Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VI, Paper ID # 421

CONTROLLING THE AGEING OF FUTURE CONCRETE

Dhruv Desai[1] and Javeed Munshi[1]

[1] Bechtel Power Corporation, Frederick, MD 21703 (jamunshi@bechtel.com)

INTRODUCTION

Concrete structures are known to age with time which can sometimes significantly degrade and eventually eliminate their functionality. The ageing process is a result of intrinsic material composition of concrete which in combination with steel reinforcement is subjected to long-term environmental factors. Given the size of investments and the risk associated with disruption of revenue as a result of degradation, there is a great interest and incentive to keep nuclear plants operational and minimize the effects of ageing. Furthermore, new generation nuclear and commercial concrete structures are already being targeted for a longer life expectancy to minimize the overall life-cycle cost. This study will discuss the common chemical and physical ageing mechanism of concrete and ways to mitigate them. Some alternatives and latest emerging technologies to mitigate ageing are also presented. The information presented in this paper can be used to minimize the age related degradation mechanism to achieve service life of 100 years or more for concrete nuclear structures of the future.

CHEMICAL AGEING MECHANISMS

Depending on exposure conditions, there are various types of chemical attacks which can degrade the performance of concrete. These attacks can occur concurrently or independently and involve chemical reactions with cement paste or aggregate in concrete. Chemical causes of deterioration can be grouped in three categories (a) hydrolysis of cement paste components by soft water; (b) cation exchange reactions between aggressive fluids and the cement paste; and (c) reactions leading to formation of expansion products Mehta (1986). Various forms of ageing due to chemical processes are described below.

Table 1 Common Chemical Ageing Mechanisms and Mitigation

Mechanism	Description	Mitigating Measures
Efflorescence and Leaching	Efflorescence involves deposition of crystalline salt deposits on concrete surface due to evaporation of water containing dissolved salts on the surface and occurs as a result of water percolating through concrete Naus(2007). Leaching involves movement of ions via the pore system from the interior of concrete to the outside surface; this occurs as a result of dissolving of solid lime compounds within the concrete by water that has penetrated Naus (2007). See Naus (2007), Neville (1995) & Halvorsen (1966)	Efflorescence and leaching can be mitigated by making concrete less porous and reducing the amount of moisture in the concrete pores. This can be achieved by specifying low w/cm ratio and specifying use of pozzolons ACI 201.2R (2008) and/or ground granulated blast furnace slag. Use of vapor barriers on surface of concrete and allowing for drainage of water away from concrete also help in minimizing moisture ingress and subsequently mitigate efflorescence and leaching ACI 201.2R (2008)
Sulfate Attack	Sulfate attack has two principal mechanisms; the first mechanism involves formation of ettringite and gypsum in the	• Use of cement containing low tri calcium aluminate Mather (1968) (ASTM Type V cement containing less than 5 percent tri

