Durability — Critical Issues for the Future

by P. Kumar Mehta

There has been astronomical growth in the portland cement concrete industry during the 20th century because concrete has become the material of choice for construction of bridges, dams, highways, and urban transit facilities — the symbols of modernity. Worldwide consumption of concrete today is approximately 8 billion tonnes (8.8 billion tons) per year and, due to increasing urbanization, it is expected to grow steadily during the next century.

Public concern for lack of durability is perceived as a threat to the glorious future of concrete and it has been a subject of several recent published reports.[1-8] A critical review of the possible causes underlying this problem is presented here. Although some solutions are also suggested, the primary purpose of this article is to provide a forum for discussion of certain issues that require critical examination. This analysis is especially critical now, on the eve of entering the new millennium.

How serious is the problem of concrete durability?

In the 1930s, when the current boom in concrete construction began, it was generally believed that concrete structures typically designed for a service life of 40 to 50 years would actually last much longer with little or no maintenance. Until the 1970s, any cases of premature deterioration of concrete were treated as exceptions that were caused either by an inappropriate specification or the use of improper materials and construction practice. Durability of concrete attracted serious attention in the United States after the publication of a 1987 report by the National Materials Advisory Board.[2] According to this report approximately 253,000 concrete bridge decks, some of them less than 20 years old, were in varying states of deterioration and about 35,000 were being added to this list every year.

In the same year Litvan and Bickley[3] published the results of a survey on the durability of concrete in automobile parking structures in Canada. Numerous parking structures had shown serious deterioration much before their intended service life. Cases of premature and serious deterioration of concrete in recently built undersea tunnels in several countries were reported by Gerwick,[4] in marine piles by Khanna et al,[5] and in railway ties by Shayan and Quick.[6] Investigations have shown that, in general, the structural design, the specified materials, and the construction practice had followed the state-of-the-art.

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In response to the upsurge in concrete bridge deck cracking in the 1970s, the construction practice in the United States gradually moved toward the use of higher strength concrete mixtures. This does not seem to have helped. According to the results of the National Cooperative Highway Research Program's (NCHRP) latest survey, more than 100,000 concrete bridge decks developed full-depth transverse cracks spaced 1 to 3 m (3 to 10 ft) before the concrete was one month old.[7]

Mainly due to economic factors, the durability of concrete is being taken much more seriously now than before. Estimates for repair and rehabilitation of existing concrete infrastructure run into the billions of dollars. Many public agencies are already spending a significant proportion of their annual construction budget, up to one-third in some cases, on repair and rehabilitation. This is due in part to the high cost of construction and materials today. As a result, it is more economical to extend the service life of an existing structure, with only minor maintenance expense, than to replace it with new construction. It seems, therefore, that economic realities of today are partly responsible for a growing interest in building more durable structures with an intended service life of 100 years or more.

Current approaches and critical issues

Historically, the perception that there is a direct relation between the strength of concrete and durability has been at the heart of most of the approaches that have been made toward proportioning of durable concrete mixtures. Experience shows that concrete mixtures having 35 to 40 MPa (5075 to 5800 psi) compressive strength at 28 days, when made with suitable materials and handled with good construction practice, show adequately low permeability and perform well under most environmental conditions. Typically, these concretes have moderate cement content (300 to 350 kg/m^3 [500 to 590 lb/yd^3]) and water-cement ratio (*w/c*, 0.45 to 0.55). Concrete mixtures made with lower cementitious materials contents and higher *w/c* are more porous and permeable, and therefore less durable.

The advent of high-range water-reducing admixtures (superplasticizers) in the 1970s provided an impetus for the development of very high-strength concrete mixtures with high cement content (400 to 500 kg/m^3 [675 to 840 lb/yd^3]) and very low *w/c* (0.25 to 0.35). The high-early strength and low permeability have made these mixes attractive for use in aggressive environments, such as exposure to seawater and de-icing chemicals. This approach assumes that the stronger the concrete, the more durable it would be under severe environmental conditions. This assumption needs critical examination.

Major advancements have been made in understanding and controlling the primary causes of deterioration of concrete, namely the corrosion of reinforcing steel, frost action, alkali-aggregate expansion, and sulfate attack. It is assumed that material specifications and test methods grounded in the current knowledge base, which incidentally rests upon a reductionist approach to concrete science,[8] are adequate to deal with durability problems. This issue needs further examination because many structures built in accordance with codes or guidelines of recommended practice have shown deterioration much before their intended service life.[6-8] If our structural design, materials specifications, and construction practices are satisfactory, why then are we having so many durability problems?

Another issue that requires critical study is the comparison of the cost-benefit ratio between the traditional low-cost technology and the costly new technologies that are now available for enhancement of durability of concrete structures exposed to aggressive environments. How much enhancement in the durability of reinforced concrete structures can be expected, and at what cost, by the use of new materials and methods, such as superplasticizers, superpozzolans, epoxy-coated or corrosion-resisting steels, corrosion-inhibiting admixtures, and cathodic reinforcement protection?

