SP 126-1

Durability of Concrete— Fifty Years of Progress?

by P.K. Mehta

Synopsis: With special attention to durability of concrete, the author reviewed the proceedings of the cement chemistry congresses as well as other symposia held during the last 50 years by ACI, ASTM, and RILEM. What is presented here is not a comprehensive progress report on the subject of concrete durability but rather a state-of-the-art report from the author's perspective. It seems that, in spite of some important discoveries which are valuable from the standpoint of durability enhancement, today more concrete structures seem to suffer from lack of durability than was the case 50 years ago.

In order of decreasing importance, the major causes of concrete deterioration today are as follows: corrosion of reinforcing steel, frost action in cold climates, and physico-chemical effects in aggressive environments. There is a general agreement that the permeability of concrete, rather than normal variations in the composition of portland cement, is the key to all durability problems. There is also a general agreement that rapid growth of the concrete construction industry after 1940's led to the production and use of wet concrete mixtures, which were able to meet the strength requirement via a change in the composition of portland cement, but were unsatisfactory from the standpoint of corrosion of reinforcing steel, resistance to freezing and thawing cycles, and chemical attacks. A rise in chemical aggressivity of the environment through the increasing use of de-icer salts, and an increase in land, water, and air pollution, has also contributed to concrete durability problems.

Although significant advancements have been made in regard to understanding and control of various physical and chemical phenomena responsible for concrete deterioration, the trend towards less durable concrete structures has yet to be reversed. One of the reasons is that most of the information from tests on durability is in fragmentary form and cannot be easily synthesized into a complete understanding of actual, long-term, effects on field concrete. An over-reliance on test methods and specifications dealing with different aspects of durability has therefore become a part of the problem since accelerated laboratory tests do not correlate well with behavior of concrete structures in practice.

Keywords: Alkali-aggregate reactions; chemical attack; corrosion; deterioration; durability; freeze thaw durability; microcracking; permeability; predictability tests; reinforcing steel.

P. Kumar Mehta, FACI, is Professor in the Civil Engineering Department at the University of California at Berkeley. He is the author of numerous papers including a text on concrete, and was recently awarded the ACI's Wason Medal for Materials Research and the Malhotra Award for research on supplementary cementing materials.

INTRODUCTION

The author did not fully realize the immensity of the task when he volunteered to review the major publications of last 50 years on the subject of concrete durability. The Proceedings of the International Conference on Concrete Durability (1), which was held four years ago in Atlanta, Georgia, to honor Katherine and Bryant Mather, contain well over 2000 pages covering more than 100 papers. In addition, the proceedings of symposia sponsored by ASTM (2), ACI (3), and RILEM (4,5), as well as eight international congresses on the chemistry of cement contain a wealth of information on the subject. For instance, at the Eighth International Congress at Rio de Janeiro in 1986, the state-of-the-art report on chemical aspects of durability alone contains a reference to 244 papers (6). Similar reports on the chemical aspects of durability presented at the Seventh Congress at Paris in 1980 (7), at the Fifth Congress at Tokyo in 1968 (8), at the Fourth Symposium at Washington D.C. in 1960 (9), and at the Third Symposium at London in 1952 (10), contain references to 291, 128, 105, and 82 papers, respectively. Interestingly, the proceedings of the Second Symposium at Stockholm in 1938 contain only one paragraph on the subject of chemical resistance, and no other references to concrete durability.

To the above-cited literature on the chemical aspects of concrete durability, if one adds the published literature on deterioration of concrete due to freezing-thawing cycles and corrosion of reinforcing steel, the exercise of doing a comprehensive review simply becomes unmanageable. Under these circumstances, one can at best undertake a review of the previously published reviews. This is exactly what the author has done and reported in this paper. Besides highlighting the major findings from earlier reports (1-10), the author has also attempted to present a synthesis of knowledge accumulated during the last 50 years.

