Marine Concrete Technology

G.M. Idorn

Market Development and Research
Ramboll & Hanneman A/S
Teknikerbyen 38
2830 Virum, Denmark

ABSTRACT

Fort Lauderdale (Florida). ISSN 0749-0208.

This paper deals with the early development of concrete technology and the structural development by means of reinforced concrete which made the Western European and North American rise as industrial regions and leaders of the world trade possible during the 19th century. The early recognition of the importance of strength of concrete and of resistance of structures to the marine environments, and the historic development of durability preserving technology is described. The more recent experience with the effects of deleterious factors, inherent and associated with the investments in construction development in harsher environments in developing countries, is discussed. Recent attention to the importance of monitoring of concrete curing is referred to. Together with research on the nature of the microstructure of fresh concrete this new development is considered essential as the basis for forthcoming development of concrete technology for marine constructions.

ADDITIONAL INDEX WORDS: Concrete, sea water, exposure, climate, durability, workability, curing, history.

INTRODUCTION

The great British engineer John Smeaton invented manufactured hydraulic cement by burning and grinding blends of limestone and clay. He wanted something stronger and more durable than the classic blends of slaked lime and pozzolans, which had been used in Europe since the Roman era. He needed the cement because in 1756 he had been commissioned to build a new Eddystone Lighthouse which could resist exposure to waves and sea water attack, (SMEATON, 1813). His lighthouse which is shown in Figure 1 in a reproduction of a painting made in 1846 was situated at the west outlet of the Channel. It became a remarkable landmark for the development of marine transportation during the 19th Century, and his cement became a remarkable precursor for the use of concrete in marine construction.

The invention of Portland cement by J. Aspdin followed in 1824. Thereafter the classic uses of timber, natural stone and brickwork in port and coastal structures were gradually replaced by mass concrete which was more versatile and could be made by unskilled labourers. The breakthrough of reinforced concrete at the end of the 19th Century enabled engineering skills and imagination to develop modern port and marine constructions. This development comprised structures which depended on strong, heavy concrete where masses were required for mechanical resistance against wave action like in breakwaters, and refined, reinforced structures where high tensile/flexural stresses occurred like in bulwarks, wharfs, shed foundations etc. Thus, port and marine construction has had a significant share in the growth of cement consumption in the world from 24 million tons annually in 1920 to about a billion tons now.

In the classic civil engineering perception, concrete was generally considered almost infallibly durable. Textbooks sometimes even referred to ancient Roman structures, made with hydraulic lime pozzolan mortars, as demonstrations of concrete longevity, and remarkably old Portland cement structures do exist as monuments of past craft and engineering skill. It should not be ignored, though, that many old marine concrete structures have succumbed to destructive forces in their functional environ-

89030 received 12 May 1989; accepted in revision 27 February 1991.
Figure 1. The Eddystone Lighthouse built in 1756 by the British engineer John Smeaton. Reproduction of a painting made by the Danish artist Anton Melbye in 1846.

ment, and that much early research and engineering development had to be dedicated to efforts for ensuring improved durability.

The long lasting port and marine construction boom in Europe during the second half of the 19th Century created much attention to the chemical attack on Portland cement concrete by the sulphates in sea water. Interaction with the calcium aluminate in the cement was found to create the expansive calcium sulphoaluminate hydrate (ettringite), popularly designated the "cement bacillae", which was believed to cause microcracking in hardened cement paste, and subsequent macrocracking of concrete in marine concrete structures.

Comprehensive cooperative research under the auspices of the International Navigation Association in Europe found pozzolanic cements effective as preventive means due to supplementary hydration of the added siliceous materials with the calcium hydroxide which is released by the hydration of the Portland cement. The densification of the cement paste attained by this reaction was also believed to impede ingress of the deleterious, dissolved salts from sea water (Idorn, 1958; Lea, 1970).

