CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

Optimization of ultra-high-performance concrete with nano- and micro-scale reinforcement

Libya Ahmed Sbia1, Amirpasha Peyvandi2*, Parviz Soroushian1 and Anagi M. Balachandra3

Abstract: Ultra-high-performance concrete (UHPC) incorporates a relatively large volume fraction of very dense cementitious binder with microscale fibers. The dense binder in UHPC can effectively interact with nano- and microscale reinforcement, which offers the promise to overcome the brittleness of UHPC. Nanoscale reinforcement can act synergistically with microscale fibers by providing reinforcing action of a finer scale, and also by improving the bond and pullout behavior of microscale fibers. Carbon nanofiber (CNF) and polyvinyl alcohol (PVA) fiber were used as nano- and microscale reinforcement, respectively, in UHPC. An optimization experimental program was conducted in order to identify the optimum dosages of CNF and PVA fiber for realizing balanced gains in flexural strength, energy absorption capacity, ductility, impact resistance, abrasion resistance, and compressive strength of UHPC without compromising the fresh mix workability. Experimental results indicated that significant and balanced gains in the UHPC performance characteristics could be realized when a relatively low volume fraction of CNF (0.047 vol.% of concrete) is
used in combination with a moderate volume fraction of PVA fibers (0.37 vol.% of concrete).

**Subjects:** Composites; Concrete & Cement; Structural Engineering

**Keywords:** carbon nanofiber; ultra-high-performance concrete; polyvinyl alcohol (PVA) fiber; optimization

1. Introduction

Ultra-high-performance concrete (UHPC) materials provide compressive strengths higher than 150 MPa (22 ksi) and tensile strengths greater than 8 MPa (1.1 Ksi) (Graybeal, 2007; Habel, Viviani, Denarié, & Brühwiler, 2006; Magureanu, Sosa, Negruțiu, & Heghes, 2012; Wille, Naaman, & Parra-Montesinos, 2011).

The exceptional mechanical and durability characteristics offered by UHPC (FHWA, 2011; Van Tuan, Ye, van Breugel, & Copuroglu, 2011) are made possible by the use of high contents of cementitious binder with very low water/binder ratios (less than 0.25) (Barnett, Lataste, Parry, Millard, & Soutsos, 2010; Ding, Liu, Pacheco-Torgal, & Jalali, 2011; Peyvandi, Sbia, Soroushian, & Sobolev, 2013; Schröfl, Gruber, & Plank, 2012), dense packing (Wille, Naaman, El-Tawil, & Parra-Montesinos, 2012) particulate matter (aggregate, cement, supplementary cementitious materials, and inert powder) lowering maximum aggregate size, effective use of pozzolanic reactions to realize the binder structure and capillary pore system, and use of macro/microscale fibers (Kang & Kim, 2011; Yang, Joh, & Kim, 2011) to overcome the brittleness of UHPC.

In order to overcome the extreme brittleness of UHPC, this cement-based material usually incorporates fibers (of different types). Steel fibers are commonly used in UHPC (Kang, Lee, Park, & Kim, 2010; Wille & Loh, 2010). Slender fibers of high elastic modulus, tensile strength, and bond strength to cementitious paste improve the tensile strength and toughness of UHPC, and mitigate crack propagation under extreme loading and environmental effects. Fibers at microscale diameter at practically viable volume fractions, however, produce at relatively large fiber-to-fiber spacing (Peyvandi, Soroushian, & Jahangirnejad, 2013). Fine cracks can thus initiate and grow between microscale fibers before they reach the fiber-matrix interfaces (Foti, 2013; Konsta-Gdoutos & Metaxa, 2010; Li, Wang, & Zhao, 2005; Metaxa, Konsta-Gdoutos, & Shah, 2010; Yoo, Lee, & Yoon, 2013). Finer (nanoscale) reinforcement can be dispersed in the space between microscale fibers to effectively mitigate the inception and growth of such fine cracks.

