max. aggregate or 1.5 times max. bar dia., whichever is greater			Same as for reinforcing steel		

*Including atmospheric zone subject to salt spray
**Atmospheric zone not subject to salt spray.

6.2 Prestressing Tendons

As was the case for reinforcing steel, prestressing tendons should be stored and placed so that they are kept free of mud, rust, grease, insoluble oil, deposits of salt, or any other material that may adversely affect bond or durability.[50-53,125-127]

It is essential that welding, flame cutting, or similar operations be conducted in such a manner that prestressing tendons are not subjected to excessive temperatures, welding sparks, or electric ground currents.[50,125-127,137] This requirement is necessary because excessive heat can affect metallurgical properties of the prestressing steel and result in premature rupture when tendons are stressed. Under certain conditions, excessive strand lengths beyond the point of tendon anchorage may be removed using a welding torch.[127,137] However, this should only be done under controlled conditions with proper precautions to insure that tendon materials are not subjected to excessive heat. Manufacturers' recommendations should also be consulted.

Ducts for prestressing tendons should be accurately located and securely fixed in position.[50-53,125-127] Procedures for installation of ducts are described in Reference 132. Unless other values are given in the construction specifications, tolerances for placement of reinforcement ducts are given in the ACI Building Code.[125] As was the case for ordinary reinforcing steel, tolerances on concrete cover over reinforcement are important.[50-53]

ACI Committee 357 recommends that when flexible metal ducts are specified they should be supported on curved bearing plates.[50] This is to prevent local crushing of ducts during concrete placement.

All tendon ducts should be inspected prior to placement for holes or openings that would permit intrusion of water, cement paste, or concrete.[50-53,125-127,132,137] Common practice is to tape joints and splices in ducts to insure that they are watertight.[137] Ends of ducts should be sealed during construction to prevent entry of water that may collect within the ducts and lead to subsequent corrosion of prestressing tendons.[50]

The interior of ducts may be protected from excessive rust by use of chemically neutral protective agents, such as vapor phase inhibitor powders.[50,137]

Under certain loading conditions it may be necessary to design prestressing such that tendon profiles are not straight. For such situations, air vents are provided at peaks and drains are provided at valleys of the duct profile. During inspection of ducts prior to placement of concrete, the location of vents and drains should be verified. Drains are used to draw off any water that may have collected in the valley of ducts during construction prior to placement of tendons. Vents are used during grouting to insure that pockets of air will not collect at the crest of the duct profile.

In certain design and construction situations, continuity of prestressing tendons may be accomplished by using coupled anchorages. These provide a means for tying adjacent sections of tendons together and permit tendons to be stressed at intermediate locations.[132] It is necessary to provide coupler housings in the section of ducts where coupled anchorages will be located. Prior to placement of concrete, the location and the length of these coupler housings should be verified to insure that problems will not be encountered during stressing operations.

Immediately prior to placement of concrete, all ducts should be inspected for damage that may have occurred during placement of reinforcement, placement of forming, or other construction operations. Any damage including punctures or tears in the duct material should be repaired prior to concrete placement.[127]

End anchorage plates for the prestressing system should be placed and secured to insure that construction tolerances will be met. This is necessary because high localized stresses occur within the end anchorage region during stressing of tendons. Therefore, the bearing plate and tendon anchorage must be properly aligned. ACI Committee 301 recommends that the bearing surface between anchorages and concrete be concentric with and perpendicular to the tendons to within $\pm 1^{\circ}$.[127]

6.3 Formwork and Embedments

The formwork system for concrete structures includes the "sheathing" that comes in contact with the concrete and all supporting members, hardware, and braces.[147] Minimum performance requirements are given in the ACI Building Code.[125,126] ACI Committee 301 also gives recommendations for formwork.[127] These performance requirements and recommendations are applicable to concrete marine structures.

Detailed information on formwork is given in a "Recommended Practice for Concrete Formwork" prepared by ACI Committee 347.[147] This recommended practice includes information on materials for formwork, and design and construction requirements. Additional detailed information on formwork is available in standard reference books.[148,149]

Basically, formwork for concrete should result in a final structure that conforms to the shape, lines, dimensions, and tolerances stated in the construction specifications and drawings. The forms should be constructed, supported, and braced to maintain their shape and position. Joints in formwork should be sufficiently tight to prevent leakage of mix water or mortar. Formwork should also be constructed so as not to damage previously placed concrete.

Prior to placement of concrete, any standing water or other foreign materials should be removed from the formwork.[127] Forms should be cleaned between uses to remove accumulated mortar or grout.[120,127] Formwork surfaces that come into contact with fresh concrete should be coated with release agent as required in the contract specifications. Excess form release agent should not be allowed to stand in puddles in the forms nor should such agents coat hardened concrete against which fresh concrete is to be placed.[127]

Precast concrete units (unreinforced, reinforced, or prestressed) are sometimes used as forms for cast-in-place concrete. This type of formwork system is used, for example, in the Belden system for construction of concrete barges.[34,35] ACI Committee 347 has prepared a general guide for the use of precast concrete units as forms for cast-in-place concrete.[150] If precast concrete segments are used as forms, they should be placed and secured in position so that the final structure will conform to the shape, lines, dimensions, and tolerances stated in the construction specifications. Precast segments should be tied together and supported in accordance with the construction specifications. If the final location of the precast segment is such that it will be exposed, materials and construction requirements for the segments should be the same as for cast-in-place marine concrete. This would include requirements on concrete mix characteristics as well as cover over reinforcing and prestressing steel.

During preparation of formwork and subsequent concrete placement operations, construction loads should be monitored so that formwork supports are not overloaded.[125-127] Often, construction loads that result from material storage or movement of equipment can be higher than design loads for the completed structure.

All items to be embedded in concrete should be inspected prior to placement of concrete to insure that they are properly located and secured in position.[127] For marine concrete structures, particular care should be taken to insure that metallic embedments and anchors are electrically isolated from primary steel reinforcement.[50] ACI Committee 357 recommends that exposed steel and anchor systems be isolated from primary steel reinforcement by at least 2 in. of concrete.[50] This committee also recommends that sacrificial anode type cathodic protection systems be used for externally exposed steel rather than impressed current type systems.[50] This recommendation is based on the concern over potential stray currents that may occur with use of impressed current systems. Committee 357 also notes that it is not desirable to have cathodic protection systems govern the design of steel reinforcement details.[50]

All embedments should be free of oil, grease, dirt, paint, rust, deposits of salt, or any other material that may adversely affect bond or durability. DNV recommendations indicate that fully embedded steel items should be protected from corrosion by meeting requirements for concrete cover.[51]

During inspection prior to concreting, all insert sleeves and anchor slots should be checked for voids that may lead to intrusion of mortar during placement of concrete.[51]

ACI Committee 301 recommends that if premolded water stops are used to provide watertight construction joints, they should be of maximum practicable length in order to minimize the number of end joints.[127] This recommendation is intended to insure that such joints will be fully effective.

6.4 Construction Joints

A construction joint is the surface where two successive placements of concrete meet. This type of joint should be distinguished from a "cold joint" which refers to the discontinuity that is formed when a concrete surface inadvertently hardens before the next batch is placed against it.[120]

The location of construction joints must be carefully planned so that integrity and watertightness of the structure is maintained.[50,52,125,126] Deviations in the specified location of construction joints should only be made after approval of the project engineer.[126]

Where a construction joint is to be made, the surface of the hardened concrete should be thoroughly cleaned to remove all laitance and unsound material.[50,52,120,125-127] Laitance is a layer of weak or nondurable material that contains cement and fines from aggregate. This is brought to the top of concrete by bleed water. Larger amounts of laitance are obtained in mixes that have high slump or that are overworked during placement or finishing. Cleaning of the hardened concrete surface should uniformly expose coarse aggregate. Such cleaning can be accomplished by wet abrasive blasting or by high pressure water jet.[50] ACI Committee 357 recommends that the maximum size aggregate be exposed to about 25% of its nominal diameter.[50]

Specifications may call for use of an epoxy resin or other type bonding agent. Such materials should be used in accordance with the construction specifications and manufacturers' recommendations.[50,151,152]

For watertight construction joints, ACI Committee 357 recommends that cement content of the concrete at the start of the next placement be increased.[50]

Prior to concrete placement, construction joints should be inspected for standing water, form release agents, or other foreign materials that may have come into contact with the hardened concrete surface against which fresh concrete is to be placed.[125,127] Removal of such materials will insure adequate bond between the freshly placed and the hardened concrete surface.

If precast segmental construction techniques are being used, joints between segments should be treated in accordance with the construction specifications prior to post-tensioning. Generally, cement or epoxy mortar will be used to obtain uniform bearing and a watertight joint.[38,39,137]

7. INSPECTION DURING CONCRETING

After reinforcement, prestressing ducts, formwork, embedments, and construction joints have been inspected for compliance with construction specifications, placement of concrete can proceed. General recommendations for measuring, mixing, transporting, and placing concrete are given by ACI Committee 304.[123] These recommendations are applicable to use of concrete in marine structures.

7.1 Batching and Mixing Concrete

Procedures for batching and mixing concrete were discussed in Section 5 of this Commentary. Batch plant operations should be monitored throughout the duration of the project to insure that concrete of uniform quality, meeting construction specifications, is used in the vessel. Materials and mix proportions should be in accordance with the construction specifications. Documentation in the form of delivery tickets for each batch of concrete should be completed at the point of receipt and maintained with project records.

7.2 Transporting Concrete

Concrete can be transported by a variety of methods and equipment. Commonly used equipment includes truck mixers, agitating or nonagitating trucks, buckets, power buggies, chutes, belt conveyors, pneumatic guns, and concrete pumps.[120,123] Selection of the particular type of equipment to be used will depend upon the project and the contractor. The basic objective is to move the concrete from the mixer to the point where it is needed as rapidly as possible without segregation or loss of ingredients.[120]

Segregation can be defined as "separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform."[84] In concrete, segregation refers to the separation of coarse aggregate from the sand cement mortar.[84,120] For extremely wet mixes, segregation can also occur by separation of cement paste from the mix.[84] Concrete with too little coarse aggregate is susceptible to shrinkage and cracking, while concrete with too much coarse aggregate can become too harsh for full consolidation, which frequently causes voids or honeycombing.[120] Therefore, methods and equipment used to transport, place, and consolidate concrete should not result in segregation.[120,123,125-127]

Most specifications for structural concrete require that transporting and conveying equipment be adequate to insure a continuous supply of concrete without excessive delays between batches.[120,123,125-127] Excessive delays can lead to cold joints if the fresh concrete is placed against concrete which has reached initial set. Setting time of concrete is a term used to describe the stiffening that occurs after cement and water are mixed.[84] Initial and final setting times for portland cement paste are determined by tests using either the Vicat apparatus or a Gillmore needle.[120] Essentially setting time is a measure of cement hydration reactions. Setting time of cement paste is related to setting time of the concrete.[120]

Concrete begins to stiffen as soon as cement and water are mixed. However, the degree of stiffening that occurs within the first 30 minutes is usually not harmful.[120] Many specifications require that concrete be placed within a maximum elapsed time of 1.5 hours after cement and water are mixed.[120,123] However, this elapsed time limit may need to be reduced during hot dry weather or if accelerating admixtures are used in the mix.[120,123]

ACI Committee 304 gives specific recommendations for placing concrete with belt conveyors and by pumping methods.[153,154] General recommendations on pumped concrete and on design of concrete mixes for "pumpability" are also available in the literature.[155,156] For concrete that is to be pumped, trial batches should be used to determine compatibility of the concrete mix and the pumping equipment unless such compatability has been documented by prior experience.[154]

Concrete should not be pumped through pipe made of aluminum or aluminum alloy.[126,127,154] Reports have indicated that concrete pumped through aluminum pipe exhibits expansion. Expansion apparently is caused by reactions between abraded aluminum particles and alkalies in portland cement. This has resulted in formation of expansive hydrogen gas and a significant reduction in concrete strength.[157]

If lightweight aggregate is to be pumped, recommendations of ACI Committee 213 should be consulted.[67]

Upon completion of daily concreting operations, transporting and placing equipment should be cleaned. Prior to start-up operations on the following day, equipment should be checked to insure that no foreign materials will be introduced into the fresh concrete mix.[120,127]

7.3 Placing Concrete

Concrete placed in the structure should meet requirements for slump as defined in the construction specifications. Concrete that has obtained initial set or that has been contaminated by foreign materials should be rejected.[125-127] In some cases, it may be acceptable to add small amounts of water and remix concrete at the point of placement.[120,123,127] This practice is termed "retempering" and it is done to add plasticity to concrete that has undergone initial stiffening. However, addition of water should only be done under strict supervision and control. The following conditions should be met:

(a) Maximum allowable water-cement ratio should not be exceeded.

(b) Maximum allowable slump should not be exceeded.

(c) Maximum allowable mixing and agitating time (or drum revolutions) should not be exceeded.

(d) Concrete should be remixed for at least half the minimum required mixing time or number of revolutions.[120,127]

(e) Test cylinders should be made to check strength of the concrete.

(f) The location of the concrete in the structure should be recorded.

Incoming batches of concrete should be inspected to insure that they do not contain ice or other foreign materials.[125-127] Rejection of concrete batches should be indicated on delivery tickets.

Because uniformity of fresh concrete properties is dependent upon uniformity of concrete temperature, it is important that maximum and minimum temperatures of the fresh concrete be controlled during all seasons.[120,123,125-127] The ACI Building Code requires that complete records of concrete mixing and curing temperatures be kept when ambient temperatures rise above 95^{o}F or fall below 40^{o}F.[125,126] Generally, construction specifications will include limits on maximum and minimum temperatures of concrete to be deposited in the structure.

Recommendations for cold weather concreting are given by ACI Committee 306.[141] These recommendations are applicable to concrete marine structures except for provisions permitting use of calcium chloride as an accelerating admixture. ACI Committee 357 recommends that for offshore concrete structures, use of calcium chloride as an accelerating admixture should be prohibited.[50] For construction during cold weather, equipment should be provided to heat concrete materials and protect concrete from freezing during mixing, conveying, placement, and curing.[125,126,141] Formwork, reinforcement, embedments, and other items in which concrete will come in contact should be free of frost.[125,126]

During hot weather concrete mix proportions, mixing, conveying, placement, and curing methods should be designed to prevent excessive concrete temperatures or water evaporation that can impair strength or serviceability.[125,126] ACI Committee 305 provides detailed recommendations for hot weather concreting.[140] These recommendations are applicable to concrete marine structures.[50]

When concreting under adverse weather conditions precautions should be taken to insure that quality and uniformity of concrete placed in the vessel is satisfactory. For example, during rain, procedures should be established to prevent rain water from increasing the amount of mix water in the fresh concrete or from damaging concrete surfaces.[127]

During placement concrete should be deposited continuously as near as possible to its final position.[120,123,125-127] Placing should be carried out at a fast enough rate so that concrete can be kept plastic and free of cold joints. Placement techniques should be selected to avoid segregation.[120,123,125-127] ACI Committee 304 provides specific recommendations.[123]

After placement, concrete should be thoroughly consolidated by vibration to ensure that it is worked around all reinforcement, embedded fixtures, and into corners of forms.[120,123,125-127] This is to insure that no voids or stone pockets are left in the concrete. ACI Committee 309 gives specific recommendations for consolidation of concrete.[158]

In some cases, concrete may be placed by pneumatic guns. This is termed "shotcreting." This method has been used for construction of concrete barges.[34,35] Shotcrete is mortar or concrete that is sprayed under high pressure onto a surface.[159] It is applied either as a dry or a wet mix.[159] With the dry process, cement and aggregates are mixed in a relatively dry state and conveyed to the nozzle before water for hydration is added. With the wet process, all materials including water are premixed and no water is added at the nozzle. Recommendations for shotcreting are given by ACI Committee 506.[160,161]

Shotcrete is commonly used for roofs, walls, prestressed tanks, reservoir linings, canal linings, swimming pools, and tunnels.[160] It is also used for repair, strengthening, encasement, and coating of concrete, masonry, and steel structures.[160] Properly applied, it has excellent bond and strength characteristics. Quality of shotcrete work is dependent on skill of the application crew.[120,160] Only experienced nozzlemen should be employed.[120] Water-cement ratios for shotcrete in place range from 0.35 to 0.50 by weight.[160] Compressive strengths at 28 days range from 4000 to 7000 psi.[160]

7.4 Control Tests

Numerous control tests are available to monitor quality of fresh concrete placed in a structure. Conduct, evaluation, and assessment of tests should be under supervision of qualified and experienced laboratory personnel.[120] ACI Committee 301 recommends that all testing agencies meet requirements of ASTM Designation: E329, "Recommended Practice for Inspection and Testing Agencies for Concrete, Steel, and Bituminous Materials as Used in Construction."[127] Frequency of testing will be defined by provisions of the construction specifications.

Provisions for obtaining representative samples of fresh concrete are given by ASTM Designation: C172, "Standard Method of Sampling Fresh Concrete." This includes sampling from stationary paving and truck mixers, and from agitating and nonagitating equipment used to transport central mix concrete. For concrete that is pumped, sampling at both the truck discharge and point of final placement should be used to determine if any changes in slump, air content, or other significant mix characteristics occur.[154] However, quality of the concrete placed in the structure can only be measured at the placement end of the line.[154] Recommended methods for sampling shotcrete are given by ACI Committee 506.[161]

The slump test, conducted in accordance with ASTM Designation: C143, "Standard Test Method for Slump of Portland Cement Concrete," is used to evaluate consistency of the concrete mix.[120] Consistency is the relative mobility or ability of the freshly mixed concrete to flow. Although the slump test is not a direct measure of workability of concrete, it is a relatively simple test and is useful for determining variations in uniformity of concrete mixes.[84,120]

Unit weight of freshly mixed concrete is determined in accordance with ASTM Designation: C138, "Standard Test Method for Unit Weight, Yield, and Air

Content (Gravimetric) of Concrete."[120] The unit weight test provides a simple method of evaluating uniformity of concrete batches and for determining the quantity of concrete produced per batch. The test also provides an indication of air content because the amount of entrained air in the mix affects unit weight. Unit weight tests are particularly important for floating structures because unit weight of the fresh concrete provides an indication of in-service weight.

