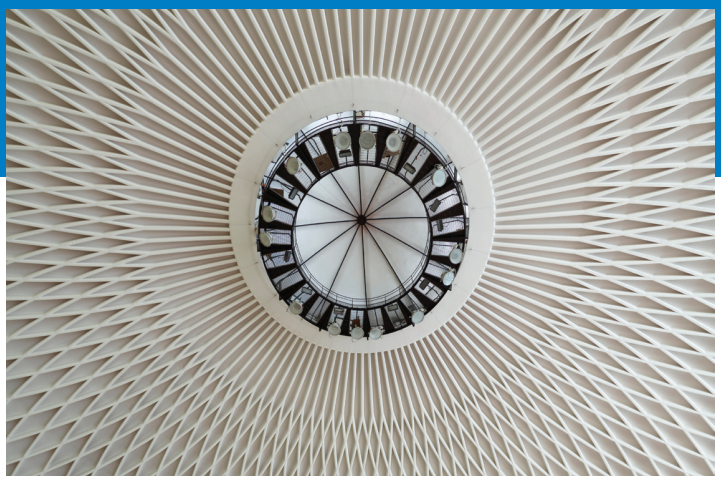
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Durability and Sustainability of Concrete Structures – Workshop Proceedings

SP-305

Editors:
Mario Alberto Chiorino, Luigi Coppola, Claudio Mazzotti, Roberto Realfonzo, and Paolo Riva

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Cover photo: Interior of the concrete dome of Small Sports Palace in Rome, Italy, 1957, by Pier Luigi Nervi with Annibale Vitellozzi. Courtesy of PLN Project Association

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Preface

With the dawn of twenty-first century, the world has entered into an era of sustainable development. The main challenge for concrete industry is to serve the two major needs of human society, the protection of the environment, on one hand, and - on the other hand - meeting the infrastructural requirements of the world growing population as a consequence of increase in both industrialization and urbanization. In the past, concrete industry has satisfied these needs well. Concrete is an environmentally friendly material useful for the construction of vast infrastructures. Skyscrapers, highway bridges, roads, water retaining structures and residential buildings are all testimonials to concrete's use and versatility. However, for a variety of reasons the situation has changed dramatically in the last years. First of all, the concrete industry is the largest consumer of natural resources. Secondly, portland cement, the binder of modern concrete mixtures, is not as environmentally friendly. The world's portland cement production, in fact, contributes to the earth's atmosphere about 7% of the total CO_2 emissions, CO_2 being one of the primary greenhouse gases responsible for global warming and climate change. As a consequence, concrete industry in the future has to face two antithetically needs. In other words how the concrete industry can feed the growing population needs being – at the same time - sustainable?

ACI Italy Chapter has been playing a significant role in the last years in the broad area of concrete technology in Italy and, in particular, in the field of concrete durability and sustainability. ACI Italy Chapter has become increasingly involved in research and development dealing with durability and sustainability issues such as reduction in CO_2 emissions, use of recycled materials and innovative products, design of durable structures and maintenance, repair and refurbishment of concrete infrastructures.

In October 2015, the American Concrete Institute Italy Chapter (ACI IC) and the Department of Civil, Chemical, Environmental, and Material Engineering (DICAM) of the University of Bologna sponsored the First International Workshop on "Durability & Sustainability of Concrete Structures" in Bologna (Italy). The workshop was co-sponsored by the American Concrete Institute and ACI Committee 201. The proceedings of the workshop were published by ACI IC as SP305. The proceedings consist of forty-eight refereed papers concerning reduction in green house gases in cement and concrete industry, recycled materials, innovative binders and geopolymers, Life Cycle Cost Assessment in concrete construction, reuse and functional resilience of reinforced concrete structures, repair and maintenance, testing, inspection and monitoring.

Many thanks are extended to the members of the technical paper review panel. Without their dedicated efforts it would not have been possible to publish the proceedings. The cooperation of the authors in accepting reviewers' comments and suggestions and in revising the manuscripts accordingly is greatly appreciated.

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SUSTAINABILITY AND HIGH-PERFORMANCE OF CONCRETE – A REVIEW

Tarun R. Naik, Fethullah Canpolat and Giacomo Moriconi

Synopsis: Concrete durability-related properties are known to be negatively affected due to expansion and cracking that result from factors such as freezing and thawing actions, alkali-aggregate reactions, sulfate attack, corrosion of the reinforcement, shrinkage, and other similar factors. Durability, and, therefore, sustainability of properly designed and constructed concrete structures depends primarily upon the quality of the materials of construction and other simple, but critical, steps. Concrete construction can last 100 years or more if five simple "steps" are followed: (1) materials selection; (2) structure design; (3) construction; (4) quality management; and, (5) timely evaluation, maintenance, and repairs. This is a holistic approach. Most mistakes are made in not satisfactorily following Steps 4 and 5. Conventional mixture proportioning technique used for production of high-strength concrete does not guarantee long-term durability of concrete. Concrete mixtures must be proportioned to attain desired workability, high-dimensional stability, high-strength, and high-durability related properties; i.e., high-quality concrete (HQC). However, mixture proportioning requirements for HQC must be varied according to the type and expected use of the concrete construction. HQC mixtures must have high-quality constituent materials: durable aggregates, low heat of hydration cement, mineral additives, and chemical admixtures. Furthermore, the mixing water must be minimized (i.e. a low water to cementitious materials ration, W/Cm). A strict quality control is also needed in various aspects of the production of HQC. Research activities conducted at the UWM Center for By-Products Utilization (UWM-CBU), CANMET, and elsewhere, have demonstrated that HQC mixtures can be proportioned to obtain strength in excess of 100 MPa (14,000 psi) and service life of 100 plus years.

