Concretes for the 21st century

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• Chronolia™
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INTRODUCTION

As part of the Excellence 2008 strategic plan, innovation in concrete is clearly identified as one of the Group's key strategic priorities for the coming years.

Bruno Lafont, Chairman and CEO of Lafarge:

"Innovation has to be one of the driving forces in our strategy. We intend to increase the lead on our competitors by making the most of our strong research potential and our ability to launch new products on the market, generating added value for our customers".

As a pioneering force in concrete innovation, Lafarge has launched several new concrete products over the last few years. These include Ductal®, Agilia® and Artevia®, now worldwide brand names. These innovations were made possible by in-depth knowledge of cement, additives, aggregates and the interaction between these materials in concrete production, developed by Lafarge in the last 15 years.
WHAT IS CONCRETE?

Concrete: a mixture of cement, crushed stone (aggregates) and sand, to which you add water, thus forming a mineral material that is as resistant as stone. This apparently simple definition belies the outstanding properties of a material also referred to as “liquid stone”.

Houses, offices, hospitals, roads, bridges, tunnels, dams, ports... none of these structures would be possible without concrete, whose qualities and regular performance have made it the second most used product in the world, after water.

Outstanding properties

The popularity of concrete in today's world - and most likely in tomorrow’s world as well - can be attributed essentially to a set of unique and unparalleled qualities that are highly valued in the construction industry:

- **mechanical resistance**: concrete has excellent compressive strength, ranging from 20MPa (2kg/mm²) up to 200MPa in the case of the strongest concretes, making it eminently suitable for building foundations and bridge pylons, for example. Embedded steel reinforcement gives “reinforced concrete” traction qualities that make it a very versatile construction material.

- **durability**: research into concrete mix formulation and greater control over its behavioural mechanisms have led to improved performance in terms of durability. As a result, structures such as the Millau Viaduct or the Channel Tunnel can be guaranteed for over 100 years.

- the **thermal inertia** of a material is its ability to store thermal flows for subsequent slow release. It is a highly sought-after property in buildings, as it contributes to thermal comfort and saves on air conditioning and heating, thereby helping to combat climate change. Concrete, as a kind of reconstituted stone, has a high density (2400kg/m³) that gives it great capacity for accumulating and absorbing heat.

- **acoustic comfort**: concrete, being a dense material, does not transmit the vibrations of sound waves, making it eminently suitable for motorway noise-control walls, for example.

- **fire resistance**: when exposed to flames and heat, concrete does not “melt” or burn, so does not release toxic fumes or gases. Moreover, its low thermal conductivity stops heat from spreading throughout the building.

Concrete is a very versatile material that can be adapted to meet widely differing needs. Thanks to "made-to-measure" mix designs, it offers a unique solution for architectural creativity.
WHY INNOVATE IN CONCRETE?

While it appears to be a simple material on the surface, concrete is in fact highly complex with thousands of different applications and formulations. Recent years have witnessed a revolution in this field with the appearance of ultra-high performance concrete, offering increased ductility, durability and resistance, in addition to self-placing concretes which significantly enhance aesthetic appearance and facilitate use on the building site. These innovations would not have been possible without significant scientific research to understand the behavioral mechanisms of concrete on a nanometric scale.

Meeting customers’ increasingly complex requirements

With their exceptional qualities, these materials meet the increasingly complex requirements of architects, engineers, owners and contractors. Designers and builders working with concrete want to create more lightweight structures, with more sophisticated forms using concrete with a more aesthetic appearance. They are seeking more durable and resistant concrete offering enhanced acoustic and thermal insulation properties.

Limiting environmental impact

The building sector is responsible for about 40% of worldwide greenhouse gas emissions. New solutions must therefore be found to reduce the ecological footprint of buildings. This obviously involves reducing CO₂ emissions linked to the production of construction materials. Lafarge has been working on this for several years, particularly through its voluntary commitment to reduce its worldwide emissions by 20% per ton of cement between 1990 and 2010.¹ However, about 80% of CO₂ emissions from a building stem from use throughout its service life. It is therefore necessary to rethink building systems to design buildings which consume less energy. Concrete can play a key role in this through its thermal inertia. Lafarge is also developing new concretes that are lighter, more resistant, offering a higher performance and that require fewer raw materials and less energy to produce.

¹ By the end of 2006, these emissions had fallen by 14.2% compared with 1990
How to Innovate in Concrete?

