Building Durable Structures in the 21st Century

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At the dawn of the 21st century, we are inheriting a world that has seen unprecedented demographic, social, technological, and environmental changes during the last 100 years. These changes have had a great impact on all industries, including the construction industry. So far, the concrete construction industry has met the need for housing and infrastructure in a timely and cost-effective manner. We are now entering an era when the industry faces an additional challenge: how to build concrete structures that are environmentally more sustainable. Climate change resulting from the high concentration of greenhouse gases in the atmosphere has emerged as the most threatening environmental issue and, as discussed below, the construction industry happens to be a part of the problem.[1,2]

The primary greenhouse gas is carbon dioxide and, during the 20th century, its concentration in the environment has risen by 50%. Carbon dioxide is a major by-product in the manufacturing of the two most important materials of construction: portland cement and steel. Therefore, the construction industry needs to determine how future infrastructural needs can be met without further increases in the production of cement and steel. Conservation of these materials through enhancing the durability of structures is one of the ways by which the construction industry can become a part of the solution to the problem of sustainable development.

Some 2000-year-old unreinforced concrete structures, such as the Pantheon in Rome and several aquaducts in Europe, made of slow-hardening, lime-pozzolan cements, are in excellent condition, while the 20th century reinforced concrete structures that are constructed with portland cement are quickly deteriorating. When exposed to corrosive environments like deicer salts and seawater, serious durability problems have occurred in bridge decks, parking garages, undersea tunnels, and other marine structures less than 20 years old.[3-5]

In the past, it was generally found that neither structural design nor materials were responsible for the lack of durability. In most cases, it was the construction practice that turned out to be the culprit. Inadequate consolidation or curing of concrete, insufficient cover for the reinforcement, and leaking joints are examples of poor construction practice. A serious issue now is the growing evidence of premature deterioration in recent structures that were built in conformity with the state-of-the-art construction practice. This means that the premature deterioration of concrete structures will continue to occur at unacceptably high rates unless we take a closer look at the current construction practice to understand and control the primary causes that adversely affect the durability of concrete. Deterioration, such as corrosion of reinforcing steel and sulfate attack, occurs when water and ions are able to penetrate into the interior of concrete. This penetration happens when interconnections between isolated microcracks, visible cracks, and pores develop.[6] Therefore, deterioration is closely associated with cracking. The causes of cracking are many; however, there is one cause that has emerged as the most predominant factor in the cracking of concrete structures at early ages, namely, the use of high-early strength cements and concrete mixtures to support the high speed of modern construction.

In this article, the authors have presented a historical review to show how the concrete industry in the 20th century, while responding to calls for higher and higher strength, inadvertently violated a fundamental rule in

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materials science that there exists a close connection between cracking and durability. To pursue the goal of building environmentally sustainable concrete structures, a paradigm shift in certain beliefs and construction practices is needed.

Before 1930

According to Burrows, photographs of two independent surveys on the condition of portland cement concrete structures built before 1930 were shown at the 1931 ACI convention.[7] Deterioration of concrete had occurred either due to crumbling (possibly from exposure to freezing and thawing) or due to leaching from leaking joints or poorly consolidated concrete. No cases of cracking-related deterioration were reported. It is known that concrete with pre-1930 portland cements developed strengths at a very slow rate because they were coarsely ground (~ 1100 cm^2/g, Wagner specific surface) and contained a relatively small amount (less than 30%) of tricalcium silicate C_3S. Burrows believes that the transition from a concrete that deteriorated by crumbling or leaching to one that deteriorates by cracking occurred when cement manufacturers started making faster-hydrating portland cements by raising the fineness and the C_3S content. His observation is confirmed by the results of a 1944 survey, as discussed next.