Before proceeding with this review, the author considers it worthwhile to address the question, "**how serious is the durability problem with modern concrete structures?**" In presenting his summary of the report of the National Materials Advisory Board's committee on concrete durability, Skalny (11) questioned whether we are losing the battle for concrete durability. He made a reference to the **epidemic of bridge deck deterioration in the United States.** Some 253,000 bridge decks are in varying states of deterioration and approximately 35,000 are being added to this list every year. The cost of bridge deck repair and rehabilitation is $50 billion, and the overall cost of repairing or replacing all deteriorated concrete structures is estimated to be about $200 billion. The title of the NMAB Report, "Concrete Durability - A Multi-Billion Dollar Opportunity," seems to provide an answer to Skalny's question.

Concrete durability specialists in Europe seems to confirm the U.S. experience. For instance, O'Brien et al (12) of Arup Research and Development, London, said, "**Concrete durability is a growth industry**: this is not to say that there is a great increase in the volume of durable concrete being produced. It is more the increase in the number of people devoted to detailed research together with contracts dedicated to repair, refurbishment or replacement."

Reports from other parts of the world are equally disturbing. For example, Seabrook (13) reported that in 1987-88, on the eastern seaboard of Canada 400 of the ten-year old concrete piles of the Rodney Terminal in St. John, which suffered cracking and spalling from freezing-thawing cycles, had to be repaired by epoxy injection. Gerwick (14), in a paper on future opportunities for concrete structures in the marine environment, said,

> "Tremendous strides have been made in the understanding of durability in corrosive environments, yet it still remains the foremost problem facing structural concrete used today. We have only to look at the new Florida keys bridge or at many other recent undersea tunnels to see that we don't yet have foolproof answers. Indeed at one time I thought of titling this talk--**Tunnels in Trouble.** The Kanmon tunnels between Honshu and Kyushu respectively leak so badly that it affects not only the concrete tunnel liners but the rails and the running equipment. The Hong Kong tunnels were designed for a 120 year life and the concrete liners are in major disruption after only 4 to 10 years. The concrete in the Dubai tunnel (built in 1975) leaked so badly that the tunnel had to be completely repaired at a cost twice that of original construction. The Suez tunnel reports similar difficulties... The new dry dock at Abu Dhabi is reportedly also severely damaged."

It should be emphasized here that around the world there are many 50-90 year old concrete structures still in good condition. On the other hand, numerous cases of deterioration in recently built structure go unreported. Therefore, the above examples of concrete deterioration are not isolated examples. That is why a feeling of uneasiness seems to be growing among the users that concrete as a material of construction is probably not as durable as claimed by its enthusiastic advocates. For instance, in his state-of-the-art report at the 1987 International Symposium on Concrete Durability, Neville (15) said, "This symposium is concerned with concrete durability, and it is tempting to ask why after all these years of research there are still so many problems with the durability of concrete. Possibly, there are even more problems these days than, say, fifty years ago."

Lack of durability manifests in the form of cracking, spalling, loss of strength, or loss of mass. Many physical and chemical causes can be responsible for deterioration, and mechanisms and control of these causes are well-described in concrete textbooks (16-19). A concrete in an advanced state of deterioration is generally found to be suffering from more than one cause, and in the post-mortem it usually becomes very difficult to identify the first cause which might have broken down the ability of concrete to resist attack from a host of other causes. However, failure analysis reports from around the world show that, in order of decreasing importance, the following causes of deterioration need most attention: corrosion of reinforcing steel, frost action in cold climates, chemical effects on hydrated cement paste from external agents (viz., water containing carbon dioxide, sulfates or chlorides), and physical-chemical effects from internal phenomenon, such as alkali-aggregate reaction, and salt weathering. A comprehensive review of the primary causes of concrete deterioration, which is presented next, is therefore not in order of their importance.

