Development of Onsite Test Methods to Evaluate Fiber Stability in UHPC

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Abstract

While it is generally expected that UHPC is self-consolidating, it is often challenging to achieve the desired workability, which creates an obstacle to the wide adoption of this new material. The viscosity of Ultra-High-Performance Concrete (UHPC) is a major factor in maintaining uniform fiber distribution, especially in deep components, as the density of steel fibers is much higher than that of the paste, which makes it prone to segregation. Currently, fresh UHPC workability largely relies on the flow (spread) test, which is insufficient to evaluate fiber stability. Furthermore, due to the lack of effective quality control of UHPC during production and construction, different levels of fiber segregation are often observed in highly flowable UHPC mixtures, which could lead to significant concern in the structural performance of cast-in-place or precast concrete components. This paper presented a preliminary study of developing a set of onsite fresh and hardened UHPC test methods to evaluate the fiber stability of UHPC. Results showed that methods such as the Visual Stability Index (VSI), mini-V-funnel, and falling ball test could successfully assess fiber stability in fresh UHPC. In addition, besides the Hardened Visual Stability Index (HVSI), a surface electric resistivity meter could be an effective tool for the in-situ evaluation of fiber distribution in hardened UHPC products. The development of onsite QA/QC methods and assurance of appropriate fiber stability is essential for having a quality product to ensure that fibers are well-distributed as assumed in design and avoid disposal of costly products.

Keywords: UHPC, flow, fiber, stability, segregation, workability

1. Introduction

Ultra-high-performance concrete (UHPC) is a new class of concrete that has mechanical and durability properties that far exceed those of conventional concrete. The use of UHPC will result in significant improvements in the structural capacity and durability of structural components. Due to its superior characteristics, UHPC has drawn substantial interest in the bridge community at both federal and state levels (Graybeal 2014). Besides the bridge deck connections applications in multiple states, Federal Highway Administration (FHWA) Every Day Counts (EDC-6) program "UHPC for Bridge Preservation and Repair" emphasizes the use of UHPC for other bridge applications due to its excellent mechanical and durability properties. Due to a large amount of fine powders and the very low water-to-cement ratio in UHPC, the workability of UHPC is very different from conventional concrete (Sbia et al. 2017). While it is generally expected that UHPC is self-consolidating, achieving the desired workability while maintaining stability is often challenging. As shown in Figure 1, severe fiber segregation could lead to aesthetics, structural, or durability concerns.

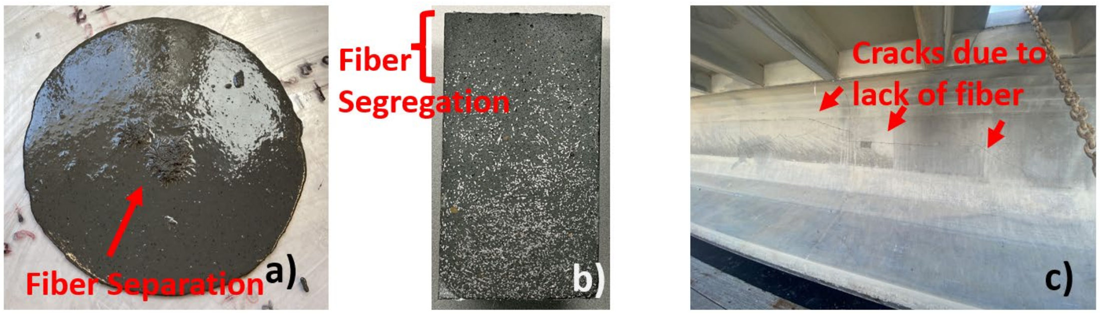

Figure 1. Fiber stability in UHPC (a. Fiber separation observed during flow test; b. Fiber segregation observed in concrete cylinders; c. Cracks in precast UHPC element due to fiber segregation)

