CONCRETO EN ESTRUCTURAS MAR ADENTRO

Por

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Sinopsis: Este trabajo da a conocer los antecedentes relacionados con el uso de concreto en estructuras mar adentro para la explotación de hidrocarburos. Se describen estructuras cimentadas en el fondo, flotantes y otras más especializadas. Se discute el uso de materiales para concreto y la mano de obra de la zona para producir concreto con resistencia moderada para estas plataformas. Se describen las diversas propiedades de tanto el concreto fresco como endurecido que son esenciales en el diseño y construcción de estructuras mar adentro. Se toman en cuenta los diseños especiales y las normas de seguridad. No se requiere de prácticas de construcción especiales. Las estructuras pueden construirse en diques secos, en deslizadores o barcazas sumergibles. Partes de las estructuras pueden ser de concreto prefabricado. Todas esas estructuras involucran alguna maniobra marina. Requieren de muy poco mantenimiento aun en ambiente marino severo y, por consiguiente, los costos de su ciclo de vida tienden a ser bajos.

Palabras Clave: Construcción en barcaza, materiales de construcción, propiedades del concreto, calidad del concreto, prácticas de construcción, diseño, construcción en dique seco, estructuras de concreto flotantes, maniobras marinas, estructuras de concreto en mar adentro, concreto prefabricado, seguridad, construcción en deslizadores.

CONCRETE FOR OFFSHORE STRUCTURES

By

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Synopsis: The paper provides background information related to the use of concrete in offshore structures for the development of hydrocarbon resources. Bottom-founded structures, floating structures, and other more specialized structures are described. The use of local concrete materials and labor to produce moderate strength concrete for these platforms is discussed. The various properties of both the unhardened and hardened concrete that are essential in the design and construction of offshore structures are described. Special design and safety considerations are noted. No special construction practices are required. The structures can be built in dry docks, on skidways, or on submersible barges. Portions of the structures can be precast concrete. All of these structures involve some marine operations. The structures require very little maintenance even in the severe marine environment and thus tend to have low life-cycle costs.

Keywords: Barge construction, concrete materials, concrete properties, concrete quality, construction practices, design, dry dock construction, floating concrete structures, marine operations, offshore concrete structures, precast concrete, safety, skidway construction.

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INTRODUCTION

Offshore concrete structures are generally understood to be those structures exposed to an open-sea environment (1,2). They are designed to remain permanently or semi-permanently fixed to the sea bed by gravity, piles, or anchors, or to remain afloat and moored. They are often associated with the exploration and production of hydrocarbons but may have many other specialized uses.

Like most other types of concretes, concretes for use in offshore structures are usually made with local materials by local labor in conformance to local guidelines or specifications. Thus, they can vary widely in quality. Depending on their particular application, their strengths can vary from 25 to 65 MPa (3600 to 9500 psi). They are all required to be extremely durable. Once a concrete structure is placed in the sea, maintenance becomes very difficult due to the hostile environment and is very expensive. Some offshore concrete platforms have design lives of 50 to 70 years.

The use of concrete in marine structures goes back to the ancient Romans and Greeks. The use of concrete as a hull construction material for commercial vessels began at the end of the 19th century (3). Initial applications were generally world-wide and consisted of concrete barges and pontoons. The first reinforced concrete sea-going ship was the "Namsenfjord", constructed in Norway in 1917. The first concrete platform for oil and gas production in the Gulf of Mexico was installed in 1950. Since that time, more than 1000 related concrete structures have been built in that area (4) with the first concrete gravity base structure in U.S. waters being installed in 1978 (5). The first large offshore concrete platform for the North Sea (Ekofisk Tank) was installed in 1973. Three concrete platforms, functionally similar to those of the North Sea, have been built in Brazil for South American offshore waters (6). Concrete has a long history and a significant and successful presence in offshore and marine applications.

Throughout the paper, reference will be made to things that are "onshore", "inshore", and "offshore". Onshore is on the land. Inshore means that the location is away from the land but is close enough to the shore to be in protected waters with respect to the open sea. Offshore means that it is located in the open sea. The term "owner" is also frequently used. The owner of an offshore structure can be a single company, or it can be a collection of companies who retain varying percentages of the operation but who have designated a single company to operate and maintain the facility.

