Creating a Novel Ultra-High Performance Concrete

Introduction

The robust physical qualities, relatively inexpensive, and readily available constituents of conventional concrete makes it the most ubiquitous construction material throughout the world. Although it is robust and inexpensive, there are many construction areas where conventional concrete is lacking in strength, ductility and durability and is therefore incapable of meeting structural design requirements. Ultra High Performance Concrete (UHPC) is a dense, (often fiber-reinforced) material that takes concrete to the next level with enhanced compressive/tensile strength, increased durability and ductility. Currently, the only UHPC product commercially available in the US is a patented product distributed by a French-based company, through Canada. Due to the limitations of conventional concrete and lack of competition within the United States, there is a great need for novel and innovative Ultra High Performance Concrete (UHPC) products, as well as associated fabrication, testing and monitoring techniques.

To create a new UHPC – using local materials and with the ability to cast substantial sizes and widths in-field to produce compressive strengths of over 30 ksi -- is a current goal and the basis for this paper. Prior research indicates that UHPC with compressive strengths of between 20 to 24 ksi can be manufactured using local materials [7, 11, 12]. Building on and optimizing this prior research will support the development of novel UHPC materials, advanced curing methods, and integrated structural health monitoring (SHM) systems. The plan will include an evaluation of test formulations, aggregate grading and treatment systems, admixtures, and reinforcing fibers. Mixing techniques will be optimized to produce a homogenous fresh concrete mixture with the correct workability and flowability for field-cast pouring and curing. A smart sensor-based prototype curing and SHM system will be developed as the basis for creating a UHPC that can be cured in a practical and consistent method.

This paper provides an overview of the current state of UHPC use within the United States and an optimization plan for creating novel UHPC materials that will be capable of being field-cast using locally available materials.

Definition of UHPC

Though a solid definition for UHPC is still being developed, one commonly accepted definition is as follows:

> *"UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, water-to-cementitious ratio less than 0.25, a high percentage of discontinuous internal fiber reinforcement, and mechanical properties with compressive strength greater than 21.7 ksi and sustained post-cracking tensile strength greater than 0.72 ksi [1]."*

Within the scope of this definition, fiber reinforcement is considered an integral part of the UHPC material. For the purposes of this paper, the above definition of UHPC will be assumed. Other definitions indicate fiber reinforced UHPC as being separate from non-fiber reinforced UHPC [5, 6]. In comparison to UHPC, conventional concrete usually has a compressive strength in the range of 6 to 9 ksi and do not use fiber reinforcement.

Fig. 1 (a-b): Conventional concrete bridge vs. UHPC Bridges, Source [10]

The microstructural properties of the mineral matrix of an UHPC result in a highly compact, dense material with low porosity. The high density UHPC concrete is responsible for a substantial part of an UHPC's superior compressive strength and durability. Additional strength and ductility are achieved by UHPC's unique ability to strain-harden (flex, deform and self-strengthen) before fracturing; a behavior that is often exhibited by metals under tensile or bending stress [11]. The strain hardening behavior of UHPC is attributed to "fiber bridging." Fiber bridging occurs when an initial crack develops and the reinforcing fibers respond by exerting forces across the width of a crack. An increase in overall strength results that prevents the crack from developing further [11, 12]. Because of these unique physical characteristics, UHPC's are more resistant to cracking and last considerably longer than conventional concrete.

Fig. 2 - 3: Examples of UHPC Components and Embedded Steel Fibers, Source: [14]

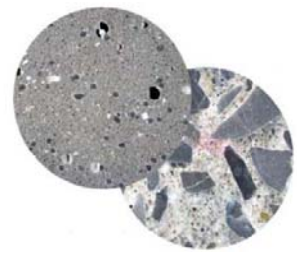

Fig. 4: Examples of UHPC and conventional concrete (ERDC) Source: [10]

Normal Concrete
w/c = 0.45,
30 MPa (4 ksi)

Ultra High Performance – Fiber Reinforced Concrete
w/c = 0.19,
290 MPa (42 ksi)