For structural lightweight concrete, unit weight should be determined in accordance with ASTM Designation: C567, "Standard Test Method for Unit Weight for Structural Lightweight Concrete."[127] If the construction specifications include limits on air-dry unit weight of the lightweight concrete, data on fresh unit weights should be correlated with those for air-dry unit weights so that fresh unit weight can be used as a basis for acceptance.

A number of methods are available for measuring air content of fresh concrete.[120] These include ASTM Designation: C231, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method," ASTM Designation: C173, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method," and ASTM Designation: C138, "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete." It should be noted that these methods measure total air content of fresh concrete. They cannot differentiate between intentionally entrained air and accidentally entrapped air.[84] For normal weight concrete, the pressure method (ASTM Designation: C231) is the most popular and is well suited to site use.[84,120] The volumetric method (ASTM Designation: C173) is used for lightweight aggregate concrete.

Temperature of fresh concrete can be measured with an armored thermometer.[120] These are designed to withstand rough handling that can occur at the site. The thermometer should be accurate to within $\pm 2^{\circ}F$.[120]

Specimens for strength tests should be made and cured in accordance with ASTM Designation: C31, "Standard Method of Making and Curing Concrete Test Specimens in the Field."[120,125-127] Frequency of sampling should be in accordance with the construction specifications.

8. INSPECTION AFTER CONCRETING

After concreting is completed it is necessary to insure that concrete is properly finished and cured, and that formwork removal does not damage the young concrete or threaten safety of construction workers. Additional operations after concreting include evaluation of strength of hardened concrete, post-tensioning, and grouting.

8.1 Finishing, Curing, and Formwork Removal

The term "finishing" refers to the leveling, smoothing, and texturing of newly placed concrete to obtain the desired appearance and serviceability. For concrete vessels it is particularly important that decks or other flatwork be properly finished. This is because improper finishing operations can affect durability of the flatwork surface.

A principal cause of surface deterioration in concrete flatwork is finishing while bleed water is still on the surface.[120] If the concrete surface is finished while bleed water is present, serious dusting or scaling will result because the free water will mix with surface cement paste and increase its effective water-cement ratio. Finishing operations should not be undertaken if free water is accumulated on the concrete surface.[120,123]

Another problem frequently encountered in concrete flatwork is "over finishing." Screeding, floating, and trowelling operations should be performed to minimize working of the concrete.[120,123] If concrete is overworked, excess fines and water are brought to the top which can result in a less durable surface.[123]

Curing is the process of maintaining the necessary moisture content and temperature in freshly placed concrete. This insures hydration of cementitious materials so that desired properties of the concrete are developed.[162] Curing has a very significant influence on strength, durability, watertightness, and volume stability of hardened concrete.[84,120] It is essential that hydration of cement and mixing water be allowed to occur. Most fresh concrete contains sufficient water for complete hydration of cement. If sufficient water is lost by evaporation, hydration reactions will be incomplete and quality of the concrete will be reduced.

Two basic methods are used to cure concrete. The first maintains a moist environment by application of water and the second prevents loss of mixing water by sealing concrete surfaces to prevention evaporation. ACI Committee 308 has developed a recommended practice for curing concrete.(162)

A number of methods are used for water curing of concrete. These include ponding or immersion, spraying or fogging, and saturated wet covering.(162) When using water curing ACI Committee 357 recommends against use of seawater.(50) This recommendation is based on the concern that chloride ions in sea water will penetrate "young" concrete in which cement has not hydrated sufficiently to provide adequate impermeability. Penetration of chloride ions can affect durability.

Curing concrete by prevention of loss of mixing water can be accomplished by sealing the surface of the concrete with impervious paper or plastic sheets, or by applying membrane curing compounds.(120,162) For curing offshore concrete structures, ACI Committee 357 recommends the use of a heavy duty membrane curing compound or a curing mat cover.(50)

DNV recommendations provide that concrete be protected against drying out for a period of at least two weeks.(51,53)

In addition to maintaining a moist condition, it is essential that freshly cast concrete be protected against weather that is either too hot or too cold. Recommended practices for protecting and curing concrete in hot and cold weather are given by ACI Committees 305 and 306, respectively.(140,141) During hot weather, continuous moist curing for the entire curing period is preferred.(120) Additional measures may include erection of wind breaks or sun shades.

During cold weather, insulating blankets may be used or heated enclosures may be constructed.(120,141) If the structure is enclosed and heated during construction, care should be taken to insure that freshly placed concrete is not exposed to carbon dioxide from exhaust gases of heaters.(120,141) Carbon dioxide can combine with calcium hydroxide of fresh concrete to form a weak layer that results in a soft chalky surface.(120,141)

Concrete that has been damaged by freezing during cold weather or by accelerated evaporation during hot weather should be rejected and replaced unless the project engineer determines that the damage will not impair strength or serviceability of the vessel. Tests should be conducted to evaluate strength of damaged concrete.

It is common for precast concrete structures to use accelerated curing methods. These methods accelerate strength gain by supplying heat and moisture to the concrete.[120] Recommendations for steam curing concrete at atmospheric pressure are given by ACI Committee 517.[163] Use of an accelerated curing process should be documented to insure that strength and durability of the resulting concrete are equivalent to that obtained by standard moist curing.

After concrete has cured and developed sufficient strength, formwork removal can proceed. It is preferable to base formwork removal on development of a concrete strength specified by the design engineer. This strength should be included in the construction specifications. The construction specifications should also indicate the method of test to be used for evaluation of concrete strength. Strength can be based on test cylinders cast during construction or may be based on nondestructive methods for evaluating hardened concrete.[148] It is important to consider construction loads, as well as dead loads of the completed structure, when determining concrete strength for formwork removal.[125-127,148] In some cases, curing requirements may necessitate that forms remain in place longer than would be necessary based on strength evaluation.[148]

Construction specifications may also provide for use of the maturity measurement method for determining strength development of concrete prior to formwork removal.[148] This method requires evaluation of a time-temperature record for the concrete during curing.[84]

Forms and shoring should be stripped using procedures that will not impair safety or serviceability of the structure.[125-127,148]

Once formwork has been stripped, concrete surfaces should be inspected to determine if they are in accordance with the construction specifications.[127] Holes left by form ties should be filled in accordance with the construction specifications. Surface defects such as honeycombing should be evaluated with regard to their significance for serviceability of the vessel. Repair procedures should be in accordance with construction specifications.

8.2 Control Tests of Hardened Concrete

Control specimens for evaluating strength of hardened concrete should be cured in accordance with ASTM Designation: C31, "Standard Method of Making and Curing Concrete Test Specimens in the Field."[125-127]

Concrete compressive strength is the most common standard test for evaluating concrete quality. This property is determined in accordance with ASTM Designation: C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." Although not required by the ASTM standard, it is good practice to weigh control cylinders prior to testing. This permits evaluation of unit weight of concrete in the test cylinders and may be extremely useful in evaluating test results, particularly if inconsistencies in strength data are found. Frequency of strength testing should be in accordance with the construction specifications.

Construction specifications may require testing of tensile splitting strength of the hardened concrete. This test is conducted in accordance with ASTM Designation: C496, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens." It provides a relative measure of direct tensile strength of the concrete.(84)

Criteria for evaluation and acceptance of concrete strength results should be included in the construction specifications. Criteria given in the ACI Building Code or in ACI specifications for structural concrete for buildings may serve as a guide.(125-127) ACI Committee 214 has developed detailed recommendations for evaluation of strength test results.(164) Additional material is available in a collection of papers from a 1971 symposium on this topic.(165)

8.3 Post-Tensioning and Grouting

Requirements for application and measurement of prestressing force are essential to insure that the amount of prestressing assumed in design is actually provided in the structure.(126) Because of the importance of stressing operations and because of safety, it is important that stressing be carried out under supervision of experienced personnel.(132) Stressing operations should not begin until concrete has reached its specified strength.(127,132) The sequence of stressing operations should be in accordance with the construction specifications.(127,132,166) The sequence of stressing is important because as each tendon is stressed it imparts load into the structure. If stressing operations are not in accord with the designer's plan, it is possible that concrete will be overstressed. Specified concrete strength at the time of stressing is usually between 60 and 80 percent of its 28-day strength.(132)

Prior to start of stressing operations, all components of the tensioning equipment should be accurately set, aligned, and securely supported. This will insure that localized stress concentrations that can lead to premature failure are not induced. Sufficient power should be available to accommodate stressing operations.[132]

Stressing forces should be determined by measurement of both tendon elongation and jacking force.[51,53,125-127,132,166] Jacking forces can be determined with a calibrated pressure gage or load cell. Some specifications require that the tensioning force be measured by load or pressure cells that have an accuracy of at least ± 2% of the required tensioning force.[166] Jacking force is related to tendon elongation by the modulus of elasticity of the prestressing steel.[132] Specifications generally require that measured tendon force agree with the force calculated from measurement of tendon elongation by within five percent.[125-127,132] Frictional losses that occur throughout the length of the tendon should be included when determining the relationship between tendon force and elongation.

Occasionally, individual wires in prestressing strand or wires in multi-wire tendons may break or lose anchorage during stressing. Most specifications require that the total loss of prestress resulting from unreplaced broken tendon elements shall not exceed two percent of the total applied prestress for the member.[125-127] Maximum stressing force levels should not exceed values given in the construction specifications.[132]

Safety precautions should be taken during stressing operations to insure that personnel will not be injured by premature fracture of tendons.[132] Accidental failure of tendons or stressing equipment is not common, but because of the extremely high forces involved in stressing, it is essential that personnel do not remain behind stressing equipment while forces are being applied.[132]

Prior to grouting, some specifications require that tendon ducts be washed with water containing a small percentage of lime to clear ducts of foreign materials.[127,132,137] The Post-Tensioning Institute's guide specifications indicate that washing may be undesirable for large tendons because it is difficult to remove water from the ducts.[132] When tendons are flushed, water may be removed by oil-free air pressure, or it may be displaced by grout.[132]

Grouting of post-tensioning tendons is used to provide bond between tendons and structural concrete, and to provide permanent corrosion protection for tendons. Grouting procedures should be in accordance with construction specifications. The Post-Tensioning Institute has developed a recommended practice for grouting post-tensioned prestressed concrete.[132] Generally, grouting should take place as soon as possible after tendons have been stressed. Gerwick recommends that grouting take place within "48 hours after placing the steel and within 24 hours after stressing."[137] The effectiveness of grout for providing corrosion protection has been demonstrated in several evaluations made on existing structures.[167,168]

The objective of grouting is to fill the entire space between the tendon and duct with uniform dense grout material. Procedures for batching, mixing, and pumping grout should minimize formation of air pockets or development of air voids from excessive bleeding.[137] Equipment should be capable of continuous mechanical mixing and agitation that will produce a uniform distribution of materials.[132] Grout may be screened prior to its introduction into the pump to insure that undispersed cement or foreign materials are not pumped.[132] Procedures for filling the pump should be such that it can be operated continuously to prevent air from being drawn into the post-tensioning duct.[132] If there is a delay in grouting operations that results in stiffening of grout, water should not be added to increase flowability.[125-127,132]

Temperature of grout during mixing and pumping should not be higher than $90^{\circ}F$.[125,126,132] This is because grout may stiffen and become difficult to pump at higher temperatures.

During grouting, vents left in tendon ducts are opened and then closed in sequence so that any remaining flushing water or entrapped air is removed.[127,132,137] Grouting pressures should be monitored so that maximum limits are not exceeded.[132,137] Excessive pressures can result in segregation of grout which in turn can lead to blockage. In extreme cases excess pressures can damage the structural element.[132] If blockage occurs during grouting, all grout should be removed from the duct by flushing it with water.[127,132,137]

When grouting long vertical tendons or steeply inclined tendons, it is important to insure that bleeding will not lead to pockets of water at the upper end of the tendon.[50,132,137] This is accomplished by proper mix design, which may include use of thixotropic admixtures, and by proper use of vents for allowing air and water to escape at crests of the ducts.[132,137]

During cold weather, grout should be protected from freezing.[50-53, 125-127,132,137] Some specifications require that the temperature of members at the time of grouting be above 35°F and be maintained above 35°F until field-cured 2-in. cubes of grout reach a minimum compressive strength of 800 psi.[125,126,132] At 35°F grout can be expected to reach 800 psi cube strength in approximately 5 days.[132] DNV specifications require that during grouting, and for the first two days after grouting, the temperature of the structure should not be allowed to fall below 40°F.[51,53] Similar recommendations are given by Gerwick.[137]

After stressing and grouting operations are completed, anchorage components must be permanently protected against corrosion.[50-53,125-127,132,137] A recommended method is to use recessed end anchorages that can be completely covered with a dense portland cement grout or an epoxy mortar.[49,50,97,132,137] In filling the recessed pocket particular attention should be directed to obtaining good bond between the hardened concrete and the filler material. This is especially important where anchorages may be subjected to dynamic loads.[50] ACI Committee 357 recommends against provisions for inspection access to anchorages because such provisions can reduce effectiveness of the corrosion protection system.[50] A recent evaluation of performance of post-tensioned beams subjected to a freeze-thaw environment confirms that the most effective type of anchorage protection is a recessed pocket that is covered with grout.[169]

A discussion of experiences gained in tensioning and grouting offshore concrete structures in the North Sea has been published by Long.[170] His paper provides data on actual construction practices with particular emphasis on placement and grouting of long vertical tendons.

9. IN-SERVICE INSPECTION

After a vessel has been constructed and put into service, it should be surveyed on a periodic basis for signs of deterioration of concrete, corrosion of reinforcement, and damage from overload, impact, abrasion, or fire. A well-designed and properly constructed concrete vessel should have a long service life. The American Bureau of Shipping estimates that service life of concrete vessels could approach 40 years.[171] The service life of fixed offshore concrete structures is normally 25 to 30 years.[172]

The frequency of in-service inspections for concrete vessels will depend, to a great extent, upon classification society rules for maintenance of class and U.S. Coast Guard regulations. Basic requirements of the American Bureau of Shipping for steel vessels include:

(a) An annual survey for damage or deterioration

(b) A biennial drydocking survey

(c) A special periodic survey every 4 or 5 years which includes a detailed inspection of the total vessel.[171,173]

These basic requirements may be varied under special procedures as approved by the classification society.[171,173] ABS recognizes that past experience with concrete vessels indicate that the biennial drydocking requirements can be relaxed. ABS will accept an internal examination of the hull in lieu of drydocking.[171,173]

Det Norske Veritas guidelines for floating concrete structures require the hull to be subjected to a biennial survey and a special survey every fourth year.[53-55] The biennial survey, which does not require drydocking, is intended to evaluate overall condition of the vessel. This includes inspections for excessive cracking, spalling, deterioration of concrete, and corrosion of reinforcement or embedded steel. The special four-year survey is to be carried out in drydock if possible. However, DNV guidelines permit visual inspection of submerged zones by divers or remote control cameras in lieu of drydocking.[53-55]

Lloyds Register of Shipping provides for periodic survey of prestressed concrete ships in general accordance with requirements for steel ships.[174] Annual surveys are conducted on vessels while they are in service. The surveys are intended to reveal any damage or deterioration of the vessel. Drydocking surveys are required at two-year intervals but requests to use underwater examinations in lieu of drydocking are considered.[174] Special surveys which include drydocking are conducted at periods that depend upon the age of the ship. These are intended to be detailed examinations of the entire vessel.

Bureau Veritas also requires annual surveys while the vessel is in service, drydocking surveys at intervals of 2 to 2.5 years, and special surveys every fourth or fifth year.[46] Bureau Veritas maintains some flexibility in scheduling surveys and also considers underwater surveys in lieu of drydocking.

Most classification society personnel note the lack of experience in evaluating concrete vessels relative to steel. Therefore, requirements on the intervals between surveys should be considered to be in a state of evolution.

In-service inspections of concrete vessels should be planned in advance to insure that all critical items will be covered. Data sheets should be prepared to assist the inspector. An example of a survey data sheet used by DNV for inspection for fixed offshore structures is shown in Fig. 13.[172] The initial survey will usually consist of an overall visual inspection of the hull to observe any obvious signs of deterioration or damage. This may be supplemented by detailed visual inspection which may include cleaning of hull sections to remove marine growth.[43-55,172,175] Areas that are suspect based on visual examination may require follow-up evaluation by nondestructive testing techniques or coring.[53-55,172,175]

Visual inspection is the primary method for surveillance of concrete vessels. Surveys should be made by trained personnel who are familiar with concrete construction.[54,55,172,175] At the time of inspection, records should be available on the design and construction of the vessel, and on previous in-service inspections.[54,55] Preferably, records should be available to document the complete history of the structure. They should include a description of the structure, data on dimensions and material properties, construction records, and data on any previous repairs.[54,55] This "history" will provide a data base for evaluation of the condition of the vessel, for evaluation of causes of any observed damage or deterioration, and for evaluation of the most effective and economical repair techniques.