TYPES OF CONCRETE STRUCTURES

Offshore structures used in conjunction with hydro-carbon exploration and production can generally be grouped as either being bottom-founded or floating. Many of the bottom-founded structures are also required to float at various stages of their life. The following descriptions of the various types of platforms are very brief but are intended to give the reader a feeling for the enormous versatility that can be realized when concrete is used.

Bottom-founded Structures

Bottom-founded structures can be further identified as:

1. Gravity Base Structures.
2. Concrete Cylinder Pile Supported Structures.
3. Floatable/Bottom-founded Concrete Hull Structures.

Examples of each are shown in Fig. 1, 2 and 3.

The gravity base structure (Fig. 1), commonly called a GBS, maintains its position on the sea bottom due to its very large weight. The sliding force and over-turning moment due to the maximum environmental loads are resisted by the weight of the concrete, the operating weights on the structure, and any additional ballast weight that is contained within the structure. This type of structure is common where produced oil must be temporarily stored before being removed to a tanker or pipeline. The practical range of water depths for these platforms is 40 to 350 m (130 to 1150 ft.). These structures are built at onshore or inshore locations and floated out to their final location. They can also be re-floated when platform removal is required (7). More detailed descriptions of these types of platforms can be found in (1), (2) and (8).

Concrete cylinder piled structures (Fig. 2) were the earliest type of concrete offshore platform used. The first Gulf of Mexico platform of this type was installed in 1950. More than 1000 of these platforms have been installed in Lake Maricaibo in Venezuela (4). They consist of an array of prestressed concrete piles which are driven into the seabed. The piles are arranged so that a prefabricated template deck can be placed over the array to form the working surface of the platform. The decks can be made of concrete or any other suitable construction material. Concrete jackets are often placed around the piles in the splash zone and boat impact region of the platform. Steel cross bracing between piles may also be used to stiffen the overall arrangement when the piles become fairly long. The practical range of water depths for these platforms is from 5 to 20 m (16 to 65 ft.). The use of concrete cylinder piles is also common for support of docks, wharves, bridges and roadways over water.

The floatable/bottom-founded concrete hull platforms generally consist of a barge-like concrete hull which is designed to float. Extending upwards from the hull are posts or columns which act as the support frame for the platform (Fig. 3 and 4). These posts or columns can be made of concrete or steel. The hull is floated to its desired location and then water- ballasted down until it sits on the seabed. It is then "pinned" to the seabed by spud piles around its perimeter. These piles maintain the platforms position and help resist sliding and overturning as the platform does not have sufficient on-bottom weight by itself. Once the hull is piled into position, the topsides deck and equipment are usually added using a crane barge. This type of platform has many variations. It can accommodate some subsea storage of produced oil in the hull. The practical range of water depths for these platforms is from 4 to 30 m (13 to 98 ft.). Platforms of this type that are in use in the Gulf of Mexico have, on numerous occasions, been refloated and reused at different locations. Table 1 is a listing of this type of structure constructed by one firm for the Gulf of Mexico and shows typical concrete hull dimensions.

Floating Structures

Floating structures are those structures which will perform their operational function while in a floating mode. These structures will require a permanent mooring system. In general, the current family of floating concrete structures includes:

1. Concrete Tension Leg Platform (TLP).
2. Deep Draft Concrete Floaters (DDCF).
3. Concrete Production/Storage Barges.

Examples of each are shown in Figs. 5, 6 and 7. Large concrete buoy-type floating structures have also been conceptualized.

Concrete Tension Leg Platforms (TLPs) (Fig. 5) derive their name from the fact that they are fastened to large anchors on the seabed by long tethers which have a predetermined amount of tension in them. These tethers, which originate at the corners of the platform, keep the floating platform in a very precise position. The platform itself can have various configurations but generally resembles the semi-submersible drilling rigs which are common throughout the offshore petroleum industry. It consists of an arrangement of base pontoons, shafts or columns which extend upward from the pontoons, and a deck which sits on top of the shafts or columns. The entire hull (pontoons and shafts) and the deck can be made in concrete. The practical range of waterdepth for use of this type of platform is from 300 to 1500 m (1000 to 5000 ft.). The size of the TLP is generally dictated by the amount of operational weight to be carried. Current designs have ranged as high as 50,000 tonnes (55,000 tons).