Graphite nanomaterials, including carbon nanotube (CNT), lower cost carbon nanofiber (CNF), and graphite nanoplatelet (Musso, Tulliani, Ferro, & Tagliaferro, 2009; Nochaiya & Chaipanich, 2011; Peyvandi, Soroushian, Balachandra, & Sobolev, 2013), offer desired geometric and mechanical properties for reinforcement of cementitious materials (Gay & Sanchez, 2010; Melo, Calixto, Ladeira, & Silvo, 2011; Tyson, Abu Al-Rub, & Yazdanbakhsh, 2011). Surfaces of graphite nanomaterials can also be modified for effective interaction with the cementitious matrix. In addition, nanomaterials improve the packing density of cementitious paste, tend to preserve the fresh mix workability, and provide high specific surface areas for nucleation of cement hydrates (Peyvandi, Sbia et al., 2013; Wille & Loh, 2010). Finally, the closely space nanomaterials can provide tortuous diffusion paths into UHPC, thereby improving the impermeability and durability of concrete (Kalaitzidou, Fukushima, & Drzal, 2007; Peyvandi, Soroushian, Balachandra, & Sobolev, 2013).

CNTs are not economically viable nanomaterials for use in concrete. CNFs, on the other hand, approach the desired geometric and mechanical characteristics of CNTs at a fraction of their cost. Surfaces of CNFs are also more energetic (active for convenient surface modification to introduce OH
or COOH groups) than CNTs, and can thus be modified for effective interactions with cement hydrates (Galao, Zornoz, Baeza, Bernabeu, & Garcés, 2012).

When compared with steel fibers (which are commonly used in UHPC), polymer fibers offer improved stability in corrosive environments, lower diameters, and higher aspect ratios which could benefit their reinforcement efficiency in concrete. Polymer fibers, on the other hand, provide lower elastic moduli than steel, and thus offer lower reinforcement efficiency in concrete. Among the polymer fibers used in concrete (polypropylene, poly vinyl alcohol (PVA), nylon), PVA fibers offer elastic moduli (~30 GPa (4,350 Ksi)) which are about an order of magnitude higher than those of polypropylene and nylon fibers (but still below that of steel, which is 200 GPa (29,000 Ksi)). PVA fibers have a relatively simple chemical structure with a pendant hydroxyl group which benefits their interfacial interactions with cement hydrates.

The work reported herein concerned development of a new class of UHPC through complementary/synergistic use of CNF and PVA fiber. An optimization experimental program was designed and implemented in order to identify the optimum dosages of nano- and microscale reinforcement in UHPC.

2. Materials and experimental procedures

2.1. Materials

The materials used in this experimental work included: Type I Portland cement, non-densified silica fume (with ~200 nm (7.87 × 10^{-6} in) mean particle size, ~15 m²/g (73,230 ft²/lb) specific surface area > 105% and 7-day pozzolanic activity index), superplasticizer (ADVA® Cast 575 from W.R. Grace Co., polycarboxylate-based, conforming to ASTM C494 Type F), silica sand (> 99.5 wt.% SiO₂, ball milled and sieved to two particle size categories: 0.1–0.18 mm (0.004–0.007 in) and 0.18–0.5 mm (0.007–0.02 in), granite coarse aggregate (with 8 mm (0.315 in) and 3.5 mm (0.138 in) maximum and mean particle size, respectively), oxidized CNF shown in Figure 1 (with 60–150 nm (2.36–3.94 × 10^{-6} in) diameter, 40–100 μm (0.0016–0.0039 in) length, and >95% purity), obtained from Applied Sciences, Inc. (brand name Pyrograf III Type PR24), and PVA fibers with 13 mm (0.52 in) length and 13 μm (0.0005 in) diameter, specific gravity of 1.3 (81.12 lb/ft³), and tensile strength of 1,200 MPa (174 Ksi). Surface of oxidized CNFs were treated following the procedures described later. Table 1 compares the properties of nano/microscale fibers used in this study.

2.2. Optimization experimental program

In order to find the optimum dosage of nano- and microscale reinforcement, an optimization program was designed based on response surface analysis principles, using the Central Composite Method. Thirteen different combinations of CNF and PVA fiber volume fractions were considered in this test program. The maximum PVA fiber volume fraction beyond which fresh mix workability would be compromised was identified as 0.55% by volume UHPC materials.
An upper limit of 0.067% by volume of UHPC materials was chosen for CNF based on preliminary studies which indicated that the CNF dispersion would be disturbed at higher volume fractions for the materials and methods used in this investigation. It should be noted that an optimization experimental program incorporates few excursions beyond these upper limits in order to test their viability. The optimization experimental program is presented in Table 2. The UHPC mix used in the optimization experimental program comprised cement: silica fume: coarse aggregate: fine aggregate: water: superplastisizer at 0.25: 0.093: 0.155: 0.38 (0.11, sand 0.1–0.18 mm (0.004–0.007 in)): 0.075: 0.018 weight ratios.