With regard to structural damage, the interior and exterior of the hull should be visually inspected for signs of impact damage, excessive distortions, flexural cracking, torsional cracking, shear cracking, and concrete crushing.[50-55,171-176]

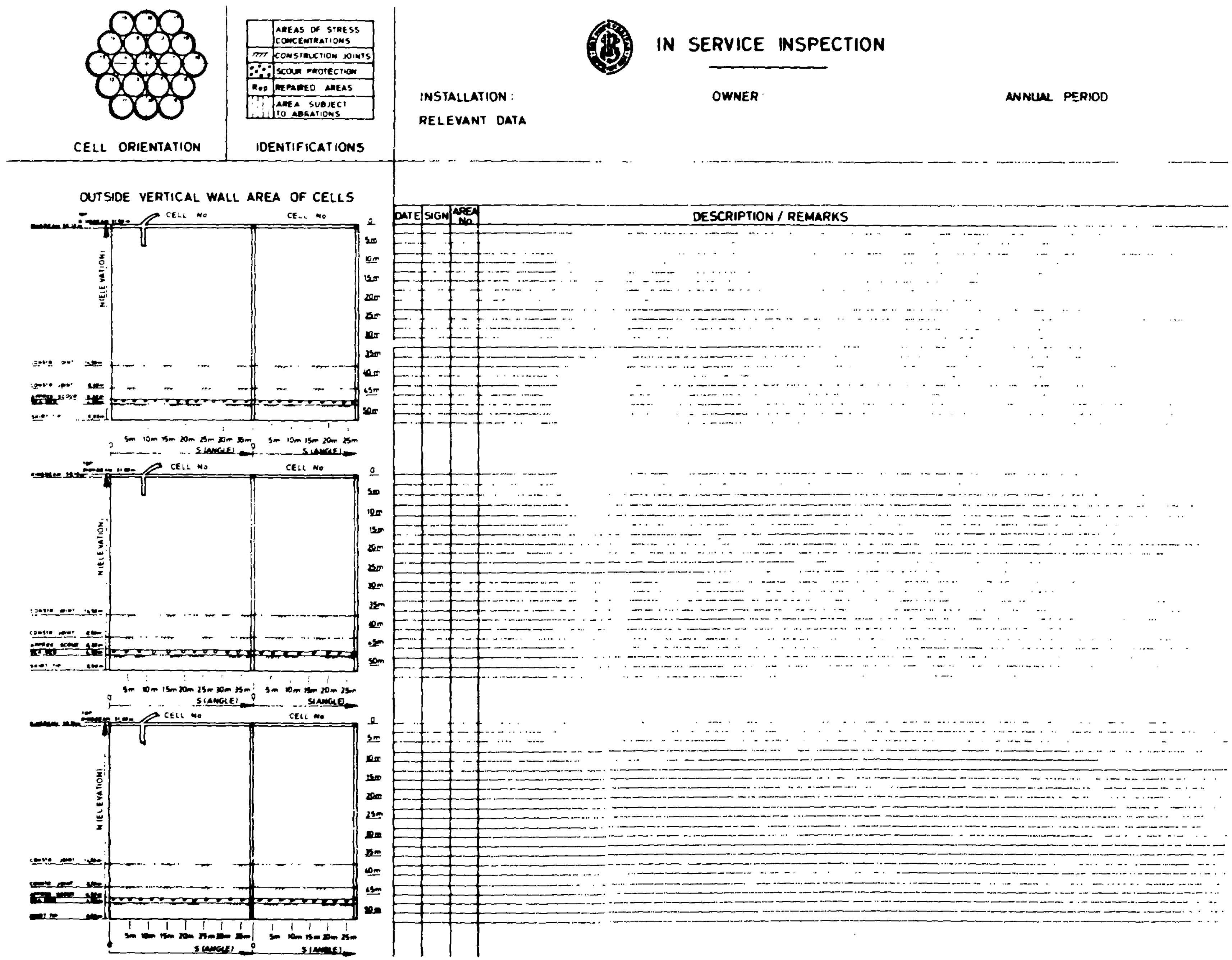


Fig. 13 Example of Survey Data Sheet (172)

While it is not the function of an inspector to evaluate the significance of structural damage, it is helpful to recognize that cracking can be initiated by a wide variety of forces that are applied to the structure. With the hull acting as a large beam element, hogging and sagging waves induce bending stresses that must be resisted by the post-tensioning forces applied during construction.[177] In a similar manner, the reinforcement and post- tensioning built into the structure must resist twisting and shearing of the hull as it is subjected to nonuniform wave forces. Local structural elements are subject to impact damage and bending caused by hydrostatic pressure.

If cracking, concrete crushing, or excessive distortions are observed during the hull survey, their significance should be evaluated prior to undertaking any repairs. It is particularly important that the cause of damage be determined to insure future serviceability of the vessel.

With regard to durability, the interior and exterior of the hull should be inspected for signs of cracking, spalling, scaling, disintegration, popouts, erosion, corrosion, and water leakage.[50-55,171-175] ACI Committee 201 has developed a guide for making condition surveys of concrete in service.[176] Although developed for land-based structures, this guide provides excellent illustrations of different types of deterioration that can occur in concrete structures. Many of these types could be encountered in concrete vessels.

Areas most susceptible to deterioration or damage should be given primary consideration. These would include the splash zone, areas of stress concentration or critical load transfer, areas containing construction joints, and areas previously repaired.[50-55,172,175]

Particular attention should be given to areas around prestressing tendon anchorages. These should be inspected for signs of potential corrosion or deterioration. Any exposed metal components or embedments should also be carefully inspected.[50-55] Cathodic protection systems should be examinmed and serviced if required.[53-55]

If the vessel is to be surveyed without drydocking, submerged zones must be inspected by divers or by remote control television equipment.[53-55] If divers are to conduct the inspection they should be qualified, expe ienced individuals who have been trained for examination of concrete hulls. They should be adequately briefed on the project.[175] Although most tasks that can be performed under dry conditions can also be performed by experienced divers, it is important to recognize that divers will be working under less than ideal conditions.[175,178,179] A major problem is that of visibility. In addition, when working in cold water, a diver's mental and physical efficiency can be reduced significantly.[179] Communication with a diver is another important factor, from both the viewpoint of safety of the diver and efficiency of the survey.[175,179]

A detailed description of underwater inspection procedures for offshore facilities has been published by Goodfellow.[178] This includes a review of diving techniques and use of remote control television systems that have been developed for inspection of fixed offshore platforms.

Based on both general and detailed visual surveys of the vessel, areas that require detailed examination and nondestructive testing should be clearly marked. Causes of deterioration or damage should be evaluated before repairs are undertaken.[50-55,171-175]

10. IN-SITU TESTING OF HARDENED CONCRETE

Although visual inspection represents the primary method of surveying concrete vessels, supplementary tests are available to evaluate quality and integrity of the structure. Test methods described in this section can be used to evaluate concrete strength, presence of internal voids, extent of deterioration or corrosion, and severity of cracking. The particular method selected will depend upon conditions to be evaluated, available access to the structure, and the type of information required. General guidelines for evaluation are contained in ASTM Designation: C823, "Standard Recommended Practice for Examination and Sampling of Hardened Concrete in Constructions." This standard includes recommendations for preliminary investigations, assembly of records, and detailed investigations. Sampling requirements are also outlined.

A complete photographic record should be maintained throughout the evaluation and testing process.

The following sections describe methods used for in-situ testing of hardened concrete. In many situations more than one method may be used to obtain the required data. If testing must be conducted on submerged portions of a vessel, the accuracy and reliability of methods selected should be documented prior to start of testing.[175]

10.1 Core Tests

The most common method for determining in-situ strength of hardened concrete in structures is to drill cores for testing. Figure 14 shows a drilled core. Drilled cores should be obtained in accordance with ASTM Designation: C42, "Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." This standard contains limits on the size of test specimen, preparation of cores for testing, moisture conditioning, capping, and measurement of dimensions prior to testing.

When evaluating strengths based on core test results, it is important to recognize that strength of cores will be lower than the corresponding strength of laboratory cured cylinders of the same concrete and at the same age.[180,181] The ACI Building Code considers concrete in an area represented by core tests to be adequate if the average strength of three cores is equal to at least 85% of the specified compressive strength of the concrete, and if no single core is less than 75% of the specified strength.[125,126] This requirement is

Fig. 14 Concrete Core

consistent with recommendations of ACI Committee 301.[127] Core tests do not represent the specified compressive strength for a number of reasons. The specified compressive strength is based on standard tests of molded concrete cylinders. Thus, in comparing core strengths with standard cylinder strengths, differences in size of specimens, conditions of obtaining samples, and procedures for curing must be recognized.[109,126]

With regard to size of test cores, the diameter should be at least three times the maximum nominal size of coarse aggregate used in the concrete. The length of the specimen should be as close as practicable to twice its diameter. These provisions are intended to insure that the core is large enough to be representative of the in-situ concrete. In addition, tests have shown that compressive strength is significantly affected by the ratio of length-to-diameter of the test specimen.[84] For this reason, a length-to-diameter ratio of two is preferred. ASTM Designation: C42 provides correction factors for different length-to-diameter ratios. Cores that have lengths less than their diameters should not be used.

ASTM Designation: C42 recommends that cores be submerged in lime saturated water for at least 40 hours immediately prior to making compressive strength tests. This standard permits use of other types of moisture conditioning under direction of the agency for which testing is being done.

The ACI Building Code provides that if concrete in the structure being evaluated will be dry under service conditions, cores should be air dried for seven days before test and then tested in a dry condition.[125,126] If the concrete in the structure will remain wet under service conditions, cores should be immersed in water for at least 48 hours and tested wet.[125,126] Similar recommendations are given by ACI Committee 301.[127] These requirements are an attempt to provide core strength data for moisture conditions relevant to the in-service condition of the structure. Generally, cores tested in a dry condition will produce higher strengths than those tested in a saturated condition.[180]

Prior to testing, cores should be examined for any damage that may have occurred during drilling. During drilling care should be taken to insure that primary reinforcement or post-tensioning tendons are not severed. Cores used for determining tensile strength should not contain embedded reinforcement. Cores for determining compressive strength may contain embedded reinforcement within limits of requirements in ASTM Designation: C42.

After taking samples, core holes should be repaired in accordance with procedures outlined in specifications for the conditions survey.

Although core tests are commonly used, and do provide a "direct" measure of in-situ concrete properties, they are time consuming and require repair of areas that have been drilled. Estimates of in-situ concrete properties can also be obtained by a variety of nondestructive tests. A complete summary of nondestructive test methods has been published by Malhotra.[182] The most common methods and those most relevant to concrete vessels are summarized in the following sections.

10.2 Rebound Hammer Tests

The rebound hammer test is based on the principal that rebound of an elastic mass "depends on the hardness of the surface against which the mass impinges."[84] General requirements for rebound hammer tests are given by ASTM Designation: C805, "Standard Test Method for Rebound Number of Hardened Concrete."

The most common device for rebound testing is the Schmidt rebound hammer, which was developed in 1948 by Ernst Schmidt.[84,182,183] The Schmidt hammer is shown in Fig. 15. It consists of a spring loaded mass which has a fixed amount of energy imparted to it by retracting a plunger against the spring.[84,182,183] During testing, the plunger is pressed against the surface of the concrete under test. Upon release, the mass rebounds from the plunger which is still in contact with the concrete surface. The distance traveled by the mass is indicated by a sliding scale on the hammer and is read as the hammer rebound number.

The hammer can be calibrated by testing 6x12-in. cylinders cast from concrete representative of that used in the structure to be evaluated. Since the rebound number is sensitive to the type of aggregate used, it is important that the calibration sample be made from representative aggregates. Malhotra describes details of a recommended calibration procedure.[182]

The rebound hammer test is also sensitive to variations in surface condition of the concrete. Surface imperfections may not be indicative of conditions internal to the structure. For example, surface moisture conditions or carbonation of concrete at the surface will affect rebound number readings.[84,182,183] Malhotra[182] lists the following factors that affect rebound number:

Fig. 15 Schmidt Rebound Hammer

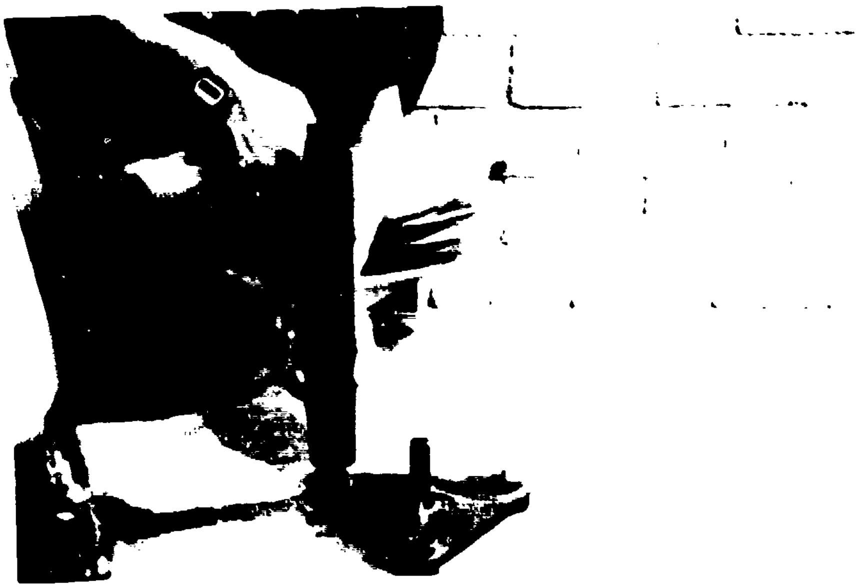


Fig. 16 Windsor Probe

(a) Smoothness of surface under test

(b) Size, shape, and rigidity of test specimen

(c) Age of test specimen

(d) Surface and internal moisture condition of the concrete

(e) Type of coarse aggregate

(f) Type of cement

(g) Type of form

(h) Carbonation of concrete surface.

Neville notes that the rebound number is also affected by relative position of the rebound hammer during testing. Thus, concrete tested in a vertical position will have a different rebound number when tested in a horizontal position.(84)

Despite its limitations, the rebound hammer provides a simple and inexpensive method for evaluating uniformity of concrete in-situ, for detecting of areas of poor quality or deterioration, and for determining relative changes of concrete properties with time.(182) The method is not recommended for determination of concrete strength.(182)

10.3 Penetration Tests

Penetration tests are based on evaluating in-situ strength as a function of depth of penetration of a metal probe that is driven into concrete with a fixed amount of energy.(84,182,183) Evaluation of concrete by penetration methods is covered by ASTM Designation: C803, "Tentative Test Method for Penetration Resistance of Hardened Concrete." The most common penetration technique used in the United States is the Windsor probe. This equipment, which is shown in Fig. 16, is a powder actuated device that drives a metal probe into the concrete surface with a standard powder charge. Penetration of the probe is determined by measuring the exposed length with a calibrated depth gage. Concrete strength is inversely proportional to depth of penetration of the probe. The method is sensitive to aggregate hardness, as was the Schmidt hammer. Although both the Windsor probe and the Schmidt test hammer are hardness testers, the probe penetrates into the concrete. Therefore, it is less sensitive to surface characteristics.(182) Malhotra describes a recommended calibration procedure for the Windsor probe and recommends that the probe be calibrated for the type of concrete under investigation.(182) Because the probe is sensitive to aggregate hardness, it is essential that calibration charts be established for each type of aggregate that was used in the in-situ concrete.[84,182]

Penetration tests can be used to assess the uniformity of concrete in-situ, to determine areas of poor quality or deterioration, and to provide a relative measure of changes in concrete properties with time.[182] The test is not recommended for determining absolute values of compressive strengths.[84,182]

10.4 Pullout Tests

The pullout test method measures the force required to pullout an insert embedded in concrete. The method is covered by ASTM Designation: C900, "Tentative Test Method for Pullout Strength of Hardened Concrete."

When a tensile force is applied to the insert, the concrete is subjected to combined tension and shear. The magnitude of the pullout force can be related to compressive strength of the concrete.[182,183] Figure 17, taken from ASTM Designation: C900, illustrates the pullout test arrangement. The relationship between pullout strength, which is a measure of shear strength, and compressive strength of the concrete is reasonably linear.[182,183] There is some indication, however, that this relationship is influenced by maximum aggregate size.

As originally introduced, the pullout test arrangement required inserts that were cast in fresh concrete during construction. Recently, methods have been proposed in which inserts are placed in hardened concrete. This is accomplished in several ways. A method developed at the Building Research Establishment in England uses wedge type anchor bolts as inserts. These are placed in a cylindrical hole drilled into the concrete.[184] A Danish method uses a special drill bit that not only drills a cylindrical hole, but undercuts the hole such that an expansion ring insert can be used as the pullout device.[185]

Pullout tests provide a measure of concrete strength in the structure and the tests are reproducible to within acceptable limits.[182,183] The tests have a disadvantage in that they leave cone shaped cavities in the concrete that must be repaired after testing.

