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Durability of Concrete

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D.W.S. Ho

National University of Singapore

41.1 Introduction

Concrete is a composite with properties that change with time. During service, the quality of concrete provided by initial curing can be improved by subsequent wetting as in the cases of foundations or water-retaining structures. However, concrete can also deteriorate with time due to physical and chemical attacks. Structures are often removed when they become unsafe or uneconomical.

Lack of durability has become a major concern in construction for the past 20 to 30 years. In some developed countries, it is not uncommon to find large amount of resources, such as 30 to 50% of total infrastructure budget, applied to repair and maintenance of existing structures. As a result, many government and private developers are looking into lifecycle costs rather than first cost of construction.

Durability of concrete depends on many factors including its physical and chemical properties, the service environment and design life. As such, durability is not a fundamental property. One concrete that performs satisfactory in a severe environment may deteriorate prematurely in another situation where it is consider as moderate. This is mainly due to the differences in the failure mechanism from various exposure conditions. Physical properties of concrete are often discussed in term of permeation, the movement of aggressive agents into and out of concrete. Chemical properties refer to the quantity and type of hydration products, mainly calcium silicate hydrate, calcium aluminate hydrate, and calcium hydroxide of the set cement. Reactions of penetrating agents with these hydrates produce products that can be inert, highly soluble, or expansive. It is the nature of these reaction products that control the severity of chemical attack. Physical damage to concrete can occur due to expansion or contraction under restraint (e.g., drying shrinkage cracking, frost action, cyclic wetting and drying), or resulting from exposure to abrasion, erosion or fire during service. It is generally considered that the surface layer or cover zone plays an important role in durability as it acts as the first line of defense against physical and chemical attacks from the environment.

Although durability is a complex topic, some of the basic fundamentals are well understood and have been documented. Many premature failures in recent years are due mainly to ignorance in design, poor specification or bad workmanship. The following discussions should be considered as a summary of commonly accepted knowledge published in various textbooks, codes of practice, and recent conference proceedings listed at the end of the chapter. These publications are useful guides for further details and information.

41.2 Permeation Properties

Permeation defines the ease with which fluids, both liquids and gases, can enter into, or move through concrete. The ability of fluids to enter into concrete is sometimes refers to as penetrability of concrete. Three fluids are relevant to durability and they are water, carbon dioxide and oxygen. Water can be detrimental in either its pure (uncontaminated) form or if it is contaminated with aggressive ions such as chlorides and sulfates.

Concrete is a porous medium with permeation properties controlled by the microstructure of its hardened cement paste, which in turn, is determined by the cementitious materials (CM) used, the water to cementitious material ratio (W/CM), the paste volume, and the extent of curing and compaction. Within this cement paste, the transition zone, i.e., the interface between the cement paste and the aggregate, is known to be more porous than the bulk of the cement paste. Thus, it is the microstructure of this transition zone that controls the permeation of concrete. As far as the ease of movement of fluids through concrete is concerned, three transport mechanisms should be distinguished and they are permeability, diffusion and sorption.

Permeability refers to the flow of water through concrete under a pressure differential. The rate of flow follows Darcy's law for laminar flow through a porous medium. It depends on the pressure gradient and size of interconnected pores in the cement paste. For flow to occur, the concrete has to be in its saturated conditions with relevant pores being continuous and greater than 120 nm. Quantitatively, this property is discussed in terms of the coefficient of permeability, commonly expressed in meters per second (m/s). Permeability is a relevant property to be measured in assessing the durability and serviceability of structures like dams, foundations, and underground structures, where they are in constant contact with water.

Diffusion is the process whereby gases (e.g., carbon dioxide or oxygen) or ions in solution (e.g., chlorides) enter concrete under a differential in concentration. The diffusion of these species can be described by Fick's law. Diffusivity or diffusion coefficient, in m^2/s, is often used to refer to the rate at which these species entering concrete. In addition to concentration gradient and sizes of capillary pores, the rate of diffusion is influenced by the type of penetrating species and the chemical properties of the concrete. Diffusion of gases is very slow in saturated concrete and is, therefore, a property relevant to concrete in aboveground structures such as buildings and bridges, where concrete is partially dry. For the durability of submerged or underground structures, the diffusion of chloride and sulfate ions should be considered.