	hardened concrete causing cracking and exfoliation and the second mechanism involves softening and dissolution of the hydrated cementing compounds due to direct attack on these compounds by sulfate or by their decomposition when calcium hydroxide reacts with the sulfates and is removed USACE (1995). See USACE (1995), Naus (2007), Swenson (1999), USACE (1995), Trinh et al. (1997).	calcium aluminate) • Use of cement, pozzolans and/or ground granulated blast furnace slag for each exposure class based on severity in accordance with Table 6.3 of ACI 201.2R (2008) • Limiting w/cm ratio for each exposure class in accordance with Table 6.3 of ACI 201.2R (2008)
Delayed Ettringite Formation (DEF)	DEF occurs when ettrigite forms in concrete in its hardened state leading to expansion and cracking due to rigidity of the concrete which does not allow room for free expansion. There are two commonly occurring causes (a) Improper curing/placing practice for fresh concrete that leads to high initial temperature of > 70 ^{o}C resulting in decomposition of ettrigite formed at that stage (b) Cement used in concrete having high sulfur contents and sulfur having low solubility Naus (2007). See Naus (2007) & Collepardi (1999).	• Lowering the curing temperature in order to prevent delay in formation of ettringite • Limiting clinker sulfate levels in order to reduce the amount of sulfate available for reaction Naus (2007) • Avoiding excessive curing for potentially critical sulfate to aluminate ratios Naus (2007) • Preventing exposure to substantial water in service Naus (2007) • Using air entrainment in order to allow space for pressure relief if ettringite formation occurs after the concrete has hardened Naus (2007)
Acids	Concrete containing Portland cement is highly alkaline and as a result does not exhibit good resistance when exposed to acids; the component of concrete most vulnerable to acid attack is $Ca(OH)_2$ but acids can also attack the C-S-H leading to disintegration of the cement paste Neville (1995). The resulting new compounds if soluble are leached out and if insoluble can stay in situ and are disruptive (Neville 1995). See Naus (2007),Neville (1995), U Litzner et al (1999) & Romben (1978)	• For mild exposure, use of Pozzolons and/or ground granulated blast furnace slag to reduce the amount of $Ca(OH)_2$ available for reaction and at the same time reduce permeability of concrete Neville (1995) • For severe exposure in addition to aforementioned measures, use of protective barrier systems in accordance with ACI 515.1R (1985)
Alkali Aggregate Reactions	Alkali aggregate reactions can be classified into (a) alkali silica reaction & (b) alkali carbonate reactions. Alkali silica reaction involves reaction between the siliceous constituents in the aggregates and the alkaline hydroxides in the pore water derived from the alkalis (Na_2O and K_2O) in the cement resulting in an alkali-silicate gel which forms either in planes of weakness or pores in the aggregates (where reactive silica is present) or on the surface of the aggregate particles Neville (1995). Alkali Carbonate reaction	• Use on non-reactive aggregates if available; aggregates shall be evaluated for reactivity using the guidelines of ACI 201.2R (2008) Section 5.3 • Beneficiation of aggregate to reduce or eliminate the reactive material CAN/CSA A23.1 (2009) Annex B • Limiting total alkali content in concrete CAN/CSA A23.1 (2009) Annex B • Use of fly ash, ground granulated blast-furnace slag and/or silica fume in accordance with guidance in Ref CAN/CSA A23.1 (2009) Annex B

	typically involves dolomitic limestones that consist of a fine grained matrix of calcite and clay in which larger crystals (20-80 um) of euhedral dolomite rhombohedra are suspended Ozal (1994); the dolomitic crystals in the aggregates react with the alkalis resulting in de-dolotimization and production of brucite, ($MgOH_2$), and calcite ($CaCO_3$). See Naus (2007), Neville (1995), CAN/CSA A23.1 (2009), Mindness et al (1981) & Ozal (1994)	• Use of lithium salts in accordance with guidance in Ref CAN/CSA A23.1 (2009) Annex B
Biological Attack	Biological attack can be classified into two types (a) Mechanical deterioration caused due to growth of moss, lichen, algae, roots of adjacent plants/tress which enter through cracks and weak spots in concrete and lead to increased cracking and deterioration of concrete due to the resulting bursting forces (b) Chemical deterioration of hydrated cement paste or calcareous components of concrete caused by release of sulfuric acid or nitric acid produced due to metabolic action of microrganisms or release of corrosive chemicals which promotes corrosion of steel Naus (2007). See Naus (2007), Neville (1995) & Naus et al (2006)	For measures for mitigation/prevention for attack by acids produced due to biological growth in concrete, refer to the section on "Acids". For prevention of mechanical deterioration due to plant growth, an active external management program to prevent/control growth is required.
Carbonation	Carbonation involves reaction of the hydrated cement paste with atmospheric carbon dioxide in presence of moisture which can lead to carbonation shrinkage Neville (1995) and lowering of pH in concrete which can alter the passivating environment around reinforcement Naus (2007). See Naus (2007), Neville (1995), Lea (1970) Pullar-Strecker (1987) & Clifton (1991)	•Specifying minimum cover to reinforcement in order to prevent carbonation from reaching to reinforcement Naus (2007) •Specifying a low w/cm ratio Naus (2007)
Reinforcing Steel Corrosion	Corrosion of steel is an electrochemical process and can occur in form of local pitting corrosion which leads to reduction of reinforcement thickness at individual locations or in form of a general corrosion which leads to a relatively uniform reduction in thickness along the length of corroding reinforcing steel Naus (2007). It occurs when the reinforcing steel is exposed to both oxygen and water and the passive protective layer around the steel is destroyed either due to (a) carbonation (b) leaching of alkaline	• Specifying a minimum reinforcement cover for the expected exposure condition Naus (2007) • Limiting the chloride content in new concrete ACI 201.2R (2008) • Specifying a low w/cm ratio Naus (2007) • Increase in concrete resistivity by use of silica fume, slag cement and use of fly ash ACI 201.2R (2008) • Use of corrosion resisting reinforcement (described in more detail in a latter section in this paper)

