

Durability of Concrete Exposed to Marine Environment—A Fresh Look

by P.K. Mehta

Synopsis: From recently reported case histories of concrete deterioration in seawater, the author has taken a fresh look at the conclusion presented on this subject at the last CANMET/ACI Conference on the Performance of Concrete in Marine Environment. It is confirmed again that between seawater and the constituents of hydrated cement paste harmful chemical reactions, such as carbonation, sulfate attack, and magnesium ion attack can be limited to the surface when well known measures to assure low permeability of concrete have been put into practice.

From standpoint of permeability of concrete the topics discussed in detail include selection of materials and mixture specifications, concreting practice, and control of in-service cracking due to thermal gradients, frost attack, improper loading conditions, fatigue, and corrosion of the embedded steel in concrete. The ACI and FIP Recommended Practice for offshore concrete structures, and recent field experience from the North Sea are compared, to highlight the issues that are relevant to long-time durability of concrete. Since high-strength concretes (50 to 70 MPa), containing water-reducing and mineral admixtures are relatively impermeable, in the opinion of the author they offer an excellent solution to the problem of durability of concrete in seawater environment.

Keywords: concrete construction; concrete durability; corrosion; deterioration; fatigue (materials); marine atmospheres; mix proportioning; permeability; reinforced concrete; reinforcing steels

P. K. Mehta, F.A.C.I., is Professor in the Civil Engineering Department at the University of California at Berkeley. He is the author or coauthor of more than 120 technical papers and a book on microstructure and properties of concrete. In March 1988, he received the Wason Medal for Materials Research awarded by the A.C.I.

INTRODUCTION

At the last CANMET/ACI Conference on the Performance of Concrete in Marine Environment, the author (1) reviewed the case histories of several concrete structures, which had shown damage on long-term exposure to seawater. From mineralogical analyses of deteriorated concrete samples, it was possible to describe the physical and chemical interactions between seawater and the typical constituents of portland cement paste. It was concluded that magnesium, sulfate, and chloride ions, and dissolved CO_2 present in seawater, can indeed act as agents of destruction for all the hydration products of portland cement (namely, the calcium silicate hydrates, calcium aluminate and sulfoaluminate hydrates, and calcium hydroxide). The case histories clearly showed that although portland cement paste contained seeds of potential deterioration, these seeds did not germinate and grow into products which caused serious deterioration unless seawater was able to penetrate into the interior of concrete. Permeability rather than the chemistry of concrete was thus identified as the most important factor in long-term durability.

Based on a review of some recently reported case studies of concrete deterioration in marine environment, this paper takes a fresh look on the conclusions drawn by the author eight years ago. Also included here are recent developments, and a review of some current design codes as well as field practice for the construction of modern sea structures.

RECENT CASE HISTORIES OF CONCRETE DETERIORATION

In 1979 the western half of the Hood Canal (Washington State) floating bridge broke up and sank during a heavy storm (2). Although corrosion of the reinforcing steel was not the principal cause of the mishap, inspection of the eastern half of the bridge revealed severe steel corrosion in several areas including the concrete deck slabs. It was suspected that the concrete had become permeable to seawater as a result of microcracks formed by numerous wetting/drying, heating/cooling, and loading/unloading cycles. Parallel to visible cracks, the corrosion in the reinforcing steel was found to be most severe (Fig. 1).

In 1980, spandrel beams of the San Mateo-Hayward bridge in California had to be repaired due to serious cracking of concrete caused by corrosion of the embedded steel (Fig. 2). High quality concrete (370 kg/m³ cement content and 0.45 water-cement ratio) had been used for making both steam-cured precast beams and naturally-cured cast-in-place beams, which were made 17 years ago. No

cracks and corrosion were in evidence in the cast-in-place concrete, however all steam-cured beams showed cracks and corrosion at the underside and windward faces which were directly exposed to seawater spray. It is suspected that in the massive beams (7.9 x 3.7 x 1.8 m), a combination of heavy reinforcement and differential cooling rates in different parts of the beam (subsequent to the heating cycle in steam-curing) produced invisible microcracks, which later became continuous in the part of the structure that was exposed to severe weathering. Thus under adverse service conditions presented by the typical marine environment, even an impermeable concrete, could eventually become permeable and therefore vulnerable to a corrosion-cracking cycle, leading to serious structural damage.