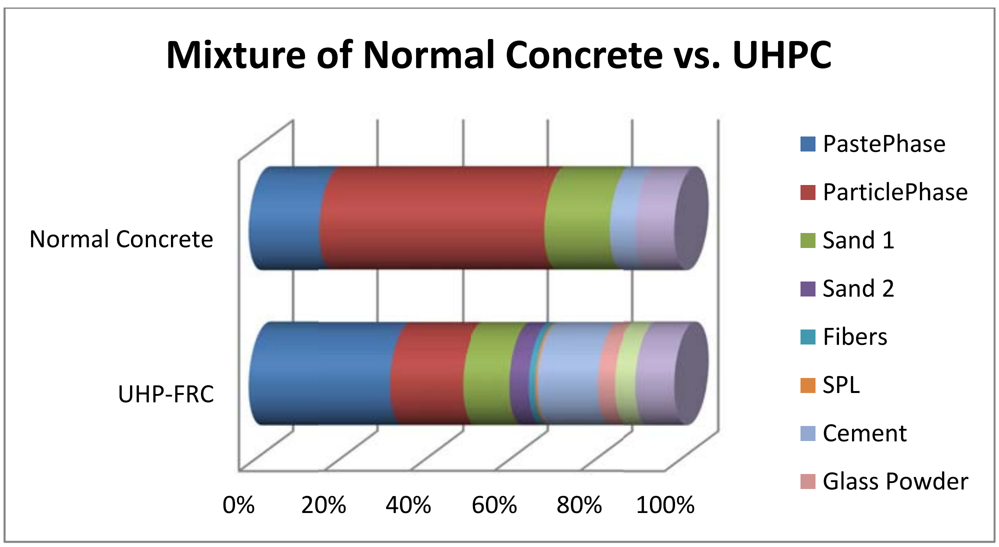

Fig. 5: Example of mix proportions by volume of normal concrete as compared with Ultra-High Performance – Fiber Reinforced Concrete (UHP-FRC), Source: [5]

Efforts to Promote the use of UHPC

Although it has been in use for a longer period of time in Europe and other global markets, within the past ten years, UHPC has slowly begun to gain acceptance within the United States. The US government, construction industry and academic leaders are making extensive efforts to promote the commercialization and application of UHPC. Towards this end, the US Federal Highway Administration (FHWA) has been sponsoring the large-scale use of UHPC in the construction of a wide variety of bridge superstructures throughout the US [1, 8]. The FHWA highway projects are being closely monitored and have provided an immense amount of useful information that is compiled in the FHWA HPC Design Guide and available to the general public.

Fig. 6: First UHPC Bridge Constructed in the United States (in Iowa), Source: [1]

In addition to FHWA projects, the Department of Homeland Security has held collaborative workshops to promote commercialization of UHPC within all market sectors. As a result of these workshops, industry sector concerns have been identified and plans have been proposed to address some of these concerns. For example, liability and cost issues have been identified as major concern for construction companies that may want to use UHPC [10]. Homeland security leaders are in the process of examining ways to decrease private sector liability such that there would be less risk involved when private companies use UHPC in bridges and buildings.

UHPC usage is also being strongly promoted by North American industrial and academic partnerships, resulting in focus groups such as the "UHPC Working Group" [6]. This organization is currently working towards creating standardized guidelines for all aspects of UHPC, including fabrication, testing and nomenclature. For example, one of the initial tasks for the UHPC Working Group is to create a globally accepted definition for UHPC and set of ASTM-based testing standards.

In order for the US government and private sectors to stay globally competitive with regard to UHPC, there is a definite need for increased research and development of both pre-cast and field-cast structures. Since pre-cast UHPC structures have the benefit of being manufactured under controlled conditions, there is a slightly greater need for the research and development of novel fabrication and testing procedures for field-cast structures. In particular, research in the area of field-casting large slabs that employ locally available materials and novel curing processes, is of critical importance for making UHPC a practical, cost-effective and widely accepted material [7].