Concurrently, the growth of the steel industry in continental Europe created the incentive to granulate blast furnace slag, and to use it finely ground in blends with Portland cement. Experience has proven quality concrete made with the blast furnace slag cements very resistant to marine exposure (Campus, 1947; Eckhardt and Kronsbein, 1950; Kramer, 1960; Schroder, 1986; Regourd, 1980).

In the northern countries freezing and thawing usually have proven more deleterious to marine concrete than chemical attack (Kennedy and Mather, 1953; Idorn, 1962) until adequate air entrainment was introduced after World War II.

Stanton (1940) discovered that hitherto unexplained cracking and expansion in concrete structures in California were caused by chemical reactions between alkalis from Portland cement, and siliceous rock types in the concrete aggregates. Such deleterious reactions were then found to be widespread, first in North
America, then in Europe, and later on in other parts of the world. It was found in the USA, and confirmed by European research, that pozzolanic materials in the cement could impede or prevent the reactions becoming deleterious (Davis, 1950; Pepper and Mather, 1959; Andreason and Christensen, 1957). More recently it has been recognized that pozzolanic reactions (also with fly ash and blast furnace slag in blends with Portland cement) actually are alkali silica reactions in an advantageous modification (Idorn and Roy, 1985).

In the making of marine concrete the importance of good workmanship was acknowledged early on—the harshness of the environment has, so to say, imposed obvious demands for quality. Idorn (1958) compiled descriptions of the meticulous guidelines for concrete making which were prepared and used by the civil engineers of the Danish Board of Maritime works when the comprehensive construction of breakwaters, sluices and fishing ports commenced early this century, especially on the West Coast of Jutland. At that time there was also intensive correspondence and exchanges between European coastal engineers and authorities regarding large scale, experimental concrete field test sites at breakwaters and jetties. Thus, the narratives of Danish experience of those days are likely to represent general European practice.

It is a characteristic feature of this classic concrete technology in marine construction that the entire quality assurance was based upon control of the concrete materials (which did not comprise chemical admixtures) and of the processing, namely the workability and the handling of the fresh concrete and the subsequent wet curing. Optimum granulometry of fine and coarse aggregates, to give suitable rheology with moderate cement contents after sufficient mixing time, was applied along with thorough, human motorised compaction and effective wet curing. This was genuine process control at the completion of which the experienced engineers knew that the product had attained the anticipated quality.

Generalised standard specifications did not exist or were rudimentary, and specimen testing did not exist. The need was not there, and the facilities not available.

Basic Concrete Technology Issues

The general development of structural engineering with concrete has for some decades come to rely primarily on the compressive strength of concrete as the decisive parameter for the behaviour of the material in its structural functions. Correspondingly, the engineering quality control during concrete production has been satisfied by sample testing of the consistency of fresh concrete—the slump test—and with documentation of the quality of hardened concrete by compressive strength testing of cubes or cylinders. These are prepared and tested under controlled laboratory conditions which are not quantifiably related to the conditions for the strength development of the concrete in the structure. Gradually, more tests of the materials and of hardened samples of concrete have been added for quality assurance, but so far primarily with the use of empiric test methods on selected and laboratory treated samples of the fresh concrete. Direct analytical tests describing the basic characteristics of the concrete in a given structure are as yet a rarity.

This generally adopted approach to quality assurance has been adequate as long as the major uses of concrete structures were of conventional design and confined to relatively benign climates, where the civil and industrial development was concentrated. These conditions have also prevailed while accumulation of experience with the durability of the concrete provided solutions to specific causes of deterioration, like sea water attack, freezing and thawing, and alkali aggregate reactions, when problems appeared with these troublemakers. This general evolutionary development has also been adopted for concrete in port and coastal engineering.

