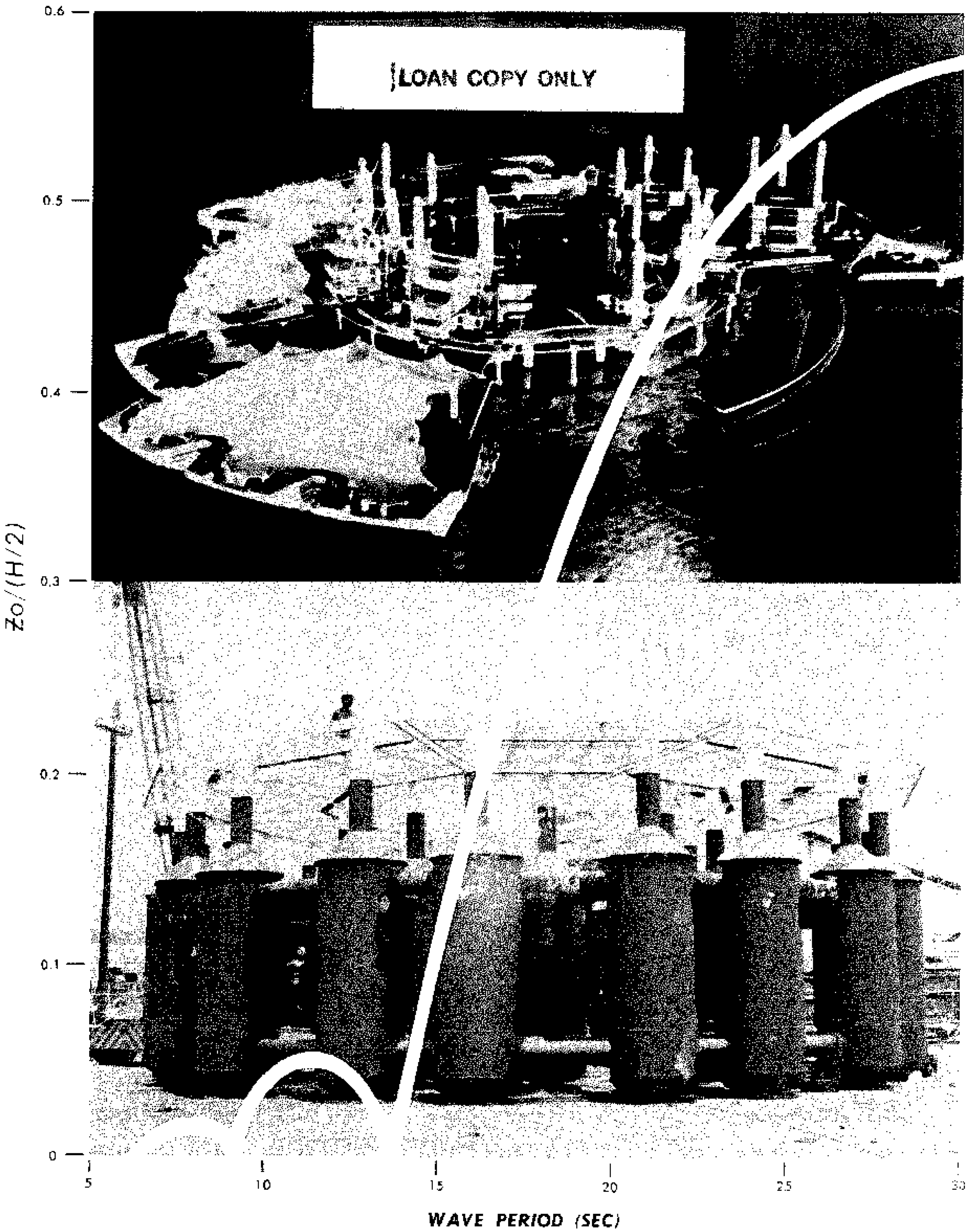
UNIHI-SEAGRANT-CR-74-02

HAWAII'S FLOATING CITY
DEVELOPMENT PROGRAM
CONCRETE FOR LARGE FLOATING STRUCTURES



HAWAII'S FLOATING CITY DEVELOPMENT PROGRAM

Technical Report No. 4

UNIHI-SEAGRANT-CR-74-02

Concrete for Large Floating Structures

by

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AN INTRODUCTORY NOTE

At the time this work was accomplished, Douglas Wilson was a graduate student in engineering at the University of Hawaii. In this effort, Doug was supervised by Guy N. Rothwell, Chief Engineer of the System Sciences Division of the Oceanic Foundation. Bonnie Rhodes and Diane Henderson of The Oceanic Foundation worked the original manuscript into form for publication.

The contribution of Cement & Concrete Products Industry of Hawaii (CCPI) is gratefully acknowledged; their resource materials and library facilities were used extensively. In particular, the assistance and guidance of Mr. Watson Clifford of HC&D, Inc. is appreciated.

The work presented here is a survey and compilation of information pertinent to the interests of Hawaii's Floating City Program. Therefore, no original research results will be found in this report. Rather, it is a distillation, analysis and organization of information gleaned from thousands of pages of classical engineering documents and recent resource reports. I believe anyone concerned with the employment of concrete as a marine structural material will find this document both interesting and valuable.

Joe A. Hanson
Program Manager

Abstract

This report is the result of an investigation of the suitability of reinforced concrete as a structural and hull material for use in large floating platforms. History, materials, methods, and quality control requirements are reviewed. The findings support the conclusion that high quality concrete is acceptable and economical for application to large floating platforms, and that both design and quality control requirements can be met within the present state of the concrete art.

TABLE OF CONTENTS

GLOSSARY

Admixture - a material added to a normal concrete or grout mix to modify or improve its properties.

Air entrainment - the introduction of minute air bubbles into concrete during mixing, produced by an air-entraining admixture (essentially foaming agents). Primary function is improved durability and resistance to disruptive action of alternate cycles of freezing and thawing.

C_3A, C_2S, C_4AF, etc. - abbreviations for different formulations of portland cement, indicating ratio of

C the calcium, CaO
S the silica, SiO_2
A the alumina, Al_2O_3
F the iron, Fe_2O_3

Cavitation - pitting of concrete caused by the collapse of vapor bubbles in flowing water.

Coarse aggregate - inert material, generally hard, durable rock which is at least 3/8 inch in diameter.

Concrete - a composite material of inert fragments embedded in a cementing matrix, generally a mixture of portland cement, sand, gravel and water.

Consistency - the degree of plasticity of fresh concrete or mortar. Slump is the normal measure of consistency for concrete; flow is the normal measure for mortar.

Creep - inelastic behavior of concrete under stress, occurring over periods of weeks or months.

Curing - maintaining temperature and humidity for a period following placing and finishing of concrete, to ensure proper hydration and hardening.

Entrainment - see Air entrainment

Fine aggregate - inert material, usually sand, which is less than 3/8 inch in diameter.

Ferro-cement - a reinforced mortar material, a combination of steel in the form of wire mesh--usually in multiple layers--and a rich portland cement. Ratio of steel to concrete is much higher than in ordinary reinforced concrete.

Grout - a fluid mixture of cement and water, or cement and sand and water.

Heat of hydration - the heat given off during the chemical combination of water with cement.

Hydration - the chemical reaction between water and portland cement to form a new compound.

Hydraulic cement - a cement capable of setting and hardening under water.

Impermeability - the property of high resistance to the flow of water through hardened concrete.

Lightweight concrete - concrete having a substantially lower unit weight than normal, made either by use of low density aggregates (pumice, perlite, scoria, etc.) or by purposeful inclusion of voids or cellular structure.

Mortar - a mixture of cement, sand and water.

Normal weight concrete - made with sand and gravel, or sand and crushed rock of a silicone or limestone constituency, having a unit weight of about 140 to 150 lb/ft^3.

Peeling - a process in which think flakes of matrix or mortar are broken from concrete surface.

Plastic mix - fresh concrete mix which is workable, cohesive, and without tendency to segregate.

Post-tensioning - a method of prestressing concrete after the concrete has been cast and hardened, usually by inserting steel tendons through holes or ducts left in the concrete, and then stretching and anchoring the tendons against the concrete.

Precast - concrete formed and cast and cured in one area, then transported to and erected in its final location.

Prestressed concrete - concrete in which stresses have been introduced before it is called upon to sustain loads, usually by embedding steel tendons to impart a compressive stress which will ofset an opposite tensile stress during use.

Pretensioning - a method of prestressing in which steel tendons are stretched between anchors, the concrete is cast and allowed to harden, and the tendons are released, imparting prestress to the concrete through bond.

Scaling - the breaking away of a hardened concrete surface, usually to a depth of 1/16 to 3/16 inches.

Segregation - the tendency for the coarse particles to separate from the finer particles in handling.

Set - a description of the stiffening of cement paste. *Initial set* refers to the first stiffening when the gel has first formed; *final set* refers to attainment of significant rigidity.

Slump - a measure of the workability and flowability of fresh concrete mixes, generally increased by increasing the water content. Measured by using a slump cone or Kelly ball.

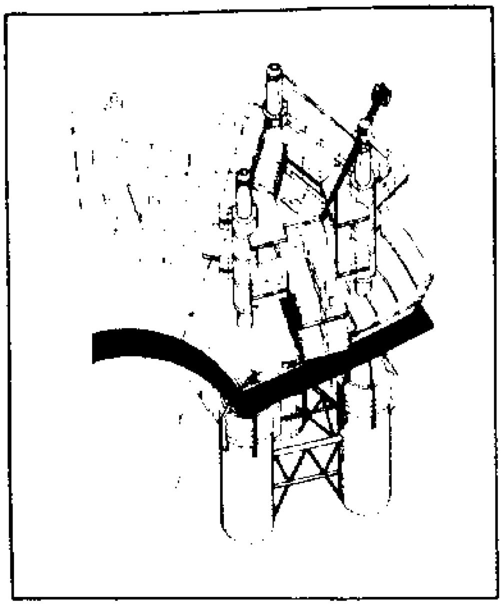
Spalling - detachment of flaky fragments from a concrete mass, caused by a blow, internal expansion or weathering action.

Tremie - a pipe through which concrete may be placed under water.

Workability - the quality of a concrete mix which allows mixing, placing and finishing without significant segregation.

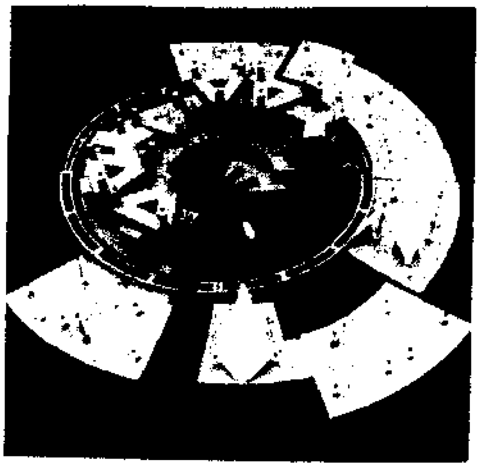
I. INTRODUCTION

Hawaii's Floating City Project had its formal inception in 1970, with the award of a grant by the State of Hawaii to the Department of Architecture, University of Hawaii, for a project to investigate the possibilities and opportunities that might lie in the construction of an urban center aboard a very large, deep-sea, floating platform. This work resulted in the conceptual design of a ring-shaped floating city with inner and outer rings consisting of up to thirty independently stable modules, all rigidly connected to form the final city, but separately removable for repair or renovation. The typical module would be supported from three or four vertically oriented, fully submerged buoyancy chambers, each topped by a structural column which would pass through the elevated main deck structure to form the core of a moderately high-rise superstructure building.



Typical module

The city was envisaged as housing a broad range of domestic, commercial, recreational, industrial and public activities, all served and supported by a complete suite of on-board public utilities, and linked with Honolulu and the world by a variety of transportation and communications services. In general, the industrial, utility and commercial services would utilize available space in the submerged buoyancy chambers. At the lowest levels would be found fuel and water storage, as well as sewage treatment facilities and variable ballast tanks. Above these would be power generation, air conditioning and desalination plants, as well as other machinery spaces. Also included would be warehousing and cold storage, maintenance and repair shops, and some commercial spaces, such as stores and offices. At the top of the buoyancy chambers, where windows on the sea could be provided, would be restaurants, apartments and places of public assembly.



Superstructure model

The main deck structure, located above the highest waves, would contain commercial and recreational facilities and transportation terminals. The weather surface of the main deck structure would be landscaped as a park. Finally, the superstructure would contain mainly living space, either apartments or hotel rooms.

Concrete was to be considered as the principal structural material. The city site was chosen as five miles south of Honolulu in the open ocean, where water depth is 600 meters.

In subsequent years, engineering studies of various aspects of this concept have been made, including environmental conditions of the site, hydrostatics and hydrodynamics of the city's form and feasibility of the modular approach. Studies for the current year include an examination of the requirements for internal environmental control, a structural design investigation, a review of applicable transportation methods, a survey of potential construction sites and methods, and the study contained in this report.

Specific objectives of this report are:

- To determine the suitability of concrete,
- To review the state-of-the-art of concrete use in structures floating on and exposed to the ocean environment,
- To identify the types and properties of concrete that make it a suitable construction material,
- To identify the critical properties related to concrete usage in the marine environment that may cause difficult construction, damage, or failure,
- To identify important factors affecting the above critical properties,
- To identify damage prevention and repair techniques in the ocean environment.

Contents of the Report

A brief history of marine concrete use is presented in Section II.

Section III contains a review and summary of concrete technology to date, with particular emphasis on the properties and types of concrete suitable for marine structures.

In Section IV, the effects of the ocean environment on concrete are examined, and critical parameters in the design and construction of large floating platforms are identified. Factors affecting the strength-to-weight ratio, permeability and durability of marine concrete structures are discussed.

In Section V methods are described for obtaining high quality concrete, and techniques are discussed for damage prevention, maintenance and repair in the ocean environment.

The summary and conclusions are presented in Section VI.

The state-of-the-art of the concrete industry in Hawaii is reviewed briefly in an appendix.

At the end of the report, following the list of references cited in text is an extensive bibliography. These references are listed alphabetically within specific areas of interest as follows:

General references on concrete
Mixing and curing water for concrete in the marine environment
Corrosion of concrete and reinforcement in the marine environment
Durability of concrete in the marine environment
Floating concrete structures
Special types of concrete
Permeability of concrete
Miscellaneous

II. BRIEF HISTORY OF MARINE CONCRETE USE

Concrete has been used successfully in the marine environment for hundreds of years, beginning with the first known use by the early Romans. An excellent history of marine concrete use has been compiled by J. J. Hromadik and others (1). Much of the following material has been drawn from that article.