Fig. 7: Longitudinal connections cast between deck-bulb-tee girders. Field cast UHPC can simplify connection details and construction (NY DOT), Source: [1]

UHPC Issues

Due to the enhanced strength, ductility and durability associated with UHPC there are a myriad of potential applications including; earthquake resistant structures, blast proof bunkers, longer lasting and more durable bridges, highways, dams and tunnels. However, there are a number of issues with deploying UHPC in the US construction industry.

1. ***Expense and Lack of Control:*** Currently, there is only one commercially available UHPC product in North America [1, 3, 4, 13]. This UHPC is a pre-packaged, proprietary material that must be shipped to the fabrication site through a dedicated supplier. The cost of this product can be as much as 10 times that of conventional concrete. Thus, the current limited choices for UHPC materials results in a situation where the end user is highly dependent on a single supplier and is therefore subject to any unforeseen logistical issues that may arise with regard to shipping, cost increases and the supply chain of the raw materials.

2. ***Lack of Local Materials Use:*** The available UHPC in the United States tends to employ both a patented aggregate and concrete formulation. In this regard local materials such as aggregates and readily available cements are not utilized to the extent possible, thus substantially increasing costs. Since the aggregate portion of a UHPC can constitute over two-thirds of the mixture, reducing the need to ship any substantial amount of aggregate, will result in significantly lower shipping costs [8].

3. ***Sensitive In-Situ Fabrication:*** UHPC is known to be more sensitive than conventional concrete throughout the entire fabrication process, including: proportion and type of constituents, mixing methods, setting times, curing methods and environmental conditions [1]. For example, curing conditions such as temperature and humidity are extremely critical for creating UHPC with the highest compressive strengths (>30ksi). Innovative fabrication methods are needed so that UHPC's may be created that are reliable and of the highest compressive strengths.

Fig. 8: Curing of UHPC Bridge Deck Source: [8]

4. ***Lack of Established Standards:*** Though many conventional ASTM tests can be adapted for UHPC [1, 4], there exists a need for establishing uniform manufacturing procedures; including proper gradation and sizing of coarse and fine aggregates, standardized tolerances and testing procedures for raw materials, pre-cured and post-cured concrete. In addition, a solid determination of which performance characteristics are critical for a given UHPC application is also in need of research [1, 7, 8]. For example, the high energy absorption capacity of UHPC has been determined from static strength testing, however the performance of many UHPC elements under severe impulsive loading have not been investigated [2, 3].

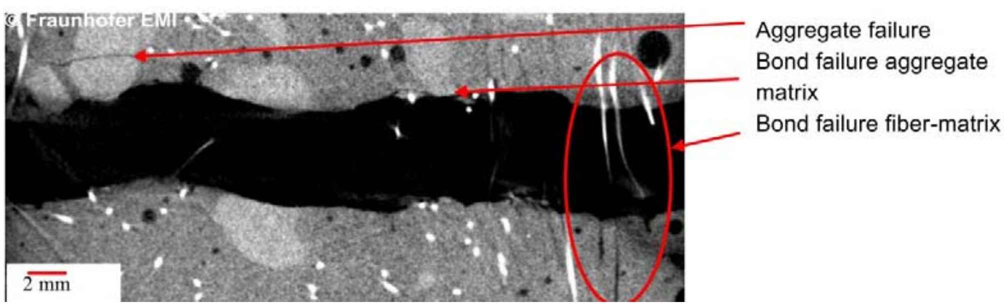

Fig.9: Computer tomography detailing a macro-crack due to bending in a blast load, Source: [15]

5. ***Need for Dedicated UHPC Facilities and Workforce Training:*** Since UHPC has different raw materials and fabrication processes than that of conventional concrete, there is a need for dedicated fabrication facilities. At this time, due to the cost of UHPC and its limited use within the United States, the financial incentive is not present for the majority of US concrete manufacturers to obtain the required equipment and set aside dedicated facilities. Additionally, concrete workers will require specialized training for deploying UHPC.