CHEMICAL ASPECTS OF CONCRETE DURABILITY

The solid hydration products and the pore fluid in hydrated portland cement paste are alkaline, therefore they readily enter into deleterious chemical reactions with acidic waters. Even fifty years ago, it was well known that natural waters containing carbon dioxide, sulfates, and chlorides eventually weaken the cementing property and must not be permitted to penetrate into cement mortar or concrete. For instance, in 1938, Hedstrom (20) made the following comment at the Second International Symposium on the Chemistry of Cements:

> The chemical resistance is, as regards concrete, to a considerable extent dependent on its structure, **especially its permeability.** Even as regards hardened cement the physical structure must be taken as an essential factor for the resistance. Of importance in this connection are the permeability, the structure of gels remaining after chemical attack which may constitute a protective layer, and the structural changes caused in the surface layer by carbonation in the air.

It is significant that in 600 pages of the Proceeding of the 1938 Symposium on the Chemistry of Cements, the above comment was the only statement on the subject of concrete durability. There were no papers and no discussions on topics such as, corrosion of reinforcing steel, sulfate attack, carbonation, and alkali-silica reaction. **Were the cement and concrete researchers of early 1900's ignorant of durability problems, or did they believe that normal variations in the chemistry of portland cement were of no major consequence to durability as long as you pay attention to the first line of defense, i.e., the impermeability of concrete?**

The first major paper dealing with chemical aspects of the durability of cement products was presented by Thorvaldson (10) at the Third International Symposium on the Chemistry of Cements, in 1952. This paper contained a detailed account of the history of search for a cement of portland type which would be resistant to the action of sulfate water. Beginning with Ferrari's work in Italy in 1920, and subsequently Fleming's investigations in Canada in 1930's, the development and sulfate resisting properties of modern ASTM Type V cements were described by the author, and a test for evaluation of sulfate resistance using lean (high-porosity) mortar prisms was proposed.

The following remarks by Thorvaldson (10) show that the controversy on the possible mechanisms associated with ettringite formation in sulfate attack is not new:

> While the formation of crystals of sulfoaluminate and gypsum in portland cement mortars during disintegration in sulfate solutions is well established, many **experimental observations throw doubt on the assumption that physical forces of crystallization are the primary cause of expansion and loss of strength** ... Many observations suggest that, (i) volume changes in the mortars are controlled by osmotic forces associated with the swelling and shrinkage of gels, that (ii) the chemical reactions condition the gel systems and destroy cementing substances (while the formation of crystalline material is incidental to these chemical reactions), and that, (iii) the increased resistance to volume changes with increased richness of mix may not be primarily due to decreased permeability

> but rather due to the maintenance of condition within the mortar which are unfavorable to the swelling of gels.

Thorvaldson's comment raises the interesting possibility that concrete could expand and crack from internal hydraulic pressures (of the type developed by frost action), which may be caused by swelling of gel-like reaction products formed as a result of chemical attack, such as alkali-silica reaction, sulfate attack, and corrosion of reinforcing steel. Research studies during the 1970's and 1980's seem to support Thorvaldson's hypothesis. For instance, experimental evidence was presented by Mehta and Hu (21) that microcrystalline ettringite goes through considerable swelling on moisture absorption. Figg, and Mehta (22) believe that silica gel produced by the action of a caustic solution (formed on hydration of a high-alkali portland cement) on particles of a reactive-silica aggregate swells in the alkaline environment by water adsorption. The authors also believe that swelling of iron hydroxide gels in an acidic environment (Cl^-, CO_3^{--}) can be one of the possible mechanisms responsible for expansion and cracking of concrete from corrosion of reinforcing steel. Thorvaldson's comments also help to explain why lowering of the alkalinity by pozzolanic additions would improve the resistance of concrete to sulfate-related expansion and alkali-silica expansion, and why too much lowering of the alkalinity from excessive use of pozzolanic additions may be detrimental with regard to expansion associated with corrosion of reinforcing steel.

