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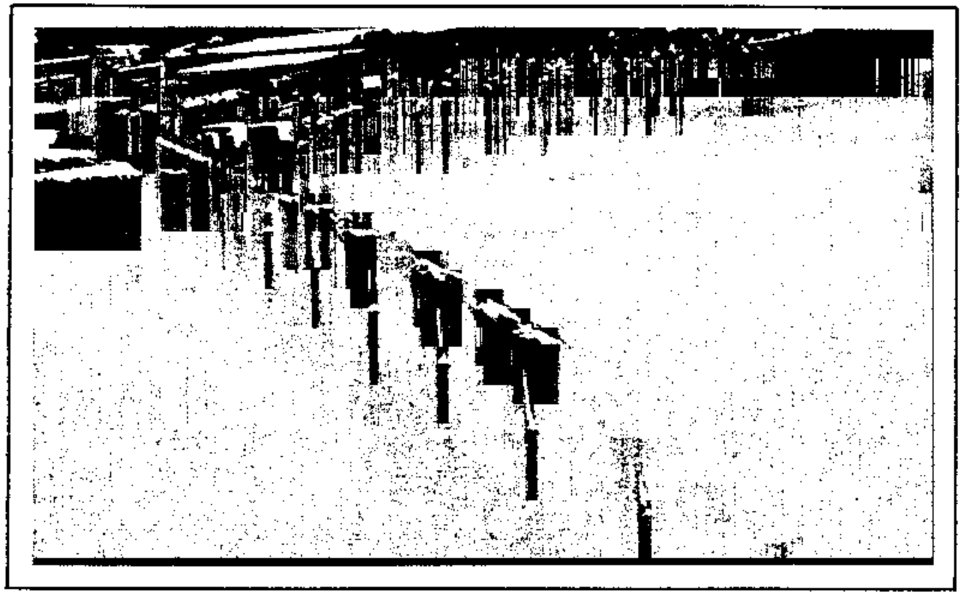

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Editor

The Art and Science of High-performance Concrete

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Synopsis: The development of high-performance concrete is a giant step in making concrete a high-tech material with enhanced characteristics and durability. High-performance concrete is an engineered concrete obtained through a careful selection and proportioning of its constituents. The concrete is made with the same basic ingredients but has a totally different microstructure than ordinary concrete.

The low water/binder ratio of high-performance concrete, that is its universal characteristic, results in a very dense microstructure having a very fine and more or less well connected capillary system. These two microstructural features translate into different macroscale properties in terms of mechanical strength, durability and shrinkage, which makes high-performance concrete quite a different material than ordinary concrete.

High-performance concrete's dense microstructure make the migration of aggressive ions more difficult, consequently high-performance concrete are more durable when exposed to aggressive environmental conditions. However, the same microstructural characteristic can also result in autogeneous shrinkage due to self desiccation. This problem can be resolved by proper water-curing.

Keywords: High-performance concrete, durability, microstructure, low water/binder ratio, autogenous shrinkage, self-desiccation, total shrinkage, permeability, water-curing.

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INTRODUCTION

When Professor Mehta asked me to present a paper on high-performance concrete in tribute to Mario Collepardi, my first reaction was: what could I write about high-performance concrete that was not already known? It occurred to me that we are living in a world that is inundated with information and that too much information is as bad as none at all. It is increasingly difficult to sort out the good information from the bad, to find that pearl of new information hidden under the ocean of words published to promote scientific careers.

It is almost a cliché to say that concrete is the most widely used material, outstripped only by drinking water and that, only if looked at cumulatively over many years. On the other hand, it is also commonly said that no material is more misused, either through ignorance, unconsciously, or deliberately. Why? Because the ingredients of good and bad concrete are identical: only their proportions differ and because concrete technology is apparently so simple that 20 years of doing it right or wrong is equated to 20 years of experience. In fact, one of the major challenges facing us is that concrete involves very simple technology and very complex science. We are grateful to you, Mario, for having shed some revealing light on a number of its aspects.

The recent developments in the field of high-performance concrete have been a giant step in making concrete a high-tech material with enhanced characteristics and durability. They have even led to it being a more ecological material in the sense that the component admixtures, aggregates, and water are fully used to produce a material with a longer life cycle. Be that as it may, we know that concrete will never be a durable material when measured against a geological time frame. Any concrete, if we look far enough into the future, will end its life cycle as limestone, clay, and silica sand, which are the most stable mineral forms of calcium, silica, iron, and aluminum in the Earth's environment. Therefore, all we can do is to extend the life cycle of this artificial rock as much as possible.

WHAT IS HIGH-PERFORMANCE CONCRETE IN 1997?

The concrete that was known as high-strength concrete in the late seventies is now referred to as high-performance concrete because it has been found to be much more than simply stronger: it displays enhanced performance in such areas as durability and abrasion resistance. Although widely used, the expression "high-performance concrete" is very often criticized as being too vague, even as having no meaning at all. And what's more, there is no simple test for measuring the performance of concrete.