Critical Aspects UHPC

In order for the UHPC issues presented above to be properly addressed, expanded research and development of UHPC formulations is required. A variety of new UHPC materials are needed that are flexible enough to incorporate local materials and to be field-cast under varying environmental condition, while still maintaining a high compressive and tensile strength. Smart-sensor based curing systems will be a crucial part of creating a UHPC that meets the demands of both pre-cast and field-cast structures. In addition to evaluating optimal raw material types (including admixtures, accelerators, plasticizers, water-reducers), the following critical UHPC aspects will be evaluated:

1. Aggregate Grading
2. Fiber Reinforcement
3. Curing
4. Heat Dissipation
5. Testing and Analysis

1. ***Aggregate Grading:*** Sieve procedures will be created for size gradation of the fine and coarse, local material aggregates, as well as procedures for pre-washing and drying aggregates in the field. Since the size of coarse aggregates used in typical UHPC mixes are typically much finer (1/8") than those used in conventional concrete mixes, aggregate gradation will be one major area of focus for optimizing strength. Large scale, aggregate coatings and vacuum suction methods will be evaluated to enhance aggregate/cement bonding.

Fig. 10: UHPC Aggregate Types, Source [8]

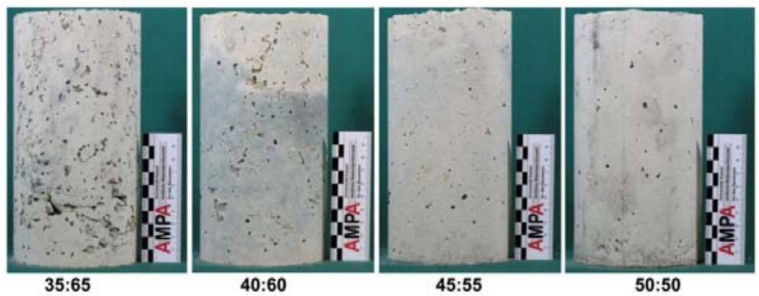

Fig. 11: Dimensional stability and surface appearance of concrete specimens with different ratios of mortar to aggregate. Source: [15]

2. ***Fiber Reinforcement:*** Evaluation of fiber type, shape, dispersal and orientation will performed to optimize reinforcement strength and to minimize "balling" of fibers during mixing, casting and curing. It is known that UHPC fiber length generally needs to exceed the largest coarse aggregate size for maximal strength [1]. Steel fibers have an advantage in terms of strength and decreased cost but have disadvantages in terms of their corrosion potential. Synthetic fibers are non-corrosive, and are a better match for concrete due to their coefficient of thermal expansion and contraction, but are often more difficult to obtain. Homogenous dispersal and optimal orientation of the reinforcing fibers is considered critical to achieving the maximum pre/post cracking strength, while maintaining the optimal ratio of compressive to tensile strength.

Fig. 12 (a – e): UHPC fiber types: a) Long smooth macro fiber, b) Hooked A macro fiber, c) Hooked B macro fiber, d) Twisted macro fiber, and e) Short smooth micro fiber. Source [16]

3. ***Curing:*** Curing of UHPC is known to be a highly sensitive process that is extremely dependent on a variety of environmental conditions - including temperature and humidity levels as well as correct timing. Optimizing the curing process is considered absolutely critical for creating a final UHPC product with the desired performance characteristics. Due to the critical nature of this process, the team is developing a novel prototype <u>Curing and Structural Health Monitoring (SHM) Control System</u> to provide real-time, processed data for the accurate analysis and control of critical curing factors and the long-term monitoring of the overall health of the final UHPC structures. Smart sensor-based curing

system will estimate concrete maturity based on Nurse-Saul and Arrhenius maturity functions. The system will automatically, and in real-time, determine maturity of concrete structures and be able to:

- **Detect bubbling, micro-cracking, and other defects**, that can drastically affect overall structural integrity during the curing process using a suite of smart sensors: including thermography, PZT, temperature/maturity and moisture sensors
- **Check the quality of the UHPC after the curing process** using impact hammers and P-wave sensors to monitor the transmission of sound waves to identify any cracks or imperfections in the core of the structure and to correlate with stiffness and strength properties; and
- **Provide strain energy-based SHM** on the surface and rebars of the UHPC structure using strain gages, accelerometers and specialized algorithms to identify fatigue.

