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# Dynamic Shear Energy Absorption of Ultra-High Performance Concrete

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***Abstract*—**The exemplary mechanical performance and durability of ultra-high performance concrete (UHPC) has led to its rapid emergence as an advanced cementitious material. The uncharacteristically high mechanical strength and ductility of UHPC makes it a promising potential material for defense structures which may be subject to highly dynamic loads like impact or blast. However, the mechanical response of UHPC under dynamic loading has not been fully characterized. In particular, there is a need to characterize the energy absorption of UHPC under high-frequency shear loading. This paper presents preliminary results from a parametric study of the dynamic shear energy absorption of UHPC using the Charpy impact test. UHPC mixtures with compressive strengths in the range of 100-150 MPa exhibited dynamic shear energy absorption in the range of 0.9-1.5 kJ/m. Energy absorption is shown to be sensitive to the water/cement ratio, silica fume content, and aggregate gradation. Energy absorption was weakly correlated to compressive strength. Results are highly sensitive to specimen preparation methods, and there is a demonstrated need for a standardized test method for high frequency shear in cementitious composites.

***Keywords*—**Charpy impact test, dynamic shear, impact loading, ultra-high performance concrete.



## I. Introduction

UHPC is a rapidly-emerging advanced concrete material that exhibits compressive strength in excess of 150 MPa, tensile strength in excess of 10 MPa, and significant post-cracking tensile capacity [1], [2]. The exemplary performance of UHPC is derived from: (1) low water-to-cementitious materials ratio (*w/cm*), which is facilitated by the inclusion of high-range water-reducing admixtures (super-plasticizers); (2) optimized packing density resulting from the inclusion of finely-graded sand and silica fume and the exclusion of coarse aggregates; and (3) enhanced ductility resulting from the inclusion of fiber reinforcement. In addition to excellent mechanical performance, the durability of UHPC is far superior to that of conventional concrete [1]-[3]. The superior mechanical performance and durability of UHPC has led to its implementation in a variety of applications, including bridge decks, girders, piles, seismic columns, wind turbine towers, and complex architectural elements [3]-[6]. UHPC is particularly suitable in applications which require enhanced ductility and energy absorption, or when limitations on the physical size of concrete members enhanced strength.

The strength, ductility, and durability of UHPC also make it ideal for use in structures which may be subject to hazardous loadings. This includes bunkers, barriers, or storm and blast shelters, or other structures which have a high likelihood of experiencing projectile impact or explosive blast loads [7]-[11]. The performance of these types of structures relies on the impact strength of the materials used in construction. A number of studies have discussed the blast and impact resistance of UHPC using both experimental and numerical methods [7]-[9], [12]-[15], but these studies have focused on the macroscale impact performance.

The present study investigates the impact resistance of UHPC at a material level rather than at a structural level. Preliminary experimentation has identified that UHPC fails in shear when loaded at high strain rates. Therefore, the specific goal of this study is to investigate the high-frequency shear strength of UHPC. This is accomplished by evaluating specimens using the Charpy impact test in a shear-dominated (deep beam) test configuration.

A few authors have previously investigated the impact resistance of UHPC using the Charpy impact method [16]-[18]. Yu et al. [16], [17] and Yalcinkaya et al. [18] both tested the impact resistance of un-notched prismatic UHPC specimens using the Charpy impact test. The former studies tested specimens measuring 25.4 x 25.4 mm in cross-section and 40 mm in span, while the latter tested specimens measuring 10 x 10 mm over the same span. These studies all reported impact energy absorption in units of energy (J) without normalization by specimen size. Those specimens tested by Yu et al. [16], [17], which were likely to be shear-dominated, exhibited impact energy absorption in the range of 20—80 J. Those tested by Yalcinkaya et al. [18], which were likely to be bending-dominated, exhibited impact energy absorption in the range of 2—10 J. Both studies concluded that fiber content was the most significant factor in improving impact resistance in UHPC. Yalcinkaya et al. [18] acknowledged the detrimental effects of saw-cutting specimens from larger blacks, which caused the development of microcracks in specimens.

