The next generation of Ultra-High-Performance Concrete

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Abstract:

In the 1980's, the laboratories of AALBORG PORTLAND A/S, in Denmark, conducted pioneering research to develop very dense cement-based binder-matrices, in order to fully exploit the performance of concrete. These efforts based on the AALBORG WHITE® Portland cement resulted in the first ever patented ultra-high performance steel fiber reinforced concrete – bearing the name Compact Reinforced Composite, CRC®. Now an Innovation Team from AALBORG PORTLAND's parent company Cementir Holding is further developing the very complex binder technology behind Ultra-High-Performance Concrete (UHPC) with an optimized mixture of materials. This technology is based on a further refinement of Cementir Holdings recently patented binder technology, FUTURECEM™. This product employs a unique selection of binder components already well known to the cement and concrete industry to provide highly advantageous pozzolanic reactions. It has the advantage of not being constrained by the availability and quality of waste materials from other industries.

This paper will describe the principles behind the technology, the performance parameters that can be achieved and outline the benefits that can be realized with this new material. In addition, this paper will make the case that UHPC has the potential to become the most sustainable of construction materials. It aligns perfectly with societal megatrends that favor fast-track construction, prefabricated building components and ease of installation all while delivering on the promise of low weight and enduring aesthetics. UHPC is highly efficient in material optimization with excellent strength to mass ratios. Properly designed and installed UHPC building elements yield high energy efficiency, great resilience and durability, are low maintenance and can have a high degree of component reuse. A great deal of attention is placed on the impressive strength of these materials, however the sustainable design potential for their use will come from other performance parameters such as the ability to safely reduce the amount of cover over reinforcing. To fully realize UHPC's potential, mixtures must perfectly balance component chemistry and particle packing to minimize shrinkage and cracking, have low permeability and in architectural applications, provide good aesthetics. This paper will demonstrate an innovative approach to achieving these goals and exceed the most optimistic aspirations of the CRC® pioneers that introduced the world to UHPC.

Keywords: ultra-high-performance concrete, UHPC, fiber-reinforced concrete, durability, pozzolan, CRC, DSP.

1. Introduction

Our modern world is constantly developing with an accelerated increase in population. More and more efficient construction materials are required to fulfill the huge demand for beautiful, durable, and ecologically sustainable building solutions. Concrete in its many varieties is the world's construction material of choice. Its versatility, resilience, ease of use and relatively low-cost fosters inventiveness and encourages diverse applications which in turn create a continuous need for state-of-the-art cementitious product types. UHPC is one such product.

The creation of Ultra-High-Performance Concrete in the 1980s represented a break though in concrete innovation (Bache 1987). This new material achieved ultra-high compressive strength, exceptional durability and with the addition of fibers, an extraordinary ductile behaviour. It has taken decades for researchers and structural engineers from around the world to recognize how these features could be game changers in the construction business. It is now widely recognized that UHPC construction elements can be much thinner and therefore lighter-weight than traditional elements, furthermore its low permeability makes it suitable for use in aggressive environments. Building projects that exploit these advantages realize the benefits of material optimization, improved logistics, reduced environmental impacts and lower costs.

Even though UHPC has been available for more than two decades, there is no worldwide agreement on how to classify the material. The most used European standard characterizing UHPC is French standard NF P 18-470 (2016) which classifies UHPC based on the unconfined compressive strength of cylinders with nominal dimensions of 110 mm x 220 mm. According to this standard, UHPC for non-structural or architectural applications must have a 28-day compressive strength around 130 MPa while structural applications must achieve compressive strength of at least 150 MPa at 28-days. It also requires structural applications make use of steel fibers while non-structural applications can use a wide range of fiber types. In contrast in 2018 the American Concrete Institute published ACI 239R-18 "Ultra-High-Performance Concrete: An Emerging Technology Report", which defines ultra-high-performance concrete as having a minimum compressive strength of 22,000 psi (150MPa) and discusses the role of fibers to impart ductility to the material.