Sorption or absorption is a result of capillary movement of liquids in the pores of the hardened cement paste under ambient conditions. Note that capillary suction occurs in dry or partially dry concrete, a condition commonly occurred in practice for aboveground structures. Sorption is relevant, particularly to coastal structures, where chloride salts carried by wind deposit on concrete surfaces. Once wetted by rain, water carrying chloride ions is absorbed into the concrete. The rate at which liquids, mainly water, absorbed into concrete is often referred to as sorptivity or absorptivity, in $m/s^{0.5}$. This parameter is highly dependent on the initial moisture content of the concrete and therefore, the test method used.

To achieve good quality concrete in practice with low permeation properties, engineers should specify concrete with low water to cementitious materials ratio, adequate initial curing and proper compaction. In testing for permeation properties, it is important to recognize the type of structure under consideration and its service environment. This helps to identify the transport mechanism and the appropriate permeation property to be measured.

41.3 Reinforcement Corrosion

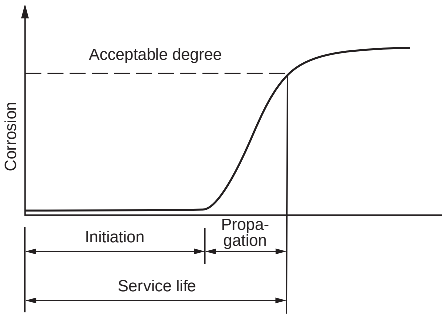

FIGURE 41.1 Schematic diagram of corrosion process of steel in concrete.

Reinforcement corrosion and the subsequent spalling of the cover concrete have been major issues in construction for many years. In theory, embedded steel should not corrode. It is protected against corrosion because of the passivating film of g-ferric oxide, which is formed and maintained in the alkaline environment produced by cement hydration. Hydration products, mainly calcium hydroxide and small proportions of sodium and potassium hydroxides, give the pore solution of concrete a pH of around 13. However, aggressive agents such as carbon dioxide or chloride ions can destroy this passivating film. Once destroyed, corrosion proceeds with the formation of electrochemical cells on the steel surface. Finally, the corrosion product causes cracking and spalling of the concrete cover. Thus, the corrosion process of steel in concrete can be divided into two stages — initiation and propagation (Fig. 41.1). The initiation stage is determined by the ingress of carbon dioxide or chloride ions into the concrete cover while the propagation stage, or corrosion rate, is dependent on the availability of water and oxygen in the vicinity of the steel reinforcement. The time before repair is required, often referred to as the service life of the reinforced concrete element, is determined by the total time of these two stages.

Carbonation

Carbonation is defined as the process whereby carbon dioxide in air diffuses into concrete, dissolves in the pore solution, and then reacts with the hydroxides, converting them to carbonates with a consequent drop in pH to a value less than 9. Depassivation of steel occurs as pH of the pore solution approaches 11. Carbonation continues from the concrete surface, as a penetrating front, throughout the life of the structure, with depth, d, proportional to the square root of time, t, as follows

$$d = C\, t^{0.5},$$

where C is referred to as carbonation coefficient or rate of carbonation, often expressed conveniently in mm/÷year.

In practice, the depth of carbonation can be determined by spraying a phenolphthalein solution onto a freshly broken concrete sample. This colorless solution changes to pinkish purple at pH values greater than about 9.5, indicating uncarbonated concrete.

The rate of carbonation is very much moisture dependent, i.e., the macro- and micro-climatic conditions of the exposed concrete element. Carbonation of concrete is known to be highest at RH between 40 to 70%, but negligible in dry conditions (<25% RH) due to insufficient water to promote the reaction. Negligible carbonation is also expected at high humidity (>90% RH) because water in pores of cement paste inhibits diffusion. Compared with tropical environment, concrete exposed to temperate climate are expected to have higher carbonation rates. In practice, vertical surfaces such as building facades carbonate faster than horizontally exposed surfaces like top surface of roof slabs and balconies because horizontal surfaces have a higher frequency and longer duration of wetting.

Temperature can also influence the rate of carbonation with higher rates at higher temperatures, but the influence is less significant compared to the moisture content of concrete. Carbon dioxide content is another influencing factor. In rural areas, carbon dioxide content in air is about 0.03% by volume. However, in cities, the concentration is much higher and could be in the order of 0.3% in densely populated areas. In vehicular tunnels, the concentration could reach 1% giving very fast rate of carbonation.

