Concrete in Canada: Fifty Years of Progress – Present Concerns

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Concrete in Canada
Fifty years of progress – Present concerns

by
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Concrete in Canada: Fifty Years of Progress – Present Concerns

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Abstract  Over the past 50 years, concrete in Canada has evolved from a simple robust material to a complex composite with impressive improvements in the material properties. Due to the development of water reducers and silica fume, the performance of concrete has improved from the conventional 30-MPa concrete before the CN Tower (1973) to the ultra-high strength 200-MPa concrete used in the Passerelle de Sherbrooke (1998). This paper retraces this evolution of concrete with a focus on both the technical improvements and the important structures built with these technologies. Recent progress in blended cements and PCE superplasticizers is also presented, along with the concerns and current challenges to ensure an optimized and safe use of these new concrete admixtures.

Keywords: Concrete science, water reducers, polysulfonate-based plasticizers, silica fume, high performance concrete, superplasticizers, poly-carboxylate ether plasticizers, ultra-high strength concrete, blended cement, sustainability.
1 Introduction

This paper presents the progress achieved in Canada in the production of concrete during the last fifty years and discusses some present concerns. This progress will be linked to improvements of the microstructure of the cement paste following the implementation of several technological breakthroughs. In each case, a spectacular Canadian concrete structure will illustrate the achievements realized from 1970 to 2000.

However, now that blended cements are commonly used to decrease the carbon footprint of concrete structures and a new family of superplasticizers has been introduced into the market, some concerns have arisen regarding the current adoption of these new technologies. If corrective actions are not taken soon at the level of the cementitious binder, some of the progress achieved during the last fifty years might be in jeopardy. Fortunately, the solutions to these concerns may not be difficult to implement. Let us start our journey by looking at concrete in Canada just before the construction of the CN Tower in 1973.

2 The lignosulfonate era

Before the construction of the CN Tower in 1973 (Figure 1), the strongest concrete generally available in Canada was 30 MPa air entrained concrete having a slump of 100 mm. This concrete was manufactured using lignosulfonate-based water reducers whose dispersant properties were limited. Usually, they permitted a 5% to 8% (in the best case) water reduction. These lignosulfonates were derived from a by-product of the pulp and paper industry. However, by carefully selecting the concrete ingredients for the CN Tower, John Bickley was able to produce a 50 MPa air entrained concrete using Type 20 cement (which would today be designated as MH or MS) with a $C_3A$ content of about 6%. The designer Frantz Knoll had demanded a Type 20 cement to reduce the heat development in the large members of the base of the Tower (1.2 m thick) and thus, to reduce thermal shrinkage. Inadvertently, the selection of this cement having a low $C_3A$ content was a key factor for the successful placement of the concrete of the CN Tower (Bickley 2012): a lower
content of C₃A active sites (which tend to bind directly with lignosulfonate polymers before being neutralized by the dissolved gypsum) resulted in a higher availability of the lignosulfonates to disperse cement particles.

During the autumn, as the ambient temperature was decreasing, Bickley decided to replace a part of the Type 20 cement by an equivalent amount of Type 10 cement in 10% increments so that the last 100 m of the tower were built using regular Type 10 cement. Until the construction of Burj Khalifa in Dubai, the CN Tower was the highest free-standing concrete structure in the world. The concrete of the CN Tower also survived the effects of time, with some maintenance such as the repair of ~1 m³ damaged concrete near the top of the tower performed a few years ago.

3 The polysulfonate era

At the end of the 1970s, the powerful dispersing properties of two polymers were discovered almost simultaneously in Japan (polynaphtalene sulfonate - PNS) and in Germany (polymelamine sulfonate – PMS). These two polymers had a well-defined structure, so that commercial superplasticizers only differed by their degree of polymerization, their degree of sulfonation and the percentage of sulfonated β-sites, depending on how well controlled their fabrication was and the purity of the naphthalene and melamine used to manufacture them.

