Crack-Free, High-Performance Concrete Structures

Start water curing at the proper time, and use fog sprays or other evaporation-retarding methods when plastic shrinkage is a concern

BY RICHARD MORIN, GILBERT HADDAD, AND PIERRE-CLAUDE AÏTCIN

Several recent papers and presentations tend to promote the myth that it is impossible to build virtually crack-free structures when using high-performance concrete. Several high-performance concrete structures do have a very poor appearance due to the presence of many cracks. But since the City of Montreal enforced its new specification on detailing, placing, and curing of high-performance concrete 3 years ago, virtually crack-free structures have been constructed. The high-performance concretes specified by the City of Montreal are air-entrained (5 to 8% air content), contain 7 to 8% silica fume, and have water-cementitious materials ratios (*w/cm*) of 0.35 or 0.37, producing design characteristic compressive strengths of 60 or 50 MPa (8700 or 7250 psi), respectively.

In any repair work or reconstruction that could have a high social cost, the City of Montreal has developed a three-level defense barrier against the corrosion of steel reinforcement. Their three level system consists of a:

- **Primary level**, using virtually crack-free, high-performance concrete;
- **Secondary level**, using galvanized steel rebars with sacrificial cells; and
- **Tertiary level**, systematically using corrosion inhibitors in all high-performance concrete.

When forecasted social costs are lower, Montreal uses only the secondary or tertiary defense level. Moreover, in the case of bridge and overpass decks, a membrane is placed between the concrete slab and the asphalt overlay.

A three-level defense barrier may be perceived as a "belt and suspenders" approach to fighting corrosion in an urban environment. But it is only necessary to take a hour-long taxi drive on the highways crossing Montreal to be convinced that it is a necessary and safe approach.

The only way to increase the durability of a reinforced concrete structure is to build it with crack-free concrete with a *w/cm* low enough to make it impervious. How low should the *w/cm* be? Presently, a value typically between 0.35 and 0.37 is a good compromise for producing durable concrete that can be easily placed and cured in the field. Circular columns can be built using 60 MPa (8700 psi) air-entrained concrete with a *w/cm* between 0.33 and 0.35 because plastic shrinkage is not a concern and the control of autogenous shrinkage is not so critical. As will be discussed later, the lower *w/cm* even helps to reduce thermal expansion before a peak temperature is reached.

Bridge decks and sidewalks are built with 50 MPa (7250 psi) air-entrained concrete having a 0.37 *w/cm* because plastic shrinkage and autogenous shrinkage are easier to control at the higher *w/cm*. Also, concrete with a slightly higher *w/cm* allows external curing water to penetrate more easily and to remain longer in the outer layer of the concrete.

The specified slump for these concretes is 180 ± 40 mm (7 ± 1.5 in.), but for sidewalks the slump is reduced to 80 to 100 mm (3 to 4 in.). Such mixtures are robust enough to be handled safely and efficiently by general contractors.

PORTLAND CEMENT HYDRATION

Based on the work of Powers,[1] Jensen and Hansen[2] schematically represented the hydration reaction (Fig. 1). This schematic clearly shows that full hydration cannot be achieved in a closed system, which is a system where there is neither loss nor gain of water from the outside, unless the water-cement ratio (*w/c*) is greater than or equal to 0.42. In such a system, which contains more water than necessary to hydrate the cement, a certain gas-filled porosity is always present, whatever the degree of hydration.

Jensen and Hansen have also shown that if an external source of water is available during the hydration of the cement, it is possible to obtain hydrated cement paste with no empty pores (except