The present study investigates the high-frequency shear strength of UHPC using the Charpy impact test in a similar manner as Yu et al. [16], [17]. A parametric analysis was used in order to determine the effects of various UHPC mixture parameters on the resulting impact resistance. The UHPC mixtures evaluated in this study do not include fiber reinforcement in order to isolate the effects of other mixture parameters. The results of this study will provide valuable

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information for the design of UHPC mixtures for defense and other applications.

## II. Experimental Methods

### A. Mixture Proportioning

A number of proven and reliable proprietary UHPC products are available on the commercial market in the United States. However, the objective of the present study was to perform a parametric analysis of the impact strength of UHPC as a function of mixture proportion parameters. This required precise knowledge of constituent materials and compositions, and the ability to modify their proportions. To that end, a non-proprietary UHPC mixture based on locally-available materials was developed following the principles outlined by Allena and Newtson [19].

UHPC mixtures were typically comprised of ordinary portland cement, silica fume, super-plasticizer, and finely-graded sand. Protland cement was sourced from Ash Grove Cement Company, Inkom, ID, and met the specifications of ASTM C150 [20] for cement types II-V. Dry densified silica fume was sourced from BASF udner the trade name Rheomac SF 1000. Type F high-range water-reducing admixture [21] was sourced from BASF under the trade name MasterGlenium 3030. Fine industrial quartz sand was sourced from Rocky Mountain Supply, Pocatello, ID. In the supplied condition, the sand gradation was such that 60% by mass was retained on a US Standard No. 40 sieve. The sand was further processed through a US Standard No. 30 sieve such that the maximum particle size was 595 µm.

UHPC mixture proportions utilized in this study are given in Table I. The control mixture included a total of 1113 kg/m$^3$ cementitious materials, which included 20% silica fume and 80% portland cement by mass. The water-to-cementitious materials ratio (*w/cm*) was 0.20. Three parameters were varied for the parametric study: *w/cm*, silica fume, and sand gradation. *w/cm* was varied from 90—120% of the control value (0.18≤*w/cm*≤0.24). The super-plasticizer dosage was adjusted according to manufacturer recommendations. Silica fume replacement was varied from 80—120% of the control value (16—24% of total cementitious materials). Sand gradation was altered in mixture S1 so that only the fraction coarser than 595 µm was included, and in mixture S2 such that an equal mass of sand coarser and finer than 595 µm was included.

### B. Specimen Preparation

UHPC mixtures were prepared in a variable-speed benchtop mixer. Sand, cement, and silica fume were first charged into the mixing bowl and mixed for five minutes. Water was then charged into the bowl with the mixer running. Superplasticizer was added after mixing for five additional minutes. Due to the high mixing energy requirements of UHPC, each batch was then mixed for between 30 and 90 minutes until the mixture was homogenous and workable.

Once adequately mixed, UHPC was cast into cubic specimens for the determination of compressive strength and prismatic specimens for the determination of impact energy absorption. Cubic specimens measured 50.8 x 50.8 x 50.8 mm and were cast in three lifts in stamped metallic molds. Specimens were manually rodded between lifts and trowel-finished. Prismatic specimens measured 25.4 x 25.4 x 50.8 mm and were cast in two lifts in machined acrylic molds. Specimens were manually-rodded between lifts. Immediately after casting, a V-notch as shown in Fig. 1 was formed in the specimen surface using a machined acrylic form. Specimens were trowel-finished with the notch forming bar in place.

TABLE I
UHPC Mixture Proportions (kg/m$^3$)

| Mixture | Portland cement | Silica fume | Sand | Water | Super-plasticizer | *w/cm* |
|---|---|---|---|---|---|---|
| Control | 890 | 223 | 837 | 223 | 29.7 | 0.20 |
| W1 | 890 | 223 | 837 | 268 | 28.2 | 0.24 |
| W2 | 890 | 223 | 837 | 245 | 29.0 | 0.22 |
| W3 | 890 | 223 | 837 | 201 | 30.4 | 0.18 |
| SF1 | 935 | 178 | 837 | 223 | 29.7 | 0.20 |
| SF2 | 912 | 201 | 837 | 223 | 29.7 | 0.20 |
| SF3 | 868 | 245 | 837 | 223 | 29.7 | 0.20 |
| SF4 | 846 | 268 | 837 | 223 | 29.7 | 0.20 |
| S1 | 890 | 223 | 837[a] | 223 | 29.7 | 0.20 |
| S2 | 890 | 223 | 837[b] | 223 | 29.7 | 0.20 |

[a]100% of sand retained on No. 30 sieve
[b]50% of sand retained on No. 30 sieve

Following casting, specimens were open-air cured in their molds for 24h at 23±2 ˚C. Specimens were then demolded and cured in saturated limewater for 28d at 50±1.5 ˚C.