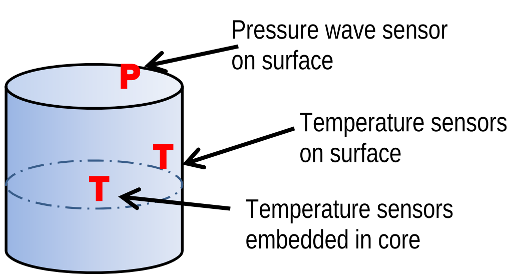

Fig. 13: Sensor monitoring system for curing UHPC

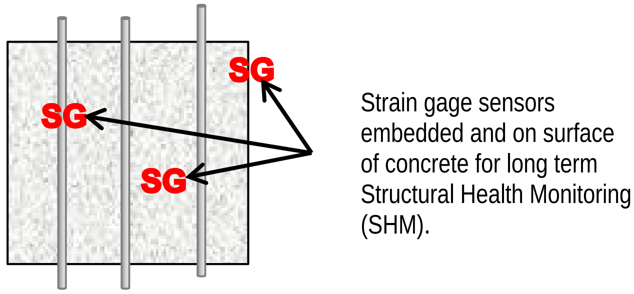

Fig. 14: Example of embedded SHM system in UHPC

4. ***Heat Dissipation:*** The internal chemical reactions during concrete curing generate large amounts of heat and therefore proper heat dissipation procedures become crucial during the field-casting of larger concrete slabs. Therefore, the proposed curing research will also investigate novel methods for heat dissipation. For example, while steel circulating pipes were used in the past to cool with water or air, the use of high-strength fiber reinforced polymer (FRP) composite pipes, which will not corrode over the life of the structure, will be investigated [11, 12]. After the UHPC curing is complete, the buried FRP composite pipes could be filled with high-strength grout (strength exceeding 30 ksi) to maintain compressive strength.

5. ***Testing and Analysis:*** Ultimately, testing and analysis will be performed on both fresh and hardened UHPC specimens. Physical characteristics such as flowability, workability, compressive/tensile strength, ductility and durability will be evaluated. The use of in-situ, nondestructive, monitoring techniques (such as ultrasound and instrumented hammer) will be employed. Performance models and computational tools will be developed to appropriately analyze the UHPC samples; from the processing stage through the final hardened slab. Prototype SHM/Smart-Curing System will be employed to provide crucial, non-destructive information on the state of the concrete pre/post cure and will be capable of evaluating the long-term physical condition of a UHPC based structure.

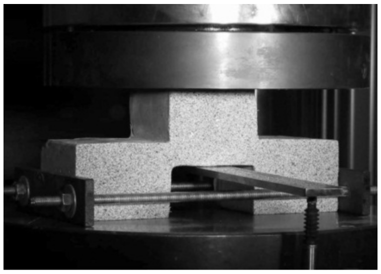

Fig. 15: Shear strength testing on UHPC specimen, Source [15]

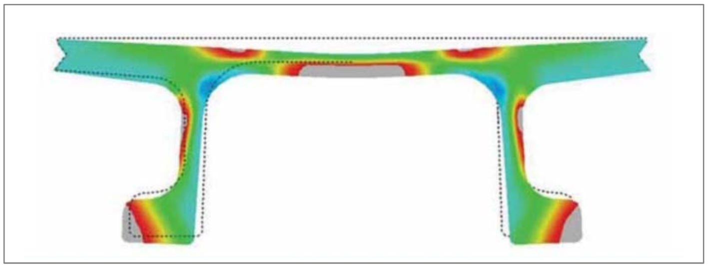

Fig. 18: UHCP Hotspot Analysis using FE Computer Modeling, Source [1]

Collaborative Team and Facilities

The collaborative team of Erallo Technologies (Erallo) and Constructed Facilities Center (CFC) at West Virginia University (WVU) (CFC-WVU) will be working on the UHPC project. The team has extensive knowledge in structural engineering, high performance concrete, concrete mix design including alternative mixes such as alkali activated concrete, and concrete testing/smart-sensor technologies and concrete characterization from microstructure to the structural element level. This collaborative team is currently in year two of a Phase II SBIR program developing Structural Health Monitoring (SHM) techniques for use on bridge structures.