With reinforced concrete structures exposed to marine environment, structural cracking does not lead to corrosion as long as the remaining concrete is impermeable, and especially if the concrete is fully submerged under water. It is assumed that reinforced concrete will crack in service, however the designers tend to limit the crack widths in the belief that a relationship exists between crack width and corrosion. Beeby (3) proposed that although larger cracks are likely to cause the breakdown of the passivity of the reinforcement rather earlier and hence initiate the corrosion earlier, there is no reason to expect the rate of corrosion to be influenced by the surface cracks unless these cracks represent widespread internal cracking.

Many investigations are reported in the published literature on the rates of diffusion of oxygen, water vapor, and chloride ions in hydrated cement pastes because their presence at the surface of steel is necessary before galvanic corrosion cells can form. In high quality concrete the transport of gases and ions by diffusion is an exceedingly slow process, however it is relatively faster by permeation through an interconnected network of microcracks and capillary voids. In a diagrammatic presentation (Fig. 3), Mehta and Gerwick (2) proposed that such a network of microcracks already exists in concrete and that the widening of microcracks in service due to numerous causes would precede the corrosion process.

Researchers with practical experience in concrete durability problems seem to concur with the viewpoint expressed by Mehta and Gerwick (2). For example, Idorn* says, "I agree fully that cracking in concrete is the primary precursor to corrosion, also where chloride ions are involved. By nature reinforced concrete has cracks, and due to practical conditions most structures have cracks from the beginning that are wide enough to cause ingress of saline water by capillary action. Naturally in this way as soon as chloride ions reach the rebar, one has a powerful anodic-cathodic potential, and with free moisture abundantly present, corrosion will proceed. The possible concurrent ingress of chloride ions by diffusion will be a much slower process."

Gjorv and Kashino (4) were able to obtain valuable data from a detailed investigation on durability of concrete in a 60- year old reinforced concrete pier in Oslo harbor, before the structure was demolished. Originally, a non air-entrained concrete of 25 to 30 MPa quality (350 kg/m³ cement content, 0.53 water-cement ratio) had been prescribed. However after 60 years of seawater exposure the concrete in the deck had a compressive strength of 42 - 45 MPa and

*G. M. Idorn, private communication, October 8, 1986.

a permeability coefficient of 2.5 to 8×10^{-13} kg/Pa m.s. The permeability of concrete in the pillars was even lower. Although an ordinary portland cement with a relatively high C_3A content ($> 9\%$) had been used, the low permeability of the concrete provided satisfactory chemical resistance. This confirms the observation made by several other investigators cited earlier by the author (1) that, with concrete exposed to marine environment the high C_3A content of the cement has no adverse effect on durability as long as the concrete has a low permeability. Only to a depth of approximately 5 mm and in large air voids, precipitation of ettringite crystals was noted by Gjorv and Kashino (4). The authors reported the existence of some microcracks to a depth of about 10 to 35 mm, but these cracks were suspected to be the result of thermal stresses during construction.

By subjecting concrete samples to freezing and thawing tests in the laboratory, it was confirmed that the concrete had a poor frost resistance. In the tidal zone, all pillars had either been repaired or were severely damaged by the action of frost. An analysis of the air-void system of a concrete sample showed 1.7% total air content, of which voids below 300 μm comprised only 0.4%, and the average void spacing was 0.35 mm.

Gjorv and Kashino (4) found very interesting results in regard to depth of carbonation, chloride penetration, and corrosion of steel in concrete. In the upper part of the deck and in the fully submerged part, the carbonation depth was quite low (1 to 8 mm); only in the lower part of the deck carbonation depths up to 33 mm were recorded. Similarly, in the upper part of the tremie-cast pillars the depth of carbonation was high (23 to 24 mm) but in the tidal zone and submerged parts it was quite low (1 to 7 mm). In the lower part of the deck, the chlorides had penetrated to a depth of more than 80 mm and the chloride content at the steel bar was 0.05 to 0.1% by weight of concrete. In the fully submerged part, the corresponding chloride content was 0.3 to 0.35%.

