Durability of Concrete – The Zigzag Course of Progress

by P.K. Mehta

Synopsis: Concrete design and construction practices today are essentially strength-driven. However, due to escalation in the repair and replacement costs of structures and a growing concern about sustainability of the concrete industry, more attention is being paid now to durability issues. An overview of the state of the built infrastructure in the world shows that the current methods for achieving considerable enhancement of durability of concrete structures are proving inadequate, especially with concrete members exposed to severe weather conditions. It seems that inhomogeneities in the microstructure of concrete are responsible for microcracks which, when subjected to tensile stress from weathering and loading effects during the service, grow into macrocracks. When the macrocracks, voids, and microcracks become interlinked there is a sudden increase in the rate of transport of water, carrying harmful ions and gases from the surface into the interior of concrete. This point marks the initiation and progressive deterioration of the material from one or more causes. A three-stage concrete damage process is discussed to show what changes in concrete technology are needed for radical enhancement in the durability of structures to be built in the future.

Keywords: concrete; damage; deterioration; durability; holistic; macrocracks; microcracks; microstructure; sustainability

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INTRODUCTION

Approximately fifteen years ago, at the Second CANMET/ACI International Conference on Concrete Durability held in Montreal in 1991, the author presented a comprehensive paper on durability of concrete structures in North America[1]. This paper was based on a review of several important publications on the subject during the previous 50-years period. The title of the paper was "Durability of Concrete - Fifty Years of Progress?" The title was derived from the conclusion that an unusually large number of concrete structures, many of them hardly a few years old, were found in a state of deterioration. This was attributed to developments since the 1940's in the concrete industry that were driven by the speed of construction, and the strength of concrete rather than durability as the principal object of structural design and construction. Presented here is an update on the state of durability of concrete structures today. It seems that in spite of an accumulated knowledge base on how to build durable concrete structures, there has been essentially no progress on this issue.

There are compelling reasons why the concrete construction practice during the 21st century will have to be driven by durability rather than by the strength considerations. For instance, increasing carbon emissions, global warming, and a credible threat of climate change have brought to public attention the issue that sustainable economic development cannot occur without reducing the wasteful consumption of natural resources through radical enhancement of durability of manufactured products. Note the following excerpts from a March 2001 report, " Vision 2030: A Vision for the U.S. Concrete Industry", issued by the Strategic Development Council, an organization of senior concrete industry executives dedicated to promoting the development of new technologies for which there is near-term commercial demand[2].

> *The industry will be able to offer better products, including durable constructed facilities with low maintenance cost….*
>
> *Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases.*

In this paper, I have used a holistic approach that involves a search for the root causes behind commonly known durability problems. This approach has led to identification of the three stages of concrete damage process. For radical enhancement of durability of concrete structures, it is proposed that the damage process must not be permitted to go beyond the first stage, which can be achieved by understanding and control of the microstructure of concrete.

CONCRETE DURABILITY – A GLOBAL OVERVIEW

It was nearly 20 years ago when the U.S. National Materials Advisory Board, in 1987, sounded an alarm bell by reporting that concrete bridge-decks, built since the 1970's, were suffering from an epidemic of durability problems that would require billions of dollars to fix. Meanwhile, more cases of serious and premature deterioration of concrete infrastructure have been reported from around the world. To site a few examples, Khanna et al.[3] in 1988 reported the results of an investigation of premature deterioration in reinforced concrete piles of the Rodney Terminal at St. John in New Brunswick, Canada. The investigation revealed that thermal cracks during the pile manufacture were precursors to serious cracking from cycles of freezing and thawing, and from reinforcement corrosion. Gerwick[4] in 1989 reported similar cases of premature cracking and deterioration in reinforced concrete lining of undersea tunnels in Dubai, Hong Kong, and Japan. In the 1990's, Shayan and Quick[5] from Australia, and Collepardi[6] from Italy reported cases of premature cracking and deterioration in prestressed concrete railway sleepers.