10.5 Ultrasonic Pulse Velocity Tests

The ultrasonic pulse velocity method uses the propagation of longitudinal compression waves to determine the in-situ condition of hardened con-

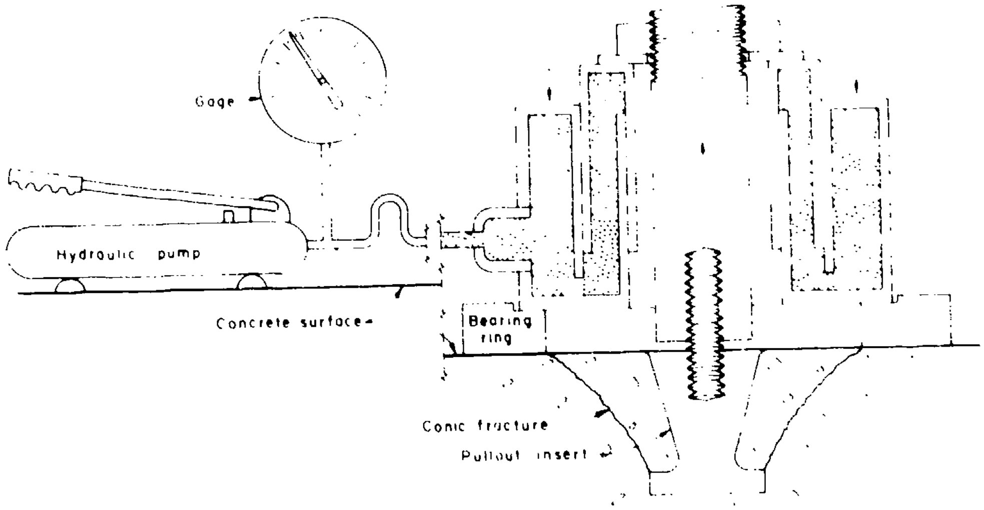


Fig. 17 Pullout Test Arrangements - ASTM Designation: C900

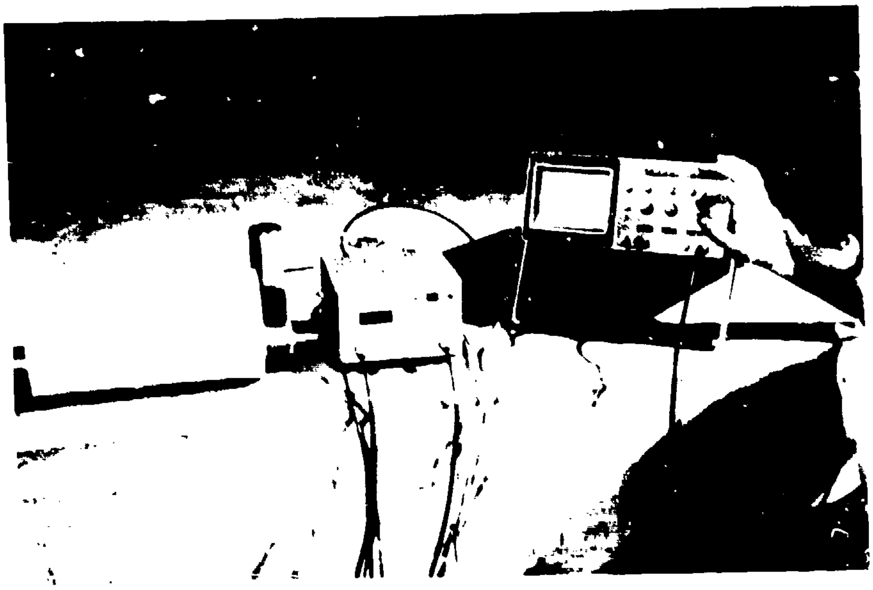


Fig. 18 Pulse Velocity Equipment

crete.[84,182,183] The time of travel of an ultrasonic pulse passing through the concrete is measured electronically. Changes in longitudinal wave velocity indicate variations in density of concrete, presence of internal voids, presence of internal cracks, and uniformity of the concrete. Pulse velocity equipment has been used for a number of years for field evaluations of concrete structures.[186,187]

The ultrasonic pulse velocity test method is covered by ASTM Designation: C597, "Standard Test Method for Pulse Velocity Through Concrete." The test apparatus, which is shown in Fig. 18, consists of a transducer that emits an ultrasonic pulse which travels through the concrete to a receiving transducer. The ultrasonic pulse is then converted into an electrical impulse which is displayed on an oscilloscope. The path length between transducers is divided by the time of travel to obtain the average velocity of the wave of propagation.[84,182,183]

Techniques for measuring pulse velocity through concrete include direct transmission, semidirect transmission, and indirect or surface transmission.[182] These are illustrated in Fig. 19. The direct transmission method is most common and is preferred to the other techniques because it provides a well defined path length and maximum sensitivity. The surface transmission test is least desirable because path length of the wave is not well defined. Surface transmission measurements only indicate quality of the concrete near the surface.[182]

The following factors influence pulse velocity measurements:

(a) Path Lengths - Path lengths should be long enough to avoid errors introduced by the heterogeneous nature of concrete.

(b) Contact Surface - Acoustical contact between the surface of the concrete and the face of each transducer must be maintained.

(c) Lateral Dimensions of the Test Structure - If the shape of the structure is such that its least lateral dimension, that is the dimension measured at right angles to the pulse path, is less than the wave length of the pulse vibrations, the pulse velocity may be reduced.

(d) Presence of Reinforcing Steel - The presence of reinforcing steel can have a considerable effect on pulse velocity because the pulse velocity in steel can be as much as twice that of plain concrete.

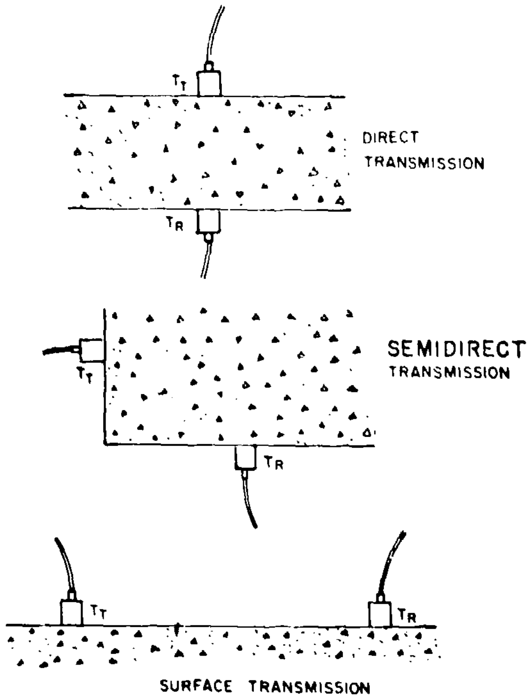


Fig. 19 Techniques for Measuring Pulse Velocity Through Concrete (182)

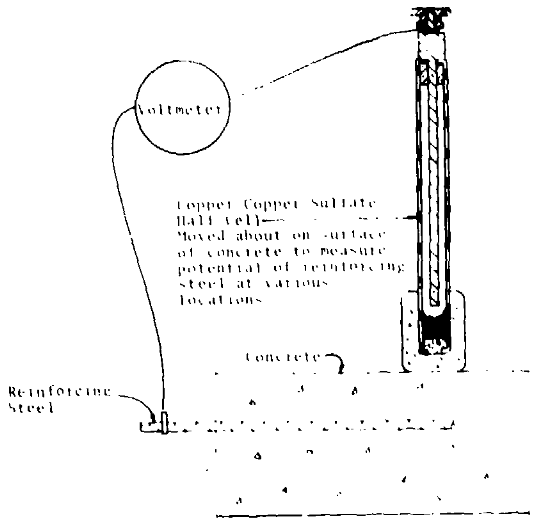


Fig. 20 Copper-Copper Sulfate Half Cell Circuitry - ASTM Designation: C876

Correction factors are available to account for effects of reinforcement in the concrete.[182]

(e) Temperature of Concrete - Temperature effects are not significant if the ambient temperature of the concrete is between 40 and 80 F. Correction factors are available for other temperatures.[182]

Pulse velocity tests are primarily used to determine homogeneity of concrete, the presence of voids, cracks, or other imperfections, and changes in concrete properties that may occur with time. With regard to assessment of concrete quality, pulse velocity ratings have been suggested.[182,186,187] However, such ratings should be used with caution because of the wide variety of factors that can influence in-situ concrete quality.[187]

Use of pulse velocity techniques for evaluation of concrete strength should be done with care.[84,182,183] Correlations between strength and pulse velocity have been developed.[84,183] However, because of the considerable influence of concrete moisture content on pulse velocity, it is essential that calibration of pulse velocity data include effects of moisture.[84] Pulse velocity can also be related to the modulus of elasticity of concrete.[84,182,187]

Malhotra suggests that instead of using pulse velocity as a predictor of concrete properties, the pulse velocity method should be used as a control test in its own right.[182]

Although only limited data are available, ultrasonic pulse velocity methods are applicable for use underwater.[175] Obviously, test data would need to be calibrated to account for effects of moisture in the concrete.

10.6 Durability Tests

Tests for in-situ concrete durability include methods for evaluating corrosion activity, methods for evaluating deteriorated concrete, and methods for evaluating composition of hardened concrete.

Corrosion activity of reinforcing steel in concrete can be evaluated by measurement of electrical potentials.[92,188,189] The test method is covered under ASTM Designation: C876, "Standard Test Method for Half-Cell Potentials of Reinforcing Steel in Concrete." Using this method, electrical potentials are measured between reinforcing steel and a copper-copper sulfate cell, which is moved around on the surface of the concrete to measure potentials at various locations. This is illustrated in Fig. 20, which is taken from ASTM Designation: C876. Generally, measurements are made over a grid on the surface of the concrete to establish topographic maps of electrical potentials. These maps provide a basis for evaluating the level of corrosion activity and for estimating the location of corrosion activity.

Underwater measurements are possible with this method, however, data obtained must be carefully interpreted. Field measurements have indicated that even though large potentials indicating severe corrosion activity have been measured in saturated concrete, relatively little corrosion activity was actually supported.[92]

Data on electrical potential measurements are often supplemented with tests for chloride concentration in concrete located around reinforcing steel.[188,189] Concrete is sampled by drilling holes into the structure and collecting the powder for laboratory analysis. A method for determining chloride content of the sample has been described by Stark and Perenchio.[188]

In conjunction with measurements of corrosion activity, it is often necessary to obtain data on the location and depth of reinforcing steel.[92,188,189] The most common method for determining reinforcement location is based on a magnetic device that is sometimes termed a "cover meter."[182] The cover meter consists of a U-shaped magnetic core on which two coils are mounted. Alternating current is passed through one coil and current induced in the other coil is measured. The induced current depends upon mutual inductance of the coils and upon the presence of steel in the concrete being tested.[182] This method has been successfully used to determine bar cover to within ±1/8 in. and to locate reinforcement to within ±1/2 in.[182,188,190] For structures that contain large amounts of reinforcement, problems can be encountered in determining cover because of effects of secondary reinforcement on the magnetic field.[182] Use of a cover meter is shown in Fig. 21.

Samples of deteriorated concrete may also be subjected to petrographic examination. Recommendations for such examinations are given by ASTM Designation: C856, "Standard Recommended Practice for Petrographic Examination of Hardened Concrete." Petrographic examinations are used for detailed evaluation of condition of the concrete, causes of deterioration, and probable future performance of the concrete. They can also be used to determine if in-situ concrete was made in accordance with job specifications.

Petrographic examinations may be supplemented with mechanical and physical tests to determine cement content, water-cement ratio, air content,

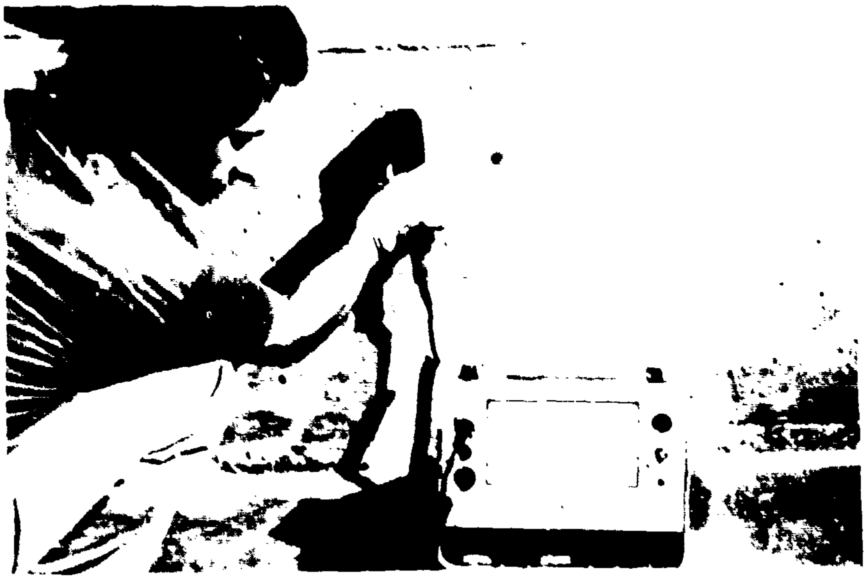


Fig. 21 Use of a "Cover Meter"

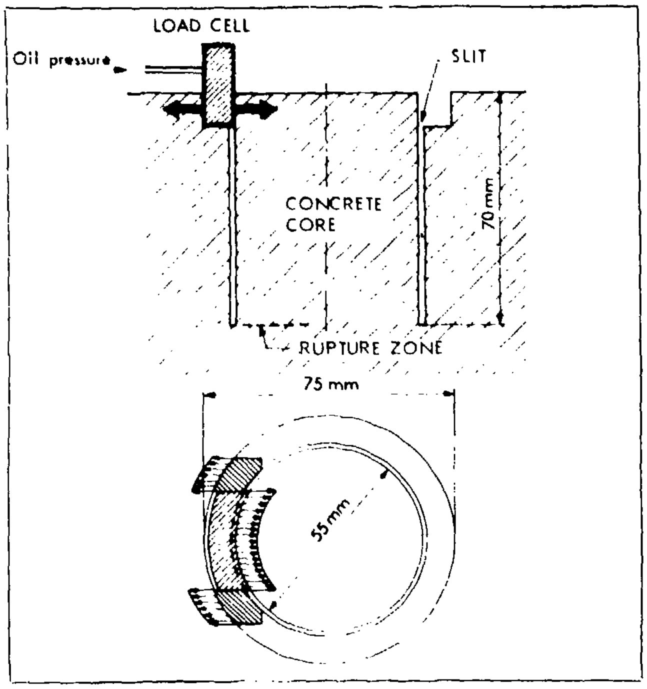


Fig. 22 "Break-Off" Test (191)

air-void distribution, and other properties that may have a bearing on the performance of in-situ concrete. Selection of particular test methods to be used will depend upon the nature of the deterioration to be evaluated.

10.7 Other Tests

In addition to tests described above, other methods are available for evaluating the in-situ condition of concrete. In most cases these have not developed to the point where they have been standardized by ASTM.

A recent Norwegian development for determining in-situ strength of concrete is the "break-off" test.[191] This method is illustrated in Fig. 22. Concrete strength is estimated by breaking off a concrete core that is formed by casting a tubular mold in the fresh concrete. The flexural capacity of the core is correlated with compressive strength. Although the test is relatively simple and gives reasonable strength correlation, it must be preplanned because tubular molds must be inserted during casting. The method appears most applicable for concrete flatwork.

A proprietary ultrasonic test device that eliminates some of the disadvantages of through-transmission techniques has been successfully used to evaluate in-situ concrete condition.[192] This technique, termed "the pulse echo method," is shown in Fig. 23. Using this method, a mechanical wave is generated by striking a blow at one face of the member being evaluated. This wave passes through the member and reflects from the opposite face. Knowing the path length and time of travel, pulse velocity can be calculated. Generally, a Schmidt hammer is used to generate the mechanical wave. An obvious advantage of the pulse echo approach is that access to only one face of the member is required.

A useful attribute of the pulse echo technique is its ability to locate discontinuities such as cracks within the member. Although normal pulse velocity methods can be used to determine the existence of discontinuities, they cannot be used to locate the exact position. With the pulse echo device, as the mechanical wave passes through an interface between materials of different density, part of the energy is reflected. For example, if the wave passes through a crack approximately perpendicular to its line of travel a concrete-to-air interface is encountered. Part of the energy is reflected at the interface and the remainder passes through to the back face of the member.

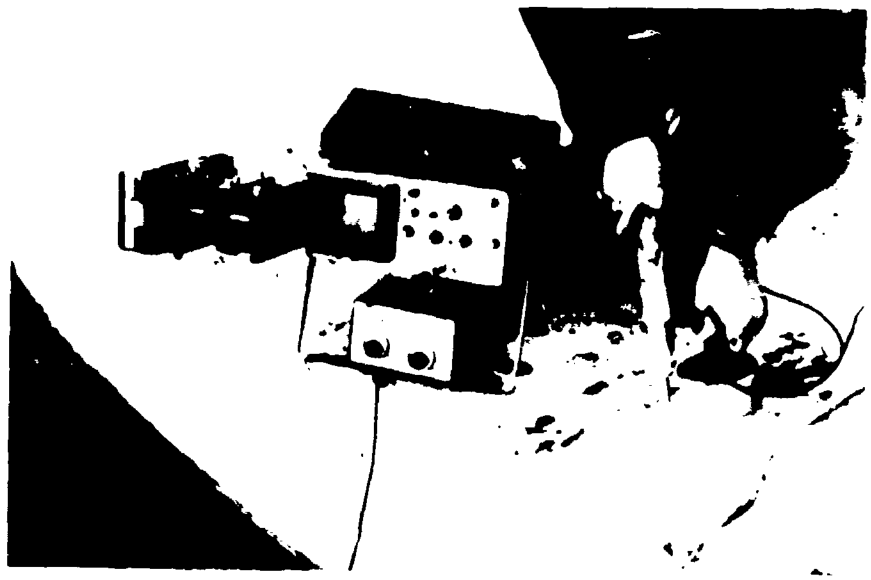


Fig. 23 Pulse-Echo Test Equipment

The presence of an intermediate signal is an indication of the location of a crack within the member.

An indication of relative crack width is also obtained from the strength of the signal reflected from the back face. As the crack width increases, more energy will be reflected at the crack resulting in a weaker signal returning from the back face. At some point all energy will be reflected at the crack and none will penetrate to the back face. Thus, the pulse echo technique is extremely useful for determining the propagation of cracking and, thereby, the extent of damage in the structure.