A. Fixed Structures

The earliest known use of concrete in the marine environment was in the first century by the Romans who constructed concrete pillars for a wharf in the Bay of Pozzuoli. This concrete, made of natural pozzolana (volcanic ash), lime, water, and broken stone, was non-reinforced. Parts of the original structure were so resistant to sea water that it is still considered serviceable after 19 centuries of submergence.

The Roman mixture of lime and natural pozzolana was used until the 18th century, when it was improved in England by mixing the pozzolana with hydraulic lime which contained a considerable amount of clay.

The invention of portland cement is generally credited to Joseph Azpdin, an English mason. In 1824 he obtained a patent and named his product "portland cement" because it produced a concrete that resembled a natural limestone quarried in England on the Isle of Portland. The first portland cement made in the United States was produced at a plant in Coplay, Pennsylvania in 1872.

In the latter half of the 19th century, docks and wharves built of portland cement concrete were invariably non-reinforced. Most of these proved durable and are still in use.

The first maritime structure made of reinforced concrete in Great Britain was built in 1899 at Southampton. This structure, which was still in service and in excellent condition in 1955, was made with a "very dry" concrete (that is, concrete of a low water/cement ratio). Similar structures made with "rather wet" concrete (high water/cement ratio) tended to be weak and permeable and deteriorated after a few years of service.

Early in the 20th century, the use of precast concrete construction techniques became extensive. An example of marine precast concrete use is the San Mateo-Hayward Bridge spanning San Francisco Bay, which was built in 1928 and 1929. After 22 years of service, extensive repairs to the corroded reinforcement were required. The corrosion was caused by high porosity (due to a high water/cement ratio) and exposure to the marine environment rather than by the precasting technique.

The most recent marine concrete work of major magnitude began in 1966 when the first of 57 tube sections was fabricated for use in the San Francisco Bay Area Rapid Transit System.

B. Floating Structures

The first floating structures made of portland cement mortar, the forerunner of today's ferro-cement, were the 10-foot reinforced mortar rowboats built in 1848 by J. L. Lambot of France (2, 3). More than a century later, one of these boats was still afloat. Lambot's principles have been used by many boat builders. An early application is a small concrete scow which has been in continuous use at the Amsterdam Zoo since 1887.

As presently accepted, ferro-cement construction was developed by the Italian structural engineer, P. L. Nervi, who in 1943 began building a series of surface craft constructed of ferro-cement (4). In 1946, he built his largest vessel, the Irene, which displaced 165 tons. Her hull was nearly one and a half inches thick, and after eight years of sea service required no maintenance.

From 1914 to 1918 many ocean-going concrete barges were constructed in Great Britain. The Armistice, a 2500-ton concrete ship built in 1919, was 205 feet long and survived until 1969 when she was scuttled at sea because her hull was badly spalled (5).

The concrete vessels built in the United States and Europe during both world wars have been estimated to represent a total displacement of 500,000 tons (6). Although these concrete ships and barges were structurally sound, further development was apparently undesirable because conventionally reinforced concrete hulls are heavier than comparatively thin steel hulls.

The experience gained in building concrete hulls during World War II, however, led to improved methods of fabricating floating concrete platforms. Recently there have been many proposals for constructing large floating platforms--such as floating airport runways, floating tanker terminals, and strategic military bases such as the mobile ocean basing systems proposed by the Naval Civil Engineering Laboratory (1).

The most significant structure demonstrating the technical capabilities presently available for building large concrete offshore floating structures is the Ekofisk--a prestressed concrete oil storage and tanker-loading caisson built in 1971-1972 in Stavanger, Norway (7). While floating, it displaced 215,000 tons. It was towed into position in the North Sea and then ballasted with sea water until it rested on the sea bed in 70 meters of water. Once in position, the caisson was anchored by its own weight plus the weight of its contents with no additional anchorage.

Its one-million-barrel crude oil reservoir is a slip-formed nine-cell structure, somewhat similar to a grain silo, measuring 50 by 50 meters and rising 90 meters from the base. The complete unit is surrounded by a perforated breakwater wall (Jarlan patent) of mixed precast and poured construction. The breakwater wall is nearly circular, with a mean diameter 95 meters, and is joined to the reservoir structure by perforated slip-formed bracing walls which are effectively continuations of the tank's inner walls. The reservoir and perforated outer sea wall are carried on a cellular raft foundation.

Competitive designs of both steel and concrete alternatives were proposed for the Ekofisk. The prestressed post-tensioned concrete island structure was adopted on cost and operational grounds. All of the designs considered involved building the complete structure on the coast and towing it to the site. *In situ* construction was ruled out because of the distance from shore and the severe weather conditions of the North Sea.

Figure 1 shows Ekofisk enroute to its North Sea site.

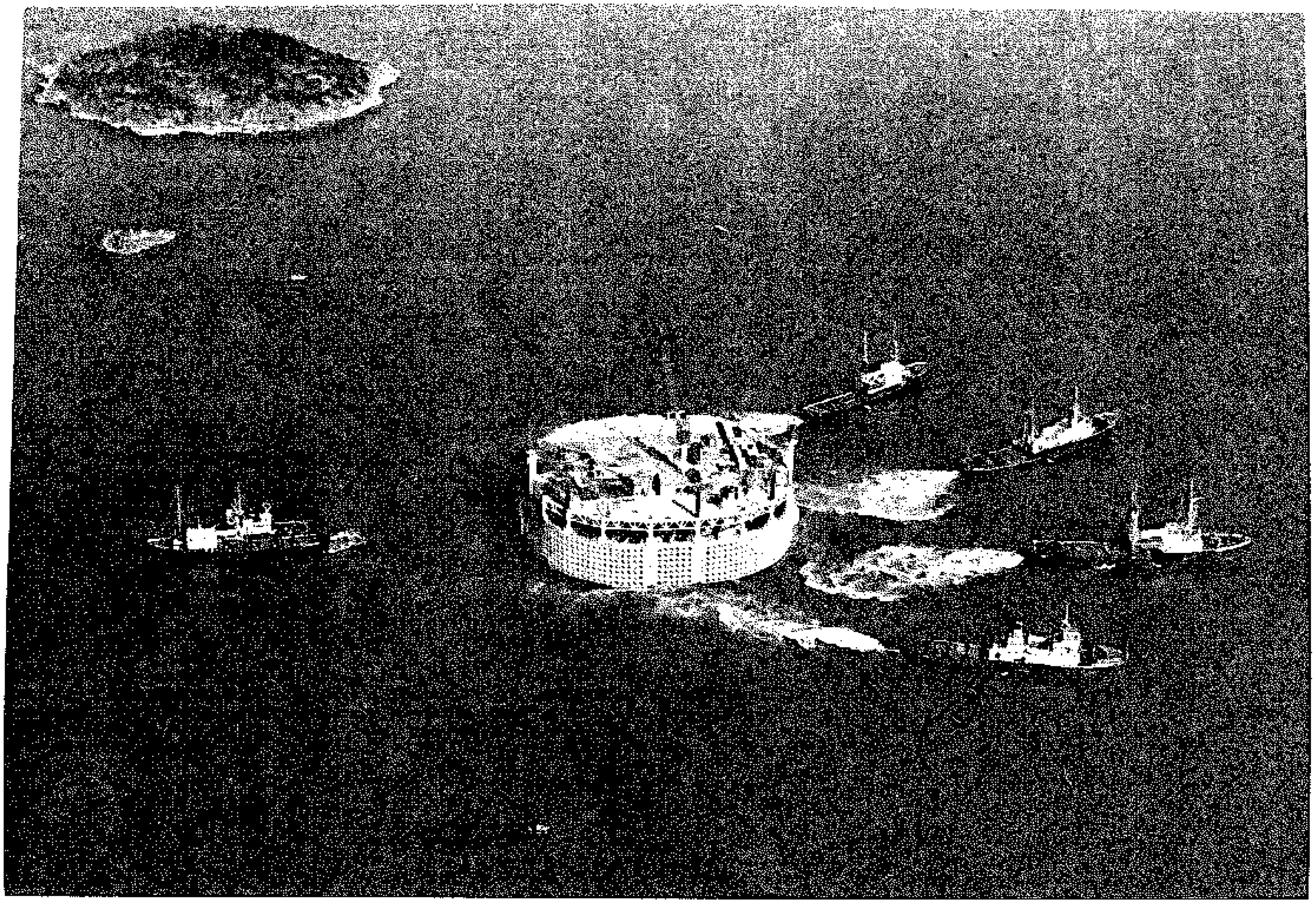


Figure 1 -- Ekofisk (Photograph by C.G. Doris Co.)

III. REVIEW OF CONCRETE TECHNOLOGY TO DATE

Gerwick, in an excellent review of the state-of-the art of marine concrete technology in 1969, states:

> "Concrete is extensively employed for the construction of structures and facilities in marine environments. Properly made and engineered concrete is strong, dense and durable. It can be produced readily and economically throughout the world to a great extent with local materials. It can be molded to almost any desired shape and imparted before use with desired stresses to resist designed loads. Under water, concrete will continue to gain in strength with time, and quality concrete can endure under marine service conditions for 50 years or more." (8)

Although concrete is an extremely complex substance whose properties vary tremendously over wide ranges, its behavior in the field is well understood. Vast amounts of test data have been accumulated by the portland cement manufacturing industry, the ready-mix concrete batching industry, and the construction industry.

Because of the quantity of technical literature available, this review is restricted to concrete use and concrete properties, with particular emphasis on the properties and types of concrete suitable for marine structures. Other aspects of concrete technology are touched upon briefly, and more information can be found by consulting the references at the end of the report.

In this section, the general properties of concrete are reviewed, followed by brief descriptions of storing and handling techniques, mixing methods, techniques for transporting, placement and consolidation of fresh concrete, and curing methods. Reinforced prestressed and precast concrete applications are considered next. Finally, special concrete types suitable for use in large floating platforms are described, and the significant properties of each are outlined. These special concrete types include structural lightweight, lightweight insulating, heavyweight, coral, polymer, ferro-cement, tremie, grout and hydraulic cements, and Wirand concrete.

A. General Properties of Concrete

Concrete is a composite material consisting of a water-cement paste, aggregates and admixtures. The proportions of each may vary considerably as shown in Figure 2, depending on the type of finished concrete desired. When properly mixed and cured, these components form a rock-like substance that is strong, dense, and durable. A cross section of hardened concrete is shown in Figure 3. Reinforcing materials, such as steel rods, bars, or meshwork, may be embedded in structural concrete to impart additional strength.

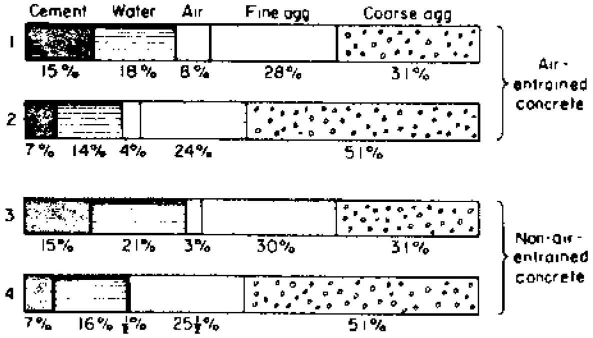


Figure 2 -- Range in proportions of materials used in concrete. Bars 1 and 3 represent rich mixes with small aggregates; 2 and 4 represent lean mixes with large aggregates. (Portland Cement Association, Illinois).

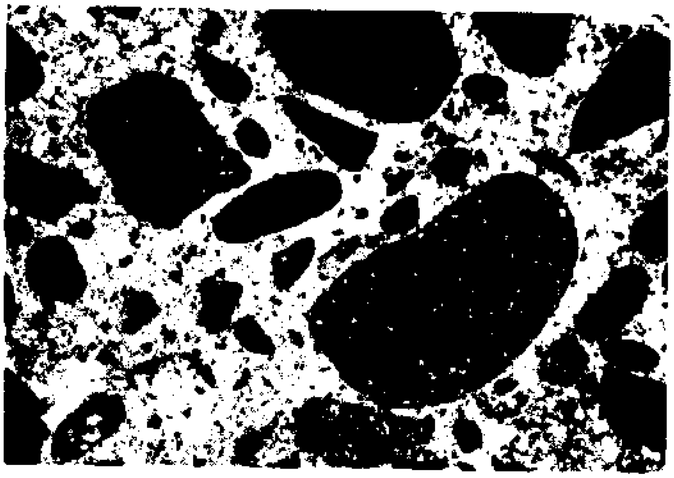


Figure 3 — Cross-section of concrete. Cement and water paste completely coats each aggregate particle and fills all of the space between particles. (Portland Cement Association)

For any practical purposes, there are four basic states through which any concrete mix passes sequentially: the premix state, the fresh concrete state, the hardened state, and the aged state.

The physical and chemical properties of finished concrete are directly related to the properties of the materials used in the premix state. By controlling the quality of these materials, and by adjusting the mix design, the final properties can be modified to suit a wide range of applications.

1. Properties of Raw Materials in the Premix State

The premix concrete state occurs before the components--portland cement, aggregate, water and admixtures--are mixed together. In this state, the physical and chemical characteristics of the components are individual and unaffected by other components.

a. Portland Cement

Specifications for the manufacture of five basic types of portland cement are provided by the American Society for Testing and Materials (ASTM C150) (10). Each type is used for a particular purpose.

Type I is a general purpose cement suitable for all uses where special properties are not required. It is used where concrete is not subject to adverse conditions such as excessive heat generated due to hydration, or sulfate attack from soil or water.

Type II cement is used where precaution against moderate sulfate attack is important, as in sea water exposure.

Type III cement provides high early strength and is used when forms are to be removed as soon as possible, or when structures must be put into service quickly.

Type IV cement is used where the rate and amount of heat generated due to hydration must be minimized.

Type V cement is used only in concrete exposed to severe sulfate action.

(Types IA, IIA, and IIIA are air-entraining portland cements and are otherwise the same as Types I, II and III, respectively.)

The differences in the chemical properties of these five cement types may be seen in Table 1, which lists ASTM's standard chemical requirements for portland cement (10). Table 2 lists the optional chemical requirements, which may be useful or necessary for specific applications.

Similarly, Tables 3 and 4 show ASTM's standard and optional physical requirements for the five types of cement. Further detailed information is contained in various industrial concrete handbooks (9, 11).