The handling of concrete as a material has thus been on a course of pleasant convenience until the post World War II construction era gained its breakthrough during the 60’s and 70’s. It was then that the structural design became greatly refined with higher and earlier strength (and heat) yielding cements. The construction industries became mechanized and conscious of time saving on sites, the classic workmanship became unadaptable and disappeared, and the very hot and the very cold climates with extremes of deleterious impact now
The Need for Strength

Concrete in breakwaters, jetties, groins and other marine structures, the function of which is to absorb the energy of waves, must be constructed to resist truly enormous pressures and instantaneous impact. CARSON (1952) mentions that at Wick in Scotland an 800 ton anchored concrete block at the end of a breakwater was lifted over the structure in a gale. Five years later a new breakwater unit, weighing 2600 tons, was displaced in another gale.

Table 1 is a record of major cases of storm damage to newer concrete breakwaters and jetties in the Mediterranean in the 1960–70 decade (BRUUN, 1985). Apparently, the damage has most often been considered as structural failures. Nevertheless, insufficient tensile and flexural strength of unreinforced mass concrete to resist the wave action may well have played a part in these failures. Uncontrollable high tensile and flexural stresses may, for instance, be imposed by waves where dolosse or other interlocking structural elements are used for the construction of breakwater and jetty slopes.

The need for high concrete strength has been accommodated by the cement technology development, and also by introducing much higher cement contents than in the past. Generally, high strength concrete is also considered desirable as a means of attaining good durability, because a low w/c (synonymous with high strength) is believed to result in low permeability and therewith high resistance to deterioration of concrete in sea water. In modern concrete technology this is, however, a simplification. Both the nature and the effects of various kinds of deterioration of marine concrete, and the ways in which low permeability of the concrete may be obtained, require special attention.
Figure 2 (from Idorn and Roy, 1984) illustrates a case where combinations of modern cement, high cement content and increased initial concrete temperatures (by steam injection in the mix) in a temperate environment caused exorbitant temperature gradients—over 90°C in the center vis-a-vis 30°C on the surfaces—6 hours after casting of a 1.70 m wide concrete cylindric dolos-leg. This temperature development caused simultaneous interior expansion and surface shrinkage, enough to result in initial cracking deep into the mass concrete from the surfaces. Upon demoulding and cooling down such cracks may become invisible, but little resistance remains against handling or the impact of waves.

Alkali Silica Reactions

Map cracking due to alkali silica reactions may also severely reduce the integrity of concrete in marine structures against the impact of waves in storms. Now almost 50 years since the discovery, this kind of concrete deterioration has been found in many parts of the world. The original American identification of reactive rock types and their avoidance, or the use of low-alkali cement as precautions do not suffice today. Neither can the conventional test methods and acceptance criteria ensure the immunity of concrete towards these reactions, especially not in marine environments. The current state of the art therefore suggests careful and meticulous assessments of all facets of any major structural project case as part of the concrete mix design during the phase of the structural design:

- Environmental exposure
- Structural system
- Availability of non-reactive vis-a-vis susceptible aggregates
- Characteristics of available cements
- Characteristics of available siliceous, preventive materials to blend with the available cement
- Requirements for the concrete strength and durability

The quantification of this system approach is inevitably more complex than what usually appears in textbooks, technical guides or national standards and codes of engineering practice.

Table 2 shows that only a few rock types with certainty can be considered non-reactive. Recent experience has shown that where igneous, crystalline or volcanic rocks have been exposed to severe metamorphic alterations or to weathering induced by long-term tropical heat, they may secondarily have acquired susceptibility to the alakalis in concrete.

Figure 3 illustrates the range of mineral composition and morphology of the susceptible rock types which under various conditions have been found are able to cause deleterious alkali silica reactions.

Figure 4 illustrates the variety of features of cracking in reacted aggregate particles of the rock types which, according to numerous case investigations, are characteristic results of the rock composition and morphology, if at all the reactions result in such cracking and in associated radiating microcracking in the ambient cement paste.

The variety range of characteristics of the susceptible rock types and the features of reaction in them, as illustrated in Figures 3 and 4, suggests one of the reasons why test methods, which do not account for the varieties of the material, cannot reveal how reactions may occur and affect concrete in specific structures with one or another type of the aggregates concerned.

