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Review

Cements of yesterday and today Concrete of tomorrow

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Abstract

Concrete, the most widely used construction material, is evolving. Modern concrete is more than simply a mixture of cement, water and aggregates; modern concrete contains more and more often mineral components, chemical admixtures, fibres, etc. Of course the utility market will stay the major market of concrete but niche markets implying the use of "à la carte" smart concretes will also develop. The development of these smart concretes results from the emergence of a new science of concrete, a new science of admixtures and the use of sophisticated scientific apparatus to observe concrete microstructure and even nanostructure. It is not sure that present cements are far superior to cements made 30 to 40 years ago. A high C_3S and C_3A content, a high Blaine fineness are not needed anymore to make a high-initial-strength concrete, it is simply necessary to lower the water/cement or water/binder ratio. Concrete compressive strength is a function of the closeness of the cement particles as well as cement dosage. In fact, reactive powder concretes testing 200 MPa are preferably made with coarse cements not so rich in C_3S and C_3A, that is, cements for which it is easy to control the rheology. Present cement acceptance standards that were very safe when 20- to 25-MPa concretes were the most used concretes are not always appropriate to test cements that are to be used in conjunction with superplasticizers to make high-performance concrete. Moreover, up to now too much emphasis has been placed on 28-day compressive strength and not enough on concrete durability. It is very important to design concrete mixtures that keep their 28-day compressive strength over the life of the structure under its peculiar environmental conditions. Finally cement and concrete will have to evolve in the respect of the environment within a sustainable development perspective, which means that more mineral components will be blended with clinker and water/binder ratios will be lowered in order to increase the life cycle of concrete structures and lengthen as much as possible the use of hydraulic binders and aggregates.

Keywords: Portland cement; Mineral component; Admixture; High-performance concrete; Sustainable development

1. Introduction

Cement is still an essential material in making concrete, but, in some modern concretes it is no longer the most important material because these concretes are composite materials. In a composite material, it is impossible to decide which is the most important material because, by its nature, a composite material has properties that are always much better than the simple arithmetical addition of the individual properties of each component. In the fable of the blind and the lame, it is impossible to decide which, between the blind and the lame, is the most important person.

Modern concrete is more than simply a mixture of cement, water, and aggregates. Modern concrete contains more and more often mineral components having very specific characteristics that give specific properties to concrete, and also chemical admixtures that have even more specific effects. Modern concrete is becoming a very complex chemical material where mineral products and amorphous products, and not just ground clinker and calcium sulfate, interact with organic molecules or polymers. These organic molecules are specially developed to highlight certain characteristics of concrete or correct certain deficiencies of current cements because current cements can present some deficiencies in some of their applications.

It would be pretentious to believe that nothing else will be discovered in the domain of concrete. The science of concrete is only beginning to develop and it should be expected that in the years to come, new types of concretes that will better fulfill different socioeconomic needs will be developed.

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The first question that can be raised is: is the cement industry presently prepared to face such a trend?

The development of different types of concrete will not necessarily result in an increase in the number of cement types to be produced, but it will require that the quality of the cement be much more consistent than at present. In the future, cements will have to fulfill tighter specifications.

The development of numerous high-tech concretes will also not necessarily result in an increase of the overall consumption of cement or binder used in a cubic metre of concrete because cement and binders will be used more and more efficiently: in the best-case scenario, in developed countries, it will be possible to make more concrete with the same amount of binder.

The binders of tomorrow will contain less clinker so that the cement industry will become the hydraulic binder industry, an industry that will market fine powders that harden when they are mixed with water. Interestingly, this increasing use of mineral components other than ground clinker will help the cement industry to fulfill some of its objectives in a sustainable development perspective, which will be imposed by governments. It is already very important that today's cement industry highlight this new role.

The second question that can be raised is: is the cement industry presently well prepared for this drastic change?

2. Concrete, the most widely used construction material in the world

According to CEMBUREAU, in 1900, the total world production of cement was about 10 million tonnes; in 1998 it was 1.6 billion tonnes. If we suppose that on average 250 kg of cement are used to produce 1 m^3 of concrete, in 1900 only 40 million m^3 of concrete were used, whereas in 1997 the amount produced was about 6.4 billion m^3. This is a little more than 1 m^3 of concrete per person per year, or more than 2.5 tonnes of concrete per person per year. Only fresh water is used in larger amounts, and this is very often because it is wasted.

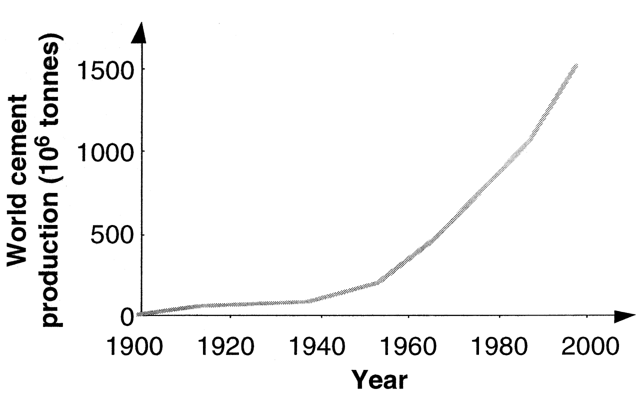

Fig. 1. World production of cement during the twentieth century, according to CEMBUREAU.