### 2.3. Surface treatment of CNFs

In order to facilitate the dispersion of CNFs in the UHPC mixing water, and also enhance their interactions with cement hydrates, hydrophilic groups were introduced on existing surface defects of nanofibers. Polyacrylic acid (PAA) was used to modify the CNF surfaces. PAA carries a high density of COOH groups, wrapping of CNFs with PAA to improve dispersion of CNFs in water, and their bonding with cement hydrates. For the purpose of modifying CNFs with PAA, CNFs were dispersed in water in the presence of PAA at PAA:CNF weight ratio of 0.1:1.0 (Peyvandi, Soroushian, Abdol, & Balachandra, 2013).

In order to disperse nanoparticle which tend to cluster due to secondary interactions over their large surface areas, a sonication technique was employed (Materazzi, Ubertini, & D’Alessandro, 2013; Raki, Beaudoin, Alizadeh, Makar, & Sato, 2010). Nanomaterials were mixed with PAA in 30% of the mixing water of UHPC, and sonicated for 30 min. The resulting dispersion was exposed to microwave radiation for 10 min at 400 W powers, and stirred for 12–15 h. The dispersion was sonicated again following the procedures described in the following section.

### 2.4. Nanomaterial dispersion method

Nanomaterials were dispersed in 30% of the UHPC mixing water using a sonicating horn following the procedure described below:

(i) The required amount of nanofiber was added to the mixing water with superplasticizer, and stirred for 12–15 h; and (ii) the mix was sonicated in a cycle comprising: (a) 10 min of sonication at 40, 40, 65, and 75% of maximum power (40 W) with 1-minute breaks in between, (b) pulse (1 min on, 30 sec off) for 10 min at 80% of maximal power, and (c) repeating the previous (pulsing) step after 2 min of rest.

### 2.5. Preparation of UHPC samples

ASTM D192 and C305 procedures were used for mixing of UHPC. This procedure involved: (i) 5 min of mixing of dry ingredients (cement, silica fume, sand, and coarse aggregate) in a Hobart Model A200F

---

**Table 1. Properties of CNF and PVA fiber**

| Property                  | CNF (nanoscale reinforcement) | PVA fiber (microscale reinforcement) |
|---------------------------|-------------------------------|--------------------------------------|
| Diameter nm (in)          | 60–150 (2.36–3.94 × 10⁻⁶)     | 13 × 10⁻³ (0.0005)                   |
| Length μm (in)            | 40–100 (0.0016–0.0039)        | 13 × 10⁻³ (0.52)                     |
| Density g/cm³ (lb/ft³)    | 1.95 (121.7)                  | 1.3 (81.12)                          |
| Tensile strength of MPa (Ksi) | 5000 (725)                | 1200 (174)                           |

**Table 2. Volume percents with respect to concrete material of PVA fiber and CNF used in the optimization experimental program**

| Mix No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|----|
| Carbon nanofiber | 0.04 | 0.04 | 0.04 | 0.00 | 0.08 | 0.04 | 0.08 | 0.04 | 0.04 | 0.00 | 0.10 | 0.04 |
| PVA fiber    | 0.30 | 0.30 | 0.70 | 0.60 | 0.00 | 0.30 | 0.60 | 0.30 | 0.30 | 0.00 | 0.30 | 0.30 |
mixer at Speed 1; (ii) adding water (with dispersed nanomaterials) followed by mixing for 1 min at Speed 1, 2 min at Speed 2, and (while adding PVA fibers) 2 min at Speed 3; and (iii) casting concrete into molds per ASTM C192, and consolidating the specimens on a vibration table (FMC Syntron Power Plus) at intensity of 10. The specimens were moist-cured inside molds (ASTM C192) at room temperature for 20 h after casting, and were then demolded and subjected to 48 h of steam curing at 70 °C (158°F). The specimens were then conditioned at 50% relative humidity and ambient temperature for 7 days prior to testing.