1930-1950

In 1944, the U.S. Public Roads Administration undertook an extensive survey of concrete bridges in California, Oregon, Washington, and Wyoming. According to Jackson, the purpose of the survey was to investigate the causes of an alarmingly rapid rate of disintegration of concrete in these and other western states.[8] In all, some 200 structures from small, single-span bridges to large multispan bridges, 3 to 30 years old, were inspected. Jackson observed that there was sufficient evidence to show that concrete structures built after 1930 were not proving as durable in service as earlier structures. For example, 67% of the pre-1930 bridges were found to be in good condition as compared to only 27% of the post-1930 bridges. Because the construction technology had remained essentially the same, Jackson concluded that the change in the cement fineness was the probable cause of the problem. He reported that, in 1930, as a result of users' demand for higher early strength, the ASTM specification was changed to permit more finely ground portland cement. Jackson theorized that "modern cements, ground to a Wagner fineness of 1800 cm^2/g do not make as durable a concrete as the more coarsely ground cements in use 25 years ago." Note that a Wagner fineness of 1800 cm^2/g corresponds to a Blaine fineness of about 300 m^2/kg.

The U.S. Bureau of Reclamation conducted a series of field and laboratory studies that confirmed Jackson's theory. The results from two of these, reported by Brewer and Burrows in 1951 and by Backstrom and Burrows in 1955, are discussed in Reference 7.

1950-1980

Since 1950, several important changes have taken place in the concrete construction practice. Changes such as rapid development of the ready-mixed concrete industry, placement of concrete by pumping, and consolidation by immersion vibrators triggered the need for high-consistency concrete mixtures which, before the advent of high-range water-reducing admixtures in 1970, were made by increasing the water content of fresh concrete. Consequently, to achieve sufficiently high strength levels at early ages for the purpose of maintaining fast construction schedules, further increases were made in the fineness and the C_3S content of the general-purpose portland cement. By 1970, according to Price, the C_3S content of the ASTM Type I portland cements in the U.S. had risen up to 50% and the Blaine fineness to 300 m^2/kg.[9]

The impact of this drastic change in the composition and hydration characteristics of general-purpose portland cement on durability of concrete can be judged from the fact that with the 1945 cements, a 0.47 water-cement ratio (*w/c*) concrete typically gave 4500 psi (31 MPa) strength at 28 days. With the ASTM Type I portland cements available in 1980, it was possible to achieve the same strength with a lower cement content and a much higher *w/c* of 0.72. Being more permeable, this concrete naturally proved less durable in corrosive environments.

The performance of concrete in bridge decks serves as an accelerated field test for durability, because bridge decks are generally exposed to deicer chemicals and frequent cycles of wetting-drying, heating-cooling, and freezing-thawing. A 1987 report of the U.S. National Materials Advisory Board made a startling observation that concrete bridge decks, mostly built after the 1940s, were suffering from an epidemic of durability problems.[3] It was estimated that 253,000 bridge decks, some of them less than 20 years old, were in varying states of deterioration and that the number was growing at the rate of about 35,000 bridge decks every year.

There are reasons to believe that the acceleration of bridge deck durability problems since 1974 is directly attributable to the use of cements and concrete mixtures possessing relatively high strength at early ages. Neville has also stated that the deterioration of concrete increased because cement specifications did not have limits on fineness, C_3S, and early strength.[10] Today, ASTM Type I and II cements can be found with more than 60% C_3S and higher than 400 m^2/kg fineness. Gebhardt has compiled a comprehensive survey of North American cements produced in 1994.[11] His analysis of the data for 71 ASTM Type I cements and 153 Type II cements showed that, except for a lower C_3A content in Type II cement, there is essentially no difference in the compo-

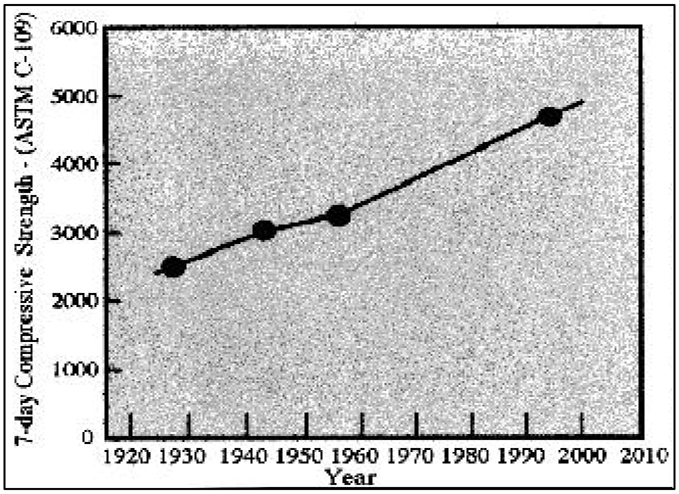

Fig. 1: Increase in the 7-day strength of ASTM Type I portland cement, produced in the U.S. during the last 70 years (adapted from Reference 11)