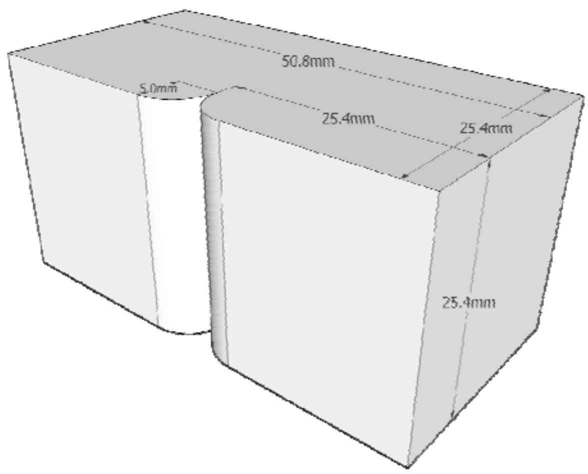


Fig. 1 Notched Charpy specimen dimensions

### C. Test Methods

The 28-d compressive strength of UHPC cubes was determined in accordance with the specifications of ASTM C109 [22]. Cubic specimens were tested using a standard hydraulic compression tester having a capacity of 1,300 kN. The loading rate was increased from 0.5 MPa/s as recommended by ASTM C109 to 1.0 MPa/s as recommended by Graybeal and Davis [23]. Compressive strength results are reported as the average strength of nine replicate specimens.

The 28-d impact energy absorption of V-notched prismatic specimens was measured by the Charpy impact test in general accordance with the specifications of ASTM E23 [24]. The Charpy impact testing apparatus over a span of 40 mm is shown in Fig. 2. Specimen dimensions were measured in three representative locations by Vernier caliper. The Charpy pendulum was locked in the raised position, and the specimen was installed into the apparatus as shown in Fig. 3. The pendulum was then released, causing the anvil to impact and subsequently fracture the specimen. The energy absorbed is the difference between the total potential energy of the pendulum and the residual energy after impact as measured by the maximum height achieved by the pendulum following the impact event considering losses due to drag [26]. In contrast to previous studies which report the impact energy absorption in units of energy (J) without normalization, this study report impact energy normalized by the specimen thickness in the direction of impact (i.e., the notch ligament length) in order to account for variations in the notch depth.

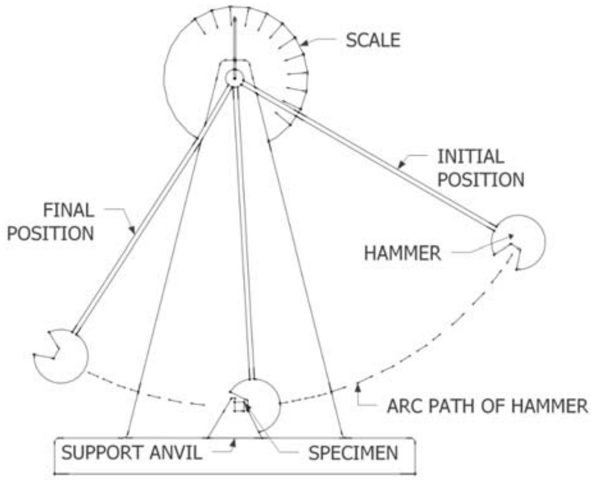


Fig. 2 Charpy impact testing apparatus

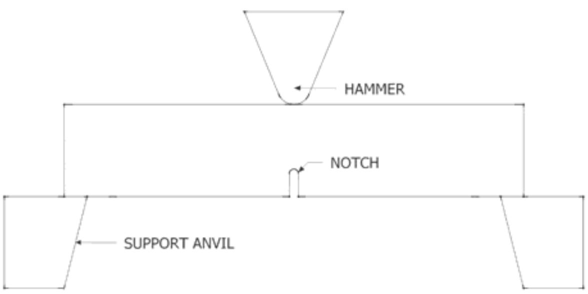


Fig. 3 Charpy impact loading configuration

## III. Results and Discussion

### A. Compressive Strength

The 28-d compressive strength of the control UHPC mixture was approximately 140 MPa. Increased *w/cm* resulted in reduced compressive strength, as shown in Fig. 4. This result is consistent with expectations based on the known behavior of ordinary portland cement concrete and UHPC. The highest observed compressive strength was approximately 145 MPa with *w/cm*=0.18.