Recent developments in nondestructive testing of concrete have also led to use of radioactive methods for locating reinforcement and for determining density and uniformity of structural concrete.[109,182] These methods will undoubtedly become more popular as experience is gained with their use and costs of testing are reduced.

A final method that may be considered for evaluation of in-situ capacity of a structure is the load test. If load tests are to be used they should be planned and conducted to ensure that the tests properly simulate forces that occur in service. In addition, all tests should be carefully monitored to insure safety of personnel during loading.

11. REPAIRS

Because repair techniques are highly dependent upon specific conditions of the particular job being evaluated, it is not possible to provide general recommendations that will strictly apply to all situations. However, certain basic principals apply and these will be covered in the following sections. ACI Committee 357 recommends that methods for repair of concrete sea structures should follow accepted practices for general concrete construction.[50]

11.1 Evaluation for Repair

A systematic approach is required for evaluation of structural damage and selection of subsequent repair procedures.[192] Johnson[193] lists the following basic steps in the repair process:

(a) Find the deterioration

(b) Determine the cause

(c) Evaluate strength of the existing structure

(d) Evaluate need for repair

(e) Select and implement repair procedure.

Each of these steps will significantly influence the success or failure of the repair process.

It is particularly important to determine the cause of damage or deterioration. If this is not done there will be no way to insure that repairs will last.[193] In selection of the repair technique, proper consideration must be given to effects that the repairs may have on future serviceability. Selection of a repair procedure that is incompatible with future service or function of the vessel may lead to additional durability or serviceability problems.[50,52,77,193,194]

In addition to determining cause of damage, it is also essential to establish the extent of damage.[77] This will establish a basis for evaluation of serviceability and strength of the vessel.

After selection of a repair procedure, complete plans and specifications should be developed prior to start of work.[193] This will insure proper planning and will serve as a basis for evaluation of repair operations. It is useful if representatives of all interested parties, including the U.S. Coast Guard, owner, classification society, contractor, and testing laboratory review repair specifications prior to start of operations so that clear lines of communication are established.

Because of the uniqueness of most repair jobs, qualification tests to evaluate methods, equipment, and workmanship will often be required.[55] If procedures must be documented prior to start of operations, "trial runs" should be made under realistic conditions.[55]

11.2 Repair Materials

Unless otherwise specified, materials for repair of concrete vessels should meet the same standards as specified for new construction.[50,52] In all cases, materials selected should be compatible with the concrete that is being repaired.[50,52,109,193,194] Repair materials should respond to changes in temperature and loads in the same way as the original concrete.[194]

Materials used for repair of concrete include conventional portland cement mortar, conventional portland cement concrete, latex modified portland cement concrete, and polymer concrete.[194] Latex modified concrete and polymer concrete are relatively recent developments that have gained widespread use because, when properly formulated, they exhibit rapid set characteristics, they are compatible with conventional portland cement concrete, they have good bond characteristics, they reduce permeability, and they have high strength characteristics.

Latex modified concrete consists of conventional portland cement mortars or concrete to which a latex such as polyvinyl acetate, acrylic, styrene-butadiene, or vinylidene chloride are added.[194] The latter three latexes are particularly suitable for wet environments.[194] General information on mix proportions and batching procedures for latex modified portland cement concretes are given in Reference 194.

The most commonly used polymer concretes are those made with either an epoxy system with curing agents or methyl methacrylate monomer with an initiator and promoter.[194] Epoxy systems consist of combinations of preformulated epoxy resins, fine, and coarse aggregate.[194] ACI Committee 503 has prepared a standard specification for repairing concrete with epoxy mortar.[195] Additional specifications for epoxy systems are contained in ASTM Designation: C881, "Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete." Epoxy resins are also used for injection repair of cracks and for bonding materials to hardened concrete.[194,196]

ACI Committee 357 recommends that when epoxy resin materials are used they should be of a moisture resistant type which can withstand damp or wet environments.[50] The Committee also recommends that the epoxy formulation be adapted to the particular environmental conditions anticipated. This may include damp concrete and low temperatures, for example.[50]

Polymer concrete made with methyl methacrylate consists of aggregate combined with a monomer that is polymerized in place.[194] The monomer system can be obtained in prepackaged form. In some applications, hardened portland cement concrete has been impregnated with methyl methacrylate which is then polymerized in place.[197] However, this approach may have limited application for marine structures because the hardened concrete must be dried prior to impregnation.

In the following sections general comments are given on repair techniques for specific types of damage. More detailed information on repair techniques is available in References 77, 109, 122, 172, 175, 189, 193, and 194. Examples and case studies of repairs on concrete marine structures are given in References 198 through 202.

11.3 Repair of Cracks

As is the case for all repairs, the cause of cracking should be determined prior to selection of the repair method.[50] It is also important to determine if the crack is dormant or if it is still active.[193,194] Evaluation of crack stability should include consideration of movements due to temperature as well as those due to load.

Epoxy resins are commonly used to repair cracks.[109,193,194] These may be introduced into the crack by gravity feed or by pressure injection. Epoxy resins can be formulated to bond to wet concrete and to cure under moist conditions. The rate of epoxy injection should be controlled so that seawater is displaced, but not mixed with the epoxy.[55] In addition, injection pressures must be controlled to insure that hydraulic pressures will not lead to splitting forces.[50] Details of crack injection procedures are given in Reference 109.

The size of cracks that must be repaired is not readily quantified. The American Bureau of Shipping requires repair of cracks that have widths greater than 0.005 in.[171] Det Norske Veritas requirements imply that cracks larger than 0.008 in. should be considered important enough to be recorded and accounted for during annual surveys.[53] ACI Committe 357 defines narrow cracks as being less than 0.01 in. in width.[50]

ACI Committee 357 recommends that dormant narrow cracks be sealed against ingress of moisture by use of low viscosity epoxy resins.(50) These may be introduced into the crack by gravity feed or by pressure injection. For wider cracks, and when continued movement of the crack is anticipated, ACI Committee 357 recommends that the crack be chased and sealed with an elastic material, or injected with epoxy and covered with a flexible strip.(50) This recommendation is essentially the same as that of the FIP.(52)

It is preferable that cracks be free of dust, oil, or other foreign material that may block flow of epoxy resin or that may reduce bond of the resin.(109,194) Generally, it is impractical to clean cracks that are less than 0.02 in. wide.(109) The necessity for cleaning is more critical for cracks on horizontal surfaces.

Pulse velocity techniques have been used to monitor and evaluate quality crack repair by epoxy injection.(203) Another method to evaluate success of crack repairs is to drill cores across the repaired area for visual inspection.(199)

11.4 Repair of Surface Damage

Surface damage includes spalls, scaling, deterioration, delamination, and cavities caused by minor impact. A variety of patching and overlay techniques are available for repair of surface damage.(77,109,175,193,194)

The basic requirement for success of any repair is proper preparation of the contact surface between the existing and new material.(109,193,194) All loose, unsound, disintegrated, and contaminated concrete must be removed. After removal of unsound concrete, the area to be repaired should be treated with high pressure water or a vacuum cleaner to remove loose particles and dust.(194)

Care should be taken not to damage existing reinforcing steel. ACI Committee 546 recommends that for cases in which delaminations or spalls extend beyond reinforcing steel, and require that more than half the perimeter of the reinforcing be exposed, the entire bar should be exposed. Concrete should be removed so that sufficient clearance under the bar is available for encasement and bond with the repair material.(194)

Surface damage can be repaired using patches or overlays of portland cement concrete, latex modified portland cement concrete, or epoxy concrete.(109,122,193,194) Portland cement dry-pack mortar can be used to patch cavities that have a relatively high ratio of depth to area.[77,122] Bonding agents may be used between the existing surface and the new repair material.[77,109,122,152,193,194]

After application of the repair material, procedures should be instituted to insure that proper curing is achieved.[77,109,122,193,194] In many cases, bond between new patches and existing concrete can be tested by "sounding" the area for hollow pockets or voids.[194]

11.5 <u>Repair of Impact, Fire, or Structural Damage</u>

Once the extent of damage has been determined and the structural adequacy of the vessel has been assured, a number of different repair techniques may be selected for restoring serviceability. These would include repairs using portland cement concrete, latex modified concrete, or epoxy concrete.

As was the case for surface damage, the first step in the repair is to remove all unsound material and clean all existing surfaces to which new concrete must be bonded.[109,122,193] If reinforcing steel is to be replaced, or if new steel is to be added, locations of lap or mechanical splices should be in accordance with the repair specifications. All welding of reinforcement should be done in accordance with American Welding Society procedures.[136]

In the case of fire damage, evaluation of the extent of damage will include assessment of effects of high temperatures on properties of the concrete and the reinforcement.[109,204]

Replacement of large areas of concrete can be achieved by forming and casting concrete using procedures for new construction, by using preplaced aggregate concrete, or by using shotcrete.[109,193] With preplaced aggregate concrete, graded aggregate is placed in forms and then cement grout is injected to fill voids between the aggregate particles. This method is often used for underwater repair of piers or spillways.[109,122] Shotcrete is commonly used for large expanses of relatively shallow areas.[109,122,193,194] Properly applied, it has excellent bond and strength properties.

When repairing damaged areas, proper bond between existing concrete and the repair material must be given special attention. This is particularly important in concrete vessels because construction joints represent potential "weak links" with regard to leakage and corrosion control.[171] Bonding agents may be specified.[171,193,194] In addition, procedures for proper curing of repair materials should be established.[109,122,193,194]

11.6 Repair of Corrosion Damage

When repairing spalls or delaminations that have resulted from reinforcing bar corrosion, it is particularly important to remove all unsound and disintegrated concrete and to completely clean corroded reinforcement.[175,194] ACI Committee 546 recommends that special consideration be given to removal of concrete contaminated with chlorides and that all concrete that shows evidence of active or potential corrosion be removed.[194] Consideration must also be given to the fact that if the structure is contaminated with chlorides, electrolytic conditions will be changed by application of the repair material.[77] The consequences of these changed conditions must be evaluated before repairs are undertaken.

If reinforcing steel has corroded to the extent that the bar area no longer meets ASTM Specifications, new steel should be added. This should be done for deteriorated ties or stirrups as well as for main reinforcing bars.

One unique technique that has been used in repair of corrosion damage has been to "purge" chlorides out of the contaminated concrete.[92,189] This is done by covering the contaminated area with an electrolyte containing an ion-exchange resin and then impressing an electrical potential between the reinforcement, which serves as a cathode, and surface mounted metal plates which serve as anodes.[189] The technique, however, is fairly new and has not had widespread application. It has one disadvantage in that it may increase the potential for corrosion in areas adjacent to the treated zone because it results in differential electrolytic conditions.[92]

After cleaning corroded reinforcement, it is sometimes advantageous to cover the exposed steel with an epoxy coating.[92] This helps to insulate the steel from development of future potential corrosion cells.

After placing and curing the repair material. A protective coating may be applied over the concrete surface.[92] This may require coating of uncorroded areas as well as those areas that have been repaired in order to avoid the creation of differential electrolytic conditions.

11.7 Underwater Repairs

Although it is preferable to conduct repairs in dry dock, methods are available for repairing concrete structures under water.[175,205] Billington has published details on materials and procedures for underwater repair of concrete structures.[205] Additional material is presented by Perkins.[109]

Generally, epoxy resins can be used underwater to seal cracks and to patch surface damage.[109,205] Concrete can be placed underwater by the tremie* method, but this technique is not particularly applicable to repair of vessels.[109,205] Grout injection of preplaced aggregate may be a viable option.[109,205] Injection of epoxy mortars by pumping from the surface has been successfully used for repair of fixed concrete off-shore structures.[55] Precautions for underwater concreting should include those necessary to insure adequate bond and uniform density of repair materials.[55]

*Tremie concrete is placed under water through a pipe which has a hopper for concrete at its upper end. The lower end of the pipe is kept in the mass of freshly placed concrete.

12. INSPECTION OF CONCRETE VESSELS

The quality of concrete structures is highly dependent upon workmanship exhibited in construction. Performance of the structure will depend to a great extent on how closely the construction process represents design and code requirements. Because of the importance of on-site workmanship, it is essential that inspection and quality control tests be conducted in a responsible and competent manner.[125-127] ACI Committee 301 recommends that all testing agencies meet requirements of ASTM Designation: E329, "Recommended Practice for Inspection and Testing Agencies for Concrete, Steel, and Bituminous Materials as Used in Construction."[127]

It is important that the entire process of concrete inspection be understood. In addition to the "U.S. Coast Guard Inspection Guide for Reinforced Concrete Vessels" and this Commentary on the Inspection Guide, a number of additional references are available to assist the marine inspector.

ACI Committee 311 has produced an "ACI Manual of Concrete Inspection," and an "ACI Standard Recommended Practice for Concrete Inspection."[206,207] Waddell has prepared a "Concrete Inspection Manual," which is used by the International Conference of Building Officials.[208] A PCA publication entitled "Concrete Pavement Construction - Inspection at Batch Plant and Mixer" provides useful information on concrete materials handling and production.[209] ASTM Committee C9 on Concrete and Concrete Aggregates has assembled a publication on, "Significance of Tests and Properties of Concrete and Concrete-Making Materials." This publication contains detailed discussions of sampling practices and tests on properties of fresh and hardened concrete.[210]

In addition, a basic library for use in construction and in-service inspections of concrete vessels should be maintained. This library should include the latest editions of the following references:

(a) "Design and Control of Concrete Mixtures," Portland Cement Association, Skokie.

(b) "Properties of Concrete," A. M. Neville, Pittman Publishing, NY.

(c) "ACI Manual of Concrete Practice," American Concrete Institute, Detroit.

(d) "ACI Manual of Concrete Inspection," Publication SP-2, American Concrete Institute, Detroit.

(e) "Concrete Manual," U.S. Department of the Interior, Water and Power Resources Services, Washington, D.C.

(f) "Annual Book of ASTM Standards," Parts 4, 10, 13, 14, 15, and 31, American Society for Testing and Materials, Philadelphia.

(g) "Significance of Tests and Properties of Concrete and Concrete-Making Materials," STP 169B, American Society for Testing and Materials, Philadelphia.

(h) "Post-Tensioning Manual," Post-Tensioning Institute, Pheonix.

(i) "Manual of Standard of Practice," Concrete Reinforcing Steel Institute, Chicago.

(j) "Placing Reinforcing Bars," Concrete Reinforcing Steel Institute, Chicago.

13. REFERENCES

1. Fougner, N.K., Seagoing and Other Concrete Ships, Oxford Technical Publications, London, 1922, 216 pp.

2. Haviland, J., "American Concrete Steamers of the First and Second World Wars," The American Neptune, Vol. 22, No. 3, July 1962.

3. Anderson, A.R., "Prestressed Concrete Floating Structures (State of the Art)," Proceedings of the Spring Meeting, The Society of Naval Architects and Marine Engineers, Vancouver, B.C., Canada, May 14-17, 1975, pp. 123-144.

4. Morgan, R.G., "Concrete Ships," Proceedings of the FIP Symposium (Tbilisi, Sept. 1972), Concrete Sea Structures, Federation Internationale de la Precontrainte, London, 1973, pp. 114-119.

5. Morgan, R.G., "History of and Experience With Concrete Ships," Proceedings of the Conference on Concrete Ships and Floating Structures, University of California, Berkeley, Sept. 15-19, 1975, pp. 3-16.

6. Morgan, R.G., "Development of the Concrete Hull," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 1-21.

7. Jackson, G.W., Jr. and Sutherland, W.M., Concrete Boat-building - Its Technique and Its Future, John deGraff, Inc., Tuckahoe, New York, 1969, 106 pp.

8. Cassie, W.F., "Lambot's Boats - A Personal Rediscovery," Concrete, Vol. 1, No. 11, Nov. 1967, pp. 380-382.

9. "Correspondence: Lambot's Boats," Concrete, Vol. 2, No. 3, March 1968, p. 128.

10. "Concrete Boats and Motor Boats," Concrete and Constructional Engineering, Vol. 13, No. 1, Jan. 1918, pp. 35-44.

11. "Concrete Vessels in Holland," Concrete and Constructional Engineering, Vol. 13, No. 2, Feb. 1918, pp. 83-92.

12. Freeman, J.E., "Developments in Concrete Barges and Ships," Proceedings of the Fourteenth Annual Convention, Atlantic City, N.J., June 27-29, 1918, American Concrete Institute, Vol. 14, pp. 422-427.

13. Livingston, L.L., "Design and Construction of a Concrete Barge," Proceedings of the Fourteenth Annual Convention, Atlantic City, N.J., June 27-29, 1918, American Concrete Institute, Vol. 14, pp. 433-440.

14. "Concrete Shipbuilding - A Large Concrete Ship in America," Concrete and Constructional Engineering, Vol. 13, No. 3, March 1918, pp. 127-132.

15. Report of the Joint Committee of the American Concrete Institute and Portland Cement Association on Concrete Barges and Ships, Concrete and Constructional Engineering, Vol. 13, No. 4, April 1918, pp. 192-195; and No. 5, May 1918, pp. 257-262.

16. Wig, R.J. and Hollister, S.C., "Problems Arising in the Design and Construction of Reinforced Concrete Ships," Proceedings of the Fourteenth Annual Convention, Atlantic City, N. J., June 27-29, 1918, American Concrete Institute, Vol. 14, pp. 441-464.

17. "Reinforced Concrete Ships in U.S.A.," Concrete and Constructional Engineering, Vol. 13, No. 9, Sept. 1918, pp. 459-467.

18. Wig, R.J. and Hollister, S.C., "Concrete Ships," Concrete and Constructional Engineering, Vol 13, No. 9, Sept. 1918, pp. 486-489.