In the beginning, these superplasticizers were primarily used to increase the slump of ordinary concrete. The first major Canadian structure in which a superplasticizer was extensively used was the Olympic Stadium in Montreal in 1984 (Figure 2). For its construction the superplasticizer was imported from Europe.

Soon, Handy Chemicals from La Prairie in Quebec became the world’s leading producer of PNS, with over 80% of sulfonated sites in the β-position and a degree of polymerization of about 10. Handy Chemicals PNS was extensively used in Canada and the USA. It was quickly realized that superplasticizers could be used, not only to increase concrete slump, but also simultaneously to decrease the w/c and to increase
the slump, opening the era of High Performance Concrete (HPC) in the construction industry.

However, some odd behaviours began to be observed when using a particular polysulfonate (PS) with different Portland cements. Some superplasticizer/cement combinations were able to keep almost the same slump for 1-½ hours, while in other cases the initial concrete slump was lost after 15 minutes. In some cases, a small variation in the superplasticizer dosage could lead to segregation or a significant slump loss, while in other cases a significant variation of the dosage could be tolerated without any significant effect on the slump (Nkinamubanzi et al. 2015). To describe these strange behaviours the following expressions were coined: compatible or incompatible combinations, and robust or non-robust combinations.

It was surprising that 2 cements meeting the same acceptance standards did not behave in the same way with the same superplasticizer. A great amount of research was carried out to try to understand these strange behaviours. Eventually it was found that the compatibility and the robustness of cement/superplasticizer combinations were essentially linked to the amount and reactivity of the C₃A, the fineness of the cement and the solubility of sulfates (Kim et al. 2000).

It was eventually determined that the experimental conditions under which the acceptance standards were defined were at the origin of this “false” problem. Currently, cement acceptance tests are carried out using a cement paste or mortar having a high w/c of about 0.50 without deflocculating the cement paste with superplasticizers. In such dilute mixtures, the water controls the rheology; the cement particles are too far away from each other to interact and to have a negative effect on the rheology of the mixture in the early stages of cement hydration. In such conditions, the characteristics of the cement, its fineness and its so-called “gypsum content” are usually optimized to control the initial setting time and the early strength, not its rheology during the first 1-½ hours.

However, when dealing with mixtures having a lower w/c and therefore denser particle packing, the hydrating particles do interfere with each other and play a key role on the rheology of the mixture. It is no longer the water content of the mixture that controls the
concrete rheology but rather the rapidity with which the crystals of ettringite and C-S-H are formed at the surface of the cement particles. Therefore, it may be either more or less easy to control the rheology of low w/c concretes. In some cases, the only choice one can make when designing a low w/c concrete that can maintain its slump for 1-½ hours is to change the cement. But in other cases, it is possible to decrease the w/c down to a value close to 0.20 when the cement is not very reactive (Levy et al. 1990).

4 The era of silica fume with polysulfonates

Silica fume is a by-product of the fabrication of silicon, ferrosilicon and zirconium. The silica fumes produced in Quebec started to be used in concrete in the early 1980s, and using them, it quickly became possible to make a 100 MPa concrete (Quinn 1988). The first high performance concrete with a compressive strength higher than 100 MPa was the concrete used to build experimental columns in the Lavalin Building in Montreal in 1984 (Figure 3). It was the strongest concrete made in Canada until 1998, when the Passerelle de Sherbrooke was built (Aiïctin et al. 1985; Aiïctin et al. 1990). At that time, silica fume was not blended with Portland cement, but added separately into the mixer.

The combination of a PNS, silica fume and slag was used by John Bickley to produce a 70 MPa (non-air entrained) concrete to build Scotia Plaza in 1987 (Figure 4), the first high-rise building in Canada made with a high performance concrete. Bickley used a cementitious blend composed of 65% Portland cement, 28% slag and 7% silica fume (Ryell and Bickley 1987).