The Deep Draft Concrete Floater (DDCF) (Fig. 6) is similar in principal to the TLP but uses a conventional mooring system rather than tension tethers. It maintains its positioning during operations due to its extremely deep draft (greater than 130 m (425 ft.)), large weight, low center of gravity, and mooring from the lower portions of the hull. These factors tend to make the structure relatively insensitive to the motions of the sea.

Like the TLP, its configuration can have many variations, but in general, it resembles a TLP but with a very deep hull. Similarly, the pontoons, columns, deck, and any bracing can be made in concrete. The practical range of waterdepth for use of a DDCF is from 300 to 900 m (1000 to 3000 ft.). Like the TLP, the size of the DDCF is generally dictated by the amount of operational weight to be carried. Current designs have ranged as high as 50,000 tonnes (55,000 tons).

A variation of the DDCF is the Spar Buoy Platform (Fig. 8). It also takes advantage of the low center of gravity and heavy weight of the concrete to be relatively insensitive to the motion of the sea. It can accommodate crude storage, if desired. It also needs a mooring system (9).

Concrete Production Barges (Fig. 7) are custom-built prestressed concrete barges that provide a support surface for the process equipment, work and storage areas, and living quarters needed for offshore oil and gas production. Drilling is usually not done from these barges but is done from special drilling vessels or jack-up rigs. The production wells are usually located on a nearby unmanned fixed platform. The entire barge or selected portions of the barge can be built in concrete. A mooring system must be provided for the barge. Storage of the produced oil and other partially processed fluids can be accommodated in the barge. Large floating concrete oil storage facilities have been built in Japan. The size of the barges is influenced by the sea states in which it must operate and the amount of working area it must provide. The water depth in which a barge can operate is a function of the draft of the barge and the operational sea states. A notable production/storage concrete barge is the Ardjuna Sakti liquified natural gas (LNG) barge currently on station in the Java Sea (10). More detailed information on concrete barge-like structures and concrete hulls can be found in (1), (3), and (11).

Other Structures

Concrete subsea oil storage tanks (12,13,14) (Fig. 9) have been proposed for use in waterdepths ranging from 20 to over 400 m (65 to over 1300 ft.). These tanks can be built like the base of a GBS but are fully submerged to the seabed where they function as a gravity base structure.

Concrete wall caissons (Fig. 10) have been used to provide the retaining wall for earth filled islands. These islands provide the working surface for the oil and gas exploration and/or production. The caissons are built as floating units, towed to location, joined into a unit, and then ballasted to the sea floor. The framework of the caissons then forms the perimeter of an island. A hydraulic fill is usually used to fill the interior. When the use of the caisson retained island is complete, the caissons can be refloated, disassembled, and nature allowed to reclaim the island. A notable application was the Tarsuit Caisson Retained Island (15) where the caisson was made of lightweight aggregate concrete. Concrete caissons for an artificial island are a strong contender for development of the Wytch Farm prospect in offshore southern United Kingdom (16). The use of caissons for artificial islands is generally limited to waterdepths of less than 15 m (50 ft.)

Concrete has been used for the base of flare towers and offshore loading buoys. An entire flare boom tower made of concrete will be used for the Sliepner platform in Norway. Concrete anchors (17) for the Snore TLP have been built. The Maureen offshore development uses a concrete offloading buoy. Concrete subsea wellhead protectors for Oseberg II in the North Sea have been built (18).

The potential for concrete use is great and is limited only by the ingenuity of the concrete designer and constructor.