Thorvaldson (10) also reviewed the effect of minor components of portland cement on durability, such as free CaO, MgO, and alkalies. Hydration of coarsely ground portland cements containing large amounts of free CaO caused expansion and cracking. Better control on the chemical composition, fineness, and homogenization of the raw mix prior to clinker formation solved this problem. In regard to crystalline MgO (periclase), laboratory studies showed that the presence of more than 2-3% crystalline MgO in cement gave large expansion in an autoclave test. The test method (ASTM C 151) and the specification (max. 0.8% expansion in cement paste prisms) are still in use in North America although high-MgO portland cements, which do not meet the ASTM Specification based on the autoclave test, are being safely used in many countries of the world. In a comprehensive report on the subject, this author (23) pointed out that crystalline MgO formed at the temperature of burning of portland cement clinker (1400-1500°C) either does not hydrate under normal environmental temperatures or hydrates too slowly to cause any unsoundness in concrete.

According to Thorvaldson (10), little attention was paid to the effect on durability of small amounts of alkalies usually present in commercial portland cements until Stanton, in 1940, reported that chemical reactions between high-alkali cements and certain California aggregates (opaline chert) caused expansion and cracking. Osmotic imbibition of water by the gels produced by the alkali-silica reaction was reported to be the probable mechanism for expansion, which could be controlled by incorporation of 7-8% voids or by incorporation of suitable pozzolanic admixtures.

The following excerpt from Thorvaldson's report on durability of concrete in seawater shows that there was a recognition of the important role played by the environmental temperature in determining the rate and type of attack on concrete, and also a recognition of the fact that precise analysis or prediction of durability aspects under complex environmental conditions would be hampered by the difficulty to separate the physical effects from the chemical effects:

> There was a general agreement that if seawater penetrated mass concrete, disintegration might follow, and that such action was more pronounced in warmer seas than in northern latitudes where the effect of alternate freezing and thawing and attrition by ice were major factors. It was, however, very difficult to estimate the relative roles of physical and chemical action as each accentuates the effect of the other. A surface layer weakened by chemical action is easily removed by abrasion or may spall due to frost action, presenting a new surface for chemical attack. Physical attrition may thus mask, yet promote, chemical action.

One wonders how would the predictive models and expert systems on durability take into consideration the environmental temperature cycling effect as well as the accentuating, masking, and promotional roles of physical-chemical effects on concrete deterioration, as described by Thorvaldson 40 years ago?

At the Fourth International Symposium on the Chemistry of Cements in 1960, Bredsdorff et al. (9), and van Aardt (24) presented separate papers on internal and external destructive effects, respectively. The former paper and a discussion on the paper dealt almost exclusively with the alkali-aggregate reactivity, and consisted of approximately 60 pages and 150 references. The latter paper, which is discussed here first, described the results of author's experimental investigation on the chemistry of deterioration of different types of hydraulic cements in various aggressive media.

In regard to attack by sulfate and chloride solutions, van Aardt (24) essentially confirmed the already known state-of-the-art; however, the following comments on carbonation, sulfuric acid attack, use of calcareous aggregate, and quality of mortar are noteworthy:

> The carbonation of mortars made with portland cement is found to be beneficial, and the substitution of a calcareous aggregate for a siliceous aggregate improves the resistance of cement mortars to sulfuric acid attack. High density and **low permeability in mortars reduce their vulnerability to chemical attack, and it is stressed that quality of the mortar is of prime importance in any corrosive environment. Bad practice in this respect can outweigh improvements aimed at by the use of more corrosion-resistant cements.**

It should be noted again that impermeability, rather than the cement chemistry, is judged to be more important in determining the durability of concrete to chemical attacks. Also, the above-mentioned reference to the beneficial effect of carbonation is limited to atmospheric carbon dioxide and hard waters. Soft waters containing "aggressive CO_2" can be very corrosive (16-18). The "aggressive CO_2" is the amount of free carbon dioxide that is in excess of the quantity required for the stabilization of the carbonate-bicarbonate equilibrium in the reaction:

$$CaCO_3 + CO_2 + H_2O \leftrightharpoons Ca(HCO_3)_2$$

It is pointed out by van Aardt (24) that the higher the concentration of calcium bicarbonate, the higher will be the quantity of free CO_2 required for stabilizing the equilibrium, and hence for the same amount of free carbon dioxide the lower will be the amount of aggressive carbon dioxide. It should be noted that **limited carbonation of hydrated portland cement paste will be impermeability-improving (because the formation of calcium carbonate which is insoluble, plugs up the pores and microcracks) whereas excessive carbonation in the presence of**

"aggressive CO_2" will be impermeability-reducing (because the formation of calcium bicarbonate, which is soluble and can be leached away, widens the existing pores and microcracks).