High-performance concrete can be defined as an engineered concrete in which one or more specific characteristics have been enhanced through the selection and proportioning of its constituents. This definition is admittedly vague, but it has the advantage of indicating that there is no one single type of high-performance concrete, but rather a family of new types of high-tech concrete whose properties can be tailored to specific industrial needs.

While we could devise a slightly more technically rigorous definition of high-performance concrete that would still be quite simple, such as it being a concrete with a low water/cement ratio (or rather a low water/binder ratio) in the 0.30 to 0.35 range. But this would still be inexact because high-performance concretes with a water/binder ratio in the 0.20 to 0.30 range have been used.

This definition can be technically refined by stating that a high-performance concrete is a concrete in which autogeneous shrinkage can develop due to a phenomenon called self-desiccation when the concrete is not water cured. The technical jargon, however, does little to clarify things since very few people are familiar with the terms self-desiccation and autogeneous shrinkage.

Since there is no single best definition for the material that is called high-performance concrete, I prefer to define it as a low water/binder concrete with an optimized aggregate/binder ratio to control its dimensional stability and which receive an adequate water curing.

WATER/CEMENT OR WATER/BINDER RATIO

Both expressions were deliberately used above, either singly or together, to reflect the fact that the cementitious component of high-performance concrete can be cement alone or any combination of cement with supplementary cementitious materials, such as: slag, fly ash, silica fume, metakaolin, rice husk ash, and fillers such as limestone. Ternary systems are increasingly used to take advantage of the synergy of supplementary cementitious materials to improve concrete properties in the fresh and hardened states and to make high-performance concrete more economical.

In spite of the fact that most high-performance concrete mixtures contain at least one supplementary cementitious material, which should favor the use of the more general expression water/binder ratio, the water/binder and water/cement ratios should be alongside one another. This is because most of the supplementary cementitious materials that go into high-performance concrete are not as reactive as portland cement, which means that most of the early properties of high-performance concrete can be linked to its water/cement ratio while its long-term properties are rather linked to its water/binder ratio.

It must be emphasized that the development of high-performance concrete technology has taught us what Feret expressed in his original formula giving the compressive strength of a concrete mixture: concrete compressive strength is closely related to the density of the hardened matrix. High-performance concrete has also taught us that the coarse aggregate can be the weakest link in concrete when the strength of hydrated cement paste is drastically increased by lowering the water/binder ratio. In such cases, concrete failure can start to develop within the coarse aggregate itself. As a consequence, there can be exceptions to the water/binder ratio law when dealing with high-performance concrete. In some areas, decreasing the water/binder ratio below a certain level is not practical because the strength of the high-performance concrete will not significantly exceed the aggregate's compressive strength. When the concrete's compressive strength is limited by the coarse aggregate, the only way to get higher strength is to use a stronger aggregate.

HIGH-PERFORMANCE CONCRETE: A COMPOSITE MATERIAL

Standard concrete can be characterized solely by its compressive strength because that can be directly linked to the cement paste's water/cement ratio, which still is the best indicator of paste porosity. Most of concrete's useful mechanical characteristics can be linked to concrete compressive strength with simple empirical formulas. This is the case with elastic modulus and the modulus of rupture (flexural strength), because the hydrated cement paste and the transition zone around coarse-aggregate particles constitute the weakest links in concrete. The aggregate component (especially the coarse aggregate) contributes little to the mechanical properties of ordinary concrete. As the strength of the hydrated cement paste increases in high-performance concrete, the transition zone between the coarse aggregate and the hydrated cement paste practically disappears. Since there is proper stress transfer under these conditions, high-performance concrete behaves like a true composite material. This is clearly illustrated in Fig. 1 from Baalbaki et al. (1), which compares the shapes of the hysteresis curves of high-performance concretes that are loaded and unloaded to that of their constituent coarse aggregate.

To express this in another way, the elastic modulus (i.e., the rigidity) of a high-performance concrete can be tailored to the specific need of the designer simply by selecting the appropriate coarse aggregate. Nilsen and Aïtcin (2) have been able to make 100-MPa concrete with elastic moduli varying from 27 to 60 MPa. Therefore, the

$$E'_c = \psi(f'_c)$$

relationships found in most codes have no predictive value with respect to high-performance concrete. Recently, however, Baalbaki (3) proposed two simple models that take into account the coarse aggregate's elastic characteristics so that the elastic modulus of any type of concrete can be calculated. His two models are presented in Fig. 2(a) and 2(b); the correlation obtained with the results already presented in the technical literature and are shown in Fig. 3. This figure gives the high predictive value of what Baalbaki calls his model I (mortar and coarse aggregate).

MAKING HIGH-PERFORMANCE CONCRETE

High-performance concrete can not be made by a casual approach. Each ingredient must be carefully selected and checked, because their individual characteristics significantly affect the properties of the final product. What we have said about the coarse aggregate also holds true for the cement, the supplementary cementitious materials, the sand, the superplasticizer, and the other admixtures.