Note that carbonation in itself does not cause the deterioration of concrete. In fact, compared to the original concrete, carbonated elements tend to have slightly higher compressive strength and improved permeation properties due to the formation of calcium carbonate with a consequent reduction in the porosity of concrete. This reaction product is not detrimental to the durability of concrete as it does not leach out and is not expansive. Carbonation is not a concern for un-reinforced concrete elements such as roofing tiles and masonry blocks.

Carbonation affects only the length of corrosion initiation stage. For internal structural elements and due to the lack of sufficient moisture to initiate corrosion, concrete remains durable even though carbonation can be substantial. For external elements exposed to the weather, corrosion will occur once the concrete is carbonated close to the reinforcement. Thus, the quality and quantity (thickness) of the concrete cover are important in controlling the time to initiate corrosion. In normal practice and for typical run-of-the-mill concrete, it may take some 20 years or more to carbonate the concrete cover. Note that carbonation is not critical for concrete with high cementitious material content, low W/CM (<0.4) and low permeation properties, because carbonation is extremely slow in good quality concrete. The concern to practicing engineers is the concrete used for external surfaces of aboveground structures, such as buildings. This concrete is generally produced with high W/CM (>0.5) and limited initial curing.

Effects of Chloride

Soluble chlorides present in seawater, ground water or de-icing salts may enter concrete through capillary absorption or diffusion of ions in water. Chlorides may also present in chemical admixtures and contaminated aggregates or mixing water in the production of concrete. The presence of chlorides in reinforced concrete can be very serious and depending on the quality of concrete and its exposure environment, the total time of initiation can be relatively short.

Note that it is not the total chloride content that is responsible for corrosion. Part of the chlorides can be chemically bound to the hydrated cement paste, by reaction with C_3A to form calcium chloroaluminate, often referred to as Friedel's salt. Another proportion of chlorides is physically bound, being adsorbed on the surface of gel pores. The remaining part is the free chlorides, which are the only chlorides that are responsible for the initiation of steel corrosion. The distribution of these three forms of chlorides is not permanent and under special circumstances (e.g., carbonation or sulfate attack), some of the bound chlorides can be released as free chlorides. Due to various factors, the proportion of free chloride ions in concrete varies from 20% to more than 50% of the total chloride content.

For corrosion to be initiated, there has to be a minimum level of free chloride concentration at the steel surface. However, threshold values for depassivation is uncertain, with commonly quoted values between 0.1 and 0.4% of free chloride ions by mass of Portland cement. Due to the concern over the possibility of bound chlorides being released as free chlorides, the probability of corrosion has sometimes been expressed in terms of total chloride ion content. Buildings and bridges near the coast often suffer severe corrosion problems due to the co-existence of both carbonation and chloride penetration.

Propagation Stage of Corrosion

Once the embedded steel is depassivated, corrosion proceeds with the formation of electrochemical cells comprising anodic and cathodic regions on the steel surface, with electric current flowing in a loop between the two (Fig. 41.2). Corrosion occurs at the anode, where there is ionization and dissolution of the metallic iron to Fe^{++}.

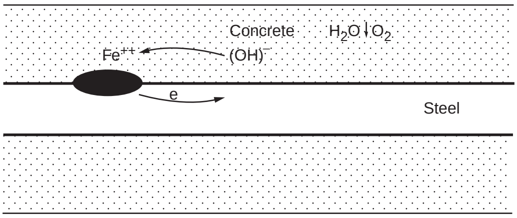

FIGURE 41.2 Schematic representation of electro-chemical reaction.

$$\text{Anode:} \qquad Fe \rightarrow Fe^{2+} + 2e^{-}$$

At the cathode, reduction of oxygen occurs. The cathodic reaction consumes electrons and leads to the formation of the OH^- ions.

$$\text{Cathode:} \qquad 0.5\ O_2 + H_2O + 2e^{-} \rightarrow 2(OH)^{-}$$

The ions formed at the cathode and anode move in the pore solution of the paste of the concrete and react chemically to produce an iron oxide near the anode, generally known as rust. It is obvious from above that for cathodic reaction, and thus corrosion, to occur, both oxygen and water are required. In dry concrete with RH less than 60% as in the case of concrete exposed indoors or protected from rain, corrosion of reinforcement may be considered negligible even though carbonation can be substantial. Corrosion may also be negligible in water-saturated concrete because of the restriction in oxygen supply. Typical examples are constantly submerged elements of offshore structures, where concrete is subjected to severe chloride attack, and due to the limited supply of oxygen, corrosion rate can be very slow. On the contrary, high corrosion rate will occur in concrete elements located in splash or tidal zones, where concrete experiences periodic wetting and drying cycles.