While the workability of UHPC is often reported in different studies, the commonly used flow (spread) test, as per ASTM C1856, is more of a quality control tool, yet insufficient to identify issues during construction. Similar to when self-consolidation concrete (SCC) was first developed, a set of tests to evaluate the different aspects of UHPC workability is urgently needed (Russell 2008). There is also a need to establish onsite tests that can be easily performed and used in the field to identify potential issues before UHPC placement. One example of issues related to UHPC workability is the lack of viscosity for fiber stability, which is usually measured in a hardened state (Ruan and Poursaee 2019; Wang et al. 2017). A recent PCI study attempted to develop a modified static segregation test for fiber stability test (similar to ASTM C1610 for SCC). However, the method requires at least 30 minutes to complete, which is too long for QA/QC (PCI TR-9-22). A previous study from the authors shows that new tests, such as the visual stability index (VSI) and flow time, can be used to determine potential fiber segregation issues. However, the test methods are relatively subjective and might not be sensitive enough to identify issues in different placement conditions (Mendonca and Hu, 2021).

This paper presented a set of tests recently developed by the research team to identify and evaluate fiber stability in both fresh and hardened UHPC mixtures. In addition, the study assesses different UHPC fiber stability test methods to ensure proper UHPC workability before casting. With the development of onsite QA/QC methods and assurance of appropriate workability before UHPC casting, the success of this project will significantly encourage producers and contractors to adopt this innovative material in different applications.

2. Experimental Program

2.1. Materials and Mixture Design

In this study, Type I/II Portland cement, fine silica sand with a maximum aggregate size of No. 8 (2.36 mm), slag, silica fume, and micro straight steel fibers (0.5 in. (13.0 mm) in length and 0.2 mm in diameter) were used. A polycarboxylate-based high-range water reducer (HRWR) and workability retaining admixture (WRT) were also used to achieve desired workability.

Since the main focus of this study was to assess fiber stability in UHPC, three slightly different mixture designs, as shown in Table 1, were used, with Mix 1 as the stable mixture, and Mix 2 and

2 are the semi-stable and very unstable mixtures, respectively. While the solid contents were kept largely constant within the three mixtures, water contents, and HRWR contents were increased in Mix 2 and 3 to achieve moderate and severe fiber segregation, respectively (Li et al. 2017). Fiber content was kept constant at 2% (by volume) within the three mixtures.

Table 1. Mixture design

Mixture ID	Unit	Cement	Slag	Silica fume	Sand	Fiber	Water	HRWR	WRT
Mix 1	pcy	1206	586	161	1570	264	307	57.6	20.7
	kg/m^3	715	348	96	931	157	182	34.2	12.3
Mix 2	pcy	1206	586	161	1567	264	315	63.0	20.7
	kg/m^3	715	348	96	930	157	187	37.4	12.3
Mix 3	pcy	1206	586	161	1567	264	328	63.0	20.7
	kg/m^3	715	348	96	930	157	195	37.4	12.3

2.2. Mixing Procedure

An IMER MIX 120 pan mixer was used to prepare all mixtures. To achieve the desired consistency, UHPC was mixed in three major steps: mixing dry ingredients, adding water and admixtures, and introducing steel fibers. The first step was started by loading air-dried sand and silica fume into the mixer and mixing for five minutes, followed by adding cement and slag and mixing for another five minutes. Before introducing water into the mixture (which starts the second step), 80% of the total HRWR and total WRT admixture were premixed with 80% of the total water, then mixed for seven minutes in the mixer. The remaining water and HRWR admixture were premixed again and loaded into the mixer when a paste-like consistency of the mixture was observed. Once a vicious and uniform mixture was achieved, the fibers were loaded for a 1-minute duration and mixed for another three minutes in the mixer before it was discharged.