What these different camps generally agree on is a reliance on a mixture formulation established decades ago having a high binder content 2,000 – 2,550 lbs/cy (900 – 1,150 kg/m^3) which includes a high percentage of silica fume with or without quartz flour for improved packing. These mixtures utilize high-range water reducers and ultra-low water to binder ratios in the order of 0.15 to 0.25 with aggregates generally no bigger than 3mm. Autogenous shrinkage should be monitored when using these mixtures. Unrestrained one-dimensional shrinkage for traditional UHPC mixtures without fibers can range between 0.08 to 0.12 % (800-1,200 µm/m) or higher. In some cases, the use of shrinkage compensating admixtures is needed to prevent shrinkage cracking (Habel et. al 2006). When properly combined these formulations can reliably achieve compressive strengths of 22,000 psi (150 MPa) and tensile strengths of 1,150 psi (8 MPa) or greater.

Cementir Holdings' premixed AALBORG EXTREME® UHPC product is based on the sustainable, FUTURECEM™ patented binder technology. At its core this patent is based on a formulation and method of cement production which combines Portland cement clinker and supplementary cementitious materials derived from heat-treated siliceous and carbonate materials. The formulation does not include the use of scarce natural materials or waste materials from other industries such as silica fume which can be subject to volatile swings in quality, availability and cost.

The primary beneficial attributes of this new binder formulation are documented along with an accounting of its achievable hardened state performance. It also sets expectations for mixing the AALBORG EXTREME® and its behaviour in its plastic state. This paper will outline how the product was engineered to deliver on the key performance targets of high flowability with a minimum 45-minutes of working time, high durability, and low shrinkage in a white Ultra-High-Performance Concrete.

2. Background

Early work on UHPC mixtures and development started in the Cement & Concrete laboratory of Aalborg Portland in Denmark during the 1970s. One of the first successful attempts resulted in a material called densified systems containing homogeneously arranged ultrafine particles (DSP). This formulation of DSP primary used ultra-fine cement and later included the addition of silica fume. Using a specific curing process, DSP was able to reach the strength of 128 MPa at 24h (Bache 1987). The same team continued the study of this new type of concrete material and in 1986 they developed a less brittle composite known as Compact Reinforced Composite. This product is still in use today and is based on a very high strength, fiber reinforced cementitious matrix and conventional steel reinforcement in high percentage (Aarup 2009).

The technology and know-how applied to create DSP and CRC technology are the basis for most modern UHPC mixtures. Commercial applications for these products have expanded and grown since the 1990s. However, in spite of the mixture technology being almost 40 years old, it has changed little from the original recipes based on silica fume and quartz flours. Our engineers asked themselves what could be improved and how a new generation of UHPC could be formulated to rely on abundant natural resources while maintaining the impressive performance being achieved in the concrete building materials marketplace.

3. UHPC Re-engineered

Commencing early in this decade Cementir Group has committed a great deal of resources into research on sustainable cement production and reducing CO_2 emissions. These efforts have culminated in the development of new patented binder technologies which in turn hold great promise in achieving a more sustainable general use concrete. This technology is also at the core of and inspiration for the binder composition of the new type of ultra-high-performance concrete described in this paper.

Our materials engineers asked themselves an important question. Could this new technology be developed with the guiding criteria of creating a new generation of sustainable concrete to meet market demand for more efficient construction materials? Could they use this technology to produce a sustainable concrete mixture that met the expectations for a typical UHPC and would also meet the demand for building materials that can be as beautiful as it is durable? As demonstrated via the testing described and the results achieved the answer is yes; UHPC can be re-engineered to use more common materials to deliver practical production benefits.

4. Testing Methods

Tests procedures are divided in three sections: fresh state properties, hardened state properties and durability parameters. For fresh properties, flow was measured in laboratory mixtures as described in ASTM C1437 without applying the described drops. The hydration kinetics were followed by isothermal calorimetry conducted per ASTM C1679 in order to evaluate the influence of admixtures like retarders and high-range water reducers on the hydration of the cement phases. Production sized batches were tested for slump flow in accordance with ASTM C1611 (Fig 1).