Cracks, microcracks, and durability

It is generally accepted that, in order of decreasing importance, the principal causes responsible for deterioration of concrete structures are the corrosion of reinforcing steel, exposure to cycles of freezing and thawing, alkali-silica reaction, and sulfate attack. In each of these four cases of concrete deterioration, water is implicated in the mechanisms of expansion and cracking. Also, water is the primary vehicle for the diffusion of aggressive ions (e.g., chloride and sulfate) into the interior of concrete.

Properly constituted, placed, consolidated, and cured concrete is essentially watertight and should therefore have a long service life under most conditions. However, as a result of environmental effects, cracks occur and as a concrete structure loses its watertightness during service, it becomes vulnerable to one or more processes of deterioration. The epidemic of cracking in modern concrete structures shows that adequate attention is not being paid to the fundamental principles of concrete technology governing cracking.

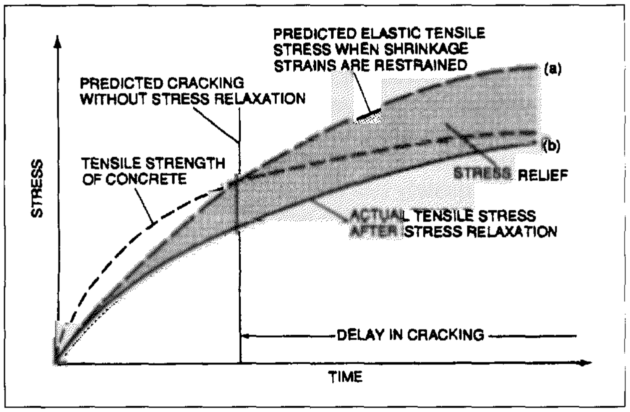


Fig. 1 — Influence of shrinkage and creep on concrete cracking.[11]

Among others, Basheer et al[9] and Idorn et al[10] have presented excellent reviews of the causation of cracking in hardened concrete. A simplistic review of the subject, based on Mehta and Monteiro's textbook,[11] is highly relevant to the issues being discussed:

• Primary causes of cracking

In general, cracks in the size range of 0.1 to 1 mm (0.004 to 0.04 in.) primarily arise from temperature gradients including frost action, humidity gradients, structural overloading, and chemical causes such as corrosion of reinforcement and alkali-aggregate reaction. Cracking during the early age is usually due to shrinkage strains from cooling or drying. When a freshly hardened concrete is exposed to ambient temperature and humidity, it experiences both thermal and drying shrinkage strains. Which one of the shrinkage strains would be dominant depends on the temperature and humidity of the environment, size of the concrete element, temperature of concrete, characteristics of concrete-making materials, and mixture proportions.

Under the restraining condition in hardened concrete, a shrinkage strain will result in an elastic tensile stress which, at first approximation, may be assumed as the product of the elastic modulus and the strain. The material cracks when the induced tensile stress exceeds its tensile strength. However, due to the viscoelastic behavior (creep) of the material, some of the stress is relieved and it is the residual stress (after the stress relaxation from creep) that determines whether or not cracking will occur.

This interplay between the tensile stress generated by restrained shrinkage and the stress relief due to creep is at the heart of early cracking in hardened concrete (Fig. 1). It is clear from the figure that the risk of cracking in concrete due to restrained shrinkage will be reduced by one or more of the following factors: a high tensile strength, a low shrinkage strain, a low elastic modulus, and high creep strain. These factors are relevant for an examination of the strength-durability relationship, as discussed next.

• Crack width and durability

Wide cracks at the surface are objectionable, especially when the concrete is exposed to an aggressive environment and a large number of cycling reversing loads. Field experience shows that under these conditions, cracks wider than 0.3 mm (0.01 in.) seldom heal. On the contrary, they tend to enlarge due to leaching and stress effects, thus providing convenient entry points for harmful agents. ACI Committee 224, Cracking, recommends 0.15 mm (0.006 in.) as the maximum limiting crack width at the tensile face of a reinforced concrete structure subjected to wetting and drying cycles or seawater spray.

In the concrete design and construction practice, crack widths are generally controlled by proper deployment of the primary reinforcement, and by the use of secondary reinforcement. With modern reinforced concrete structures, there has been a tendency to use excessive amounts of reinforcing steel in order to limit and constrain the shrinkage cracking. The implications of this approach to the long-term durability of structures exposed to aggressive water have not been considered.

It is well known that the steel reinforcement does not eliminate or reduce the shrinkage cracking in concrete; it simply transforms a few wide cracks into many fine cracks and microcracks. As discussed next, it is the unseen and the unmeasurable fine cracks and microcracks which serve as potential pathways that would eventually provide the interconnections so necessary for ionic transport between the surface of concrete and the surface of the reinforcing steel.