Table 1 - Standard chemical requirements

Cement type	I and IA	II and IIA	III and IIIA	IV	V
		(all values in percent)			
Silicon dioxide (SiO_2), min.	-	21.0	-	-	-
Aluminum oxide (Al_2O_3), max.	-	6.0	-	-	-
Ferric oxide (Fe_2O_3), max.	-	6.0	-	6.5	-
Magnesium oxide (MgO), max.	5.0	5.0	5.0	5.0	5.0
Sulfur trioxide (SO_3), max.					
when ($3\ CaO \cdot Al_2O_3$) is $\leq$ 8%	3.0	3.0	3.5	2.3	2.3
when ($3\ CaO \cdot Al_2O_3$) is $>$ 8%	3.5		4.5		
Loss on ignition, max.	3.0	3.0	3.0	2.5	3.0
Insoluble residue, max.	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate ($3\ CaO \cdot SiO_2$), max.	-	-	-	35	-
Dicalcium silicate ($2\ CaO \cdot SiO_2$), min.	-	-	-	40	-
Tricalcium aluminate ($3\ CaO \cdot Al_2O_3$), max.	-	8	15	7	5
Tetracalcium aluminoferrite plus twice the tricalcium aluminate ($4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 2\ (3\ CaO \cdot Al_2O_3)$), or solid solution ($4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 2\ CaO \cdot Fe_2O_3$), as applicable, max.	-	-	-	-	20.0

Table 2 - Optional chemical requirements

Cement Type	I and IA	II and IIA	III and IIIA	IV	V	Remarks
		(all values in percent)				
Tricalcium aluminate ($3\ CaO \cdot Al_2O_3$), max.	-	-	8	-	-	for moderate sulfate resistance
Tricalcium aluminate ($3\ CaO \cdot Al_2O_3$), max.	-	-	5	-	-	for high sulfate resistance
Sum of tricalcium silicate and tricalcium aluminate, max.	-	58	-	-	-	for moderate heat of hydration
Alkalies ($Na_2O + 0.658\ K_2O$), max.	0.60	0.60	0.60	0.60	0.60	low-alkali cement

Table 3 - Standard physical requirements

Cement Type	I	IA	II	IIA	III	IIIA	IV	V
Air content of mortar, volume %								
max	12.0	22	12.0	22	12.0	22	12.0	12.0
min		16		16		16		
Fineness, specific surface, cm^2/g (alternative methods):								
Turbidimeter test, min.	1600	1600	1600	1600	-	-	1600	1600
Air permeability test, min.	2800	2800	2800	2800	-	-	2800	2800
Soundness:								
Autoclave expansion, max. %	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strength, not less than the values shown for the ages indicated below:								
Compressive strength, psi (MPa)								
1 day	-	-	-	-	1700 (11.7)	1300 (9.0)	-	-
3 days	1200 (8.3)	900 (6.2)	1000 (6.9)	750 (5.2)	3000 (20.7)	2500 (17.2)	-	-
7 days	2100 (14.8)	1500 (10.3)	1800 (12.4)	1400 (9.7)	-	-	800 (5.5)	1500 (10.3)
28 days	-	-	-	-	-	-	2000 (13.8)	3000 (20.7)
Time of setting (alternative methods):								
Gillmore test:								
Initial set, min, not less than	60	60	60	60	60	60	60	60
Final set, h, not more than	10	10	10	10	10	10	10	10
Vicat test:								
Initial set, min, not less than	45	45	45	45	45	45	45	45
Final set, h, not more than	8	8	8	8	8	8	8	8

Table 4 - Optional physical requirements

Cement type	I	IA	II	IIA	III	IIA	IV	V
False set, final penetration, min. %	50	50	50	50	50	50	50	50
Heat of hydration:								
7 days, max, cal/g	-	-	70	70	-	-	60	-
28 days, max, cal/g	-	-	80	80	-	-	70	-
Strength, not less than the values shown:								
Compressive strength, psi (M Pa)								
7 days	-	-	-	-	-	-	-	-
28 days	3500 (246)	2800 (197)	3500 (24.1)	2800 (19.3)	-	-	-	-
Sulfate expansion, 14 days, max. %	-	-	-	-	-	-	-	0.045

Other special types of cement which are currently available but which have limited application in marine concrete use include air-entraining portland cements, white portland cement, portland blast-furnace slag cement, portland-pozzolan cement, masonry cement, oil well cement, water-proofed portland cement, plastic cement, and natural cement.

b. Aggregates for Concrete

Aggregates consist of clean, hard, strong, and durable particles free of chemicals, coatings of clay or other fine materials that may affect hydration and the bonding of the cement paste. Coarse aggregate is usually 3/8 inch or more in diameter, while fine aggregate (usually sand) is less than 3/8 inch in diameter. Details of the standard specifications for concrete aggregate can be found in ASTM C33-71 and C330 (10).

Table 5 summarizes the important characteristics, tests, and specifications for aggregates. The bulk unit weight and specific gravity of the aggregates are used in calculating the mix design. Particle shape and surface texture affect the workability of fresh concrete. Chemical stability, surface moisture and resistance to abrasion affect the strength and quality of finished concrete.

Table 5 - Characteristics of aggregates

Characteristic	Significance or importance	Test or practice, ASTU and CSA designation	Specification requirement
Resistance to abrasion	Index of aggregate quality. Warehouse floors, loading platforms, pavements.	C131	Max. percent loss
Resistance to freezing and thawing	Structures subjected to weathering.	C290, C291	Max no. of cycles
Chemical stability	Strength and durability of all types of structures	C227 (mortar bar) C289 (chemical) C586 (aggregate prism) C295 (petrographic)	Max. expansion of mortar bar Aggregates must not be reactive with cement alkalies
Particle shape and surface texture	Workability of fresh concrete.		Max. percent flat and elongated pieces.
Grading	Workability of fresh concrete. Economy.	C136 A23.2.2	Max. and min. percent passing standard sieves
Bulk unit weight	Mix design calculations.	C29 A23.2.10	Max. or min. unit weight (special concretes)
Specific gravity	Mix design calculations.	C127 (coarse aggregate) C128 (fine aggregate) A23.2.6 (fine aggregate)	
Absorption and surface moisture	Control of concrete quality.	C70, C127, C128 A23.2.6, A23.2.11	

Examples of aggregates most commonly used in the production of normal weight concrete (135 to 160 pounds per cubic foot) are sand, gravel, crushed stone, and air-cooled blast furnace slag. Expanded shale, clay, slate, and slag are used in structural lightweight concrete (85 to 115 pounds per cubic foot). Other lightweight materials such as pumice, scoria, perlite, vermiculite, and diatomite are used to produce insulating concrete (about 15 to 90 pounds per cubic foot).

Heavyweight materials such as barites, limonite, magnetite, ilmenite and iron and steel particles are used for producing heavyweight concrete (180 to 380 pounds per cubic foot).

c. Mix Water

Fresh water is used for most concrete mixes. Any natural water that is drinkable and has no pronounced taste or odor is satisfactory. Salt, brackish or contaminated water may be used under special circumstances but in general will have an adverse effect. Pure sea water may be used in the preparation of unreinforced concrete provided that an aluminous cement (Type I) is not used. Type V would be suitable, however (12).

Pure sea water is not used as a mixing water in the preparation of reinforced concrete because of the danger of corrosion of the reinforcement, particularly in the tropics (13,14).

d. Admixtures

Admixtures include all materials other than portland cement, water aggregates and reinforcing which are added to concrete, mortar, or grout immediately before or during mixing to modify or improve certain properties in the mix. Admixtures are usually organic chemicals and they can be broadly classified as follows: 1) air-entraining admixtures, 2) water-reducing admixtures, 3) set-retarding admixtures, 4) set-accelerating admixtures, 5) pozzolans (volcanic ash), 6) workability agents, and 7) miscellaneous (dampproofing and permeability-reducing agents, grouting agents, and gas-forming agents).

In many instances special properties are required, such as extended time of set, acceleration of early strength, control of alkali reactivity with certain aggregates, or the reduction of heat of hydration. These properties may be obtained using either an appropriate admixutre or an appropriate type of portland cement. A comparison of the standard requirements for each, as specified by ASTM, should reveal the best method.

e. Reinforcing

The reinforcing materials used in concrete range from bamboo to titanium, but steel is most commonly used. The American Society for Testing and Materials has established standards that designate the form and strength characteristics of reinforcing steel used in the U.S. (10).

The principal forms of reinforcing are plain bars, deformed bars, welded wire fabric, deformed welded wire fabric, and prestressing wire. Other less common forms are expanded metal mesh, structural steel and steel pipe.

2. Properties of Fresh Concrete

Freshly mixed concrete remains plastic only a short time after water has been added, but its properties are important because they affect the quality and cost of the last two states. These properties are unit weight, workability, finishability, slump, and entrained air.

With a given amount of water and cement paste, an increase in the amount of aggregate will cause stiff mixes. Consequently, stiff mixes are more economical in use of materials. However, stiff mixes may require more labor in placing, and this additional cost may offset any savings in materials.

In general, thin members and heavily reinforced members require more plastic mixtures (in order to flow around the reinforcing) than large members containing little reinforcement. Concrete of the correct plastic consistency does not crumble, but flows sluggishly without segregation (separation of fine from coarse aggregates). Mixtures of such consistency are suitable for most concrete work.

The ease or difficulty of placing and consolidating concrete is called workability. Good quality concrete is workable but does not segregate, nor does it bleed excessively (bleeding is the movement of water to the surface of freshly cast concrete). Since excessive bleeding may increase the water/cement ratio at the surface, a weak layer of poor durability may result, particularly if finishing operations take place while this excess water is present. Slump is a measure of stiffness, which is indicative of workability. Entrained air is air trapped in concrete, in microscopic bubbles--up to several percent by volume--and improves workability and freeze-thaw durability.

Generally the most economical mix is one that has the highest proportion of aggregate to cement and yet is workable at the water/cement ratio required for strength, durability and other properties.

3. Properties of Hardened Concrete

The design properties of concrete are those of hardened concrete cured 28 days. These are compressive strength, tensile strength, flexural strength, modulus of elasticity, modulus of rupture, flexural modulus of elasticity, water absorption, abrasion resistance, cavitation resistance, water permeability, thermal conductivity, diffusivity, coefficient of expansion, creep, freeze-thaw durability, impact hardness, resistance to sulfate attack, acid corrosion, drying shrinkage, bond to reinforcing, unit weight, water-cement ratio, and cement factor.

As a guide to the wide range of concrete properties that may be suitable or desirable in the design and construction of large platforms, see Table 6. This table reflects the concrete commercially available, although special mixes may also be ordered. All of the above properties have standard tests (10).

4. Properties of Aged Concrete

After many years of exposure, say fifty years, the properties of hardened concrete will have changed somewhat and may either be improved or deteriorated depending upon the environment to which it was subjected.

B. Storing and Handling Techniques

1. Portland Cement

Most portland cements are shipped by truck or barge, either in bulk or in paper bags. The U.S. bag of portland cement weighs 94 pounds; a barrel weights 376 pounds.

Bulk cement is usually stored in weatherproof bins and can be stored for a relatively long time without deterioration. Portland cement that is kept dry retains its quality indefinitely. Stored in contact with moisture, portland cement sets more slowly (because it is already partially hydrated), and the final product has less strength than dry cement.

Cement stored for long periods may develop what is called "warehouse pack," which can usually be corrected by rolling the bags on the floor to break up the lumps. If this is not accomplished easily, the cement should be tested for strength before use.

2. Aggregates

Aggregates are handled by trucks, bucket loaders, clamshells or conveyors. Care must be taken in storage and handling to minimize segregation and prevent contamination with deleterious substances. Stockpiles built up in layers of uniform thickness rather than in cone-shaped piles tend to minimize segregation. Keeping storage bins as full as possible also reduces segregation and breakage of aggregate particles. To avoid segregation of coarse aggregates, stockpiling and batching is done separately for each size-fraction (1-1/2 to 2-1/3 inches, 3/4 to 1-1/2 inches, No. 4 to 3/4 inch, etc.).

Table 6 - Range of concrete properties

Design criteria	Regular weight concrete, basalt aggregate *	Regular weight concrete, limestone aggregate **	Lightweight concrete, volcanic cinder aggregate, 'Hydrolite' *	Lightweight concrete, volcanic cinder aggregate, 'Waimea Cinder' **
Maximum compressive strength (f'c max. @ 28 days moist cure), psi	7200	6000	6000	5000
Maximum compressive strength at stress transfer for prestressed concrete (fci' @ 15 hours steam cure), psi	4500	4300	4000	3500
Split tensile ratio, Fsp (fct / $\sqrt{f'c}$)	6.7	7.5	6.7	6.3
Slump range	1 - 6"	1 - 6"	2 - 5"	1 - 3-1/2 "
Fresh unit weight (pcf)	149	137 - 145	132	125
Dry unit weight (pcf) (28 days)	147	135 - 143	123	120
Modulus of elasticity, E (@ f'c = 4000 psi), psi	3.6×10^6	4.0×10^6	3.0×10^6	2.9×10^6
Shrinkage at 28 days	.015%	.062%	.030%	.058%
Maximum flexural strength (@ 28 days moist cure), psi	750	no data	650	no data

* Clifford , Watson, S. Manager, Product Engineering Dept., HC&D, Ltd., Honolulu, personal communication

** Sekiya, Frederick K., Technical Service Director, Pacific Concrete & Rock Co., Ltd., Honolulu, personal communication

C. Mixing Techniques and Equipment

The state-of-the-art of mixing techniques and equipment is advanced enough to be directly applicable to the construction of large concrete floating platforms. Since quality concrete is essential in a floating platform, the following is a review of the mixing techniques and equipment used to obtain it.

1. Measuring Materials

In order to maintain uniform quality concrete, the ingredients are measured accurately for each batch. Most specifications require that batching be done by weight rather than by volume because of the inaccuracies in measuring solid materials (especially damp sand) by volume. Use of the "weight system" for batching provides greater accuracy, simplicity, and flexibility. Flexibility is necessary because changes in aggregate moisture content require frequent adjustments in batch quantities of water and aggregates. Water can be measured accurately by either volume or weight.

2. Mixing Concrete Specifications

All concrete is mixed thoroughly until it is uniform in appearance, with all ingredients evenly distributed. Increased output is obtained by used of a large mixer or additional mixers rather than by speeding up or overloading the equipment on hand.

If the 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. Maximum allowable differences in test results within a batch are given in ASTM specifications (10).