Once the materials have been carefully selected, their proportions must also be determined meticulously. Particular attention must be paid to water content. Even seemingly insignificant volumes of water present in the aggregates or admixtures must be accounted for. Increasing the performance of concrete is so difficult and expensive; ruining it is as easy as including a little too much water.

Compressive strengths of from 50 to 75 MPa can usually be achieved fairly easily with most cements. On the other hand, experience has shown that the problem is controlling the rheology long enough to place a 200-mm-slump high-performance concrete an hour or more after mixing, due to the potential for incompability between the cement and superplasticizer.

TEMPERATURE RISE IN HIGH-PERFORMANCE CONCRETE

There is a belief firmly rooted in the concrete community that the heat developed in any concrete is a direct function of its cement content. This does not always hold true because portland cement by itself does not develop heat. Since portland cement develops heat only as a result of hydration, it should be said that the heat developed in a concrete is a direct function of the amount of cement hydrating and is not a direct function of the total amount of constituent cement.

The amount of cement hydrating during the first hours can be limited by the amount of cement in the mixture, such as in mass concrete. Cement hydration can also be affected by the use of a retarder, a high dosage of superplasticizer, or insufficient water to hydrate all the cement in the mixture. The latter describes the usual situation in high-performance concrete.

The temperature variation in a concrete due to this development of heat is usually positive (temperature rise), but it can be negative (temperature decrease in winter conditions) or it can be almost zero when the amount of heat generated within the concrete equals the heat losses through the surface of the concrete and through the forms.

Consequently, it is not absolutely true that high-performance concrete will develop greater heat of hydration than plain concrete. In fact, it can be totally false in the case of a particular structural element or under specific conditions. This has been confirmed by the work of Cook et al. (4), in which three similar columns measuring 1 × 1 × 2.4 m were cast with three different concretes with compressive strengths of 30, 80, and 120 MPa. The temperature of the concrete was monitored at several places within the columns. Fig. 4 shows the temperature rise at the center of each column, where the temperature was always the highest, as should be expected. This figure reveals nearly identical temperature rises in the three columns, despite the fact that the cement content varied in the three mixtures from 355 kg/m^3 for the 30-MPa concrete up to 540 kg/m^3 for the 120-MPa concrete.

Faced with such results, many engineers are surprised that a plain concrete can develop as much heat and temperature rise as high-performance concrete, because it goes against the longstanding misconception myth that the temperature rise in a concrete is directly proportional to the cement content.

Indeed, Fig. 4 shows that the 120-MPa concrete evidenced the lowest temperature rise since less cement hydrated in it during the first 30 hours. 1) Less cement had the chance to hydrate in the 120-MPa concrete: 2) less water was used to make the concrete, 3) because more superplasticizer was used (it is well-known that naphthalene superplasticizers act as retarders when used at high dosages), 3) because a retarder was used so the temperature-rise curve reflects the delay in the start of hydration , and 4) because the hydrates formed in the early stage of hydration in high-performance concrete are so compact that hydration reaction proceeds much more slowly by diffusion of water through the hydrates rather than through the dissolution-precipitation process that occurs when there is plenty of water in the mixture.

Moreover, as shown by Lachemi et al. (5), temperature rise will not be uniform throughout a structure, nor is the maximum temperature reached almost at the same time because the temperature rise depends not only on the amount of heat developed within the concrete, but also on the thermodynamic conditions at the boundaries. Of course, the more massive the structural element, the higher the temperature rise; the higher the ratio of exposed surface to the volume of concrete, the lower the temperature rise. A temperature decrease can be observed under severe winter conditions. as shown by Lessard et al. (6) in a report on the reconstruction of the sidewalk entrance of a McDonald's restaurant in Sherbrooke and by Lessard et al. (7) during the construction of the Porteneuf Bridge.

Using finite-element modeling, Lachemi et al. (8) studied the influence of the ambient temperature and concrete temperature on the temperature rise in some structural elements they monitored during a field experiment. Their main findings were that the highest temperature recorded was obtained at the highest ambient temperature when a hot concrete mixture is cast, but the more critical conditions for the development of high thermal gradients are achieved when a hot concrete, cast on a cold day, cools as shown in Table 1.

CONCRETE SHRINKAGE

If water curing is essential to develop the potential strength of cement in plain concrete, early water curing is crucial for high-performance concrete in order to avoid the rapid development of autogeneous shrinkage and to control concrete dimensional stability, as explained below.