For structures in tropical marine environments, the temperatures, humidity and salinity are continuous, activating factors which accelerate and aggravate the reactions. In temperate regions the rate of the reactions may be only one fourth of that in the tropics. In marine structures in polar regions alkali silica reactions must be expected to occur at negligible, slow rates.

Experience from many countries show that in numerous structures with susceptible aggregates used in the concrete, deleterious reactions do not occur, though in some structures with concrete of the same composition damage does develop. In fact, investigations in American, Denmark, England and elsewhere suggest that
in concrete with a potential for alkali silica reactions, these most often happen without causing any damage to the concrete at all. This general feature of alkali silica reactions is another reason why none of the many existing test methods for the reactivity of aggregates are individually reliable for evaluation of the behaviour of reactive aggregates in concrete structures.

Figure 5 illustrates that deleterious alkali silica reactions may happen with susceptible, siliceous aggregate particles and alkalis from the cement. (In marine concrete possibly supplemented by the alkalis in sea water). However, when the siliceous material is of particle size ranges equal to, or less than, the cement the reactions become beneficial and provide increased denseness of the cement paste, in other words, lower permeability of concrete if properly selected and used in adequate mix design (Smolczyk, 1980; Regourd et al., 1980; Bakker, 1981; Idorn, 1984).

Map cracking in unreinforced dolosess of a concrete element may result in loss of the reliability of the structure concerned, especially in hot, marine environments. In contrast, alkali silica reactions do not usually result in significant decline of the structural reliability in reinforced concrete structures as long as the cracking does not result in severe corrosion of the reinforcement.

Sea Water Attack

Chemical decomposition of the hardened cement paste by reactions between components of the dissolved salts in sea water and hydrates of the hardened cement paste are traditionally designated sea water attack. Emphasis has historically been on the transformation of the cal-

Figure 3. Sketches displaying texture, morphology and compositions of the primary alkali susceptible rock types.

Figure 4. Characteristic features of microcracking within and radiating from siliceous aggregate particles of different mineralogy and morphology, when affected by expansive alkali silica reactions.
Figure 5. Deleterious alkali silica reactions may happen in concrete between siliceous aggregates and the alkaline hydroxide of the pore liquid. When the siliceous materials are used in a powdery state of the same particle size ranges as cement or less (silica fume), the reactions become beneficial and provide increased denseness of the concrete if properly selected and proportioned.

Cement + Calcium aluminate hydrates into complex calcium aluminate sulphate hydrates by reaction with the sulphates in sea water, which penetrate into the cement paste. The incorporation of 29–32 molecules of water causes a considerable volume expansion which is assumed to result in expansions and cracking. Aggravated sea water attack may also result in precipitation of magnesium hydroxide and gypsum upon further decomposition of the cement paste (IDORN, 1967).

Pozzolanic additions to ordinary Portland cement were used in W. Europe from the late 19th Century as a means of creating densifying secondary calcium silicate hydrates by reaction between the siliceous material and the calcium hydroxide released by the Portland cement hydration. Hereby the ingress of sea water was impeded.

During the 1930’s cements with low C₃A content were developed and widely specified on the basis of laboratory studies which showed their ability to impede chemical decomposition of the cement paste in mortar bars stored in sulphate solutions. Experiments simulating concrete exposed to sea water attack under natural conditions have in fact rarely been presented, and reports about failure cases with marine or port constructions in sea water are exceptional and usually associated with special conditions (COUTINHO, 1962).

Crystalline calcium aluminate sulphate hydrate (ettringite) is also usually found in concrete which has been exposed to fresh water for some time, because the sulphates from the gypsum content of the cement reacts with the aluminate phase. In concrete exposed to sea water ettringite is often found abundantly crystallized in micro or macrocracks, but usually with a morphology which suggests that the crystallization has taken place where there was available space.