Following are some of the highlights from Bredsdorff et al's paper (9), based on a review of 20 years of research and investigation around the world, on the problem of **concrete deterioration by alkali-aggregate reactions:**

1. In concrete, aggregate particles that contain or consist of silica in an amorphous or poorly-crystalline state, are attacked by alkalies, lime, and hydroxyl ions from the liquid phase of the cement paste. The alkali-aggregate reactions produce a silica gel holding alkali and calcium ions in the random-network of silica tetrahedra. By imbibition of water, **the gel may either swell almost without limit, or may not swell to any appreciable extent.**

2. When condition of "unlimited swelling" are present, a mortar prism or a concrete prism or even a structural member may register expansion, which, depending on the homogeneity of stress effects and conditions of restraint, **may or may not accompany cracking.** When the reactive aggregate fraction is fine, the stress distribution may be homogeneous and may result in overall expansion without noticeable cracking, especially under restraining conditions.

3. Cracking may reduce the resistance of concrete to freezing and thawing action and facilitate the corrosion of reinforcement and the leaching of the cement paste, which will gradually expose the internal microstructure of concrete to damaging action of ambient air and water. Thus secondary cracking associated with other causes is common in structures afflicted with alkali-aggregate attack.

4. Only 4 percent of the 431 concrete structures in Denmark (mostly less than 25 years old) surveyed in 1954-55 by Idorn, had shown severe deterioration involving alkali-aggregate reactions.

5. A 1914 survey of coastal structures in Denmark, built since 1870, had shown expansion and cracking of concrete associated with white exudations. At that time,the deterioration was attributed to the action of sulfates in seawater. Paulsen in 1910 invented a pozzolanic cement by intergrinding a Danish diatomaceous earth with ordinary portland cement, and on the basis of field and laboratory tests claimed that the use of pozzolanic cement increased the durability of concrete to seawater. Later studies confirmed that the primary cause of deterioration was alkali-aggregate reaction, thus it **appears that by inventing the pozzolan cement Paulsen had indeed found in 1910 a corrective measure against alkali-aggregate expansion,though he believed that he was fighting against the action of sulfates in seawater.**

In spite of Bredsdorff et al's (9) conclusion that the alkali-aggregate reactions by themselves do not present a serious durability problem, and in spite of the fact that a corrective measure against alkali-aggregate expansion was discovered in 1910 (via pozzolanic additions to high-alkali cements), considerable research is still ongoing on the subject. Now, after 50 years since the discovery of alkali-aggregate reaction, a large volume of research effort, and several international conferences on the subject, this is how one of the coauthor's (Idorn) of the Berdsdorff et al. paper recently summed up the state-of-the-art (25):

> Experience from many countries shows that in numerous structures with susceptible aggregates used in the concrete, deleterious reactions do not occur, though in some structures with concrete of the same composition damage does develop. In fact, investigations in America, Denmark, England, and elsewhere suggest that **in concrete with a potential for alkali-silica reactions, these reactions most often do happen without causing any damage to the concrete at all.** This is one reason why none of the many existing test methods for the reactivity of aggregates are individually reliable for evaluation of the behavior of reactive aggregates in concrete structures ...
>
> Map-cracking in **unreinforced** dolosses of a concrete element may result in loss of structural reliability, especially in hot, marine environments. In contrast, alkali-silica reactions do not usually result in significant decline of structural reliability **in reinforced concrete elements** as long as cracking does not lead to severe corrosion of the reinforcement.