Adjustments to the silica fume dosage had mixed effects on compressive strength, as shown in Fig. 5. It was apparent that there was an optimum silica fume dosage near 20% of total cementitious materials that resulted in the highest compressive strength. This is not an unexpected result; despite the minor strength improvement that can be expected as a result of the pozzolanic activity of silica fume, its main benefit comes from optimized packing density [1], [2]. As such, it is logical that an optimum silica fume dosage exists.

Mixtures S1 and S2, which included coarser sand fractions, also suffered from reduced compressive strength. This is again consistent with expectations based purely on the fact that the exemplary strength of UHPC is heavily reliant on optimized packing density [1], [2].

Variability in compressive strength results was high. The coefficient of variation was at least 12 percent for all mixtures. The highest coefficient of variation was 39 percent for mixture S1, which included the coarsest sand fraction. It is possible that the reduced packing density resulting from the inclusion of such a coarse sand fraction was detrimental to the uniformity of the resulting UHPC.

### B. Impact Energy Absorption

The 28-d impact energy absorption of the control UHPC mixture was approximately 1.24 kJ/m. Adjustments to *w/cm*, silica fume dosage, and sand gradation had mixed effects on the impact energy absorption. Mixture S1, which included the coarsest sand fraction, exhibited the highest impact energy absorption of 1.48 kJ/m. Mixture SF2, which included 18% silica fume, exhibited the lowest impact energy absorption of 0.95 kJ/m. Impact energy absorption results are given in Table II. The effects of *w/cm* and silica fume dosage are illustrated in Figs. 6 and 7, respectively.

Variability in impact energy absorption results was also very high—much higher than in compressive strength results. The coefficient of variations was no less than 37 percent for any individual mixture. In some cases, the coefficient of variation was as high as 81 percent. Despite this, some weak correlations are observable. The impact energy absorption tended to decrease with *w/cm*, except when the control mixture is considered. All three mixtures with altered *w/cm* exhibited impact energy absorption much less than that of the control mixture. Furthermore, an apparent optimum dosage of silica fume was also evident; the impact energy absorption was highest when silica fume was between 20% and 22% of total cementitious materials. This is consistent with the previously described compressive strength results.