Cement paste hydration is accompanied by an absolute volume contraction that creates a very fine pore network within the hydrated cement paste. This network drains water from coarse capillaries, which start to dry out if no external water is supplied. Therefore, if no drying is occurring and if no external water is added during curing, the coarse capillaries will be empty of water as hydration progresses, just as though the concrete was drying. This phenomenon is called self-desiccation. The difference between drying and self-desiccation is that, when concrete dries, water evaporates to the atmosphere, while during self-desiccation, water stays within concrete (it only migrates towards the very fine pores created by the volumetric contraction of the cement paste) (Aïtcin et al. 1997).

In ordinary concrete with a high water/cement ratio greater than 0.50, for example, there is little cement and more water than is required to fully hydrate the cement particles present. A large amount of this water is contained in well-connected large capillaries so that, in ordinary concrete, the menisci essentially created by self-desiccation appear in large capillaries so that they generate only very low tensile stresses. This means that the hydrated cement paste does not shrink at all when self-desiccation develops.

In the case of high-performance concrete with a water/binder ratio of 0.30 or less, significantly more cement and less mixing water have been used, so that the capillary network that developed within the fresh paste is essentially composed of fine capillaries. When self-desiccation starts to develop as soon as hydration begins, the menisci rapidly develop in small capillaries if no external water is added. Since many cement grains start to hydrate simultaneously in high-performance concrete, the drying of very fine capillaries, can generate high tensile stresses that shrink the hydrated cement paste. This early shrinkage is referred to as autogeneous shrinkage. Of course, autogeneous shrinkage is as large as the drying shrinkage observed in ordinary concrete when these two types of drying develop in capillaries of the same diameter.

But, if there is an external supply of water, the capillaries do not dry out as long as they are connected to this external source of water. The result is that no menisci, no tensile stress, and no autogeneous shrinkage develops within the high-performance concrete.

Therefore, an essential difference between ordinary concrete and high-performance concrete is that ordinary concrete exhibits no autogeneous shrinkage whether it is water-cured or not, whereas high-performance concrete can experience significant autogeneous shrinkage if it is not water-cured during the hydration process. Autogeneous shrinkage will not develop in high-performance concrete if the capillaries are interconnected and have access to external water. When the continuity of the capillary system is broken, then and only then, will autogeneous shrinkage start to develop within the hydrated cement paste of a high-performance concrete.

Drying shrinkage of the hydrated cement paste begins at the surface of the concrete and progresses more or less rapidly through concrete depending on the relative humidity of the ambient air and the size of capillaries. Drying in ordinary concrete is therefore rapid because the capillary network is well-connected and contains large capillaries.

Drying shrinkage in high-performance concrete is slow because the capillaries are very fine and soon get disconnected. Another major difference between drying shrinkage and autogeneous shrinkage is that drying shrinkage develop from the surface inwards, while autogeneous shrinkage is isotropic insofar as the cement particles and water are well dispersed within the concrete.

Table 2 highlights the main difference between ordinary and high-performance concrete with respect to their shrinkage behavior. The cement paste of ordinary concrete exhibits large drying shrinkage progressing from the surface inwards, whereas high-performance concrete cement paste shows low drying shrinkage, but potentially high isotropic autogeneous shrinkage when not water cured. This difference in the shrinkage behavior of the cement paste has very important consequences for concrete curing.

Although the shrinkage of the hydrated cement paste is a very important parameter with respect to concrete volumetric stability, it is not the only one: the amount of aggregate and, more specifically, the amount of coarse aggregate is a key parameter. Too often it is forgetten that the aggregates do more than simply act as fillers concrete. In fact, they actively participate in the volumetric stability of concrete when they restrain the shrinkage of the hydrated cement paste: concrete shrinkage is always much lower than that of a cement paste with the same water/binder ratio.

It is common knowledge that concrete shrinkage can be easily reduced by increasing the coarse-aggregate content; the shrinkage of the hydrated cement paste stays the same, but it is more restrained, so that the volumetric stability of the concrete is increased. Restraining the shrinkage of the hydrated cement paste by modifying the coarse-aggregate skeleton may or may not produce a network of microcracks, depending on the intensity of the tensile stresses developed by this process with respect to the tensile strength of the hydrated cement paste.

CURING OF HIGH-PERFORMANCE CONCRETE TO MINIMIZE SHRINKAGE

High-performance concrete must be cured quite differently from ordinary concrete because of the difference in shrinkage behavior described above. If HPC is not water-cured immediately following placement or finishing, it is prone to develop severe plastic shrinkage because it is not protected by bleed water, and later on develops severe autogeneous shrinkage due to rapid hydration reaction. While curing membranes provide adequate protection for ordinary concrete (which is not subject to autogeneous shrinkage), they can only help prevent the development of plastic shrinkage in high-performance concrete. They have no value in inhibiting autogeneous shrinkage. Therefore, the most critical curing period for any HPC runs from placement or finishing up to 2 or 3 days later. During this time, the most critical period is usually from 12 to 36 hours. In fact, the short time during which efficient water curing must be applied to HPC can be considered a significant advantage over ordinary concrete. Those who specify and use HPC must be aware of the dramatic consequences of skipping early water curing. Initiating water curing after 24 hours is too late because, most of the time, a great deal of autogeneous shrinkage will already have occurred and, by this time, the microstructure will already be so compact that any external water will have little chance of penetrating very deep into the concrete.