19. Denny, Major M., "Some Recent Views on Shipbuilding - A Preliminary Survey of the Possibilities of Reinforced Concrete as a Material for Ship Construction," Concrete and Constructional Engineering, Vol. 13, No. 4, April 1918, pp. 173-181.

20. "Concrete Shipbuilding in the South of England," Concrete and Constructional Engineering, Vol. 13, No. 11, Nov. 1918, pp. 579-584.

21. "Concrete Vessels in France," Concrete and Constructional Engineering, Vol. 13, No. 4, April 1918, pp. 182-191.

22. "Story of the Selma," Second Edition, Expanded Shale, Clay and Slate Institute, Washington, D.C., June 1960, 11 pp.

23. Holm, T.A., "Performance of Structural Lightweight Concrete in a Marine Environment," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 589-608.

24. Tuthill, L.H., "Concrete Operations in the Concrete Ship Program," Journal of the American Concrete Institute, Vol. 16, No. 3, Jan. 1945, pp. 137-177. (Discussion by Caff, H. and Author, Journal of the American Concrete Institute, Nov. 1945, pp. (180-1)-(180-7)).

25. "Sea-going Barges of Concrete Construction," Engineering News-Record, June 17, 1943, pp. 66-71.

26. Maxwell-Cook, P.V., Ed., "Concrete Sea Structures," Proceedings of the FIP Symposium, Federation Internationale de la Precontrainte, William Clowes & Sons Limited, London, April 1973, 255 pp.

27. "Off-Shore Structures," Proceedings of the Conference held on October 7-8, 1974, Institution of Civil Engineers, London, 1975, 208 pp.

28. Gerwick, B.C., Jr., Editor, "Concrete Ships and Floating Structures," Proceedings of the Conference held on Sept. 15-19, 1975, University of California, Berkeley, 289 pp.

29. "Design and Construction of Offshore Structures," Proceedings of the Conference held on Oct. 27-28, 1976, Institution of Civil Engineers, London, 1977, 177 pp.

30. Concrete Afloat, Proceedings of the Conference on Concrete Ships and Floating Structures, March 3-4, 1977, London, Thomas Telford Ltd., London, 1977, 204 pp.

31. Turner, F. H., Ed., "Concrete Ships and Floating Structures Convention," Proceedings of the Concrete Ships and Floating Structures Convention, Thomas Reed Publications Ltd., London, Nov. 1979.

32. Nichols, C.C., "Construction and Performance of Hood Canal Floating Bridge," ACI SP-8, Symposium on Concrete Construction in Aqueous Environments, 1964, pp. 97-106.

33. Gerwick, B.C., Jr. and Hognestad, E., "Concrete Oil Storage Tank Placed on North Sea Floor," Civil Engineering - ASCE, Aug. 1973. (Also Portland Cement Association Research and Development Bulletin RD022).

34. "Concrete Barges," Concrete Products, Jan. 1967, pp. 56-58.

35. "Foundations for Production Equipment, Tank Batteries, etc., and Oil Skimmer Barges," Marine Concrete Structures, New Orleans, 1979.

36. Yee, A.A., Lum, K.B.T., and Golveo, V.S., "Design and Construction of Oceangoing Pretensioned Concrete Barges," Journal of the American Concrete Institute, Vol. 72, No. 4, April 1975, pp. 125-134.

37. Sare, P.N. and Yee, A.A., "Operational Experience With Prestressed Concrete Barges," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 71-81.

38. Mast, R.F., "The Arco LPG Terminal Vessel," Proceedings of the Conference on Concrete Ships and Floating Structures, University of California, Berkeley, Sept. 15-19, 1975, pp. 245-256.

39. Anderson, A.R., "World's Largest Prestressed LPG Floating Vessel," Journal of the Prestressed Concrete Institute, Vol. 22, No. 1, Jan.-Feb. 1977, pp. 2-21.

40. "Design for a Concrete LNG Carrier," The Naval Architect, R.I.N.A., Jan. 1977, p. 11.

41. "Concrete Ships for Hauling LNG?," Ocean Industry, May 1977, pp. 70-74.

42. Stanford, A.E., "LNG Concrete Ship Economics," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 83-96.

43. George, J.F., "System Design Considerations for a Floating OTEC Modular Experiment Platform," Proceedings of the Sixth Ocean Thermal Energy Conversion Conference, Washington, D.C., June 19-22, 1979, p. 5.5.

44. Morgan, R.G., "Use of Concrete as a Hull Material for Offshore Vessels," Proceedings of the Second International Offshore Craft Conference, Thomas Reed Industrial Press Ltd., London, 1977.

45. Turner, F.H., "Concrete Hulls: A Progress Report," Proceedings of the Third International Offshore Craft Conference, Thomas Reed Industrial Press Ltd., London, 1979, pp. 1-4.

46. Hardy, F. and Raynaud, J., "Concrete Ship Versus Steel Ship: Is the Heavier Hull Feasible?," Bulletin Technique du Bureau Veritas, Feb. 1980, pp 8-17. (Same paper also included in Reference 31).

47. Lin, T.Y. and Chow, P.Y., "Economics and Problem Areas of Structural and Constructional Options for Large Prestressed Concrete Ships and Vessels," Proceedings of the Conference on Concrete Ships and Floating Structures, University of California, Berkeley, Sept. 15-19, 1975, pp. 64-76.

48. Hay, N.E., Jansky, C., and Mascaro, F., "The Market for Concrete Gas Carriers," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 159-165.

49. Gerwick, B.C., Jr., Prestressed Concrete Ocean Structures and Ships, Post-Tensioning Institute, Glenview, Illinois, Sept. 1975, 55 pp.

50. ACI Committee 357, "Guide for the Design and Construction of Fixed Offshore Concrete Structures," Journal of the American Concrete Institute, Dec. 1978, pp. 684-709.

51. Rules for the Design, Construction and Inspection of Offshore Structures, Det Norske Veritas, Oslo, Norway, 1977, 67 pp. plus Appendices.

52. Recommendations for the Design and Construction of Concrete Sea Structures, Third Edition, Federation Internationale de la Precontrainte, London, July 1977, 59 pp.

53. Guidelines for the Design, Construction and Classification of Floating Concrete Structures, Det Norske Veritas, Oslo, Norway, April 1978, 97 pp.

54. Furnes, O., "Guidelines for the Design, Construction and Classification of Floating Concrete Structures - An Introduction to New DNV Guidelines," Presented at Eighth FIP Congress - Seminar on Concrete Ships, London, May 1978, 31 pp.

55. Furnes, O., "Guidelines for the Design, Construction and Maintenance of Concrete Ships and Floating Structures," Concrete Ships and Floating Structures Convention, Thomas Reed Publications Ltd., London, 1980, 14 pp..

56. Provisional Rules for Prestressed Concrete Barges, Nippon Kayi Kyokai, Tokyo, Japan, 1975, 37 pp.

57. Prestressed Concrete Ships: First Report - Considerations for Design, First Edition, Federation Internationale de la Precontrainte, London, Nov. 1975, 13 pp.

58. Curry, R., ABS Proposed Method of Analysis of Prestressed Concrete Vessels (Pretensioned Strands), American Bureau of Shipping, New York, 1979.

59. Curry, R., "Concrete as a Ship and Boatbuilding Material," Symposium on Indian Shipbuilding, Indian Institute of Naval Architects, Calcutta, India, Feb. 1980.

60. Person, A., "Use of Prestressed Concrete for Ship Hulls, Some Design Considerations and Material Practices," RPT-04074-001B, Global Marine Development, Inc., Irvine, California, Sept. 1979.

61. Gerwick, B.C., Jr., "Design and Construction of Prestressed Concrete Vessels," Fifth Annual Offshore Technology Conference, Houston, Texas, April 29-May 2, 1973 (Preprint).

62. Anderson, A.R., "Code Provisions for Concrete Ships," Concrete Design: U.S. and European Practices, SP-59, American Concrete Institute, Detroit, 1979, pp. 317-327.

63. Gerwick, B.C., Jr., "Special Provisions Applicable to Concrete Sea Structures," Concrete Design: U.S. and European Practice, SP-59, American Concrete Institute, Detroit, 1979, pp. 305-315.

64. Haynes, H.H., Handbook for Design of Undersea, Pressure-Resistant Concrete Structures, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California, Sept. 1976, 35 pp.

65. Harper, W.R., "Concrete Ships Constructed by U.S. Shipping Board," Proceedings of the Eighteenth Annual Convention, Feb. 13-16, 1922, American Concrete Institute, Vol. 18, pp 83-114.

66. Nash, J.P., "Light Weight Concrete for Ships From Special Aggregate," Concrete and Constructional Engineering, Vol. 13, No. 10, Oct. 1918, pp. 548-549.

67. ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete," Concrete International, Vol. 1, No. 2, Feb. 1979, pp. 33-62.

68. Shideler, J.J., "Lightweight Aggregate Concrete for Structural Use," Journal of the American Concrete Institute, Proc. Vol. 54, No. 10, Oct. 1957, pp. 299-328 (Also PCA Development Department Bulletin D17).

69. Litvin, A. and Fiorato, A.E. "Development of a Lightweight Concrete for OTEC Cold Water Pipes," Proceedings of the Sixth OTEC Conference, Vol. 1, Washington, D.C., June 19-22, 1979, pp. 6.6-1-6.6-8.

70. Kaar, P.H., Hanson, N. W., and Capell, H.T., "Stress-Strain Characteristics of High-Strength Concretes," Proceedings, Douglas McHenry International Symposium on Concrete and Concrete Structures, American Concrete Institute, Detroit, 1977 (Also PCA Research and Development Department Bulletin RD051).

71. Berge, O., "Hydrofobe 3L - Concrete, An Attractive 'New' Structural Material," Nordisk Betong, No. 6, 1978, pp. 19-23 (in Swedish).

72. Haynes, H.H. and Eckroth, W.V. "Lightweight Concrete using Polymer-Filled Aggregate for Ocean Applications - An Exploratory Investigation," Technical Note N-1565, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California, Dec. 1979, 26 pp.

73. Gerwick, B.C., Jr., "Application of Polymers to Concrete Sea Structures," Second International Congress on Polymers in Concrete, College of Engineering, University of Texas, Austin, October 25-27, 1978, pp. 37-43.

74. FIP State of Art Report: Lightweight Aggregate Concrete for Marine Structures, Federation Internationale de la Precontrainte, London, April 1978, 25 pp.

75. Bremner, T.W. and Newman, J.B., "Lower Density Concrete for Marine Structures," Proceedings of the Eighth Congress of the FIP, Federation Internationale de la Precontrainte, London, April 30-May 5, 1978, Part 4, pp. 44-54.

76. "Structural Lightweight-Aggregate Concrete for Marine and Offshore Applications," Concrete Society Technical Report No. 16, The Concrete Society, London, May 1978, 29 pp.

77. ACI Committee 201, "Guide to Durable Concrete," Journal of the American Concrete Institute, Vol. 74, No. 12, Dec. 1977, pp. 573-609.

78. Mehta, P.K., "Durability of Concrete in Marine Environment - A Review," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 1-20.

79. Browne, R.D. and Domone, P.L.J., "The Long-Term Performance of Concrete in the Marine Environment," Off-Shore Structures, The Institution of Civil Engineers, London, 1975, pp. 49-59.

80. Gerwick, B.C., Jr., "Marine Concrete," Handbook of Ocean and Underwater Engineering, McGraw-Hill Book Co., New York, 1969, pp. 8-31 - 8-56.

81. Gjorv, O.E., "Durability of Concrete Structures in the Ocean Environment," Proceedings of the FIP Symposium (Tbilisi, Sept. 1972), Concrete Sea Structures, Federation Internationale de la Precontrainte, London, 1973, pp. 141-145.

82. Somerville, G. and Taylor, H.P.J., "Concrete Properties" Proceedings of the Eighth Congress of the FIP, Federation Internationale de la Precontrainte, London, April 30-May 5, 1978, Part 1, pp. 8-18.

83. Gjorv, O.E., Durability of Reinforced Concrete Wharves in Norwegian Harbours, Ingeniorforlaget A/S, Oslo, 1968, 208 pp.

84. Neville, A.M., Properties of Concrete, Pitman Publishing Corporation, New York, 1975, 687 pp.

85. Mehta, P.K. and Haynes, H.H., "Durability of Concrete in Seawater," Journal of the Structural Division, ASCE, Vol. 101, No. ST8, Aug. 1975, pp. 1679-1686.

86. Verbeck, G.J., "Field and Laboratory Studies of the Sulfate Resistance of Concrete," Research Department Bulletin 227, Portland Cement Association, Skokie, 1967.

87. Gjorv, O.E., "Long-Time Durability of Concrete in Seawater," Journal of the American Concrete Institute, Vol. 68, No. 1, Jan. 1971, pp. 60-67.

88. Lyse, I., "Durability of Concrete in Sea Water," Journal of the American Concrete Institute, Vol. 32, No. 12, June 1961, pp. 1575-1584.

89. Verbeck, G.J., "Mechanisms of Corrosion of Steel in Concrete," Corrosion of Metals in Concrete, Publication SP-49, American Concrete Institute, Detroit, 1975, pp. 21-38.

90. Cornet, I., Pirtz, D., Polivka, M., Gau, Y., and Shimizu, A., "Effect of Stray Electric Current on the Corrosion of Prestressed Concrete in Sea Water," Tenth Annual Offshore Technology Conference, Houston, Texas, May 1978.

91. Gjorv, O.E., "Control of Steel Corrosion in Concrete Sea Structures," Corrosion of Metals in Concrete, Publication SP-49, American Concrete Institute, Detroit, 1975, pp. 1-9.

92. Browne, R.D., "The Corrosion of Concrete Marine Structures: The Present Situation," Concrete Structures, Tapir Publishers, Trondheim, Norway, 1978, pp. 177-209.

93. Whiting, D., "Influence of Concrete Materials, Mix, and Construction Practices on the Corrosion of Reinforcing Steel," Materials Performance, Vol. 17, No. 12, Dec. 1978, pp. 9-15.

94. Beeby, A.W., "Corrosion of Reinforcing Steel in Concrete and Its Relation to Cracking," The Structural Engineer, Vol. 56A, No. 3, March 1978, pp. 77-81.

95. Beeby, A.W., Concrete in the Oceans - Cracking and Corrosion, Technical Report No. 1, Cement and Concrete Association, Wexham Springs, Slough, 1978, 77 pp.

96. Haynes, H.H. and Rail, R.D., Concrete for Ocean Thermal Energy Conversion Structures, Technical Note N-1448, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California, Aug. 1976, 47 pp.

97. Gerwick, B.C., Jr., "Practical Methods of Ensuring Durability of Prestressed Concrete Ocean Structures," Durability of Concrete, Publication SP-47, American Concrete Institute, 1975, pp. 317-324.

98. Clear, K.C., "Reinforcing Bar Corrosion in Concrete: Effect of Special Treatment," Corrosion of Metals in Concrete, <u>Publication SP-49</u>, American Concrete Institute, Detroit, 1975, pp. 71-83.

99. Backstrom, T.E., "Use of Coatings on Steel Embedded in Concrete," Corrosion of Metals in Concrete, <u>Publication SP-49</u>, American Concrete Institute, Detroit, 1975, pp 103-113.

100. Cornet, I., Williamson, R.B., Bresler, B., Nagarajan, S., and Christensen, K.A., "Chromate Admixture to Improve Performance of Galvanized Steel in Concrete Sea Structures," Proceedings of the FIP Symposium (Tbilisi, Sept. 1972), Concrete Sea Structures, Federation Internationale de la Precontrainte, London, 1973, pp. 159-163.

101. Clifton, J.R., Beeghly, H.F., and Mathey, R.G., "Protecting Reinforcing Bars From Corrosion with Epoxy Coatings," Corrosion of Metals in Concrete, <u>Publication SP-49</u>, American Concrete Institute, Detroit, 1975, pp. 115-132.

102. Griffin, D. F., "Corrosion Inhibitors for Reinforced Concrete," Corrosion of Metals in Concrete, <u>Publication SP-49</u>, American Concrete Institute, Detroit, 1975, pp. 95-102.

103. Hartt, W.H. and Rosenberg, A.M., "Influence of $Ca(NO_2)_2$ on Sea Water Corrosion of Reinforcing Steel in Concrete," Performance of Concrete in Marine Environment, <u>Publication SP-65</u>, American Concrete Institute, Detroit, 1980, pp. 609-622.

104. Robinson, R.C., "Cathodic Protection of Steel in Concrete," Corrosion of Metals in Concrete, <u>Publication SP-49</u>, American Concrete Institute, Detroit, 1975, pp. 83-93.

105. Heuze, B., "Cathodic Protection on Concrete Offshore Platforms," <u>Materials Performance</u>, Vol. 19, May 1980, pp. 24-33.

106. Gjorv, O.E. and Vennesland, O., "Cathodic Protection of Steel in Offshore Concrete Platforms, "<u>Materials Performance</u>, Vol. 19, May 1980, pp. 49-51.

107. Galler, S.R., "Boring and Fouling," <u>Handbook of Ocean and Underwater Engineering</u>, McGraw-Hill Book Co., New York, 1969, p. 7-12.

108. Mather, B., "Factors Affecting Durability of Concrete in Coastal Structures," Technical Memorandum No. 96, Beach Erosion Board, Corps of Engineers, June 1957, 27 pp.

109. Perkins, P.H., <u>Concrete Structures: Repair, Waterproofing and Protection</u>, John Wiley and Sons, New York, 1977, 302 pp.

110. Mathews, C.W., "Antifouling Marine Concrete," <u>Technical Note No. N-1573</u>, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, Ca., March 1980, 37 pp.