3. Stationary Mixing of Concrete

Concrete is mixed in a stationary mixer either on the job site or in a ready-mix plant. Mixers are available in sizes from 2 cubic feet to 12 cubic yards and may be of the tilting or nontilting type or of the open-top revolving blade or paddle type. Some are equipped with a swing discharge chute, and all can be equipped with loading skips. Many have timing devices which can be set for a given mixing time and locked so that the batch cannot be discharged until the designated time has elapsed.

Specifications usually require a minimum of one minute mixing for stationary mixers of up to one cubic yard capacity, with an increase of

15 seconds for each additional cubic yard of capacity or fraction thereof (9). The mixing period is measured from the time all solid materials are in the mixer drum, provided that all of the water is added before one-fourth of the mixing time has elapsed.

Where the mixer is charged directly from batchers, the materials are added simultaneously at such rates that the charging time is about the same. If a retarding admixture is used, it is always added at the same time in the charging cycle to prevent significant variations in the time of initial set and percentage of entrained air.

4. Ready-Mixed Concrete

Ready-mixed concrete is manufactured by one of three methods:

- Central-mixed concrete is mixed completely in a stationary mixer and delivered in a truck agitator, a truck mixer operating at agitating speed, or a special nonagitating truck.
- Shrink-mixed concrete is mixed partially in a stationary mixer, and the mixing is completed in a truck mixer.
- Truck-mixed concrete is mixed completely in a truck mixer.

For detailed specifications for ready-mixed concrete, see ASTM C94 (10).

D. Transporting, Placement and Consolidation of Fresh Concrete

1. Transporting and Placement

Method of transporting and placing fresh concrete include the use of chutes, buckets handled by cranes or cableways, trucks, pumping through pipelines or tremie, and pneumatically forcing the concrete or dry concrete materials through hoses.

Chutes. Metal or metal-lined chutes, round-bottomed and large enough to guard against overflow, are usually provided with a downpipe at the end of the chute to allow the concrete to drop vertically. The greatest objection to the use of chutes is that segregation occurs at discharge. However, with a long enough downpipe or, preferably, two sections of drop chute, segregation is eliminated or greatly reduced.

Buckets. Buckets vary in shape and size up to a capacity of eight cubic yards. Most are circular, but some large buckets used in massive work have rectangular cross sections. Buckets are handled and transported by cranes, derricks, cableways, trucks, or by a combination of these. The concrete is released by opening a gate that forms the bottom of the bucket. For massive work the buckets often have straight sides with gates that open to the full area of the bottom. For most types of work, buckets with the lower sides sloping to a smaller gate are usually preferred. For small jobs, buckets with gates that can be regulated to control the flow of concrete and closed after only part of the concrete has been deposited are preferred.

Gates may be operated manually or by mechanical or pneumatic means. For buckets handled by cableways, mechanically or pneumatically operated gates are safest, since discharge can be effected without sudden jerks on the cableway.

Belt Conveyors. The use of belt conveyors requires precautions to prevent segregation, objectionable loss of slump, and loss of mortar on the return belt. Segregation, which occurs chiefly at transfer points and at the ends of conveyors, is prevented by the use of suitable hoppers and drop chutes. Slump loss caused by evaporation or temperature rise is minimized by protecting the conveyor from the sun and wind.

Trucks. The most common method of transporting concrete is in truck mixers or agitator trucks. Transportation of ready-mixed concrete in such trucks is controlled by ASTM C94 standards (10). Truck mixers used as agitators may be loaded to the agitator capacity indicated by the manufacturer (about 30 to 35 percent more than when operated as truck mixers). Non-agitating trucks are sometimes used to transport concrete. The ordinary flat-bottom truck body with wide tailgate is not suitable except for very short distances. Truck bodies of special shape, with large fillets between sides and bottom, rounded and sloping front, and rear end tapered to a discharge gate, are much more satisfactory.

Pumps. Concrete may be pumped through a steel pipeline, particularly in tunnels and other locations where space is limited. The equipment includes a horizontal piston-type pump of rugged construction, with an inside diameter of 4 or 5 inches and a wall thickness usually of 3/16 inch. Fresh concrete can be pumped through 600 to 1,000 feet of straight horizontal pipe, depending on the size of the pump and pipe. The maximum pumping distance can be greatly extended through use of additional pumps or relays (as far as 1,600 feet), but it is reduced considerably by curves, lifts, and harsh concrete. For example, a 90-degree curve is equivalent to about 40 feet of horizontal pipe, and vertical distances are estimated on the basis of one foot vertically equivalent to 8 feet horizontally.

Rate capacities range from 15 to 100 cubic yards per hour. The maximum size of aggregate particles is 3 inches for the largest equipment. Concrete with a slump of only 1/2 inch has been pumped successfully, but best restuls are obtained with a slump of 3 inches or more and when air-entrained concrete is used. A constant supply of uniform, workable concrete, which is not likely to segregate, is necessary for successful operation of the pump. The hopper feeding the pump is often supplied with an agitator to remix the concrete and maintain uniformity.

Pneumatic Application of Concrete. Pneumatically applied mortar or concrete, sometimes called shotcrete, is an intimate mixture of portland cement, aggregate, and water shot into place by means of compressed air. With certain types of equipment, aggregate graded up to 3/4 inch can be used. The two basic processes for applying mortar or concrete pneumatically are the dry mix and the wet mix.

In the dry mix process, the cement and aggregates are mixed in a relatively dry state and conveyed through a hose to a nozzle where water is added. The dry materials are forced through the hose by at least 45 psi air pressure, with a nozzle velocity of about 400 feet per second. The minimum water pressure at the nozzle is usually 15 psi higher than the air pressure at the entrance to the material hose. In the wet mix process, the mortar or concrete is premixed before pneumatic application.

With this type of application, the unit water content can be kept to a minimum, resulting in high-strength durable concrete. In the dry mix process, the nozzleman controls the amount of water. In both processes he directs the nozzle, thereby controlling the thickness of the mortar layer and the angle of application.

Pneumatically applied mortars and concretes are used both for repair work and for new construction. The method is especially useful for conveying concrete into difficult locations, or where relatively thin sections and large areas are involved.

Placing Concrete under Water. Concrete is placed in air rather than under water whenever possible, because the quality of concrete placed under water is difficult to control. When concrete must be placed under water, the most common method is with a tremie. The tremie process consists of placing the concrete under pressure through a tube whose lower end is kept embedded in fresh concrete. In this manner, washing and segregation are substantially prevented. Pumps, pump buckets, or special bottom-dump buckets may also be used. In some cases, forms are filled with coarse aggregate and the water is displaced by pumping in cement grout through previously placed pipes.

2. Deposition Techniques

Concrete is placed as nearly as possible in its final position, because if it is moved horizontally over too long a distance within the forms, segregation will occur. In general, it is placed in horizontal layers of uniform thickness, each layer being thoroughly consolidated before the next is placed. Layers range from 6 to 20 inches thick for reinforced members, and 15 to 20 inches thick for mass work, the thickness depending upon the width between forms and the amount of reinforcement.

Drop chutes prevent incrustation of dried mortar on reinforcement and forms. If placement is completed before mortar dries, drop chutes are not needed. The height of free fall of concrete need not be limited unless separation of coarse particles occurs, in which case a limit of 3 to 4 feet may be adequate.

When concrete is placed in tall forms at a fairly rapid rate, bleeding of water to the top surface may occur, especially with non-air-entrained concrete. Bleeding can be reduced by placing more slowly and by using stiffer concrete. When practicable, the concrete is placed to a level about a foot below the top in high walls and an hour or so allowed for settling. Placing is resumed before setting occurs to avoid formation of cold joints. It is good practice to overfill the form by an inch or so and to cut off the excess concrete after it has partly stiffened. Another means of controlling the accumulation of bleed water is by increasing the amount of coarse aggregate in the mixture as the placement approaches the top of the lift.

To avoid cracking due to shrinkage, concrete in columns and walls is allowed to stand for at least two hours, and preferably overnight, before the concrete is placed in slabs, beams, or girders framing into them.

Preplaced aggregate concrete is a type of concrete made by placing coarse aggregate into the forms and pumping grout into the void spaces. The grout is a slurry of portland cement, sand, and water. Properties of the resulting concrete are similar to those of comparable concrete placed by conventional methods. Shrinkage, however, may be considerably less because of the point-to-point contact of the aggregate particles. This method has been used principally for restoration work and in the construction of tunnel linings, reactor shields, bridge piers, and underwater structures. It may also be used to produce unusual architectural effects.

3. Consolidation of Concrete

Vibration is the most commonly used method for consolidating concrete. Proper use of vibrators makes possible placement of a stiffer and harsher mix than that required for hand placing. In many cases the slump can be less than half that required for hand placing, and in most cases it can be reduced at least one third. The proportion of fine aggregate can be reduced significantly also (for example, from 40 to 35 percent).

Immersion-type vibrators are commonly used to consolidate concrete in walls, columns, beams, and slabs. Immersion spud vibrators are available with diameters of less than 1 inch to about 7 inches and frequencies of 3,600 to 13,000 rpm.

Vibrators consolidate concrete by pushing the coarser aggregate down and away from the point of vibration. This action induces the accumulation of cement paste around the vibrator, usually within 5 to 15 seconds. When the paste first appears near the top of the vibrator head, the vibrator is withdrawn vertically at about the same rate that it descended. It is then reimmersed at intervals so that zones of influence overlap.

Proper use of vibrators is essential; for example, segregation will occur if vibrators are used to move concrete horizontally, or if they are used in mixes that can be consolidated readily by hand tools.

Revibration or delayed vibration or previously compacted concrete may be done intentionally or it may occur when the underlying layer has partially hardened. This practice has been used to improve bond between concrete and reinforcing steel. In general, if toncrete becomes plastic under this action, revibration is not harmful and may be beneficial.

Form vibrators may be attached to the exterior of forms. They are especially useful for consolidating concrete in thin-walled members and where metal forms are used.

Screeds are bars used to strike off a level surface on freshly poured concrete. Vibrating screeds are used to consolidate concrete in flatwork. Some are effective to a concrete depth of about 12 inches. Additional consolidation of concrete along bulkheads is often achieved with internal vibrators.

Other methods for consolidating concrete include the use of spades or puddling sticks and various types of tampers. Hand methods generally require more fluid mixes. Spades or puddling sticks must be long enough to reach the bottom of the form and thin enough to pass between the reinforcing steel and forms.

E. Curing of Concrete

Properties of concrete such as resistance to freezing and thawing, strength, watertightness, wear resistacne, and volume stability improve with age as long as conditions are favorable for continued hydration of the cement. The improvement is rapid at early ages and continues more slowly for an indefinite period. Two conditions for such improvement in quality are required: 1) the presence of moisture, and 2) a favorable temperature.

Excessive evaporation of water from newly placed concrete can significantly retard the cement hydration process at an early age. Loss of water also causes concrete to shrink, thus creating tensile stresses at the drying surface. If these stresses develop before the concrete has attained adequate strength, surface cracking may result. All exposed surfaces, including exposed edges and joints, must be protected against moisture evaporation.

Hydration proceeds at a much slower rate when the concrete temperature is low; from a practical standpoint there is little chemical action between cement and water when the concrete temperature is near or below freezing. Too high a temperature, on the other hand, causes excessive water evaporation so that curing is incomplete. Therefore, for good curing, concrete should be moist during the hardening period and kept at a favorable temperature for hydration, usually between 73° and 150° F.

1. Curing Methods

Concrete can be cured by a number of methods, which may be classified as follows:

- Methods that supply additional moisture to the surface of the concrete during the early hardening period. These include ponding, sprinkling, and using wet coverings. Such methods afford some cooling through evaporation, which is beneficial in hot weather.
- Methods that prevent loss of moisture from the concrete by sealing the surface. This may be done by means of waterproof paper, plastic sheets, liquid membrane-forming compounds, and forms left in place.
- Methods that accelerate strength gain by supplying heat and moisture to the concrete. This is usually accomplished with steam or heating coils.

Each of these methods is described briefly below, and the relative merits of each are discussed.

Pondings or Submergence. Loss of moisture from concrete is prevented by submergence. It also is effective for maintaining a uniform favorable curing temperature. It is not recommended that the concrete be submerged until it has hardened, since segregation and leaching out of cement may occur.

Sprinkling. Continuous sprinkling with water is an excellent method of curing. A fine spray of water applied continuously through a system of nozzles or a soil-soaker hose provides a constant supply of moisture. This prevents the possibility of "crazing" or cracking caused by alternate cycles of wetting and drying. A disadvantage of sprinkling may be its cost. The method requires an adequate supply of water and careful supervision.

Wet Covering. Burlap, cotton mats, and other moisture-retaining fabrics are extensively used for curing. Treated burlaps that reflect light and are resistant to rot and fire are available.

Wet coverings of earth or sand are effective for curing, but in recent years have been largely discontinued due to their high cost. However, the method is often useful on small jobs. Moist hay or straw can be used to cure flat surfaces. This method has been largely outmoded by labor-saving curing procedures. A disadvantage of moist earth, sand, hay or straw coverings is the possibility of discoloration of the concrete. Detailed specifications for wet coverings are fiven in ASTM C171 (10) and American Association of State Highway Officials M182 and M73 (15).

Waterproof Paper. Waterproof curing paper is an efficient means of curing horizontal surfaces and structural concrete of relatively simple shapes. One important advantage of this method is that periodic additions of water are not required. Curing paper assures suitable hydration of cement by preventing loss of moisture from the concrete. It is applied as soon as the concrete has hardened and after it has been thoroughly wetted. Specifications are given in ASTM C171 (10).

Curing paper provides some protection to the concrete against damage from subsequent construction activity as well as protection from the sun. It requires periodic inspection for rips and holes which would permit loss of moisture and thus reduce its effectiveness. During hot weather, paper with a white upper surface can be used.

Plastic Sheets. Certain plastic sheet materials are used to cure concrete. They are lightweight, effective moisture barriers and are easily applied to various shapes. Specifications are given in ASTM C171 (10).

Curing Compounds. Liquid membrane-forming curing compounds retard or prevent evaporation of moisture from the concrete. They are suitable not only for curing fresh concrete but also for further curing concrete after removal of forms or after initial moist curing. They are applied by hand-operated or power-driven spray equipment immediately after the disappearance of the water sheen and the final finishing of the concrete.

Curing compounds are of four general types: clear or translucent, white pigmented, light grey pigmented, and black. Clear or translucent compounds may contain a fugitive dye which fades out soon after application, thus helping to assure a complete coverage of the exposed concrete surface. During hot, sunny days, white pigmented compounds are most effective, since they reflect the sun's rays, thereby reducing the concrete temperature.