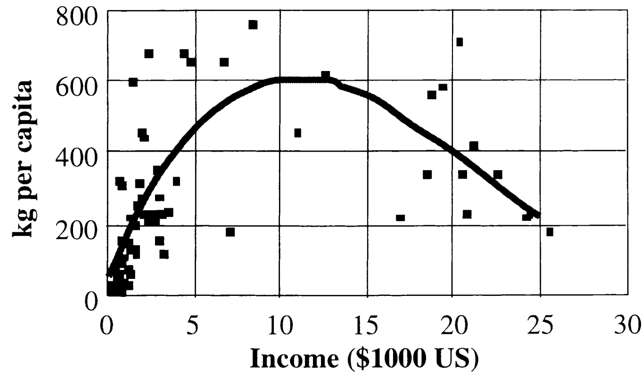

Fig. 2. Relationship between the consumption of cement and the gross national product per inhabitant [1].

In less than one century, concrete has become the most widely used construction material in the world. However, if we look closely at Fig. 1 where the progression of the amount of cement produced in the world is presented, it is seen that it is during the second half of the 20th century that the consumption of cement started to increase at a very rapid pace. Of course, it was necessary to rebuild Europe and Japan after the last war which was particularly devastating in terms of infrastructure, but the peaceful period that followed this war can be characterized by a strong urbanization in many countries and in an increase in the standard of living. Historians and sociologists teach us that a society gets richer and increases its standard of living when it becomes urbanized. The development of a city always results in a considerable increase in infrastructure needs and consequently in an increased consumption of cement: a house, a school, a hospital, a theatre, a restaurant, a sports centre, a water and sewerage network, a sewage- and water-treatment plant are always built using some concrete. It is therefore quite normal that this drastic increase in cement production occurred in the world during the second half of the 20th century.

Fig. 2 shows that it is possible to establish a direct relationship between the consumption of cement and the gross national product per inhabitant, but this figure also shows that cement consumption no longer increases when the standard of living reaches a certain level. Several reasons can be put forward: the urbanization process has reached saturation; the major parts of the infrastructure needs have been built; technological progress results in better technical uses of concrete, as with any other material, so that it is possible to satisfy any socioeconomic need with less and less material. Presently, in industrialized countries, each material is facing a saturated market, and only maintenance, replacement and the natural progression of the market are the driving forces for its use.

The only cement markets that should experience a spectacular expansion in the years to come will be in developing countries, and this raises further questions:

- What is the future of the cement plants in industrialized countries?
- Will developed countries become cement exporters?
- Where will developing countries find the money to buy these cement imports or build the cement plants they will need to face their internal cement needs?

3. Progress achieved by the cement industry in recent years

In recent years, the cement industry has achieved significant progress, specifically in the field of processes and energy savings. However, here, too, the last word has not been said in spite of the fact that, from a thermodynamic point of view, the $CaO-SiO_2-Al_2O_3-Fe_2O_3$ phase diagram is still governing Portland cement manufacture. It is already possible to decrease significantly the temperature in cement kilns by having a better control of the use of some so-called mineralizers [2].

With the years, the Portland cement process has become more and more complex, more and more technical. The processes are less robust, and require the use of powerful computing facilities to run expert systems that very often require highly skilled personnel that are not always found in developing countries, to maintain them.

Moreover, very interesting progress has been achieved in the field of sustainable development and some cement plants are already safely eliminating numerous pollutants or industrial waste [3]. Some cement plants are even producing cement at a negative cost because they are paid to eliminate these pollutants, which means that they start making money before having sold a single tonne of cement.

This raises another question: is the cement industry becoming a green industry?

There are however some fields in which the evolution of the cement industry has not been so good from a technological point of view. This will be developed later on in this paper.

4. The emergence of a science of concrete

During these last 30 years a science of concrete that is now attracting "pure" scientists has developed. Concrete is at once the fruit of a simple technology and a complex science that is beginning to be mastered, but not in all its details. In fact, the hardening of a modern concrete results from reactions between amorphous or mineral products, water, more or less complex organic molecules, and in some cases with some mineral salts. Presently, concrete studies are done using quite sophisticated observation and measurement techniques, so that we continue to improve our understanding and control of concrete technology. We are even able to develop new uses of concrete in fields that were difficult to foresee some years ago.

For example, passionate as I was in 1970 when I started to take interest in concretes known at that time as high-strength concretes, I was quite far from imagining that in 1998 the highest building in the world would be a concrete high-rise building built in Malaysia (the Petronas Towers). I was also very far from realizing that in 1998 the deepest offshore platform would be built in concrete in Norway (the Troll platform), and that this structure could be taller than the Eiffel Tower. I was far from imagining that in 1998 I could make a reactive powder concrete stronger in compression than ordinary structural steel. But it must be recognized that this spectacular progress in the field of concrete is essentially due to progress achieved in the field of admixtures, rather than progress realized in the field of cement manufacturing, as it will be seen in the next section.

4.1. Recent progress achieved in the field of chemical admixtures

The idea of adding admixtures to concrete is not new. Roman texts tell us their masons used to add egg whites or blood to their concrete [4], and now we can explain why hemoglobin is also an excellent dispersant of Portland cement particles.

The recent discovery of the beneficial effects of some organic molecules on very specific properties of concrete has been often quite fortuitous, but it can now be explained scientifically.