Concrete is a mixture of cement, aggregates and sand. When water is added to this mixture, it sets, meaning that the mixture hardens. In the past, there was no detailed study of the highly specific scientific process behind this phenomenon. Formulae were established, implemented, and the result was observed. This was therefore an empirical approach.

Research into cement and concrete has intensified with the adoption of an approach based on scientific understanding. Lafarge has been a pioneer in this field, having decided several years ago to focus its research on products rather than industrial process and setting up numerous partnerships with the world’s most prestigious universities and research centers.

Today, we try to identify the physical, chemical and physico-chemical phenomena underlying the behavior of concrete and to understand them. This is possible using the different techniques and instruments developed over the last few years: nuclear magnetic resonance, scanning or transmission electron microscopy, atomic force microscopy, nano-indentation and synchrotron radiation.

All these tools allow us to observe and better understand the physico-chemical phenomena of materials on a nanometric scale. Today therefore, we can produce a better structured material with properties boasting a significant improvement on those obtained twenty years ago. They allow the construction of structures such as the Millau Viaduct, which is a genuine technological prowess in itself that would have been impossible to achieve ten years ago. Altogether, Lafarge supplied 35,000 tons of cement as well as concrete for the bridge’s foundations and pilings – some of which reach as high as 245 meters – which harmonize with the metal deck and towers to create a brilliant blend of leading-edge technology and elegance.

Innovation at Lafarge: effective organization of Research & Product Development

Over 500 people worldwide work for Lafarge in Research & Development with the sole aim of inventing to build better in the future, by proposing new solutions which generate value for the entire building profession and reduce environmental impact.

Research: the Group currently boasts the world’s leading building materials research facility with the Lafarge Research Center (LCR) at L’Isle d’Abeau in France, which houses 6000m² of laboratory space equipped with highly sophisticated testing and analysis instruments. This research facility was set up in 1990 and now employs over 200 researchers of about ten different nationalities, working to understand basic mechanisms and validate technological breakthroughs.
LCR's research is organized by field of activity: Cement, Aggregate & Concrete and Gypsum, and by field of expertise, thus optimizing resource allocation and synergies between the teams. Teams work on understanding physical or chemical mechanisms occurring in the materials, as well as on product development projects and long-term research studies in four areas of multi-product expertise:

- Active components (mineralogy, the physico-chemical properties of cement, gypsum and additives, powder technology)
- Structured materials (concrete, mortar and gypsum rheology, the micro-mechanics of hardened materials)
- Formulation and implementation (generation of formulation rules; materials-process interface)
- Analyses and Measurements (characterization techniques: DX, FX, MEB, laser granulometry, etc.).

Current research into concrete is focusing on the development of a new range of concrete products to better meet customer challenges in terms of cracking, setting and hardening, site productivity, robustness, resistance, durability and esthetic appearance. As part of this, the L’Isle d’Abeau teams are also working to improve cement properties (consistency, ease of use, setting time, resistance in the first few hours, etc.) for greater control and more appropriate use.

Research is discontinued if the end-product is not better than or at least equivalent to the existing product in terms of sustainable development. The specific aim is to reduce the environmental impact of materials, preserve natural resources, generalize the use of recycled raw materials and reduce energy bills.

The Lafarge research teams work in regular collaboration with the most prestigious universities and engineering schools. These include the French Ecole Polytechnique and Ecole des Ponts, MIT (Massachusetts Institute of Technology), Berkeley and Princeton University in the United States, the Laval and Sherbrooke Universities in Canada, and the Lausanne Ecole Polytechnique Fédérale in Switzerland.
In 2002, Lafarge signed a framework agreement with the CNRS (France's national scientific research center), the largest facility for fundamental research in Europe. This aims to facilitate and encourage the development of joint research projects through staff secondment, cofinancing of theses or the creation of Mixed Research Units. Thus for Ductal concrete, about ten CNRS laboratories worked with Lafarge on Reactive Powder Concrete.

**Development:** organized by activity and region, the Technical Centers work closely with the research teams to develop and industrialize new products by promoting knowledge and technical know-how transfer between countries. To achieve this, each technical center has its own analysis laboratory and a product application laboratory, run by top specialists in the fundamental technical areas comprising our businesses.