Keywords: Compressive strength, Chloride-ion penetration, Permeability, High-performance of concrete, High-quality concrete.

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Fethullah Canpolat is Assistant Professor at Yildiz Technical University, Istanbul, Turkey. He specializes in Materials of Sustainable Construction and Concrete Technology. He is a former Post-Doctoral Research Associate at UWM Center for By-Products Utilization, at the University of Wisconsin-Milwaukee, where he was involved with research on the use of recyclable materials such as coal combustion products, cement kiln dust, limestone quarry fines, and foundry industry silica-dust in cement-based materials, such as concrete.

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INTRODUCTION

In design of a structure, durability characteristics of materials must be considered. Use of improper materials would lead to increased and costly repairs and maintenance. Industrialized nations allocate over 40% of their budget in repairs and maintenance, while less than 60% to new constructions[1]. The escalating cost of repairs and maintenance has forced designers and engineers to find ways and means to improve durability of concrete structures. In the last 20 years or so engineers have learned to achieve a life span of 100 years or more for concrete construction of infrastructures.

Sustainability is important to the well-being of our planet, continued growth of a society, and human development. Concrete is one of the most widely used construction materials in the world[2]. Designing for sustainability means accounting for the short-term and long-term environmental consequences in the design. In order to decrease the long-term impact of structures, the creation of durable structures is paramount.

For over 150 years, concrete has been accepted for its long-lasting and dependable characteristics. In addition to durability and dependability, concrete also has superior energy performance, is flexible in architectural and structural design, affordable, and is relatively environmentally friendly[3]. It is generally accepted that concrete will be needed to both increase the industrialization and urbanization of a society, while protecting the environment. To achieve this, the concrete industry should consider recycling of industrial by-products safely and economically. When industrial by-products, such as coal and bio-mass fly ash replace cement, maybe even up to 70%, in concrete, the environmental impact improves, along with energy efficiency and durability of the concrete[4]. Many by-products materials can be used to supplement the use of cement in concrete mixtures while improving the durability of the end product.

Concrete is by far the most important building material. Worldwide, more than 10 billion cubic yards are produced each year (2010). The reasons for the popularity of concrete are well known. If properly designed and produced, concrete has excellent mechanical and durability properties. It is moldable, adaptable, relatively fire resistant, generally readily available, and affordable. Maybe its most intriguing characteristic is the fact that it is an engineered material, which means it can be engineered to satisfy almost any reasonable set of performance specifications, more so than any other material currently available[5].

The sustainability of the cement and concrete industries leads to the efficient use of natural resources. However, the production of portland cement, an essential constituent of concrete, leads to the release of a significant amount of CO_2 and other greenhouse gases (GHGs)[6].

In accordance with ACI Committee 201[7], durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other processes of deterioration. This means that a durable concrete should maintain its original form, quality, and serviceability when exposed to various environmental conditions. The movement of water or other fluids through concrete can carry aggressive agents into the concrete that create various types of durability issues for concrete construction. In fact, permeability controls the rate at which aggressive agents such as gases (CO_2, SO_2, etc.) and liquids (acid rain, sea water, sulfate-rich water, salt-bearing snow/water, and groundwater) can penetrate into the concrete. Therefore, in order to avoid permeation of these agents, permeability of concrete must be reduced by decreasing porosity and/or increasing density of the concrete. Shrinkage of concrete and subsequent cracking must also be reduced to increase durability of concrete construction.

Durability of a structure depends upon performance of its individual components. Performance of each component depends upon its constituent materials, design, construction, and quality management. These factors play

important roles in producing durable concrete structures. Traditional design of high-strength concrete (HSC) requires minimizing water to cementitious materials ratio (W/Cm) to obtain high strengths. However, many concrete structures made with HSC in the USA and others parts of the world have shown a rapid rate of deterioration, especially in aggressive environments. Conventional mixture proportioning is often inadequate to ensure long-term durability of concrete. Thus, when long-term durability is required, a high-performance concrete (HPC) may be necessary. However high-performance of concrete is not enough. The concrete also must be durable; i.e.; high-durability (HDC). HPC is proportioned to have high-workability, high-dimensional stability, high-strength, and/or high-durability related properties. Proportioning and production of HPC can be tailored to meet strength and durability requirements for individual applications. For reinforced concrete, reinforcement should be high performance steel (HPS). A HPS material is designed and manufactured to have high strength, high strength-to-weight ratio, stiffness, ductility, weld-ability, corrosion resistance, and fracture toughness. The reinforcing bars must also have a greater thickness of concrete cover for all outdoors concrete elements than normally provided. Furthermore, the construction quality management should assure that the contract drawings and specifications are satisfied.

High-performance materials are intended to reduce cross-sections and the volume of the concrete used. They are also intended to increase the durability of concrete structures to minimize the maintenance needs of the concrete construction, and limit the amount of not environmentally-friendly special repair materials that need to be used in the maintenance of the concrete structures[8].

Pyramids in Mexico and elsewhere were constructed with high-quality mortar. These structures are many centuries old. The construction contract, for the tunnel between England and France, required 100 plus years of performance, which was achieved with HQC and a holistic approach, similar to the five steps program advocated in this paper. Many hydroelectric dams, in the USA and elsewhere in the World, were constructed with HQC and the five steps program since the early 20th century.

This review paper primarily deals with attributes required for production of sustainable and durable advanced cement-based materials, mixture proportions, and recommendations for producing HPC/HQC structures for service life in excess of 100 years.

