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Technological evolution of concrete: from ancient times to ultra high-performance concrete

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ABSTRACT: Since the fall of the Roman Empire, concrete only suffered significant advances with the discovery of portland cement. The technological knowledge that the Romans held was empirical, based on the principle of trial and error, and allowed the discovery of new materials which properties could be reproduced but not explained. The ability to go beyond empiricism was only acquired by the scientific development that occurred mainly from the twentieth century onwards. In fact, no other binder materials were used other than those used by the Romans by the beginning of the nineteenth century. Only in the late eighteenth century was there a concrete renaissance.

Nowadays, we can produce high-performance concrete with relative ease, maintaining the versatility of conventional concrete with the durability and strength of natural stone. However, it can be easily shaped, armed, hard-working pre and post tensioned with cables and mixed with different kind of fibers.

In this paper, an overview of the use of concrete from ancient times to the most sophisticated ultra-high performance concrete in use is presented.

1 INTRODUCTION

Concrete can be defined as a biphasic composite material, with a matrix (binder paste) able to incorporate a filling material (granular skeleton). Usually the binder matrix contains cement but its presence in the concrete's composition is not compulsory. Concrete can be made without cement, incorporating other available binder materials.

Clay was one of the first materials manipulated by man with the main objective of producing an artificial stone. After clay, man began to work with other binders like gypsum and lime. The contribution of Roman civilization and the use of *Roman concrete* revolutionized the construction activity and all of the Western architecture.

Later, with the invention of portland cement by Louis Vicat in 1817, of reinforced concrete by Lambot and Monier and the intervention of Architect Auguste Perret were the starting points for the widespread usage of concrete as a construction material responsible for a new approach of the twentieth century's construction.

However, since the beginning of last century, concrete in its essence has not significantly changed, remaining a mixture of aggregates, binders and water. After one century the concrete industry has yet to experience a revolutionary evolution as experienced in the telecommunications or even in the automotive industry. Nevertheless, it is worth noting the remarkable development associated with the development of superplasticizers that has led to a new type of concrete high-performance concrete (HPC). HPC is a special concrete placed according to similar procedures and made with the same materials used in conventional concrete (with careful selection) and with a low water/binder ratio. With the use of HPC, it is possible to obtain concrete with very good workability, compression strength of about 100 MPa and durability capable of ensuring a service life of 100 years or more, even under adverse environmental exposure.

Despite the high mechanical strength that can be achieved, the HPC is not the strongest material that can be manufactured with portland cement. It is possible to produce a concrete of ultra high performance (UHPC) that can reach about 800 MPa of compressive strength. These materials have a very limited application fields due to its very high price, but there are already examples of its application.

2 PRE-ROMAN CONCRETE

In early civilizations, man has used the materials that were available in nature. Quickly, man learned to mold and adapt them to his needs. The most predominant building materials were stone, wood and clay. On a smaller scale, metals, leather and vegetable fibers were used.

As time went by, mans needs increased, thus he began to use materials of increased strength, durability and better appearance. In this context, building materials consecutively developed. The importance of construction materials is so relevant that history was divided according to the predominant use of one or another material: the Stone Age, Bronze Age, Iron Age. Clay was perhaps the first material manipulated by man intentionally, with the aim of producing an artificial durable stone from soft and moldable clay. After clay man began to manipulate other bonding materials such as gypsum and lime.

Possibly between 9000 and 7000 BC, lime was already used as a material for cladding and decks and was mixed with stone to form concrete floors. Excavations in southeast of Galilee, in the city of Jericho, have revealed the existence of floors made of a material similar to concrete. In Babylon were employed blocks of clay and bitumen as a binder. The adobe blocks of the first Egyptians pyramids used mortars based on sticky clay from the Nile. Later gypsum and then lime was used.

In ancient Greece, local materials such as volcanic soil mixed with lime were used for the production of pozzolanic binder in the construction of buildings and infrastructure. The use of lime from the calcination of limestone is attributed to Greeks. The lime was used by these people who first mixed with sand and only later combined with a stone called Santorini, which is a pozzolan. The lime used was not a hydraulic binder (hardens by carbonation), but when mixed with a pozzolan it acquires hydraulic properties forming what may be called cement.