In the United States, in response to widespread cracking of concrete bridge-decks, the construction practice moved towards the use of high-performance concrete (HPC) mixtures developed under the sponsorship of Strategic Highway Research Program (SHRP). The SHRP defined HPC for bridge structures by three requirements: namely, a maximum w/c of 0.35, a minimum durability factor for protection against freezing and thawing cycles, and a minimum compressive strength. Under the SHRP program four types of HPC were developed: Very High Early Strength Concrete (14 MPa in 6 hours), High Early Strength (34 MPa in 24 hours), Very High Strength (69 MPa in 28 days), and High Early Strength with Fiber-reinforcement.[7] Based on SHRP recommendations, the U.S. Federal Highway Administration (FHWA) sponsored a national program of field testing HPC bridge decks in several states. Mehta and Burrows[8] reported unsatisfactory results from field experience with some HPC bridge decks. According to the authors:

> *A 1995 report on the condition of 29 bridges in Kansas stated that there was twice as much cracking with 6400 psi (44 MPa) concrete than with 4500 psi (31 MPa) concrete. In 1997, the high-performance concrete deck in the Louetta Overpass – a showcase bridge in Texas – cracked more than the conventional concrete deck in the adjoining lane. In Denver, the high-strength concrete in the 23rd Street Viaduct cracked even before construction was finished. This cracking was due to very high thermal contraction and autogenous shrinkage resulting from the use of a high cement content (w/c = 0.31), and a fast-hydrating Type II cement. The cement fineness was 391 m^2/kg and the C_3A-plus-C_3S content was 72%. The cracking tendency of this concrete mixture might have been exacerbated by silica fume, which tends to increase the autogenous shrinkage. In conventional concrete, the autogenous shrinkage of*

less than 50 millionths can be ignored, but a high-strength concrete mixture may have an autogenous shrinkage of several hundred millionths.

In a survey sponsored by National Cooperative Highway Research Program, full-depth transverse cracks with a 1 to 3 m spacing were reported in numerous cast-in-place concrete bridge decks even before the structures were less than one month old.[9] With massive structures such cracks are attributed to high thermal shrinkage and drying shrinkage of high-strength concrete mixtures, made with high cement content and low w/c. Concrete mixtures of this type exhibit very high early compressive strength (viz. 25-40 MPa in 1-day), and a correspondingly high elastic modulus and reduced creep potential. Consequently, they are prone to cracking at early age.

In the April 1998 issue, the ASCE News –a publication of the American Society of Civil Engineers issued a report card on the state of durability of concrete structures, in general, at the close of the 20th century. This report card assigned a "D" grade, (i.e. very poor grade) to durability. It was reported that a huge amount of money, some 1.3 trillion dollars were needed for repair and replacement.

That concrete progress is not linear, but moves in a zigzag course was demonstrated when FHWA and several other U.S. organizations stopped advocating the use of high-early strength HPC mixtures for cast-in-place, massive, bridge elements. In 1998, a FHWA report contained the following guidelines with regard to HPC for building bridges in the 21st Century[10]:

> *HPC is a concrete that has been designed to be more durable and,* ***if necessary****, stronger than conventional concrete. HPC mixtures are composed essentially of the same materials as conventional concrete but the proportions are engineered to provide the strength and durability needed for the structural and environmental requirements of the project.*

The Port Authority of New York and New Jersey maintains many transportation facilities in the New York City metropolitan area, including bridges, tunnels, and airports. The concrete used at these facilities is subjected to high traffic volume and harsh weather conditions. According to Bognacki et al.[11]:

> "*In the past, as with other specifications, our concrete specifications only emphasized a compressive strength for a mixture proportion, and did not give the same emphasis to concrete permeability and durability. It is of little consolation to know that the compressive strength met the required contract requirement when the concrete is cracked, spalled, and delaminated. This necessitates significant repair work and causes delays at these transportation facilities, inconveniencing the public.*"

Learning from experience, the Port Authority of New York and New Jersey set an example that offers a step in the right direction for concrete durability enhancement. The Agency is now specifying performance-based concrete mixtures, for instance a maximum limit of 1500 coulombs chloride permeability at 90 days by ASTM Test Method C1202, and 0.42 – 0.45 w/cm in fresh concrete by AASHTO Microwave Test, T 318-02. The Agency also requires the contractor payments to be made only after strict conformance to the specifications. To make highly durable concrete mixtures, Bognacki et al.[11] offer the following advice:

> *It is very difficult and uneconomic to produce durable concrete for infrastructure work without the use of pozzolans. Concrete mixtures with less than 400 kg/m3 cementitious material including 30 % fly ash or 40% granulated slag were user friendly, economical, and highly crack-resistant.*

CONSEQUENCES OF PREMATURE DETERIORATION OF CONCRETE STRUCTURES

One of the consequences of premature deterioration of concrete has been an escalation in the cost of litigation, repair and replacement of numerous structures that have failed to meet the service life expectation. Considering the heavy economic losses, owners and designers of concrete structures have started paying more attention to the concept of life-cycle cost.