MIXTURE PROPORTIONS FOR DURABLE CONCRETE

Concrete mixture proportion depends greatly upon its intended use because desirable attributes varies with the type of application. ACI Committee 201 offers recommendations for producing durable concrete[7].

Mixtures for durable concretes are proportioned to obtain dense concrete microstructure, especially at the interface region between the aggregate and the paste. This is accomplished through the selection of high quality constituent materials and mixture proportioning.

Table 1-- Mixture Proportions for HPC Mixes[10-11]

Mix Number	12.5 P	12.5 E	15 P	15 E
Specified Strength, MPa (psi)	85(12328)	85(12328)	100(14504)	100(14504)
Cement, kg/m^3 (lb/yd^3)	442 (744)	342(576)	479(806)	357(601)
Class C Fly Ash, kg/m^3 (lb/yd^3)	111(187)	199(335)	48(81)	165(278)
Class F Fly Ash, kg/m^3 (lb/yd^3)	0(0)	109(184)	0(0)	110(185)
Silica Fume, kg/m^3 (lb/yd^3)	28(47)	0(0)	90(152)	42(71)
Water, kg/m^3 (lb/yd^3)	164(276)	157(264)	137(231)	168(283)
Sand (SSD), kg/m^3 (lb/yd^3)	635(1069)	550(926)	702(1182)	575(968)
19 mm Aggregates (SSD), kg/m^3 (lb/yd^3)	995(1675)	898(1512)	957(1611)	877(1476)
Superplasticizer, L/m^3 (fl oz/yd^3)	4.9(126.6)	3.7(95.6)	10.2(263.6)	5.7(147.3)
Retarder, L/m^3 (fl oz/yd^3)	1.1(28.4)	1.3(33.6)	1.7(43.9)	1.5(38.8)
Measured Slump, mm (in.)	138(5.43)	243(9.57)	250(9.87)	158(6.22)
Water to Cementitious Materials Ratio (W/Cm)	0.28	0.20	0.22	0.25
Air Content, %	2.0	2.4	2.5	2.1
Air Temperature, ºC (ºF)	20(68)	20(68)	23(73)	23(73)
Concrete Temperature, ºC (ºF)	17(63)	14.1(57)	23(73)	23(73)
Concrete Density, kg/m3 (lb/ft^3)	2415(151)	2342(146)	2430(152)	2366(148)

A typical mixture for durable concrete should consist of high quality aggregate (small size, closely graded, high strength), low heat of hydration cement, pozzolanic additives (fly ash, slag, natural pozzolans, rice husk ash, silica fume, and the like), and chemical admixtures. Naik and his coworkers[9-17] and others[18-28] have reported development of concrete mixtures in order to have high-strength and high-durability related properties. Mehta and Aitcin[22] recommended that for very high strength levels of HPC (100 MPa (14504 psi) or more), size of coarse aggregate should be equal to or smaller than 10-12 mm (0.4-0.5 in.). Naik et al.[10,11,15] reported strength levels up to 100 MPa (14504 psi) for HPCs incorporating maximum size of aggregates in the range of 12-20 mm (0.5-0.8 in.).

Naik and his associates[9-17] have developed low-cost concrete mixtures incorporating large amounts of low-cost mineral admixtures such as Class C fly ash and Class F fly ash, blended ash, low amounts of silica fume, and superplasticizer. Some of the HPC mixtures as reported by Naik et al.[10-11] are presented in Table 1.

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FACTORS AFFECTING CONCRETE DURABILITY

Durability of concrete is generally expressed by its resistance to corrosion, chemical attack, freezing and thawing, abrasion, and other similar causes. Generally, the degree of concrete deterioration with respect to its age depends greatly upon concrete permeability and ingress of water and/or chemicals[9-15]. Concrete deterioration occurs due to both physical and chemical causes. The physical causes are divided into two types: surface wear and cracking[1]. The surface wear occurs due to scaling, abrasion, erosion, and cavitations. The cracking occurs in concrete because of the stresses that are generated due to volume changes from exposure to high moisture and humidity gradients, shrinkage, structural loadings, and temperature effects.

The chemical causes of deterioration can be categorized into three major classes[1]: hydrolysis, cation-exchange reactions, and expansive reactions. The hydrolysis of cement paste components occurs by soft water. The cation-exchange reactions can occur between aggressive fluids and the cement paste. The expansive reactions can occur due to sulfate attack, alkali-aggregate reactions, corrosion of steel reinforcement, freezing and thawing, and the like. The effects of physical and chemical causes cannot be separated in many circumstances. The interacting effects of these causes reduce the durability of the concrete. Therefore, concrete mixtures should be proportioned to provide high resistance to both physical and chemical processes impacting concrete strength and durability.

PERMEABILITY OF CONCRETE

Permeability dictates the rate at which aggressive agents, such as gases (CO_2, SO_3, etc.) and liquids (acid rain, road salt-bearing water, sea water, sulfate-bearing water, snow and ice water, flowing water, and other liquids), which penetrate into the concrete that can lead to various types of undesirable physical and/or chemical reactions. The primary variables influencing concrete permeability are water to cementitious materials ratio (W/Cm), pozzolans, grading and size of aggregates, compaction, and curing.

For a given cementitious material content of a concrete mixture, the space occupied by the hydration product increases with increasing the water content of the concrete mixture. However, the volume of the hydration product will remain constant irrespective of the water content of the mixture at a particular degree of hydration. Consequently, unfilled spaces, i.e., gel pores and capillary voids, will increase with the increase in water to cementitious materials ratio. Therefore, an increase in water to cementitious materials ratio will cause an increase in porosity and a decrease in density of the concrete.