CONCRETE QUALITY

There is a perception that all concrete used in offshore platforms is something unique and special and requires a technology that is beyond "normal practice" for concrete construction. If "normal practice" means the practice applied to residential construction, the perception is correct. If "normal practice" means the practice applied to any major civil engineering structure such as a building or bridge, then the perception is wrong. There is nothing unique or special in the application of proper batching, delivery, consolidation, and curing of properly proportioned concrete mixtures. In general, the recommended practices for concrete construction, including materials selection and mixture proportioning, that exist in the various building codes, specifications, and standard practices of most developed countries are entirely sufficient for use in the offshore concrete industry. Somewhat different values for water-cementitious ratio, cementing material content, and concrete cover over reinforcing bars may be required because of the marine exposure but these values are well documented. Examples are shown in Tables 2 and 3.

The concrete provided for offshore North Sea platforms has seen a gradual evolution of cube compressive strength from 50 to 70 MPa (7200 to 10100 psi) (19). Table 4 shows the strength development for platforms built by one North Sea contractor. The unique environment in which this concrete is used demands this high quality of concrete. The Ravenspurn North platform (20,21) is in a more moderate environment in the southern part of the North Sea and required only 50 MPa (7250 psi) concrete which was delivered from local ready-mix suppliers. The early concrete platforms made in the Gulf of Mexico used concrete with cylinder compressive strengths from 25 to 35 MPa (3600 to 5000 psi). Recent samples from some 33 year old platforms in the Gulf of Mexico showed an increase in strength from 50 to 69 MPa (5000 to 10000 psi) over the life of the structure (22,23). The actual strength required for a given structure depends on a large number of factors but is significantly influenced by the environmental and operating loads. When these are small, the strength of the concrete can usually be consistent with that which is commonly made in the region of the construction.

CONCRETE MATERIALS

As noted earlier, the constituents of the concrete can be local materials. They must be evaluated, however, to ensure that they have the proper concrete making characteristics and will be durable in the environment in which they are used. Most offshore concrete platforms have a service life of 20 years or more. Because of their offshore location, they are not easily accessible for remedial work when problems occur. To eliminate the high cost of future offshore repair work, the materials used and the resulting concrete must be virtually maintenance free for the service life of the structure.

The durability of offshore and marine Portland cement concrete is generally defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration while retaining its original form, quality, and serviceability when exposed to its environment. This includes resistance to deterioration from freezing and thawing action, chemical attack by the constituents of the seawater, physical abrasion due to wave action, floating or suspended solids and debris, and floating ice, corrosion of steel or other metals imbedded in the concrete, and chemical reactions associated with aggregates in the concrete (22). When considering all these deteriorating actions collectively, it is easily deduced that the most aggressive exposure a concrete can routinely experience is in a tidal zone in freezing weather. For most offshore structures, the most prevalent of the destructive mechanisms is the corrosion of reinforcing bars associated with ingress into the concrete of chlorides from the seawater.

Portland cements should have as low of a tricalcium aluminate (C_3A) content as is practical with the local cement production. This helps to reduce the possibility of attacks from sulphates. The total alkali of the cement, calculated as sodium oxide, should not exceed 0.60 percent to minimize any potential for reactivity with the aggregates. The cement should have some finely divided siliceous material added to it (23). This includes natural pozzolans, fly ash, granulated slag, or condensed silica fume. These products contribute to the formation of a denser binder which inhibits the migration of the seawater into the concrete. They also combine with the alkalis to reduce the amount of available alkalis.

Coarse aggregates can be either normal density gravel or crushed stone, or good quality lightweight aggregate. The aggregates should be evaluated with respect to their potential for reactivity with the alkalis in the cement. Those aggregates which are potentially reactive should not be used. Aggregates from areas in close proximity to the sea, should be checked for concentrations of sea salts. These salts must be washed from the aggregate before it is used. Fine aggregates can be either natural or manufactured sands. They, too, must be non-reactive and free from deleterious materials.

In no instance should seawater or brackish water be used to make the concrete. All mixing water should be potable. Washing of aggregates should also be done with potable water.

Chemical admixtures are essential for the production of durable marine concrete. Air entrainment is needed when cycles of freezing and thawing can occur.

High-range water reducing admixtures (HRWRA), commonly called superplasticizers, are required for both consolidation assistance and for improved durability. An HRWRA will allow mixing water reductions up to 30 percent without sacrificing workability. This water reduction significantly reduces the permeability of the concrete and contributes to a densification of the binder fraction of the concrete.