In recent years a more critical attitude has appeared regarding the low C₃A cements, partly because it has been widely experienced that high quality concrete of low permeability is practically immune to the weak concentrations of sulphate in sea water and definitely so in the temperate and colder climates. Besides, the C₃A component has been found to combine with ingressing chloride ions in hardened cement paste, and therefore, at least for a while, might mitigate corrosion attack in reinforced concrete. Moreover, low C₃A cements have been shown to cause higher permeability of hardened cement paste than ordinary Portland cement and in particular blended cements, (HOLDEN et al., 1953). This experience substantiates that along the North European coastlines blast furnace slag cements, for almost a century, have proven effective in the prevention of sea water attack on port and marine concrete structures. It has been experimentally confirmed that they may create so dense a micro-
structure of the cement paste that ingress of alien ions is practically prevented (SMOLCZYK, 1984; BAKKER, ibid.).

Blast furnace slag cements (and some cements with fly ash) are also advantageous by reducing the peak curing temperatures in concrete. This is because heat developed by the initial hydration of the Portland cement fraction of the blended cement is consumed by the activation of the slag fraction. The reduction of peak curing temperatures may be a particularly required effect in massive structures and in hot countries, while the attainable densification of the cement paste compared with what pure Portland cement can produce, is an advantage for ensuring concrete durability under all climatic conditions.

**Corrosion of Reinforcing Steel**

Corrosion of reinforcement has become a widespread form of deterioration of reinforced concrete structures in marine environments, especially due to the construction boom in hot countries during the last 20–30 years.

Reinforcement bars in concrete which is sound and uncracked, are protected against corrosion (i.e. passivated) by the high alkalinity of the pore liquid in the cement paste. However, if the alkalinity (i.e., pH) of the pore liquid of the cement paste in concrete is lowered substantially, the passivation is reduced or eliminated and the reinforcement may corrode. When chloride ions are able to react on the reinforcement, either by ingress through cracks or migration through the cement paste, the passivating effect is broken down and local, high rate corrosion cells may be created. Chloride induced corrosion is evident by relatively rapid progression of the deterioration once initiated and often by a wide range of severity over a given structure. Thus, completely uncorroded steel can often be found close to steel which may be practically all gone (an anode-cathode pair). Furthermore, chloride induced corrosion can have a self-reinforcing effect because cracks already present or caused by the hydraulic pressure exerted during the formation of the corrosion products may widen and serve as avenues for further ingress of chlorides which then accelerate the deterioration.

Basically, the corrosion is a hydration process which creates iron hydroxides as the product of the reactions. This means that the process is sensitive to temperature. This is one reason why corrosion happens much faster in hot countries than in the colder ones. In hot marine environments the combined effects of heat and salinity further aggravate the corrosion which may then take on a very severe course, especially in heavily reinforced structures with too small cover of the reinforcement, or with thicker but porous cover. In cases where hot weather curing has induced initial cracking due to plastic shrinkage, thermal stresses and subsequent drying shrinkage (which frequently appear as problems in hot weather concrete production), the deleterious chloride ingress will happen instantly, and corrosion damage has often become visible within a few months after casting.

**Freeze-Thaw Action**

In marine concrete in northern climates, continuous supplies of moisture and of salts may lead to durability problems due to freezing and thawing, especially to the parts of the structures which are in the splashing or tidal zones. This is because the continuous wetting-drying happens concurrently with the continuous freezing and thawing which, if not immediately, then by fatigue, results in gradual breaking down of the cement paste.

It was research in the USA which during and after World War II discovered that the entrainment of air bubbles in the fresh concrete by means of chemical admixtures could create reservoirs for relaxation of the expansive pressure in the pores of the cement paste during freezing of the capillary water to ice, and thereby make concrete resistant to frost damage, also in marine environments. This discovery has since proven to be major progress in concrete technology wherever freeze-thaw exposure is otherwise a threat to the durability of concrete.