**Key dates in concrete innovation at Lafarge**

- Opening of the Research Laboratory, the oldest research facility in the world in the cement industry
- Contribution to the development of high-performance concrete products
- Launch of two major innovations: Ductal® (ultra-high-performance concrete) and Agilia (self-placing or self-leveling concrete)
- Launch of Sensium®, a range of dust-free technological cements
- Development of water-reducer additives, for fluid concrete
- Creation of the Research Center at L’Isle d’Abeau: R&D is now focused on products and not production processes
- Launch of Artevia®, a range of decorative concrete products for outdoor applications
- Launch of Extensia™, concrete for large surfaces, and Chronolia™, quick-setting concrete
Partnerships

Today, Lafarge believes that its commitment to society must go beyond the boundaries of its own industrial sites to cover the entire value creation chain in the building industry, from its suppliers to its end-customers, to better understand the impact of its products throughout their entire life span.

Lafarge is putting this belief into practice by working with a host of partners to promote and collaborate on more sustainable materials:

- The Nanocem European Research Network was set up in 2004 and federates 12 European cement manufacturers, including Lafarge, and twenty-one academic institutions in a bid to further knowledge about construction materials. Combining company R&D with European scientific research and federating motivation and resources generate the tools and skills essential for identifying, analyzing and understanding the basic mechanisms behind cement and concrete behavior, which are the most used materials in the world.

- In 2006, an Education and Research Chair on “The Science of Materials for Sustainable Construction” was created, combining the scientific skills of France’s Ecole Polytechnique and Ecole des Ponts engineering schools with the expertise of Lafarge’s research facility (LCR) at L’Isle d’Abeau. This Chair aims to develop the scientific bases required for the interdisciplinary and multi-level approach to construction materials engineering. It also includes a high-level scientific seminar organized at the MIT on the new prospects opened up by molecular calculus, and provides opportunities for numerous formal and informal exchanges between the students, teachers and researchers from various teaching and research institutions.

- With the WBCSD (World Business Council for Sustainable Development) grouping together 180 companies, Lafarge is the driving force behind the creation and management of the five-year action program called “Towards a sustainable cement industry”. The 19 cement companies involved in this unique sector-wide initiative are seeking solutions to protect the climate and reduce fuel and raw materials consumption.

- In 2006, Lafarge joined forces with United Technologies Corp., within the WBCSD, to create the EEB – Energy Efficiency in Buildings project to identify the changes needed to design energy self-sufficient buildings.

- Lafarge has also set up partnerships with architects. Significant work has been undertaken with them to promote advancement in building methods (aesthetic appearance, height, new designs, energy efficiency) and pave the way for sustainable construction. For example, the Group has worked alongside Jacques Ferrier on the concept of an environmentally responsible tower building called “Hypergreen.”
Lafarge Innovations in Concrete

Over the last decade, Lafarge has been at the forefront of fundamental innovations in concrete, in particular with Agilia®, a range of self-placing and self-leveling concrete products, and Ductal®, ultra-high performance concrete, as well as in gypsum with Signa™, a revolutionary plasterboard, and in cement with Sensium®, a range of technological dust-free cements. Major innovations have also improved production processes, thus reducing energy consumption and the effects on the environment during material manufacturing.

As part of the Excellence 2008 strategic plan, Lafarge has developed two new concrete products called Chronolia™ and Extensia™, which represent real technological breakthrough for the building sector. With each one designed to meet a specific challenge in the building sector, these two products are the outcome of several years of work at the Lafarge Research Center at L'Isle d'Abeau, combined with field tests to validate the work of our researchers. These two value-added products will initially be rolled out in France, the UK and North America.
Chronolia™ is a quick-setting ready-mix concrete, developed to meet a specific challenge in the building sector: how to save time on the building site.

Chronolia™ combines two features requested by customers, which were previously a contradiction in terms: non-responsive for 2 hours after manufacture to enable it to be transported and handled in normal building site conditions like any normal fluid concrete, and then hyper-responsive to quickly develop high mechanical strength once it is poured. Combining these two requirements was a real technological challenge, made possible by progress in nanotechnology and the understanding of crystalline growth, and by making the most of new additive molecules and chemical concepts in terms of formulation developed at Lafarge’s Research Center.

Concrete which sets in record time, …

Chronolia™ is a brand new, high performance product, which sets in record time. Whereas between 12 and 20 hours are needed before the formwork can be removed with conventional concrete, this can be done in just 4 hours with Chronolia™.