	substances by water or (c) presence of chlorides Naus (2007). See Naus (2007), ACI 222R (2001), Gonzolez et al. (1983) & Clifton (1991).	
Post tension systems corrosion	Due to the nature of post tensioning systems including its stress state and future prestressing losses after initial installation, there is a much less tolerance for attack due to corrosion. Failures of prestressing systems in general civil engineering structures have been a result of localized attack produced by pitting, stress corrosion, hydrogen embrittlement, or a combination of these Naus (2007). See Naus (2007), Hartt (1990) & Stratfull (1983).	Mitigating measures for post tensioning system depend on the type of the tendons, type of concrete construction and local exposure conditions. It is recommended to refer to Appendix D of Post Tensioning Tendon Installation and Grouting Manual by Corven & Moreton (2004) which provides a thorough review.

PHYSICAL AGEING MECHANISMS

Physical processes involve degradation of concrete due to external factors that generally lead to cracking due to exceeding the tensile strength of concrete, or loss of surface material (Naus 2007). The load related cracking and the resulting degradation can be avoided through proper design and detailing.

Table 2 Physical Ageing Mechanisms and Mitigation

Mechanism	Description	Mitigating Measures
Plastic Settlement and Shrinkage	Cracking can occur both before and after hardening of concrete. The various types of cracking are • Plastic Settlement • Plastic Shrinkage • Early Thermal Contraction • Long Term Drying Shrinkage • Blister • Crazing.	• Plastic settlement cracking: (1) Use of air entrainment ACI 212.3R (2010) (2) Use of synthetic fibers to increase tensile strain capacity NRMCA (1994) • Plastic Shrinkage: (1) Use of synthetic fibers NRMCA (1994) • Early thermal contraction : (1) Use of Type II cement and/or pozzolons to reduce heat of hydration NRMCA (2009) • Long-term drying shrinkage : (1) Reduction of water content and use of largest practical size aggregate in concrete mixture ACI 224R (2001) (2) Use of shrinkage reinforcement with minimum 0.6 % reinforcement to control cracking ACI 224R (2001) (3) Proper detailing and use of joints ACI 224R (2001) (4) Use of shrinkage compensating concrete ACI 224R (2001) • Blisters : (1) Follow measures described in the references referred to in section on good construction practice in this paper • Crazing : (1) Follow measures described in the references referred to section on good construction practice in this paper

Salt Crystallizati-on	When concrete is exposed to sea water and repeating cycles of wetting and drying it leads to deposition of salts within the pores of concrete which are left behind when the water evaporates; on subsequent wetting the salt re-hydrates resulting in expansive force on the surrounding hardened cement paste Neville (1995); Salt weathering can also occur in desert areas and in concrete structures exposed to large quantities of dissolved salts. See Naus (2007) and Neville (1995).	• Use of properly applied sealers/barriers to prevent water ingress and/or subsequent evaporation Naus (2007). • Producing good quality concrete with low permeability Neville (1995) through use of pozzolons and/or ground granulated blast furnace slag and specifying a low w/cm ratio • Use of dense aggregate with low absorption to prevent damage to aggregate itself Neville (1995)
Freezing and Thawing	Both the cement paste and the aggregates in the concrete are susceptible to damage due to freeze thaw damage in cold climates. There are multiple theories regarding possible mechanisms ACI 201.2R (2008); for example (1) hydraulic pressure buildup when water freezes (2) osmotic pressure gradients leading water towards points of freezing (3) vapor pressure potentials (4) combinations of above (Powers 1945, 1954, 1955, 1975; Powers and Helmuth 1956, Helmuth 1960; Litvan 1972). See Mehta et al.(2005), Powers (1945, 1954, 1955, 1958, 1975) , Harrison et al. (2001) & Mindess & Young (1981).	• When available use of aggregates resistant to freeze thaw damage verified by testing using ASTM C666/C666M 2008 ACI 201.2R (2008) • Aggregate beneficiation in accordance with guidance in ACI 201.2R (2008) • Specifying low w/cm ratio to reduce amount of freezable water ACI 201.2R (2008) • Producing a well air entrained system in concrete with air voids having a minimum specific surface of 25 mm^2/mm^3 that are evenly distributed throughout the paste portion of concrete and having a spacing factor less than 0.20 mm with air content as recommended in Table 4.1 of ACI 201.2R (2008)
Abrasion, Erosion And Cavitation	Abrasion of concrete involves rubbing or grinding of aggregate or other debris against concrete surface which leads to progressive loss of materials at the concrete surface ;When the aggregates or other debris are part of a fluid flow leading to loss of materials it is described as erosion Naus (2007) Cavitation involves formation of vapor bubbles when the local absolute pressure drops to the value of the ambient vapor pressure of water at the ambient temperature; the bubbles flow towards an area having pressure and upon entering collapse with the greatest impact repeated cycles of which leads to pitting damage Neville (1995). See Naus (2007) & Neville (1995) for more information.	•For abrasion depending on the severity, specifying a certain minimum compressive strength of concrete Neville (1995). Specifying low cement content in order to keep coarse aggregate just below the surface of concrete Neville (1995). Use of shrinkage compensating concrete ACI 223R (2010) •For erosion, specifying concrete with high compressive strength and by use of hard aggregate Neville (1995).Use of low cement content USACE (1943) •For cavitation, use of high strength concrete and use of absorptive lining (which reduces local w/cm ratio) Neville (1995). Limiting maximum size of coarse aggregate to 20 mm (3/4 in) due to tendency of cavitation to remove large particles Neville (1995) & Kenn (1968). Use of smooth and well aligned surfaces Neville (1995).