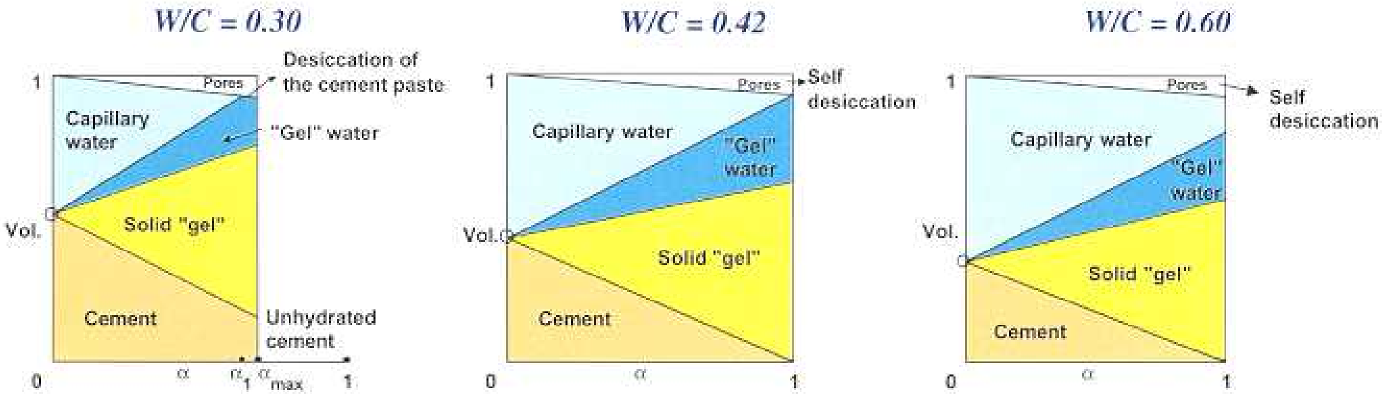

Fig. 1: Volume occupied by cement, water, and hydration products when portland cement hydrates in a closed system,[3] where α is the volume fraction of cement hydrated

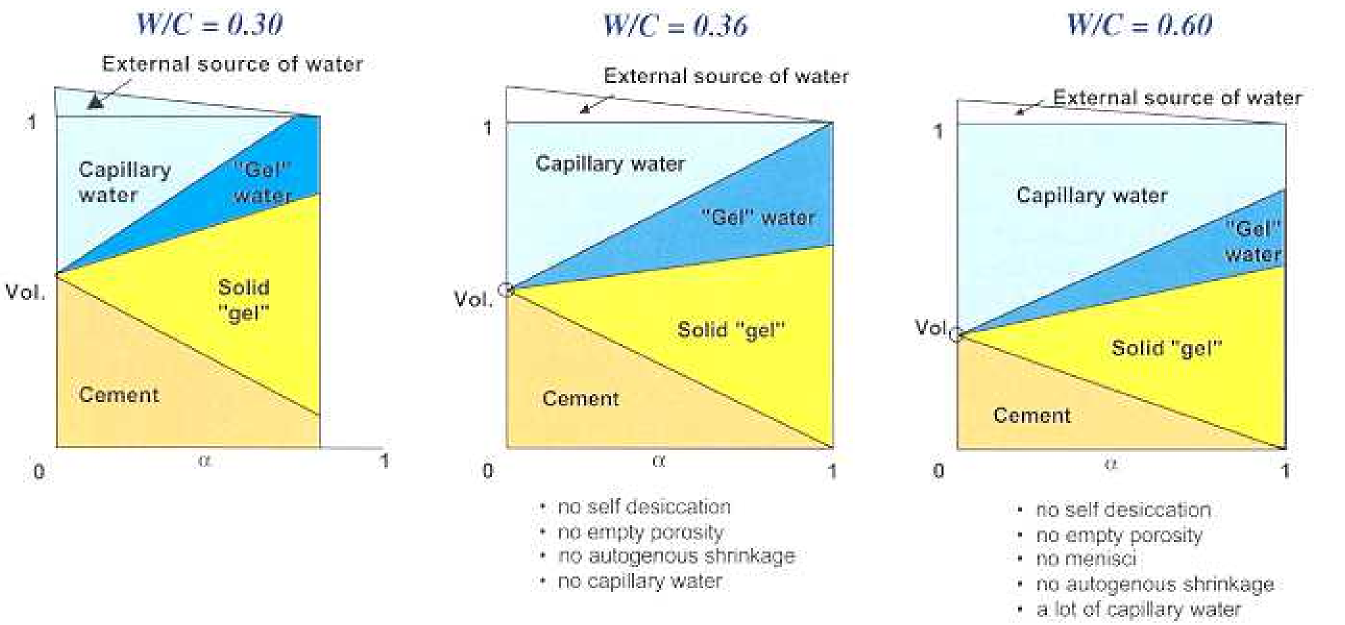

Fig. 2: Volume occupied by cement, water, and hydration products when portland cement hydrates while exposed to an external water source

for entrapped air bubbles) when w/c is less than or equal to 0.36 (Fig. 2).