Naik et al.[9-15] evaluated permeability of 40 MPa (5802 psi) concrete incorporating Class C fly ash for cement replacement levels up to 70 percent. Each mixture was evaluated for water permeability, air permeability, and resistance to chloride-ion penetration. Air and water permeability were evaluated by using the Figg Method[14]. At early ages, air permeability of the concrete was slightly increased with fly ash addition of more than 50% cement replacement. However, at later ages, especially at the 91-day age, the lowest air permeability was obtained for the concrete proportioned to replace 50% cement with Class C fly ash. At 91 days, minimum water permeability values were obtained for the 30% fly ash concrete mixture. All mixtures containing fly ash for cement-replacement varying from 30 to 50% showed excellent resistance to water permeability.

Recommendations for Low Permeability

More recently, investigations by Naik et al.[10,11,15] reported the effects of variable temperature curing environment (VTCE) on chloride-ion penetration resistance of high-performance concretes incorporating various combinations of Class C fly ash, Class F fly ash, and silica fume. In general, chloride permeability decreased (i.e., impermeability increased) with increasing compressive strength and age. All HPC mixtures showed high-strength and high-impermeability of concrete. A similar trend was also reported in another investigation[14]. Therefore, for high impermeability, HPC mixtures can be proportioned using high quality aggregates, mineral additives, and chemical admixtures at a low water to cementitious materials ratio of about 0.33 ± 0.02.

Effect of Porosity on Concrete Permeability

In general, permeability increases with an increase in porosity up to a certain level, and then the influence of porosity on permeability is quite small. A strong correlation between porosity and permeability has been reported by a number of investigators[29-33].

Researchers[34-35] have indicated that when volume fraction of porosity is less than 35%, the permeability becomes negligible. The same trend was also observed by Mehta[33] at a porosity of 30%. This may be attributed to the fact that at a low porosity, there is a large reduction in size and amount of capillary pores, and interconnection between them. Concrete porosity is highest at the interfacial region of concrete.

Inclusion of reactive pozzolanic additives such as fly ash, slag, silica fume, natural pozzolans, and rice husk ash improves concrete microstructure. This happens due to the densification of the microstructure that occurs as a result of the production of pozzolanic C-S-H. The use of pozzolanic additives is essential for densification of the interface region, in production of high-strength, high-performance, high durability concretes.

Use of high-range water- reducing admixture (HRWRA), superplasticizer, results in the production of the desired consistency of the concrete at a low water to cementitious materials ratio for a given water content. This causes reduction in the amount and size of the gel and capillary pores. As a result, a denser concrete microstructure is produced, which in turn, improves concrete strength and impermeability. Therefore, HRWRA is also needed in production of high-quality, high- strength, and/or high-performance concretes.

WEAR RESISTANCE OF CONCRETE

The surface wear of concrete occurs due to abrasion, erosion, and cavitations. ACI Committee 201[7] defines "abrasion resistance of concrete as its ability to resist being worn away by rubbing and friction." The erosion refers to the surface wear that occurs due to the abrasive action of fluids containing solid particles. Generally this type of wear is observed in hydraulic structures. The cavitations refer to the mass loss that can occur due to the formation of cavities and their subsequent collapse in water at high velocities. Various factors such as compressive strength, aggregate properties, finishing methods, use of toppings, and curing are known to influence wear resistance of concrete. Improved microstructure of concrete can also improve abrasion resistance. Naik et al.[14] showed excellent abrasion resistance of concrete made with 35% of Class C fly ash.

DETERIORATION BY CHEMICAL REACTIONS

Various chemical reactions can result in the deterioration of concrete. Generally these reactions, with a few exceptions, occur as a result of the chemical interaction between the aggressive agents present in the environment and the constituents of the concrete. The durability related chemical reaction can include hydrolysis of cement paste components, cation-exchange reactions, and expansive reactions.

Hydrolysis of Cement Component

Soft waters, resulting from melting of snow, ice, or rain coming in contact with concrete, tend to hydrolyze or dissolve the calcium containing products; e.g., $Ca(OH)_2$. However, generally hard waters (groundwater, lake water, and river water) do not participate in this reaction. $Ca(OH)_2$ is more susceptible to hydrolysis due to its higher solubility compared to other components of the hydrated cement paste (C-S-H). Due to the hydrolysis reaction, $Ca(OH)_2$ can leach from concrete, causing reduction in strength, increase in porosity, and reduction in durability. The leachate can also react with CO_2 in air, leading to precipitation of calcium carbonate on the surface. This phenomenon is termed efflorescence[1].

Recommendation to Avoid Damage due to the Hydrolysis Reaction

This can be easily avoided by using pozzolanic additives that can consume considerable amounts of $Ca(OH)_2$ generated due to the hydration reaction of the portland cement. Moreover, use of pozzolanic admixtures such as fly ash, volcanic ash, wood ash, slag, and silica fume can also improve concrete microstructure. This, in turn, increases resistance to penetration of the water into the concrete, thereby reducing the possible hydrolysis reaction.

Cation or Anion Exchange Reactions

Generally, deterioration due to exposure to acids occurs because of the reaction between acids and the calcium hydroxide of the hydrated cement paste. Mostly, these reactions cause formation of water-soluble calcium compounds that can be leached away by water or other aqueous solutions. Formation of soluble calcium salt occurs due to the cation-exchange reaction with acidic solutions containing anions[1]. The resulting soluble salts of calcium, such as calcium chloride, calcium acetate, and calcium bicarbonate, are removed by leaching.