OTHER TECHNOLOGIES

Light-Weight Aggregate and Internal Curing

American Concrete Institute (ACI) defines internal curing as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation"

Normal hydration of concrete involves reaction of water with cement resulting in formation of crystalline and gel hydration products and water incorporated in these products generally occupies less space than water in its bulk form leading to a net chemical shrinkage in hydration products which can lead to early age cracking Bentz & Weiss (2010). Internal curing provides readily available source of water in the interior of concrete which simultaneously minimizes the autogeneous stresses and strains by ensuring saturation of capillary porosity; additionally it maximizes the amount of hydration of the cement and pozzolons in the mixture which potentially leads to increased strengths and reduced transport coefficients (reduced permeability) Bentz & Weiss (2010). This contrasts with external curing in which water only penetrates a few mm into the concrete from the curing applied surfaces Bentz (2002). Research also indicates that internal curing reduces plastic shrinkage, drying shrinkage and creep Bentz & Weiss (2010) & Henkensiefken et al. (2010). Due to increased hydration and the resultant denser structure, there is a reduction in permeability of concrete Bentz & Weiss (2010).

VERDiCT

VERDiCT stands for “Viscosity Enhancers Reducing Diffusion in Concrete Technology” Bentz et al. (2013) As the name suggests, the approach involves introducing a viscosity modifier/shrinkage-reducing admixture in concrete to increase the viscosity of the pore solution. The rate at which the aggressive ions travel is proportional to the ionic diffusion coefficient. As per Walden’s rule, the ionic diffusion coefficient should be inversely proportional to the solution viscosity Robinson & Stokes (2002). Therefore, if the diffusion rate is halved by doubling the viscosity, the service life of the concrete is potentially doubled Bentz et al. (2013). Results from testing performed at NIST show reduction in diffusion coefficient and reduction/elimination of autogenous shrinkage when VERDiCT is used by itself and depending on mix design used, similar or better results when LWA is pre-wetted using VERDiCT solution Bentz et al. (2013).

HVFA Concrete

High Volume Fly ash (HVFA) concrete as defined by Malhotra and Mehta is concrete which has a fly ash content of minimum of 50 percent by mass of the total cementitious material Malhotra &Mehta (2005). HVFA concrete has several advantages over conventional concrete. Some of the advantages of using fly ash are discussed in the previous sections of this paper; however this section deals with use of HVFA. When compared with conventional concrete, HVFA concrete can have upto one third less mixing water resulting in a decrease in not only the w/cm ratio but also the total volume of the cement paste thus reducing the drying shrinkage which is directly proportional to w/cm ratio and proportion of cement paste present in concrete Mehta & Monterio (2013). Additionally, the long term strength and impermeability of HVFA concrete is generally far superior to ordinary concrete with no fly ash or small quantity if fly ash Mehta & Monterio (2005). Tests performed in laboratory also confirm the excellent durability characteristics of HVFA concrete mixtures in relation to corrosion of steel reinforcement, alkali aggregate expansion, and sulfate attack Malhotra (2002)