RESISTANCE TO FREEZING AND THAWING

A highlight of the Fourth International Symposium in 1960 was a 60-page principal report with discussions by Paul Nerenst (26), on the subject of **frost action in concrete.** In his introductory remarks, the author stated that before the Second World War the factors influencing the resistance of hardened concrete to freezing and thawing were not well known. In spite of this, durable concrete structures existed in areas exposed to numerous freezing and thawing cycles. For instance, a 100-years old coastal fortress near Copenhagen, built with portland cement concrete, was in excellent condition at the time of Nerenst's report in spite of exposure to seawater and numerous freezing-thawing cycles. Commenting that the **ideas of making good concrete were much older than 1918, the year when Abrams formulated the relation between water-cement ratio and strength, Nerenst (26) quoted from a book by Henry Reid, published in 1868:**

> "The due and thorough incorporation of the cement, sand, shingle or gravel, with **the least amount of water, is the ABC of the process of concrete making, and unless this is rigorously attended to, much disappointment will be experienced.** All ingredients should be well mixed first in a dry state, and when this is thoroughly done a quantity of water is added to render the mixture plastic enough to be placed in moulds or formwork. As a rule, the less quantity of water you can use the better. The concrete should be well rammed in as dry a state as is consistent with the proper requirements of the material, for too small a quantity of water would be as injurious as an excess; again that would be materially influenced by the amount of force applied by the impingement of the rammer. The rammer should be as heavy as should be conveniently used. Sand, where a choice exists, should be as rough and coarse as possible. A rotten or friable aggregate is to be avoided. Where practicable, concrete blocks should be placed for some days or weeks in water. **Concrete, when so treated and carefully and thoroughly mixed, will be immensely superior in quality to the ordinary sloppy and roughly-handled mixture commonly called concrete, only in many cases entitled to the name because it contains certain proportions of the necessary ingredients."**

Continuing his introductory remarks, Nerenst (26) said:

> "**In the twenties and thirties of our century the wet concrete mixtures were growing in popularity, foremost in the United States but also in many countries in Europe, and the freezing resistance of concrete was diminishing.** The low durability of concrete roads was growing to be a serious problem ..."

Nerenst's analysis of the situation is indeed thought-provoking. By abandoning the common-sense approach to overall concrete quality, as advocated by Reid in 1868, in favor of the practice of designing for strength by using Abram's relationship between water/cement and strength we might have inadvertently entered into an era when many concrete structures are being made with a high-permeability material. This material will have low-durability, because it is easily susceptible to many physical-chemical processes of deterioration, such as carbonation, alkali-aggregate attack, freezing and thawing, and corrosion of reinforcing steel. **This author was startled by the thought that researchers 50 years ago did not discuss many of the problems which afflict concrete today, not because they were less knowledgeable but because these problems were virtually nonexistent.**

According to Nerenst (26), in 1945 Powers first presented the "hydraulic pressure theory" of expansion of hardened cement pastes subjected to freezing, when the specimen had a certain minimum degree of saturation. A combination of low permeability and high rate of freezing gave rise to a hydraulic pressure gradient, which led to expansion and cracking unless the pressure was relieved by inclusion of closely-spaced air voids. To produce frost resistant concrete, Powers recommended a maximum void spacing factor equal to 0.01 in. (approx. 0.2 mm).

In his principal report on concrete durability at the Fifth International Congress on Chemistry of Cements in 1968, Valenta (8) included frost action as one of the major factors in deterioration of concrete. Confirming the findings of earlier researchers, the author observed:

> If air bubbles are to play a role favorable from the standpoint of frost resistance of concrete, they must be connected into the spatial system of capillary channels, be uniformly distributed in the microstructure of cement paste, and have small spacing. The length of and the flow conditions in the channels eventually decide the internal pressure (tension) in concrete and the suitability of the system of pores. The total air content of hardened cement paste, and more so of concrete with aggregates of diverse sizes is, therefore, not an adequate criterion of effective air entrainment.