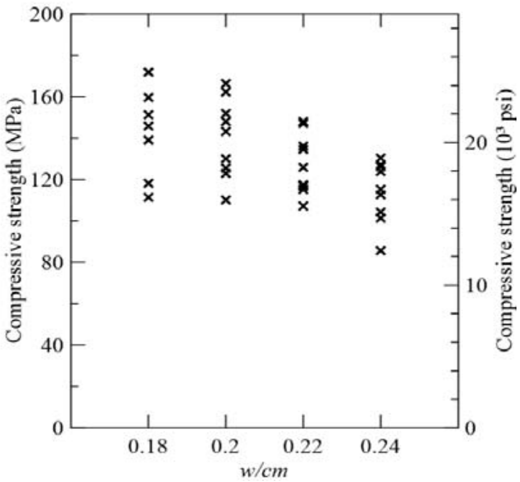


Fig. 4 Compressive strength vs. *w/cm*

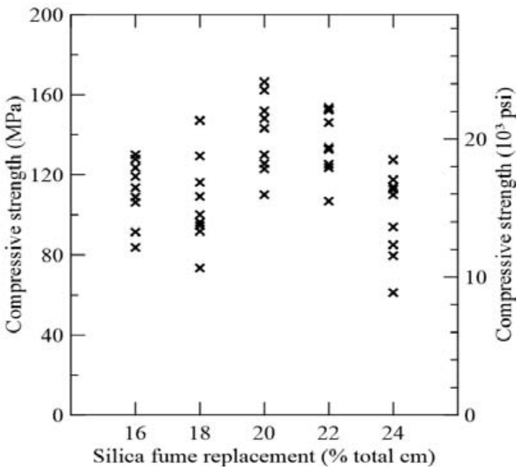


Fig. 5 Compressive strength vs. silica fume dosage

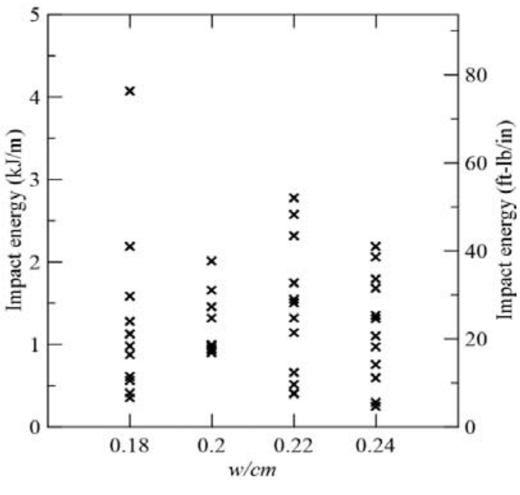


Fig. 6 Impact energy absorption vs. *w/cm*

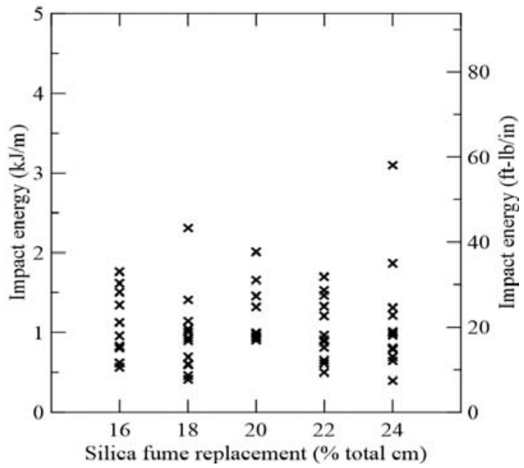


Fig. 7 Impact energy absorption vs. silica fume dosage

TABLE II
SUMMARY OF RESULTS

| Mixture | Compressive strength (MPa) | C.V. | Impact energy absorption (kJ/m) | C.V. |
|---|---|---|---|---|
| Control | 140.1 | 0.14 | 1.24 | 0.39 |
| W1 | 106.5 | 0.21 | 0.96 | 0.53 |
| W2 | 136.3 | 0.12 | 1.05 | 0.37 |
| W3 | 100.2 | 0.22 | 1.15 | 0.63 |
| SF1 | 114.1 | 0.13 | 1.2 | 0.54 |
| SF2 | 127.6 | 0.12 | 1.41 | 0.59 |
| SF3 | 145.3 | 0.15 | 1.26 | 0.81 |
| SF4 | 111.7 | 0.14 | 1.07 | 0.40 |
| S1 | 118.6 | 0.39 | 1.48 | 0.49 |
| S2 | 118.2 | 0.16 | 1.17 | 0.54 |

C.V. = Coefficient of Variation

### *C. Discussion*

It is often desirable to relate the mechanical properties of concrete to the compressive strength. The impact energy absorption of UHPC mixtures evaluated in this study is compared to the compressive strength in Fig. 8. The figure shows the average compressive strength as the abscissa and the average impact energy absorption as the ordinate. The error bars in each direction represent the sample standard deviation for each measurement. Given the small range of compressive strength values represented by these data and the large variation in the data, it is difficult to draw conclusions with respect to the correlation between compressive strength and impact energy absorption.

Although the compressive strength data exhibit a high degree of variability, the impact energy absorption data are much more variable. The likely source of this variability is in the notch formation procedure. The inclusion of a notch in Charpy specimens of metallic and plastic materials [24], [25] is intended to cause brittle failure in materials that may otherwise exhibit high ductility [26]. Ductility is not an issue when testing concrete materials; instead, the intent of the notch is to provide a stress concentration that causes preferential failure at mid-span. This results in a stable and well-defined failure plane which is convenient for normalization of impact energy absorption. However, the process of forming the notch in fresh UHPC was imprecise and poorly repeatable. The resulting notches were therefore irregular and of inconsistent geometry, which is known to have a significant effect on impact test results.