Ternary Blend Concrete

In some cases using a single type of supplementary cementitious material (SCM) (pozzolon/slag) to address one durability concern can cause reduced performance in another area Bleszynski et al. (2002). Ternary blend concrete uses at least two more SCMs in addition to ordinary Portland cement (OPC). Use of a ternary blend concrete containing silica fume and slag in a site investigation to study durability performance of ternary blend showed that the ternary blend concrete had better resistance to ASR compared to mixture containing individual SCMs or no SCMs, to ingress of chloride ions compared to mixture containing individual SCMs or no SCMs, to salt scaling compared to mixture containing only slag and fresh concrete which was flowable, thixotropic, easily placed, and finished and with a higher slump compared to mixture without SCMs or with mixture containing silica fume Bleszynski et al. (2002).Use of ternary blend concrete containing silica fume and fly ash in a laboratory study showed that the ternary blend concrete had better resistance to chloride ion penetrability compared to mixture containing individual SCMs or no SCMs, lower plastic shrinkage compared to mixture containing individual SCMs or no SCMs. Additionally, use of fly ash in concrete offset the increased demand of high range water reducing admixture that is required for concrete containing only silica fume Bouzoubaâ et al. (2004). Other durability tests were not covered in the study.

The second gateway bridge built on Brisbane river in Australia designed for a 300 year service life used ternary blend concrete involving 30 % fly ash and 21 % blast furnace slag Connal & Berndt (2013)

Corrosion Resisting Reinforcing Steel

In order to resist corrosion, various options are currently available in the market.

Epoxy coated reinforcing steel: This type of reinforcing steel uses epoxy coating to resist electrochemical corrosion. When available without any damage on surface, it is able to resist corrosion due to chlorides; however the nature of construction site makes it susceptible to surface damage, pinhole defects & holidays thus making it susceptible to corrosion.

Galvanized reinforcing steel: Galvanized reinforcing steel involves coating steel with a molten coating which results in the formation of an outer layer of pure zinc that is underlaid by several zinc-iron alloy layers; Zinc provides protection by acting as a barrier that prevents access of oxygen and moisture to the protected material, and at the same time acts as a sacrificial anode that corrodes in preference to the protected metal Darwin et al. (2009). In a study performed by Darwin et al. (2009) it was found that galvanized reinforcement had a higher average critical chloride corrosion threshold than conventional (ASTM A615) steel and a lower threshold than low carbon chromium (MMFX-ASTM A1035) reinforcement or 316LN stainless steel. Additionally, based on chloride surveys of cracked bridge decks it was concluded that, galvanized steel can be expected to increase the average time to corrosion initiation at crack locations from 2.3 years for conventional steel to 4.8 years for bars with 3 in. (76 mm) of concrete cover and corrosion initiation would be expected to occur at an average age of 15 years for ASTM A1035 reinforcement and not to occur for bars consisting of 316LN stainless steel Darwin et al. (2009).

MMFX reinforcing steel: MMFX steel provides resistance to corrosion as a result of a patented and proprietary steel microstructure. For comparison of performance see section on galvanized reinforcing steel.

Stainless Steel: In stainless steel, chromium reacts with the atmospheric oxygen to form chromium oxide which forms a passivating film which provides resistance to corrosion. Stainless steel rebars provide the best corrosion resistance among different types of rebar Darwin et al. (2009), but are usually the most expensive. For comparison of performance see section on galvanized reinforcing steel.

Fresh Concrete Quality Control

Use of good materials along with proper mixture proportioning by itself is not enough; measures ensuring appropriate quality control, testing, inspection, placement, practices, and workmanship are essential to produce durable concrete ACI 201.2R (2008). References (ACI 304R-2000, ACI SP-2-2007,ACI 318-2011, ASTM C94-2013 U.S. Bureau of Reclamation-1981, U.S. Department of Commerce-1966, Corps of Engineers-1994) provide a thorough review of the aforementioned measures.