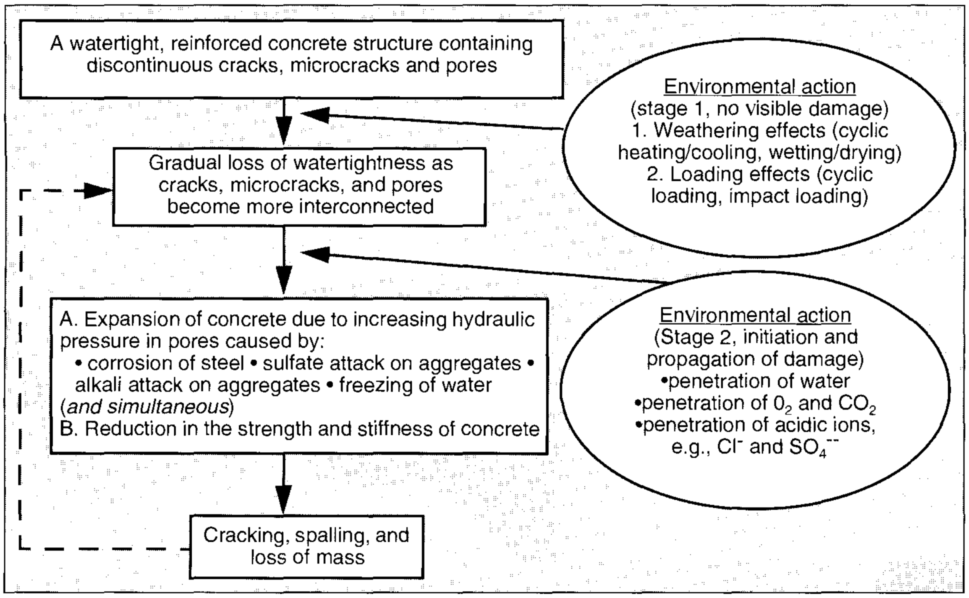


Fig. 2 — A holistic model of concrete deterioration from environmental effects.[8]

A holistic model of deterioration of concrete, shown in Fig. 2, was proposed earlier by the author.[8] According to this model, a well-constituted, properly consolidated, and cured concrete remains essentially watertight as long as the microcracks and pores in the interior do not form an interconnected network of pathways leading to the surface of concrete. Structural loading as well as weathering effects, such as exposure to cycles of heating-cooling and wetting-drying, facilitate the propagation of microcracks that normally pre-exist in the transition zone between the cement mortar and coarse aggregate. This happens during Stage 1 of the structure-environment interaction.

Once the watertightness of concrete is lost, the interior of concrete can become saturated. Consequently, water and ions which play an active role in the processes of deterioration can now be transported readily into the interior. This marks the beginning of Stage 2 of the "environmental action" during which the deterioration of concrete takes place through successive cycles of expansion, cracking, loss of mass, and increased permeability.

Unlike the previous models of concrete deterioration, based on a reductionistic approach (as discussed later), the holistic model is not "cause specific" in the sense that all of the primary causes of concrete deterioration are addressed in the model. Also, instead of singling out one of the components of cement paste or concrete as responsible for the damage, the model considers the effect of agents of deterioration on all the components of the cement paste and concrete. Furthermore, the model recognizes the laboratory and field experience in that the degree of water saturation of concrete plays a dominant role in expansion and cracking whether the primary cause of deterioration is frost action (cycles of freezing and thawing), corrosion of reinforcing steel, alkali-aggregate reaction, or sulfate attack.

Note that little or no apparent damage will be observed during Stage 1 which represents a gradual loss of watertightness. Stage 2 marks the initiation of the damage which occurs at a slow rate at first, then proceeds rather rapidly. It is suggested that during the second stage the hydraulic pressure of the pore fluid in a saturated concrete will rise due to one or more phenomena of volumetric expansion (e.g., freezing of water, corrosion of reinforcing steel, and swelling of ettringite or alkali-silica gel). At the same time, if the hydroxyl ions in the cement paste are being leached away and replaced by chloride or sulfate ions, the calcium silicate hydrate will suffer a loss of adhesion and strength. As a result of these two damaging processes, microcracks enlarge. This leads to further loss of watertightness and acceleration of the damage.

Based on the holistic approach of concrete deterioration, a two-stage damage model is illustrated in Fig. 3. Note the dormant period of damage corresponding to Stage 1 and the gradually escalating period of damage corresponding to Stage 2 of the environmental action. Due to variations in microclimate at different points within a given concrete structure, a precise determination of the length of each stage is difficult. However, as discussed later, the two-stage model of deterioration is helpful in designing cost-effective strategies for prolonging the service life of concrete exposed to aggressive environments.