A few other studies have reported Charpy impact test results for UHPC, but have done so using plain (un-notched) specimens [16]-[18]. Lavin et al. [27] performed Charpy impact testing on PVA fiber-reinforced concrete using specimens of identical geometry to those discussed in the present study, but with saw-cut notches. Lavin et al. did not report any such inconsistencies in crack geometry or prohibitively high variability in test results. As such, the continuation of this study will determine if saw-cut cracks can improve the consistency of impact energy absorption results.

Comparison of the results presented here with those from similar studies by other authors is difficult due to the lack of normalization in those studies [16]-[18]. There is bound to be some variability in specimen dimensions, and it is therefore necessary to normalize the impact energy absorption based on those dimensions. Because there is no standardized method for Charpy impact testing of cementitious composites; however, there is no consistent normalization procedure. The data in the present study are normalized by the length of the notch ligament in an effort to account for the variation in notch depth that resulted from the notch formation procedure. Other normalizations will be evaluated in the continuation of this study, such as normalization by the cross-sectional area at the notch location.

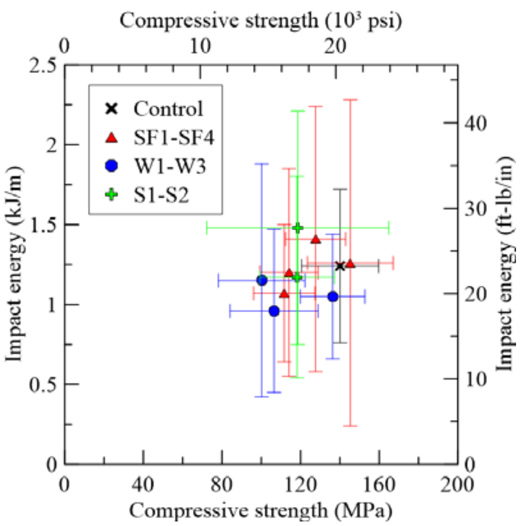


Fig. 8 Impact energy absorption vs. compressive strength

## IV. Conclusion

This paper has presented some preliminary work towards the investigation of the high-frequency shear resistance of UHPC using the Charpy impact test. The impact energy absorption of UHPC in shear-dominated loading was between 0.96 and 1.49 kJ/m. The impact energy absorption decreased as the water-to-cementitious materials ratio decreased. There was an apparent optimum silica fume dosage that resulted in the best impact energy absorption. The maximum recorded impact energy absorption was with 20% silica fume by total mass of cementitious materials. The high variability in data made any conclusions with respect to the correlation between compressive strength and impact energy absorption impossible.

A number of methods of improving data for the continuation of this study are identified. In particular, the process of forming the notch in fresh UHPC specimens was identified as a likely source of variability. Saw-cutting of notches will likely improve the repeatability and uniformity of notches in future specimens. The results presented here are of similar magnitude to those presented by similar studies, but the lack of normalization from previous studies limits the basis for comparison. This highlights the need for a standardized method for Charpy impact testing of cementitious composites.