CONCRETE PROPERTIES

Of importance to structural designers are the properties of the materials of construction at an age when appreciable loads are applied to the structure. For most offshore structures, the maximum loadings occur when the structure is put into service. This can vary from 1 to 5 years from the start of construction depending on the size and complexity of the structure and its ultimate use. The properties of hardened concrete that are used by the designers of offshore concrete platforms are:

a. compressive strength,
b. tensile strength,
c. modulus of rupture,
d. modulus of elasticity,
e. Poisson's Ratio,
f. stress-strain relationships,
g. fatigue strength,
h. absorption,
i. shear strength,
j. creep and shrinkage,
k. shear friction capacity,
l. bearing strength,
m. and, thermal properties such as the coefficient of thermal expansion, thermal conductivity, specific heat, and diffusivity.

The numerical value of each of these properties is generally not critical because the design process can usually use whatever values the selected concrete produces. The specific properties may not always be complimentary, however. For example, a very high compressive strength concrete (e.g., 65 MPa (9400 psi)) may allow compressive structural members to be reduced in cross-section for a given loading. If, however, the corresponding increase in the modulus of elasticity of that concrete allows cracking to occur at lower strain levels, then additional reinforcement may be required to reduce the cracking. Because the cross-section has now been reduced, the additional reinforcing steel adds to the congestion within the wall and makes the concrete placement more difficult. The cost of the in-place reinforcing steel may also be more than the reduction in cost due to using less concrete. Trade-off's between the various properties of the concrete should be attempted, where possible, to achieve the most efficient and cost-effective design.

All of the hardened concrete properties should be determined at advanced ages for the specific concrete to be used in an offshore structure. Unfortunately, this is not always

possible and early age properties (e.g., at 28-days age) are often used. This gives the design a conservative flavor but it may add substantial costs to the structure. There is a risk associated with extrapolating early age data, particularly with high strength concretes, because the improvement of concrete properties with age may not always follow assumed trends.

Other properties of the concrete are of concern to the constructor rather than the designer. These include:

a. workability,
b. pumpability,
c. unit weight,
d. air content,
e. consolidation,
f. thermal gradients,
g. and, finishing.

The inter-relationship of these properties is a complex problem. Of utmost importance is the unit weight of the concrete. For a structure of given dimensions and configuration, and that may also be required to carry a fixed amount of dead load while floating, variations in the concrete unit weight may adversely affect the floating stability of the structure, causing it to sink or overturn. The in-place unit weight, in turn, is affected by the mixture ingredients, their proportions, and the void content, which is both a function of the entrained air content and the entrapped air or voids remaining after consolidation. If the mixture does not have adequate workability to surround the high levels of reinforcing bars that may occur, additional voids could result in the concrete. The absorption values determined on the hardened concrete are applied to the hardened density of the concrete to establish what the concrete density is when the structure is in the water. If the actual density varies significantly, so will the actual absorption values which will be different than those used in the design process.

As described later, the typical structural members in an offshore platform are quite thick. Because most offshore codes require fairly high cement contents (see Table 2) for durability purposes, the possibility of significant heat development within the concrete exists. Limiting values for the maximum placing temperature and the maximum heat rise are contained in the Codes. Even when meeting these requirements, care must be exercised to minimize thermal gradients so that thermal cracking of the structural members does not occur.

The finish of the concrete surface of an offshore structure may seem like a non-critical item, but a poor finish can have several undesirable effects beside appearance. For most offshore structures, the governing design load is caused by the forces from sea waves acting on the surface of the structure. Rough surfaces tend to gather more wave forces and thus reduce the factor of safety planned for a structure. In cold climates, an initially rough surface tends to degrade faster when subjected to cycles of freezing and thawing because there are receptacles in the surface of the concrete for water to collect and freeze. In ice-infested waters, ice moving against and past a structure tends to abrade rough surfaces faster than smooth surfaces (23).