Chronolia™’s fast work times allow time-saving and optimization of building site organization.

… but which offers the same flexibility as conventional ready-mix concrete

Chronolia™ offers two hours of workability like conventional ready-mix concrete and it can be laid in the standard manner due to its fluidity. It can be transported, handled and cast for two hours without its workability features being affected and in any climatic conditions. It can therefore be used for all conventional ready-mix concrete applications.
A host of advantages for customers

Chronolia™ makes it possible to double the number of daily formwork/formwork removal operations on a standard building site. This obviously allows considerable productivity gains. For example, weight-bearing on wall beams is possible on the same day and work can continue without having to wait until the next day. For civil engineering work, a road can be used again three times more quickly than when conventional concrete is used. This also makes it possible to catch up on any delays accumulated on a site, e.g. through bad weather, and thus avoid late penalties being applied.

Chronolia™ also allows complete upstream reorganization of a site in terms of deadlines, cycle times and equipment use, as well as cost, e.g. regarding formwork equipment hire time, as this is used twice as fast.
Extensia™ is a low-shrinkage concrete designed for use in the construction of ground-bearing slabs for industrial, warehouse and commercial floors. Extensia™ is designed to reduce cracking in concrete slabs and the resulting requirement to install unsightly and costly control joints to the same degree as in conventional concrete.

**Joint-free slabs as large as 400m²**

Industrial concrete floors are made up of concrete slabs with induced joints within them, at 5m x 5m sections. Significant maintenance of these joints is required with a traditional concrete. With Extensia™, saw-cut sections can be extended to up to 20m x 20m. With fewer joints to maintain, superior resistance to abrasion and reduced curling at the joints (reduced shrinkage) than traditional concretes, Extensia™ offers significant savings in maintenance costs.

**Rapid execution for early loading**

Extensia™ has three essential characteristics that translate into significant time savings on the building site and early loading:

- no addition of steel mesh or fibers is required
- its level of fluidity makes it easier to install
- Extensia™ sets faster than conventional concretes, and achieves high early strengths, which means that a floor made with Extensia™ can be completed more quickly and can be loaded after only 14 days, compared to 28 days for conventional concretes.
Higher mechanical resistance

Extensia™ presents a higher level of mechanical performance than traditional concretes, with higher compressive and flexural strength. This allows a reduction in slab thickness compared to conventional concrete. Moreover, since floors made with Extensia™ are substantially stronger than those made with conventional concrete, greater variability in terms of end use is achievable for a particular floor.

A reduced environmental footprint

Thinner slabs for Extensia™ floors mean a significant reduction in the raw materials needed. This coupled with the fact that no steel mesh or steel fibers are required, means lower CO₂ emissions linked to the production of an Extensia™ slab.
Agilia® is a self-placing, self-leveling concrete which was launched in France in 2000 and is currently marketed in France, the UK, the United States, Canada and Turkey. Agilia® will be available in Chile and Spain in 2007.

**AGILIA®, the world’s first self-placing, self-leveling concrete**

- **Easy to use**, attractive and ergonomic, offering higher quality results

- **Exceptional fluidity**, to effortlessly fill in all the corners and spaces in formwork or moulds, thus avoiding some of the more physical and noisy steps on a building site, such as vibration

- **Quick** to use, and offering high-quality results when used with care

- **Generating value for our customers**, by reducing overall production costs through productivity gains

- Illustrates the **success of our vertical integration strategy**: Cement / Aggregate / Concrete

**AGILIA® in figures**

- Agilia® generated 2.4% of sales volumes and 12% of COI for Lafarge’s Concrete business in 2006

- Volumes sold 2006: 1 million m³

- Outlook for 2008: doubling of sales and profits

- Lafarge North America currently holds the record for the largest continuous cast concrete slab with Agilia®: 3114 m³ in Toronto

- In 2006, Agilia® sales rose by 33%

**AGILIA®, examples of structures**

- Agilia® serving **Le Corbusier, Saint-Pierre de Firminy Church**, in France’s Rhône-Alpes region. The St Pierre de Firminy Church is a classified building which embodies the vision of an architect whose use of oblique lines is a celebration of the harmony between buildings and nature. Agilia®’s fluidity makes it an ideal choice for complex structures.

- Agilia® for **the world’s largest aquarium in Atlanta, Georgia** (USA) housing over 100,000 animals, living in millions of litres of water held by Agilia® walls.