Water ponding, whenever possible, or fogging are the best ways to cure HPC; one of these two methods must be applied as soon as possible immediately following placement or finishing. A curing compound can be applied temporarily to prevent the development of plastic shrinkage, but the curing membrane must be removed before hydration starts. If, for any reason, water ponding or fogging cannot be implemented for 7 days, then the concrete surface should be covered with wet burlap. The burlap must be kept constantly wet with a soaker hose and protected from drying by a polyethylene sheet in order to insure that, at no time during the curing period, that the concrete is allowed to dry and experience any autogeneous shrinkage.

The water curing can be stopped after 7 days because most of the cement at the surface of concrete will have hydrated and any further water curing will have little effect on the development of autogeneous shrinkage due to compactness of the HPC microstructure. Moreover, after 7 days of water curing, HPC experiences little drying shrinkage due to the compactness of its microstructure and because autogeneous shrinkage will have already dried out the coarse capillaries pores. Even then, the best thing to do is to paint HPC with an sealing agent so that the last remaining drops of water in the concrete can hydrate more cement particles. There is no real advantage to painting a very porous concrete since it is impossible to obtain an absolutely impermeable coating; painting HPC, however, is easier and more effective.

Partial replacement of coarse aggregate by an equivalent volume of saturated lightweight aggregate has been used in an attempt to counteract autogeneous shrinkage internally. The saturated lightweight aggregate particles act as a small water reservoirs throughout the mass of concrete that can be emptied by the very fine pores created by hydration reaction. Therefore, the water in the lightweight aggregate particles is drained along with that contained in the HPC's fine capillaries. The menisci developed within the cement paste are not as small, which means lower tensile stress and less autogeneous shrinkage.

DURABILITY OF HIGH-PERFORMANCE CONCRETE

The durability of a material in a particular environment can only be established by time. This makes it difficult to precisely predict the durability of high-performance concrete since we do not have a track record for HPC exposed to very harsh environments for more than 5 to 10 years, except perhaps for some North Sea offshore platforms. It must be remembered that the first uses of high strength concrete in the late sixties and early seventies were indoor applications, mainly in columns in high-rise buildings, which is not a particularly severe environment.

Outdoor applications of high-performance concrete only date from the late eighties and early nineties, which means that not enough time has gone by to properly assess the real service life of any high-performance concrete structures under outdoor conditions.

Based on years of experience with ordinary concrete, we can safely assume that high-performance concrete is more durable than ordinary concrete. Indeed, the experience gained with ordinary concrete has taught us that concrete durability is mainly governed by concrete impermeability and the harshness of the environment.

It is easy to assess the harshness of any environment with respect to high-performance concrete because hydrated cement paste is essentially a porous material that contains some freezable water. Assessment involves simply examining how the environment will affect each of these characteristics.

On the other hand, it is not always simple to assess how easily aggressive agents will penetrate concrete. For example, water flow through a 0.70 W/C sample of concrete is easy to measure, but experience has shown that water flow almost stops when the sample is made of concrete with a 0.40 W/C, regardless of the thickness of the sample and the amount of pressure applied.

The gas permeability of concrete is also difficult to measure because experience has shown that sample preparation, particularly drying, significantly influences gas permeability. Therefore, the critical question remains how to appropriately assess the permeability of a concrete with a low W/B and a very compact microstructure.

I am convinced that, despite all the criticism leveled at it, the so-called AASHTO T-277 "Rapid chloride-ion permeability test" gives a fair idea of the interconnectivity of the fine pores in concrete that are too fine to allow water flow. Experience has revealed good correlation between the water permeability and rapid chloride ion permeability for concrete specimens with a W/C greater than 0.40. Chloride-ion permeability is expressed in coulombs, which corresponds to the total amount of electrical charge that passes during the 6-hour test through the concrete sample when subjected to a potential difference of 50 volts.

When rapid chloride-ion permeability test is performed on concrete samples with lower W/Cs, the number of coulombs passing through the sample decreases. We can easily achieve a chloride-ion permeability of less than 1000 coulombs for a high performance concrete containing about 10% silica fume and having a W/C of around 0.30. The only other way to achieve this would be with latex-modified concrete, which would be much more costly. Much lower chloride-ion permeability values can be achieved if the W/C is reduced below 0.25. Values as low as 150 coulombs have been reported, which is far lower than the 5 to 6000 coulombs for ordinary concrete.

Fig. 5 gives the rapid chloride permeability values compiled by Whiting (10). Although the spread of the values for a given W/C in this compilation can be quite large, this can be explained by the great variety of cementitious systems that were studied, and, perhaps, to a greater extent, by the presence or absence of silica fume in the mixture.