In order to avoid undue delays in the delivery of the concrete, Bickley insisted on having a small dry batch mixing plant on site in spite of the fact that the daily volume of concrete was relatively small and that 2 or 3 nearby ready-mix plants could have provided a high quality concrete. The construction period lasted 2 years. During the summer, the aggregates and the cement were so hot that the use of ice was not sufficient to cool the concrete down below 25°C; it was necessary to use some liquid nitrogen to decrease the concrete temperature (Figure 4).
Because of the great advantage of adding silica fume to concrete, cement producers in Quebec very quickly started to offer a blended silica fume cement containing 7 to 8% silica fume. That new cement was named Type 10SF and using it with a superplasticizer in concrete having a low w/c (0.30 or less), it was not too difficult to produce 70 to 100 MPa concretes having a 200 mm slump (Aïtcin and Lessard 1984). This cement was specified in most of the projects involving the use of HPC in Western Canada.

5 The era of Type 10SF and polysulfonates

5.1 First HPC Bridges in Québec

In Québec, Type 10 SF cement was used with the PNS produced by Handy Chemicals to build a series of small bridges: in 1992 the Portneuf Bridge (140 m$^3$, Figure 5), in 1993 the Montée Saint-Rémi overpass (450 m$^3$, Figure 6) and in 1995 the Jacques Cartier Bridge (2000 m$^3$, Figure 7) in Sherbrooke (Mitchell et al. 1993; Coulombe and Ouellet 1995; Lachemi et al. 1996a, 1996b; Blais et al. 1996; Lachemi and Aïtcin 1997).

These HPC bridges were built during the late fall (Portneuf Bridge), full summer (Montée St-Rémi overpass) and from May to December for the Jacques Cartier Bridge.

These HPCs were placed with buckets to keep a low spacing factor in the air network and they were carefully water cured for 7 days to avoid early autogenous shrinkage.

5.2 Hibernia Gravity Base Structure (GBS)

The Hibernia Gravity Base Structure (Figure 8) was designed using HPC in order to resist the impact of huge icebergs (Hoff and Elimov 1995; Woodhead 1993, 1993b). However, during the construction of the GBS it was found necessary to decrease the unit weight of the HPC in order to increase its buoyancy because of an overweight of the mechanical part supported by the gravity base due to late heavy mechanical additions. Two solutions were considered: increasing the air content of the concrete (1% of additional air decreases the concrete unit weight by 25 kg/m$^3$) and 50% replacement of the coarse aggregate by an equivalent volume of coarse lightweight aggregate. After
a long discussion, it was decided to implement both solutions in case of later additions of new mechanical units: the air content was slightly increased and coarse lightweight aggregates were imported from Texas to replace 50% of the coarse aggregate that had been used to build the base of the platform. In order to avoid any slump loss due to the use of the coarse lightweight aggregate, the engineer in charge of the concreting operation for Mobil, George Hoff, decided to keep the coarse lightweight aggregates continuously saturated by sprinkling water on the piles 24 hours per day.

When the first compressive tests of this lighter concrete were obtained, everybody was surprised to see that in spite of a slight increase of the air content and the use of the lightweight aggregates, the compressive strength and elastic modulus of this new concrete had not decreased but rather had slightly increased. At that time, it was not realized that the saturated coarse aggregates provided some internal curing to the high performance concrete, reducing autogenous shrinkage and increasing the amount of hydrated cement.

5.3 The Confederation Bridge

The Confederation Bridge, constructed between 1993 and 1997, links Prince Edward Island with New Brunswick (Figure 9). It is 12.9 km long and entirely prefabricated using different types of HPC (Tadros et al. 1996; Aïtcin et al. 2016a). The only two local materials used to build the bridge were the water and the entrained air! The coarse aggregate and the cement came from Nova Scotia, and the sand and the superplasticizer came from Quebec.

Concrete formulation was a great challenge, especially for the construction of the ice shields that were exposed in winter to two daily severe freezing and thawing cycles in the tidal zone, and very severe ice abrasion conditions in the spring when the ice cover in the Northumberland Strait breaks up (Aïtcin et al. 2016a). To resist ice abrasion, it was decided to increase the compressive strength of the air entrained concrete by lowering its w/c as much as possible. By substituting 15% of the Portland cement with a fly ash (which came from Nova Scotia) and by lowering the w/b down to 0.25, it was
possible to produce a 5% air entrained concrete (after pumping) with an average compressive strength of 93 MPa (Aïtcin 2007).