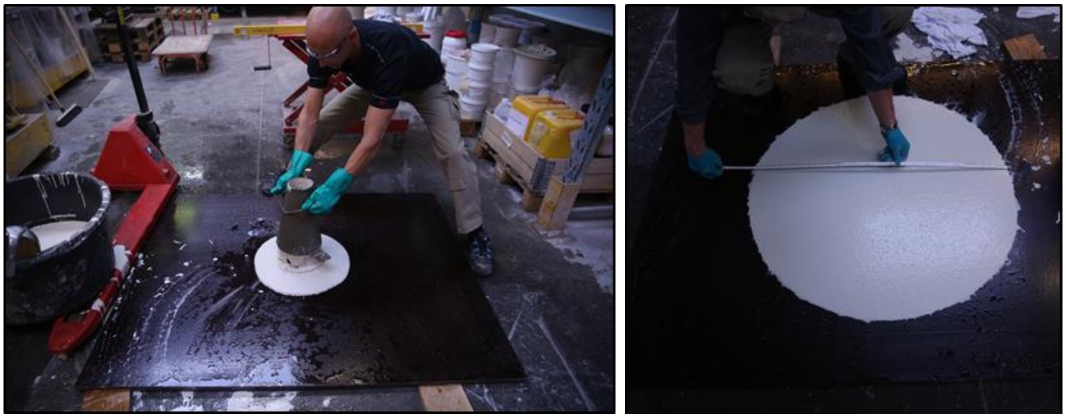

Figure 1. Flow test according to ASTM C1611– 18

Because all the research work took place at the Research and Quality Center of Aalborg Portland in Denmark, all the hardened state properties and mechanical properties were measured using European Standards. The specimens for mechanical testing were cured in sealed molds at 20 °C for 24h, followed by demolding and water-curing at 20 °C until the date of the test. Shrinkage specimens prepared per EN 12617-4 were cured in the laboratory at 20° C and 50% RH until the date of the test. Table 1 includes all the methods employed for assessment of hardened state properties and mechanical properties of the material.

Durability indicators measured as chloride migration, freeze-thaw resistance and water absorption were also analyzed; test methods applied along with the results are shown in Table 2.

5. Material

The portland cement used for the mix was AALBORG WHITE®, produced in Aalborg Portland plant located in Denmark. Newly developed powdered polycarboxylate ether high-range water reducers were added to the intermixed binders. In addition to the cement the binder combination is composed mainly of ultra-fine limestone and white calcined clay, in a fixed proportion according to the FUTURECEM™ patent. The remainder of the UHPC mix consists of quartz sand to a maximum size of 3 mm.

From the beginning, it was decided to avoid the use of silica flour to avoid Health and Safety risks related to its content of respirable quartz silica. Furthermore, it was the development team's goal to leverage the highly advantageous pozzolanic reactions achievable through the use of calcined clay and thereby reducing discoloration and the variability associated with SCMs generated as waste materials from other industries, such as silica fume, fly ash, ground granulated blast furnace slag, etc.

As the market for UHPC tends to be global components have been carefully selected to ensure low total chloride and alkali contents. This ensures the mixture will meet strict regional limits on chloride content and enable the use of the AALBORG EXTREME® in combination with the standard steel reinforcement required in typical specifications for structural concrete design.

6. Results

6.1. First attempts.

One of the main challenges when formulating UHPC is the adjustment of the workability. This property is especially crucial in architectural applications where proper distribution within the forms or molds is the key to clean accurate reflection of intricate details built into the forms or when using decorative form liners. Due to high fine particle loading and low water content, UHPC mixtures tend to be highly viscous with characteristically low flow rates. High dosages of high-range water reducers are typically needed to decrease mixture viscosity and achieve self-compacting properties (Fig. 2).

Most of the formulations tested achieved good initial flow followed by a rapid increase in viscosity and loss of flow. Rapid loss of workability creates difficulties for personnel and negatively impacts the end quality of products produced. Use of the very fine, highly reactive, calcined clay product further challenged the development of this UHPC mixture. It was quickly recognized that solving the issue of rapid increases in viscosity and loss of workability was critical to instill confidence in users of the product and ensure its viability in the market.

To extend the working time, researchers tested the addition of set retarders such as commercially available liquid lignosulphonates, citric and tartaric acid. All these products showed some partial success in terms of reaching the targeted 45-minutes of working time, however, they also came with negative impacts such as too robust retardation or aesthetic disadvantages in the cast surface. Extensive testing established a proprietary combination of commercially available admixtures that provided the targeted workability of the UHPC, while maintaining a relatively short initial set time of around seven hours. It also provided excellent 24-hour compressive strengths.