From a durability point of view, however, a fully saturated hydrated paste isn't desirable because aggressive ions can invade the concrete due to the development of osmotic pressures. It is always prudent, therefore, to let some menisci develop within the concrete. When these menisci develop in very fine pores, they act as "air plugs" that drastically reduce concrete permeability and absorbtivity.

DIFFERENCES BETWEEN PLACING AND CURING OF HIGH-PERFORMANCE AND CONVENTIONAL CONCRETES

Bleeding

From a practical point of view, high-performance concrete is quite different than conventional concrete. High-performance concretes are essentially made by decreasing the amount of mixing water, rather than by drastically increasing the cement content.[3] Consequently, they don't bleed after they have been placed, which makes them very sensitive to plastic shrinkage. If high-performance concrete is placed in hot weather, or on a dry, windy day, concrete surfaces must be protected from drying at all times by maintaining a moist environment using fog sprays.

Fog spray systems used in nurseries are inexpensive, convenient, easy to install, and efficient. Evaporation reducers, which may be used for small surfaces, are usually alipathic alcohols that cover concrete with a monomolecular layer, reducing the evaporation of water from the concrete surface.

Curing membranes should not be used because they will prevent the penetration of curing water that is needed to control the development of autogenous shrinkage.

Autogenous shrinkage

Any concrete that is not water-cured during its early hardening develops some autogenous shrinkage, irrespective of its w/c. Autogenous shrinkage is a consequence of the chemical contraction developed during cement hydration.[4] The absolute volume of hydrated cement paste is smaller than the sum of the absolute volumes of the cement and water. When there is no source of external water available during cement hydration, as shown in Fig. 1, very fine pores develop within the concrete. These very fine pores drain the water from the larger capillaries and, as a result, the concrete dries without losing any weight. Water is simply moving from the coarse capillaries to the very fine pores created during cement hydration.

This internal drying results in the formation of menisci (air plugs), which create tensile stresses causing the concrete to shrink. Concretes having a high w/c (greater than 0.42) develop autogenous shrinkage that represents less than 10% of their drying shrinkage. As these concretes do not contain a very large amount of cement, they do not develop a very strong chemical contraction. And since they contain an ample amount of water in their large capillaries, their internal drying creates menisci only in those capillaries. Because the tensile stresses developed in these large capillaries are small, autogenous shrinkage is negligible in high w/c concretes. The higher the w/c, the lower the autogenous shrinkage, but the poorer the durability of the concrete.

This is not the case in low w/c concretes that contain more cement and less water, in which the network of capillaries is finer. As soon as cement starts to hydrate, these small capillaries dry very quickly, rapidly developing menisci, and creating large tensile stresses. These large tensile stresses develop at a time when the concrete microstructure is not strong enough to resist them, resulting in cracking of the concrete. However, if there is an external source of water to replenish the capillaries at the same rate the water is adsorbed by the very fine porosity (created by the chemical contraction), no menisci are formed. If no menisci are formed, there are no tensile stresses, no autogenous shrinkage, and no cracks.

As shown theoretically by Jensen and Hansen, a cement paste with a w/c of 0.36 and benefiting from an external source of water should not shrink at all, and when fully hydrated, will contain no capillary pores. Below this threshold w/c, some autogenous shrinkage will develop despite the presence of an external water source. The lower the w/c, the more severe the autogenous shrinkage. Tazawa and Miyazawa[5] have shown that an uncured cement paste having a w/c of 0.30 could develop, in the first few days after mixing, autogenous shrinkage equal to the drying shrinkage developed during weeks of drying.

The development of uncontrolled autogenous shrinkage explains why so many improperly cured, high-performance concrete structures exhibit so many cracks.

Shrinkage-reducing admixtures

Admixture companies have developed special admixtures that reduce autogenous and drying shrinkage. Both phenomena have the same cause: menisci development. These admixtures do not prevent the formation of menisci but do decrease the tensile stresses created by the menisci. This decrease is obtained by reducing the surface tension of the interstitial water, reducing the contact angle of the menisci, or both.[6]

In Eastern Canada, shrinkage-reducing admixtures are not used because they tend to destabilize the concrete's air system. When using present shrinkage-reducing admixtures, it is almost impossible to entrain very fine air bubbles with the spacing factor needed to make concrete resistant to freezing and thawing.