**Marine Concrete in Arctic Regions**

As previously mentioned, the deleterious chemical reactions in concrete which may require that precautions are taken in temperate and warmer climates, will be much slower under arctic conditions. Adequate research and testing will probably show that the conventional acceptance criteria are superfluous, or at
The need for concrete strength as associated with low permeability arises in the arctic regions where considerable ice formations occur in the sea. The ice may impose considerable pressures (i.e., forces) on reinforced concrete structures such as floatable platforms for oil exploration. These structures must by their nature rely on sophisticated structural design so that their dead load is limited and their ability to support equipment etc. is optimized. The scouring of ice may lead to abrasion of the concrete. New concrete can be made to have very smooth surfaces. When the surfaces are abraded off, the roughness is increased and the wear and tear will proceed with increased speed. The resistance of aggregates and cement paste should therefore be primary subjects of attention in the design phase, and the obtaining of a dense microstructure of the hardened concrete ought to be a primary target for the concrete making operations and the quality management.

Interaction of Deteriorating Mechanisms

All physico-chemical deteriorating mechanisms in concrete have in common that moisture is required for the deterioration to proceed. Since moisture is a characteristic feature of the exposure of marine concrete construction, this environment is especially harsh on reinforced or plain concrete structures.

Deterioration of marine concrete structures may be initiated by a single mechanism. For instance, initial thermal stresses, drying shrinkage or alkali silica reactions may cause cracking of the concrete. If the concrete is in a temperate climate, freezing and thawing may aggravate the cracking during the winter seasons. Furthermore, the cracks may, in the case of reinforced concrete works, provide paths for the aggressive salts to reach the reinforcement and initiate corrosion.

For concrete structures located in a warm climate, the heat may in itself be an aggravating factor because heat is a driving energy source which accelerates both the onset and the progress of the deteriorating mechanisms. The classical law which ties heat and the rate of chemical reactions together states that for each increase of ten degrees celsius in temperature, the rate of chemical reactions is doubled. The fact that heat may have such considerable impact on the rate of deterioration of reinforced concrete structures is only now beginning to be realized.

Curing Technology

Heat is produced during the curing of concrete and the rate of chemical reactions between cement and water is temperature dependant in accordance with Arrhenius' law (Verbeck and Helmuth, 1968).

In relatively slender structures, the heat generated by the hydration may be released out into the surroundings and only comparatively modest temperature changes may occur across the cross-section of concrete members. In marine construction, on the other hand, the structures are often rather large, and temperature developments and especially temperature differences between the surfaces and the interior mass of the concrete may create thermal stresses and initial shrinkage which exceeds the simultaneously attained strength at early ages of the concrete.

Thermal cracking may thus occur both while the concrete is in the form, if the form is capable of releasing enough heat out into the surroundings, and if the forms are removed while the core of the concrete is still hot and the surfaces of the concrete become exposed to considerably colder air. In the latter case, the situation may be further aggravated because the still warm outer surfaces may undergo rapid drying shrinkage which will further open the thermal cracks. Severe thermal cracking may also occur if warm concrete surfaces are sprayed with cold water immediately after form removal.

It has been found by experiments utilizing ultrasonic emission that if the temperature difference between the core and the surface of the concrete structure during curing exceeds app. 20°C, there will be a considerably increased risk of developing cracks in the outer portions of the structure. When later the temperature of the core is reduced, it will tend to contract and the cracks may not be visible to the naked eye, but still be there.

While it is relatively straightforward through control of the capacity of insulation of formwork to limit the development of temperature differences during the curing of the con-
crete, a high level of insulation of the formwork may cause the overall total rise in temperature to become excessive at such early stages that the cement paste can not accommodate the concurrent, inherent thermal stresses. This may cause severe interior flaws to appear in the microstructure of the cement paste at the early stages of curing. Thus, it is often advantageous to limit the rate and degree of early heat liberation during curing, for instance by replacements of part of the cement with fly ash or ground granulated blast furnace slag.