Sprayed on membrane-forming curing compounds seal the concrete so that water is retained in the slab for cement hydration. They also can prevent bond between hardened and fresh concrete and so are not used if bond is necessary. Similarly, some curing compounds affect the adhesion of paint or resilient materials to the concrete. Manufacturers of these products should be consulted regarding specific effects of their products. Specifications are given in ASTM C309 and C156 (10).

Forms Left in Place. Forms can provide satisfactory protection against lostt of moisture, as long as the top exposed concrete surfaces are kept wet. However, if wood forms are not kept moist by sprinkling, especially during hot, dry weather, they should be removed as soon as practicable and another method of curing started (9).

Steam Curing. When early strength gain in concrete is important, steam curing can be used to advantage. Two methods for early strength gain are used: curing in live steam at atmospheric pressure (for enclosed cast-in-place structures and manufactured precast concrete units), and curing in high-pressure steam autoclaves (for small manufactured units).

A steam curing cycle consists of 1) an initial delay prior to steaming; 2) a period for increasing temperature; 3) a period for holding the maximum temperature constant; and 4) a period for decreasing temperature. The total cycle usually takes 18 to 24 hours.

Steam curing at atmospheric pressure is generally done in a steam chamber or other enclosure to minimize moisture and heat losses. Tarpaulins are frequently used to form the enclosure. Application of steam is delayed at least two hours after final placement to allow for some hardening of the most recently placed concrete. A delay period of 4 to 5 hours prior to steaming will achieve maximum early strength at 18 hours after placement (9).

Strength will not increase significantly if the maximum steam temperature is raised from 150° to 175° F. Temperatures above 180° F at atmospheric pressure are uneconomical and may result in undue reduction in ultimate strength. For detailed information on the effects of steam curing on the important properties of concrete, see reference (16).

High pressure steam curing in autoclaves takes advantage of temperatures in the range of 325° to 375° F and corresponding pressures of about 80 to 170 psig. Hydration is greatly accelerated, and the elevated temperatures and pressures may produce additional beneficial chemical reactions between the aggregates and/or cementitious materials which do not occur under normal steam curing (9).

2. Length of Curing

The length of curing is dependent upon the type of cement, mix proportions, required strength, size and shape of the concrete mass, weather, and anticipated exposure conditions. This period may be a month of more for lean concrete mixtures used in structures such as dams; it may be only a few days for richer mixes, especially if Type III or high early strength cement is used. Steam curing periods are normally much shorter. Since all the desirable properties of concrete are improved by curing, the period should be as long as practicable in all cases.

Since the rate of hydration is influenced by cement composition and fineness, the curing period is prolonged for concretes made with cements possessing slow strength gain characteristics.

For most structural uses, the curing period for cast-in-place concrete is 3 to 14 days, depending on such conditions as temperature, cement type and mix proportions. More extended curing periods are desirable for bridge decks and floating platforms because they are exposed to salts and chemical attacks.

In some cases a period of air drying of about one month may enhance resistance to scaling (flaking or chipping). Scaling may lead to future deterioration.

F. Concrete Products

Concrete products may be cast in place or precast and remotely assembled in place. Both of these categories may contain reinforced or nonreinforced concrete products. If reinforced, they may be prestressed or non-prestressed.

The discussion that follows is limited to reinforced concrete products, since unreinforced concrete is not generally used for structural purposes, with the exception of maxxive structures such as dams. Large floating concrete platforms in general require reinforcing.

1. Plain Reinforced Concrete

The first maritime reinforced concrete structure in Great Britain was built in 1899 and was still in excellent condition 56 years later. Not all reinforced concrete structures exposed to the marine environment have lasted so well. Some have spalled and cracked badly due to corroding reinforcement and needed extensive repairs. Present-day concreting practices such as those specified by ASTM and the Portland Cement Association, however, enable "non-corroding" durable concrete structures to be readily made.

2. Prestressed Reinforced Concrete

The concept of prestressing combines the durability and economy of highest quality concrete with high strength steel to form a homogeneous elastic material.

Prestressing is achieved by placing structural concrete under compressive stress before it is called upon to sustain its service loads, usually by embedding steel tendons to impart a compressive strength ahead of time to offset a service tensile stress (8).

Prestressed reinforced concrete is a good material for general marine construction. It has the strength, durability and economy needed for modern harbor and marine facilities (8). Prestressing can be accomplished either by pretensioning or post-tensioning methods. In pretensioning, steel tendons are stretched between anchors, the concrete is cast and allowed to harden, and the tendons are released, imparting prestress to the concrete through bond (8). In post-tensioning, the stress is applied after the concrete has been cast and hardened. Usually, steel tendons are inserted through holes or ducts left in the concrete and then stretched and anchored against the concrete (8).

Since 1946 there has been extensive application of prestressing and post-tensioning techniques in concrete structures, including pipes, piles, long span beams and slabs, bridges, piers, walls, roof, and offshore platforms. Modern methods of fabricating precast, prestressed concrete structural members have assured the production of much larger units than would otherwise have been possible, e.g., tanks, tunnels, prestressed pavements, aircraft runways, folded plate roofs and thin shell structures.

Prestressed concrete is a material requiring specialized knowledge. The structural design must be entrusted to a specialist in this area of engineering, the production of precast units requires unusually high quality workmanship, and the assembly and erection necessitates considerably more technical detail than is the case with conventional reinforced concrete.

Of particular importance is the need to protect prestressed tendons against corrosion. Although many successful installations have been made with uncoated (black) steel tendons, when post-tensioning is to be used in an ocean or marine-corrosive environment, protective coatings are important. One of the best methods for preventing corrosion is grouting. Cement grout is also used to bond the prestressed tendons to the concrete after post-tensioning. If the tendon is to be unbound after post-tensioning, it is sheathed in plastic tubing or heavy paper. Methods for providing unbound tendon corrosion protection include galvanizing, greasing and asphalt coating.

One further type of post-tensioning, which is particularly applicable to the underwater assembly of precast tanks and spheres, involves the use of flat jacks. These are inserted in the joint, hydraulically expanded, and then made rigid by filling the gap with pressure grout.

3. Precast Concrete

Precast units are manufactured at a central precast concrete manufacturing plant, where economy and quality can be achieved, with the completed units then shipped for installation at remote sites. If normal weight concrete is not essential, lightweight concrete may be used to minimize shipping weight and to facilitate handling. Where economy and local conditions permit, casting yards may be set up adjacent to the site for production of the precast units.

Precasting is used extensively for underwater and marine construction, and the scope and volume of its use are growing rapidly. Precast concrete has been used for intakes, discharges, drydocks, bridge piers, breakwater elements, wharves, pump houses and subaqueous tubes.

Underwater structures are frequently built of precast concrete sections jointed with tremie concrete. This combined technique is employed for bridge piers, subaqueous tubes, and drydocks. Tremie concrete bonds extremely well with precast concrete sections.

One of the newer developments in the joining ofprecast elements with post-tensioning is the juse of dry joints. The elements are cast against each other in the plant and match-marked; thus a perfect fit is ensured (17,18). They are then post-tensioned after installation and the ducts are grouted for bonding and corrosion protection.

Epoxy mortar has been used to build up and seal precast elements that are to be joined by conventional means, such as tremie concrete. These epoxy coatings bond extremely well, can be applied rather easily by a diver, and provide impermeability and a dense abrasion-resistant surface.

G. Special Concrete Types Suitable for Use in Large Floating Platforms

In addition to normal weight concrete, which has a wide range of properties that are suitable for use in large marine platforms, there are several other special concrete types. The advantages and disadvantages of these special concrete types are discussed below.

1. Lightweight Concrete

Structural lightweight concrete is obtained by using lightweight aggregates and air entrainment. It is especially suitable as a strong, lightweight structural material above decks. It would not be suitable for underwater construction, however, because of the compressive pressures to which it would be subject, and because most available lightweight aggregates are fairly porous.

Lightweight concrete is defined as concrete that has a 28-day compressive strength in excess of 2,500 psi and an air-dry unit weight of less than 115 pounds per cubic foot (9). It should not be confused with very lightweight concretes used primarily for insulating purposes.

2. Very Lightweight Insulating Concrete

Lightweight concretes used for thermal insulation may be grouped as follows:

- Those made with aggregates of expanded materials, such as perlite or vermiculite.
- Those made with aggregates manufactured by expanding or sintering materials such as blast-furnace slag, clay, diatomite, fly ash, shale or slate, or by processing natural materials such as pumice, scoria or tuff.
- Those made by incorporating in a cement paste or cement-sand mortar a uniform cellular structure of air voids by using preformed or formed-in-place foam.

These concretes would be suitable for non-structural members, or for areas requiring insulating, such as a boiler room.

Lightweight insulating concretes range in unit weight (oven-dry) from 15 to 90 pounds per cubic foot and have compressive strengths of 100 to 1,000 psi.

3. Heavyweight Concrete

Heavyweight concrete would be a suitable ballast material for a floating platform. It is normally used as a shielding material to protect men and equipment from the harmful effects of X-ray, gamma ray and neutron radiation. It is produced by using special heavy aggregates such as barite, ferrophosphorous, goethite, hematite, ilmenite, limonite, magnetite and steel punchings and shot. Such concretes have densities ranging up to 400 pounds per cubic foot.

4. Coral Concrete

Coral is a concrete aggregate economically available in the tropical zones of the Pacific Ocean. Construction of floating platforms employing coral concrete and prestressed coral concrete members could be feasible if the concrete were impermeable.

Rich cement mixtures are less permeable than lean cement mixtures, but no concrete is absolutely impermeable to water in the liquid or vapor phase. Relatively watertight coral concrete incorporating crushed coral reef aggregate can be made if the mix design is proper (a low water/cement ratio, a high cement factor, aggregate graded so as to minimize voids, very low slump). If the compaction is complete, and if moist curing is ample, then a relatively impermeable mix will result. At early ages, however, concrete containing coral aggregate that exhibits relatively high absorption will not be watertight with regard to liquid water, nor vaportight with regard to water vapor.

Tests have shown that a 28-day compressive strength as high as 9,090 psi has been obtained with a pozzolanic admixture in low permeability coral concretes (19). The main drawbacks of coral concrete are the high potential of corrosion to the reinforcement, due to salt incorporated in the coral, and difficulty in controlling the coral aggregate quality.

5. Polymer Concrete

Polymer concrete is the general term applied to concrete that has been impregnated by a monomeric resinous material and then polymerized, resulting in a concrete with a compressive strength three or four times normal strength concrete. Compressive strengths as high as 23,750 psi have been obtained in laboratory conditions (20).

Polymer concrete can be formed in one of three ways:

- By monomer or resin impregnation of existing precast concrete (polymer-impregnated concrete).
- By introduction of monomer or resin into the concrete mixer along with the aggregates, portland cement, and water (polymer-cement concrete).
- By mixing monomer or resin with aggregate only (polymer concrete).

In all three of these methods, the polymerization of the monomer or resin must be initiated by radiation, thermal-catalytic reaction, promoted catalytic reaction, or by other chemical means.

Besides high compressive strengths, low water absorption characteristics and low permeabilities can be obtained.

The major disadvantage of polymer concrete is the high cost (up to ten times the normal concrete cost) and lack of experience in its use (it has only been developed since 1967). For an example of experimental results obtained so far, see Table 7 (21).

6. Ferro-Cement

Ferro-cement is a cementitious material reinforced with closely spaced multiple layers of steel wire mesh or steel fibers with a steel/concrete ratio of 20 to 30 percent by weight (22). It exhibits a composite behavior unlike that found in standard reinforced concrete. Ferro-cement has been used in buoys, barges, liquid natural gas cargo vessels and other ship hulls. Savings are possible because of low material cost and low maintenance requirements when compared to wood and steel hulls. Automated casting procedures are being developed which will reduce fabrication costs.

The limited knowledge of ferro-cement properties is probably the main factor preventing the widespread application of the material, especially in designs traditionally reserved for non-cementitious materials (23). An important behavior property of ferro-cement that makes it a desirable material is the presence of the crack-arresting mechanism of closely spaced steel reinforcement.

Table 7 - Concrete polymer materials; summary of properties of methyl-methacrylate impregnated concrete*

Property	Control	Irradiation	Difference, percent[a]	Thermal-catalytic	Difference, percent[b]	Difference, percent[c]
Compressive strength, psi	5,267	20,255	285	18,161	244	-10
Modulus of elasticity, 10^6 psi	3.5	6.3	80	6.2	77	-2
Tensile strength, psi	416	1,627	291	1,508	262	-7
Modulus of rupture, psi	739	2,637	256	2,287	210	-13
Flexural modulus of elasticity, 10^6 psi	4.3	6.2	44	7.1	65	15
Water absorption, percent	5.3†	0.29	-95	3.58†	-33	1,130
	6.4	1.08	-83	0.34	-95	-69
Abrasion, in.	0.0497	0.0163	-67	0.0147	-70	-10
(g)	14	4	-71	4	-71	0
Cavitation, in.	0.32	0.064	-80	0.020	-94	-69
Water permeability, 10^{-4} ft per yr	6.2†	0†	-100	-	-	-
	5.3	0.8	-85	1.4	-73	75
Thermal conductivity, 73 F (23 C) Btu/ft-hr-F	1.332	1.306	-2	1.265	-5	-3
Diffusivity at 73 F (23 C), ft^2/hr	0.0387	0.0409	6	0.0385	0	-6
Coefficient of expansion, in/in.-F	4.02×10^{-6}	5.36×10^{-6}	33	5.25×10^{-6}	31	-2
Creep for 800 psi load after 90 days, 10^4 in./in.	-95**	-34	negative creep	+80	negative creep	-
Freeze-thaw durability, cycles	590;26.5†	2,420; 0.5†	310	-	-	-
percent weight loss	490;25.0	750; 4.0	53	750;0.5	53	-88
Hardness impact ("L" hammer)	32.0	55.3	73	52.0	62	-6
Resistance to sulfate attack, 300-day exposure, percent expansion	0.144†	0†	-100	-	-	-
Acid corrosion in 15 percent HCl, 84-day exposure, percent weight loss	16.4	3.64	-65	3.49	-66	-4
Corrosion by distilled H_2O, 120-day exposure at 206 F(97 C)	severe attack	no attack	-100	-	-	-

* Dried concrete specimens containing 4.6 to 6.7 weight percent PMMA.