111. Wig, R. J. and Ferguson, L.R., "Concrete in Sea Water," Concrete and Constructional Engineering, Vol. 13, No. 2, Feb. 1918, pp. 99-102; No. 3, March 1918, pp. 147-154; No. 8, Aug. 1918, pp. 410-418; No. 9, Sept. 1918, pp. 473-481; and No. 10, Oct. 1918, pp. 525-534.

112. Haynes, H.H., "Permeability of Concrete in Sea Water," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 21-38.

113. Powers, T.C., "The Physical Structure and Engineering Properties of Concrete," Research Department Bulletin 90, Portland Cement Association, Skokie, July 1958, 28 pp.

114. Verbeck, G., "Pore Structure," Significance of Tests and Properties of Concrete and Concrete-Making Materials, Special Technical Publication No. 169A, American Society for Testing and Materials, Philadelphia, 1966, pp 211-219. (Also, Portland Cement Association, Research Department Bulletin 197).

115. Powers, T.C., Copeland, L.E., Hayes, J.C., and Mann, H.M., "Permeability of Portland Cement Paste," Journal of the American Concrete Institute, Proc. Vol. 51, Nov. 1954, pp. 285-298 (Also Portland Cement Association Research Department Bulletin 53).

116. Troxell, G.E., Davis, H.E., and Kelly, J.W., Composition and Properties of Concrete, McGraw-Hill Book Co., N.Y., 1968.

117. Browne, R.D. and Domone, P.L.J., "Permeability and Fatigue Properties of Structural Marine Concrete at Continental Shelf Depths," International Conference on Underwater Construction Technology, University College, Cardiff, April 1975, 39 pp.

118. Haynes, H.H. and Highberg, R.S., "Concrete Properties at Ocean Depths," Journal of the Waterways, Harbors, and Coastal Engineering Division, American Society of Civil Engineers, Vol. 102, No. WW4, Nov. 1976, pp. 455-470.

119. Haynes, H. H. and Highberg, R.S., "Deep Ocean Study of Concrete Spheres," Proceedings of the Eighth Congress of the FIP, Federation Internationale de la Precontrainte London, April 30-May 5, 1978, Part 1, pp. 60-69.

120. Design and Control of Concrete Mixtures, Twelfth Edition, Portland Cement Association, Skokie, 1979.

121. Malhotra, V.M., Carette, G.G., and Bremner, T.W., "Durability of Concrete in Marine Environment Containing Granulated Blast Furnace Slag, Fly Ash, or Both," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 157-168.

122. Concrete Manual, Ninth Edition, Water and Power Resources Services, (Bureau of Reclamation), U.S. Department of the Interior, Washington, D.C., 1981, 627 pp.

123. ACI Committee 304, "Recommended Practice for Measuring, Mixing, Transporting, and Placing Concrete (ACI 304-73)," American Concrete Institute, Detroit, 1973, 40 pp.

124. Steinour, H.H., "Concrete Mix Water - How Impure Can It Be?," Research Department Bulletin 119, Portland Cement Association, Skokie, Nov. 1960.

125. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-77)," American Concrete Institute, Detroit, 1977, 95 pp.

126. ACI Committee 318, "Commentary on Building Code Requirements for Reinforced Concrete (ACI 318-77)," American Concrete Institute, Detroit, 1977, 132 pp.

127. ACI Committee 301, "Specifications for Structural Concrete for Buildings (ACI 301-72)," Revised 1975, American Concrete Institute, Detroit, 1971, 36 pp.

128. ACI Committee 212, "Admixtures for Concrete," American Concrete Institute, Detroit, 1981, 29 pp.

129. ACI Committee 212, "Guide for Use of Admixtures in Concrete," American Concrete Institute, Detroit, 1981, 13 pp.

130. Manual of Standard Practice, Concrete Reinforcing Steel Institute, Chicago, 1976.

131. Manual of Standard Practice; Welded Wire Fabric, Wire Reinforcement Institute, McLean, Virginia, 1979, 32 pp.

132. Post-Tensioning Manual, Post-Tensioning Institute, Phoenix, 1981, 323 pp.

133. ACI Committee E-703, "Reinforcing Steel - Its Use and Benefits in Concrete," American Concrete Institute, Detroit, 1978, 18 pp.

134. Placing Reinforcing Bars, Concrete Reinforcing Steel Institute, Chicago, 1976.

135. "Recommended Specification for Scotchkote Brand Epoxy-Coated Steel Reinforcing Bars," Pipeline Coatings and Services, Electro-Products Division 3M, St. Paul, MN, 1980.

136. Reinforcing Steel Welding Code, AWS D12.1-75, American Welding Society, Inc., Miami, 1975, 34 pp.

137. Gerwick, B.C., Jr., Construction of Prestressed Concrete Structures, John Wiley and Sons, Inc., New York, 1971, 411 pp.

138. "Check List for Certification of Ready Mixed Concrete Production Facilities," National Ready Mixed Concrete Association, Silver Spring, Md., Jan. 1976, 21 pp.

139. "Truck Mixer and Agitator Standards of the Truck Mixer Manufacturers Bureau," Truck Mixer Manufacturers Bureau, Silver Spring, Md., 1971, 16 pp.

140. ACI Committee 305, "Hot Weather Concreting," American Concrete Institute, Detroit, 1977, 16 pp.

141. ACI Committee 306, "Cold Weather Concreting," American Concrete Institute, Detroit, 1978, 22 pp.

142. Kemp, E.L., Brezny, F.S., and Unterspan, J.A., "Effect of Rust and Scale on the Bond Characteristics of Deformed Reinforcing Bars," Journal of the American Concrete Institute, Vol. 65, No. 9, Sept. 1968, pp. 743-756.

143. Black, W.C., "Field Corrections to Partially Embedded Reinforcing Bars," Journal of the American Concrete Institute, Vol. 70, No. 10, Oct. 1973, pp. 690-691.

144. Burton, K.T. and Hognestad, E., "Fatigue Tests of Reinforcing Bars - Tack Welding of Stirrups, "Journal of the American Concrete Institute, Vol. 64, No. 5, May 1967, pp. 244-252.

145. Reinforcing Bar Splices, Concrete Reinforcing Steel Institute, Chicago, 1975, 30 pp.

146. Beeby, A.W., "Cover to Reinforcement and Corrosion Protection," FIP Notes 89, Federation Internationale de la Precontrainte, Wexham Springs, England, Nov.-Dec. 1980, pp. 4-8.

147. ACI Committee 347, "Recommended Practice for Concrete Formwork (ACI 347-78)," American Concrete Institute, Detroit, 1977, 37 pp.

148. Hurd, M.K., "Formwork for Concrete," 4th Ed., Special Publication No. 4, American Concrete Institute, Detroit, 1979.

149. Peurifoy, R.L., Formwork for Concrete Structures, 2nd Ed., McGraw-Hill Book Co., New York, 1976, 333 pp.

150. ACI Committee 347, "Precast Concrete Units Used as Forms for Cast-in-Place Concrete," American Concrete Institute, Detroit, 1968, 16 pp.

151. ACI Committee 503, "Use of Epoxy Compounds With Concrete," American Concrete Institute, Detroit, 1973, 32 pp.

152. ACI Committee 503, "Standard Specification for Bonding Plastic Concrete to Hardened Concrete With a Multi-Component Epoxy Adhesive," Journal of the American Concrete Institute, Vol. 75, No. 9, Sept. 1978, pp. 442-447.

153. ACI Committee 304, "Placing Concrete With Belt Conveyors," American Concrete Institute, Detroit, 1975, 17 pp.

154. ACI Committee 304, "Placing Concrete by Pumping Methods," American Concrete Institute, Detroit, 1971, 19 pp.

155. Shideler, J.J. and Litvin, A., "Structural Applications of Pumped and Sprayed Concrete," Development Department Bulletin D72, Portland Cement Association, Skokie, 1964, 29 pp.

156. Anderson, W.G., "Analyzing Concrete Mixtures for Pumpability," Journal of the American Concrete Institute, Vol. 74, No. 9, Sept. 1977, pp. 447-451.

157. Newlon, H., Jr. and Ozol, M.A., "Delayed Expansion of Concrete Delivered by Pumping Through Aluminum Pipeline," Concrete Case Study No. 20, Virginia Highway Research Council, Oct. 1969, 39 pp.

158. ACI Committee 309, "Recommendad Practice for Consolidation of Concrete (ACI 309-72)," American Concrete Institute, Detroit, 1971, 40 pp.

159. Litvin, A. and Shideler, J.J., "Laboratory Study of Shotcrete," Symposium on Shotcreting, Publication SP-14, American Concrete Institute, Detroit, 1966, pp. 165-184 (Also PCA Development Department Bulletin D111).

160. ACI Committee 506, "Recommended Practice for Shotcreting (ACI 506-66)," American Concrete Institute, Detroit, 1966, 20 pp.

161 ACI Committee 506, "Specification for Materials, Proportioning, and Application of Shotcrete (ACI 506.2-77)," American Concrete Institute, Detroit, 1976, 7 pp.

162. ACI Committee 308, "Recommended Practice for Curing Concrete (ACI 308-71)," American Concrete Institute, Detroit, 1971, 11 pp.

163. ACI Committee 517, "Recommended Practice for Atmospheric Pressure Steam Curing of Concrete (ACI 517-70)," American Concrete Institute, Detroit, 1969, 18 pp.

164. ACI Committee 214, "Recommended Practice for Evaluation of Strength Test Results of Concrete (ACI 214-77)," American Concrete Institute, Detroit, 1976, 14 pp.

165. "Realism in the Application of ACI Standard 214-65," Special Publication SP-37, American Concrete Institute, Detroit, 1973, 215 pp.

166. "Code for Concrete Reactor Vessels and Containments," Section III, Division II, Rules for Construction of Nuclear Power Plant Components, ACI Standard 359-80, American Society of Mechanical Engineers, New York, 1980, 335 pp.

167. Schupack, M., "A Survey of the Durability Performance of Post-Tensioning Tendons," Post-Tensioning Institute, Jan. 1978, 10 pp.

168. Tamaka, Y., Kurauchi, M., Nagi, H., and Masuda, Y., "Evaluation of Corrosion Protection of Unbonded Tendons," Post-Tensioning Institute, Oct. 1978, 35 pp.

169. Schupack, M., "Behavior of 20 Post-Tensioned Test Beams Subject to up to 2200 Cycles of Freezing and Thawing in the Tidal Zone at Treat Island, Maine," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 133-152.

170. Long, J.E., "Experience in Prestressing and Grouting Concrete Offshore Structures," Design and Construction of Offshore Structures, The Institution of Civil Engineers, London, 1977, pp. 115-119. (Disc. pp. 131-133).

171. Campbell, R.A, Chang, K.T., and Stiansen, S.G., "Classification of Concrete Ships: Historical Background and Current Practice," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 51-70.

172. Fjeld, S., "Inspection, Maintenance and Repair of North Sea Concrete Structures," Maintenance of Maritime Structures, London, 1978, pp. 163-174.

173. Campbell, R., "Classification of Concrete Vessels," Proceedings of the Conference on Concrete Ships and Floating Structures, University of California, Berkeley, Sept. 15-19, 1975, pp. 228-240.

174. Beaumont, J.G., "Quality Control and Maintenance of Prestressed Concrete Ships," Concrete Afloat, Thomas Telford Ltd., London, 1977, pp. 131-146.

175. Allen, R.T.L. and Gregory-Cullen, J., "The Inspection, Maintenance and Repair of Concrete Offshore Structures," Report RR SMT-7401, Cement and Concrete Association, London, September 23, 1974, 74 pp.

176. ACI Committee 201, "Guide for Making a Condition Survey of Concrete in Service," American Concrete Institute, Detroit, 1968, 14 pp.

177. Paulling, J.R., "Ship Structural Loads for Concrete Ships and Vessels," Proceedings of the Conference on Concrete Ships and Floating Structures, University of California, Berkeley, Sept. 15-19, 1975, pp. 34-44.

178. Goodfellow, R., "Organisation of the Systematic Underwater Inspection and Maintenance of Offshore Facilities," Maintenance of Maritime Structures, The Institution of Civil Engineers, London, 1978, pp. 1-44.

179. Twine, M.E., "The Diver in the Offshore Construction Industry," Proceedings, The Institution of Civil Engineers, London, Vol. 68, Aug. 1980, pp. 455-461.

180. Campbell, R.H. and Tobin, R.E., "Core and Cylinder Strengths of Natural and Lightweight Concrete," Journal of the American Concrete Institute, Vol. 64, No. 4, April 1967, pp. 190-195.

181. Bloem, D.L., "Concrete Strength in Structures," Jounral of the American Concrete Institute, Vol. 65, No. 3, March 1968, pp. 176-187.

182. Malhotra, V.M., "Testing Hardened Concrete: Nondestructive Methods," ACI Monograph No. 9, American Concrete Institute, Detroit, 1976, 188 pp.

183. Malhotra, V.M. and Carette, G.G., "In-Situ Testing for Concrete Strength," Report 79-30, Canada Centre for Mineral and Energy Technology, Ottawa, May 1979, 20 pp.

184. Chabowski, A.J. and Bryden-Smith, D.W., "Internal Fracture Testing of In-Situ Concrete: A Method of Assessing Compressive Strength," Information Paper 22/80, Building Research Establishment, Garston, Watford, Oct. 1980, 4 pp.

185. Petersen, C.G., "Capo-Test," Nordisk Betong, No. 5, June 1980, pp. 11-14.

186. Whitehurst, E.A., "Soniscope Tests Concrete Structures," Journal of the American Concrete Institute, Vol. 47, No. 6, Feb. 1951, pp. 433-444. (Also PCA Research Department Bulletin 36.)

187. Whitehurst, E.A., "Evaluation of Concrete Properties from Sonic Tests," ACI Monograph No. 2, American Concrete Institute, Detroit, 1966, 94 pp.

188. Stark, D. and Perenchio, W., "The Performance of Galvanized Reinforcement in Concrete Bridge Decks," Final Report to International Lead Zinc Research Organization, Inc. and American Hot Dip Galvanizers Association, Inc., Project No. ZE-206, Portland Cement Association, Construction Technology Laboratories, Skokie, Oct. 1975, 80 pp.

189. Browne, R.D., Domone, P.L., and Geoghegan, M.P., "Deterioration of Concrete Structures Under Marine Conditions and Their Inspection and Repair," Maintenance of Maritime Structures, The Institution of Civil Engineers, London, 1978, pp. 137-162.

190. Stark, D., "Studies of the Relationships Among Crack Patterns, Cover Over Reinforcing Steel, and Development of Surface Spalls in Bridge Decks," Research and Development Bulletin RD020, Portland Cement Association, Skokie, 1971, 9 pp.

191. Johansen, R., "In-Situ Strength Evaluation of Concrete - The 'Break-Off' Method," Concrete International, Vol. 1, No. 9, Sept. 1979, pp. 45-51.

192. Corley, W.G., Fiorato, A.E., Oesterle, R.G., Scanlon, A., "Evaluation, Repair, and Strengthening of Reinforced Concrete Buildings," Proceedings of the US/PRC Workshop on Seismic Analysis and Design of Reinforced Concrete Structures, May 1981 (in print).

193. Johnson, S.M., Deterioration, Maintenance, and Repair of Structures, McGraw Hill Book Company, New York, 1965, 373 pp.

194. ACI Committee 546, "Guide for Repair of Concrete Bridge Superstructures," Concrete International, Vol. 2, No. 9, Sept. 1980, pp. 69-88.

195. ACI Committee 503, "Standard Specification for Repairing Concrete with Epoxy Mortars," Journal of the American Concrete Institute, Vol. 75, No. 9, Sept. 1978, pp. 454-459.

196. ACI Committee 503, "Standard Specification for Bonding Hardened Concrete, Steel, Wood, Brick, and Other Materials to Hardened Concrete with a Multi-Component Epoxy Adhesive," Journal of the American Concrete Institute, Vol. 75, No. 9, Sept. 1978, pp. 437-441.

197. Sopler, B., Fiorato, A.E., and Lenschow, R., "A Study of Partially Impregnated Polymerized Concrete Specimens," Polymers in Concrete, Publication SP-40, American Concrete Institute, Detroit, 1973, pp. 149-173.

198. Dyton, F.J., "Case Histories of Repairs of Maritime Structures," Maintenance of Maritime Structures, The Institution of Civil Engineers, London, 1978, pp. 89-103.

199. Naesje, K., Dahl, P.C., and Moksnes, J., "Structural Damage in an Offshore Concrete Platform, The Cause and the Cure," FIP Notes 76, Federation Internationale de la Precontrainte, Wexham Springs, England, Sept.-Oct. 1978, pp. 8-17.

200. Heneghan, J.I., "Shotcrete Repairs of Concrete Structures in Marine Environment, "Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 509-526.

201. Geymayr, G.W., "Repair of Concrete in Tropical Marine Environment," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 527-556.

202. Schrader, E., Dikeou, J., and Gill, D., "Deterioration and Repairs of Navigational Lock Concrete," Performance of Concrete in Marine Environment, Publication SP-65, American Concrete Institute, Detroit, 1980, pp. 557-576.

203. Amon, J.A. and Snell, L.M., "The Use of Pulse Velocity Techniques to Monitor and Evaluate Epoxy Grout Repair to Concrete," Concrete International, Vol. 1, No. 12, pp. 41-44.

204. Abrams, M.S, "Performance of Concrete Structures Exposed to Fire," Research and Development Bulletin RD060, Portland Cement Association, Skokie, 1977, 7 pp.

205. Billington, C.J., "The Underwater Repair of Concrete Offshore Structures," Eleventh Annual Offshore Technology Conference, Houston, Texas, April-May 1979, pp. 927-938.