The deterioration of concrete due to corrosion results because the corrosion product, rust, occupies a volume two to six times larger than the original steel it replaces. This increase in volume exerts substantial pressure on the surrounding concrete, causing spalling and delamination of the concrete cover. In practice, initial concerns are cracking and rust stains on the concrete surface. Rust from outer 0.1 to 0.5 mm of steel bar is sufficient to cause cracking. However, the reduction in this diameter is generally considered too small to have practical significance on the load-carrying capacity of the reinforced concrete element. Of serious concern is the falling concrete, which may pose as a safety hazard to pedestrians and vehicles traveling below deteriorated overpasses and buildings. As corrosion continues to an advanced stage, reduction in steel cross-section will lead to a decrease in load carrying capacity of the member.

Control Strategy

To improve the service life of reinforced concrete structures, it is important to have high quality, low permeable concrete with adequate cover. Other strategies can be more complex and may require advice from specialists. These include the use of corrosion inhibitors such as nitrites of sodium and calcium, and the specification of galvanized or epoxy-coated reinforcing bars. For prestigious structures or those require high durability, expensive electro-chemical protective system such as cathodic protection is sometimes employed. This involves the application of a low-voltage direct current via an anode system to inhibit corrosion by causing the steel reinforcement to act as a cathode rather than an anode as it does when it corrodes. Other electrochemical treatments, namely re-alkalization and chloride extraction, are sometimes used as rehabilitation strategies for deteriorated structures.

41.4 Alkali-Aggregate Reaction

Certain types of rock contain reactive silica, which can react with the hydroxides in pore water derived from the alkalis (Na_2O, K_2O) in the cement causing damage to concrete. The most common is the alkali-silica reaction (ASR), which can be viewed simplistically as similar to etching of glass by strong hydroxide solutions. The visual signs of ASR damage are pop-outs or “map” cracking with gels coming through cracks on the concrete surface. Reaction rims around affected aggregate particles can also be identified from cores taken from damaged structures.

The reaction starts with the attack on the siliceous minerals in the aggregate by the alkali ions released through cement hydration with the formation of an alkali-silica gel on the surface or in the pores of aggregate particles. Gel absorbs water and causes localized swelling and cracking, which could destroy the aggregate integrity or the bond between the aggregate and the hydrated cement paste. The gel goes from solid to liquid phases as water is taken up into the concrete. Some of the liquid gel is later leached out by water and deposited in the cracks.

Damage due to ASR has caused much anxiety to property owners, particularly those from government authorities, who are responsible for the structural integrity of many civil engineering structures (dams, wharves and bridges). However, it must be emphasized that the extent to which ASR can be deleterious depends on certain critical conditions such as the nature and size of aggregates, amount of reactive silica, alkali concentration and the availability of moisture. Idorn [1997] made the following observation after reviewing some 60 years of research on ASR. “It can be concluded that ASR occurs in concrete all over the world, that the majority of available aggregate materials are alkali-reactive, and that, nevertheless the majority of ASR occurring with field concrete is harmless.”

Reaction between some dolomitic limestone and the alkalis in cement, known as alkali-carbonate reaction, can also cause damage to concrete. However, reactive carbonate rocks are not very common and can usually be avoided.

Control Strategy

ASR takes place only at high pH because the solubility of the siliceous minerals increases as pH increases. The use of low alkali cement controls the alkali content and thus, the pH of the pore solution. The ‘reactive’ alkali content is generally expressed in terms of soda equivalent ($Na_2O + 0.65\ K_2O$) with a maximum level often quoted as 0.6% by mass of cement or 3.0 kg/m^3 of concrete. The use of blended cement is beneficial for various reasons. One is C-S-H formed by the pozzolanic reaction incorporates a certain amount of alkalis and thus lowers the pH.

The control of alkali-silica reaction can also be taken by avoiding reactive aggregates. A quick chemical test to determine the potential reactivity is prescribed by ASTM C289–94 [2000], where the amount of dissolved silica is measured from a sample of pulverized aggregate in a normal solution of NaOH. Another method to determine aggregate potential reactivity is to measure the physical expansion in the mortar bar test according to ASTM C 227–97a [2000].