The pier had been subjected to frequent maintenance and repair jobs during 60 years of service life. The first repairs were carried out after 10 years because of steel corrosion in deck beams; however, due to deterioration of concrete from frost action extensive repairs (by recasting and jacketing) were carried out after 16 years of service. The authors observed that cleaning and recasting of cracks in spalled areas from steel corrosion did not stop subsequent corrosion because after a few years new cracks appeared in the adjacent areas.

Although deck beams at the inner and most protected parts of the pier were in good condition, at the outer and exposed part of the pier all deck beams had suffered cracking due to rebar corrosion. Many slab sections showed a similar problem. Several of the pillars also cracked from rebar corrosion in the top part above the tidal zone; the fully submerged parts of the pillars did not show any rust staining or corrosion cracking. The findings of Gjorv and Kashino (4) are generally in accord with this author's conclusions (1), which were based on a review of case histories of other structures that had similarly been exposed for a long time to seawater.

Recently, Gerwick* found a case of very extensive corrosion of reinforcing steel on a major seawater transport project in the Middle East. He believes that the corrosion of steel due to high chloride permeability was made possible because of multiple microcracks in concrete, which occurred as a result of frequent thermal and humidity changes (extremely hot days followed by cold nights). The use of porous and permeable limestone as a coarse aggregate in the concrete probably contributed to the problem.

CONCLUSIONS FROM THE CASE STUDIES

From a review of case studies described above and in the earlier publication (1), the author firmly believes that **the permeability of concrete is indeed the key to overall durability**. For construction of durable concrete sea structures, the following lessons from the past should be helpful:

1. Harmful chemical reactions between the constituents of hydrated cement paste and seawater, such as carbonation, sulfate attack, and magnesium ion attack, can be limited to the surface when well known measures to assure low permeability of concrete have been rigorously implemented.

Unreinforced concrete structures made with low water-cement ratio and high cement contents (e.g., more than 350 kg/m^3) have generally shown a satisfactory service life in marine environment except when they had been exposed to high thermal gradients, frost action, or alkali-aggregate attack. The structures built since 1950's have usually been protected from frost action by proper air entrainment, and from alkali-aggregate attack by the use of low-alkali portland cement and/or pozzolanic additives. Both carbonation attack and sulfate attack will essentially be negligible in modern sea structures made with low-permeability concrete mixtures.

2. The causes of high permeability in newly built concrete structures are not limited to poorly proportioned concrete mixtures, such as those with low cement content, high water-cement ratio, and improper aggregate grading. With well-proportioned concrete mixtures a frequent cause of high permeability is the poor concreting practice, such as incomplete mixing of concrete, inadequate consolidation and curing after placement, insufficient concrete cover over reinforcing steel, and badly constructed joints. Areas of heterogeneity in the microstructure of hardened concrete are potential sites for development of microcracks.
3. Even well-constructed structures, made with high-quality concrete mixtures, can become permeable in service due to excessive cracking caused by various reasons, such as settlement, premature loading, overloads, and repeated impact. This is especially the case with reinforced concrete, which contain microcracks to begin with, as discussed next.

*B. C. Gerwick, private communication, 27 February 1987.

4. With reinforced concrete structures, it is a common observation that concrete spalling and cracking are frequently accompanied by corrosion of the embedded steel. The reinforcement does not prevent the cracking of concrete due to drying or thermal shrinkage; by restraining the shrinkage of concrete the steel reduces the crack widths so that instead of a few wide cracks numerous microcracks are formed. It is the widening of these cracks in service due to various causes that facilitates the permeation of ions and gases, which are needed for the corrosion process to proceed. Corrosion leads to further cracking, and this cracking-corrosion cycle results in enhanced permeability and eventually in serious structural damage.