Future Technologies

NIST is currently at the forefront of developing simple science based and rapid test methods to assist in durability based design using performance based standards; development of a new concrete resistivity test and a new mini-bar cement paste sulfate attack test is currently underway NIST (2013) A model to establish relationship between cracking and transport of chlorides is being currently developed in order to assist in increasing the accuracy of current concrete service life models which do not incorporate the effect of cracks NIST (2013)

CONCLUSION

Concrete structures are known to age with time which can sometimes significantly degrade and eventually eliminate their functionality. Given the size of investments and the risk associated with disruption of revenue as a result of degradation, there is a great interest and incentive to keep nuclear plants operational and minimize the effects of ageing. Furthermore, new generation nuclear and commercial concrete structures are already being targeted for a longer life expectancy to minimize the overall life-cycle cost. This study discusses the physical and chemical ageing mechanisms of concrete and ways to mitigate them. Some alternate and emerging technologies for ageing mitigation are also presented. The information presented in this study can be used as a basis to select appropriate mitigating measures depending upon the project situation to minimize the age related degradation mechanism and to achieve the desired service life of concrete nuclear structures.

REFERENCES

D.J. Naus, (2007) NUREG/CR-6927 "Primer on Durability of Nuclear Power Plant Reinforced Structures – A Review of Pertinent Factors" U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC 20555-0001

A.M. Neville(1995) , "Properties of Concrete", Fourth Edition, Pearson Education

P.K. Mehta (1986)," Concrete- Structure, Properties and Materials", Prentice-Hall. Englewood Cliffs, New Jersey

Halvorsen U. (1966), "Corrosion of Steel and Leaching of Lime Near Cracks in Concrete Structures", Bulletin 1, Division of Building Technology, Lund Institute of Technology, Lund, Sweden

E.G. Swenson (1999), "Concrete in Sulphate Environments," CBD-136, Canadian Building Digest, National Research Council, Ottawa, Canada.

US Army Corps of Engineers (1995), "Evaluation and Repair of Concrete Structures – Engineering Manual," EM 1110-2-2-2002, Waterways Experiment Station, Vicksburg, Mississippi

C. Trinh, L. Bucea and O.Ferguson, (1997) " Sulphate Resistance of Cementitious Materials, Mechanisms, Deterioration Processes, Testing and Influence of Binder" Proc. Concrete 97, pp. 263-268, Concrete Institute of Australia, Adelaide

H.-U Litzner and A.Baker (1999), "Design of Concrete Structures for Durability and Strength to Eurocode 2", Materials and Structures 32, pp. 323-330

CAN/CSA A23.1 (2009) Concrete Material and Methods of Concrete Construction, Annex B, Canadian Standards Association, Toronto

S. Mindness and J.F. Young, Concrete Prentice Hall, Inc Englewood Cliffs, New Jersey, 1981

M.A. Ozal, "Alkali-Carbonate rock reactions". Significance of Tests and Properties of Concrete and Concrete making materials pp- 341-364 in ASTM STP 169C, American Society of Testing and Materials, West Conshohocken, Pennsylvania, 1994.

American Concrete Institute Committee 221, "State of the Art Report on Alkali Aggregate Reactivity." ACI 221.1R-98, American Concrete Institute, Farmington Hills, Michigan, 1998.

D.J. Naus, L.R. Dole, and C.H. Mattus (2006), "Interim report: Assessment of Potential Phosphate Ion-Concrete Interactions", Oak Ridge National Laboratory Letter Report to U.S. NRC, Washington D.C.

F.M. Lea (1970), The chemistry of Cement and Concrete (Arnold, London)

P. Pullar-Strecker (1987), Corrosion Damaged Concrete Assessment and Repair, Butterworths, London,

J.R. Clifton (1991), "Predicting the Remaining Service Life of Concrete, "NISTIR 4712, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland.

ACI Committee 222 (2001), "Protection of Metals in Concrete Against Corrosion," ACI 222R-01, American Concrete Institute, Farmington Hills, Michigan.

J.A. Gonzolez, C. Alonso, and C.Andrade (1983), "Corrosion Rate of Reinforcement During Accelerated

Carbonation of Mortar Made from Different types of Cement," Corrosion of Reinforcement in Concrete Construction, Society of Chemical Industry, pp, 159-174, Ellis Horwood, England.