After pumping, it was not possible to achieve a bubble spacing factor lower than the 220 µm required at that time by the standard CSA A23.1 to make this concrete freeze-thaw resistant. The Université de Sherbrooke and the Lafarge Research Centre in Montreal thus conducted a special research program to find the maximum value of the spacing factor that could provide for this HPC a freezing and thawing resistance equal to 500 cycles according to the ASTM C666 Standard (Procedure A).

Five different concretes were designed with the materials used to build the bridge. These concretes were produced with increasing air entraining agent dosages so that the resulting spacing factors varied from 180 to 450 µm. After carrying out the freezing and thawing tests, it was found that only the concrete with a spacing factor of 450 µm failed before reaching 500 cycles; concretes with a spacing factor lower than 350 µm passed the test without any problem. Therefore, it was decided that the concrete used to build the ice-shields should have a spacing factor lower than 350 µm. In order to obtain such a spacing factor, it was found necessary to produce a concrete with a 6% air content at the batching plant so that, after pumping, the concrete air content would have dropped to 5%, leading to a good spacing factor.

At the end of the 500 cycles, Marie-Christine Lanctôt from Lafarge decided to subject one specimen of each of the four remaining concrete mixtures to further freeze-thaw cycles. She found that the four specimens failed in inverse order to their spacing factor. The concrete with the 180 µm spacing factor only failed after 1956 cycles.

Following this research program and several others freezing and thawing tests performed at the Université de Sherbrooke and at the Université Laval in Quebec City, it was decided that the Canadian Standard on freezing and thawing for high performance concrete should be revised. The Committee for CSA A23.1 decided that the 220 µm maximum spacing factor had to be relaxed in the case of high performance concrete. Now, the standard CSA A23.1 specifies a maximum spacing factor of 270 µm for high performance concrete. However, if such a spacing factor cannot be achieved, it is
always possible to proceed with an ASTM C666 Procedure A test of 300 or 500 cycles depending on the severity of the winter conditions.

Presently, a student from Memorial University of Newfoundland is following the wear of the concrete of the ice-shields of the Confederation Bridge. According to his measurements, the life cycle of this concrete is 300 years.

5.4 Reactive Powder Concrete (RPC) – Ultra-High Strength Concrete (UHSC)

Trying to reach ever-higher compressive strengths in HPC, it was soon realized that the compressive strength of the coarse aggregate would become the weakest link when testing HPC in compression.

In 1994, in Berkeley, Pierre Richard and Marcel Cheyrezy, from the Bouygues Company in France, introduced a new concept of ultra-high strength concrete that they called at that time “Reactive Powder Concrete” (RPC) (Cheyerzy and Richard 1994). To surpass the strength limit of the coarse aggregates, that fraction of the material was simply removed from the mixture. Thus, RPC is in fact a fine mortar in terms of the grain size distribution, but when very fine steel fibres are added, it behaves like reinforced concrete: the thin steel fibres behave in RPC much like reinforcing steel bars in reinforced concrete (Aïtcin and Flatt 2015).

RPC paste has a very high packing density, its water/powder ratio being around 0.20 or even less. RPC must be cured differently from HPC: after 2 days of normal curing, it is further cured for 1 or 2 days at $90^0$C, which leads to a compressive strength of 200 MPa or more! By replacing the quartz powder by iron powder having the same grain size distribution, Richard and Cheyrezy were able to reach a compressive strength of 800 MPa! In that case, the very small iron particles acted as rigid inclusions that strengthened the RPC microstructure.

The first UHSC structure built in the world was the Passerelle de Sherbooke in 1998, as shown in Figure 10 (Bonneau et al. 1996; Aïtcin et al. 1998). Every 5 years, the resonance frequencies of the structure are measured to be compared to the theoretical values calculated by the designer Pierre Richard and to the experimental values.
measured one year after the inauguration. After 18 years of service, the structure is in excellent condition and behaves as expected (Aïtcin et al. 2014).