The swelling of silica gel occurs only in the presence of water. However, in practice, it is practically impossible to keep water away from exposed concrete, particularly for water-retaining structures. Due to the presence of water under service conditions, structures like dams, piers and wharves are more vulnerable than buildings to ASR attack.

41.5 Sulfate Attack

Naturally occurring sulfates of sodium, potassium, calcium, or magnesium can be found in soils, seawater or ground water. Sulfates are also used extensively in industry and as fertilizers. These may cause contamination of the soil and ground water. Sources of sulfate can also be internal, released from the cement during service. Sulfate attack can take one of the following forms:

1. physical attack due to salt crystallization;
2. external chemical sulfate attack involving reactions between sulfate ions from external sources with compounds from set cement;
3. internal chemical sulfate attack due to late release of sulfate within the concrete.

In practice, sulfate attack is generally considered not a serious, or common problem or sole contributor to damage. However, damage of concrete railway ties in the 1980s in Germany and controversies over recent problems associated with floor slabs from 20 to 30 year old homes in California have caused considerable anxiety among engineers about sulfate attack mechanism. Latest information on the mechanism of sulfate attack was well summarized by Mehta [2000] and Collepardi [2000].

Physical Attack

This type of attack is likely to occur in permeable concrete with top surface exposed to the dry environment, while the bottom surface is in contact with the ground with salt-bearing solutions. Under these conditions, solutions rise to the surface by capillary action. Due to surface evaporation, and if the rate of evaporation is faster than the migration of salt solution to the surface, salt crystallization occurs beneath the top surface. The transformation of anhydrous Na_2SO_4 to its hydrated form, $Na_2SO_4 \cdot H_2O$, involves significant volume expansion. This generates pressure in the pores causing flaking, spalling and cracking. The damage is often in the form of surface scaling and loss of mass from the surface can be substantial. This damage should not generally lead to structural failure unless there is a significant reduction in the cross section of the member.

Damage of this type results in white crystalline deposits at the crack sites and should not be confused with efflorescence, where salt crystallization takes place on the concrete surface. Ettringite and gypsum are absent from mineralogical analysis of damaged samples.

External Sulfate

Normal Portland cement is the most vulnerable to chemical sulfate attack. The extent of damage depends on the quality of the concrete, the type of sulfate compounds involved and their concentrations. In permeable concrete, sulfate ions migrate from external sources and react with the products of cement hydration. The use of concrete with low permeation properties would seem to be an essential first step in limiting the penetration of sulfate ions into concrete.

With sodium sulfate, it attacks $Ca(OH)_2$ to form gypsum and NaOH. Gypsum then reacts with calcium aluminate hydrate forming ettringite ($CaO.Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$). The formation of NaOH ensures high alkalinity in the cement system and C-S-H remains stable. As for calcium sulfate, it only attacks the calcium aluminate hydrate to form ettringite. The formation of ettringite is accompanied by volume expansion, which causes internal stresses and cracking. For concrete in contact with magnesium sulfate, the deterioration can be more serious than the damage caused by other sulfates. Magnesium sulfate attacks C-S-H as well as $Ca(OH)_2$ and calcium aluminate hydrate. The critical consequence of magnesium sulfate attack is the destruction of C-S-H resulting in loss of cohesiveness and reduction in strength.

Due to the lime-consuming pozzolanic reaction, the incorporation of mineral admixtures as a cementitious material would be beneficial in reducing the amount of calcium hydroxide and suppressing the formation of gypsum. The use of sulfate-resisting cement with a low C_3A content will minimize the damaging formation of the ettringite.

Underground structures or elements such as tunnels, foundations, pipes, and piles are vulnerable to sulfate attack. Damaged concrete often has a whitish appearance on the surface. Damage usually starts at edges and corners, eventually reducing to a friable or even soft state. Ettringite and gypsum are both present from mineralogical analysis of damaged samples.

Internal Sulfate

This is a case of chemical attack where the source of sulfates is internal. Due to late sulfate release, ettringite is formed in the hardened concrete causing expansion and cracking. This phenomenon is often referred to as delayed ettringite formation (DEF). This phenomenon has been reported in steam-cured products using cements of high sulfate content. Ettringite is not stable at temperatures above 65ºC. Therefore, ettringite formed during the early hydration of cement decomposes when the curing temperatures exceed 65ºC. The sulfate ions released are absorbed by the C-S-H. During service, these ions are desorbed under ambient conditions with the re-formation of ettringite.