For a long time, the technology of chemical admixtures has been a reserved field for a few companies within which secrets were jealously kept, and in my opinion, this is a field that has for too long not drawn enough interest from cement companies. It must also be recognized that admixture companies have always been, and are still today, very clever at presenting themselves as a complementary industry to the cement industry, an industry essentially linked to the world of concrete and not to the world of cement. I am personally convinced that it is this desire not to face cement companies that made them select the expression "water-reducer" rather than "cement-reducer" to describe the organic molecules that are used by concrete producers to make a concrete of a given workability with less water — but also with less cement. Of course, since the work of Feret and Abrams as cited by Neville [5], it is well known that it is not the amount of cement that is used in a concrete that influences its strength and durability but rather the ratio between the amount of water and cement that is used. Feret's law, discovered in 1905, is still valid even in the case of high-performance concrete that does not contain enough water to hydrate all the cement particles [6].

Unfortunately, the admixture companies have been quite successful in deepening the mystery surrounding the use of admixtures by creating and developing an unnecessarily complex and peculiar terminology. Chemical admixtures are not such mysterious products; their action is dictated by the complex laws of physics, chemistry and thermodynamics, and for Dodson [7], there are only four types of admixtures:

1. those that disperse cement particles;
2. those that modify the kinetics of hydration;
3. those that react with one of the subproducts of hydration reaction;
4. those that have only a "physical" action.

For many years, to keep their market, chemical admixture companies were obliged to limit the price of their admixtures to be able to demonstrate to concrete producers that, from an economic point of view, it was in the end more profitable to use an admixture rather than to increase the amount of cement in order to achieve a given compressive strength. Of course, each time such a calculation has to be made it is realized that, in spite of what concrete producers are saying, Portland cement is not such an expensive material. Therefore, in its first phase of development, the admixtures industry began taking advantage of the interesting properties of some industrial by-products. This phase corresponds to the marketing of vinsol resin as an air-entraining agent, and lignosulfonates as water reducers, both products being by-products of the wood pulp and paper industry.

The almost simultaneous development in Japan and Germany [8,9], at the end of the 1960s and the beginning of the 1970s, of the exceptional dispersing properties of some synthetic polymers, known presently as superplasticizers or high-range water reducers, created a great change in the development of the admixture business. For the first time, quite pure products were specially manufactured as concrete admixtures, products more costly than lignosulfonates, and much more efficient. In fact, when using a lignosulfonate-based water reducer, it is possible, in the best case, to reduce the amount of mixing water by 8% to 10% (and of course cement by the same amount) when making a concrete having a 100-mm slump (a minimum to get an efficient placing in the field with vibrators). Suddenly, when using a superplasticizer, it was possible to make 200-mm slump concrete at almost any water/cement ratio value. This is the kind of concrete that contractors have for so long been waiting for. Even in the case of high-performance concrete with a very low water/cement ratio, it is now possible to make 200- or 250-mm slump concretes that do not contain enough water to hydrate all the cement grains and do not need to be vibrated to be placed.

Fifteen years have been necessary to see superplasticizers enter the concrete market significantly and it must be admitted that they are still not used at their full potential nor as often as they should be.

The exceptional properties of superplasticizers are at the origin of the development of the science of admixtures that very rapidly makes possible the understanding of the limits of lignosulfonates and the superiority of superplasticizers. In fact, we now know why it is quite difficult to introduce more than 1 l of a lignosulfonate water reducer into 1 m\nolimits^{3} of a concrete without seeing the negative secondary effects of the impurities contained in the lignosulfonate, although it is possible to use superplasticizers with dosages up to 15 l in high-performance concrete, and even to 40 l in reactive powder concretes [10].

However, when high superplasticizer dosages began to be used to decrease the water/cement ratio in high-performance concrete, it was realized that, in some cases, some cements and some superplasticizers were incompatible and it was no longer possible to take out the water reducer and add some more cement and water to solve the problem [11]. It became necessary to understand why this phenomenon was found only with some cements and some superplasticizers and not with others.

The very recent science of admixtures has progressed quite rapidly, but advances still have to be made because in some cases we do not yet understand well enough all the interaction mechanisms governing the mixture of Portland cement and superplasticizers. However, we know how to make 150-MPa concrete on an industrial basis. Because at such a level of strength it is the coarse aggregate that becomes the weakest link in concrete, it is only necessary to take out coarse aggregate to be able to increase concrete compressive strength and make reactive powder concrete having a compressive strength of 200 MPa; it is only necessary to confine this reactive powder concrete in thin-walled stainless steel tubes to see the compressive strength increased to 375 MPa; and when the sand is replaced by a metallic powder the compressive strength of concrete increases to 800 MPa [12].

A 1000-MPa (1-GPa) concrete is no longer a dream; it could become a reality in the next century.

What achievements have been realized in less than 30 years without any major change in the nature of Portland cement!

4.2. Progress achieved in the observation of the microstructure and understanding of the nanostructure of concretes

Several other significant achievements have been realized in the field of concrete technology due to the use of new very sophisticated scientific apparatus to observe concrete microstructure, and even more recently concrete nanostructure. The use of scanning electron microscopes has been a key factor in the emergence of these new sciences of concrete and admixtures. It is possible now to better observe and understand the effect of a particular admixture on concrete microstructure. Using these sophisticated observation tools, it has been possible to master and direct the evolution of concrete technology rather than continue to progress by trial and error to find organic molecules with useful properties when included in concrete. Macrostructural properties are intimately linked to microstructural properties. The scanning electron microscope (SEM) is now becoming an essential instrument of observation in the study of modern concrete, but we must not forget that a good visual observation or a detailed observation under an optical microscope, under polarized or natural light, are still as necessary.

An SEM is not only an instrument that makes beautiful pictures; it is an instrument that allows us to better understand what concrete is in its more intimate structure.