Other properties of the concrete that are usually not of concern to either the designer or the constructor, are the durability properties. These are of concern to the owner as the offshore structure is usually part of a profit making venture that has a prescribed life-time. Some of the durability aspects of the concrete, such as freezing and thawing resistance, are addressed in the Code requirements. Matters such as the air void system in hardened concrete, as defined by spacing factor, specific surface, and voids per millimeter (inch), have specific requirements which must be met. Guidance is also provided in the Codes to prevent or mitigate such deleterious effects as sulfate attack and alkali-aggregate reactivity through proper materials selection.

Chloride-ion permeability of the concrete should also be evaluated to insure that a satisfactory concrete is being provided to resist reinforcing bar corrosion. Although minimum concrete cover over the reinforcing bars is specified for a given exposure zone (see Table 3), this may have to be increased if the concrete to be used in the platform does not have adequate resistance to chloride-ion penetration.

The abrasion resistance of the concrete to water-borne sediments, debris, floating objects, and ice is usually not specified as it is a rather site-specific phenomenon. In offshore areas where significant abrasion can occur, such as ice-infested waters, the resistance of the concrete to the abrading medium must be evaluated and loss rates for the concrete surface determined (24). Once these rates are known, measures to accommodate or eliminate the losses, such as additional concrete cover or steel plates in the abrasion zone, respectively, can be implemented.

An evaluation of all the concrete properties noted above for a specific concrete for a specific structure is the ideal situation, but it has not often been done. When actual numerical values are not available, conservative approximations are chosen and these result in a satisfactory, but not necessarily cost efficient, design. One study that addressed most of the properties noted above, was performed on high strength lightweight aggregate for use in offshore Arctic structures and is described in (25) to (27).

DESIGN CONSIDERATIONS

As noted above, concrete offshore structures can be bottom-founded or floating. With the exception of a structure which has its base made entirely from prestressed concrete piles, most of the other bottom-founded structures are in a floating mode at some time in their early life. These structures must then include design provisions for both bottom-founded operational loads as well as those loads associated with the structures behavior as a ship.

Design codes and guidelines for offshore concrete structures have been developed by various regulatory agencies and standards groups. A listing of some of the major codes and regulations is shown in Table 5. These are constantly being upgraded as the technology advances. In general, detail design of the individual elements of an offshore concrete structure for such things as shear, tension, flexure, compression, eccentric loads, etc., is not significantly different than for any other type of concrete structure. It is only the types of loads, their frequency and duration, and their magnitude that differs from ordinary civil engineering structures.

The principal loads the offshore structure encounters are permanent loads, variable functional loads, environmental loads, accidental loads, and deformation loads. These various loads are combined in realistic manners to determine their net effect.

Permanent loads include the weight of the structure, any permanent equipment, ballast that will not be removed, and the external hydrostatic sea water up to mean sea level. Variable functional loads are the loads associated with the normal operation of the structure. Loads in this category that are unique to offshore structures include variable ballast, installation and drilling loads, vessel impact, fendering and mooring, weight of petroleum products temporarily stored in the platform, helicopter loads, and crane operations.

Environmental loads include waves, wind, current, ice and snow, and earthquake. Accidental loads include fire, explosion, ship impact, unintentional flooding, unintentional ballast distribution, and changes in presupposed pressure differences. Examples of deformation loads include prestressing, concrete shrinkage, and thermal gradients.

The geotechnical considerations offshore are much more complex than onshore. For bottom-founded structures, this is an extremely critical area of design. The anchors and moorings of floating structures are also significantly influenced by the subsea soil conditions. Seismically active areas warrant special consideration. Specialists in subsea foundation problems, not onshore foundation specialists, should always be used to work this part of the design problem.

For the initial offshore concrete structure in a country or region that has never used one before, it is desirable to use the design expertise of companies or firms that have prior experience with these structures. Such firms exist in North America, Europe, Scandinavia, United Kingdom, and Japan. By involving local design firms in partnerships with these experienced firms, the philosophy and mechanics of the design process can be transferred to the local regions.

SAFETY CONSIDERATIONS

Modern offshore concrete platforms are designed with sufficient redundancy to resist major accidental loads. Concrete has exceptionally good impact resistance and only a few isolated instances of structural damage due to ship impact have been reported. Sufficient ductility can be designed into structural concrete elements to eliminate the problem of progressive collapse. The fire resistance of concrete is well known with concrete often