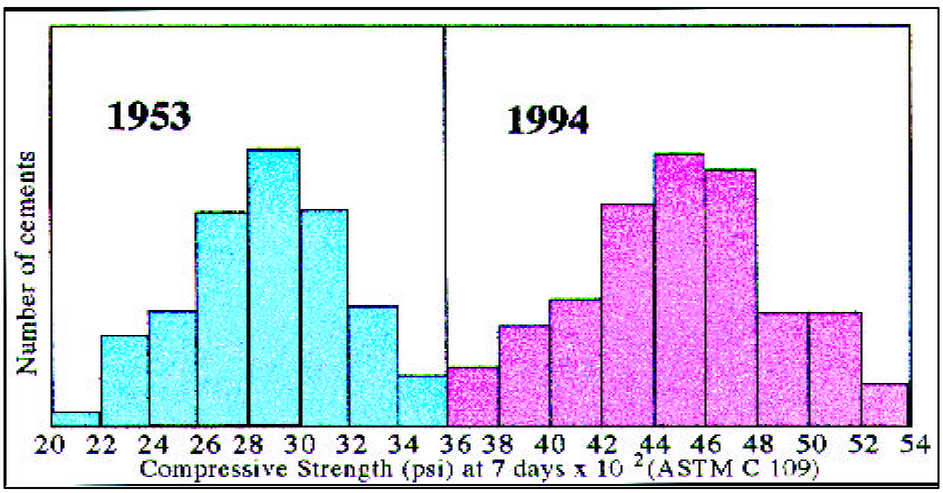

Fig. 2: Distribution of ASTM Type II portland cements produced in the U.S., according to the 7-day strength (adapted from Reference 11)

sition and physical properties of the two cement types. The average C_3S content and fineness for both cement types is approximately 56% and 375 m^2/kg, Blaine, respectively. In both cases, the compressive strength of ASTM C 109 mortar cubes at the ages 1, 3, 7, and 28 days is approximately 2000, 3600, 4500, and 6000 psi (14, 25, 31, and 41 MPa), respectively. The author concluded: “It appears that the general property of moderate heat of hydration as a defining characteristic of Type II cement has been lost over the years, except when a moderate heat cement was specifically designated and produced.”

Figure 1 shows that the 7-day compressive strength of ASTM Type I portland cement has doubled, from about 2500 to 4500 psi (17 to 31 MPa) during the last 70 years. In regard to ASTM Type II cements, Fig. 2 shows that until 1953, at least 50% of the cements had less than 3000 psi strength at 7 days, whereas in 1994, none had such a low strength. Moreover, approximately 50% of the Type II cements had 7-day strength in the 4500 to 5400 psi (31 to 38 MPa) range. Now, commercially available portland cement easily meets the ASTM 28-day minimum strength requirement in 3 to 7 days. Well suited for the fast schedules of the construction industry, the demand for today’s portland cements have virtually driven the slower-hardening and more durable portland cements of the past out of the market place.