The first uses of magnetic resonance to study the nanostructure of concrete are very encouraging and have already resulted in giant steps in the understanding of the true nature of the calcium silicate hydrates that are formed during cement hydration that are still identified with the very vague notation C–S–H because we have nothing better to describe it. We are beginning to understand better what we already know quite well in the case of the intimate structure of the silicon–oxygen tetrahedron and aluminum–oxygen octahedron or magnesium–oxygen octahedron in kaolin and chrysotile asbestos, two close cousins of C–S–H. Kaolin and chrysotile asbestos are, respectively, aluminum silicate hydrates and magnesium silicate hydrates.

The aluminum ion, which has a 0.50-Å radius in an aluminum–oxygen octahedron in kaolinite, fits quite well with the plane composed of silicate tetrahedra. Contrary to this, the magnesium ion which is a little larger, 0.78 Å, forces the octahedron planes to curve and results in the formation of a fiber: asbestos fibres. Because the calcium ion is much larger, 1.06 Å, it does not allow the formation of large planar or fibrous structures but rather a structure where there are small amounts of silica tetrahedra and of alumina octahedra that can only develop as very small crystals.

Finally, due to the progress realized with the Atomic Force Microscope, it is now possible to explain why, when the C/S ratio of C–S–H is low, the intrinsic strength of C–S–H increases.

5. Cements of yesterday and today

5.1. Evolution of their characteristics

Generally speaking, the cements of yesterday were not as fine and did not contain as high an amount of C_3S as today's cements but these are not the only differences. Others, more hidden, have important technological impacts. Before discussing these hidden differences, the first two differences will be reviewed.

It is supposedly from the pressure of contractors that some cement companies decided to increase the fineness and the C_3S content of their cements in order to allow contractors to remove formwork from the concrete more rapidly and so increase their competitiveness.

Personally, I cannot accept such an argument because I do not see how the competitiveness of contractors is improved by the fact that all the cement companies are offering contractors cements that have an increased fineness and C_3S content. This attitude has even had a negative effect on the cement industry because with these new cements it is possible to achieve a higher 28-day compressive strength using less cement, but this higher 28 day compressive strength is achieved at the expense of long-term durability. For example, at a certain time, the state of California was obliged to end what was known in California as the "Blaine war." Cement producers should rather ask themselves seriously what the advantages and the disadvantages are in increasing the specific surface and the C_3S content of a cement when making concrete. There are many other, much less dangerous ways, to increase initial compressive strengths of a concrete.

Of course, in some cases, these increases in the fineness and C_3S are justified, for example in the case of a structural concrete used in a mild environment, but in many cases these increases in the fineness and C_3A content have catastrophic results when concrete is exposed to harsh environmental conditions.

In fact, when a finer cement richer in C_3S is used, it is possible to reach a higher 28-day compressive strength with a higher water/cement ratio. According to Wischers [13], in 1960 in England, a 30- to 35-MPa concrete could be made using 350 kg/m^3 of cement and a water/cement ratio of 0.45. In 1985, the same structural concrete could be made using only 250 kg/m^3 of cement and a water/cement ratio of 0.60. For the designer who is making structural calculations, these two concretes are equivalent. However, from a microstructural point of view, the porosity and the permeability of these two concretes are completely different. A concrete having a 0.60 W/C ratio will carbonate more rapidly than a concrete having a W/C ratio of 0.45 and its durability to sea water, freezing and thawing, and deicing salts will also be not as good.

As soon as a concrete is exposed to a severe environment, the key factor that conditions its durability is its W/C ratio and not its compressive strength. It must be admitted that at an equal fineness and an equal content of C_3S, 28-day compressive strength depends on the W/C ratio, but this is no longer the case when the fineness and the C_3S content are different.

Therefore, the good old cements of yesterday that were coarser and less rich in C_3S were used to make concretes whose compressive strength continued to increase after 28 days, whereas our modern efficient cements have achieved almost all the strength they can at 28 days. For the designer and the cement producer, these cements are equivalent, but for owners concerned with maintenance costs and life cycle, the good old concretes were finally much stronger and more resistant than their 28-day compressive strength indicated.

5.2. Standards

Portland cement is a very complex mineral product composed of at least five principal mineral phases C_3S, C_2S, C_3A, C_4AF, and calcium sulfate, and made from very simple raw materials that contain also small amounts of oxides other than SiO_2, CaO, Al_2O_3, and Fe_2O_3 that result in what are called minor phases in the cement. These minor phases are quite different from one cement to another. Taking into account these differences in the composition of cement, it is absolutely fundamental that a given Portland cement satisfy the requirements of different criteria of standards so that it will be possible to make a concrete that has predictable characteristics and be adaptable to precise needs.

The tests performed on mortars or pure pastes with a W/C ratio of about 0.50, which is a quasi-universal way of testing cement in the world, have for a long time been very safe from a W/C point of view because most industrial concretes had a W/C ratio higher than 0.50, but this is no longer true. The rheology of low W/C ratio concretes is no longer dictated by the amount of water used to make them or by the shape of coarse aggregates, but rather by what is now called the compatibility between the cement and the admixtures used. This raises very important questions:

Are the standards that are presently used in the world to test cement well adapted to the real world of concrete? Are we testing the right properties?

My answer is yes, if the long-term objective of the cement industry is to base its development on the use of a commodity product having a 20-MPa compressive strength. My answer is no, if the long-term objective of the cement industry is to transform some of the concrete that will be used into smart concretes that will be able to face the competition of other construction materials and keep its share of the construction market.