206. ACI Committee 311, "ACI Manual of Concrete Inspection," Publication SP-2, American Concrete Institute, Detroit, 1975, 268 pp.

207. ACI Committee 311, "Recommended Practice for Concrete Inspection (ACI 311-75)," American Concrete Institute, Detroit, 1974, 6 pp.

208. Waddell, J.J., Concrete Inspection Manual, International Conference of Building Officials, Whittier, 1976, 332 pp.

209. "Concrete Pavement Construction - Inspection at Batch Plant and Mixer," Publication EB084, Portland Cement Association, 1980, 10 pp.

210. ASTM Committee C-9, "Significance of Tests and Properties of Concrete and Concrete-Making Materials," Special Technical Publication 169B, American Society for Testing and Materials, Philadelphia, 1978, 872 pp.

APPENDIX A - REINFORCED AND PRESTRESSED CONCRETE

Because concrete has a much higher compressive strength than tensile strength, concrete structures are reinforced with steel when tensile forces must be resisted.

A.1 Reinforced Concrete

Figure A.1 illustrates the behavior of a plain (unreinforced) concrete beam in flexure. As loads are applied, the beam deflects. At the top of the beam concrete is compressed while at the bottom it is stretched. With increasing load and deflection the tensile capacity of concrete at the bottom of the beam is exceeded. Cracks develop and quickly propagate through the beam causing a sudden loss of load capacity. Once the concrete cracks, there is no material available to resist tensile forces.

Figure A.2 illustrates the behavior of a reinforced concrete beam. Reinforcing bars are located near the bottom of this beam. Prior to cracking, that is prior to exceeding the tensile capacity of the concrete, there is little difference in the behavior of the unreinforced and reinforced beam. However, once cracking occurs, steel bars in the reinforced beam resist tensile forces while concrete at the top of the beam resists compressive forces. The beam maintains its load capacity well beyond occurrence of cracking.

The load versus deflection curves in Figure A.3 illustrate the effectiveness of reinforcing concrete.

A.2 - Prestressed Concrete

With reinforced concrete, it is necessary for the structural member to deflect and crack prior to full utilization of reinforcement. The fundamental concept of prestressed concrete is to apply some level of "precompression" to the member prior to subjecting it to load. In this way, when loads are applied to the member, net tensile forces are not induced until the precompression is overcome. Fully prestressed members are designed so that service loads will not cause net tensile stresses.

Prestressed concrete members are produced by pretensioning or post-tensioning. Both methods are illustrated in Fig. A.4. Pretensioned members are commonly cast in a stressing bed. High-strength steel tendons are placed in a form and stressed. Then concrete is cast and cured. When the concrete

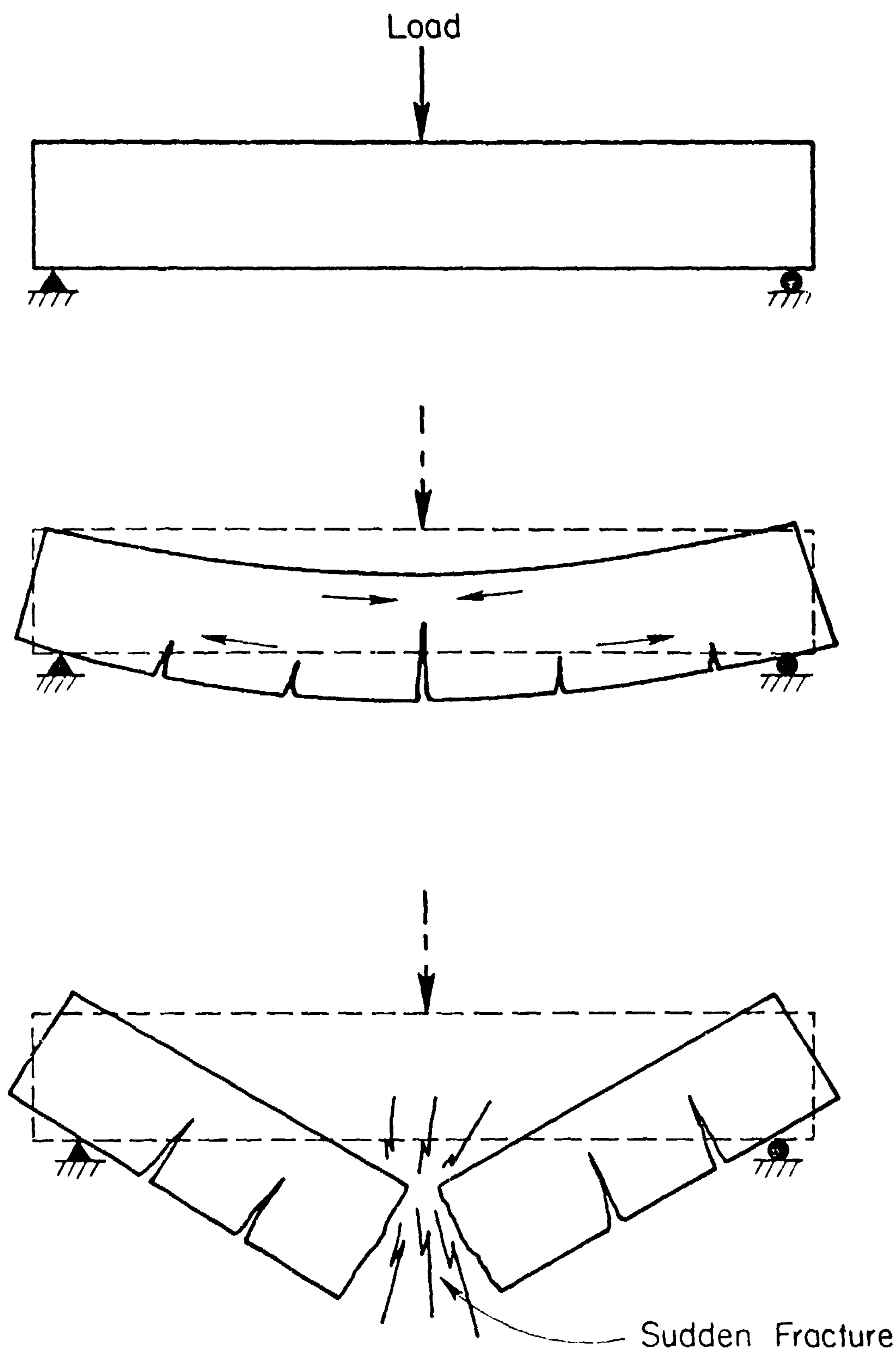


Fig. A1 - Plain Concrete Beam Under Load

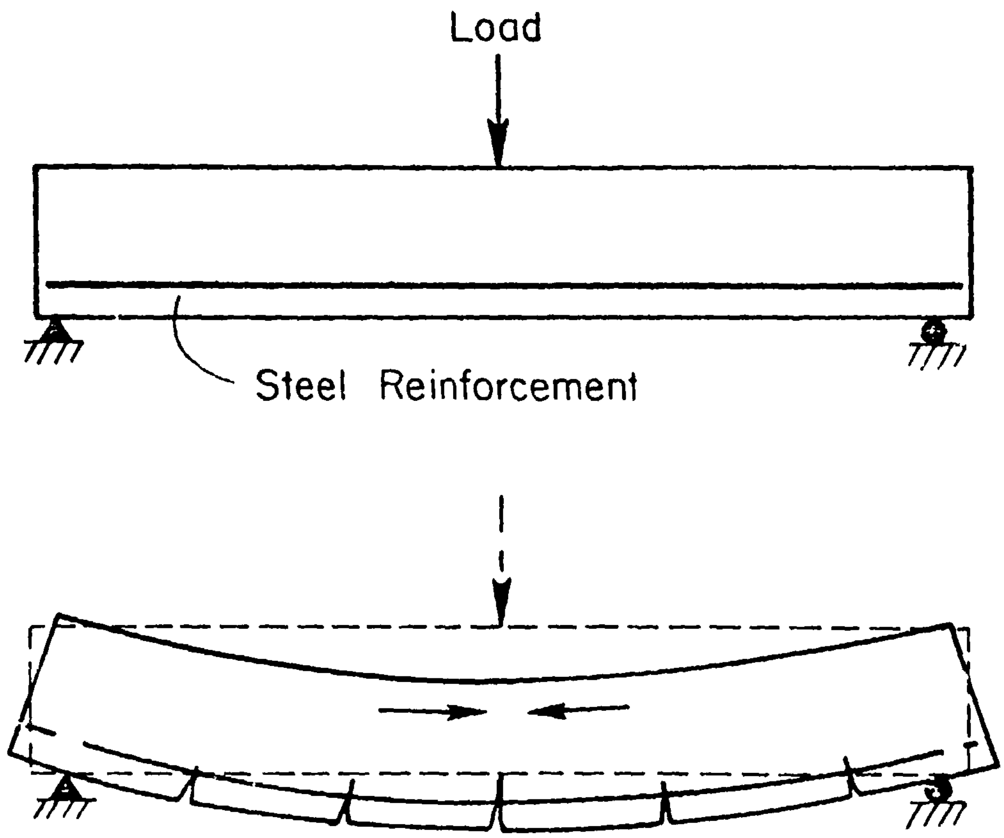


Fig. A2 - Reinforced Concrete Beam Under Load

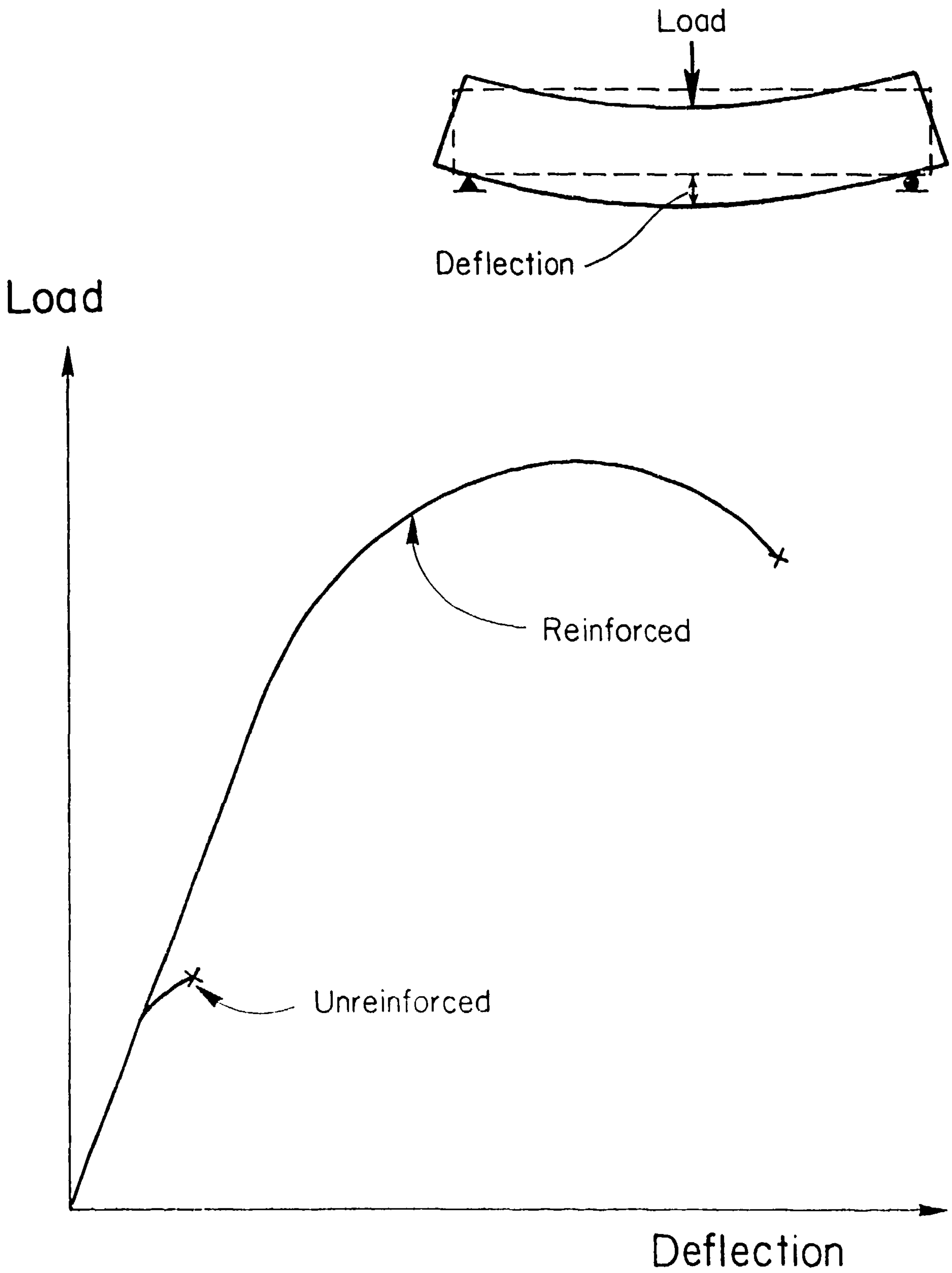
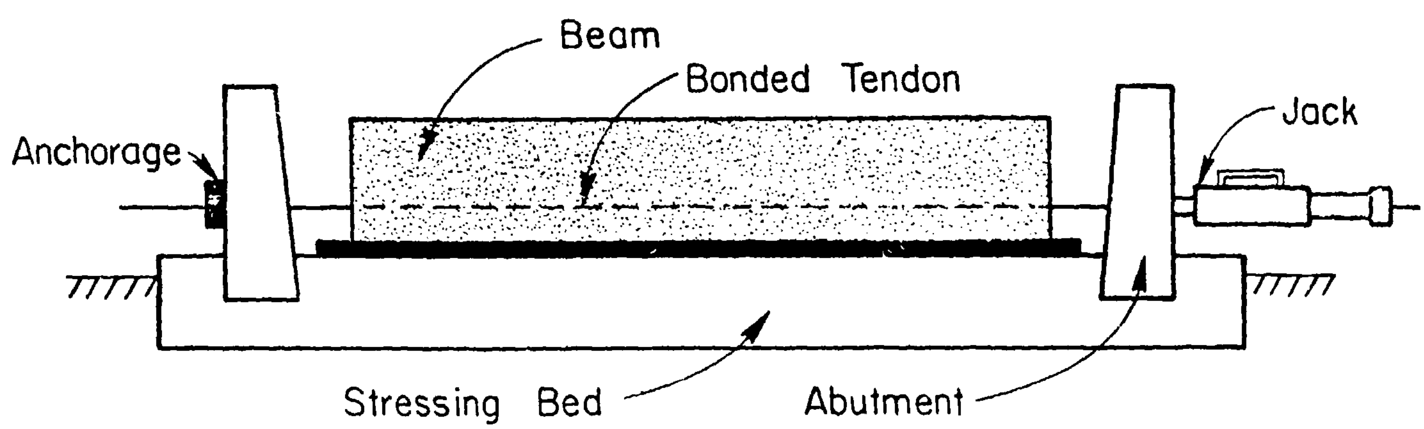


Fig. A3 - Load Versus Deflection Relationships for Plain and Reinforced Beams

Pre-Tensioning



Post-Tensioning

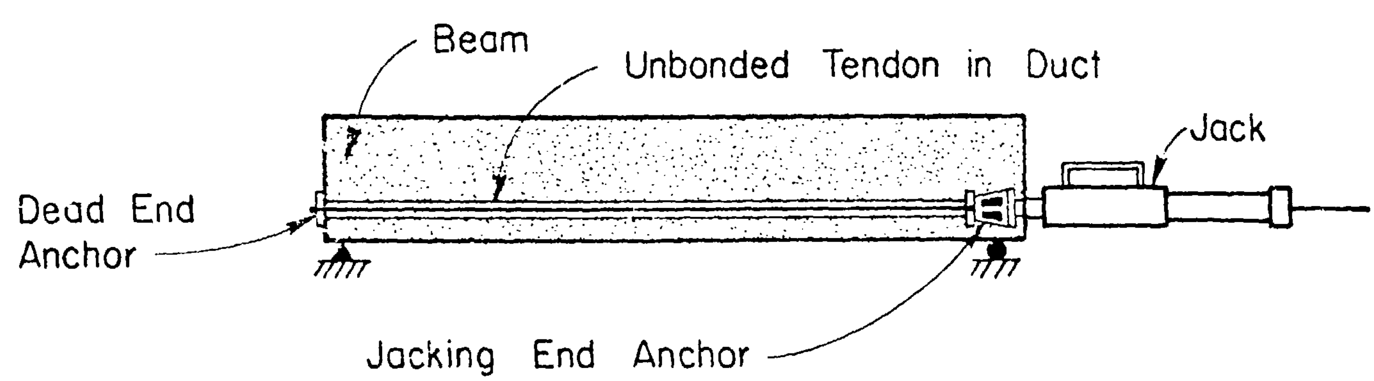


Fig. A4 - Types of Prestressing

achieves sufficient strength, tendons are released. This induces compression forces in the concrete.

Using post-tensioning, concrete members are cast with preformed voids or ducts. Tendons are inserted in the ducts and stressed against the hardened concrete. After stressing, the area between the tendon and the duct can be filled with grout to provide bond and corrosion protection.

APPENDIX B - ABBREVIATIONS

ABS = American Bureau of Shipping

ACI = American Concrete Institute

ASTM = American Society for Testing and Materials

AWS = American Welding Society

DNV = Det Norske Veritas

FIP = Federation Internationale de la Precontrainte

NRMCA = National Ready Mixed Concrete Association

PCA = Portland Cement Association

PTI = Post-Tensioning Institute

TMMB = Truck Mixer Manufacturers Bureau