6 Concrete Canada: the Network of Centres of Excellence on High Performance Concrete

In 1980, the Federal Government launched the program of Networks of Centres of Excellence in order to create 14 pan-Canadian research networks by combining academics and people from the industry to increase the Canadian level of applied research and to accelerate technological transfers. Concrete Canada became one of these networks and it was subsidized to a level of about $10 million over a period of 9 years, which greatly contributed to the acceptance of HPC throughout Canada (Aïtcin et al. 1993; Bickley and Mitchell 2001).

It was during the existence of Concrete Canada that the Hibernia GBS and the Confederation Bridge were built with high performance concrete and that the Passerelle de Sherbrooke was erected using UHSC.

7 The Era of PCEs

While water reducers were initially cheap industrial by-products, the discovery of the very efficient dispersing properties of polysulfonates completely changed our vision of admixtures. More expensive synthetic polymers specifically made for concrete proved to be a cost-effective means of drastically improving some properties of concrete. Nowadays, synthetic chemical admixtures are used on a daily basis not only to disperse cement particles and/or lower the w/c, but also to modify viscosity, to reduce shrinkage, to form expansive products, to mitigate corrosion and to improve other concrete characteristics.

7.1 Pumping aids and viscosity modifiers

Initially, pumping aids were developed to facilitate the pumping of normal concrete and to cast concrete under water without risk of washing out or segregation. It was soon
realized that by adjusting the dosage of this new type of admixture it was possible to modify, almost at will, the viscosity of concrete and to produce what it is now called “self-compacting concrete” (SCC). SCC was first developed in Japan to decrease the cost of the concrete placement because of the high cost of construction workers and its use is now becoming very common all over the world. In most high-rise buildings currently under construction, the floors are constructed with a 30-to-40-MPa SCC pumped directly where needed. Subsequently, these floors are generally post-tensioned.

The construction of the Confederation Bridge represented one of the first major uses of a viscosity modifier in a concrete structure in Canada. SCC was primarily used to cast the base of the piles of the bridge under water using Welan gum, a microbial polysaccharide resulting from sugar fermentation with specific bacteria.

### 7.2 Polycarboxylate ether based polymer (PCE)

Around 1990, it was discovered that a new family of polymers could also be used to disperse cement particles very efficiently. This new family of superplasticizers is now known under the name of polyacrylate ethers or polycarboxylate ethers (PCEs). Most PCEs have been found to be more powerful than polysulfonates on a weight basis and to retard less the initial setting and hardening.

PCEs are composed of a “backbone” on which some lateral chains are grafted, as illustrated in Figure 11. They do not work mainly by electrostatic repulsion like polysulfonates, but rather primarily by steric repulsion (Aïtcin and Flatt 2015).

While PNS and PMS are well-defined polymers with simple configurations, this is not the case for PCEs, with possible variations of the backbone chain, the length and the nature of the lateral chains and the density of the grafted chains. Therefore, the term PCE covers a great range of polymers and it is not certain that we have yet found the most efficient combination of the fundamental parameters that control the efficiency of this new type of superplasticizer (Gelardi et al. 2015).
However, it was quickly realized that PCEs had a tendency to entrain coarse air bubbles with a diameter on the order of several hundreds of micrometres, a ten-fold increase when compared to the size of the entrained air bubbles obtained with a good air entraining agent. Roughly, it can be said that a good air-entraining admixture stabilizes air bubbles having a diameter of the same order of magnitude as cement particles (about several tens of micrometres) while a PCE entraps irregular air bubbles having the same size as sand grains (a few millimetres in diameter).

The effects of these additional coarse air bubbles are illustrated by two cases in which such bubbles can cause problems in Canada: industrial floors requiring a floor hardener and freeze-thaw resistant concretes.