5.3. Cement admixture/compatibility

According to concrete producers and contractors, compatibility problems between water reducers (based on lignosulphonates) and cement occurred some years ago, although not as often as with today's superplasticizers. However, scientific documentation of these compatibility problems is quite rare. It seems that the phenomenon has not received all the necessary attention from the admixture manufacturers and cement producers. Moreover, each time a solution was found in the field to solve the problem (very often, it consisted of the replacement or omission of the admixture), nobody was interested anymore to know what had happened. In the rare cases found in the literature (Ranc [14], Dodson and Hayden [15]), it seems that one frequent cause was the presence of a high amount of anhydrite in the calcium sulfate. Of course, a cement producer can satisfy the SO_3 content of present standards by adding either gypsum or a mixture of gypsum and anhydrite, but it seems that when the amount of anhydrite is too high, and a lignosulphonate was used, the rate of solubility of sulfate ions was drastically reduced (Ranc [14]).

The frequency of incompatibility problems has increased drastically with the use of superplasticizers in high-performance concretes having a low water/cement ratio or a low water/binder ratio; that is, a water/binder ratio much lower than the one used in the sacrosanct standards. As in such cases it is no longer possible to solve the problem by taking out the superplasticizer, it became necessary to study the problem in more detail. Of course, presently, this problem is not yet important for the cement industry. It is much more important for the admixture industry because high-performance concrete is a very promising market; several litres of superplasticizer are used in each cubic meter of high-performance concrete. This situation, which is not a general one for any cement and superplasticizer, has attracted the attention of admixture companies and some university researchers who are trying to understand it from a fundamental point of view.

This strong desire to understand and solve the compatibility problem is, as far as I am concerned, one of the reasons for the rise of the science of admixtures.

Although we still do not understand fully how superplasticizers interact with all the cement and the sulfate phases in Portland cement, we already have found some practical solutions to solve the incompatibility problems in many cases. The double introduction method is one of these methods. It consists in adding the superplasticizer in two doses: the first time at the beginning of the mixing, and the second time at the end of the mixing, or just before placing the concrete in the field. We can also cite the addition of a very small amount of retarder or the addition of some sodium sulfate. However, there are still problems of cement/superplasticizer combinations that are not solved.

In fact, if the SO_3 content of today's cements and of yesterday's cements have not changed, this is not true for the SO_3 content of the clinker. Not long ago, the SO_3 content of clinkers was usually in the order of 0.5%, but it can be as high as 1.5% in some cases or even higher (values as high as 2.5% have been reported). As the maximum amount of SO_3 permitted by standards in a cement is still 3.5%, cement companies are in some cases limited in the amount of calcium sulfate they can add to their clinker.

If, from a purely chemical point of view, the SO_3 content of modern cements is the same, it is not sure that, from the solubility rate of SO_4^{2-} ions, it is the same when the SO_3 given by the chemical analysis is coming from an alkali sulfate, or if it is dissolved in the C_2S in the clinker, or if the SO_3 is combined in one form of the calcium sulfate that has been added in the clinker during its grinding.

The recent results obtained at the University of Sherbrooke by Jiang et al. [16] seem to demonstrate, from a rheological point of view, that for many cements there is an optimal amount of soluble alkalis. This ideal alkali soluble content is not reached with some modern cements because, in order to please some agencies specifying the use of cements having a low alkali content in order to avoid potential, or very often imaginary, alkali aggregate reactions, some cement companies are selling cement with an unnecessary too low alkali content.

Another problem that could cause trouble in the years to come is the influence of the SO_3 content in the delayed ettringite formation (DEF). A number of researchers who were working in the field of the alkali aggregate reaction, which does not seem to interest as many people any more, are switching to DEF. Already, many papers have been written on the subject, intensive courses have been given, and a book written on this subject.

6. Concretes of yesterday and today

6.1. A commodity product or a niche product

For a long time, the concrete industry and designers have produced and specified a universal concrete, good enough to be used under any circumstances, whose compressive strength was usually between 15 and 25 MPa. In some countries, with the years, it has been possible to see a slight increase in concrete compressive strength so that presently in some developed countries the concrete used for structural purposes has a compressive strength between 25 and 35 MPa. This does not mean that 20-MPa concrete is no longer used: there are numerous applications where a designer does need a concrete with a compressive strength higher than 20 MPa (footings, basements, etc.), but more and more structures are built with a slightly stronger concrete.

However, during the 1970's concrete having a higher strength (40 to 50 MPa) began to be specified for columns in high-rise building, because slender columns offered more architectural possibilities and more renting space [17]. With the years, the name of these initial high-strength concretes has been changed to high-performance concrete because it was realized that these concretes have more than simply a high strength. These concretes started to be used outdoors and faced more severe environments such as offshore platforms, bridges, roads, etc. Little by little, it was realized that the market for this concrete was not only the high-strength market, but also more generally the market for durable concrete that represents more or less one third of the present market for concrete.

It has also been realized very recently that this type of concrete is more ecologically friendly, in the present state of technology, than usual concrete because it is possible to support a given structural load with less cement and of course, in some cases, one-third of the amount of aggregates necessary to make a normal strength concrete. Moreover, the life cycle of high-performance concrete can be estimated to be two or three times that of usual concrete. In addition, high-performance concrete can be recycled two or three times before being transformed into a road base aggregate when structures have reached the end of their life. High-performance concretes, which are simply concretes with a low W/C or W/B ratio, are economical concretes on an initial cost basis, because it is possible to build an equivalent structure with less formwork, less concrete to be placed and less reinforcing steel. The Quebec Ministry of Transportation has calculated that the initial cost of a 50- to 60-MPa concrete bridge is 8% less than that of a 35-MPa concrete without taking into consideration the increase in the life of the bridge [18].