However, the above thermal decomposition mechanism on DEF has been considered by many as far too simplistic. In a holistic approach mechanism [Collipardi, 2000], three conditions must be satisfied for DEF to occur and they are (a) presence of microcracks, (b) late sulfate release and (c) exposure to water. Concrete microcracking can be promoted by steam curing process during manufacture or localized high stress in prestressed members. Alkali-silica reaction could also generated cracks around aggregates. Gypsum contaminated aggregates or sulfur-rich clinker can be sources of sulfate, which are not immediately available at early hydration, but can feed DEF later. Sulfates could also be available due to thermal decomposition of ettringite from early hydration in overheated concrete. Exposure to water facilities the migration of these sulfate and other reactant ions, followed by deposition of ettringite inside existing microcracks. Damage results from ettringite swelling or crystal growth.

Control Strategy

Highly permeable concrete exposed to sulfate-rich soils or ground water can deteriorate resulting from physical and chemical attacks. In the control of sulfate attack, it is therefore important to use high quality, low permeable concrete. The use of sulfate resisting or blended cement is an added advantage. Prestressed products produced by steam-curing process are more prone to DEF-related problems. Irrespective of the source of sulfate, the presence of interconnected microcracks and water is a necessary condition of any sulfate-related concrete. In view of the above, care should be taken in the manufacturing process of precast products to minimize the development of microcracks. During service, a good drainage or waterproofing system may be necessary to keep concrete in a relatively dry state.

41.6 Acid Attack

As with sulfates, acids can be found in soils and ground water. These may be organic in nature resulting from plant decay (e.g., humic acid) or dissolved carbon dioxide, or may be derived from industrial wastes, effluents and oxidative weathering of sulfide minerals. Liquids with pH less than 6.5 can attack concrete. The attack is considered severe at pH of 5.5 and very severe at 4.5. Concrete is held together by alkaline compounds and is therefore not resistant to attack by strong acids. They do not go into complex chemical reactions similar to those in sulfate attack, but simply dissolve the hydrated compounds of the set cement. The ultimate result of sustained attack is the disintegration and destruction of the concrete.

The mechanism of attack is the reaction between cement hydrates, mainly the calcium hydroxide and C-S-H, and the acid, resulting in the formation of calcium salts associated with the acid. The dissolution of these salts lead to further exposure of cement hydrates to attack. The rate of damage is controlled by the solubility of the calcium salt. That means more rapid deterioration occurs under conditions of flowing water, rather than static.

Acid rain, which consists of mainly sulfuric acid and nitric acid, may cause surface weathering of the exposed concrete.

The reduced content of calcium hydroxide of concrete incorporating fly ash or ground granulated blast furnace slag is generally considered to be beneficial in reducing the rate of attack. However, it appears that the permeation property of concrete is of less importance in acid attack.

Action On Sewers

This is a special case of acid attack with sulfuric acid produced by the activities of microorganisms. Domestic sewage by itself is alkaline and does not attack concrete, but severe damage can occur above the level of flow. This occurs when anaerobic bacteria, found in the slime layer of sewer walls, convert sulfates in the sewage to hydrogen sulfide. Anaerobic bacteria become more active at higher temperatures and at slightly alkaline solutions. At high enough concentrations or due to turbulence, H_2S volatiles from the effluent and accumulates on the roof or upper part of the sewer. It then dissolves in the moisture films on the exposed concrete surfaces and undergoes oxidation by aerobic bacteria, finally producing sulfuric acid. It is this acid that attacks concrete. In localized areas, pH values can be as low as 2.

Since damage occurs only on exposed surfaces, sewers running full are not attacked. Chlorination and the injection of compressed air into rising mains have been used successfully to extend the life of sewers. Other effective measures include the removal of slime deposits, increase in flow velocities, and forced ventilation of sewers. It has also been found that the use of limestone, instead of siliceous, aggregates could greatly improve the durability of sewers.

41.7 Seawater

Concrete exposed to seawater can be subjected to both physical and chemical attacks. Seawater contains a number of dissolved salts with a total salinity of around 3.5% and pH values ranging from 7.5 to 8.4. Typical composition of seawater is sodium chloride (2.8%), magnesium chloride (0.3%), calcium chloride (0.1%), magnesium sulfate (0.2%), calcium sulfate (0.1%) and some dissolved carbon dioxide.