There is another important reason why the goal of achieving a radical enhancement in durability of yet-to-be-built concrete structures will have to be pursued with a sense of urgency. Among the manufacturing industries, the concrete industry is the largest consumer of materials in the world. It is estimated that today, globally, we are producing concrete at the yearly rate of some 12,000 million tonnes. The concrete industry therefore requires a very large volume of natural materials like sand, gravel, and crushed stone. Furthermore, it is consuming approximately 1,700 million tonnes/year cementing materials composed mostly of portland-cement clinker – a manufactured product that not only is highly energy-intensive but also responsible for large emissions of carbon dioxide, which is the most voluminous global-warming gas. Portland-cement clinker production also consumes large amounts of limestone and fossil fuels. Due to unsatisfactory durability of a large number of concrete structures, considerable volumes of concrete are being used for repair and replacement of structures. ***In short, the resource productivity of the concrete industry is not high, and the industry is not sustainable at its current global rate of consumption of natural resources and production of green-house gas emissions.***

For sustainable development, an obvious long-term approach is to plan for a gradual reduction in the future concrete consumption rates through radical enhancement in durability[12]. Reinforced concrete structures are typically designed for a service life of 40 to 50 years. Extension of service life by 10 to 20 years, or by a factor of two at the most, has been possible by adopting special methods that target a specific cause of potential distress, for instance the use of corrosion-inhibiting admixtures and epoxy-coated steel to mitigate the reinforcement corrosion. If we want to enhance the durability of concrete infrastructure by a factor of 5 or 10, the current methods are obviously inadequate.

Hawken et al[13] described a movement, launched in 1994, by the Factor Ten Club which is composed of a group of scientists, economists, and business-people. This group believes that, within 30 years, nations of the world can achieve a ten-fold increase in resource use efficiency, corresponding to a 90% reduction in the consumption of energy and materials. For example, in order to increase the resource efficiency of the concrete industry by factor 10, most of the concrete infrastructure being built today ought to be designed for a service life of 500 years instead of the conventional 50. This is not an unrealistic goal. In fact, as will be discussed in this paper, we do have the science and technology to achieve a radical enhancement in durability of ordinary concrete by a cost-effective method.

A SEARCH FOR THE ROOT CAUSE OF DAMAGE

Field experience with deteriorated concrete structures shows that, ***in order of decreasing frequency, the apparent causes of deterioration generally are the corrosion of steel reinforcement, frost action, alkali-silica reaction, and sulfate attack.*** In practice, the deterioration of concrete is seldom due to a single cause; at the advanced stages of material's degradation, more than one deleterious process is found at work. Usually the physical and chemical processes of deterioration are so closely intertwined and mutually supporting that separation of cause from effect becomes impossible. If we examine the mechanisms of deterioration separately, they appear to be different from each other. However, irrespective of the apparent cause of deterioration, it is generally observed that the ***material failure occurs through a succession of expansion and cracking cycles in which the presence of free water is always necessary***.

It is well known that ordinary concrete mixtures, with moderate cement content (300 to 350 kg/m^3) and moderate w/c (0.45 – 0.60), when properly consolidated and cured, are essentially watertight. So, what is the source of free water in hardened concrete? For an answer to this question let us examine the four causes of deterioration of concrete individually:

<u>Frost Action</u>

Commenting on the ***damage to concrete by frost action,*** Valenta[14] suggested how the material lost its watertightness:

> *Continuous microcracks, linking into wider cracks originating from the concrete surface, play the greatest role in reducing concrete's impermeability. By facilitating the ingress of water from external sources, they would increase the degree of saturation of concrete, which is a necessary pre-requisite for any damage to be caused by frost action.*

<u>Reinforcement Corrosion</u>

To highlight the role of water and microcracks in *the reinforcement-corrosion-related damage* to concrete structures, Mehta and Gerwick[15] described a case history from the

San Francisco Bay Area. In 1980, several 17-year-old, heavily reinforced spandrel beams of the San Mateo-Hayward Bridge had to undergo expensive repairs due to serious cracking that was attributed to corrosion of the embedded steel reinforcement. The beams had been made with a high-quality concrete (370 kg/m^3 cement, 0.45 w/c). The damage was confined to the underside and windward faces of beams directly exposed to seawater spray. Interestingly, only the precast, steam-cured beams had been damaged; no cracks and corrosion were observed in the naturally cured, cast-in-place beams made at the same time with the same concrete mixture, and exposed to the same environment of service.

The authors proposed that, as a result of heavy reinforcement and differential cooling rates, microcracks must have occurred in the massive beams (8 by 3.7 by 1.8 m) during the steam-curing process. These pre-existing microcracks later enlarged and became continuous on exposure to more severe weathering action on the windward faces. Thereafter, penetration of the salt water to the surface of the reinforcing steel set the stage for the corrosion-cracking-corrosion type of chain reaction, which led to serious damage. A diagrammatic presentation of the Mehta-Gerwick hypothesis is shown in Fig. 1.