Around 1000 BC, in Kamiros on the island of Rhodes, Greece, a storage reservoir of water was built in concrete. Laboratory studies have demonstrated the surprising quality of concrete that has, to date, good physical and mechanical performance, showing that, for three millennia, the Greeks already had a good empirical knowledge of concrete technology. The dosage of the materials (siliceous gravel, medium and fine limestone aggregate, volcanic soil and lime as a binder creating low porosity and good water tightness) was mixed in such proportions that the resulting grading curve practically overlaps the ideal curve proposed by Fuller, twenty centuries later. This concrete is now presenting a compressive strength of about 13.5 MPa (Koui & Ftikos (1998)).

3 ROMAN CONCRETE

In most cases, especially in large buildings and monuments, the traditional construction methods used by the Greeks was the employment of stone columns and beams structural elements to define spaces. The Romans had a different approach and began to use concrete as a structural material, creating large spaces with vaults and domes of great span and height, which until then had never been created. That was made possible through development and use of concrete. The contribution of Roman civilization and the use of *Roman concrete* (*opus cementicium* or *concretus*) revolutionized the Western architecture.

When the Romans conquered the Greek Empire, they assimilated many aspects of Hellenic culture and technology and had by that time a practical-minded, intuitive way of solving engineering problems. By the availability of raw materials, namely cementitious materials, they manufactured hydraulic concrete for the construction of buildings, bathrooms, aqueducts, bridges, roads and other public works in general and spread this type of material throughout the Empire, which expanded across Europe, Asia and Africa.

The Romans left a legacy of extreme importance for future generations, which consisted of the architectural treaty of Marcos Vitruvius Pollio, entitled *De Architectura* (1st century BC and only discovered in 1415). In this treaty Vitruvius explains the way of producing *Roman concrete*.

The excellent quality with which the Roman concrete was produced allowed them to be durable until today. This was due to an extensive artificial pozzolans usage such as calcined kaolinite (*testa*) or calcined volcanic stones (*carbunculus*) and reactive sand, from natural origin, called *harena fossicia*. The reactive material used by the Romans must not be confused with the traditional pozzolan Pozzuoli, near Naples. This, according to Volume II of the Treaty of Vitruvius, was used exclusively in construction works in contact with water or foundations of bridges, while the reactive sand and calcined clay or stones were used in buildings.

Thus, Romans developed concrete technology intensively, giving the name *concretus* to this material, which in Latin means *mixed* or *cast*.

Figure 1. Roman concrete: *opus incertum*, *opus mixtum* and *opus reticulatum*.

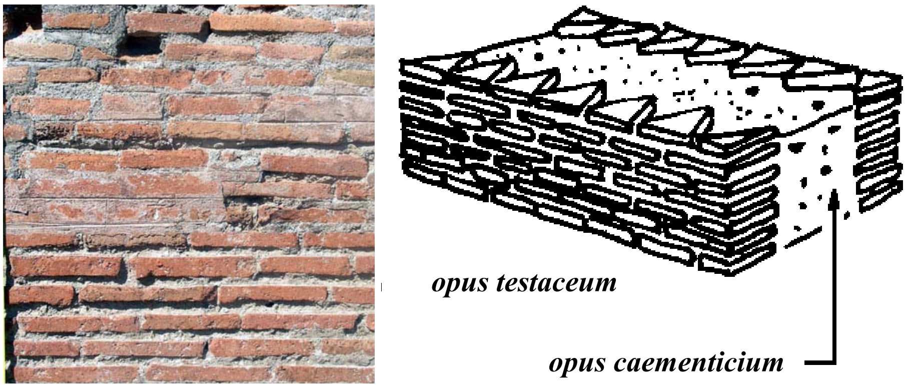

Figure 2. Roman concrete: *opus testaceum*.

For simple concrete structures, Romans used different expressions for concrete according to the material used or how it was disposed on the external sides of the walls. *Opus incertum* when irregular pieces of stone were used (Figure 1); *opus reticulatum*, when the walls were made with square blocks arranged diagonally (Figure 1); *opus testaceum* when they were covered with one or two layers of brick (Figure 2); *opus mixtum* when there was mixture of the above types (Figure 1).