2.6. Test procedures
Workability of fresh UHPC mixtures was evaluated using static and dynamic flow table tests (ASTM C230). Three-point flexure tests (ASTM C78) were performed on prismatic 150 × 50 × 12.5 mm (6 × 2 × 0.5 in) specimens. Impact tests (ASTM D7136) were performed on 150 mm (6 in) specimens with thickness of 12.5 mm (0.5 in). Abrasion tests (ASTM C944) were performed on cylindrical specimens with 150 mm (6 in) diameter by 12.5 mm (0.5 in) height. Compression tests (ASTM C109) were performed on 50 mm (2 in) cubic specimens. Three specimens were subjected to each test condition.

3. Experimental results and discussion
The fresh mix (static and dynamic) flow test results for UHPC mixtures with CNF and/or PVA reinforcement systems are summarized in Figures 2 and 3 versus PVA fiber and CNF concentrations, respectively. The trends depicted in Figure 2 indicate that PVA fibers have pronounced adverse effects on fresh mix workability. Fiber interactions and adsorption of water on their hydrophilic surfaces are some key factors which compromise fresh mix workability. The experimental results presented in Figure 3 indicate that fresh mix workability is not strongly influenced by the addition of CNFs (at volume fractions considered here). This can be explained by the contributions of nanofibers to the packing density of the particulate matter in the fresh cementitious matrix. Dispersed nanofibers can fill the fine space between cement and silica fume particles, thereby increasing the density of particulate matter in the binder. As a result, more water becomes available to lubricate the particles (in lieu of filling the inter particle pores). The benefits to fresh mix workability resulting from more efficient use of water towards lubricating particles compensates for any adverse effects of nanofibers on the fresh mix flow. It should be noted that the wide scatter in test results observed in Figure 3 is because the PVA fiber volume fraction (the key factor affecting flow) is not constant for different data points depicted in this figure.

Typical flexural load–deflection curves for UHPC materials with CNF and/or PVA fiber reinforcement are presented in Figure 4.

The hybrid reinforcement system comprising PVA fiber and CNF is observed to produce the least brittle material among those considered, with improved flexural strength. The instrumented flexure tests suited measurement of large post-peak deformations, but not the pre-peak elastic deformations. Hence, no definitive assessments could be made of the nanomaterial effects on flexural stiffness. As far as the post-peak ductility is concerned, nanofibers alone made relatively small contributions to ductility. They were, however, effective in enhancing the ductility of PVA fiber reinforced materials. This observation points at the synergistic actions of nano- and microscale discrete reinforcement systems. This synergistic action could result from the benefits of nanofibers to the pullout behavior of PVA fibers. The particular discrete reinforcement systems considered in this investigation did not produce strain-hardening behavior. The flexural strength, maximum deflection, and energy absorption capacity as well as the impact resistance, abrasion weight loss, and compressive strength test results are presented in Figure 5. Maximum deflection corresponded to the point on flexural load–deflection curve where the flexural load-carrying capacity of the test specimen diminished. Flexural energy absorption capacity is the total area underneath the flexural load–deflection curve up to the maximum deflection. Response surface plots based on these test data, which show the trends in effects of steel fiber and CNF volume fractions on different material properties are presented in Figure 6. Each response surface plots a particular response (e.g. flexural...
strength) as a function of two variables: fiber and nanofiber volume fractions. Synergistic actions of CNF and PVA fiber towards improvement of UHPC material properties are observed in the case of impact resistance and maximum deflection test results.

Desirability (canonical) analysis of experimental results helped to determine the optimum combination of PVA fiber and CNF for achieving balanced gains in engineering properties of UHPC. The desirability function approach is used commonly for simultaneous optimization of multiple responses. In this approach, each response is first converted into an individual desirability function, and then the overall desirability function is maximized. All properties were given similar weights in the optimization process, and the objective of optimization (response surface analysis) was to identify the reinforcement condition which simultaneously maximizes. The following properties (with the targeted levels reflecting the preferred UHPC properties): flexural strength (14.3 MPa (2,070 psi) target value), maximum deflection (11.0 mm (0.43 in) target value), energy absorption capacity (1,400 N mm (398 lb in) target value), impact resistance (4.50 mm/mm (4.5 in/in) target value), compressive strength (152 MPa (22 Ksi) target value), static flow (180 mm (7.2 in) target value) and dynamic flow (250 mm (10 in) target value), and minimize abrasion weight loss (1.12 g (0.04 oz) target value). Outcomes of this optimization process indicated that the optimum hybrid reinforcement system
Figure 3. Effects of CNF volume fraction (with respect to anhydrous cementitious materials) on fresh mix static and dynamic flow (regression lines and 80% confidence intervals are shown, PVA fiber volume fraction varies).