Other means of controlling autogenous shrinkage

Weber and Reinhardt[7] have suggested the use of saturated, lightweight coarse aggregate, and recently Jensen and Hansen[2] suggested the use of water-saturated, super-absorbent polymers as a source of internal water. Saturated, lightweight aggregates have been extensively used to increase the buoyancy of offshore platforms.

WHEN SHOULD CURING BEGIN AND END?

To avoid plastic shrinkage, fog spraying must start or evaporation reducers must be applied as soon as the concrete surface is finished. Since autogenous shrinkage is linked to cement hydration, water curing must start before the end of the dormant period, as soon as hydration starts. Since hydration also generates heat, a thermocouple or a maturimeter can be used to determine when to start water curing. As shown in Fig. 3, however, heat develops quite slowly at the beginning of hydration because portlandite precipitates at this time and adsorbs heat. It would be more appropriate to measure electrical conductivity using conductimeters that are now available. As Fig. 3 shows, concrete electrical conductivity decreases after the precipitation of portlandite and after the formation of the first calcium-silicate-hydrate bridges between cement particles (structuration threshold).[8]

If a concrete surface is allowed to dry before water curing is applied, menisci that form in the capillaries near the surface can prevent future ingress of water, thus defeating the purpose of wet curing. It is therefore essential to ensure a continuous presence of water from the surface to the interior of the concrete.

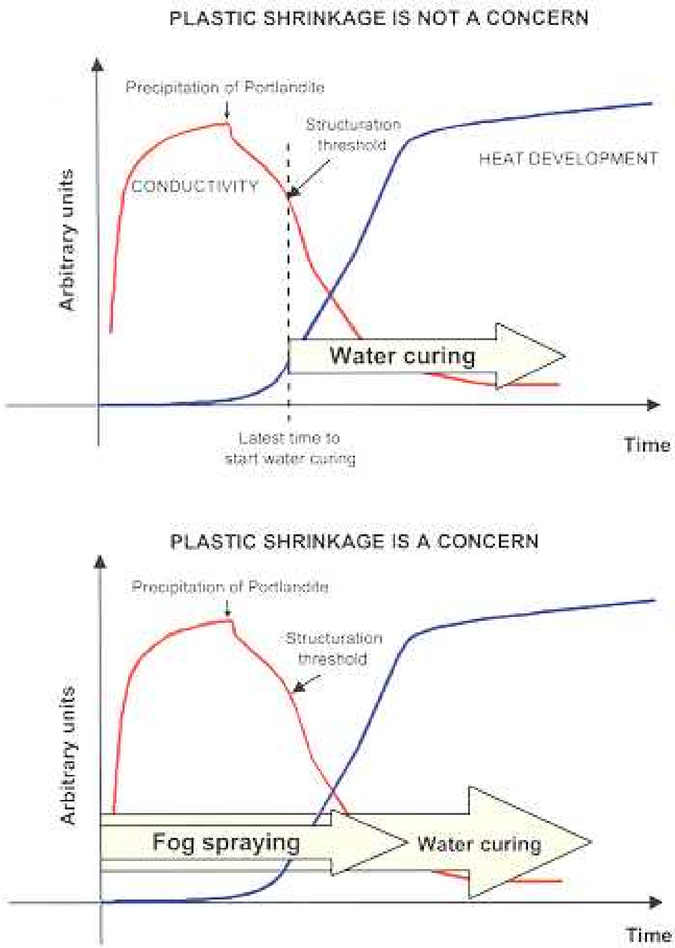

Fig. 3: The blue line shows that heat generation from the portland cement hydration reaction begins slowly. When the temperature starts to rise, water curing should begin. The red line shows electrical conductivity, which can be measured to help determine when water curing should start. When plastic shrinkage cracking is a concern, fog spraying is also needed

ENSURING VIRTUALLY CRACK-FREE CONCRETE

Ensuring crack-free, high-performance concrete is analogous to winning a race against cracking. In this relay race, the successive runners are: the designer, the specifier, the materials specialist, the constructor, and the curing subcontractor.

The designer must take into account the shape, size, and restraint conditions of the particular element, and allow volume changes to occur without creating tensile stresses that exceed the tensile strength of the concrete.

Materials must be selected and proportioned to minimize volume change while producing a concrete that is workable during placing, and with the strength and durability needed to perform well under service conditions.

Construction practices must ensure that concrete is placed at a proper consistency and thoroughly consolidated to its maximum density, to develop its maximum tensile strength.