### 7.2.1 Industrial floors with a floor hardener

Because of the use of polycarboxylates in the formulation of some water reducers, Canadian non-air entrained concretes may contain up to 2.5 to 3% of entrapped air (instead of the 1-1.5% measured before the use of PCE-based water reducers). Furthermore, it has been observed that when using a floor hardener on an industrial floor, delamination of the hardened surface is likely to occur after a few months of service if the concrete has an air content greater than 3%. Therefore, to build an industrial floor free of delamination, it is imperative to add an air detraining admixture to reduce the entrapped air content down to 1.5% and to eliminate the coarse air bubbles (several hundred micrometres in diameter) entrained by the polycarboxylate water reducer or superplasticizer.

### 7.2.2 Freeze-thaw resistant concrete

In the case of concrete fluidized with a PCE and used in freeze-thaw conditions, it is imperative to check the spacing factor of the air entrained concrete—and not just the total air content—because the 2 to 3% air content associated with the use of PCE drastically increases the spacing factor of the bubble network. Thus, a measured air content of about 6%—a value usually insuring a good spacing factor with lignosulfonates and PNS—may not be sufficient to protect the concrete against freeze-
thaw cycle because there is ~1.5% of entrapped air and ~1.5% of air entrained by the PCE, which leaves only about 3% of small protecting entrained air bubbles.

If the spacing factor is too high, the use of an air detraining agent before the introduction of the air entraining agent is not recommended: it lengthens the mixing period and the remnants of the air detraining agent interfere with the action of the air entraining agent. Therefore, when concrete has to be freeze-thaw resistant, the use of PCE superplasticizers require special attention compared PNS superplasticizers that do not entrain coarse air bubbles.

8 The era of blended cement

To lower the carbon footprint of concrete structures, the partial substitution of the “pure” Portland cement by an equivalent volume of cementitious material or filler is very efficient: each kilogram of cement that is replaced by a supplementary cementitious material results in a reduction of about 0.6 to 1 kg of CO$_2$ emitted during the fabrication of this cement. However, the substitution of a part of the Portland cement by a less reactive material generally results in a significant decrease in the initial strength of the concrete and, in the case of limestone filler concrete exposed to severe conditions (e.g., marine applications), the long-term durability can also be affected.

To achieve an acceptable early compressive strength in concrete made with blended cement, three approaches can be used:

- a chemical approach consisting of increasing the C$_3$S and C$_3$A contents of the clinker used to make the blended cement;
- a physical approach consisting of grinding the blended cement finer than a usual Portland cement to make it more reactive; or,
- a physical approach consisting of increasing the packing density of the cementitious paste by using a superplasticizer.

Let us review these different solutions.
8.1 Increasing the C$_3$S content of the clinker

To increase the C$_3$S content of the clinker—the cement component responsible for concrete early strength—it is necessary to increase the lime content of the raw feed, which means an increase in the amount of CO$_2$ emitted during the manufacture of the clinker. This increase in CO$_2$ emissions partially counteracts the reduced CO$_2$ emitted during the production of the blended cement. This is not a fully sustainable solution.

8.2 Increasing the C$_3$A content of the clinker

C$_3$A plays an important role in the very early strength gain of a cement paste through the rapid formation of ettringite. As ettringite is “poison” to concrete from a rheological and durability point of view, the use of a clinker rich in C$_3$A means more placement problems and more problems related to delayed ettringite formation, or secondary ettringite formation within the concrete if external SO$_4^{2-}$ ions penetrate into the hardened concrete. This solution generally decreases the durability of concrete and thus, it is not a sustainable solution.

8.3 Grinding the blended cement finer

The grinding of cement consumes electrical energy; when this electrical energy is produced from a fossil fuel, part of the benefit of blending the cement is lost by this additional CO$_2$ emission. This is not by itself a completely sustainable solution.