The relatively high compressive strength of *Roman concrete* associated with the knowledge (despite empirical and still somewhat incipient) of resistance of materials and structural behaviour allowed the construction of audacious structures, with arches, vaults and domes of large spans and also, the construction of thinner walls.

The *Roman concrete* has provided substantial technological advances and led to major developments in architecture and engineering. The *Roman concrete* was the most important legacy that Romans left to mankind in the art and technique of building.

4 PORTLAND CEMENT

Since the fall of the Roman Empire, concrete only suffered significant advances with the discovery of portland cement. The technological knowledge that the Romans held was empirical, based on the principle of trial and error, and allowed the discovery of new materials whose properties could be reproduced but not explained. The ability to go beyond empiricism was only acquired by the scientific development occurred mainly from the twentieth century onwards. In fact, no other binder materials were used other than those used by the Romans by the end of the eighteenth century.

Only in the late eighteenth century was there a *concrete renaissance*. A historic landmark of concrete is associated with John Smeaton in 1756, hired with the purpose of building a lighthouse to withstand the harsh conditions of the site. He developed studies to find a binder that while immersed in sea water maintained a high resistance. After several studies he found a hydraulic binder consisting of a mixture of lime with a little gypsum, Italian pozzolan and clay, which brought sand and slag iron. Thus, Smeaton manufactured a concrete. The obtained binder was appointed by Smeaton as cement and he found that this material showed a hardening similar to Portland stone. Hence the origin of the name *portland cement* used even today.

In 1812 Louis Vicat was in charge of the construction of Souillac bridge, in France. During this he began the study of the causes of lime hydration and 5 years later, published the results of their experiments: *Recherches Expérimentales sur les Chaux des Construction, les Bétons et les Mortiers Ordinaires,* which showed that the combination of burned limestone and clay led to the obtaining cement. Souillac bridge was thus the first concrete bridge (not reinforced), and Louis Vicat was considered the inventor of artificial cement.

During 1824 the englishman Joseph Aspdin patented the manufacture of portland cement, by a process similar to the one employed by Vicat, but probably only differed from it because of a higher heating temperature, which allowed him to obtain the tricalcium silicate, thus achieving higher resistance than those obtained by Vicat.

5 REINFORCED CONCRETE

Portland cement concrete, despite its undeniable qualities did not start a revolution in the construction industry. The concrete was not more than an artificial stone which required that the structural design respected the fundamental principles of building in masonry due to the reduced tensile strength, a characteristic of stone materials.

But in 1847 Joshep-Louis Lambot patented a boat in concrete (ferrocement), which was exposed in the Universal Exhibition of Paris in 1855 (Figure 3).

Figure 3. Lambot boat, 1847.

Figure 4. First reinforced concrete bridge, Monier, 1875.

Reinforced concrete (RC) did not have the expected impact, but it caught the attention of a successful Parisian gardener, Joseph Monier. Since then, Monier replaced the wood or ceramic buttonhole previously used (which putrefied or fractured easily) and started to produce concrete boxes for this purpose. Due to the success of the new material and his high strength, Monier registered a patent (1866) and, in turn, began to produce bowls, boxes, water pipes, the first tank (with 25 m^3 in 1868), to build in 1875, its first bridge (Figure 4), a structure of 4 m wide by 16.5 m span, for pedestrian traffic, in Chazelet, France.

Regardless of who was the real inventor of RC, Lambot and Monier can be considered as the precursors of RC. After the discovery of RC, its application in construction spread rapidly. At this time several methods of construction were used and patented. In 1852, François Coignet was the first to apply RC in slab construction. In 1854, W. Wilkinson, of Newcastle, called a patent for a constructive system of RC. The first application of RC in the U.S.A. occurred in 1871/75, on the construction of a building in Port Chester, New York, by W. E. Ward.

Since 1890 RC began to experience a widespread usage, thanks to the achievements of François Hennebique (Figure 5) and the experimental and theoretical studies of Considére, Rabut and Mesnager which established the fundamental laws of resistance applied to RC.