Curing practices must ensure that water never escapes from the capillaries near the surface. This is done by maintaining a permanently humid surface and supplying enough external water to fill the pores created by volumetric contraction during hydration. Wet curing must be maintained until the concrete has developed a tensile strength high enough to resist shrinkage forces that could crack the concrete.

Autogenous shrinkage during curing is helpful in one case—that of concrete columns or piers. These are usually massive structural elements with a low surface-to-volume ratio that doesn't allow heat to escape quickly during curing. Surface-to-column ratio is inversely proportional to column diameter for circular columns, so columns with a larger diameter develop a higher peak temperature.

It must be emphasized that high-performance concrete does not develop more heat than 30 to 35 MPa (4500 to 5100 psi) concrete. This is because the heat generated by concrete is proportional to the amount of cement hydrating. Because high-performance concretes contain much less mixing water than conventional concretes and also contain superplasticizers that have a tendency to delay and smooth cement hydration, peak temperatures are almost the same as those reached with conventional structural concretes.[9]

During the temperature rise, concrete is expanding (thermal expansion) while autogenous shrinkage is reducing this expansion (Fig. 4). However, as high-performance concrete starts to cool after reaching its peak temperature, autogenous shrinkage and thermal contraction act together; this is why it is very important to lower and delay the peak temperature as much possible. It is also important to delay, as much as possible, the removal of forms for columns and piers in order to avoid adding the effect of thermal shock to thermal contraction and autogenous shrinkage. Thermal shock can cause surface cracking that permanently damages concrete covering the reinforcing steel.

Reducing the peak temperature (➡ ① on Fig. 5) requires lowering the initial concrete temperature by adding ice, cooling the plastic concrete with liquid nitrogen, or placing the concrete at night. Using a blended cement is another alternative. Using a high dosage of superplasticizer or a retarder (➡ ② on Fig. 5) helps to delay the peak temperatures.

FIELD APPLICATION

The reconstruction work done in 2000 and 2001 on the Décarie Highway in downtown Montreal illustrates a practical application of the concepts discussed.

Décarie Highway is an 8-km-long (5 mi), north-south highway with a traffic density of 150,000 vehicles per day. This highway is 15 m (49 ft) below the level of the adjacent streets and is crossed by 27 overpasses. It was built in 1966-67 using 30 MPa (4500 psi) air-entrained concrete. After 35 years of service in a very severe environment, the regularly repaired bridge decks, parapets, and sidewalks of the bridge decks were demolished and rebuilt.

The bridge decks and the tops of the walls have been rebuilt with a 0.37 *w/c*, air-entrained concrete using silica fume-blended cement (8% silica fume), except for one bridge deck that was rebuilt using a blended cement (20% Class F fly ash + 5% silica fume) and the same 0.37 *w/c*. The specified slump of all these concretes was 180 ± 40 mm (7 ± 1.5 in.) at the delivery point. The specified air content was 5 to 8%. The concrete producer was asked to provide results showing that with such an air content, the concrete had a spacing factor complying to CSA Standard A 23.1 (1995) for high-performance concrete, which means the average spacing factor was lower than 230 μm with no individual value greater than 260 μm.

Concrete was placed at night to ensure a smooth delivery schedule and to avoid the heat of the day.

COST OF WATER CURING

The reconstruction program also included some shotcrete repairs on the vertical walls along the highway. Since it was impossible to rely on fire hydrants to provide water along the 8-km-long (5 mi) project, a 100 mm (4 in.) temporary water line was laid on the side of the highway under repair and tapped for the necessary curing water.

Installation of the temporary water line cost $100,000 CAN ($60,000 U.S.). By accounting for all the water curing requirements and implementations, the contractor estimated the relative cost of water curing to be 1.5% of the total project cost.

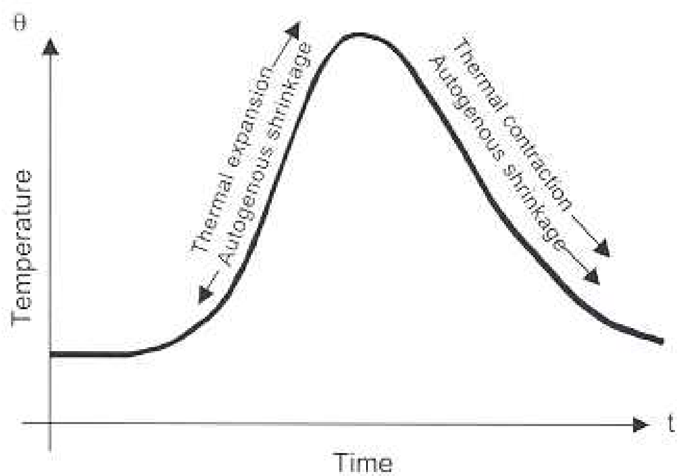

Fig. 4: During the early stages of curing a column or pier, autogenous shrinkage decreases thermal expansion. After the peak temperature is reached, however, autogenous shrinkage and thermal contraction act together in reducing volume