• Strength-durability relationship

Suppose that the early strength of a concrete mixture is increased substantially by the use of a high early-strength portland cement or by a drastic reduction in *w/c*, achieved

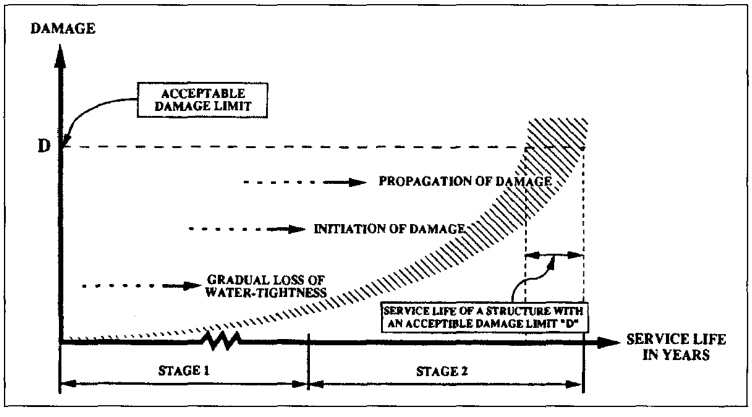


Fig. 3 — A two-stage damage model for predicting the service life of a concrete structure.[8]

through an increase in the cement content at a given or a reduced water content. In Fig. 4 it is shown how this would affect the principal factors influencing the cracking behavior of concrete, namely the drying shrinkage, thermal shrinkage, creep, elastic modulus, and tensile strength. Obviously, with the increasing proportion of cement paste, the concrete's extensibility (crack resistance) would decrease because of increase in both the drying shrinkage and thermal shrinkage.

At the same time, an increase in strength will tend to increase the elastic modulus and reduce the creep coefficient, which would also have an adverse effect on the concrete extensibility. This is the reason why high early-strength concrete mixtures are generally more prone to cracking than moderate or low-strength concrete mixtures. Of course, structural cracks in high-strength concrete can be controlled by the use of sufficient steel reinforcement but, as discussed above, this practice does not help the concrete durability problem. According to the holistic model of concrete deterioration, shown in Fig. 2, it is not the strength but the soundness (freedom from cracking) of concrete under service conditions that plays an important role in assuring the watertightness and durability.

Field experience also shows that high early-strength concrete mixtures, which are being favored by the building industry from the standpoint of speed of construction, are more crack-prone. According to a recent report by Shapiro,[12] cracked pier caps have delayed the opening of the Taipei's 6.8 mi (11 km) elevated transit line. The cracks pose no threat to structural safety but could affect the 100-year design life of the $10 billion system. The use of a rich concrete mixture with high cement content was reported to be a factor in cracking. Contractors apparently thought that a higher than designed strength would help to speed up the construction work.

Similarly, the following conclusions were drawn by Rogalla et al[7] from the 1995 NCHRP survey finding that more than 100,000 concrete bridge decks in the United States showed transverse cracking even before structures were less than one month old:

1. A combination of thermal shrinkage and drying shrinkage caused most of the cracks, not traffic loads or vibration during the hardening of concrete.

2. Generally, decks are made of high-strength concrete. These concretes have a high elastic modulus at an early age. Therefore, they develop high stresses for a given temperature change or amount of drying shrinkage, and most important, the concrete creeps little to relieve these stresses.

3. High-strength concretes typically contain more cement, therefore they shrink more and produce higher temperatures during early hydration. Modern cements are apt to cause cracking because they are finer and contain higher sulfate and alkali contents.

Already in 1939, Carlson[13] had observed that, in concrete subject to drying, at least a part of the advantage of using a finer ground cement may be offset by a greater degree of internal cracking. The author concluded, "it is almost a rule in concrete-making that whatever improves one quality is likely to hurt others." Clearly, numerous cases of cracking and premature deterioration of concrete bridge decks and other structures could have been avoided if proper attention was paid to basic principles of concrete technology, as discussed above, and to the words of wisdom from past researchers.

In an earlier paper, the author[14] has discussed the worldwide trend since the 1930s toward the production of high early-strength portland cements, which are implicated in less durable structures built with 20 - 30 MPa (2900 - 4350 psi) concrete mixtures containing low cement content and high *w/c*. Note that before the 1930s, typically the tricalcium silicate content of normal portland cement was below 30 percent and the ASTM Standard Specification permitted particles 22 percent larger than 75 μm (3 mils). Starting in the 1950s, the tricalcium silicate content of normal portland cement (ASTM Type I) has risen to 50 percent or more, and essentially no particles are larger than 75 μm.

Forced by today's construction timetables, the high early-strength mixtures made with modern portland cement typically contain a cement content of 400 kg/m^3 (675 lb/yd^3) or more. These mixtures are more prone to cracking and therefore would suffer from lack of durability in a severe environment. It is obvious that if long-term service life is the goal, a proper balance between a too high and a too low cement content must be sought.

Deficiencies in the science of concrete durability

Current theories on the mechanisms responsible for deterioration of concrete due to various causes are based on a reductionistic approach in science, which is being seriously challenged in all fields of human endeavor.[8] According to this approach, all aspects of a complex phenomenon (or a complex microstructure) can be fully understood and controlled by reducing it to parts and by considering only one part at a time.