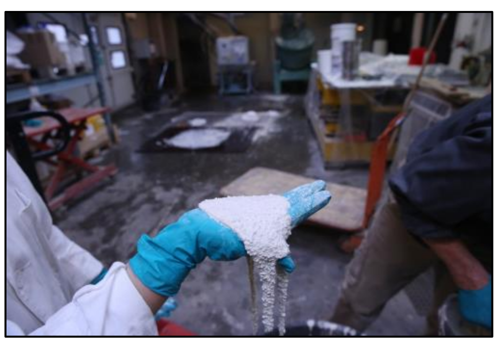

Figure 2. Self-compacting behavior of the material

6.2. Test results with the final mix.

<u>*6.2.1. Fresh state and mechanical properties.*</u>

Laboratory measurements of the mixture’s slump flow were made immediately after mixing and 45-minutes after water addition. The material underwent flow testing per ASTM C1611 to verify it has 100% flow retention after 45-minutes. Air content and density were measured and according to ASTM C173 and ASTM C138 (Fig. 3). Tabulated results of testing for initial flow and flow retention along with fresh density and air content are reported in Table 1.

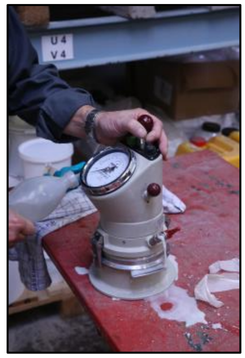

Figure 3. Equipment for measuring fresh density and air content

The material's hardened mechanical properties were also determined and are listed in Table 1 and Table 2. Compressive strength was measured in cubes and cylinders at 1-day and 28-days.

Table 1. Methods and results for fresh state and mechanical properties

<table>
<tr><th>Property</th><th>Test method</th><th>Dimensions (mm)</th><th>Units</th><th>Result</th></tr>
<tr><td>Fresh state properties</td><td colspan="4"></td></tr>
<tr><td>• Initial flow</td><td rowspan="2">ASTM C1437-15 (mini-cone with no drops)</td><td rowspan="6"></td><td rowspan="4">mm</td><td>(270 ± 30)</td></tr>
<tr><td>• 45 min. flow</td><td>(270 ± 30)</td></tr>
<tr><td>• Initial flow</td><td rowspan="2">ASTM C1611</td><td>(920 ± 30)</td></tr>
<tr><td>• 45 min. flow</td><td>(920 ± 30)</td></tr>
<tr><td>• Density, Unit Weight</td><td>ASTM C138</td><td>Kg/m³</td><td>2,425</td></tr>
<tr><td>• Air content</td><td>ASTM C173</td><td>%</td><td>(1.5 ± 0.5)</td></tr>
<tr><td>Mechanical Properties</td><td colspan="4"></td></tr>
<tr><td>• 1d - Compressive Strength (prisms)</td><td>EN 196-1</td><td>40x40x160</td><td>MPa</td><td>88</td></tr>
<tr><td>• 1d - Compressive Strength (cylinders)</td><td>EN 12390-3</td><td>100x200</td><td>MPa</td><td>86</td></tr>
<tr><td>• 1d - Compressive Strength (cube)</td><td>EN 12390-3</td><td>150x150</td><td>MPa</td><td>97</td></tr>
<tr><td>• 28d - Compressive Strength (prisms)</td><td>EN 196-1</td><td>40x40x160</td><td>MPa</td><td>158</td></tr>
<tr><td>• 28d - Compressive Strength (cylinders)</td><td>EN 12390-3</td><td>150x300</td><td>MPa</td><td>144</td></tr>
<tr><td>• 28d - Compressive Strength (cylinders)</td><td>EN 12390-3</td><td>100x200</td><td>MPa</td><td>138</td></tr>
<tr><td>• 28d - Compressive Strength (cubes)</td><td>EN 12390-3</td><td>150x150</td><td>MPa</td><td>143</td></tr>
<tr><td>• E-modulus (cylinder)</td><td>EN 12390-13</td><td>100x200</td><td>GPa</td><td>50</td></tr>
<tr><td>• Flexural strength (prisms)</td><td>EN 12390-5</td><td>100x100x500</td><td>MPa</td><td>14</td></tr>
</table>

6.2.2. Shrinkage and durability indicators.

Linear shrinkage at 28 and 90 days at 20°C, together with other durability indicators measurements are listed below in Table 2.