† From survey series; all other data from CP-1 test series. Results based on average of 1 to 3 test measurements for each property.

[a]

$$\text{Difference, percent} = \frac{\text{radiation} - \text{control}}{\text{control}}\,(100)$$

[b]

$$\text{Difference, percent} = \frac{\text{thermal} - \text{control}}{\text{control}}\,(100)$$

[c]

$$\text{Difference, percent} = \frac{\text{thermal} - \text{radiation}}{\text{radiation}}\,(100)$$

** Control creep data are for 30 days in test.

7. Tremie Concrete

This is concrete placed under water. In the tremie process, the concrete is placed under pressure through a tube whose lower end is kept embedded in fresh concrete, thus substantially preventing washing and segregation. Tremie concrete is used for many different underwater purposes, including mass underwater concrete structures, repairs to underwater concrete, construction and joining of precast concrete sections under water.

Good tremie concrete can give strengths of 4,000 to 6,000 psi. There is no drying shrinkage associated with the curing process, since it is placed under water. The fact that the concrete is placed under pressure accounts for its generally high density. It bonds well with steel, rock, timber and other concrete. Reference (24) describes tremie concrete procedures and techniques in considerable detail.

8. Grouts and Hydraulic Cement

Grout is a fluid mixture of cement and water or cement, sand and water. Grout can be pumped under pressure into a mass of aggregates to fill the voids; it can also be used to join underwater precase elements or to repair holes in concrete.

Hydraulic cements are special types of cement which set and harden when mixed with water. A paste made from a hydraulic cement, with or without an aggregate, will set and harden not only in air but also if immersed in water. Certain hydraulic cement grouts set in four or five minutes, show excellent bonding characteristics and compressive strengths higher than 5,000 psi, have no setting shrinkage, and are chemically resistant (8).

9. Wirand Concrete

The Battelle Development Corporation, through an arrangement with the inventor, James Romualdi, has developed Wirand concrete to the point where it is a product ready for application testing. Basically, the material consists of a more or less normal concrete mix to which has been added the proper quantity of metal fibers in the form of short lengths (about 1 inch) with a diameter of about 10 mils. The properly spaced, randomly oriented fibers serve as crack arresters and prevent the small cracks which form in the matrix from propagating. The material can be handled with the same equipment and by the same techniques used for normal concrete.

The properties of Wirand concrete which make it a very attractive material when compared to normal reinforced concrete can be summarized as follows (25):

- Fatigue strength is more than 50 percent better than than of normal concrete.
- Tensile and compressive strengths exceed those of normal concrete.
- The material is much more resistant to spalling and cracking due to flexure.
- The abrasion resistance is greater than that of normal concrete by a factor of 2:1.
- Tests indicate 90 percent greater resistance to damage as a result of repeated freeze-thaw cycles.
- Impact resistance is a great deal better than that of normal material.
- Resistance to thermal shock is far superior to the resistance of normal material.
- Resistance to salt scaling is at least equal to that of ordinary concrete.

Since this is a relatively new product, the only known disadvantage at the present time it its cost.

IV. CONCRETE FOR LARGE FLOATING MARINE PLATFORMS

Steel is the traditional material for construction of ships and floating platforms. If concrete is to be a successful competitor in the field of very large floating platforms, it must be not only cheaper, but at least as reliable as steel and a great deal easier to maintain.

Among the properties that are especially important in a floating platform are strength, unit weight, permeability, durability, modulus of elasticity and thermal conductivity.

For a required level of strength, a minimum structural weight is desired; hence the strength-to-weight ratio is a critical parameter in the design and cost of a structure.

The strength-to-weight ratio is directly related to the water/cement ratio used in the design mix. The water/cement ratio, in turn, is a critical factor affecting concrete permeability, and in the marine environment permeability is a critical parameter directly affecting the ultimate durability of the concrete.

For a fuller appreciation of the interrelationships of these critical concrete properties and parameters, the effects of the ocean environment on concrete are reviewed below. This is followed by an identification of the critical factors affecting the strength-to-weight ratio, permeability and durability of concrete in floating platforms.

A. Effects of the Ocean Environment on Concrete

An excellent discussion of the general effects of the ocean environment on concrete is found in Gerwick (8). The majority of the material presented in this section is drawn from that publication.

Submergence. The general effect of submergence on concrete is positive. Good quality concrete submerged in seawater continues to cure and increases in compressive strength with the passage of time. In fact, submergence provides a near perfect curing environment; the water for hydration is held within the concrete and any heat generated by the reaction is absorbed and dissipated into the water. With continuous submergence there can be no shrinkage due to drying. Temperature change is also minimized, thus lessening the rate and amount of expansion and contraction of the concrete.

Permeability. Permeability is another matter. Experiments show that no matter how high the quality of the mix, concrete is always permeable to some degree. Seawater tends to flow through the material either by pressure differential or by capillary attraction. If the water vapor is continuously evaporated from one surface, then the flow of seawater through the concrete will be continuous. This process will result in some residual salt being left in the concrete.

Chemical Constituents of Seawater. The primary chemical constituents of water are the ions of chloride, sodium, magnesium, sulfate, calcium and potassium. Thus seawater is an electrolyte and plays a major role in any electrolytic (galvanic) action between salt concentrations and steel in concrete.

The pH of seawater is about 8. Since the corrosion of reinforcing steel occurs below a pH of 11, alkalinity must be supplied by the cement (usually about 13).

Corrosion may also be a problem in areas where considerable quantities of H_2S are present, since weak acid attacks on the cement will occur. Concrete can be made resistant to moderate sulfate concentrations if less than 5 percent tricalcium aluminate cement is used.

Pressure. The effect of pressure on concrete is not fully established. It is generally expected, however, that concrete placed in about 200 feet of water will be dense and strong. Experiments have shown that concrete cured at a pressure equal to a 600-foot depth has a lower compressive strength than concrete cured at atmospheric pressure (26), and further studies are indicated in this area.

Temperature. The structural properties of concrete generally improve at lower temperatures, with both compressive strength and modulus of elasticity reaching higher values. Hydration (concrete curing) proceeds at a much slower rate when the concrete temperature is low than when it is high.

In warmer water, chemical and electrochemical attack on the concrete and its reinforcement is more severe.

Movement of Water. Waves breaking directly on structures exert dynamic pressures. Such cyclic loading may produce fatigue stress. Splashing waves deposit salt on the surface of the structure above the waterline. Intermittent wetting and drying may eventually lead to galvanic action on the embedded reinforcing steel. Similar problems may occur from seawater flowing through the concrete under water and evaporating from the inside surface of the structure. The waves may also throw salt and spray up into the air where it is carried onto exposed concrete surfaces well above the waterline.

Moving water affects fresh concrete placement under water. Even small leaks in the walls of caissons or in tremie pipes can cause serious turbulence inside, resulting in segregation and leaching out of cement. When grout is intruded into aggregate, or when concrete is placed without a full protective enclosure, the moving water will pull out cement from the surface. A layer of graded rock and sand is commonly used as a protective cover. Other types of covers, such as weighted tarpaulins, can be used in special cases.

Marine Organisms. Marine organisms directly attack concrete by boring into it and reducing its strength. Fouling may also occur which adds weight and increases resistance to wave and water movement. Barnacles and similar growth may increase the effective diameter of piles and columns, as well as spoiling the hydraulic characteristics of shape and surface. Marine organism may be removed by mechanical means but this may abrade the surface of the concrete. Chemical impregnation of concrete to prevent fouling has a limited effective life because the chemicals used are subject to leaching.

Tsunamis. Large unmoored floating platforms at sea should not be adversely affected by tsunamis, since in the open ocean, heave caused by a tsunami would be almost undetectable. On the other hand, the effects of explosive forces are severe on underwater structures because of the incompressibility of water surrounding the structure. Explosive forces stem from the shock waves produced by detonation of explosives underwater. Concrete structures are resistant to external explosive forces because of their high compressive strength, low modulus of elasticity, generally heavy mass and thick walls. Internal explosive forces, however, are very disruptive. For example, caissons and cofferdams have been accidentally destroyed when explosives were used inside them to remove rock or concrete. The explosion waves can travel up holes in the concrete and may produce their most destructive effect some distance away from the blast.

Ice. The formation of ice must be considered in climates where the temperature is low. Ice loading on a structure may increase the weight of the structure. In addition, ice forming on the surface of the structure increases the surface area against which wind, waves, and currents act and disrupts the designed hydraulic characteristics.

Ice may exert destructive expansive pressures as it forms inside an enclosure. This could occur in a small hole sleeved in the concrete, in a large enclosure such as the inside of a cylinder pile or caisson, or in a rock pocket, crack or damaged surface.

B. Critical Factors Affecting the Strength-to-Weight Ratio

As in all structural materials, and especially for floating construction, concrete must provide an acceptable margin of load-carrying capacity, over and above its structural weight, in order to be useful. This idea is formalized in the concept of strength-to-weight ratio. For concrete, this ratio may assume a wide range of values, depending on its ingredients and the methods used in its mixing, placement and curing. Some of the critical factors which affect the strength-to-weight ratio of concrete are discussed below.

1. Mix Design

Water/Cement Ratio. The water/cement ratio and compressive strength of concrete are related. A decrease in the water/cement ratio of a mix increases the compressive strength obtainable, all other parameters being equal. Thus, for a given unit weight, a low water/cement ratio should result in a high strength-to-weight ratio.

Cement Type. High-early-strength portland cement (Type III) can be used to obtain a high strength-to-weight ratio early in the curing period. The ultimate strength-to-weight ratio, however, will be the same as for other cement types.

Aggregate Type, Quantity, and Quality. The specific gravity and the packing density of aggregates affects the unit weight of concrete. High specific gravity aggregates increase the total weight and hence act to lower the strength-to-weight ratio. Lightweight aggregates do the opposite. For aggregates of a given specific gravity, proper grading of the aggregates will increase the packing density and thus the total quantity of aggregate in the concrete. The resulting increase in unit weight, however, is usually offset by a gain in compressive strength.

Water. The quantity of water affects the strength more than the unit weight of concrete and thus is a critical parameter affecting the water/cement ratio. The use of seawater is controversial. It produces concretes of good early strength, but often somewhat reduced later strengths and affects the strength-to-weight ratio accordingly. Contaminated water generally reduces the strength.

Admixtures. Admixtures that increase the strength of the concrete will increase the strength-to-weight ratio. Gas-forming agents reduce the unit weight but also tend to reduce the strength. Thus, for an optimum strength-to-weight ratio, judicious control of the mix design is required.

Polymerization of Impregnated Monomers. This is an extremely beneficial method for increasing the strength of concrete; however, at present it is an expensive process. Experiments have shown that an increase in strength of up to 400 percent can be obtained with only a 6 percent increase in unit weight (21).

2. Mixing, Handling, Transport and Placement

Improper mixing and handling of concrete reduces the quality of the concrete. This generally means lesser strengths for any given mix and hence a lower strength-to-weight ratio. Transport of fresh concrete without segregation, together with good consolidation of placed concrete, usually produces a stronger concrete and hence a higher strength-to-weight ratio.

3. Curing of Concrete

Moist Curing. Tests indicate that the length of moist curing is a primary factor in the strength of concrete (9). During this period the unit weight generally drops slightly from that of fresh concrete due to loss of water. Thus the strength-to-weight ratio also increases with the length of moist curing.

Steam Curing. The purpose of steam curing is to accelerate strength development of concrete at early ages. However, it reduces the ultimate strength and the strength-to-weight ratio accordingly.

Age. The age of concrete is a secondary parameter affecting the the strength-to-weight ratio. Generally, submerged concrete increases in strength with age because curing continues. In seawater, however, corrosion may reduce strength.

C. Critical Factors Affecting Permeability

There are many factors which affect the permeability of concrete. Some of these are the amount of water, the water/cement ratio, slump, cement factor, the length and type of curing, porosity, the use of admixtures, the pressure, polymerization of concrete, cracks and joints.

1. Water Content

Water/Cement Ratio. Experiments using electrical resistance probes to trace moisture permeation through concrete showed that the water/cement ratio is the critical factor in determining the permeability of concrete (27). Generally, the water/cement ratio must not exceed 0.6 by weight if poor bonding between aggregate particles is to be avoided and permeability kept low (19). An increase in the quantity of mixing water will reduce the watertightness regardless of the curing period or the characteristics of the cement used.

Slump. An increase in the total amount of water also affects the slump. This in turn affects the permeability as can be seen in Figure 4 (28).

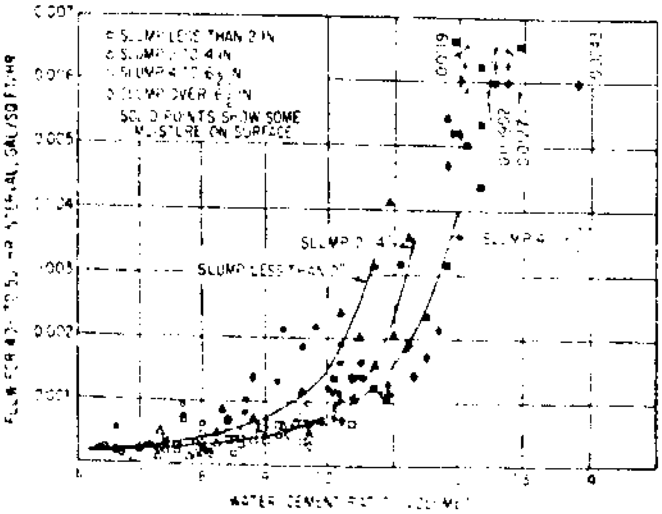


Figure 4 - Effect of water-cement ratio and slump on permeability.

2. Cement Characteristics

Tests using cements of different characteristics showed that the development of watertightness at an early age was comparable with the development of compressive strength. Those cements which gained their strength rapidly during the first few days were found also to gain watertightness more rapidly.

3. Aggregate Size

Introduction of aggregate particles into paste tends to reduce the permeability in three ways: 1) by reducing the number of channels per unit of cross section, 2) by interrupting a portion of the paths of flow per unit of gross cross section, and 3) by lengthening the path of flow per unit linear distance in the general direction of flow.

However, voids form under the aggregate particles and tend to increase the permeability. With paste of a given composition and with graded aggregates, the permeability is greater the larger the maximum size of aggregate (29), as shown in Figure 5.