Recommendations to Resist Acid Attack

Generally, portland cement concrete possesses poor resistance to acid attack. Thus, portland cement concrete is not expected to withstand high concentrations of acid for a long time. However, a concrete having dense microstructure should provide protection against mild acid attack. Concrete incorporating mineral and chemical admixtures can be proportioned at low water to cementitious materials ratio to produce relatively impermeable concrete. If required, concrete can also be coated with barrier coatings to protect it from various chemicals[7].

DETERIORATION OF CONCRETE DUE TO SALT CRYSTALLIZATION

If salt containing water enters into concrete and crystallizes in the pores, damage to concrete can occur. The damage occurs in the form of cracking due to the pressure generated from the crystallization of the water in the pores. Structures such as retaining walls or slabs of permeable concrete can face this problem.

Recommendation to Minimize Deterioration Due to the Crystallization of Salts

The remedy for the problem is to proportion the concrete to have high impermeability. This will restrict entry of salt solution in the pores, and thus will avoid or minimize the damage associated with the crystallization.

EXPANSIVE REACTIONS

Several reactions in hydrated cement paste cause formation of expansive products. When the levels of the resulting expansions become high, concrete can experience high internal stresses resulting in large deformation and displacement in various parts of the structure of the concrete including cracking, spalling, and popouts. These reactions generally occur due to sulfate attack, alkali-aggregate attack, corrosion of steel reinforcement in concrete, freezing and thawing, and other similar situations.

Sulfate Attack

Sulfates resulting from natural sources are found in soil and groundwater. Presence of sulfate containing soil and groundwater adjacent to concrete structure can result in sulfate attack to the exposed face of the concrete. The damage resulting from sulfate attack becomes significant when sulfate concentration becomes high due to evaporation of the sulfate-bearing water. The use of sulfate-based fertilizers in agricultural soil and water also cause increases in sulfate concentration in the soil and groundwater. Additional sulfate can results from sewage, effluent from furnaces burning high-sulfur containing fuels, and chemical industries using sulfuric acids. The structures exposed to sea water also experience damage due to the sulfate attack. A reaction between the sulfate entering the concrete and the hydrated lime generated during the hydration of cement causes formation of gypsum. The reaction of gypsum with C_3A present in the cement results in the formation of calcium sulfoaluminate, called ettringite. Both of these reactions cause increase in volume[1,7]. The resulting expansion can cause cracks in the concrete, which increase permeability of the concrete. The increased permeability can lead to accelerated deterioration of the concrete due to increased ingress of aggressive ions, besides sulfate ions.

Recommendations to Reduce Sulfate Attack

In order to protect against sulfate attack, concrete should be proportioned to obtain dense microstructure at a low water to cementitious materials ratio using a sulfate resisting cement. Use of pozzolans can also result in consumption of hydrated lime, formed during the hydration of cement, thereby reducing the amount of gypsum formation or ettringite formation[43].

Studies have revealed that use of 15 to 25% pozzolanic additives can increase sulfate resistance of concrete[35]. ACI Committee 201[7] has made recommendations for protecting normal weight concrete due to sulfate exposures.

Alkali-Aggregate Reaction (ASR)

The alkali hydroxides generated during cement hydration can react with amorphous (reactive) silica containing aggregates, causing formation of expansive products. The resulting expansion can be high enough to cause cracking in the concrete, leading to loss of strength and durability of the concrete. If present, both hydroxyl ions and alkali ions can participate in the reaction[1].

Recommendations to Avoid ASR

The alkali content of the concrete mixture should be maintained low by selecting suitable cement, aggregate, admixtures, and pozzolans. Attempt should be made to use relatively nonreactive aggregates. Investigations in England and Germany have shown that total alkali content of concrete from all sources should be less than 3 kg/m^3 (5.05 lb/yd^3) to avoid alkali-silica reaction[1]. Use of Class F fly ash in the 25% range or more also reduces the danger of alkali-silica reaction[35]. Recently published information also shows that Class C fly ash can be effectively used to minimize ASR[43].

Corrosion of Reinforcement

Generally, concrete provides sufficient protection of embedded materials against corrosion (rust forming reaction) because of its high alkalinity and high electric resistivity. Corrosion of reinforcement in concrete occurs due to an electrochemical process.

The electrochemical potential occurs due to the differences in moisture content, oxygen concentration, electrolyte concentration, surface characteristics of the steel reinforcement, and by contact of dissimilar metals, or when significant variation occurs in the properties of the reinforcement[7].

A corrosion cell is formed along the steel reinforcement or other embedded metal in the concrete because of the formation of an anode and a cathode. The corrosion occurs at the anode.

Recommendations for Resistance to Corrosion

Concrete should be proportioned to have dense microstructure to resist ingress of water, oxygen, and chloride-ion. ACI Building Code 318 specifies that maximum water soluble chloride-ion concentration should be less 0.06, 0.15, and 0.30 percent by weight of cement, for prestressed concrete, reinforced concrete, and other concretes, respectively, when exposed to chlorides in service. A minimum concrete cover of 50 mm for walls and 75 mm for other members exposed to the outdoor environment is specified by ACI Building Code 318 for protection

against corrosion. Both reinforcing bar coating and cathodic protection approaches have been used to avoid corrosion of the steel reinforcement. However, these methods are not economically attractive compared to that provided by high-quality concrete (HQC).

Freezing and Thawing Resistance

In cold climates, concrete is susceptible to damage due to the freezing and thawing actions. The high levels of tensile stresses generated due to freezing and thawing actions can cause damage to the concrete. For acceptable performance under freezing and thawing, concrete should have 4 to 7% air content with air bubble spacing factor less than 200 μm and specific surface greater than 24 mm^2/mm^3 [37]. Investigations by Naik et al. and others[38-39] have shown adequate performance due to freezing and thawing actions when concrete was proportioned to have adequate strength and appropriate air-void systems before the concrete is allowed to be exposed to freezing and hawing environment.