The acceptance of high-performance concrete is slow, but it is progressing constantly and this progression will continue at the beginning of this new century because designers and owners will realize the value and durability of this concrete.

Of course, high-performance concretes are not a panacea that will stop the development of all other kinds of concrete. High-performance concrete has its limitations, but it is durable concrete that will allow designers and architects to go beyond the limits of present concrete.

In parallel to these developments in the field of high-performance concrete, it has been possible to see recently other high-tech concretes that were taking some niche markets, such as fiber-reinforced concrete, roller-compacted concrete and reactive powder concrete. All these concretes are designed for small but lucrative markets where competition is limited. Only serious companies are involved in these markets, because they are the ones at the cutting edge of technology. When they are able to provide such high-tech concretes they are able also to supply the large amounts of regular concrete that must be used to complete the building of the infrastructure.

It is obvious that this short list of special concretes is not exhaustive and will grow very rapidly with time because it will be more and more interesting to offer to contractors more elegant, more durable and more profitable solutions than the one that can be put into practice with 20 to 30 MPa concrete. The development of BOOT (build, own, operate and transfer) projects will undoubtedly accelerate this trend towards the formulation of niche concretes and, interestingly enough, sometimes it might be discovered that some of these concrete could benefit additional markets for which they were not initially conceived. For example, it is possible to cite the case of self-compacting concrete that was developed in Japan to facilitate the placing of concrete in congested structural elements, and is now starting to be used as ''silent concrete'' or ''noiseless'' concrete, because it can be cast any time of the day or night without disturbing the neighborhood since it does not need to be vibrated. When such a concrete is used in a precast plant, this precast plant can be less noisy than a discotheque.

6.2. Strength or durability

The design of concrete structures is done by structural engineers, engineers that know only one thing about the material: its 28-day compressive strength, and who do not understand very much about concrete durability.

The knowledge of the 28-day compressive strength of a concrete is, of course, fundamental to make calculations that will allow the construction of a structure that is safe, but it is necessary to be sure that this concrete will keep its mechanical strength during the whole life of the structure. Unfortunately, many examples show us concretes that had an adequate 28-day compressive strength but have lost most of their functionality because they were facing an environment for which they were not conceived or because they were not placed or cured correctly. It is not necessary to go beyond such examples to find the reason for the very poor image that concrete has with the public: it is sufficient to look at the very poor appearance of many present infrastructures, or the numerous repair works that are consuming so much time and so many dollars. It is a pity to have to demolish so many infrastructures that have reached only half of their intended life cycle, without mentioning the enormous socioeconomic costs associated with these repairs (deviations, traffic jams, loss of time, pollution, etc.).

The cement industry is paying a very high price for these errors and, instead of taking advantage of the very lean budgets allocated for the construction of new infrastructures that would use some cement, these budgets are used to do repair work that consumes very little material but a lot of labour. Contractors do not care because, in both cases, the volume of the work to be done in terms of dollars is the same.

Several codes now are emphasizing concrete durability rather than strength when selecting the concrete to be used to build a structure. It is about time!

The problems of external parking garages built in Canada with 20-MPa concrete caused a great deal of trouble to the cement and concrete industry due to their poor freezing and thawing and scaling resistance. Accelerated carbonation of 20-MPa concrete in Europe is also costing cement companies a lot, just as seawater attack is doing in the Middle East.

Moreover, it is necessary to foresee a more rapid degradation in the future of the infrastructure and limestone monuments in large cities due to atmospheric pollution in highly urbanized areas. In fact, hidden inside a porous 20-MPa concrete is a whole world of microscopic life. Bacteria, germs, moss and lichens are prospering in concrete pores. *Thiobacillus ferroxidans* bacteria need calcium sulfate to develop. This calcium sulfate is present as the result of the attack of limestone or concrete by acid rain, but these bacteria then reproduce, as a by-product, sulfuric acid that attacks concrete and limestone to make new calcium sulfate.

High-performance concrete, which has a much lower porosity, better withstands the effect of pollution, and this will be one of the reason for their growing use in the future simply because they are less porous. As far as the additional megapascals that are a characteristic of high-performance concrete are concerned, designers will have to learn how to use them efficiently.

Having worked in a BOOT project, I have seen that, when a contractor has to maintain a structure for 25 or 30 years and guarantee a 100-year life cycle, he does not hesitate very long about the quality of the concrete that he uses: he uses high-performance concrete.

6.3. The race for more MPas

Although concrete compressive strength is not its essential characteristic because it is its durability that it is more important, it must be admitted that these two characteristics are intimately linked to one another. The overwhelming importance of the compressive strength in the codes and the ease with which it is measured can explain why the increase of the compressive strength of concrete has been, in a certain way, a constant preoccupation. Periodically, some researchers announce that they have succeeded in making a concrete with a very high compressive strength, but it must be admitted that all these efforts translate into very few industrial applications, except perhaps the "densified cement/ultra-fine particle-based material" (DSP) concept developed by Bache [19] and the reactive powder concept (RPC) developed by Richard and Cheyrezy [12] that was used for the first time during the construction of the Sherbrooke pedestrian bridge [20].