Krauss and Rogalla proposed another reason why the cracking and deterioration of concrete in bridge decks have increased substantially since the mid-1970s.[12] They pointed out the coincidence between an upsurge in deterioration problems and a major change in the AASHTO Specification in 1974. For over 40 years, from 1931 to 1973, the AASHTO Specification for bridge deck concrete required 3000 psi (20.7 MPa) as the minimum 28-day compressive strength. This concrete is characterized by a low elastic modulus and high creep at early ages and is therefore less prone to cracking from thermal and drying-shrinkage stresses. In response to increasing cases of reinforcement corrosion resulting from the widespread use of deicing salts on roads and bridges, AASHTO decided that something had to be done to reduce the permeability of concrete. Consequently, in 1974, AASHTO made a change in the concrete specification requiring a maximum 0.445 *w/c*, a minimum 362 kg/m^3 (610 lb/yd^3) cement content, and a minimum 4500 psi (30 MPa) compressive strength at 28 days. Krauss and Rogalla believe that, due to the high thermal and drying shrinkage, low creep, and high elastic modulus at early ages, these concrete mixtures were crack-prone and therefore less durable in corrosive environments. One unfortunate result of the AASHTO reduction of the *w/c* from 0.53 to 0.445 was that some people thought that if reducing the *w/c* 0.53 to 0.445 was a good idea, it would be an even better idea to reduce it further to values like 0.3 because this is now possible with the high-range water-reducing admixtures. As discussed next, cases of severe cracking have been reported in many structures built with very low *w/c* concrete mixtures.

1980 to present

Since the early 1980s, increasing use of high-range water-reducing admixtures and highly reactive pozzolans like silica fume has made it possible to make concrete mixtures possessing high workability at very low water-

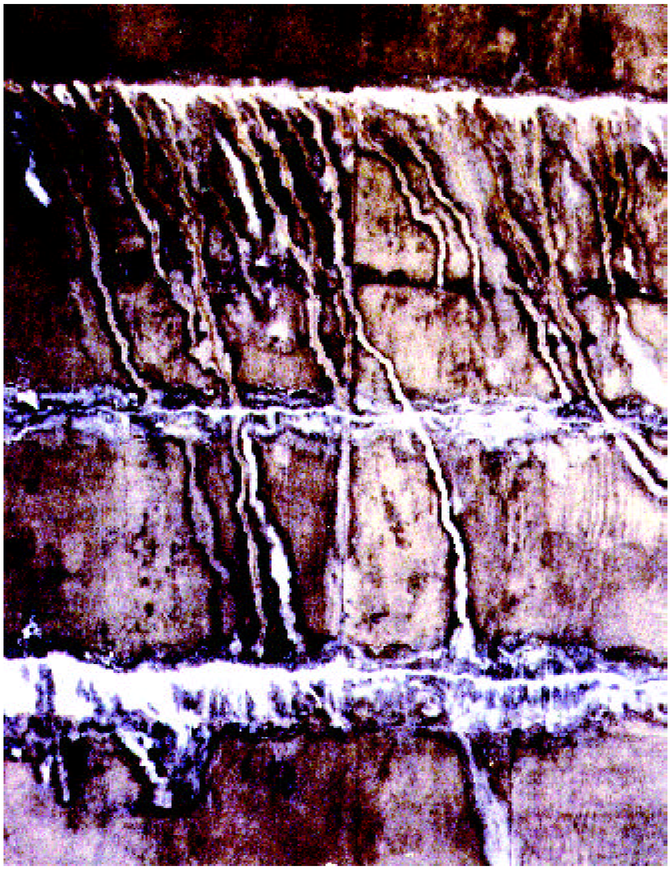

Fig. 3: Photograph of early-age cracking in the high-performance concrete used in the construction of the new 23rd Street Viaduct in Denver, Colo.

cementitious materials ratio *(w/cm)*. Called high-performance concrete,* the product is normally characterized by 50 to 80 MPa (7500 to 12,000 psi) compressive strength at 28 days and a very low permeability in *laboratory specimens*. Due to the high strength and high elastic modulus at relatively early ages, the product quickly found its way into fast-track projects such as structural members for tall buildings. The use of high-performance concrete where impermeability and durability are prime considerations has generated considerable controversy, as explained below.

The 1996 report by Krauss and Rogalla contains the results of a survey of 200,000 newly constructed bridges in the U.S. and Canada.[12] The report showed that more than 100,000 concrete bridge decks had developed transverse cracks soon after construction. This was attributed mainly to thermal contraction by the authors. Usually, the cracks were full depth and spaced 1 to 3 m (3.3 to 10 ft) apart along the length of the bridge. The authors concluded that, under adverse environmental conditions, the crack growth reduced the permeability of concrete and accelerated the rate of corrosion of reinforcing steel and deterioration of concrete. It seems that deterioration problems with concrete bridge decks probably increased in the mid-1970s after AASHTO mandated the use of high-strength concrete mixtures, and the problem was not resolved in the 1980s when high-performance concrete with even higher early strength was incorporated into the highway construction practice.