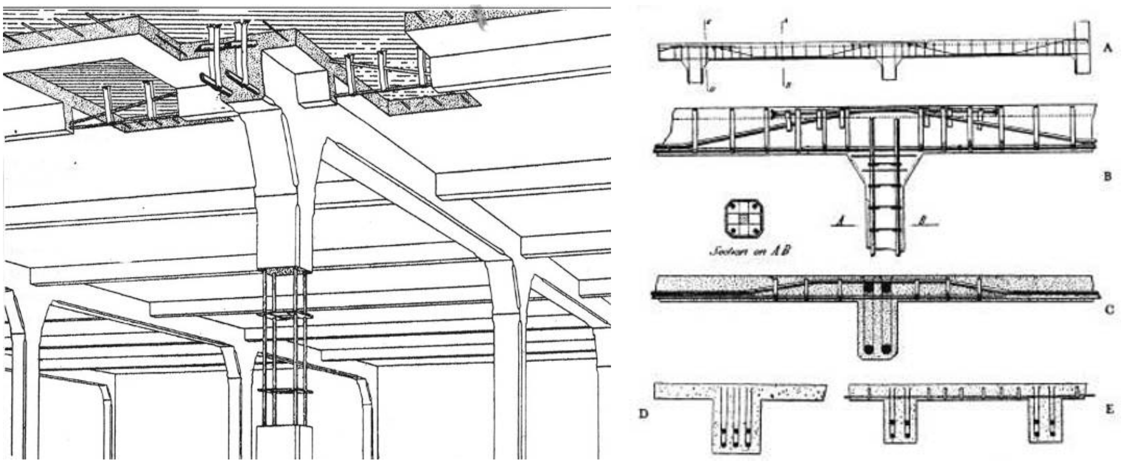

Figure 5. Hennebique system of reinforced concrete.

In 1898 the French architect Auguste Perret begins to exploit the possibilities of RC structural system notably by increasing the aperture of fenestration. The building of the Rue Franklin in Paris, built between 1902 and 1905 is one of the first built with RC structural material, taking advantage of this material, and stands as a landmark in the history of RC.

The consolidation of knowledge about RC created the opportunity to explore new architectural forms, increasingly audacious, and gradually abandoning the construction of wood and masonry.

Since the beginnings of the twentieth century until nowadays, the concrete has been accepted and integrated into new concepts of architecture, played by great masters such as Le Corbusier, Eduardo Torroja, Pier Luigi Nervi, Felix Candela, Frank Lloyd Wright, Eero Saarinen, Oscar Niemeyer, Tadao Ando, Rem Koolhaas and many others.

6 HIGH-PERFORMANCE CONCRETE

High-performance concrete (HPC) emerged as a result of the development of high-strength concrete. Compressive strength has evolved from about 25 MPa to 30 MPa achieved in the 1960s, reaching to 150 MPa nowadays.

The success of HPC is based on the fact that its components do not differ from those used in conventional concrete, requiring only the mandatory use of superplasticizers (SP) and in some cases mineral additions, while retaining the essential conditions of implementation and does not substantially interfere in the processes and equipment commonly used in conventional concrete. The HPC maintains the versatility of conventional concrete and reaches the durability and strength of natural stone but a stone, that can be easily shaped, armed, hard-working pre and post tensioned with cables and mixed with different kind of fibres.

Although the designation HPC is still not consensual and could be considered somewhat ambiguous, to produce a HPC a low value of W/C ratio is compulsory, and for this it is essential to use a high range water reducing admixture, a SP. Thus, a HPC can be reasonably defined as a concrete with a low W/C ratio, less than 0.4. This value is not fixed arbitrarily, and reflects the extreme difficulty or even impossibility, for such values of W/C, to produce workable concrete that can be put into frameworks without the inclusion of a SP.

The amount of binder to be used in the manufacturing of HPC, generally, is greater than 400 kg/m^3 reaching in certain specific cases values of 600 kg/m^3 or even higher (Camões (2002)).

The amount of water to be added should be as small as possible to meet the requirements prescribed for workability. With the use of SP it is possible to have very workable concrete with W/C less than 0.3 and slumps of about 200 mm. Minimizing the amount of water to be added to the mixture and allowing the SP to control the rheological properties of the fresh concrete, one can maximize parameters related to concrete durability. The addition of fly ash (FA) can contribute significantly to reducing W/C, given its expected beneficial effect on workability.