Essentially, the heat generated by the reactions between the Portland cement and the water helps to activate the reactions of the fly ash or slag. Accordingly, the initial temperature rise of blended cement concrete is reduced and the early strength development is delayed. This may under some conditions mean longer time from the placement of the concrete until forms can be removed. Further, caution is required to assure optimum wet curing conditions both when Portland and blended cements are used.

During the design and planning prior to the construction of marine concrete structures, it is therefore recommendable to carefully consider the curing technology aspects involved. Based upon previous research by Freiesleben Hansen and Pedersen (1977) and Freiesleben Hansen (1978), planning of the curing technology for construction projects and systematic monitoring of the actual curing during the construction phase was gradually implemented at major bridge projects for the Danish Road Directorate during the 1970's. The curing technology system was described for the design, pre-construction trial and site monitoring during the construction of the Danish Faroe Bridges, 1981–84 (Idorn, 1985; Gotfredsen and Idorn, 1986). The system is being further developed elsewhere (Maage and Helland, 1988).

For the current Great Belt Link construction projects in Denmark the curing technology requirements regarding temperature differences in concrete elements during the curing phase have been specified as follows:

(1) The maximum temperature of the concrete during hardening may not exceed 50°C unless it is documented that the strength after 112 days of hardening is not reduced. The concrete temperature must, under no circumstances, exceed 70°C.

(2) In a deck or wall where the thermal expansion is not obstructed by neighboring structures, the difference between the mean temperature and the surface temperature must not exceed 15°C. This will normally correspond to a temperature difference between the middle and the surface of the structure, not exceeding 20°C.

The difference between the mean temperature of neighboring decks and/or walls cast at the same time shall not exceed 20°C.

The difference between the mean temperature of earlier casts and of neighboring newly cast decks and/or walls shall not exceed 12°C.

The above temperature differences may be exceeded if it is documented that the tensile stresses from these differences are always less than the current tensile strength of the concrete.

For tunnel elements it shall further apply that the difference between the mean temperature of the top slab and the mean temperature of the bottom slab, both located between the same two vertical construction joints, shall never exceed 12°C.

(3) Stripping, tensioning and the carrying of traffic and other loads on structural parts can only take place after the contractor has demonstrated that the structure has obtained the necessary strength. The demonstration shall be based on temperature registrations in the structure.

With corresponding requirements for the contents of fly ash, silica fume and entrained air etc. and for the quality control, the curing technology has been established as an integral part of modern concrete technology in this project. Since the project has been designed and is being constructed by consortia with the participation of major foreign engineering companies, the principles of this new development will soon become acknowledged international practice, and initial thermal cracking therewith a deleterious factor of the past for concrete structures. The specific requirements for individual structures cannot, however, be copied from the above specifications for the Great Belt Link construction works. The design of suitable requirements are required for any type of structure and environment with follow-up trial testing and site monitoring of the actual curing progress in the concrete.
WORKABILITY OF CONCRETE

Experienced crews and site engineers at marine construction works in the past were able to prepare, place and compact (without vibrators) dry concrete of suitable and uniform workability without arbitrary specimen testing. Careful aggregate gradings, low C3S cements of coarse grinding, long mixing times and hard, physical compaction work helped to ensure that the placed concrete acquired a dense microstructure and thus was well prepared for the subsequent periods of effective wet curing. The limited attainable quantity of concrete per pour and day, and the labour intensity of this kind of “low technology” site operations were not critical economic factors of the construction work in those days.

In contemporary concrete technology, the development of pumping concrete since World War II has inadvertently introduced a direct and effective monitoring of the suitability and uniformity of the workability of concrete. This is because successful and profitable use of concrete pumping indispensably depends upon that quality of concrete. Besides, the development of chemical admixtures, and the use of ground, granulated blast furnace slag, fly ash, or silica fume have made it possible to improve the workability of fresh concrete, where the basic materials, Portland cement and aggregates are difficult to combine to provide adequate fresh concrete under present day working conditions. Nevertheless, in many cases concrete structures of today have been made to possess less than anticipated and required homogeneity and denseness of its hardened microstructure due to insufficient uniformity of the fresh concrete.