In terms of chemical attack, the damage from sulfates is not significant because in seawater, the deleterious expansion resulting from ettringite formation does not occur. The ettringite as well as gypsum are soluble in the presence of chlorides and can be leached out by seawater. Frost damage, abrasion due to wave actions, salt crystallization, and biological attack are other factors that may lead to the deterioration of concrete. However, the main durability concern for marine structures is the corrosion of the reinforcement resulting from chloride ingress. Of particular interest is the splash and tidal zones.

To be durable under seawater exposure conditions, concrete must have an adequate cover and low permeation properties with the appropriate choice of cementitious materials. Seawater should never be used as mixing water for the production of reinforced or prestressed concrete structures.

41.8 Physical Attrition of Concrete

Under many circumstances, concrete surfaces are subject to wear with progressive loss of mass from the concrete surface. Abrasion is a major concern to the durability of pavements or industrial floors with damage resulting from impact or wearing action by vehicular traffic. Damage may also occur due to erosion on spillways of hydraulic structures caused by water-borne solids moving at high speed, or offshore structures subjected to wave action. Another possible damage to hydraulic structures is by cavitation, which relates to the formation of vapor bubbles and their subsequent collapse due to sudden change of direction in rapidly flowing water.

Set cement paste does not have a good resistance to attrition, especially when it has a high porosity and low strength. Hard-wearing aggregates should be used for improved abrasion resistance. Heavy-duty industrial floors or pavements could be designed to have a 25 to 75 mm thick topping of low water-to-cement ratio. Small aggregates of 12.5 mm maximum size should be used to minimize the effect of aggregate pull out. To reduce the formation of a laitance or weak surface, it is often recommended to delay floating and finishing until the concrete has lost its surface bled water. In contrast to abrasion and erosion, the use of high quality concrete may not be effective in reducing damage from cavitation. The best solution appears to lie in the design by removing the causes of cavitation.

41.9 Frost Action

In cold climates, physical damage to concrete structures resulting from frost action or freeze-thaw cycles is a major concern requiring expensive repair and maintenance. The problem is common to all porous materials but the degree of damage depends on the pore system. Set cement paste, which has large pore system and small pore diameter, represents the worst situation.

As temperature drops, some of the water in the pore system begins to freeze at about –5°C. Water expands upon freezing and the associated 9% increase in volume generates hydraulic pressure, causing localized fracture within the cement paste. Damage can be avoided if pressure can be released by allowing the water to move out of the paste or to adjacent pores, where there is plenty of space.

Resistance of concrete to frost action can be improved by air entrainment, with air content between 3 and 6% of the volume of concrete being appropriate for most applications. The incorporation of air-entraining agent in a concrete mixture allows the distribution of free space throughout the entire cement paste in the form of tiny air bubbles. The addition of this admixture will obviously increase the yield of the fresh concrete and reduce the strength of the hardened concrete. Note that frost damage occurs mainly in saturated concrete. For partially dry concrete, many of the pores are empty and can play the role as air-entrained bubbles.

41.10 Action of Heat and Fire

In the design of residential buildings and public facilities, human safety is one of the major considerations. In general, concrete is considered to have good properties with respect to fire safety. Unlike timber, concrete is non-combustible and does not release toxic fumes on exposure to high temperatures. In practice, structural components are required to maintain their integrity over a desired length of time, often referred to as fire rating. Unlike steel, concrete is able to maintain sufficient strength at temperatures about 700 to 800°C over several hours. This is important in terms of safety because materials with a high fire rating allow rescue operations to proceed with reduced risk of structural collapse.

Fire creates high temperature gradients and because of this, the hot surface layer tends to craze, followed by spalling from the cooler interior of the concrete member. The reinforcement may become exposed and the action of fire accelerates. The extent of damage depends on the temperature reached, loading conditions under fire, and characteristics of the concrete, which includes the quality of concrete and type of aggregates used. In general, concrete heated while under load retains a higher proportion of its original strength compared to unload concrete. Concrete of low permeability may suffer serious spalling. This occurs when vapor pressure or steam inside the concrete increases at a faster rate than the pressure relief by the release of steam to the atmosphere.

Under exposure to high temperatures, concrete made with limestone or light-weight aggregates performs better than concrete with siliceous aggregates. This could be due to the lesser difference in the coefficient of thermal expansion between the cement paste and these aggregates compared to siliceous aggregates, resulting in a stronger transition zone. In addition, at about 570°C, siliceous aggregates containing quartz undergo deleterious expansion due to phase transformation.