According to Krauss and Rogalla:

"When high cement content HRWR admixtures (superplasticizer) and silica fume are used, 1-day moist-cured compressive strengths of 27.6 to 55 MPa (4000 to 8000 psi) have been achieved. These concretes would have 1-day modulus of elasticity of 28.8 to 35.8 GPa (3.6 to 5.2×10^6 psi), - values 3 to 7 times those of a nominal 20.7 MPa (3000 psi) concrete used before 1974. These very high-strength concretes also have significantly reduced creep potential. The brittleness relates to dramatically reduced creep potential and the observed early cracking or other unusual cracking that is not consistent with engineer's experience with more conventional concrete."[12]

Field experience with bridge decks in Virginia, Kansas, Texas, and Colorado cited by Burrows confirms Krauss and Rogalla's conclusions.[7] In 1974, bridge deck cracking in Virginia reportedly increased when the strength requirement was raised from 3000 to 4000 psi. Similarly, 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 before construction was finished (Fig. 3). 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 fineness was 391 m^2/kg and the C_3A-plus-C_3S content was 72% and was the highest of approximately 200 Type II North American cements produced in 1994. The cracking tendency of this concrete mixture was further exacerbated by the addition of silica fume, which is known to increase the autogenous shrinkage of concrete. In conventional concrete, the autogenous shrinkage of less than 50 millionths can be ignored, but a high-

***High-Performance Concrete** (HPC) is concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. Thus, a high-performance concrete is a concrete in which certain characteristics are developed for a particular application and environment. Examples of characteristics that may be considered critical in an application are: ease of placement, compaction without segregation, early age strength, long-term mechanical properties, permeability, density, heat of hydration, toughness, volume stability, and long life in severe environments. (Editor) strength concrete may have an autogenous shrinkage of several hundred millionths, which is as high as the drying shrinkage.

Lessons from 20th century experience

The authors have drawn the following conclusions from the 20th century concrete construction practice:

1. A number of field surveys during the 20th century have shown that since 1930 whenever cement and concrete strengths were raised, this was generally followed by a corresponding increase in deterioration problems;

2. A gradual increase in the C_3S content and fineness of general-purpose portland cements have enabled these cements to develop very high strengths at early ages. There is a general trend now to produce correspondingly high early-strength concrete mixtures containing large proportions of modern portland cement. Compared to old concrete mixtures, modern concrete tends to crack more easily due to lower creep and higher thermal shrinkage, drying shrinkage, and elastic modulus. There is a close, inverse relation between high strength and early-age cracking in concrete;

3. There is a close relationship between cracking and deterioration of concrete structures exposed to severe exposure conditions;

4. Premature deterioration of concrete structures has occurred even when state-of-the-art construction practice was followed. This shows that there is something wrong with the current durability requirements for concrete in our codes, as discussed below; and

5. When considering the service life of actual structures, the results of laboratory tests on concrete durability should be used with caution because the cracking behavior of concrete is highly dependant on the specimen size, curing history, and environmental conditions. Laboratory specimens are small and usually not restrained against volume change. Laboratory tests of rich mixtures containing a fast-hydrating cement may yield low permeability values. The same concrete mixture when used in an actual structure may not prove to be durable if exposed to frequent cycles of wetting-drying, heating-cooling, and freezing-thawing. Under similar circumstances, inadequately cured concrete containing a high volume of fly ash or slag will also crack and deteriorate in the field, whereas well-cured specimens may have given excellent performance in a laboratory test on permeability.