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## References

[1] B. Graybeal, "Material Property Characterization of Ultra-High Performance Concrete (FHWA-HRT-06-103)," Federal Highway Administration, Washington, DC, 2006.W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.
[2] B. Graybeal, "Ultra-High Performance Concrete (FHWA-HRT-11-038)," Federal Highway Administration, Washington, DC, 2011.
[3] H. Russell and B. Graybeal, "Ultra-high performance concrete: A state-of-the-art report for the bridge community (FHWA-HRT-13-060)," Federal Highway Administration, Washington, D.C., 2013.
[4] J. Resplendino, "First recommendations for ultra-high-performance concretes and examples of application," in *International Symposium on Ultra High Performance Concrete*, 2004.
[5] S. Rahman, T. Molyneaux and I. Ptnaikuni, "Ultra high performance concrete: Recent applications and research," *Australian Journal of Civil Engineering,* vol. 2, no. 1, pp. 13-20, 2005.
[6] M. Schmidt and E. Fehling, "Ultra-high-performance concrete: Research, development and application in Europe," *ACI Special Publication,* vol. 228, pp. 51-78, 2005.
[7] N. Yi, J. Kim, T. Han, Y. Cho and J. Lee, "Blast-resistant characteristics of ultra-gigh strength concrete and reactive powder concrete," *Construction and Building Materials,* vol. 28, no. 1, pp. 694-707, 2012.
[8] M. Rebentrost and G. Wight, "Investigation of UHPFRC slabs under blast loads," in *Proceedings, Ultra-High Performance Fiber Reinforced Concrete 2009*, 2009.
[9] B. Ellis, B. DiPaolo, D. McDowell and M. Zhou, "Experimental investigation and multiscale modeling of ultra-high-performance concrete panels subject to blast loading," *International Journal of Impact Engineering,* vol. 69, pp. 95-103, 2014.
[10] B. Lukic and P. Forquin, "Experimental characterization of the punch through shear strength of an ultra-high performance concrete," *International Journal of Impact Engineering,* vol. 91, pp. 34-45, 2016.
[11] K. Wille, A. Naaman and G. Parra-Montesinos, "Ultra-hgih performance concrete with compressive strength exceeding 150 MPa (22 ksi): A simpler way," *ACI Materials Journal,* vol. 108, no. 1, 2011.
[12] P. Maca, R. Sovjak and P. Konvalinka, "Mix design of UHPC and its response to projectile impact," *International Journal of Impact Engineering,* vol. 63, pp. 158-163, 2014.
[13] Y. Farnam, S. Mohammadi and M. Shekarchi, "Experimental and numerical investigations of low velocity impact behavior of high-performance fiber-reinforced cement based composite," *International Journal of Impact Engineering,* vol. 37, no. 2, pp. 220-229, 2010.
[14] L. Mao, S. Bernett, D. Begg, G. Schleyer and G. Wight, "Numerical simulation of ultra high performance fibre reinforced concrete panel subjected to blast loading," *International Journal of Impact Engineering,* vol. 64, pp. 91-100, 2014.

[15] C. Wu, D. Oehlers, M. Rebentrost, J. Leach and A. Whittaker, "Blast testing of ultra-high performance fibre and FRP-retrofitted concrete slabs," *Engineering Structures,* vol. 31, no. 9, pp. 2060-2069, 2009.
[16] R. Yu, L. van Beers, P. Spiesz and H. Brouwers, "Impact resistance of a sustainable Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) under pendulum impact loadings," *Construction and Building Materials,* vol. 107, pp. 203-215, 2016.
[17] R. Yu, P. Spiesz and H. Brouwers, "Static properties and ipmact resistance of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC): Experiments and modeling," *Construction and Building Materials,* vol. 68, pp. 158-171, 2014.
[18] C. Yalcinkaya, J. Sznajder, A. Beglatigale, O. Sancakoglu and H. Yazici, "Abrasion resistance of reactive powder concrete: The influence of water-to-cement ratio and steel micro-fibers," *Advanced Materials Letters,* vol. 5, no. 6, pp. 345-351, 2014.
[19] S. Allena and C. Newtson, "Ultra-high strength concrete mixtures using local materials," *Journal of Civil Engineering and Architecture,* vol. 5, no. 4, pp. 322-330, 2011.
[20] American Society of Testing and Materials, ASTM C150-16 Standard Specification for Portland Cement, ASTM International, 2016.
[21] American Socienty of Testing and Materials, ASTM C494-15a Standard Specification for Chemical Admixtures for Concrete, ASTM International, 2015.
[22] American Society of Testing and Materials, ASTM C109-16a Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or (50-mm) Cube Specimens), ASTM International, 2016.
[23] B. Graybeal and M. Davis, "Cylinder or cube: Strength testing of 80 to 200 MPa (11.6 to 29 ksi) ultra-high-perofrmance fiber-reinforced concrete," *ACI Materials Journal,* vol. 105, no. 6, pp. 603-609, 2008.
[24] American Society of Testing and Materials, ASTM E23-16b Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, ASTM International, 2016.
[25] American Society of Testing and Materials, ASTM D6110-10 Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastic, ASTM International, 2010.
[26] A. LeChatalier, "On the fragility after immersion in a cold fluid," *French Testing Commission,* vol. 3, 1892.
[27] T. Lavin, H. Toutanji, B. Xu, R. K. Ooi, K. R. Biszick and J. A. Gilbert, "Matrix design for strategically tuned absolutely resilient structures (STARS)," in *Proceedings of SEM XI International Congress on Experimental and Applied Mechanics*, Orlando, Florida, 2008.