Table 2. Shrinkage and durability indicators

	Method	Unit	Value
Chloride content		Wt. to cement (%)	<0.09
Water soluble alkali content (Na_2O+0,658•K_2O)		kg/m^3	<3.4
Chloride migration Coefficient 28d 56d	NT Build 492	x10-12 m^2/s	 0.35 0.27
Freeze/thaw resistant – scaling (112 cycles)	EN 12390-9	Kg/m^2	0.00
Water absorption	EN 1015-18	Kg/(m^2•min$^{0.5}$)	<0.02 (W_C2)
Linear shrinkage – 28d	EN 12617-4	µm/m	388
Linear shrinkage – 90d			504

7. Discussion

The UHPC mixture was characterized through testing of three parameters: fresh state properties, hardened state properties and durability indicators.

The main focus with respect to fresh state properties was on slump flow and its retention over time. As shown in Table 1, the material is self-compacting and achieves 100% flow retention after 45-minutes from water initial addition. This is obtained despite the high content of fine particles together with the highly reactive calcined clay additions, which normally result in a negative effect on the workability. This property was a high priority for developers as a highly desirable characteristic for the industrial production processes of typical concrete precast manufacturers and placement crews.

Further suitability for use in precast applications are the reduced demolding times made possible by the UHPC's relatively short setting time and very high compressive strength after 24 hours – around 85 MPa. The other hardened properties of this material meet the stated targets for UHPC for use in architectural applications and deliver on the promise of this exciting new class of concrete materials.

AALBORG EXTREME® provides a user friendly, safe, and reliable UHPC formulation suited for industrial production processes and the production of architectural UHPC building elements. Its mechanical performance may be adjusted by combining it with the suitable fiber additions and by adjusting the water dosage within a framework set by a target flow and desired performance.

A thin slice of fluorescence-impregnated concrete of 20μm thickness was placed between two glass plates, and was analyzed in the microscope, allowing for the assessment of the microstructure. Micro cracking, water-cement ratio, homogeneity of the binder paste, adhesion of cement pastes to aggregates, secondary reactions, and degree of hydration were all evaluated. This examination reveals a very homogeneous super-dense concrete with very low water-cement ratio, no macro or micro cracks, and good bond to aggregates. This translates into the superior performance of the UHPC documented in the very low water absorption, chloride penetration, and zero degree of freeze/thaw scaling, as reported in Table 2.

8. Conclusions

Starting with a solid background in conventional UHPC formulations a talented team of investigators at the Cementir Group Research and Quality Center in Denmark has developed and tested a new type of UHPC mixture based on FUTURECEM™ technology. This UHPC product utilizes a sustainable binder combination composed of AALBORG WHITE® cement, limestone and calcined clay. From an ecological standpoint this integrated binder mixture is on solid ground because it relies solely on materials that are readily available in nature. Unlike most other formulations it is not constrained by the availability, consistency or quality of waste materials from other industries.

Regardless of a mixture's makeup to be commercially viable, preblended UHPC must solve the persistent placement and workability issues these materials commonly experience today such as flow retention and rheology. By carefully balancing binder type, chemistry, and advance admixture technologies this material is designed to be fully self-compacting with a working time of a minimum of 45-minutes. The mixture produced has a relatively short concrete setting time and rapid strength development. It is essential to note that along with the work of creating a balanced binder combination careful attention was paid to maximize particle packing thereby ensuring very low shrinkage. This in turn greatly enhances its ultra-high-performance and increases the value-added properties realized by its user.

AALBORG EXTREME® meets or exceeds all relevant requirements for UHPC and addresses the needs of commercial concrete plants and their placement crews. Architectural UHPC applications will benefit from its mechanical and durability performance and bright white color. This said, the material is suitable for structural applications with very low alkali and chloride contents. This new binder technology is certainly an efficient solution for UHPC; it provides an answer to the modern world's demand for innovative building materials that are resilient, versatile, sustainable and dually functional as architectural elements with ultra-high-performance.

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