Durability requirements in the codes of recommended practice

The current concrete construction practice for structural concrete in the U.S. is governed by the ACI Building Code 318 or modified versions of it. The code was reformatted in 1989 to emphasize that, when durability requirements are important, the selection of mixture proportions shall be governed primarily by the durability considerations. Although the goal is well-intentioned, the recommended practice to pursue this goal has become counterproductive from the standpoint of building durable and environmentally sustainable concrete structures. To illustrate this point, an analysis of how the ACI 318-99 durability requirements would affect the mixture proportions of concrete for a reinforced structure, with 3000 psi (20 MPa) specified strength and exposed to deicing chemicals or seawater, is presented below.

Cement content: According to the code, a maximum 0.40 *w/cm* and a minimum 5000 psi (35 MPa) concrete mixture shall be specified. Generally, the average concrete strength will be from 700 to 1400 psi (5 to 10 MPa) higher than the specified strength, depending on whether or not field strength test data are available to establish a standard deviation. For a 1 in. (25 mm) maximum-size aggregate and 4 in. (100 mm) slump, the ACI 211 tables for nonair-entrained concrete recommend 325 lb/yd^3 (195 kg/m^3) water content. A normal water-reducing admixture, by reducing the water requirement 7 to 8 %, will bring down the water content to 300 lb/yd^3 (180 kg/m^3). Thus, at the maximum permitted 0.40 *w/cm*, one would need 750 lb/yd^3 (450 kg/m^3) cement content. If the water reduction is doubled by the use of a high-range water-reducing admixture, one would still need 690 lb/yd^3 (410 kg/m^3) cement. Theoretical considerations as well as field experience shows that these cement contents are too high to obtain crack-free, durable structures.

Water content: ACI 318 controls the water content by specifying a maximum limit on *w/cm*. As shown above, this approach is unsatisfactory when the cementitious material happens to be exclusively or mostly portland cement. From standpoint of durability, it is apparent that a direct control on the maximum allowable water content in the concrete mixture is essential.

Mineral admixtures: Mineral admixtures, such as ground granulated blast-furnace slag and ASTM Class F fly ash, are highly effective in reducing the heat of hydration, strength, and elastic modulus of concrete at early age. This is why properly cured concrete mixtures containing high volumes of slag or fly ash (50% or more by mass of the cementitious material) are generally less crack-prone and therefore less permeable in service, which is an important factor in controlling the deterioration of concrete from causes such as reinforcement corrosion, alkali-aggregate expansion, and sulfate attack. The construction codes should incorporate guidelines on the use of a high volume of mineral admixtures in concrete structures designed for durability.

Crack width and durability

There are no clear guidelines in the *ACI Manual of Construction Practice* on the relationship between crack width and durability of reinforced concrete structures exposed to different environmental conditions. Although ACI 224R-98 suggests 0.15 and 0.18 mm as maximum tolerable crack widths at the tensile face of reinforced concrete structures exposed to deicing chemicals or seawater, respectively, the report also contains a disclaimer that the crack-width values are not a reliable indicator of the expected reinforcement corrosion and concrete deterioration. For a designer to exercise engineering judgement on the extent of needed crack control, at least some understanding of the effect of cracks and microcracks (less than 0.1 mm) on the permeability of concrete is necessary. A brief summary is presented herein.

Generally, at the interfacial transition zone between the cement mortar and coarse aggregate or reinforcing steel, a higher than average *w/cm* exists, which results in higher porosity, lower strength, and more vulnerability to cracking under stress. Thus, when a structure or a part of the structure is subject to extreme weathering and loading cycles, an extensive network of internal microcracks may develop. Under these conditions, the presence of even a few apparently disconnected surface cracks of narrow dimensions can pave the way for penetration of harmful ions and gases into the interior of concrete.

Paradigm shifts needed in the construction practice

It is a myth that durable and sustainable concrete structures can be built according to current practice when the materials and mixture proportioning are correctly specified and the specifications are meticulously followed. This is because the materials and the construction practice in the 20th century, developed primarily to meet the need for high-speed construction, have generally proven harmful to the durability of concrete structures exposed to severe environmental conditions. We have reached a point in time when some sacrifice in the speed of construction seems to be necessary if it is important to pursue the goal of durable and environmentally sustainable concrete structures. This, obviously, will require a change in the mindset of owners, builders, and designers. Some of the badly needed paradigm shifts in the current construction practice are briefly discussed below.