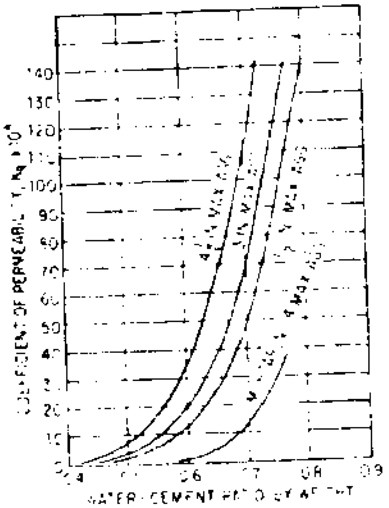


Figure 5 - Relation between coefficient of permeability and water/cement ratio for mortar and for concrete with three different maximum coarse-aggregate sizes. K_q is a relative measure of the flow of water through concrete in cu. ft/yr/ft^2 of area for a unit hydraulic gradient.

It is possible however to use large size aggregate and still obtain low permeability. For example, tests made on Boulder Dam mass concrete containing 9-inch gravel and four sacks of low-heat cement per cubic yard of concrete showed that it was relatively impermeable and that flow through its pore structure was negligible (30).

4. Moist Curing

Tests indicate that the length of moist curing is a primary factor in the building up of watertightness of concrete (31) and that continued moist curing of a particular specimen increases the watertightness of that concrete, because continued hydration of the cement reduces the volume of pores through development of gel.

The effect of the length of the curing period on the permeability is shown in Figure 6. It is apparent that curing during the early life of the concrete is especially effective in reducing permeability. The relation between the water/cement ratio and length of curing on permeability is shown in Figure 7.

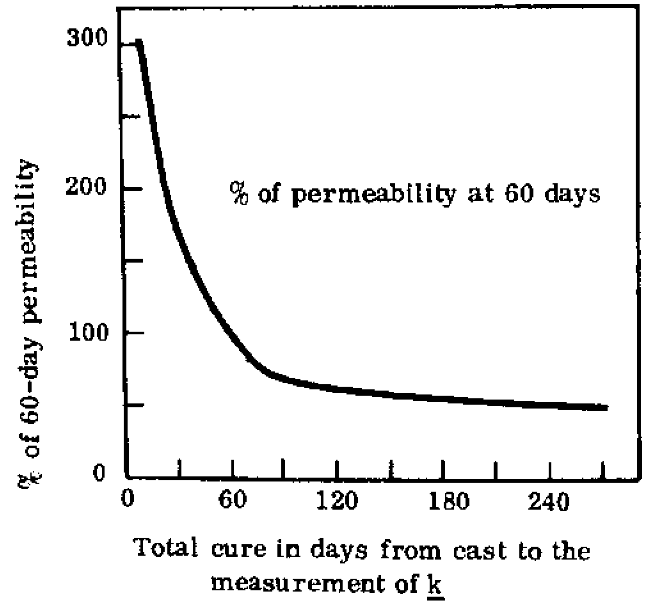


Figure 6 - Effect of length of curing period on permeability (29)

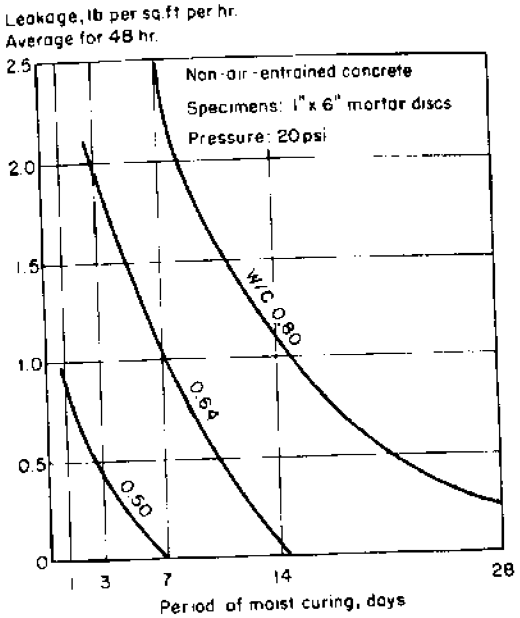


Figure 7 - Effect of water/cement ratio and curing on permeability. Note that leakage is reduced as the water/cement ratio is decreased and the curing period increased (9).

5. Steam Curing

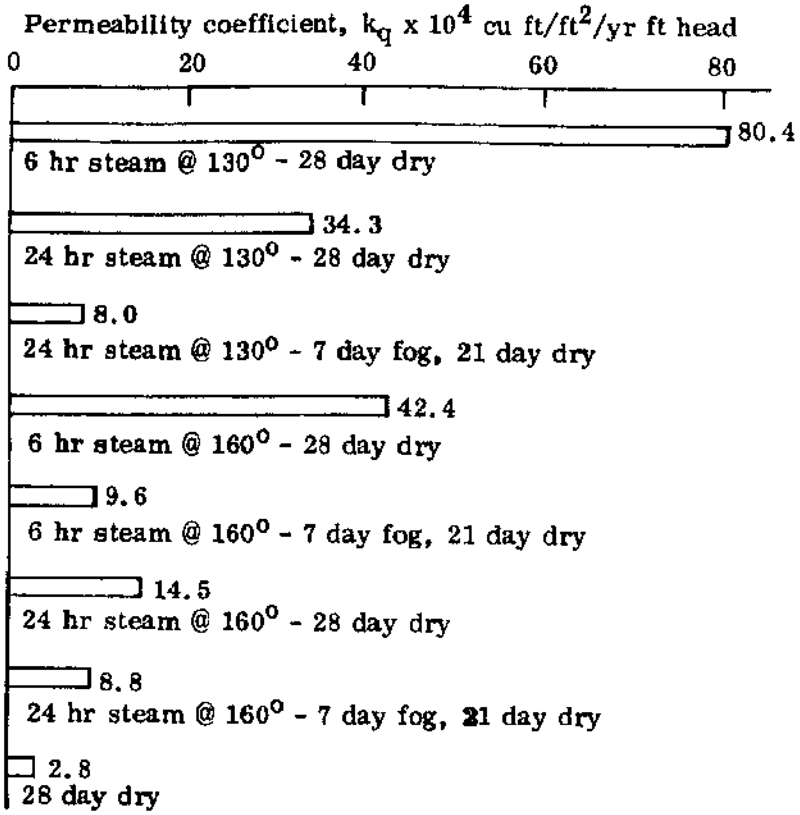
The purpose of steam curing is to accelerate strength development of concrete at early ages. Permeability of concrete specimens subjected to steam curing is greater than that of companion specimens continuously moist cured for 28 days (16,32).

In normal construction these differences are not usually significant. By good steam curing procedures, permeability may readily be held within normal limits. In cases where unusually low values of permeability are desired, additional moist curing may be required. For a comparison between fog-cured and steam-cured concrete, see Figure 8 (16).

6. Admixtures

Admixtures are classified into 15 groups according to type of material constituting the admixture or to the characteristic effects of their use (33).

The general effect of a water-reducing admixture on the hardened concrete is an improved compressive strength and some decrease in permeability. This occurs because for concrete of a given workability, there is a reduction in the water/cement ratio.



* $k_q = 15.0 \times 10^{-4}$ is arbitrary limit of acceptability for permeability coefficient

Figure 8 - Permeability of fog-cured and steam-cured concrete (16).

Damp-proofing admixtures, usually water-repellent materials, only reduce the rate of penetration of water into dry concrete and cannot be expected to prevent altogether the water penetration into dry concrete. Similarly, permeability-reducing admixtures only reduce the rate of transmission of water through unsaturated concrete from the damp side to the dryer side and do not stop the transmission of water through unsaturated concrete.

Generally, since the watertightness of concrete depends primarily on the amount of cement and mixing water used, and the length of the moist-curing period, damp-proofing and permeability-reducing admixtures may not be needed.

Studies of some of the common powdered admixtures show that additions of those materials which require extra water to maintain plasticity reduce the watertightness, while with those materials which require no extra water there is some slight improvement. The changes brought about by these additions are quite insignificant in comparison with the reduced permeability produced by a few days moist curing or a moderate reduction in the water content.

The use of a pozzolanic admixture as a replacement for part of the cement can reduce the liquid permeability. According to Lorman (19), the benefits of the pozzolan may be expectably less if the concrete is made with aggregate that has poor particle shape.

Use of admixtures should in no case be considered as a substitute for careful choice of materials and mixes, for skilled workmanship or for adequate curing. In no case can an admixture be expected to compensate for cracks or large voids in the concrete, although it may minimize the probability of their occurrence.

7. Polymer Concrete

Experiments using polymer concrete show that negligible values of water permeability can be obtained.

> "Compared with a value of 6.18 x 10^{-4} ft/yr for the control, a permeability of zero was obtained for a 1.4% methyl-methacrylate sample polymerized by radiation in the second series of experiments. Polymer concrete showed reductions in permeability of 72 to 85% in the third series. Extremely large increases in permeability, greater than 450%, were obtained with unimpregnated samples treated by either heat or irradiation (it is suspected that these specimens were cracked.)" (21)

8. Porosity

The porosity of concrete may not wholly affect permeability because all capillaries are not continuous and all voids are not connected. Generally speaking, however, the permeability can be reduced by reducing the porosity.

To obtain minimum porosity, the aggregate gradation must be such that the finer particles occupy the interstices among the coarser particles when all are packed together. This produces a minimum permeability because the size of available capillaries throughout the cement gel is reduced. An additional benefit of reduced porosity is increased density and reduction in the amount of cement paste needed to coat each aggregate particle (19).

Any portland cement concrete incorporating crushed porous coral reef aggregate will eventually be practically impermeable to water in liquid or vapor phase, if the mix design is proper, if the compaction is complete, and if the moist curing is ample (19). At early ages, concrete containing coral aggregate that exhibits relatively high absorption will be neither watertight nor vaportight.

9. Placement

Handling, placing and compacting concrete in forms is an important step in the production of watertight concrete. Every attempt must be made to avoid segregation, which may cause honeycombing or a porous structure.

10. Pressure

Tests indicate that more water will flow through specimens at high hydrostatic pressures than at low hydrostatic pressures. Long time tests under high pressure show that clogging of the void spaces is not enough to prevent flow through concrete, although the flow may be slow enough so that the surface appears dry.

Complete impermeability may be obtained by using impermeable surface coatings, such as epoxy.

D. Critical Factors Affecting Durability

An excellent discussion of the problems of durability of concrete in the marine environment is found in Gerwick (8). The majority of the material presented in this section is drawn from that publication.

Durability of concrete refers to the useful lifetime of the structure and the amount of repair required to keep it in service. The marine environment constitutes a very severe test of the durability of concrete. Improperly constructed concrete structures may suffer rapid and serious deterioration. The concrete itself is subject to chemical attack and disruption by freezing and thawing; reinforced concrete is subject to electrochemical corrosion. Abrasion by moving sediments or by ice, cavitation produced by pounding surf, and attack by marine organisms all contribute to deterioration of marine concrete. Whereas structures made of high quality concrete have been known to endure under marine service conditions for fifty years or more, many early failures have been observed, due either to lack of adequate quality control, or to ignorance of the mechanisms through which deterioration occurs.

1. Abrasion

The movement of sand and debris in water against the surface of concrete may cause the surface to wear. Sharp corners are particularly subject to breaking and spalling and should therefore be avoided in the design.

Concrete may be made quite resistant to abrasion by increasing its strength and density through the use of a well-compacted, workable mix with a low water/cement ratio. Hard abrasion-resistant aggregate should be selected. Good finishing, preferably machine finishing where possible, and adequate curing will produce an abrasion-resistant surface. The use of steel forms and form vibration is recommended where practical.

Resistance to cavitation is difficult to achieve, but damage may be minimized by using a dense, hard concrete. Selection of aggregates to give high bond is another method, for example, crushed rock may be better in this respect than gravel.

2. Marine Organisms

Some of the marine organisms that attack concrete are the rock-boring mollusk Pholadidae, the boring clam Lithophaga, and the barnacle. The rock-boring mollusk is able to bore only in poor, weak concrete. The boring clams deposit acids which dissolve the cement and attack most easily porous concrete. The barnacle shell exerts high pressures on the surface of the concrete as it grows from the embryonic stage to maturity. This pressure may erode the concrete and destroy bitumastic coatings that may have been used.

These organisms operate most often in tropical and subtropical waters, and their attacks are normally effective only on weak, porous and soft concrete. A hard, dense concrete surface will generally provide adequate protection for many years.

3. Chemical Attack

Sulfates and chlorides in seawater combine with cement to form soft, slightly soluble compounds such as magnesium hydroxide which expand and disrupt the concrete. Chemical attack proceeds most rapidly in warm seawater and is of major significance in tropical and subtropical waters.

Impermeability is the best means of protecting the concrete. The use of cement containing moderate or low amounts of C_3A (less than 8 percent) will produce concrete of moderate sulfate resistance. Corners and sharp edges are highly vulnerable to attack and should be avoided.

That chemical attack can satisfactorily be minimized has been demonstrated by tests on large unreinforced concrete blocks placed in tidal zones at San Pedro, California. After 27 years of immersion they have shown no disintegration (34). A British study on concrete piles over a period of 23 years produced similar results (35).

4. Corrosion of Reinforcement

When reinforcement corrodes, the oxidation products expand, spall and crack the concrete, hence reducing the durability. This generally takes place in permeable, porous concrete which is exposed alternately to salt-water splash and to air. Salt of varying concentrations is deposited in the concrete, setting up electrochemical cells which corrode the reinforcing steel. The differences in salt concentrations may be due to varying amounts of splash on the exposed faces and the differences in permeability of various regions of the concrete. Salt may also enter the concrete through the mixing or curing water or as deposits on the aggregate.

The use of dense and impermeable concrete retards corrosion of reinforcement. The chloride concentration in the mix must also be kept as low as possible by ensuring that the aggregates are salt free, that the mixing and curing water does not contain chlorides, and that the admixtures do not contain chlorides. This is important in hot, humid, subtropical or tropical climates where the corrosion process is rapid.

5. Cement

Portland cement provides protection to concrete both chemically and physically. Besides forming a protective cover, the cement in the concrete forms calcium hydroxide during hydration. This creates and maintains a pH of about 13 and causes a thin oxide protective film to form over the reinforcing steel. If the pH is reduced to below 11, corrosion may take place. The pH may be lowered by carbon dioxide from the air neutralizing the calcium hydroxide during hydration or by the presence of chlorides.

The chloride content may be kept low by using a cement with a high C_3A content. This helps prevent steel corrosion; however, too high a C_3A content renders the concrete subject to chemical attack. Thus a moderate C_3A cement (such as Type II) would be a good choice for marine exposure.