In short, to obtain long-term durability of concrete sea structures, the control of concrete cracking in service is of as much importance as the control of concrete permeability through proper mix proportioning and concreting practice.

RECOMMENDED PRACTICE FOR MODERN CONCRETE SEA STRUCTURES

Lessons from case studies of concrete deterioration by seawater, as summarized above, have been generally incorporated into industry codes which, when carefully followed, should enable us to build concrete sea structures that will remain serviceable for longer periods than the structures built in the past. However, many modern sea structures built during the last 10 to 15 years are required to withstand unprecedented demanding stress conditions. For example, offshore concrete structures in the Arctic and the North Sea, which are exposed to enormous hydrostatic and differential pressures, not only require very high strength but also resistance to abrasion and impact from floating ice, and are heavily reinforced as well as prestressed.

To protect the embedded steel from corrosion, it has become imperative that concrete mixtures with very low permeability are used. The recommended practice for durability of reinforced and prestressed concrete in offshore structures has for obvious reasons the most stringent requirements in the construction industry. A brief review of the recommended practice will be useful here because the technology of making high strength-high impermeability concrete has generated considerable research and development in the field of new materials and concreting practices.

In the United States and Canada, the report by ACI Committee 357 (ACI 357R-84) is used for the design of fixed reinforced and prestressed concrete structures for service in a marine environment. In Europe and Asia, for the design and construction of concrete sea structures it is customary to use the recommendations of the International Federation of Prestressed Concrete Structures (FIP, 4th edition, 1984). From standpoint of durability both the ACI and FIP codes provide that a coastal or offshore structure be divided into three zones: the SUBMERGED ZONE where the concrete is continuously under water, the SPLASH ZONE where the concrete is constantly subjected to wetting and drying, and the ATMOSPHERIC ZONE which is above the splash zone. Since the severity and type of durability problems are different for different zone, the properties of a concrete mixture need not be the same for the entire structure.

Generally speaking, for long-time durability of coastal and offshore structures the concrete must show resistance to: THERMAL CRACKING, FROST ACTION, ABRASION/EROSION LOSS, and EXPANSIVE CHEMICAL AND ELECTROCHEMICAL PHENOMENA (such as alkali-aggregate reaction and corrosion of reinforcing steel). The permeability of concrete is important in all three zones because it influences all physical and chemical phenomena causing concrete deterioration. It should be noted that the abrasion/erosion loss is usually limited to the splash zone whereas most other durability problems can occur both in the splash zone and the atmospheric zone (1).

On long-time exposure to seawater the concrete in the submerged zone, if permeable, may experience a mild deterioration, caused by chemical attack. The rate of attack is very slow because the insoluble products of chemical interaction between seawater and hydrated portland cement paste - such as brucite (magnesium hydroxide), aragonite (calcium carbonate), and ettringite (calcium sulfoaluminate hydrate) - deposit in voids and microcracks, thereby reducing the permeability of concrete. From a study of the pore size distribution of hydrated portland cement paste by mercury intrusion porosimetry, Midgley and Illston (5) have concluded that even the penetrating chlorides reduce the size of small pores thus reducing the permeability. It should be noted that this sort of protection form the sealing of voids and microcracks by the formation of insoluble products will not be available in the splashing zone because there the structure is constantly under the influence of tidal action and impacting solids, such as sand, gravel, and ice. As a result of loss of cover due to abrasion and microcracking, the concrete gradually become more permeable and, therefore, vulnerable to other types of attacks.

Although both the ACI and FIP recommendations for design and construction of concrete sea structures were published quite recently (1985), it is not surprising that the recommended practice lags behind the current (1986-87) field practice. A sufficient amount of published data is now available from field experience in the North Sea where 20 offshore concrete platforms have been constructed during the period 1972-87 (6,7). It will be useful therefore to compare the North Sea field practice with the ACI and FIP recommendations regarding the selection of concrete-making materials, concrete mix proportions, and construction practice for long-time durability. The recommendations on the selection of materials and mix proportions are summarized in Tables 1 and 2, respectively, and will be discussed next.