P. K. Mehta (1986), Concrete - Structure, Properties, and Materials, Prentice-Hall, Inc., Englewood Cliffs, New Jersey

J.R. Clifton, "Predicting the Remaining Service Life of Concrete," NISTIR 4712, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, 1991

W.H. Hartt (1990), "A Critical Evaluation of Cathodic Protection for Prestressing Steel in Concrete" pp 515-524 in Proceedings of the Third International Symposium on Corrosion of Reinforcement in Concrete Construction

R.F. Stratfull (1983), "Criteria for the Cathodic Protection of Bridge Decks" Chapter 18 in Corrosion of Reinforcement in Concrete Construction, Society of Chemical Industry, London, United Kingdom

P. Kumar Mehta, Paulo J.M. Monterio, (2005) "Concrete Microstructure, Properties, and Materials", Tata McGraw-Hill, third edition

Powers, T.C (1958) "The Physical Structure and Engineering Properties of Concrete Bulleting 90, Portland Cement Association, Skokie IL

Powers, T. C., (1945), "Working Hypothesis for Further Studies of Frost Resistance of Concrete," ACI Journal, Proceedings V. 41, No. 4, Feb., pp. 245-272

Powers, T. C., (1954), "Void Spacing as a Basis for Producing Air-Entrained Concrete," ACI Journal, Proceedings V. 50, No. 9, May, pp. 741-760

Powers, T. C., (1955), "Basic Considerations Pertaining to Freezing and Thawing Tests," Proceedings, V. 55, ASTM International, West Conshohocken, PA, pp. 1132-1155

Powers, T. C., (1975), "Freezing Effects in Concrete," Durability of Concrete, SP-47, American Concrete Institute, Farmington Hills, MI, pp. 1-11

Powers, T. C., and Helmuth, R. A., (1956), "Theory of Volume Changes in Hardened Portland Cement Paste During Freezing," Proceedings of the Highway Research Board, 32, pp. 285-297

Helmuth, R., 1960, "Capillary Size Restrictions on Ice Formation in Hardened Portland Cement Pastes," Fourth International Symposium on the Chemistry of Cement, Washington, pp. 855-869

Litvan, G. G., (1972), "Phase Transitions of Adsorbates: IV, Mechanism of Frost Action in Hardened Cement Paste," Journal, American Ceramic Society, V. 55, No. 1, pp. 38-42

ACI 201.2R-08 (2008) Guide to Durable Concrete, American Concrete Institute, Michigan

L Romben (1978), Aspects of testing methods for acid attack on concrete. CBI research 1:78, 61 pp (Swedish Cement and Concrete Research Inst)

ACI Committee 515 (1985), "A Guide to the Use of Waterproofing, Damp-proofing, Protective, and Decorative Barrier Systems for Concrete (ACI 515.1R-79)," American Concrete Institute, Farmington Hills, Mich., 1979 (Revised 1985)

ACI Committee 212.3R -10 (2010), "Report on Chemical admixtures for Concrete", American Concrete Institute, Farmington Hills, Michigan.

ACI Committee 224R -01 (2001), "Control of cracking in concrete", American Concrete Institute, Farmington Hills, Michigan.

Collepardi M, (1999) Concrete International, Vol 21, No. 1, pp. 69-74

T.A. Harrison, J.D. Dewer, and R.V Brown (2001), "Freeze Thaw resisting concrete- Its achievement in the UK", CIRIA C559, Concrete Society, London, United Kingdom

S. Mindess and J.F. Young, "Concrete", Prentice- Hall, Inc,Englewoods Cliff, New Jersey, 1981

ASTM C666/C666M (2008) "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", ASTM International, West Conshohocken, PA

ACI 223R-10 (2010), "Guide for the use of shrinkage compensating concrete", Michigan

US Army of Corps of Engineers (1943), Concrete Abrasion Study Bonneville Spillway Dam, Report 15-1 (Bonneville, Or)

M.J. Kenn, Factors influencing the erosion of concrete by cavitation, CIRIA, 15 pp (London, July, 1968)

Dale P Bentz, W, Jason Weiss (2010) "Internal Curing: A 2010 State of the Art Review", National Institute of Technology

Bentz, D. (2002) "Influence of Curing Conditions on Water Loss and Hydration in Cement Pastes with and without Fly Ash Substitution", NISTIR 6886, U.S. Department of Commerce.

Henkensiefken, R., Briatka, P., Bentz, D., Nantung, T., & Weiss, J. (2010) "Plastic Shrinkage Cracking in Internally Cured Mixtures Made with Pre-wetted Lightweight Aggregate. Concrete International" , 32 (2), 49-54.

Dale P. Bentz, Kenneth A. Snyder, Max A. Peltz (date retrieved 04/22/2013) "Viscosity Modifiers to Enhance Concrete Performance" Engineering Laboratory, National Institute of Standards and Technology (NIST)

Robinson, R.A., and Stokes, R.H., Electrolyte Solutions (2002) (2nd Revised Edition), Dover Publications Inc., Mineola, NY, 2002.