Sulfate Attack

Commenting on the ***sulfate-related damage*** to concrete sleepers by delayed-ettringite formation, Collepardi[6] made the following observation:

> *Previously microcracked beams when exposed to alternate cycles of rain and sunshine were severely macrocracked and damaged; those exposed to rain but kept under shade showed less distress; and those totally protected from rain and direct exposure to sun remained undamaged, without any growth in the microcracks.*

Alkali-Silica Reaction

In regard to concrete ***damage from alkali-silica reaction***, Swamy[16] made the following comments:

> *Funny things can then happen in real life – the interior columns of an exposed bridge, sheltered from direct sunlight and rain, may show no cracking whilst the exterior columns may develop extensive cracking. A structural member, when partly sheltered and partly exposed by the nature of the structure, showed very different crack patterns, with extensive cracking in the exposed faces and little or no cracking on the sheltered parts.....*
> *Exclude water - and one can almost have a trouble-free reaction even if concrete contains reactive aggregates and mobile alkalis. Marked deterioration due to the alkali-silica reaction, in field practice, therefore, occurs under wet environmental conditions.*

Thus, with every one of the four causes discussed above, water turns out to be the common cause of concrete damage, and interlinking of macrocracks and voids by growth in microcracks appears to be the source of penetration of free water into hardened concrete.

A HOLISTIC APROACH TO DETERIORATION OF CONCRETE

In a 1994 paper, the author[17] proposed a holistic approach to concrete deterioration. Unlike the previous reductionistic approaches, the holistic approach is not "cause specific" in the sense that all of the primary causes of concrete deterioration are addressed together. Also, instead of singling out one of the several components of the cement paste or concrete as responsible for the damage, this approach considers the effect of the service environment on all of the components of the material. Furthermore, it takes into consideration the field experience that the degree of water saturation of concrete plays an important role in expansion and cracking mechanisms regardless of other factors that might have contributed to the damage (i.e., frost action, corrosion of reinforcing steel, alkali-aggregate reaction, or sulfate attack).

Among the key features of the holistic approach to concrete deterioration, the point worthy of special attention is that during the first stage, little or no apparent damage to the structure takes place as long as it remains watertight. The second stage marks the initiation of the damage which occurs at a slow rate at first, and then proceeds rather rapidly as the system becomes more permeable. It is suggested that during the latter part of this stage the hydraulic pressure of the pore fluid in saturated concrete rises due to one or more expansive phenomena (e.g., freezing of water, corrosion of the reinforcing steel, and swelling of microcrystalline ettringite or alkali-silica gel). If, at the same time, the hydroxyl ions from the cement paste are being leached away and replaced by acidic ions, such as chloride or sulfate, the calcium silicate hydrate would suffer a loss of adhesion, and as a consequence the concrete strength and elastic modulus are reduced. The damage to the structure accelerates when the microcracks have grown into macrocracks as a result of the two mutually reinforcing processes of damage. ***These features of the holistic approach emphasize the common role of microcracks in the initiation and propagation of concrete damage, and provide the basis for the three-stage concrete damage process that will be discussed later.***

MICROCRACKS – THEIR SIGNIFICANCE AND ORIGIN

For a variety of well-known reasons, even with structural members designed for compressive loads, tensile stress and tensile cracking are unavoidable. The reinforcement of concrete with steel does not eliminate tensile cracks but it does restrict the crack-widths to 0.15 mm or less. The fine cracks, known as microcracks, are too small to be visible and quantified, and are therefore ignored in the structural design and construction practice. It is generally accepted that microcracks caused by settlement, plastic shrinkage, restrained thermal shrinkage and drying shrinkage, and accidental overloads would not have any adverse effect on the static behavior of concrete structures. However, due to the important role played by microcracks in determining the permeability and durability of concrete in service, it is desirable to understand their origin and growth.

Hydration reactions of portland cement minerals produce a multiphase product that consists primarily of an adhesive, poorly crystalline, C-S-H (calcium silicate hydrate) phase, and some well crystalline products including calcium hydroxide. In freshly mixed and compacted concrete, water films forming around the coarse aggregate particles raise the w/c in close proximity to these particles. In the interfacial transition zone between a coarse aggregate particle and cement mortar, the spaces with high w/c become filled with a porous framework of large, plate-like, oriented, and non-adhesive crystals of calcium hydroxide. In conventional concrete mixtures this is a weak area that is highly vulnerable to microcracking. Therefore, the tensile stress generated by differential movement between the cement paste and the aggregate is relieved by the formation of microcracks in the interfacial transition zone. It means that ordinary concrete will contain microcracks in the interfacial transition zone even before a structure is loaded. The amount of microcracking present depends on numerous parameters including the size and grading of aggregate, cement content, water content, degree of consolidation, curing conditions, and humidity and temperature gradients to which fresh concrete has been exposed.