Figure 6 is a photomicrograph of the microstructure of hardened cement paste in concrete from a marine structure which was examined due to early deterioration appearing as severe cracking and corrosion of the reinforcement, intense ingress of chloride ions from the saline environment, which was aggravated by daily heating/drying—cooling/condensation cycles, and crumbling of concrete surfaces due to salt crystallization.

The picture shows that the cement paste in its initial fresh state has coagulated into very compact micropatches alternating with very diluted spaces. A general, anticipated w/c of about 0.45 is on the microscale probably down to 0.2 in the coagulated parts of the paste, and towards 1.0 or more in the diluted regions. The consequence of such a microstructure of the cement paste in the fresh concrete is, that the concrete becomes initially susceptible to bleeding, early shrinkage and cracking due to thermal stresses, and this damage cannot be remedied by any curing precaution. Subsequently such concrete has acquired a lasting inferior resistance towards environmental and inherent deleterious factors of any kind, whether freezing-thawing with or without salting in cold climates, heat and salt ingress in warm environments or alkali silica reactions.

It is likely that the “durability crisis” for concrete which has received much public attention in recent years, is much more associated with the existence of inhomogeneity in the microstructure of hardened concrete than generally acknowledged. Apparently, the conventional reliance on an overall low w/c as a measure of low permeability—and adequate durability—does not suffice, because the low w/c in itself does not ensure homogeneity of the microstructure in the fresh cement paste.

CONCLUDING REMARKS

This brief survey demonstrates that the curing technology system is now under introduction at major construction works in Europe as an integral part of the concrete specifications and the quality control during construction. Current research comprises a thorough study of the rheology of fresh concrete. One aim of this research is to improve the means of monitoring the homogeneity of the cement paste in fresh concrete as a basic condition for obtaining a dense, homogeneous microstructure of hardened concrete. As the results of this and contemporary studies elsewhere become available during the forthcoming years, it is anticipated that the properties of fresh concrete and corresponding means of monitoring will become as indispensable as part of modern concrete technology and quality control as curing technology is now on its way to be.

The strategic aim is that the classic sample testing by slump test of the fresh concrete and cube/cylinder strength test of the curing phase will be replaced by a modern process monitoring system in keeping with the contemporary conditions for concrete production in construc-
tion practice, and with the economy and reliability requirements for concrete structures. This is not least important for the spectacular current and the future development of marine construction works in the arctic as well as the sun-belt development regions of the world.

Figure 7 (from IDORN, 1985) illustrates that also the realm of research and development regarding cement and concrete is changing profoundly. The classic system consisted of the building and construction professions and the cement industries. The contemporary research and development must operate in a more complex pattern of industries and their primary and secondary products. Besides, the electronic industries and their impact on the development of cement and concrete technology, are now forcefully entering these fields of engineering development.

Concurrently, only a few of the large research institutes of bygone days remain, and many university research establishments with ample funding for long-term exploratory research and free, academic exchange opportunities have been severely cut. The pressures on current research for reliance on ad-hoc funding and the subsequently changed criteria for preference of subjects and goal setting are felt everywhere.

The pleasantry and resourcefulness of the vanished research systems are not likely to come back. This means that the engineering and construction enterprises on their own must invest more than in the past in research and development, and in knowledge regarding effective implementation of new research. They must also acquire the capability to evaluate and develop new technology within the modern complex of options regarding source materials and processing technology for the differentiated requirements for the building and construction
products. These demands are particularly relevant for successful production and innovation of marine concrete structures.

LITERATURE CITED


Campus, F., 1947. Tests concerning the disintegration of mortar and concrete in sea water, as carried out in the Outer Harbor of Ostend since 1934. Der Ingenieur, pp. 41–49.