Recommendations for Freezing and Thawing Resistance

Mather[37] reported that concrete with and without fly ash will be durable against freezing and thawing if: (1) it is properly air entrained; (2) it has attained about 28 MPa (4061 psi) compressive strength when subjected to freezing and thawing environment; (3) it is made with sound aggregates; and, (4) proper construction practice, in particular surface finishing operations, are followed. He concluded that concrete will be immune to the effects of freezing and thawing even when critically saturated with water if it is made with sound aggregates, has a proper air-void system, and has matured so as to have a compressive strength of above 28 MPa (4061 psi). Other investigations as reported by Naik et al.[30-31] have also supported these conclusions.

Salt Scaling Resistance

Salt scaling resistance of concrete depends significantly upon properties of the surface layer of the concrete[35]. Soroushian and Hsu[38] indicated that salt scaling resistance of concrete is decreased if the freshly-placed concrete is subjected to excessive vibrations during its placement, trowelled too early and too long, and subjected to plastic shrinkage and/or excessive bleeding. This occurs because concrete produced under such conditions experiences increased micro-cracking and bleed channels, which in turn, increases the penetration of the salt solutions in the concrete. To avoid these issues proper mixture proportioning, finishing, and curing must be implemented.

Naik and Singh[36] measured salt scaling resistance of fly ash concrete systems. Concrete mixtures were proportioned to incorporate Class C fly ash to replace 20 and 50% of cement and Class F fly ash to replace 40% of cement. The water to cementitious materials ratio was varied between 0.25 to 0.35. At 50 cycles of freezing and thawing treatments, the salt scaling resistance for the 20% Class C and the 40% Class F mixtures was rated as 2, and the 50% Class C fly ash mixture was rated as 4 according to ASTM C 672 visual rating. Thus, the high-volume Class C fly ash performed poorer than the other two fly ash concrete mixtures in regards to salt scaling resistance. However, field records at up to 20 years of age for pavements constructed in Wisconsin do not show deceased salt scaling resistance of concrete up to 70% cement replacement with Class C or Class F fly ash[44]. Also studies[14,39,41] at the UWM Center for By-Products Utilization, have shown high scaling resistance for concretes up to 45% cement replacement with fly ash.

Recommendations for Resistance to Salt Scaling

Concrete should be proportioned to achieve dense microstructure at a low water to cementitious materials ratio. The dense microstructure will resist penetration of the salt containing liquid, thereby increasing concrete resistance to salt scaling. Based on the investigations by Naik and his associates[14,39], concrete with up to 40% fly ash can be proportioned at a water to cementitious materials ratio of about 0.33 to obtain excellent resistance to salt scaling.

FIRE RESISTANCE OF CONCRETE

Both cement paste and aggregate contain constituents that are subject to decomposition upon heating. The factors such as concrete permeability, size of elements, location of reinforcement and other embedded metal items, and rate of thermal rise, dictate the level of internal pressure generation on heating[1]. When the rate of temperature rise is high, permeability is low, and large amounts of evaporable water is present, concrete is susceptible to fire damage. This damage could be significant when the rate of increase of the vapor pressure is higher than the pressure relieving ability of the fire-exposed concrete.

Recommendations to Minimize Damage from Fire

Since the porosity and mineralogy play important role for the concrete resistance to fire, these factors must be controlled to attain the desired level of fire resistance. Low porosity aggregate should be used to avoid the problems due to the moisture movement. Siliceous aggregates containing quartz, such a granite and sandstone, are susceptible to fire damage due to the expansion resulting from phase transformation of quartz at a temperature of about 570 ºC (1058 ºF)[1]. Carbonate rocks exhibit the same trend as that for siliceous aggregate but at a higher temperature of about 700 ºC (1092 ºF).

CONCLUDING REMARKS

Durable concrete should be proportioned to attain high resistance to both physical and chemical causes that affect concrete durability adversely. Generally, conventional mixture proportioning of HSC at a low water to cementitious materials ratio does not ensure long-term durability. Consequently, attempts must be made to proportion HPC mixtures for obtaining both high-strength and high-durability related properties (HSC/HQC).

Concrete is a hybrid particulate composite material. It is composed of three major phases: particles (coarse aggregate and sand), matrix (hydrated cement paste, hcp), and the interfacial region between aggregate and the hcp. The aggregates are less permeable compared to the hcp. The interface region between the hcp and aggregate is more porous and weak compared to the other two phases. Furthermore, each of these phases at a microscopic level can be treated as a multiphase material.

HPC mixtures are proportioned to obtain uniform and dense microstructure of the concrete, thus densifying the interfacial region between cement paste and aggregate. This is accomplished through careful mixture proportioning using high quality of constituent materials. The constituent materials include high strength aggregate (closely graded), low heat of hydration cement, mineral additives, and chemical admixtures. Judiciously selected mixing technique is used to obtain cohesive mixture at a low water to cementitious materials ratio. Such concrete mixtures attain dense microstructure and thus high impermeability.

The introduction of pozzolanic additives, such as coal fly ash, natural pozzolans, slags, rice husk ash, wood ash, and silica fume, cause refinement of the grain and pore structures, especially in the interfacial region. Concrete permeability increases with an increase in the porosity and decreases with an increase in density. For achieving high durability, concrete porosity should be kept low so as to reduce its permeability. A very low permeable concrete will reduce or eliminate ingress of water and other aggressive chemicals and gases. This will lead to improved concrete durability due to avoided expansive reaction that can occur in presence of these aggressive agents.