8.4 Increasing the packing factor of the cementitious paste

In our opinion, increasing the packing factor of the cementitious paste is the most sustainable approach to increasing the early strength gain of the concrete. Since the cementitious particles are now much closer to each other there is no need to develop as much “glue” to create strong inter-particle bonds. Moreover, while the C-S-H is creating the first inter-particle bonds, the non-reacted cores of the cementitious or filler particles contribute to the concrete early strength by acting as strong inclusions that transfer stresses, leading to acceptable early strength of blended-cement concrete.
The effect of increasing the packing density is schematized in Figure 12 which presents a simple cement paste model showing (a) a cubic arrangement of cement particles for conventional cement paste, (b) the replacement of 12.5% of cement particles by a SCM, and (c) a body-centred cubic model with 50% of cement particles replaced by a SCM (Aïtcin et al. 2016b).

8.5 Combining the last two approaches

At the present time, it would appear that a combination of grinding the supplementary cementitious materials a bit finer to make them more reactive and decreasing the w/b of the cementitious paste is the most efficient and sustainable solution to increase the early strength of blended cement.

9 Durability of modern concrete

The durability of concrete is closely linked to its capacity to prevent movement of water and aggressive ions in its porous network. Thus, increasing the density of concrete and reducing its connected porosity are key means of improving durability. This became possible with the availability of water reducers and superplastizers, which allowed a reduction of the water-to-cement ratio leading to closer packing of the cement grains and to denser hydrates. Eventually, the very dense UHPC reached new heights in terms of durability, as the cement paste became almost impenetrable by water and ions. Nevertheless, although PCE provide very beneficial reduction of w/c, special care should be given to the entrained-air network in order to ensure high durability to freeze-thaw cycles.

The incorporation of very fine particles of silica fume also contributes significantly to the densification of the cementitious matrix, in particular in the interfacial transition zone – a layer of higher porosity around the large aggregates where the ions penetrate and diffuse more rapidly (Scrivener et al. 2004; Ollivier et al. 1995). Similarly, the use of blended cement provides increased durability to concrete, as the pozzolanic reaction of supplementary cementitious materials refines the pore structure, densify the hydrate structure and influences the chemistry of hydrates – which may affect the capacity to
bind aggressive ions (Florea & Brouwers 2012; Beaudoin et al. 1990). Furthermore, the pursuit of early-strength development with blended cement provides a new opportunity to improve durability by increasing packing density with finer particles and lower w/b. In those systems, the anhydrous grains stand closer to each other, the hydrates fill the space more rapidly and densely, and the relative amount of hydrates is reduced – the replacement of hydrates by anhydrous particles is beneficial because the latter are stronger and less porous (Wilson et al. 2017).

10 Conclusion

Over the last 50 years, the Canadian concrete industry took advantage of some technological breakthroughs in the areas of admixtures and supplementary cementitious materials to improve the performance of concrete with respect to both the strength and the durability. Several spectacular Canadian structures built during that period testify to this progress: the CN Tower, the Scotia Plaza, the Hibernia Gravity Base Structure, the Confederation Bridge and the Passerelle de Sherbrooke, among many others.

The concrete industry is now into a new era with blended cement and new types of admixtures (such as polycarboxylate-based superplasticizers). In this context, our vision of concrete development, production and placement methods should evolve rapidly from the accepted knowledge of the last 50 years. The microstructure of the cementitious paste is being greatly modified with blended cement and the mode of action of PCEs is completely different from that of PNS. Thus, mastering of the use of blended cement and PCEs represents a new challenge for the concrete community and this challenge has to be handled as soon as possible!

But who will take care of this new challenge: the cement industry, the concrete industry, the admixture industry, researchers? The authors are convinced that a coordinated effort amongst these four entities has to be pursued for the benefit of the construction industry.
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Figure 11. Typical comb-like structure of a PCE polymer (courtesy of R. Flatt)
Figure 12. Schematic representation of different cementitious systems: (a) a cubic arrangement of cement particles for cement paste with a water-to-binder ratio w/b=0.87, (b) the replacement of 12.5% of cement particles by SCM with the same w/b, and (c) a body-centred cubic model with 50% of cement particles replaced by SCM, representing a w/b =0.27 (figure by W. Wilson)
315x101mm (300 x 300 DPI)