(a) Static flow

(b) Dynamic flow

Figure 4. Typical flexural load-deflection curves of UHPC materials with CNF and/or PVA fiber reinforcement.
comprises CNF at 0.047 vol.% of UHPC and PVA fiber at 1.20 vol.% of UHPC. Table 3 shows the improvements in material properties of UHPC at the predicted optimum reinforcement condition. Gains in different material properties of UHPC are also presented in Table 3. The fact that the optimized system comprises both PVA fiber and CNF points at their synergistic actions towards enhancement of the UHPC material properties. It is worth mentioning that the contribution of PVA fibers to the flexural strength of UHPC benefits from the relatively small thickness (12.5 mm, 0.5 in) of flexure test specimen compared to the fiber length (13 mm, 0.52 in). In spite of the flexibility of PVA fibers, this relatively small thickness could produce a tendency towards planar (in lieu of spatial) orientation of fibers. This geometric constraint does not alter the spatial orientation of nanofibers which have micrometer-scale lengths.

Figure 5. Experimental results on hardened UHPC material properties (means and standard errors).
Effective use of nanomaterials in concrete requires thorough dispersion of nanomaterials, and their effective interfacial interactions with cement hydrates. Given the fine dimensions of nanomaterials, their dispersion and interfacial interactions in concrete benefit from increased volume fraction, fineness, and density of the binder in concrete. Therefore, nanomaterials tend to be more effective in higher performance concrete. The efforts taken in this project to ensure thorough dispersion and effective interfacial interactions of nanofibers, and also the use of UHPC have produced percent gains in material properties at relatively low nanofiber dosages which surpass those reported in the literature.

### 4. Summary and conclusions

A hybrid (micro/nanoscale) reinforcement system comprising CNF and PVA microfiber was optimized for balanced improvement of UHPC material properties. Oxidized CNF used in this investigation offers approach the desired geometric, mechanical, physical, and stability characteristics of CNT at about half the cost. CNF is produced at commercial scale, and is readily available for purchase. When compared with microscale (PVA) fibers, CNF offers distinct features for effective control of microcrack inception and growth. Micro- and nanoscale reinforcement offer the potential for complementary/synergistic actions in high-performance cementitious matrices because they function of different scales, and also because nanofibers can enhance the bonding and pullout behavior of microscale fibers. Surface treatment methods were developed to enhance the dispersion and interfacial interaction of CNF in cementitious matrix. An optimization experimental program was designed and implemented in order to identify the optimum dosage of PVA and modified CNF in UHPC. The material

| Flexural strength, MPa (psi) | Maximum deflection, mm (in) | Energy absorption capacity, N mm (lb in) | Impact resistance, mm/mm (in/in) | Abrasion weight loss, g (oz) | Compressive strength, MPa (psi) | Static flow, mm (in) | Dynamic flow, mm (in) |
|-----------------------------|-----------------------------|----------------------------------------|---------------------------------|-------------------------------|-------------------------------|----------------------|---------------------|
| 14.3 (20770) | 11 (0.43) | 1445 (411) | 4.13 (4.13) | 1.12 (0.04) | 139 (20.1) | 127 (5.1) | 178 (7.0) |
| Improvement (%) | 9.2 | 1000.0 | 70.0 | 158.2 | 33.9 | 7.5 | −57.5 | 28.8 |
properties included fresh mix workability, flexural strength, energy absorption capacity and maximum deflection, impact and abrasion resistance, and compressive strength. Experimental results confirmed the synergistic/complementary action of nano- and microscale reinforcement in UHPC. The optimum reinforcement system, which comprised PVA fiber and CNF of 0.37 and 0.047 vol.% of UHPC improved the flexural strength, maximum deflection, energy absorption capacity, impact resistance, abrasion weight loss, and compressive strength of plain UHPC by 9.2, 1000.0, 700.0, 158.2, 33.9, and 7.5%, respectively. At the volume fractions considered here, modified CNF did not significantly alter the work abilities of fresh UHPC mixtures; PVA fiber, on the other hand, compromised the UHPC fresh mix workability. It should be noted that the discrete (nano- and microscale) reinforcement systems selected as optimum in this investigation corresponds to particular concrete materials, mix designs and production conditions, and fiber and nanofiber geometric, surface, and material characteristics. The material properties obtained in this investigation can be further improved through refinement of these parameters and identification of the corresponding optimum discrete reinforcement systems.