As a result, our test methods for durability, materials specification, and codes of practice have failed to consider that durability is a holistic (pertaining to the whole) performance

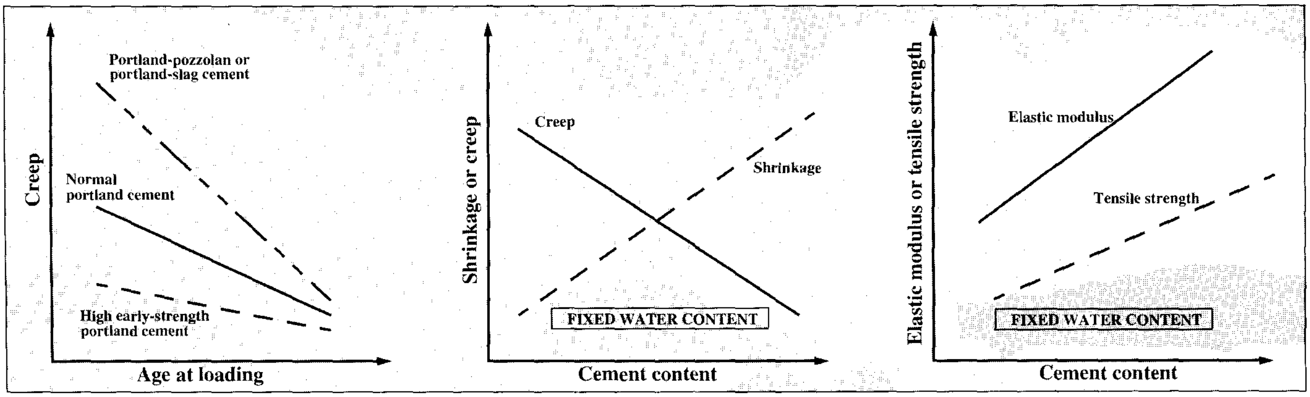


Fig. 4 — Relationship between concrete strength and other properties of concrete.[11]

criterion which must take into consideration the effect of all agents of deterioration, including the weather, on all the components of concrete. The following examples will illustrate this point.

- **Corrosion of reinforcing steel**

Most codes and guidelines for concrete practice, limit the content of chloride ions in concrete due to their adverse influence on the passive film on the surface of steel. Based on the Pourbaix Diagram, it is accepted that the reinforcing steel will be depassivated and will corrode when the Cl^-/OH^- ratio in concrete exceeds 0.6. Many researchers have questioned the validity of the Pourbaix Diagram in concrete technology because the full chemistry of the pore fluid in the cement paste (which is more complex and varies with cement composition) is ignored. Also, in addition to the passive film on the steel surface, usually there is a solid calcium hydroxide layer or scale in the interfacial zone between the steel and concrete.

This scale acts as a buffer to protect the passive film against chloride attack. Not much consideration is given as to how the presence of other acidic ions such as sulfate and carbonate would influence the chloride attack on the calcium hydroxide scale. More importantly, the mechanisms explaining the expansion and cracking of concrete only consider how the carbonation of concrete or chloride ingress would affect the reinforcing steel; the effect of these aggressive agents on the properties of concrete itself is completely ignored. Also, most of the models predicting the deterioration of concrete due to the reinforcement corrosion do not take into consideration the climate conditions (daily cycles of wetting/drying and heating/cooling) which, by influencing the degree of microcracking and permeability, not only determine the electrical resistivity of concrete but also the supply of adequate oxygen and water necessary to support the electrochemical corrosion process.

- **Alkali-aggregate reaction**

Concrete is also known to deteriorate due to interaction between certain aggregate types and the highly alkaline solution resulting from the hydration of a high-alkali portland cement. Aggregates containing reactive silica are usually implicated in this problem, which is generally referred to as the "alkali-silica reaction." Although alkali-silica reaction (ASR) was discovered more than 50 years ago, numerous deficiencies in our knowledge on the subject have been pointed out in a comprehensive study by Helmuth and Stark.[15] According to the authors, although cracking may be initiated by expansion of aggregate particles, swelling pressure of gels appears to be the major ASR damage mechanism for enlargement of cracks.

In a review of the causes and control of expansion associated with ASR, Swamy[16] states that with the swelling-type ASR gels, the alkali-aggregate reaction is unlikely to create structural distress in a well-detailed reinforced concrete member. Obviously, a holistic approach to durability of concrete structures must consider structural design and detailing in addition to materials, mixture proportions, and processing methods, as illustrated in Fig. 5.

Also, the current ASR models are not holistic in the sense that they ignore the effect of incorporation of alkali ions in the principal hydration product of cement, namely the calcium silicate hydrate (CSH). High-alkali cements generally produce a CSH that is more gelatinous and more prone to drying shrinkage. In their model for ASR cracking in concrete pavements, Helmuth and Stark propose that the first stage involves drying shrinkage and fine cracking at the concrete surface, without appreciable ASR product or expansion. This is consistent with the holistic model shown in Fig. 2, i.e., an increase in the permeability of concrete from environmental effects (such as drying shrinkage cracking) is a precursor to the penetration of moisture, which is essential for the swelling of alkaline gels.