The rapid chloride-ion test also reveals that the connectivity of the pore system decreases drastically as the water/binder ratio decreases, making the migration of aggressive ions or gas more difficult in high-performance concrete than in its plain counterpart. The author believes that this is the best indication that the service life of high-performance concrete should exceed that of ordinary concrete in the same environment. It is difficult to determine the number of years by which the service life would be extended because the predictive models developed for ordinary concrete cannot be readily extrapolated to include high-performance concrete. However, this much can be said that some high-performance concrete structures will outlast the average life span of a human being in developed countries.

FREEZING AND THAWING DURABILITY OF HIGH-PERFORMANCE CONCRETE

This subject has always been and remains controversial (Philleo (11)). First of all, no single test can be used to ascertain if a particular concrete is resistant to freezing and thawing. Secondly, standards such as ASTM C666 propose more than one procedure for determining freezing and thawing resistance, and selecting the proper procedure is not always straightforward. Thirdly, the freezing and thawing rate can vary over a large range when these tests are performed, which can influence the test results. Fourthly, an arbitrary value for a durability factor is usually specified to distinguish a freezing and thawing resistant concrete from the one which is not. Finally, there is the issue of how many freezing and thawing cycles a concrete must resist in order to be declared freezing and thawing resistant.

In North America, freezing and thawing resistance of concrete is assessed using Procedure A (freezing and thawing in water) of ASTM C666. If the durability factor of concrete is still above 60% after 300 cycles, the concrete is said to be freezing and thawing resistant.

As this test takes too long to perform (usually more than 10 weeks) several other criteria giving a more rapid assessment of freezing and thawing resistance have been developed and correlated to the ASTM C666 test. This is the case, for example, with the use of entrained air spacing factor as a freezing and thawing acceptance criterion. Measuring the spacing factor of a particular concrete is not so easy but it can be done within a week or less. To illustrate this point, Canadian Standard CSA A23.1 specifies that ordinary concrete can be classified as freezing and thawing resistant if its average spacing factor is less than 230 µm with no individual values higher than 260 µm. When this criterion was adopted by the CSA Committee, it was noted that the value also protected ordinary concrete from the scaling action of deicing salts. This has now been forgotten.

Experience has proven that this criterion is not valid for high-performance concrete, since HPC with spacing factors as high as 350 µm, and even in one case of 425 µm, were found to resist 500 freezing and thawing cycles. Therefore, the current formulation of CSA A23.1 is unduly severe for high-performance concrete. In addition, it almost always makes it very difficult to pump the concrete since it is usually difficult to keep the spacing factor of a pumped high-performance concrete below 230 µm.

Even if we acknowledge that the results of the ASTM C666 Procedure A test can be substituted for CSA A23.1, it is still not clear how many cycles high-performance concrete should have to withstand before it is considered freezing and thawing resistant. A recent study carried out by Aitcin et al. (12) involving different high-performance concretes with the same water/cement ratio but with spacing factors varying from 190 µm to 425 µm revealed an inverse relation between the spacing factor and the number of freezing and thawing cycles to failure. For instance, it took 2000 freezing and thawing cycles to fail a high-performance concrete with a spacing factor of 190 µm when tested in accordance with ASTM C666 Procedure A. The concrete was completely destroyed after 2150 cycles.

The freezing and thawing resistance of high-performance concrete is destined to remain controversial for some time because there is no consensus on how freezing and thawing durability should be tested. There is no question, however, that the provisions under Canada's A23.1 standards are too severe. Any concrete meeting this criterion will exhibit good good freezing and thawing resistance, but high-performance concrete that fails to meet this standard may pass ASTM C666.

Two high-performance concrete mixtures were used to reconstruct two entrances to a McDonald's restaurant in Sherbrooke (6). The non-air-entrained concrete used to build one entrance failed to meet both CSA A23.1 and ASTM C666 criteria; the air- entrained concrete passed ASTM C666, but failed CSA A23.1 criteria. After four winters, during which it can be assumed that the concretes averaged 50 freezing and thawing cycles annually in "saturated conditions" with exposure to deicing salts, there is an almost imperceptible difference between the two. The jury will remain out on the freezing and thawing issue until the findings of such field tests have been analyzed.

THE FUTURE OF HIGH-PERFORMANCE CONCRETE

High-performance concrete is not a passing fad. It is here to stay, not because of its high strength, but because of its durability. Under current codes, you can build an outdoor concrete parking garage with 20-MPa concrete and its columns and slabs will be somewhat bigger than if a 80-MPa concrete had been used. The life cycle of the parking garage will be very short in an environment as severe as ours in Eastern Canada, because 20-MPa concrete cannot adequately protect the reinforcing steel against corrosion from the deicing salts carried in by automobiles. The service life would be somewhat longer in a less severe environment, but would still be short due to carbonation.