Acknowledgments
The authors wish to acknowledge the support of the National Science Foundation (NSF).

Funding
The research that is the subject of this paper was funded by the National Science Foundation (NSF) under grant number IIP-1142455.

Author details
Libya Ahmed Sbia1
E-mail: sbia@egr.msu.edu
Amirpasha Peyvandi2
E-mail: Amirpasha.peyvandi@gmail.com
Porviz Saroushian1
E-mail: porviz@egr.msu.edu
Anag M. Balachandra1
E-mail: Abmetnaco@gmail.com

1 Department of Civil and Environmental Engineering, Michigan State University, 3546 Engineering Building, E. Lansing, MI 48824-1226, USA.
2 Bridge Department, HNTB Corporation, 10000 Perkins Rowe, Suite No. 640, Baton Rouge, LA, 70810, USA.
3 Metna Co., 1926 Turner St., Lansing, MI 48824-1226, USA.

Citation information
Cite this article as: Optimization of ultra-high-performance concrete with nano- and micro-scale reinforcement, L.A. Sbia, A. Peyvandi, P. Saroushian & A.M. Balachandra, Cogent Engineering (2014), 2: 900673.

References
Barnett, S. J., Lataste, J. F., Parry, T., Millard, S. G., & Soutsos, M. N. (2014). Cogent Engineering

Barnett, S. J., Lataste, J. F., Parry, T., Millard, S. G., & Soutsos, M. N. (2010). Performance of carbon nanofiber-cement composites with a high-range water reducer. Transportation Research Record: Journal of the Transportation Research Board, 2142, 109–113. http://dx.doi.org/10.3141/2142-16

Graybeal, B. A. (2007). Compressive behavior of ultra-high-performance fiber-reinforced concrete. ACI Materials Journal, 104, 146–152.

Hobel, K., Viviani, M., Denarié, E., & Brühlwiler, E. (2006). Development of the mechanical properties of an ultra-high performance fiber reinforced concrete (UHPFRC). Cement and Concrete Research, 36, 1362–1370. http://dx.doi.org/10.1016/j.cemconres.2006.03.009

Kolatzidou, K., Fukushima, H., & Drzał, L. T. (2007). Multifunctional polypropylene composites produced by incorporation of exfoliated graphite nanoplatelets. Carbon, 45, 1446–1452. http://dx.doi.org/10.1016/j.carbon.2007.03.029

Kang, S. T., & Kim, J. K. (2011). The relation between fiber orientation and tensile behavior in ultra high performance fiber reinforced cementitious composites (UHPFRC). Cement and Concrete Research, 41, 1001–1014. http://dx.doi.org/10.1016/j.cemconres.2011.05.009

Kang, S. T., Lee, Y., Park, Y. D., & Kim, J. K. (2010). Tensile fracture properties of an ultra high performance fiber reinforced concrete (UHPFRC) with steel fiber. Composite Structures, 92, 61–71. http://dx.doi.org/10.1016/j.compstruct.2009.06.012

Konsta-Gdoutos, M. S., Metaxa, Z. S., & Shah, S. P. (2010). Multi-scale mechanical and fracture characteristics and early-age strain capacity of high performance carbon nanotube/cement nanocomposites. Cement and Concrete Composites, 32, 110–115.

Li, G. Y., Wang, P. M., & Zhao, X. (2005). Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes. Carbon, 43, 1239–1245. http://dx.doi.org/10.1016/j.carbon.2004.12.017

Maugerano, C., Sosa, I., Negruțiu, C., & Hughes, B. (2012). Mechanical properties and durability of ultra-high-performance concrete. ACI Materials Journal, 109, 177–184.

Materazzi, A. L., Ubertini, F., & D’Alessandro, A. (2013). Carbon nanotube cement-based transducers for dynamic sensing of strain, Cement and Concrete Composites, 35, 2–11. http://dx.doi.org/10.1016/j.cemconcomp.2012.12.013

Melo, V. S., Colixto, J. M. F., Ladeira, L. O., & Silva, A. P. (2011). Macro- and micro-characterization of mortars produced with carbon nanotubes. ACI Materials Journal, 108, 327–332.
Metaxa, Z. S., Konsta-Gdoutos, M. S., & Shah, S. P. (2010). Carbon nanofiber-reinforced cement-based materials. Transportation Research Record: Journal of the Transportation Research Board, 2142, 114–118. http://dx.doi.org/10.3141/2142-17