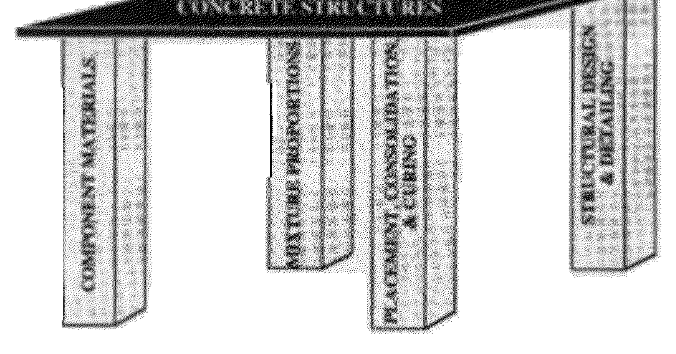


Fig. 5 — A holistic approach to durability of reinforced concrete structures.[1]

Cost-benefit analysis of high-performance concrete

The use of high-strength (> 40 MPa [5800 psi] compressive strength) concrete mixtures, developed initially in 1970s, has been extended to aggressive environments where durability is a prime consideration. This is because, in laboratory tests, the permeability of high-strength concrete mixture has been found to be sufficiently low; that high strength does not necessarily mean a low permeability and high durability in service is an issue which has attracted some attention recently.

In 1993, an ACI subcommittee defined high-performance concrete (HPC) as the concrete which meets special performance and durability requirements that cannot always be achieved routinely by using only conventional materials and normal construction practice. Meeting these requirements may involve enhancement of placement and compaction without segregation, early-age strength, toughness, volume stability, or service life in a severe environment. By implying that durability is no longer mandatory for HPC (it is one of the options), this definition has caused confusion because in the earlier literature, high durability was always associated with HPC.

In accordance with ACI definition, Goodspeed et al[17] developed several types of HPC for highway structures, including one which would develop 21 MPa (3045 psi) minimum strength in 4 hours. This paper has generated a very lively discussion, highlighting the conflict between high early-strength and long-term durability requirements. In addition to the problem of defining HPC, there are issues related to cost and complexity of the technology.

The following excerpts, taken from a recent paper by the author,[18] illustrate the complexity of the current approach to HPC technology:

What makes the task of a concrete technologist rather formidable is the intelligent choice between numerous types of chemical and mineral admixtures that are being promoted for use in high-performance concrete. For instance, with highly reinforced structures a superplasticizer has to be invariably used to obtain high workability in concrete mixtures with less than 0.4 *w/c*. An air-entraining admixture is used when the concrete is expected to perform well under conditions of freezing and thawing. Depending on job conditions, set-accelerating and set-retarding admixtures have been used at numerous jobs. Recently, other chemical admixtures, for example calcium nitrite, are being promoted as corrosion inhibitors for reinforcing steel. The use of epoxy-coated reinforcing steel and cathodic protection are among other options that have been incorporated into the construction practice for some newly built reinforced concrete structures exposed to corrosive environment.

Economic and environmental considerations have accelerated the use of pozzolanic and cementitious materials, either as concrete admixtures or as components of blended portland cements. Fly ash and blast furnace slag are widely available as industrial by-products in many countries of the world. Therefore, portland-pozzolan cements containing fly ash, and portland-slag cements containing granulated blast furnace slags are commonly available. During the last 15 years, silica fume (a by-product of the silicon metal and ferrosilicon alloy industries), which is a highly active pozzolan, has found application in many high-strength concrete projects throughout the industrial world. The use of silica fume may be desirable for making very high-strength concrete mixtures (> 100 MPa [14.5 ksi] compressive strength), but it is not the most cost-effective solution for making durable concrete for use in aggressive environments.

The selection of materials and mixture proportions for concrete should be guided by the performance characteristics sought, and the cost. Gerwick[19] has given a list of preventive and mitigating measures which are commonly adopted for minimizing the degradation of concrete due to corrosion of reinforcing steel. Representative values of their cost are appended in parentheses (given as a percentage of the first cost of the concrete structure). A part of this list is reproduced below. These costs are valid for western countries, as of 1994, and can be used for comparison purposes:

1. Use of fly ash or slag as a partial replacement for cement (0 percent).
2. Pre-cooling of the concrete mixture (3 percent).
3. Use of silica fume and a superplasticizer (5 percent).
4. Increase cover by 15 mm (0.6 in.) (4 percent).
5. Addition of corrosion-inhibiting admixture (8 percent).
6. Epoxy-coating of reinforcing steel (8 percent).
7. External coatings (20 percent).
8. Cathodic protection (30 percent).

The adoption of any one of the first four options — the use of fly ash or slag as a partial replacement for cement, precooling of fresh concrete (in the case of massive structural members), the use of silica fume with a superplasticizer, or an increase in the cover thickness — will reduce the permeability of concrete. This will have the effect of stretching Stage 1 of the damage model shown in Fig. 3 at a modest or negligible increase in cost (viz option 1).