Selection of Concrete-Making Materials

Cement Composition—The ACI maximum limit of 10% C_3A in portland cement is based on the questionable assumption that cements with higher than 10% C_3A are susceptible to sulfate attack in seawater. Although seawater typically contains 2700 mg/liter sulfate ions, which is nearly twice the concentration for which the ASTM Type V portland cement ($< 5\% C_3A$) is generally recommended, the author (1) cited three case studies where no sulfate attack was observed in long-time (46 to 67 years) seawater exposure of concretes made with cements containing 14 to 17% C_3A . These were low-permeability concretes with high cement content. Similarly, Mather (8) confirmed that concrete prisms made with a high- C_3A (12.5%) ASTM Type III portland cement, did not show any lack of chemical durability after more than 30 years of seawater exposure at Treat Island, Maine. It seems that ettringite does form as a result of chemical interaction

between seawater and portland cement paste but the formation of ettringite in the presence of seawater is not accompanied by expansion and cracking. A possible explanation for this phenomenon is that ettringite expands only when it forms in an environment saturated with hydroxyl ions. The deleterious expansion does not occur when hydroxyl ions in a cement paste have been replaced with chloride ions (9).

From standpoint of chloride corrosion of steel, recent research studies seem to provide some justification for a minimum C_3A limit in portland cement, although it is worth emphasizing that the chloride diffusion alone is not sufficient to cause corrosion. Page et al (10) investigated the influence of different cement types on rates of chloride diffusivity in the hydrated cement pastes. The diffusion rates for chloride ions in ASTM Type I cement pastes were not found to be significantly different between cements with 7.7% C_3A and 14.3% C_3A . On the other hand, an ASTM Type V portland cement (1.9% C_3A) showed a significantly higher chloride diffusion rate than Type I portland cements. Recent work by Rasheeduzzafar et al (11), from laboratory and field tests in the Middle East, has confirmed that the chloride diffusion rate with Type V portland cement paste is somewhat higher than with Type I portland cement. More importantly, blended portland cements containing 30% Class F fly ash or 65% granulated blast-furnace slag were found to produce pastes with considerably lower diffusion rates than portland cements.

As for the current field practice, it may be noted from Table 1 that for the construction of Condeep SP Gullfaks C the Norwegian Contractors switched from a coarser Type I portland cement to a finer Type II (moderate C_3A) portland cement. This was done from cement-superplasticizer compatibility considerations and to obtain better slip-forming characteristic in concrete.

It seems that the limits on the C_3A content of cement, such as given by the ACI Recommended Practice, are outdated. The fineness and the C_3A content of a cement may be important from the standpoint of their influence on the rheology of superplasticized concretes, and not due to any long-term durability effects as implied in the ACI recommendations. Theoretically, for concrete sea structures the use of any ordinary portland cement (6-12% C_3A) should be satisfactory provided the cement is compatible with the admixtures to be used which, of course, among other things, will also depend on the alkali content of the cement. In the current field practice heat of hydration and permeability considerations require that, respectively, the use of the ASTM Type III and Type V portland cements be discouraged and the use of portland-pozzolan cements and portland- blastfurnace slag cements be given special consideration.

Admixtures--There seems to be sufficient evidence that, for obtaining impermeability and abrasion resistance* which are essential for long-time durability of concrete exposed to seawater, both water-reducing and mineral admixtures should be used. The FIP recommendation provide that high-quality pozzolanic materials, such as special silica fumes may be added to produce improved strength, durability, and workability. However, contrary to overwhelming evidence from both laboratory and field practice, the ACI 357R-84 does not appear to take a clearly supportive stand in favor of the use of

*Abrasion/erosion resistance is needed mainly in the splash zone.

pozzolanic and cementitious admixtures in concrete sea structures (silica fume and ground granulated blast-furnace slag are not even mentioned in the ACI recommendation). However, some recent publications provide a wealth of useful information on the composition and properties of important concrete admixtures (12-16).