Malhotra, V.M. and P.K. Mehta, (2005) "High Performance High Volume Fly Ash Concrete" 2nd edition, Supplementary Cementing Materials for Sustainable Development, Ottawa, Canada

Malhotra, V.M. (2002) Concrete International, Vol 24 No.7, pp 30-34

ACI 304R (2000) "Guide for Measuring, Mixing, Transporting, and Placing Concrete", American Concrete Institute, Farmington Hills, Michigan.

ACI SP-2 (2007) "Manual of Concrete Inspection", American Concrete Institute, Farmington Hills, Michigan

ACI 318 (2011) "Building Code Requirements for Structural Concrete and Commentary" American Concrete Institute, Farmington Hills, Michigan

ASTM C94 (2013), "Standard Specification for Ready-Mixed Concrete", ASTM International, West Conshohocken, PA

U.S. Bureau of Reclamation, (1981), Concrete Manual, 8th Edition, Denver, 627 pp.

U.S. Department of Commerce, (1966), "A Study of Mixing Performance of Large Central Plant Concrete Mixers," Bureau of Public Roads, Washington, D.C.

Corps of Engineers, (1994), "Standard Practice for Concrete for Civil Works Structures," EM-1110-2-2000, Washington, D. C., 119 pp.

Roland Bleszynski, R. Doug Hooton, Michael D. A. Thomas, and Chris A. Rogers (2002), "Durability of Ternary Blend Concrete with Silica Fume and Blast-Furnace Slag: Laboratory and Outdoor Exposure Site Studies" , ACI Materials Journal, September-October 2002, American Concrete Institute, Farmington Hills, Michigan

Nabil Bouzoubaâ, Alain Bilodeau, Vasanthy Sivasundaram, Benoit Fournier, and Dean M. Golden. (2004) "Development of Ternary Blends for High Performance Concrete" ACI Materials Journal, January- February 2004, American Concrete Institute, Farmington Hills, Michigan

David Darwin, JoAnn Browning, Matthew O'Reilly, Lihua Xing, and Jianxin Ji (2009), "Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars" ACI Materials Journal, March-April 2009, American Concrete Institute, Farmington Hills, Michigan

John Connal, Marita Berndt (date retrieved 04/22/2013) , "Sustainable Bridges – 300 Year Design Life for Second Gateway Bridge"

NIST "Long Term Performance of Concrete Project" (date retrieved 04/22/2013) http://www.nist.gov/el/building_materials/inorganic/ltpc.cfm

National Ready Mix Association, NRMCA (1994), "CIP-24 Synthetic Fibers for Concrete"

National Ready Mix Association, NRMCA (2009), "CIP-42 Thermal Cracking of Concrete"

Mather, B., (1968), "Field and Laboratory Studies of the Sulphate Resistance of Concrete," Performance of Concrete-Resistance of Concrete to Sulphate and Other Environmental Conditions, Thorvaldson Symposium, University of Toronto Press, Toronto, ON, Canada, pp. 66-76.

P. Kumar Mehta, Paulo J.M. Monterio (date retrieved 04/22/2013) http://www.ce.berkeley.edu/~paulmont/241/high_performance_concrete.pdf

John Corven and Alan Moreton (2004), "Post Post-Tensioning Tendon Installation and Grouting Manual", Federal Highway Administration, FHWA

COPYRIGHT TRANSFER AGREEMENT

The below text in italic is for your information and agreement prior to submittal of the paper.

The author(s) warrants that the submitted manuscript is the original work of the author(s) and has never been published in its present form.

The Lead Author, with the consent of all other authors, by submitting the manuscript for publication in SMiRT-22 transactions, hereby transfers copyright interest in the submitted manuscript to IASMiRT subject to the following.

- *The Lead Author and all coauthors retain the right to revise, adapt, prepare derivative/ expanded works, present orally, or distribute the work.*
- *In all instances where the work is prepared as a "work made for hire" for an employer, the employer(s) of the author(s) retain(s) the right to revise, adapt, prepare derivative/expanded works, publish, reprint, reproduce, and distribute the work provided that such use is for the promotion of its business enterprise and does not imply the endorsement of IASMiRT.*
- *It is recognized that an author who is a U.S. Government employee and who has participated in the submitted work does not own copyright in it.*

Note: If the manuscript is not accepted by IASMiRT or is withdrawn prior to acceptance by IASMiRT, this copyright transfer will be null and void.