Where thermal cracking is of concern, the most cost-effective approach from the standpoint of durability is to use as low a portland cement content as possible and a large amount of a cementitious or pozzolanic admixture. It is noteworthy that Malhotra[20] has developed superplasticized concrete mixtures typically containing 150 kg/m^3 (250 lb/yd^3) ASTM Type I portland cement and 210 kg/m^3 (350 lb/yd^3) fly ash. These mixtures show high ultimate strength and high durability. High volume fly ash mixtures were also investigated by Ravina and Mehta[21] without the use of a superplasticizer.

The other four options, namely the use of a corrosion inhibiting admixture, epoxy-coated steel reinforcement, external coatings for concrete, and cathodic protection are much more expensive and are expected to prolong Stage 2 of the damage model. There is limited information regarding the length of service life extension from the use of these expensive options, once the first line of defense, i.e., watertightness, is breached. Experience in the field of human health shows that preventive measures are always more cost effective than the use of remedial measures after the body has become afflicted with a disease.

Conclusion

As we approach the next millennium, it is prudent to take a critical look at the technological alternatives available to us for building durable concrete structures in the future. We must not forget that concrete is the material of choice because of its ability to resist water, low initial cost, and low maintenance cost. When it loses its watertightness during service, concrete becomes vulnerable to a variety of deterioration processes. Generally, it is not lack of strength but the lack of soundness (freedom from cracking) which accounts for an increase in the permeability during service. Therefore, a holistic approach to durability must place equal emphasis on the structural design, selection of materials, mixture proportions, and processing methods that protect the soundness of a concrete structure in the environment of exposure.

Since the 1930s, due to increasing demand for concrete structures, the building industry has been driven by a demand for high speed of construction. The development of high early-strength portland cement and its use in concrete mixtures with high *w/c* fulfilled the need of the construction industry but sowed the seeds for the concrete durability problems which are being noticed more and more with structures built during 1930-70. High-performance concrete mixtures developed during 1970-80 may not necessarily insure long-term durability in severe environments unless they are designed for dimensional stability and soundness. Also, the high cost of unconventional materials and methods may be justified for special projects but, for a majority of concrete structures, the use of such materials and methods will be uneconomical. Recent research and development studies have generally ignored that concrete is the material of choice for construction, mostly because of its low cost and water-resisting property.

To provoke a discussion on the technology alternatives for enhancement of durability of concrete, the author would like to raise the following questions:

- **Construction speed** — Have we reached the point when we should no longer be driven by demands for higher and higher speeds of construction? Is it not time that, instead of looking only at the initial cost of construction, we start taking a holistic view of all other costs, including the life-cycle cost, the ecological cost, and the social cost (i.e., labor employment), of the current trends in construction practice?
- **Life cycle cost** — A slowing down of the speed of construction would, obviously, result in a higher initial cost due to increase in the cost of labor, materials (i.e., formwork), and capital (interest expense). However, these costs can be easily offset by not using costly materials and methods that

are being recommended for the purpose of enhancing the service life, namely, silica fume, corrosion-inhibiting chemicals, epoxy-coated reinforcing steel, external coatings, and cathodic protection. Furthermore, from the standpoint of life cycle cost it may be noted that these materials and methods offer only a limited advantage when the watertightness of concrete is not preserved by the selection of proper materials, mixture proportions, and construction and design practices.

Which one of the two is the better alternative: the use of conventional materials and concrete mixtures that would not develop high strength at early ages but would produce a sound concrete, or the use of expensive materials and methods that may not result in a watertight concrete but attempt to provide protection to the reinforcing steel after the concrete has become permeable?

- **Materials and mixture proportions** — To produce a slow-hardening concrete with high creep and low elastic modulus at early ages, it is not necessary to go back to the coarse ground, low tricalcium silicate cements of the past. For general construction purposes, instead of ASTM Type I portland cement, why don't we require the use of blended portland cements containing large amounts of fine particles of relatively less active materials, such as slag and fly ash?

Furthermore, for the purpose of practicing industrial ecology for sustainable development, don't we have an ethical responsibility to insure that cement and concrete industries utilize as much of the cementitious and pozzolanic by-products as possible? Environmental considerations demand that we consider limiting the use of neat portland cement to special applications, such as cold weather concreting. To permit a wider use of large amounts of slag and fly ash in concrete, the pros and cons of designing structures on the basis of 56- or 90-day strength, instead of 28-day strength, should be examined. It is also clear that concrete mixtures must not be proportioned to achieve early strengths far exceeding the structural requirement.

Do we recognize the problem that concrete mixture proportioning procedure based on *w/c* alone has not been a reliable criterion to achieve the watertightness of concrete in service? Keeping both the water and cementitious contents as low as possible and the aggregate content as high as possible provide one way to reduce both the drying and thermal shrinkage, and the shrinkage-related cracking. To achieve this, it is obvious that more attention will have to be paid to aggregate grading than specified by current codes of practice.

- **Codes of practice** — Do we accept that we need a paradigm shift in the concrete science and technology, emphasizing that durability is related to the soundness (freedom from cracking) not to the strength of concrete? To this end, all specifications and codes which imply that durability of concrete is related to strength require a critical review. Field experience in North America with concrete bridge decks and parking garages and with concrete bridges in Norway[22] has shown that current codes of practice are inadequate to insure long service life of structures exposed to severe environmental exposure. Also, the practice of indiscriminate and excessive use of reinforcing steel, which tends to increase microcracking in concrete, needs a close scrutiny.