This author believes that by improving the workability, reducing the heat of hydration, and increasing the strength of the transition zone between aggregate and cement paste, fine particles of a mineral admixture are able to enhance the homogeneity in hardened concrete microstructure. This improves the ability of a concrete to resist microcracking, which is important for maintaining the impermeability during service. The amount of a mineral admixture needed for this purpose will vary with its particle size and chemical composition. Whereas 15 to 25% fly ash by weight of total cementitious materials may be adequate, generally 50 to 70% granulated blast-furnace slag is needed to achieve similar properties. Due to the exceedingly small particle size, only 5 to 10% condensed silica fume is usually enough.

Similarly, to enhance the homogeneity in hardened concrete microstructure, it is essential to use a low water-cement ratio and to obtain a proper dispersion of the cementitious materials in a fresh concrete mixture. Water-reducing admixtures are commonly used for this purpose. In earlier work (Condeep Beryl A, 1974), a lignosulfonate type water-reducing agent was employed. This type of admixture is produced from an industrial by-product containing certain impurities which, when present in excessive amounts, are known to cause considerable air entrainment and set retardation in fresh concrete mixtures. High-purity naphthalene or melamine sulfonate type water-reducing admixtures, also called superplasticizers, are now preferred because they do not lead to excessive retardation and air entrainment. Furthermore, as illustrated by Fig. 4, the naphthalene or melamine sulfonates are better dispersing agents for cement-water suspensions than lignosulfonates. This is because lignosulfonate molecules exhibit a high degree of cross-linkage and form spherical microgel flocs which, unlike the linear molecules of a superplasticizer, are not able to cover the cement grains efficiently.

Air entraining admixtures are now invariably used in concrete mixtures when resistance to cracking due to freezing and thawing cycles is desired. With ordinary concrete (0.4 or higher water-cement ratio), air entrainment with a minimum spacing factor of 0.2 mm is recommended. Researchers including Malhotra (17) have shown that it is difficult to entrain sufficient air with the desired minimum spacing factor when the silica fume content is more than 20-30% by weight of cement. In laboratory tests by the author, air-entrained concretes with up to 15% silica fume performed satisfactorily to freezing and thawing cycles (ASTM C 666 Procedures A and B). Pigeon et al (18) reported from laboratory tests on concretes containing 9% condensed silica fume and 0.3 water/cement ratio that enough freezable water was present in these low water cement ratio specimens to cause damage in freezing and thawing tests, unless air entrainment was used. With the particular materials and test conditions used by the authors, the value of critical spacing factor was 400 μm for the silica fume concrete, and 400 μm without the silica fume. As a safeguard against the loss of air on incorporation of a fine sand, a pozzolan, or a superplasticizer in a concrete mixture, it is essential that the air content and the void spacing are confirmed by taking core samples of hardened concrete from the structure.

Both ACI and FIP warn that when two or more admixtures are used, their compatibility with the cement and aggregate types to be used for concrete-making, should be documented. Also, to protect reinforcing and prestressing steel from corrosion, no CaCl_2 or admixtures containing chlorides should be used.

In regard to the North Sea field practice, it may be noted that the concrete for Gullfaks C (1986-87) contains 5% condensed silica fume by weight of cement and 6 liters/m³ of a naphthalene sulfonate superplasticizer (7). Air entrainment was used for the splash-zone concrete, and a spacing factor of 250 μm was obtained with 3 to 5% air.

Aggregates

ACI 357R permits any natural sand and gravel or crushed rock that conform to ASTM C 33 specifications for concrete aggregates. FIP recommends that aggregates likely to undergo physical or chemical changes should be avoided. In addition to these recommendations there are other points discussed below, which must be considered in the selection of aggregate for obtaining long-time concrete durability.

Microcracking in the transition zone between coarse aggregate particle and cement paste seems to be the most important cause for the increase of concrete permeability in service. The particle size, shape, and mineralogy has a great influence on the strength and therefore the microcracking behavior of the transition zone. Generally, normal-weight aggregate particles that are larger than 20 mm and either too elongated or too flat tend to accumulate bleed-water in their proximity. This results in a porous and weak transition zone, which microcracks easily and can thus become a contributing factor in increasing the permeability of concrete. Table 1 shows that the maximum size of aggregate for concrete used in the construction of Condeep structures in the North Sea has been reduced from 32 to 20 mm, although the recommended practice in the codes makes no attempt to suggest a relationship between the maximum size of aggregate and the permeability of concrete.