Concrete made with siliceous or limestone aggregates show a color change with temperature. This provides useful information in estimating the maximum temperature reached in a fire. The color of concrete remains unchanged up to about 300°C. Between 300 and 600°C, it is pink to red. Then the concrete changes to grey between 600 and 900°C, and buff above 900°C.

As for the cement paste, when temperature reaches about 300°C, the interlayer water and some chemically bound water from the cement hydrates are lost. At about 500°C, decomposition of the calcium hydroxide begins. Complete decomposition of C-S-H occurs at temperatures around 900°C. For practical purposes, approximately 600°C is considered the limiting temperature for structural concrete.

41.11 Design for Durability

There are two approaches in the specification of concrete for durable structures and these are prescriptive and performance based specifications. Current prescriptive method focuses on important factors including service life, exposure environment, quality of concrete, and other interdependent considerations such as cover thickness, strength, curing and workmanship. An alternative approach based on performance tests and fitness for purpose has occasionally been suggested and used [Ho and Lewis, 1988]. However, there are difficulties in its implementation. One difficulty lies in developing a commonly accepted test, which directly assesses the resistance of concrete to a particular deterioration process. Others include the establishment of relationship between the test and real performance, availability of standard sampling and test procedure, and guidance on the level of performance required under various exposure conditions. These difficulties have to be overcome before the performance approach can be implemented in general practice.

Service Life

In general construction, concrete structures and members are usually designed for a service life of 40 to 60 years. Within this design life, concrete is expected to meet all essential properties or exceed minimum acceptable values, when routinely maintained. Guidance for durability criteria for this design life is usually provided by national standards. More stringent requirements should be considered for structures requiring longer service life such as monumental or civil engineering structures (power stations, tunnels, dams, etc). For temporary structures with short service life, some relaxation of requirements may be acceptable. It is emphasized that durability is a complex topic and compliance with requirements stated in local standards may not necessary be sufficient to ensure a durable structure for an intended service life. If in doubt, specialist advice should be sought.

Exposure Environment

Exposure classifications are generally based on climatic conditions under which the concrete surfaces are exposed. Important factors include temperature, humidity, and frequency of wet-dry cycles. Compared to arid or temperate climates, tropical environment is generally considered to be more aggressive to exposed concrete. The presence of aggressive ions (sulfates and chlorides) is discussed in terms of surfaces in contact with the soil and seawater, or proximity of the structure to the coast and industrial areas. Correct interpretation of classifications and subsequent decision on the exposure class for a structure or member under consideration cannot be over-emphasized.

Concrete Quality

In the prescriptive approach, quality of concrete is specified in terms of materials selection and production process. No matter how well a mixture is selected and proportioned, inferior concrete will result from poor workmanship.

The initial step is to determine the type of cementitious material, its content, and the water-cementitious material ratio, as these are critical material properties for durability. Other factors such as aggregates and chemical admixtures are interacting factors, must be considered collectively in mixture design. For the materials and proportions required for durability, a corresponding strength will be achieved. This should be compared with the strength required for load-bearing capacity of the structure under consideration with the higher value adopted.

The next step is the specification of production process, which includes workmanship and curing. Workmanship relates to the degree of compaction and surface finish that can be achieved. The use of rigid formwork and intense vibration in the manufacture of precast products often gives better quality concrete compared to that obtained with standard consolidation (poker vibrators) on site. Curing promotes cement hydration. The duration and type of curing techniques are critical parameters and must be clearly defined. More importantly, the curing process specified has to be appropriate and can be achieved in practice for the concrete member under consideration. Note that the quality of concrete achieved with water-adding technique (e.g., water spray, wet hessian) is considered more effective than curing with water-retaining techniques (e.g., curing compound) [Ho, 1998]. However, water-adding curing techniques can be difficult to implement in many construction sites, without substantial increase in cost or delay in construction progress.

Cover Thickness

Besides quality, the quantity (thickness) of the cover determines the level of protection afforded by the concrete to the steel reinforcement against corrosion. The cover also acts as the first defense against other physical and chemical attacks. For durability, the cover thickness should be as large as possible, but this should be kept to a minimum for structural efficiency and the control of surface crack widths. The quantity and quality of the cover should be considered collectively because many codes of practice allow the reduction of cover thickness with increase in concrete quality.

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