6. Cover

While adequate concrete cover is important to prevent or inhibit the movement of oxygen and carbon dioxide to the steel, there are many instances of successful marine structures which had very little cover. For example, some floating ships were built in 1918 which operated for several years with a design cover of 1/4 inch but an actual measured cover as low as 1/16 inch (34). Other structures and test specimens have proved entirely durable with covers of 3/16 to 1 inch. However, in all these cases, the cover provided was especially dense and impermeable.

7. Cracks

Cracks in the concrete cover have long been blamed for accelerating corrosion of reinforcing steel. More recent tests and experience seem to indicate that hairline cracks may not be as serious as was formerly thought. Large cracks above the waterline are serious factors aiding the corrosion process. As the oxidation continues, concrete is spalled off, exposing the reinforcement and eventually leading to progressive deterioration and eventual failure.

8. Freezing and Thawing

The durability of concrete is often determined from the freeze-thaw test (10). Repeated freezing and thawing of saturated concrete is a very destructive weathering action. The U.S. Army Corps of Engineers has conducted extensive tests of beams stored in tidal zones at Treat Island, Maine, under various conditions of loading and with varying degrees and kinds of reinforcement, including prestressed concrete. These tests have established the absolute need for air entrainment for this type of exposure (36). With air entrainment and with properly made concrete, good durability can be obtained.

V. MAINTENANCE AND REPAIR OF CONCRETE IN THE MARINE ENVIRONMENT

A. Maintenance of Quality Concrete

Concrete of good quality if known for requiring little or no maintenance even after years of service; however, periodic inspection and testing for cracks, spalling or corrosion is needed in order to determine whether repairs are required. Generally, poor quality concrete (low strength, high permeability, poor corrosion resistance) may require maintenance within a few years.

1. Good Quality Concrete Defined

General deterioration of concrete is best prevented by using good quality concrete originally, but what is "good quality" for conventional structures may be unacceptable for floating platforms. Basically good quality concrete is that which meets the design specifications and behaves as predicted. It also implies that the mix is properly proportioned, carefully placed, well cured, and so watertight that moisture cannot be seen coming through the concrete. This requires:

- Low water/cement ratio, not exceeding 5 gallons of mixing water per sack of portland cement.
- Suitable workability, to avoid mixes so harsh and stiff that honeycombing occurs, and those so fluid that bleeding occurs.
- Thorough mixing.
- Proper placing and consolidation to fill all corners and angles of forms without segregation of materials.
- Adequate curing.

2. Consequences of Damage

In a concrete floating platform, the consequences of damage are much more spectacular and dangerous than in a land-based platform. For example, cracking and permeability could cause flooding and sinking of a floating platform whereas on a land-based platform, such weaknesses may be ignored or simply covered over.

Corrosion of the reinforcing must also be prevented, since underwater repairs are difficult and expensive.

Extensive and detailed inspection of the whole concreting operation is essential, from the preparation of raw materials to the repair of damaged concrete before launching. High quality concrete must be obtained. No mistakes or use of inferior materials can be allowed as it may jeopardize the safety of the platform.

3. Protective Coatings

Protective coatings or surface treatments prolong the useful life of a concrete structure. The best material for a given case will depend on many factors, including concentration of solution, temperature, taste, odor and abrasive action of the damaging agent. Economy is also a consideration, since a more expensive durable means of protection may provide more continuous service over long periods than a cheaper less effective coating.

Some common protective treatments are magnesium fluosilicate or zinc fluosilicate, sodium silicate (water glass), drying oils, cumar, varnishes and paints, bituminous or coal tar paints, tar and pitches, bituminous enamel, bituminous mastic, vitrified brick or tile, glass, lead, sheets of synthetic resin, rubber and synthetic rubber. More detailed information on protective treatments and the effects of these substances on concrete may be found in reference (37).

B. Repair Required

Repair of the general deterioration of concrete will prevent more serious damage. The loss of a protective coating may lead to spalling and corrosion. Fouling by marine organisms may increase the weight of the structure and weaken the concrete surface.

Cracks in Concrete. Cracking of concrete is very common and in many cases can lead to significant structural damage. Cracks are part of the general deterioration process and range from surface hairline cracks to open, deep cracks. Most cracking results from the following actions to which concrete can be subjected:

- Volumetric change
  Drying shrinkage, creep under sustained load, thermal stresses including elevated temperatures, chemical incompatibility of concrete components.

- Direct stress due to applied loads or reactions; or internal stresses due to discontinuity, reversible fatigue load, long-term deflection, camber in prestressed concrete; or environmental effects including differential movement in structures.

- Flexural stress due to bending.

While the net result of these three actions is the formation of cracks, the mechanisms of their development are not identical. Volumetric change generates internal microcracking which may develop into full cracking. Direct internal or external stress or flexural stress due to applied loads and reactions could generate either internal microcracking, such as in the case of fatigue due to reversible load, or flexural microcracking. For detailed information on control of cracking in concrete structures, see reference (38).

Corrosion. There are two aspects to concrete corrosion: the corrosion of the concrete itself and the corrosion of the reinforcement.

The corrosion of concrete can be reduced by using Type II or Type V cement and by ensuring high quality (sound, nonreactive aggregates, clean, uncontaminated water, proper grading of aggregates, proper mixing and placing, adequate vibration and curing).

The corrosion of reinforcement can be reduced by 1) an increase in the cement content, 2) a decrease in the permeability, 3) an increase in the depth of concrete cover over steel, 4) by not using salt or contaminated mix water, and 5) a protective covering on the reinforcement.

Permeability. As previously mentioned, high permeability of a floating platform may be disastrous. Generally the flow of water through the matrix is minimal, but leakage through joints and cracks must be controlled.

Failure. This may consist of creep that has led to spalling of the concrete or reinforcement that has yielded.

C. Methods of Repair

Repairs to the underwater portion of floating concrete structures may be made by one or a combination of several methods. These include 1) encasement, 2) patching with underwater cement or gunite, 3) patching with underwater epoxy, 4) filling with underwater concrete by either the tremie or the grout-intrustion method, or 5) replacement (8).

Proper preparation of the area to be repaired is essential. All foreign matter, including marine growth, must be removed. Loose concrete must be chipped out to sound concrete. Corroded reinforcing bars must be supplemented by new bars of adequate length for a splice. The space left behind any reinforcing bars must be of adequate size to enable the concrete or grout to flow into it. Where possible a key should be formed to lock the patch.

For underwater repairs a form must be placed to contain the patch and to protect it from flowing water and grout leaks. Tremie concrete, with "pea" gravel as the coarse aggregate, may be placed either by gravity flow or by use of a low-pressure grout pump. Such underwater patches have proved to bond well and are an excellent means of repairing fairly large holes or cavities. Smaller holes and cracks are best repaired by using underwater-setting hydraulic cements or underwater epoxies.

Underwater repair of damaged concrete structures, while expensive and requiring engineering control and skilled personnel, has generally proved fully satisfactory in restoring structural integrity. However, repairs in the tidal and splash zones often have not been complete successful.

Where the damage is to the concrete only, as from collision or impact, the main concern is thorough cleaning, keying and bonding. Where the deterioration is caused by corrosion of the reinforcement due to salt cells in permeable concrete, repair of one area, even when done with great care, may merely move the location of the galvanic cell. In this case, it is necessary to make the surface of the entire area impermeable (for example, by coating it with a waterproofing compound). Even then, there may be continued galvanic action with absorbed water as the electrolyte; however, in only one major case did this residual action continue to be serious (39).

VI. SUMMARY AND CONCLUSIONS

1. The terms "quality control" and "high quality concrete" have been used many times in this report. The obvious message is that the performance of concrete in the field can be made satisfactory and predictable only if great care is exercised in its manufacture. Existing quality control methods for engineering structures can, <u>if diligently practiced</u>, ensure concrete of sufficient performance to meet the design requirements of large floating structures. It does not appear that special quality control techniques will have to be worked out for this application.

2. Concrete of adequate strength for large floating structures is widely available. For optimum structural efficiency, the concrete design should reflect awareness that the strength-to-weight ratio of the structure is more important than the absolute value of the concrete strength. For conventional aggregates (150 pounds per cubic foot), a 28-day crushing strength of from 6,000 psi to 8,000 psi should be used. For concrete from lightweight aggregates, a lower 28-day strength may be tolerated depending upon its density and other properties. In any case, structural concrete below 4,000 psi does not appear useful in a floating platform.

3. For all useful concrete mixes, permeability will be significant: whereas it can be held to low levels, it cannot reasonably be eliminated without resort to waterproof coatings or impregnation. More study of permeability is needed, especially for the case of elevated hydrostatic pressure.

4. High durability against abrasion, cavitation, and weathering can readily be achieved by good design. However, corrosion of reinforcing and other embedded metal is entirely another matter. The structure may be short-lived unless corrosion can be effectively prevented. Principal means for doing this include anti-corrosion coatings on reinforcing, adequate cover, and careful concrete placement and curing. More study of corrosion control seems warranted.

5. Except for exotic concretes (for example, irradiated polymer mixes), costs should not be far out of line with those encountered on shore. Because of the designer's emphasis on weight saving, estimation of cost of structural concrete per unit of gross displacement is probably more meaningful as a figure of merit than cost per cubic yard placed.

APPENDIX

THE CONCRETE INDUSTRY IN HAWAII

The concrete industry in Hawaii is large enough, competent enough, and well enough supplied with natural resources and skilled labor to successfully construct and outfit floating platforms of great size, i.e. in the 200,000 to 1,000,000 ton displacement range.

In 1972, approximately 2.2 million tons of concrete were produced on Oahu (40). A floating platform of 1-million-ton displacement would require approximately 300,000 tons of concrete over a construction period of four years, or 75,000 tons per year, which is 3.4% of Hawaii's annual production.

Interviews with executives in the concrete industry have revealed a receptive attitude toward such a project and assurance that it would not tax the industry's reserves and would stimulate the industry's capacity.

Hawaii's mineral resources are heavily exploited by the local mineral production industry. In 1970, approximately $29 million worth of cement, clay, lime, pumice, pumicite, volcanic cinder, sand, gravel, stone, gem stone, salt, and dimension stone were produced in Hawaii, as shown in Table A1 (41).

Honolulu County produced by far the largest share ($24 million), as shown in Table A2.

In Honolulu alone, thousands of hotel rooms have been built of concrete during the last ten years. Statistical quality control methods are in general use and in fact are specified in all government and large commercial construction projects. The latest in concrete batching equipment is available to ensure good quality ready-mix concrete.

Sources of Raw Materials

Cement. At present, two cement plants are required to supply the needs of the islands. Hawaiian Cement Corporation operates a plant at Barber's Point, and Kaiser Cement & Gypsum Corporation operates a plant near Nanakuli, both on Oahu. In 1970, shipments of portland cement were a record 2,162,000 barrels valued at $10.3 million.

Table A1 - Mineral production in Hawaii[1]

Mineral	1969 Quantity	1969 Value (thousands)	1970 Quantity	1970 Value (thousands)
Cement (thousand 376-lb barrels)	2,075	$10,544	2,163	$10,334
Clay (thousand short tons)	2	9	2	11
Lime (thousand short tons)	9	287	9	338
Pumice, pumicite, and volcanic cinder (thousand short tons)	403	783	350	933
Sand and gravel (thousand short tons)	552	1,816	514	1,679
Stone (thousand short tons)	6,534	16,059	6,331[2]	15,538
Value of items that cannot be disclosed: gem stones, salt and dimension stone (1970)		41		132
TOTAL		29,539		28,965

[1] Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

[2] Excludes dimension stones; included with "Value of items that cannot be disclosed."

Table A2 - Value of mineral production in Hawaii, by counties

County	1969 (Thousands)	1970 (Thousands)	Minerals produced in 1970, in order of value
Hawaii	$2,039	$2,215	Stone, pumice, volcanic cinder.
Honolulu	24,337	23,919	Stone, cement, lime, clays, salt
Kauai	839	766	Stone, sand and gravel, volcanic cinder.
Maui	2,324	2,065	Sand and gravel, volcanic cinder, lime, stone gemstones
TOTAL	29,539	28,965	

Raw material used in making this cement included 477,000 tons of basalt, 44,000 tons of silica sand, and 19,000 tons of gypsum. The silica sand, gypsum, and some clinker were imported. The two plants purchased 52.5 million kilowatt-hours of electric energy.

Sand and Gravel. In 1970, 514,000 short tons of sand and gravel, valued at $1.7 million, were produced by 17 companies. Most of the production was from Maui County, with the two largest companies being HC&D Ltd. and Maui Concrete and Aggregates, Inc. The sand and gravel was used for construction, paving, fill, and other purposes.

Stone. In 1970 eleven operators crushed 4.7 million tons of traprock valued at $11.8 million. Leading counties were Honolulu and Hawaii, and leading producers were Lone Star Cement Corporation, HC&D Ltd. and Pacific Concrete and Rock Co., Ltd. The stone was used for construction and for fill.

Ten operators crushed 1.2 million tons of limestone valued at $3.1 million for construction, cement, lime and agricultural purposes. The leading producers (Honolulu County) were Pacific Concrete and Rock Co. Ltd., Kaiser Cement & Gypsum Corporation, and Hawaiian Cement Corporation.

Sixteen operators crushed 380,000 tons of miscellaneous stone, valued at $631,000 for use in construction. The leading county was Hawaii and the leading producers were Puna Sugar Company and Yamada Sons, Inc. A small quantity of dimension stone was quarried for rubble and for rough architectural uses. Miscellaneous stone included aa, lava, and moss rock.

Admixtures. Admixtures are imported and readily available from local chemical distributors. Air-entraining admixtures, although used extensively in other areas for increased freeze-thaw durability, are not generally needed in Hawaii.

Steel Reinforcement. Most of the steel reinforcing bar used in Hawaii is produced at Hawaiian Western Steel Ltd. in Campbell Industrial Park. Junked cars are compressed and melted down to produce 50,000 tons of reinforcing annually. Two grades of reinforcing are available: 40,000 psi and 60,000 psi yield strength. Prestressing wire of 250,000 and 270,000 psi yield strength is imported from either the U.S. Mainland or Japan.

Industry Support

A consortium of local companies, known as Cement & Concrete Products Industry of Hawaii (CCPI), has shown continued interest in the Floating City project by making available its personnel and its extensive reference library.

HC&D, a leading member of CCPI, in particular has support the project intensely, not only be offering technical advice but by donating land for assembly of the 1:20 scale model of the Floating City platform and by giving freely of other equipment and facilities.

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