Burj Dubai is currently the tallest building in the world and is also the tallest man-made structure in the world. Its construction began in September 2004 and has been formally opened in January 2010. This is a HPC structure 818 m high with 160 floors on which were used 330,000 m^3 of concrete and 30,000 tonnes of reinforcing steel (www.burjkhalifa.ae (2010)).

Due to its location, the concreting was carried out in adverse conditions. Once the local temperatures reach 50 º C, it was necessary to carry out concreting at night and use the adding of ice to lower the temperature. Due to pumping, the HPC had high workability (slump/flow = 600 mm) which enabled to establish a new world record for pumping height maximum practiced during the construction that reached 601 m, taking the concrete along its course for about 40 minutes. In addition to the high workability, it was also required high compressive strength (28 days required f_k = 80 MPa, 56 days: obtained f_m = 103.5 MPa) and high modulus of elasticity (90 days: required E_{90} = 44 GPa, 56 days: obtained E_{56} = 48 GPa). These characteristics were obtained with a mix-design of concrete containing 13% FA, 10% SF and a water/binder ratio of 0.3.

7 ULTRA HIGH-PERFORMANCE CONCRETE

Despite the high mechanical strength that can be achieved with HPC, it isn’t the most resistant material that can be manufactured with portland cement. With an extreme reduction of porosity it is possible to obtain an ultra high-performance concrete (UHPC). However, these materials have a very limited scope due to its very high price (from € 300,00 to € 1.000,00 per m^3).

UHPC continues to be a cementitious material but is very different from conventional or even high-performance concrete, namely at the micro level. It is in UHPC that the potential for resistance associated with the cement is maximized through the substantially porosity reduction. Many UHPC are made with portland cement, however, some are made with aluminous cement or cement with a very low C_3A content.

This porosity reduction was possible using packing density models for dry granular mixtures, which were already known to spherical particles. Applied to concrete, the validity of these models, however, lacked one essential fact: the cement particles are not spherical. Only when SF addition (which have approximately spherical particles) started to be used and did the study of granular mixtures (cement + SF) using optimization models of compactness turn out to be successful.

Moreover, when trying to obtain mixtures with minimal porosity, portland cement is a major disadvantage, because during the hydration process the volume of hydrated material is smaller than the volume occupied by cement plus water. That is, the cementitious materials increase its porosity during hardening. During hydration there is a volume contraction of about 10%. Thus, there is an additional intrinsic porosity of about 10% in materials made with Portland cement to be taken into account and, if possible, reduced or even cancelled. However, as the hydration reaction does not take place instantaneously, it is possible to eliminate mechanical part of such porosity, putting pressure while the cement paste is still plastic and has not yet developed a sufficient internal cohesion, capable of resisting the external pressure applied.

In this context, a new cementitious material was developed, for which it is necessary to optimize the granular skeleton by using packing density models and reducing shrinkage applying pressure during cure.

The UHPC is a very ductile material for structural applications that requires the inclusion of fibres or to be confined in, for example, steel tubes.

Thus, it is possible to produce a composite material extremely resistant presenting enough ductility, which can be used for very high performance structural applications.

In Table 1 one can see a comparison between conventional concrete (CC), HPC and UHPC (Shah (2000)).

Table 1. Comparison between CC, HPC and UHPC (Shah (2000)).

Parameter	CC	HPC	UHPC
Compressive strength (MPa)	< 50	≅ 100	> 200
W/Binder	> 0.5	≅ 0.3	< 0.2
Chemical admixture	not necessary	SP necessary	SP essential
Mineral addition	not necessary	FA or SF current	SF or ultra-fine essential
Fibres	beneficial	beneficial	essential
Air entraining agent	necessary	necessary	not necessary
Processing	conventional	conventional	thermal treatment plus pressure
Chloride diffusion coefficient (steady state) ($x10^{-12}$ m^2/s)	1	0.6	0.02

Depending on how it is achieved the very high compactness required, several authors have proposed different types of UHPC, for example, the DSP (densified with small particles), the MDF (macro defect free) or the RPC (reactive powdered concrete). Among UHPC the RPC has been the most successful, with practical application and having the following main characteristics:

- much more homogeneous than a HPC due to the limited size of the particles (<300 μm);
- increased density of the mixture using optimum granular mixtures;
- pressure application during the initial phase of hardening, reducing shrinkage;
- microstructure improvement through heat treatment;
- improved ductility by introducing selected metallic microfibers.