Musso, S., Tulliani, J. M., Ferro, G., & Tagliaferro, A. (2009). Influence of carbon nanotubes structure on the mechanical behavior of cement composites. Composites Science and Technology, 69, 1985–1990. http://dx.doi.org/10.1016/j.compscitech.2009.05.002

Nochaia, T., & Chaparian, A. (2011). Behavior of multi-walled carbon nanotubes on the porosity and microstructure of cement-based materials. Applied Surface Science, 257, 1941–1945. http://dx.doi.org/10.1016/j.apsusc.2010.09.030

Peyvandi, A., Sbia, L. A., Soroushian, P., & Sobolev, K. (2013). Effect of the cementitious paste density on the performance efficiency of carbon nanofiber in concrete nanocomposite. Construction and Building Materials, 48, 265–269. http://dx.doi.org/10.1016/j.conbuildmat.2013.06.094

Peyvandi, A., Soroushian, P., Abdol, N., & Balachandra, A. M. (2013). Surface-modified graphite nanomaterials for improved reinforcement efficiency in cementitious paste. Carbon, 63, 175–186. http://dx.doi.org/10.1016/j.carbon.2013.06.069

Peyvandi, A., Soroushian, P., Balachandra, A., & Sobolev, K. (2013). Enhancement of the durability characteristics of concrete nanocomposite pipes with modified graphite nanoplatelets. Construction and Building Materials, 47, 111–117. http://dx.doi.org/10.1016/j.conbuildmat.2013.05.002

Peyvandi, A., Soroushian, P., & Jahangirinejad, S. (2013). Enhancement of the structural efficiency and performance of concrete pipes through fiber reinforcement. Construction and Building Materials, 45, 36–44. http://dx.doi.org/10.1016/j.conbuildmat.2013.03.084

Raki, L., Beaudoin, J., Alizadeh, R., Makar, J., & Sato, T. (2010). Cement and concrete nanoscience and nanotechnology. Materials, 3, 918–942. http://dx.doi.org/10.3390/mater3030918

Schröfl, C., Gruber, M., & Plank, J. (2012). Preferential adsorption of polycarboxylate superplasticizers on cement and silica fume in ultra-high performance concrete (UHPC). Cement and Concrete Research, 42, 1401–1408. http://dx.doi.org/10.1016/j.cemconres.2012.08.013

Tyson, B. T., Abu Al-Rub, R. K., & Yazdanbakhsh, A. (2011). Carbon nanotubes and carbon nanofibers for enhancing the mechanical properties of nanocomposite cementitious materials. Journal of Materials in Civil Engineering, 23, 1028–1035. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000266

Van Tuan, N., Ye, G., van Breugel, K., & Copuroglu, D. (2011). Hydration and microstructure of ultra high performance concrete incorporating rice husk ash. Cement and Concrete Research, 41, 1104–1111. http://dx.doi.org/10.1016/j.cemconres.2011.06.009

Wille, K., & Loh, K. J. (2010). Nanoengineering ultra-high-performance concrete with multiwalled carbon nanotubes. Transportation Research Record: Journal of the Transportation Research Board, 2142, 119–126. http://dx.doi.org/10.3141/2142-18

Wille, K., Noaman, A. E., El-Tawil, S., & Parra-Montesinos, G. J. (2012). Ultra-high performance concrete and fiber reinforced concrete: Achieving strength and ductility without heat curing. Materials and Structures, 45, 309–324. http://dx.doi.org/10.1617/s11527-011-9767-0

Wille, K., Noaman, A. E., & Parra-Montesinos, G. J. (2011). Ultra-high performance concrete with compressive strength exceeding 150 MPa (22 ksi): A simpler way. ACI Materials Journal, 108, 46–54.

Yang, J. H., Joh, C., & Kim, B. S. (2011). Flexural strength of large-scale ultra high performance concrete prestressed T-beams. Canadian Journal of Civil Engineering, 38, 1185–1195. http://dx.doi.org/10.1139/L11-078

Yoo, D. Y., Lee, J. H., & Yoon, Y. S. (2013). Effect of fiber content on mechanical and fracture properties of ultra high performance fiber reinforced cementitious composites. Composite Structures, 106, 742–753. http://dx.doi.org/10.1016/j.compstruct.2013.07.033