Every day my students are making concretes of 400 MPa, using appropriate, simple mechanical and thermal treatments. Pierre Richard, for his part, has been able to make an 800-MPa concrete using a metallic powder, so that a 1000-MPa reactive powder concrete (1 GPa) is no longer a concrete of utopia. What is the future of such a concrete three times stronger in compression than steel? Nobody knows, but I have no doubt that in this century this type of concrete could be made and perhaps used. The importance of the compactness of the aggregate skeleton, the importance of appropriate thermal treatments, and the benefits of confinement were well known. The creative work of Pierre Richard has been to transform these well-known technologies into a simple and usable concept.

Of course, the price of 1 m^3 of reactive powder concrete is frightening to many engineers who still compare this price to the price of 1 m^3 of ordinary concrete or to high-performance concrete. However, it should be realized that the unit price of reactive powder concrete must not be calculated in relation to 1 m^3, but rather to 1 tonne of material, because reactive powder concrete has to be compared to steel and not to ordinary, or high-performance, concrete.

When the Sherbrooke pedestrian bridge was built, the cost of the materials used to make the 200-MPa reactive powder concrete could be estimated roughly to be US\$1000/m^3. Presently the same reactive powder concrete could be produced for US\$750/m^3, and in the near future, it could be possible perhaps to make it for US\$600 to

US$650/m^3. The cost of the materials used to make a reactive powder concrete can be split roughly in two equal parts, the cost of the powders, and the cost of the fibers.

However, even at US$1000/m^3, that is US$400/tonne, in some applications where durability and compressive strength are keys factors, reactive powder concrete can compete with structural steel that costs US$1200 to US$1500/tonne.

Moreover, in some applications, reactive powder concrete should not compete only with steel but also with pig iron, aluminum and even wood.

7. The concrete of tomorrow in a sustainable development perspective

The concept of sustainable development is not a passing fad but rather a policy that will last and become more important because the great ones of this world are breathing the same polluted air as all of us. It is no longer possible in the northern hemisphere to live in the fashionable west ends of large cities to benefit from pure air, because these areas are situated at the east of another urbanized center and are receiving their pollution. Because the presidents and prime ministers of the G8 countries are breathing the same polluted air as everyone else, sustainable development concerns them as much as the rest of us; this is why sustainable development will survive the departure of current presidents.

Is it absolutely necessary to satisfy at any price the avidity of shareholders, or is it better to preserve this heritage for our children and grandchildren and the children and grandchildren of these shareholders?

When it is realized that only one-third of the world has the advantage of a high standard of living and that this one-third is not interested in going back to the living conditions of the good old days, and that two-thirds of the world has only one thing in mind, that is to benefit from the same standard of living as us, it is obvious that it is urgent that a sustainable development policy be enforced all over the planet in order to avoid repeating the same errors that were made and resulted in the present situation. The application of such a policy will not be easy because it is always others that are polluting and wasting more than we are.

The cement and concrete industry has no choice: it must add this direction to its development and its other constraints. I have no doubt that the cement and concrete industries will succeed in making this change. The cement industry, or rather the hydraulic binders industry that will be the name of the cement industry in the next century, will be a GREEN industry. There is no choice, there is no point in complaining or fighting back, it is better to face as soon as possible this new situation and transform the cement and concrete industry into in a GREEN industry and to proclaim this loud and strong to the public. In the end, there are numerous ways of doing this and this commitment must be known to the public.

The concrete of tomorrow will be more durable and will be developed to satisfy socioeconomic needs at the lowest environmental impact. The cost of a project in the future will have to incorporate not only the present economic costs that we are used to calculating now, but also social and environmental costs ranging from the extraction of the raw materials, to their utilization, and also including their elimination at the end of the life cycle of the structures.

7.1. The ecological impact of concrete

It is not satisfactory to say that the energy content of 1 m^3 of concrete is negligible because, at 6.4 billions times a small energy content, it is no longer negligible. There are numerous ways of decreasing the emissions of CO_2 and NO_x and to decrease the amount of aggregates that are necessary to make concrete structures. It will also be necessary to learn how to incorporate ecological and socioeconomic costs when evaluating a given project.

When the importance of such costs is taken into account, it will be found that high-performance concrete and reactive powder concrete are not such costly materials compared to 20- to 30-MPa concrete because these materials are more durable, can be recycled very easily several times before ending as a granular material as a road base, and require the use of less material.

The beginning of the 21st century will see cement companies developing alternative binders that are more environmentally friendly from a sustainable development point of view. This is why the use of mineral components that has not been promoted very strongly during the last 30 years will be exploited more seriously. It is no longer necessary to read back the Roman texts over again to be convinced of the need to use natural pozzolans. The cement and concrete industry will begin to control the artificial pozzolans market (metakaolin, rice husk ash, diatomaceous earths, amorphous silica, calcined clay or shale). It is no longer true that the blending of any mineral component decreases the early compressive strength of concrete because, since it is possible to use superplasticizers, the initial compressive strength of a concrete is no longer controlled only by the amount of C_3S and the fineness of the cement, but also by the density of the hydrated cement paste. This density is a function of the water/binder ratio and/or of the water/cement ratio. In a very dense system (with a very low W/B ratio) it is not necessary to have too much glue (C–S–H) to obtain the necessary MPa to allow the contractor to rapidly remove the formwork of a structure. However, at present, such a solution is not always practical or economical so that there is a practical limit above which the use of pure Portland cement is less expensive when a high early compressive strength is necessary.