1. The belief that society is being well served by high-speed construction is questionable due to dramatic changes during the 20th century. Globally, we do not have a labor shortage, but we do face a serious problem of man-made climate change which brings into the limelight the construction materials like steel and concrete that are being produced at a great cost to the environment. Therefore, conservation of materials, not the construction speed, should be the new emphasis of the concrete industry in the 21st century.

2. The belief that the higher the strength of concrete, the more durable will be the structure, is not supported by field experience. High-early strength concrete mixtures are more crack-prone and deteriorate faster in corrosive environments. Codes should be amended to stress this point adequately.

3. Many reductionistic or narrow solutions to concrete durability problems have been tried in the past without much success. We must recognize the fact that durability cannot be achieved without a holistic approach. In its report, ACI Committee 201, Durability of Concrete, does not consider the cracking-durability relation, because cracking is not a part of the mission of this committee. Concrete cracking happens to be the responsibility of ACI Committee 224 which does not want to deal with durability. The root causes of many durability problems can be traced to this kind of reductionistic approach. By ignoring the cracking-durability relationship and by overemphasizing the relation between strength and durability, ACI 318 is not helping the cause of constructing durable and environmentally sustainable concrete structures. A paradigm shift to a holistic approach to control cracking in concrete structures is necessary to create a much closer working relationship between the structural designer, materials engineer, and construction personnel than exists today.

4. The belief that the durability of concrete can be controlled by controlling the *w/cm* is not correct because it is not the *w/cm* but the water content that is more important for the control of cracking. A reduction in the water content will bring about a corresponding reduction in the cement content at a given value of strength, which in turn, will reduce thermal contraction, autogenous shrinkage, and drying shrinkage of concrete. Therefore, to achieve durability, the standard practice for selecting concrete mixture proportions will have to undergo a fundamental change.

Note that a change in emphasis from the *w/cm* strength relation to the water content-durability relation will provide the needed incentive for a much closer control of the aggregate grading than is customary in the current construction practice. A substantial reduction in water requirement can be achieved by using a well-graded aggregate. Additional reductions in the water content of concrete mixtures can be realized by the use of midrange or high-range water-reducers, high-volume fly ash or slag cements, and coarse-ground portland cements.

5. To serve the goal of materials conservation, a paradigm shift is needed from prescriptive to performance-based standard specifications for materials. For example, ASTM C 1157-98a, Standard Performance Specification for Hydraulic Cement, describes a general-use cement (Type GU), which has maximum limits of 2900 psi (20 MPa) and 4350 psi (30 MPa) on the 3- and 7-day compressive strength, respectively. This specification also covers a moderate-heat cement (Type MH) with 2175 and 2900 psi (15 and 20 MPa) maximum strength at 3 days and 7 days, respectively. There are no restrictions on the composition and fineness of the cements; however, to satisfy the maximum on strength, the fineness and the C_3S content of modern portland cement will have to be controlled. This can be achieved by making a coarse-ground, low-C_3S portland cement or by blending normal portland cement with a high volume of fly ash or slag. Compared to the Type I/II cements conforming to ASTM C 150, the Type GU and Type MH cements produced according to ASTM C 1157-98a are expected to be less crack-prone.

Conclusions

In the 20th century, the concrete construction industry, driven primarily by the economics of higher and higher speeds of construction, increasingly used cements and concrete mixtures possessing high-early strength. Consequently, the field experience with many modern concrete structures shows that they are crack-prone and those exposed to severe environments tend to deteriorate much faster than their anticipated service life. To build environmentally sustainable concrete structures, it is clear that instead of strength, the 21st century concrete practice must be driven by considerations of durability. The transition can be achieved by major paradigm shifts in the selection of materials, mixture proportions, and construction practice as outlined in this article.

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Received and reviewed under Institute publication policies.

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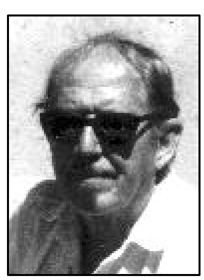

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