References

1. Mehta, P.K., and Gerwick, B.C., "Concrete in the Service of Modern World," *Proceedings* of the International Conference on Concrete in the Service of Mankind, University of Dundee, Scotland, June, 1996.

2. Report of the National Materials Advisory Board, *Concrete Durability - A Multibillion Dollar Opportunity*, Publication No. NMAB-437, National Academy of Sciences, Washington, D.C., 1987, 94 pages.

3. Litvan, G., and Bickley, J., "Durability of Parking Structures," *Concrete Durability - Proceedings of the Katherine and Bryant Mather International Symposium*, SP-100, American Concrete Institute, Detroit, 1987, pp. 1503-1526.

4. Gerwick, B.C., "Pressing Needs and Future Opportunities of Concrete in the Marine Environment," *Proceedings* of the Gerwick Symposium on Durability of Concrete, University of California, Berkeley, 1989, pp. 1-5.

5. Khanna, J.; Seabrook, P.; Gerwick, B.C.; and Bickley, J., "Investigation of Distress in Precast Concrete Piles at Rodney Terminal, Saint John," *Concrete in Marine Environments*, SP-109, American Concrete Institute, Detroit, 1988, pp. 277-320.

6. Shayan, A., and Quick, G.W, "Microscopic Features of Cracked and Uncracked Railway Sleepers," *ACI Materials Journal*, V. 89, No. 4, 1992, pp. 348-361.

7. Rogalla, E.A.; Krauss, P.D.; and McDonald, D.B., "Reducing Transverse Cracking in New Concrete Bridge Decks," *Concrete Construction*, V. 40, 1995, pp. 735-738.

8. Mehta, P.K., "Concrete Technology at the Crossroads - Problems and Opportunities," *Concrete Technology: Past, Present, and Future*, SP-144, American Concrete Institute, Detroit, 1994, pp. 1-31.

9. Basheer, P.A.M.; Long, A.E.; and Montgomery, F.R., "An Interaction Model for Causes of Deterioration and Permeability of Concrete," *Concrete Technology: Past, Present, and Future*, SP-144, American Concrete Institute, Detroit, 1994, pp. 213-231.

10. Idorn, G.M.; Johansen, V.; and Thaulow, N., "Assessment of Causes of Cracking in Concrete," *Concrete Science III*, edited by J. Skalny, Am. Ceramic Society, 1992.

11. Mehta, P.K., and Monteiro, P.J.M., *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill, 1996, 548 pages.

12. Shapiro, D., "Cracked Pier Caps Delay Rapid Transit Line," *Engineering News Record*, December 19, 1994, p. 53.

13. Carlson, R.W., "Remarks on Durability of Concrete," *ACI Journal*, V. 10, 1939, pp. 359-366.

14. Mehta, P.K., "Durability of Concrete - Fifty Years of Progress?," *Durability of Concrete - G.M. Idorn International Symposium*, SP-126, American Concrete Institute, Detroit, 1991, pp. 1-31.

15. Helmuth, R. and Stark, D., "Alkali-Silica Reaction Mechanism," *Concrete Science III*, edited by J. Skalny, American Ceramic Society, 1992.

16. Swamy, R.N., "Alkali-Aggregate Reaction — The Bogeyman of Concrete," *Concrete Technology: Past, Present, and Future*, SP-144, American Concrete Institute, Detroit, 1994, pp. 105-139.

17. Goodspeed, C.H.; Vanikar, S.; and Cook, R., "High-Performance Concrete Defined for Highway Structures," *Concrete International*, V. 18, No. 2, February, 1996 and No. 8, August, 1996.

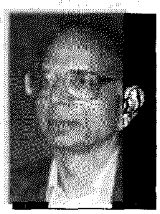
18. Mehta, P.K., "High-Performance Concrete for the Future," *Proceedings*, International Congress on High Performance Concrete, University of Santa Catarina, Florianopolis, Brazil, June 1996.

19. Gerwick, B.C., "The Economic Aspects of Durability — How Much Added Expense Can Be Justified," *Proceedings*, P.K. Mehta Symposium on Durability of Concrete, Nice, France, 1994.

20. Malhotra, V.M., "CANMET Investigations Dealing with High Volume Fly Ash Concrete," *Advances in Concrete Technology*, Natural Resources, Ottawa, Canada, 1994, pp. 445-482.

21. Ravina, D., and Mehta, P.K., "Compressive Strength of Low Cement/High Fly Ash Content Mixtures," *Cem. Conc. Res.*, V. 18, No. 4, 1988, pp. 571-583.

22. Gjørv, O.E., "Steel Corrosion in Concrete Structures Exposed to Norwegian Marine Environment," *Concrete International*, V. 16, No. 4, April, 1994, pp. 35-39.



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