Until recently, when Portland cement was compared to the other principal binders still in use in the industry, gypsum and lime, it could be said that gypsum and lime were more ecologically friendly. Gypsum and lime are used in a cyclic way due to the chemical reactions involved whereas the use of Portland cement is linear [20]. However, if the time scale is changed, this conclusion is no longer valid. In fact, if the time scale is increased to a geological scale, all concrete will one day end its life as a mixture of limestone, clay, iron oxide and sand that are the stable form of calcium, aluminum, iron and silicon ions in our environment on earth. This is what we learn from observing nature.

7.2. The binders of tomorrow

I do not pretend to read tea leaves, but I can make some predictions. It is not too risky to do so when you are over 60 years old. In any case, I am prepared to take the credit for all the right predictions and the blame for the wrong ones.

The binders of tomorrow will contain less and less ground clinker; they will not have necessarily such a high C_3S content; they will be made with more and more alternative fuels. They will have to fulfill tighter standard requirements and they will need to be more and more consistent in their properties, because the clinker content will be lower in the blended cements. The binders of tomorrow will be more and more compatible with more and more complex admixtures, and their use will result in making more durable concrete rather than simply stronger concrete.

This is only the beginning of the list of all the qualities that the binders of tomorrow will have without specifying that these binders will also have to be inexpensive. This is the challenge for the cement industry!

7.3. The admixtures of tomorrow

Admixtures will be more and more numerous, and they will more often be made specifically for the concrete. They will be more and more pure, more and more specific, and more and more precise in their action. It will become more and more difficult to blame the admixture in the case of incompatibility and it will be necessary for cement producers to provide a list of compatible and incompatible admixtures to their customers in order to specify the right admixture and the admixture that will be unsuitable.

Admixtures are becoming an essential component in making concrete. This is not a new constraint and neither is it a very interesting constraint because the marriage of cement and admixture has to be seen as a technological opportunity that very few cement producers are presently realizing. The marriage of organic and mineral chemistry, and the chemistry of amorphous and colloidal materials, is the secret of the success of concrete in this century.

7.4. The concrete of tomorrow

The concrete of tomorrow will be GREEN, GREEN, AND GREEN. Concrete will have a low water/binder ratio, it will be more durable and it will have various characteristics that will be quite different from one another for use in different applications. The time is over when concrete could be considered a low-priced commodity product; now is the time for concrete "à la carte".

Concrete and cement producers have to realize that they can make more profit by selling small amounts of concrete "à la carte" rather than a cheap commodity product. Contractors and owners have to realize that what is important is not the cost of 1 m^3 of concrete but rather the cost of 1 MPa or 1 year of life cycle of a structure. When the cement and concrete industry as well as contractors and owners realize that, then the construction industry will have made a great step forward.

I am personally convinced that the greater use of BOOT projects will force contractors to put into practice, and owners to accept, a revolution in the construction industry.

The concrete producer of tomorrow will have to know how to play with all the different types of concrete offered by the cement and admixture producers to provide contractors with concrete that will be more high-tech and more economical, not in terms of the cost of 1 m^3, but in terms of performance.

The concrete industry of tomorrow will have to continue to produce a commodity product but also to produce niche concretes with a high added value.

8. The development of the concrete industry and the cement industry in the 21st century

I have presented my personal thoughts on the past history of cement and concrete and my predictions for the future. As you will have noted, I am not totally objective in this field. My love of concrete is great but it is not without limits, because I know concrete too well not to realize that it is not the "only" material of the future. It is simply a marvelous material, flexible in its composition, ecological when we take care, and a material still full of unexplored possibilities or even unexploited possibilities.

The years to come will not be more difficult than the present or the past ones; they will simply be different, with new challenges to face.

Cement and concrete will remain, at least during the first half of the 21st century, the most widely used construction materials in the world, although this future concrete could be quite different from that used today. The concrete of this century will be a concrete having a balanced ecological content; concrete will be a material made and used to serve human beings, and not simply to maximize the short-term profit of some shareholders.

The competitiveness of the cement industry will be a function of the speed at which these changes are made. This is quite a difficult task for a heavy industry that is still too fragmented and an industry that for so long rested on its laurels, an industry that for too long had only to wait to pick up orders, an industry that has for too long been showing very little interest in concrete, which is its only market.

As we enter a world where the main wealth will be knowledge, and before leaving the university world, I would like to take the opportunity to pass a very strong message: it will be vital that during the 21st century the cement industry takes more interest in universities. Not all university professors are dreamers! This cooperation is vital for the sake of the industry in order to train the engineers who will make the cement industry more competitive but, also, and this is more important, to give the desire to future engineers, administrators, and architects who are studying in universities, and who one day will become decision-makers, to think of concrete when they have to select the material they will use for a construction project.

It is at the University of Toulouse in France that I fell in love with concrete, because two professors made me share their passion for concrete. It is at the University of Sherbrooke that I tried to transmit this passion for concrete and cement to my students and, very modestly, I think this has been the biggest achievement in my career as a professor.

9. Conclusion

After reading this presentation on the cements of yesterday and today and on the concrete of tomorrow, I would be very happy if only one thing is remembered: each time one of the parameters in the process of cement making is modified for any reason, on top of the two questions that have legitimately to be answered about the economic and acceptance standard consequences of this move, it will be necessary to raise another question: what will be the result of this modification on the quality of the concrete that will be made with this new cement? Quality means durability more than strength. Cement is made to make profit, but also to ensure the competitiveness of concrete as a universal construction material. It is totally wrong to think that cement is solely a material that has to fulfill standards on mortars that are more and more outdated and very far from the real world of concrete. What can be done with cement except make concrete?

This is the challenge of the cement and concrete industry for the 21st century. It is a stimulating challenge.

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