The potential tools and strategies to meet the environmental challenges can be summarized as follows: (1) replace as much portland cement as possible by supplementary cementitious materials, especially those that are by-products of industrial processes, such as coal fly ash, bio-mass ash, ground granulated blast furnace slag, and silica fume; (2) use recycled materials in place of natural resources; (3) improve durability and service life of structures, thereby reducing the amount of materials needed for their replacement; (4) improve concrete's mechanical and other properties, which can also reduce the amount of materials needed; and, (5) reuse wash water.

Due to the low permeability, HPCs have high resistance to various physical and chemical effects that positively impact the concrete strength and durability-related properties. Thus, HPC would have high resistance to abrasion, alkali-silica reaction, corrosion, salt scaling, freezing and thawing, and other similar deteriorating actions. At the present time, it is possible to proportion concrete for strengths exceeding 150 MPa and service life of over 100 years.

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REFERENCES

1. Mehta, P.K., and Monteiro, P.J.M., "Concrete Structure, Properties and Materials", Prentice-Hall, Inc., Englewood Cliff, New Jersey, Second Edition, 1993, 548 pp.

2. Naik, T.R., "Sustainability of the cement and concrete industries", *Practice Periodical on Structural Design and Construction*, ASCE, 2008, pp. 98-103.

3. Cement Association of Canada 2004, "Concrete Thinking for a Sustainable Future", http://www.cement.ca/cement.nsf/e/6ABDCDE126A87A6C85256D2E005CC53B?OpenDocument (November 15, 2005).

4. Naik, T.R., Ramme, B.W., Kraus, R.N. and Siddique R., "Long-Term Performance of High-Volume Fly Ash Concrete Pavements", *ACI Material Journal*, Vol. 100, No. 2, 2003, pp. 150-155.

5. Meyer, C., "The greening of the concrete industry", *Cement & Concrete Composites*, Vol. 3, No. 8, 2009, pp. 601–605.

6. Malhotra, V.M., "Role of Supplementary Cementing Materials and Superplasticizers in Reducing Greenhouse Gas Emissions", Proc. ICFRC International Conference on Fiber Composites, High-Performance Concrete, and Smart Materials, Chennai, India, 2004, pp. 489-499.

7. ACI Committee 201, "Guide to Durable Concrete", ACI 201, American Concrete Institute, Detroit, Michigan, 2001, 41 pp.

8. Coppola, L., Cerulli, T., and Salvioni, D., "Sustainable Development and Durability of Self-Compacting

Concretes", Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Las Vegas, NV, 2004, pp. 29–50.
9. Committee 1993, "High-Performance Materials and System: An Essential Program for America and Its Infrastructure", Prepared by the Planning Committee for the Nationally-Coordinated Program on High-Performance Concrete and Steel, for Civil Engineering Research Foundation (CERF), American Society of civil Engineers, New York, 1993, 58 pp.
10. Naik, T.R., Singh, S.S., Olson, W.A., and Beffel, J.C., "Effect of Temperature and Fly Ash on Behavior of High-performance Concrete", CANMET/ACI/JCI Fourth International Conference on Recent Advances in Concrete Technology, Tokushima, Japan, June 1998, pp. 7-11.
11. Naik, T.R., Singh, S.S., Olson, W.A., and Beffel, J.C., "Temperature Effects on Strength and Durability of High-performance Concrete", PCI/FHWA International Symposium on High-Performance Concrete, New Orleans, LA, October 20-22, 1997.
12. Olson, Jr., W.A., "Temperature Effects on the Permeability of High-Performance Concrete", M.S. Thesis, University of Wisconsin - Milwaukee, 1994.
13. Naik, T.R., and Ramme, B.W., "High Early Strength Fly Ash Concrete for Precast/Prestressed Products", *PCI Journal*, Vol. 35, No. 6, Nov. /Dec., 1990, pp. 72-78.
14. Naik, T.R., and Patel, V.M., and Brand, L., "Performance of High-Strength Concrete Incorporating Mineral Admixtures", ACI National Spring Convention, Washington, D.C., 1992.
15. Naik, T.R., Singh, S.S., and Mohammad M., "Properties of High Performance Concrete Incorporating Large Amounts of High-Lime Fly Ash", *International Journal of Construction and Building Materials*, U.K., Vol. 9, No. 6, 1995, pp 195-204.
16. Beffel, J.C., "Temperature Effects on ASR and Sulfate Resistance of High-Performance Concrete", M.S. Thesis, University of Wisconsin - Milwaukee, 1995.
17. Patel, V.M., "Full-Scale Beam Tests for Shear Strength of High-Strength Concrete", M.S. Thesis, University of Wisconsin - Milwaukee, 1992.
18. Brand, L., "Shear Strength of Reinforced Concrete Beams for High-Strength Concrete", M.S. Thesis, University of Wisconsin - Milwaukee, 1992.
19. Mehta, P.K., "Pozzolanic and Cementitious By-Products in Concrete - Another Look", Proceedings of the Third International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, V.M. Malhotra, Ed., ACI SP-114, 1989, pp. 1-43.
20. Mehta, P.K., "Concrete Technology at the Crossroads - Problems and Opportunities", Proceedings of the V. Mohan Malhotra Symposium on Concrete Technology - Past, Present, and Future, P.K. Mehta, Ed., ACI SP-144, 1994, pp. 1-30.
21. Aitcin, P.C., and Neville, A., "High-Performance Concrete Demystified", *ACI Concrete International*, January 1993, pp. 21-26.
22. Mehta, P.K., and Aitcin, P.C., "Principles Underlying Production of High-Performance Concrete", *Cement, Concrete, and Aggregates, ASTM*, Vol. 12, No. 2, Winter, 1990, pp. 70-78.
23. Aitcin, P.C., Sarkar, S.L., Regourd, M., and Hornain, H., "Microstructure of a Two-Year-Old Very High Strength (100 MPa) Field Concrete", Proceedings of Symposium in Utilization of High Strength Concrete, Tapir Publishers, Trondheim, 1987, pp. 99-109.
24. De Larrand, F., Ithurralde, G., Acker, P., and Chavel, D., "High-Performance Concrete for a Nuclear Containment", Proceedings of the Second International Symposium on High-Strength Concrete, ACI SP-121, 1990, pp. 5549-5576.
25. Gjorv, O.E., "High Strength Concrete", Advances in Concrete Technology, V. M. Malhotra, Ed., CANMET, Ottawa, Canada, 1994, pp. 19-82.
26. Aitcin, P.C., "Durable Concrete - Current Practice and Future Needs", Proceedings of V. Mohan Malhotra Symposium on Concrete Technology - Past, Present, and Future, P.K. Mehta, Ed., SP-144, 1994, pp. 85-104.
27. Collins, M., Mitchell, D., and MacGregor, J.G., "Structural Design Considerations for High-Strength", *ACI Concrete International*, Vol. 15, No. 5, 1993, pp.27-34.
28. Webb, J., "High-strength Concrete: Economics, Design, and Ductility", *ACI Concrete International*, Vol. 15, No. 1, 1993, pp. 27-32.
29. Papworth, F., and Ratcliffe, R., "High-Performance Concrete - The Concrete Future", *ACI Concrete International*, Vol. 16, No. 10, 1994, pp. 39-44.
30. Powers, T.C., Copeland, L.E., and Hayes, J.C., "Permeability of Portland Cement Paste", *Journal of the American Concrete Institute*, *Proceedings*, Detroit, MI, Vol. 26, No. 3, 1954, pp. 285-298.
31. Naik, T.R., Singh, S.S., and Hossain, M.M., "Permeability of Concrete Incorporating Large Quantities of Fly Ash", A final technical report prepared for Electric Power Research Institute, Palo Alto, CA, 1993.
32. Naik, T.R., Singh, S.S., and Hossain, M.M., "Permeability of High-Strength Concrete Containing Low Cement Factor", *ASCE Journal of Energy Engineering*, New York, NY, Vol. 122, No. 1, 1996, pp. 21-39.
33. Mehta, P.K., "Concrete Structures, Properties, and Materials", Prentice-Hall, Inc., Eaglewood Cliff, New