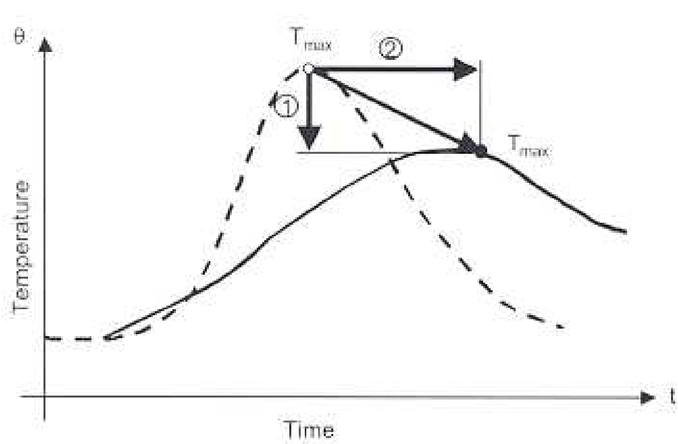

Fig. 5: Decreasing and delaying the peak temperature in columns and piers reduces the probability of cracking

For small projects in urban areas, where a fire hydrant is available on the same side of the street where work is to be done, the cost of water curing could be as little as 0.1% of the total project cost. When fire hydrants are on the other side of the street, so the water line must cross the street, the cost of water curing could represent between 0.1 and 0.5% of the total cost of the construction work. In any case, it is indeed a very low price to pay for virtually crack-free structures.

In 2000, only 12 hairline cracks were found on the 3.6 km (2.3 mi) tops of the walls that were rebuilt. All of these cracks were injected. In 2001, seven hairline cracks were found on the tops of the walls of about the same length.

Moreover, the last 10 bridge decks reconstructed in 2001 were carefully inspected and found to be absolutely crack free; the impervious membrane was then applied.

CRACK-FREE CONCRETE IS POSSIBLE

It is possible to build virtually crack-free, high-performance concrete structures. The race against cracking can be won if the design, materials, construction, and curing practices are oriented toward this overall objective, taking into account the well-known and identified causes of cracking. The science of concrete tells us when the most critical period for cracking occurs, and the different means we presently have to control cracking. It is up to us to transfer this knowledge to the field in order to build durable concrete structures.

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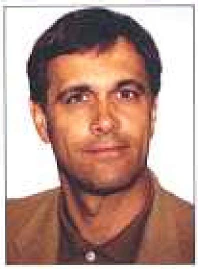
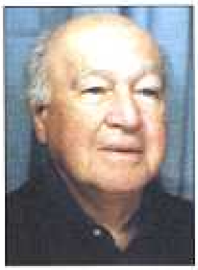
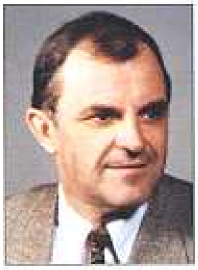


Richard Morin is Head of the Civil Section for the Laboratories of the City of Montreal, in charge of quality control for all civil construction works. He actively promotes the use of high-performance concrete, self-compacting concrete, and roller-compacted concrete.



Gilbert Haddad, FACI, is Technical Director, Concrete and Materials, for Terratech, a division of SNC-Lavalin, Inc. He is a member of ACI Committees 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete; 301, Specifications for Concrete; 306, Cold Weather Concreting; and 308, Curing Concrete.



Pierre-Claude Aïtcin, FACI, was a Professor of Civil Engineering at the Université de Sherbrooke. He has served as a member of ACI Committees 234, Silica Fume in Concrete; and 363, High-Strength Concrete. From 1990 to 1998, he was Scientific Director of Concrete Canada, the Network Centres of Excellence on High-Performance Concrete. He is the author of the book *High-Performance Concrete*.