Valenta also made some interesting comments about the role of voids present at the cement paste-aggregate transition zone on frost damage in concrete. According to him, there are usually large voids caused by entrapped air adhering to rough surface of coarse aggregate. There seems to be close connection between high permeability of concrete and a combination of high water-cement ratio and high specific surface of aggregate. Since the flow of water in concrete follows the path of least resistance, the relatively high permeability of concrete creates conditions leading to strong hydraulic pressures. Further, according to Valenta (8), **continuous microcracks sometimes linking into wider cracks originating from the concrete surface, play the greatest role in reducing impermeability. By appreciably facilitating the ingress of water from external sources, they would increase the degree of saturation of concrete, which is a necessary prerequisite for any damage to be caused by frost action.**

Valenta (8) presented detailed data on the influence of various factors on the quantity and distribution of pores in air-entrained concrete. In particular, the effects of varying water-cement ratio, admixture type, and vibration time on air content and specific surface of air bubbles were presented. Also given were the effects of cement fineness and grain size of fine aggregate. According to Valenta, several research studies had shown that sand grain sizes, between 0.3 and 0.6 mm, exercised a decisive influence on the air-entraining properties of concrete. The author also cited a research study in France which showed that frost damage in some aggregates followed essentially the same physical-mechanical laws as in saturated cement paste. Higher water absorption in a calcite aggregate with a fine pore structure (capillary pores up to 5 μm diameter) was found to be decisive for the poor performance of concrete on freezing.

In spite of voluminous literature on air entrainment of concrete and durability of adequately air entrained concrete subjected to freezing and thawing cycles (such as ASTM C 666), many reports in the published literature show that concrete structures continue to deteriorate from frost action. Among the reasons for this is the difficulty of maintaining the desired air-void spacing in hardened concrete due to incompatible concrete-making ingredients, high water content of concrete mixtures, overmixing, improper handling of fresh concrete, overvibration during consolidation, etc.

For use in cold climates, there is now evidence in favor of the superior field behavior of low water-cement ratio concrete mixtures without entrained air, compared to high water-cement ratio concrete mixtures with entrained air. Sturrup et al (27) presented Ontario Hydro's experience on evaluation and prediction of concrete durability to frost action. The paper is unique in the sense that, in addition to the results from accelerated tests (ASTM C 666), the results from a 28-year outdoor exposure test on companion specimens of both air and non-air entrained concretes are presented. One of the conclusions from this paper is as follows:

> In the outdoor exposure tests, equal deterioration is being observed in a low water-cement ratio (0.5 or 0.6) non-air-entrained concrete compared to a higher water-cement ratio (0.7 to 0.8) air-entrained concrete. In contrast, by Procedure A (ASTM C 666 test method) a non-air-entrained concrete with a water/cement ratio of 0.5 has much lower durability than an air entrained concrete with a water-cement ratio of 1.0. **While the benefits of entrained air are obvious, Procedure A has overemphasized these benefits with respect to non-air entrained concrete. If acceptable results are obtained by Procedure A, the field performance should be good; but if poor results are obtained the field performance cannot necessarily be predicted.**

Sturrup et al's work clearly shows that "overmagnification or poor reproduction" of real exposure conditions in laboratory tests can produce misleading results. The authors reported that in field structures such as dams, some of them up to 50 years old, where the maximum water-cement ratio was established (0.5 to 0.6) on the basis of exposure and **then rigidly controlled**, the non-air-entrained concrete continues to be in good condition.

Interestingly, Sturrup et al (27) also reported that a section of the Otto Holden dam, built with **non-air-entrained concrete containing fly ash**, is in good condition after 33 years of service and is at least comparable in performance to the neighboring non-fly ash concrete. It is well known that the incorporation of mineral admixtures in concrete, such as fly ash and silica fume, generally requires much larger dosages of air entraining admixtures to obtain the