Therefore, at the dawn of the twenty-first century, it is not particularly difficult to predict that the use of high-performance concrete will increase in order to extend the service life of concrete structures exposed to severe environments (12). The durability of a concrete structure depends on several factors, one of which is the durability of the concrete itself. As the durability of concrete is essentially linked to its permeability, high-performance concrete, which has a compact microstructure and a very low permeability, should obviously be more durable than ordinary concrete. It must be emphasized, however, that good concreting practice including good curing are essential to creating a durable structure. It would be a pity if improper practice and poor curing resulted in a structure with impervious concrete in between the cracks.

We still do not know how to make high-performance concrete with low permeability but without the high strength. Therefore, designers have to learn to take advantage of the extra strength provided by durable, low W/C concrete. One day, we may be able to make durable concrete of lower strength.

Another reason that will lead to a greater use of high-performance concrete in the 21st century will be society's greater interest in ecological concerns (13). Many others share my opinion that we cannot continue the wasteful use of our natural resources and energy that characterized the 19th and 20th centuries. In this sense, high-performance concrete is more ecological than ordinary concrete. So, when we use high-performance concrete, we use a concrete with a denser microstructure, so that we get the sought property with fewer materials.

Moreover, the 21st century will also be the century of recycling. Recycling paper, cardboard, aluminum, steel, and even plastic has already become quite common in many countries. The trend towards recycling has already reached the concrete field. We must remember, however, that recycling a material results in a product of lower quality. This is because the original purity of all the materials that were necessary to insure the making of a high performance material and the profitability of a very efficient manufacturing process is lost when different additives are combined with the very pure raw materials in order to enhance the final performance of the product. Concrete production has not reached the same degree of sophistication as rubber manufacturing, but concrete is becoming more complex everyday. Up to 40 different chemicals are mixed with raw rubber to make ordinary automobile tires, but not all of the major rubber manufacturers use the exact same chemical ingredients during processing. The sequence of addition is also different, which makes one rubber tire different from the next.

Another new development is reactive-powder concrete, which can have compressive strength of about 200 MPa in unconfined state and as high as 350 MPa when confined in thin steel tubes. Moreover, the addition of steel fibers to reactive-powder concrete produces a material offering a modulus of rupture as high as 25 to 35 MPa in addition to high compressive strength (14, 15).

Reactive-powder concrete will pose no threat to the high-performance concrete market for years to come. Once we are able to produce and to use reactive-powder concrete and to design with it at an industrial scale, high-performance concrete will have already won over a significant part of the market of ordinary concrete.

Now that 1000-MPa portland cement-based materials can be made, only a pessimist could refuse to see the future of high-performance concrete.

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Table 1 Predicted temperature at the centre of the massive girder

Fresh concrete temperature	Ambient Temperature		
	10°C	20°C	28°C
10°C	58	61	63
18°C	67	69	70
25°C	75	76	77

Table 2 Essential difference between the shrinkage of an ordinary concrete and a high-performance concrete

Type of Shrinkage	Ordinary Concrete	High-performance Concrete
Autogeneous	Very few or none	High*
Drying	Very high	Very few

* with no external water

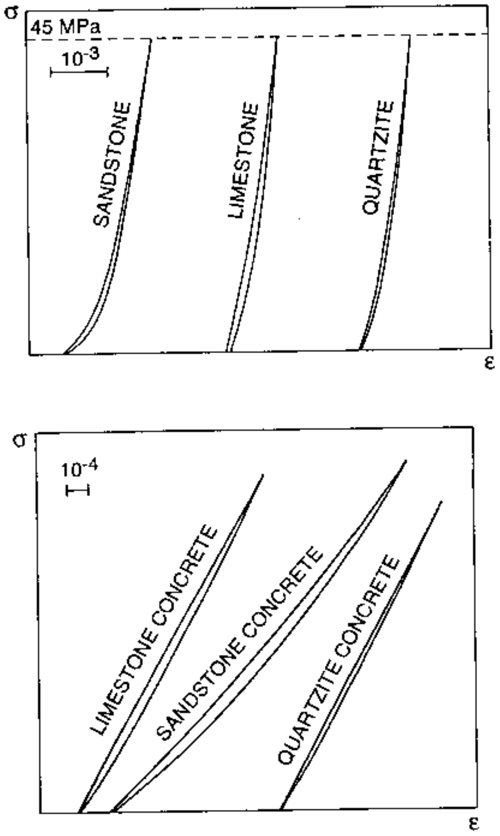
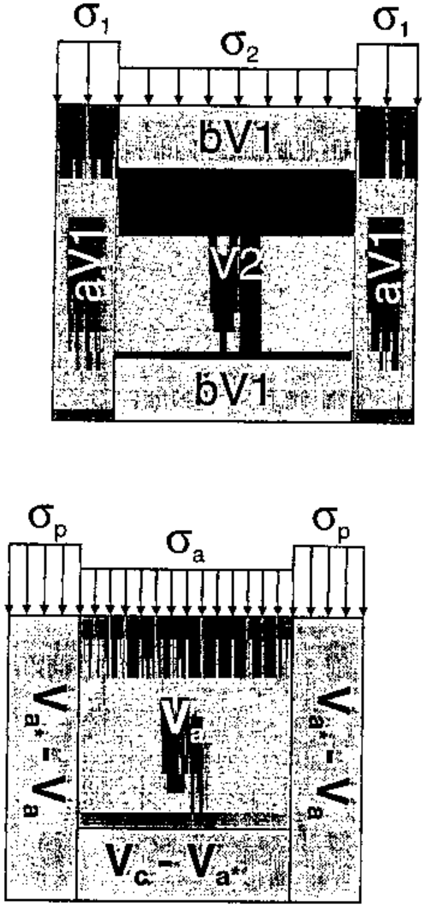