The collaborative team has access to dedicated, well-equipped, concrete fabrication and testing facilities where test cylinders and large scale slabs can be manufactured and tested. The CFC-WVU labs are equipped with sophisticated concrete characterization equipment including instrumented hammer, ultrasonics and scanning electron microscope. CFC-WVU has three large, high bay testing laboratories with heavy duty cranes, loading dock, and storage space, where structural members, such as slabs, columns and beams, can be tested. Some of the available structural testing equipment includes a column-buckling machine up to 110 kips capacity, a structural torsion machine for samples up to 10 ft. in length, several other frames and actuators from 100 kips up to 400 kips, three MTS servo-hydraulic fatigue testing systems, and a programmable Thermotron environmental chamber.

Fig. 19: Instron 3 test equipment at CFC-WVU laboratory

Anticipated Benefits and Applications

Since the initial cost is approximately 20% more than conventional strength concrete, there are valid concerns about UHPC for use in large-scale construction projects. However, studies have shown that if cost of UHPC is considered over its entire life cycle, the initial increase in cost is more than made up for in the long term savings. Long term savings are realized in a decrease in the actual amount of concrete material used (for a given strength requirement), decrease in maintenance and repair, costs and a longer projected lifespan for UHPC based structures [1, 8].

At this time, there is only one commercially available UHPC for wide-scale distribution within North America. Since this product is patented and uses specialized, non-local, patented aggregate components, the cost for UHPC is prohibitive (at 10 to 20 times) in comparison to conventional concrete. Our initial market research suggests that the novel UHPC material described herein would cost substantially less than the currently-available patented UHPC product; by employing local material aggregate and readily available commercial admixtures. In addition, these UHPC materials will employ smart sensor based predictive tools to monitor curing and final strength of the structures. These technologies will be used to maximize the structural performance of the UHPC and will enhance the ability for UHPC to be employed in field-cast applications.

In general, the greater availability of novel UHPC's and fabrication processes will expand concrete usage in all areas where enhanced strength, durability and ductility is needed, including bridges, highways, airports, dams, tunnels and any structures that require enhanced impact, shock and blast resistance. In addition, UHPC use has potential for used as a repair material of for damaged conventional concrete structures. Applications include; security sensitive projects where there is a need to protect against intrusion (such as banks, prisons and bomb shelters) as well as structures that need to withstand impact and shock from natural disasters or explosive projectile weapons. In the future, UHPC smart materials may be adopted as the next level of high performance concrete, with embedded nanomaterials such as carbon nanotubes and metallic based nanoparticles and used for applications such as energy harvesting.

Conclusion

In order for the United States civilian and military sectors to stay globally competitive with regard to UHPC structures, there is a great need for increased research and development of novel materials, fabrication processes and SHM systems. Concrete panels (slabs and walls) play an important part in protecting buildings against the extreme loading conditions caused by blast, shock and impact, yet the performance potential for these structures is limited by conventional concrete as the only option.

Currently the only UHPC product commercially available in the US is a patented product which severely limits price competitiveness through competition as well as limiting end users to one supplier and lack of control over the raw materials chain. The only major area of UHPC usage in the US is occurring in subsidized, special FHWA bridge and highway projects [1, 8, 10]. Due to major promotional efforts being made by government, industry and academic leaders towards the expanded use of UHPC, there is an emerging market for novel UHPC products and competition to the one existing UHPC being distributed in the United States.

Fig. 20: UHPC bridge in Austria, Source: [10]

Erallo's Ultra High Performance Concrete (UHPC) material will be cost-effective and local materials-based (to the region of construction), attaining high compressive strength of 25 to 30ksi (25,000-30,000psi) while retaining the durability characteristics required for structures employed in a "harsh" environment. Erallo's UHPC material will be directly applicable in areas where conventional concrete is lacking in performance and current UHPCs are cost-prohibitive. In addition, Erallo proposes the development of a smart sensor-based curing procedure to regulate the curing process and maximize the strength and performance of the final UHPC structure. An innovative Structural Health Monitoring (SHM) system will be employed to monitor the safety of any UHPC structure and provide unique opportunities for maximizing the overall lifetime.