Let us now examine the influence of microcracks on the behavior of concrete in a structure exposed to stress effects from mechanical loading and environmental loading under severe climatic conditions. From a typical strain-stress diagram of a concrete specimen loaded under compression it can be seen that, until about 50 percent of the ultimate stress, there is no significant change in the strain/stress ratio; however, beyond this point the stress/strain curve begins to deviate appreciably from the straight line as increasingly higher strains are recorded with every unit of additional stress. This phenomenon is attributed to increase in the length, width, and number of pre-existing microcracks in the interfacial transition zone and the beginning of some microcracking in the matrix mortar. In the long run, the proliferation and growth of microcracks will have the effect of reducing significantly both the elastic modulus and the tensile strength of concrete.

Also, when the growing microcracks link up with existing macrocracks and voids in concrete, this is the point in time that marks a sudden increase in the permeability. The internal damage begins when the water carrying corrosive ions and gases starts to penetrate more readily into concrete. As described earlier, once concrete becomes saturated and any one of the four above-described expansive phenomena is initiated, the hydraulic pressure in the pore fluid would increase, enabling the microcracks to grow. The end result is a further loss of watertightness of concrete followed by expansion, cracking, spalling, and loss of mass. ***Obviously, for a holistic approach to durability, the microcracks and their growth under service conditions is another common denominator that must be controlled if we want to achieve a radical enhancement in concrete durability. To achieve this objective, we must understand and control the microstructure of concrete.***

STAGES OF THE CONCRETE DAMAGE PROCESS

In 1982, Tuutti[18] presented a schematic diagram (Fig. 2) of the two-stage concrete damage process of reinforcement corrosion. There is no corrosion in the initiation stage during which chloride ions or CO_2 are penetrating into concrete. Once the chloride or CO_2 have reached the surface of the reinforcement, the corrosion process will begin and propagate with time. The end of service life is assumed to have reached when the damage to concrete requires repair or replacement. The durability of concrete can be enhanced by delaying the initiation period through methods such as, the use of corrosion inhibiting admixtures, epoxy-coated reinforcing steel, and coating the surface of concrete. These methods are costly and have not yielded radical enhancements in durability, e.g. by factor 5 or 10.

To achieve a radical enhancement in durability of reinforced concrete structures, I suggest for consideration a three-stage damage process that is graphically presented in Fig. 3. Let us assume that growth of microcracks in the concrete microstructure is a form of "internal damage", because microcracks provide the bridges that interlink macrocracks and voids. This eventually leads to a breach of water-tightness of concrete, which is a necessary pre-requisite for the subsequent stages of damage. It may be concluded, therefore, that before the stages of "initiation" and "propagation" of damage, there exists a stage of "no damage", neither external nor internal (i.e. growth of microcracks).

The concept of "no damage" state is useful for achieving a radical enhancement in concrete durability. Clearly, without the growth in microcracks, there would be no increase in the permeability of concrete. Any method that successfully prolongs Stage 1 of the damage process (Fig. 3), would have the effect of delaying exposure of the structure to subsequent stages of damage. Thus, by holding the structure in Stage 1 for a very long period of time, it is possible to achieve a radical enhancement in durability.

MODIFYING THE MICROSTRUCTURE OF CONCRETE

As mentioned earlier, the defects and inhomogeneities present in the microstructure of hydrated cement paste (e.g., capillary voids and oriented layers of crystalline calcium hydroxide) are the primary source of microcracks in concrete. The interfacial transition zone next to the coarse aggregate particles (also next to the steel reinforcement) tends to contain a relatively large proportion of capillary voids and microcracks. Reducing the area of the interfacial transition zone in concrete, and elimination of the defects and inhomogeneities within the hydrated cement paste seem to be the proper tools to control microcracks.

The use of low w/c, as mentioned by the ACI Building Code and other codes for durable concrete, enables a reduction in the volume and size of capillary voids, but this alone is not sufficient to reduce the cement paste content of concrete which is the source of microcracking from thermal shrinkage and drying shrinkage. To reduce the cement paste content, both the water content and the cement content must be reduced as much as