Figure 1 Hysteresis curve of loaded and unloaded high-performance concrete compared to that of their constituent coarse aggregate (from Baalbaki (1))



bV1	hydrated cement paste in the transition zone
aV1	hydrated cement paste
V2	volume of the coarse aggregate

V_c	Volume of the composite
V_a	Volume of the coarse aggregate

$a = V_a / V_c$

V_{a*}	Compacity of the aggregate skeleton

$a^* = V_{a*} / V_c$

$\mathbf{a^* = 1 - 0{,}47\,(d / D)^{0{,}2}}$ **[Caquot formula]**

d	minimum size of the fine aggregate
D	maximum size of the coarse aggregate

Figure 2 Models developed by Baalbaki

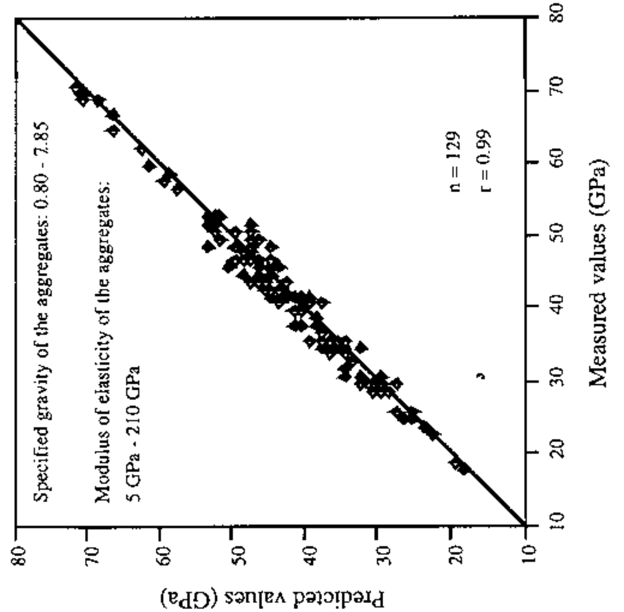


Figure 3 Correlation obtained by Baalbaki when applying his two models with published data

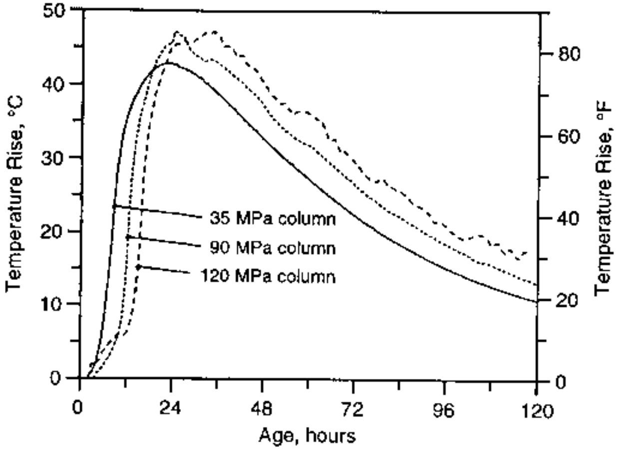


Figure 4 Temperature rise at the centre of three high performance concrete columns (after Cook et al. (4))

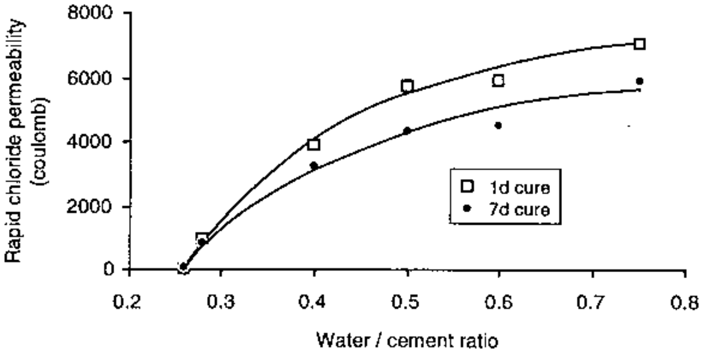


Figure 5 Chloride ion permeability as a function of the W/B ratio (after Whiting (10))