Sandstones and quartz aggregates do not form strong chemical bonds with portland cement paste and their coefficients of thermal expansion are also considerably higher than the cement paste. On the other hand, limestone and lightweight aggregates not only form strong chemical bonds but also show less mismatch with the cement paste matrix regarding thermal and elastic properties. Consequently, in seawater exposure, concrete mixtures made with limestone aggregate (2), and with lightweight aggregate (19) have shown better durability than similar concrete mixtures made with quartz or sandstone aggregates.

The aggregates for the splash zone concrete, where resistance to heavy erosion is required, should be hard and strong. Also, a relatively high coarse to fine aggregate ratio (e.g., 65 to 35%) should be used. Field experience with moderately good-quality concrete (30 to 40 MPa) and also with high-quality concrete (50 to 60 MPa) has shown that under conditions of severe abrasion/erosion, it is usually the coarse aggregate-cement paste bond that fails, which causes the aggregate particles to pull out. The incorporation of a highly reactive pozzolanic material, such as condensed silica fume into a concrete mixture improves considerably the aggregate-cement paste bond and, consequently, the

abrasion/erosion resistance of the concrete. Gjorv et al (20) reported that a very high-strength concrete mixture (150 MPa), containing a jasper or quartz-diorite aggregate, a superplasticizer, and condensed silica fume, showed an abrasion or wet-erosion loss of the same order as that of a granite element used for reference purposes.

Concrete Mixture Specifications

Specifications for structural concrete usually contain a minimum 28-day compressive strength requirement, a maximum permissible water to cement ratio, a minimum cement content, and a minimum consistency for placement and consolidation of the fresh concrete mixture. Except freeze-thaw resistance, the 28-day strength is generally used as an index of concrete permeability and durability. In Table 2 the ACI and FIP recommendations on concrete mix proportions for offshore structures are compared with the North Sea field practice. In spite of the severity of seawater environment, it is regretful that test methods and specifications for concrete permeability have not yet found their way into the ACI and FIP recommended practice.

The compressive strength requirements in Table 2 show that both the FIP and the ACI strength specifications are behind the North Sea concrete construction practice by approximately 15 years. The Ekofisk and Beryl A Condeep structures, built in early 1970's, contained concrete that barely qualifies as high-strength (40 MPa). The modern concrete sea structures in the North Sea are built with very-high-strength (minimum 60 MPa) concrete (7). For instance, the specified strength (56 MPa) for Gullfaks C concrete is approximately 50% higher than the Beryl A concrete (36 MPa). The actual 28-day compressive strength of the Gullfaks C concrete core samples was found to be approx. 70 MPa. It should be noted that, in general, the higher the strength the higher will be the impermeability.

Both the FIP and the ACI recommendations require a minimum cement content of approx. 360 kg/m^3 (600 lb/yd^3), however the former recommends a minimum of 400 kg/m^3 cement for the splash zone concrete mixture. The use of high cement content in massive structures frequently leads to thermal cracking, which has the effect of increasing the permeability and reducing durability. In 1970's some thermal cracking was noticed in an offshore concrete structure. Consequently for the construction of Statfjord C (1981), the cement content was limited to 380 kg/m^3 . In spite of a lower cement content, approximately 20% higher strength than the Beryl A concrete (430 kg/m^3 cement) was obtained by the use of a finer cement, a smaller size aggregate, and a superplasticizer.

Compared to the Beryl A concrete, with Gullfaks C (1986) more than 50% increase in the concrete strength was achieved by using essentially the Statfjord C concrete mixture except that the cement content was increased from 380 to 430 kg/m^3 and, additionally, 5% of a reactive pozzolan (20 kg/m^3 silica fume) was used as a supplementary cementing material. In order to prevent thermal cracking adequate measures were taken to control the temperature gradients in concrete.