- Agilia® for a **residential building in Vancouver**, British Columbia, boasting a combination of Architectural, Horizontal and Vertical Agilia® products. Agilia® was used for all the inside and outside walls, and for the 22 figures cast on site.

For further information: [http://www.lafarge-betons.com/](http://www.lafarge-betons.com/)
Artevia® is a range of decorative concrete products for outdoor applications offering esthetic, economic and durable solutions thanks to the properties offered by concrete. Launched in 2004, Artevia® is now available in a dozen countries. Volumes sold increased by 35% in 2006. The Artevia® range of decorative concrete products includes: Artevia Roche, Artevia Poli, Artevia Color, Artevia Empreinte and Artevia Sable.

### ARTEVIA®, Advantages

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<th>Benefits</th>
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<tr>
<td>• Excellent adaptation to complex shapes</td>
<td>• Blends esthetically into the surroundings respecting the architectural environment</td>
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<td>• Quick installation, low maintenance</td>
<td>• Enhances the regional character of the surface by using aggregates sourced locally</td>
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<tr>
<td>• Durability</td>
<td>• Flexible creative design options through varied colours and surface appearances</td>
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<tr>
<td>• Resistance to wear and tear</td>
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### ARTEVIA®, esthetic concrete

- **Artevia Empreinte** concrete can be used for developing surfaces with a host of prints (blocks, slabs).

- **Artevia Color** is a process-coloured concrete offering a host of creative design options for outside applications.

- **Artevia Sable** is a mix with a sand and clear cement base which gives the rustic appearance of sand without the disadvantages (no mud or dust).

### ARTEVIA®, decorative concrete

- **Artevia Relief** concrete displays the aggregates on the surface of the concrete in relief.

- **Artevia Roche** concrete offers a surface appearance similar to that of natural cut stone.

- **Artevia Poli** decorative concrete produces a smooth marble-like polished finish. Can be used for interior applications.
Ductal® is ultra-high performance concrete launched in 2001. Ductal® combines technical performance and esthetics thanks to its high mechanical resistance, flexibility and ease of use.

**DUCTAL®, fibre-reinforced, ultra-high performance concrete**
- **Compressive strength**: 6 to 8 times higher than traditional concrete
- **Flexural strength**: 10 times higher than traditional concrete
- **Ductility**: deformability under excess weight without breaking
- **Superior surface quality**
- **Long service life**: aggression-resistant, Ductal® is 100 times more durable than reference standards
- **Fluid, easy to cast**: it can replicate the most minute of formwork details.

**DUCTAL®, a sustainable material**
- **Its thermal properties** help to reduce energy consumption in the home and thus greenhouse gas emissions
- **Its production** requires fewer natural resources and less energy than traditional concrete, thus limiting production-related CO2 emissions

**Ductal® solution**

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<th>Primary Energy</th>
<th>CO2 Emissions</th>
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<tbody>
<tr>
<td>54</td>
<td>47</td>
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Comparison between a Ductal® solution and a mixed concrete/steel solution to build a bridge, in terms of raw materials consumption, energy consumption and CO2 emissions.

**DUCTAL®, examples of projects and structures**

- **Footbridge of Peace** in Seoul spanning 130m with its deck a mere 3cm thick for an end beam static height of 1.30m, designed by architect Rudy Ricciotti. It was opened in Seoul in April 2002 and stretches across the Han river to join the Sunyudo Island, a natural park, at the heart of South Korea’s capital.

- **RATP Bus Office in Thiais, France**, this Ductal® clad new peri-urban type building combines functionality with esthetical appearance. Completely in keeping with the surrounding environment, it offers a modern and attractive visual experience. It was designed by architects Emmanuel Combarel and Dominique Marrec.

- **Hypergreen**, the concept of a versatile and environmentally-friendly tower building, able to generate most of the energy required for its own needs and developed in partnership with the architect Jacques Ferrier. It was showcased at the MIPIM in 2006.

- **MUCEM, Musée des Civilisations d’Europe et de la Méditerranée**, this museum building is “a mineral building in a desert of light”, according to architect Rudy Ricciotti, who designed it as a glass structure enshrouded by a mantel of Ductal®. When finished in 2011, it will be located at the foot of Marseilles’ Saint-Jean Fort and the entrance to the Port de la Joliette.

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