Jersey, 1986, 450 pp.
34. Massazza, F., “Action of Environmental Conditions”, RILEM REPORT 11: Interfacial Transition Zone in Concrete, J.C. Maso, ed., E&FN SPON, London, England, U.K., First Edition, 1996, pp. 132-149.
35. Powers, T.C., Copeland, L.E., and Mann, H.M., “Capillary Continuity or Discontinuity in Cement Pastes”, *Journal of PCA Research and Development Laboratories*, Skokie, IL, Vol. 1, No. 2, 1959, pp. 3-4.
36. Costa, U., and Massazza, F., “Permeability and Pore Structure of Cement Pastes”, Proceedings of the Second International Conference on Engineering Materials, Bologna-Modena, Italy, June 19-23, 1988, as reported by Massazza (1996).
37. Naik, T.R., and Sing, S.S., "Use of High-Calcium Fly Ash in Cement-Based Construction Materials", Proceedings of the Fifth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Milwaukee, WI, USA, June 1995, pp. 1-44.
38. Mather, B., "How to Make Concrete That Will Be Immune to the Effects of Freezing and Thawing", ACI Symposium on Performance of Concrete in Aggressive Environment, San Diego, CA, October 1989.
39. Naik, T.R., Ramme, B.W., and Tews, J.H., "Pavement Construction with High Volume Class C and Class F Fly Ash Concrete", Fourth CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Istanbul, Turkey, May 1992.
40. Naik, T.R., Singh, S.S., and Hossain, M.M., "Freezing and Thawing Durability of Concrete Incorporating Class C Fly Ash", CBU Report No. 199, Center for By-Products Utilization, University of Wisconsin-Milwaukee, Final Progress Report Prepared for EPRI, June, 1994.
41. Soroushian, P., and Hsu, J.W., "Fly Ash Effect on the Scaling Resistance of Concrete: A Literature Review", Proceedings of the Ninth International Ash Use Symposium, ACAA, Vol. 1, EPRI GS-7162, Palo Alto, CA, January 1991, pp. 13-1 to 13-15.
42. Naik, T.R., Singh, S.S., Kraus, R.K. and Hossain, M.M., "Deciding Salt Scaling Resistance of High-Volume Fly Ash Concrete Using Various Sources of Fly Ash", Proceedings of the Workshop on Flowable Slurry Containing Fly Ash and Other Mineral By-Products, Fifth CANMET/ACI International Conference, Milwaukee, WI, USA, June 1995.
43. Bentur, A., and Odler, I., “Development and Nature of Interfacial Microstructure,” RILEM Report 11: Interfacial Transition Zone in Concrete, J.C. Maso, ed., E&FN SPON, London, England, U.K., First Edition, 1996, pp. 18-44.
44. Wu, Z. and. Naik, T.R., “Use of clean-coal ash for managing asr Constructed since 1984”, ACI International Spring 2004 Centennial Convention, Technical Session Sponsored by ACI Committee 232 on Fly Ash and Natural Pozzolans in Concrete, Washington, D.C., March 2004.