The microstructure of RPC is quite different from other types of concrete, as is evident from observing Figure 7, which compares the microstructure of a HPC with a RPC (photos at the same scale) (Dugat et al (1996)).

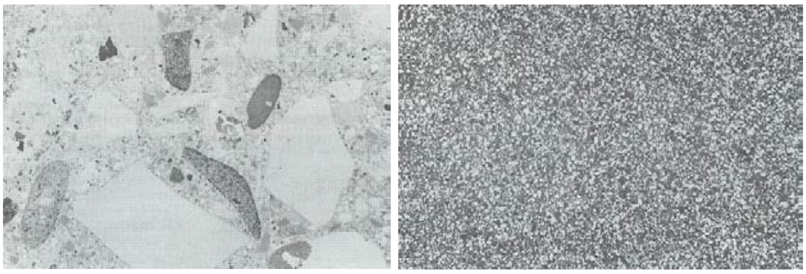

Figure 7. Microstructure of a HPC (left) and an RPC (right).

Figure 8. LRT Train Station, Shawnessy, Canada, 2003. Selfcompacting RPC. Shell thickness: 20 mm.

The low porosity of the RPC is the basis of the excellent properties related to durability and transport mechanisms, which allows its application to store nuclear waste with high radioactivity.

This kind of concrete has been applied, namely in the construction of pedestrian bridges and thinner slabs and shells (Figure 8).

8 CONCLUSIONS

After water, concrete is the second most consumed material by men and it has been used since ancient times.

The technological evolution since pre-roman concrete was most influenced by the discovery of portland cement in the early years of the XIX century. Since then, high-performance concrete and ultra high-performance concrete are the most recent evolutions of this kind of structural construction material.

The HPC, primarily due to its high durability, is particularly suited for structures located in particularly aggressive environments. The use of this type of concrete allows structures to have an estimated high service life of 100 or more years and can be considered as one of the largest developments in technology suffered on concrete. However, this development can not be regarded as revolutionary and the HPC should be understood as an evolution of conventional concrete. The main difference between conventional and HPC is that the HPC must include SP that allows a substantial reduction of the W/Binder ratio below to 0.4.

The HPC is manufactured, in general, using high cement content, and is endowed with high mechanical strength and durability. However, for most practical applications, the compressive strength of a conventional concrete is sufficient. However, it is unlikely that this HPC will be used everywhere, but they will, as now, be applied in particular situations such as bridges and tall buildings.

HPC is not the most resistant and the most durable concrete that is possible to make with portland cement. By a very high porosity reducing, thermal treatment and applied pressure during curing period, it is possible to produce an even better concrete: an ultra high-performance concrete. With such a concrete, when reinforced with fibres, one can produce elements with tensile strength similar to the steel ones. However, this kind of concrete has a limited application because of its extremely high price.

9 REFERENCES

Aïtcin, P.-C. 1992. The use of superplasticizers in high performance concrete. *High performance concrete – from material to structure*, Yves Malier ed., E&FN SPON, London, 14-33.

Camões, A. 2002. *High performance concrete with fly ash incorporation*. PhD thesis, University of Minho, in Portuguese.

Dugat, J., Frouin, L. & Clavaud, B. 1996. RPC : Microstructure analysis, *4th International Syposium on Utilization of High-strenght/High-performance Concrete*, Paris, pp. 1351-1357.

Koui, M & Ftikos, Ch.. 1998. The ancient Kamirian water storage tank: A proof of concrete technology and durability for three millenniums. *Materials and Structures*, Vol. 31, pp. 623-627.

Larrard, F. 1992. Ultra fine particles for making very high performance concretes. *High performance concrete – from material to structure*, Yves Malier ed., E&FN SPON, London, 34-47.

Richards, P. 1996. Reactive powder concrete: a new ultra-high strength cementitious material, *4th International Syposium on Utilization of High-strenght/High-performance Concrete*, Paris, pp. 1343-1349.

Shah, S.P. 2000. High performance concrete: past, present and future. International symposium *High performance concrete – workability, strength and durability*. Hong-Kong and Shenzhen, China, Volume 1, pp. 3-29.

www.burjkhalifa.ae, accessed in February 2010.