References

1. Graybeal, B. (2011). "Ultra High Performance Concrete", TechNote, Report No. FHWA-HRT-11038, Federal Highway Administration, McLean, VA.
2. Pimienta, P and Chanvillard, G. (2004). "Retention of the Mechanical Performance of Ductal® Specimens Kept in Various Aggressive Environments", FIB Symposium 2004, April 26-28, Avignon, France.
3. Cavill, B., Rebentrost, M. and Perry, V. (2006). "Ductal® - An Ultra-High Performance Material for Resistance to Blasts and Impacts", 1st Specialty Conference on Disaster Mitigation, May 23-26, 2006, Calgary, Alberta, Canada.
4. Ahlborn, T., Harris, D., Misson, D. and Peuse, E. (2011). "Strength and Durability Characterization of Ultra-High Performance Concrete Under Variable Curing Conditions", TRB 2011 Annual Meeting.
5. Naaman, A. (2012) "The Path to Ultra-High Performance Fiber Reinforced Concrete (UHP-FRC): Five Decades of Progress", Ultra-High Performance Concrete and Nanotechnology in Construction, Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials Symopsium, Kassel Germany March 7-9, 2012.
6. Ahlborn, T. and Steinberg, E., (2012). "An Overview of UCPC Efforts in North America", Ultra-High Performance Concrete and Nanotechnology in Construction, Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials Symopsium, Kassel Germany March 7-9, 2012.
7. Fidjestol, P., Thorsteinsen, R. and Svennevig, P. (2012). "Making UHPC with Local Materials", Symopsium, Kassel Germany March 7-9, 2012, Ultra-High Performance Concrete and Nanotechnology in Construction, Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials Symopsium, Kassel Germany March 7-9, 2012

8. Graybeal, B, Hartmann, J and Simon, M. (2005). "High Performance Concrete Structural Designer's Guide", by the High Performance Concrete Technology Delivery Team, 1st Ed., Research Section, March 2005 pg 15 – 33, October 22, 2004 (Texas DOT) FHWA Pub. No. FHWA-ERC-02-006
9. Nematollahi, B. Saifulnaz, R., Mohd, M. and Voo, Y. (2012). "Review on Ultra High Performance 'Ductile' Concrete (UHPdC) Technology", International Journal of Civil and Structural Engineering, Vol. 2, No 3, 2012
10. "Ultra High Performance Concrete - Pathway to Commercialization", Department of Homeland Security - Science and Technology, Ultra High Performance Concrete (UHPC) Workshop, January 11 – 12, 2011, Columbia University, New York City, NY.
11. Hota V.S. GangaRao, Narendra Taly and P. V. Vijay (2006). Reinforced Concrete Design with FRP Composites, CRC Press, November 20th 2006
12. Manish, R. 2011. "Reinforced Concrete as a Repairing Material: Development and Evaluation of High Performance Fibers", WVU Master's Thesis. Dept of Civil and Environmental Engineering, Morgantown, WV.
13. Clavaud, et al. 2000. United States Patent. No. 6,080,234, June 27, 2000, Lafarge Materials, France.
14. Christoph Roller, Christoph Mayrhofer, Werner Riedel, Klaus Thoma (2012). Engineering Structures (online 9 January 2012). Residual load capacity of exposed and hardened concrete columns under explosion loads. Department of Safety Technology and Protective Structures, Fraunhofer-Institute for High-Speed Dynamics, Ernst-Mach-Institut, Am Klingelberg 1, 79588 Efringen-Kirchen, Germany
15. Symopsium, Kassel Germany March 7-9, 2012, Ultra-High Performance Concrete and Nanotechnology in Construction, Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials Symopsium, Kassel Germany March 7-9, 2012
16. Seung Hun Park, Dong Joo Kim, Gum Sung Ryu, Kyung Taek Koh (2012). Cement and Concrete Composites, Tensile behavior of Ultra High Performance Hybrid Fiber Reinforced Concrete, Volume 34, Issue 2, February 2012, Pages 172–184.