2.3. Test Methods

Due to the similar self-consolidating nature of UHPC and self-consolidation concrete (SCC), some test methods for the workability of SCC can be modified and adapted for UHPC. As ASTM 1856 is insufficient to reflect the different aspects of the workability of UHPC, the researchers have developed various tests to evaluate UHPC workability, particularly fiber stability (see Table 2). Besides static and dynamic flow (ASTM C1856 and C1437) that can be used to access characteristics related to the flowability and stability of UHPC. Additional tests, such as the Visual Stability Index (VSI), mini-V-funnel, penetration, and falling ball tests, could be used to assess the fiber stability of UHPC.

Table 2. Comparison of SCC and UHPC test methods included in the current study

State	SCC Test Method (Standards/References)	UHPC Test Method (Standards/References)
Fresh	Slump flow (ASTM C1611)	Flow Spread (ASTM C1856/C1437)
	Visual Stability Index (VSI) (AASHTO T347)	Visual Stability Index (Mendonca and Hu, 2021)
	V-Funnel (Elinwa et al. 2008)	Mini V-Funnel
	T50 (AASHTO T347)	Flow Time
	Falling Ball (Douglas et al. 2015)	Falling Ball
Hardened	Hardened Visual Stability Index (HVSI) (AASHTO R81)	HVSI (Mendonca and Hu, 2021)
	Electric Resistivity (AASHTO T358)	Electric Resistivity

In addition, to justify the efficiency of the workability measurement on fiber stability, the research is to evaluate the fiber stability of UHPC at hardened states. In addition to the Hardened Visual Stability Index (HVSI) (Mendonca and Hu 2021), a surface electric resistivity meter could be an effective tool for in-situ evaluation of fiber distribution in a quantitative manner after demold as its readings are highly dependent on fiber content. As steel fiber is highly conductive, locations in the component with a high or low amount of fibers (due to fiber segregation) show significantly different electric resistivity. The abovementioned tests were performed to justify the developed fresh UHPC test for fiber stability to predict fiber segregation in the lab- and site-casted UHPC.

2.3.1. Flow and Flow Time Test

The flow table test for UHPC was conducted according to ASTM C1856. The diameter of the flow at 2 minutes and the time when it reached 10 in. (254 mm) were measured and reported as Flow and T_{10in}, respectively. The stability of fibers was observed through Visual Fiber Index (VSI) as per Mendonca and Hu (2021) based on the degree of fiber separation observed (see Figure 2a as an example). VSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixture, respectively.

2.3.2. Mini V-Funnel Test

A V-shaped funnel (mini-V-funnel) with approximately 0.09 ft^3 (2.5 liters) internal volume and 0.75 in. (19 mm) square opening, as shown in Figure 2a, was used to assess the flowability and fiber stability in UHPC mixtures. Upon the completion of mixing, UHPC mixture was loaded into the mini-v-funnel continuously without any efforts of temping or compaction, while the opening at the bottom of the v-funnel was blocked by hand. After the mini-V funnel was filled, the material was then allowed to flow out freely under gravity. The time for the material to wholly discharge (when the light was observed from the top of the opening) was recorded as T_{V0}. Visual fiber stability was also reported based on if fibers were stuck inside the neck of the funnel and reported as VFS_{V0}. The mini-V-funnel test was also conducted in the same manner except for allowing the mixture to settle in the funnel for 2 minutes, and report as T_{V2} and VFS_{V2}. It is evident that after 2 minutes of settling, the flow time could increase significantly with a higher inclination to fiber segregation if the mixture is not stable.

2.3.3. Falling Ball Test

As shown in Figure 2c, a brass ball with a diameter of 1 in. (24.4 mm) and a mass of 0.195 lb (88.4 grams) was used for the falling ball test. Upon the completion of mixing, the UHPC sample was loaded into a 4"×8" (101.6mm×203mm) cylinder without any tamping or compaction. The brass ball was placed at the top surface of the concrete and then allowed to sink gradually into UHPC under gravity. The time until no further downward movement and immersion distance were recorded as T_{FB} and L_{FB}, respectively. An L_{FB} less than 8 in. (203 mm) means the brass ball cannot drop to the bottom of the cylinder, which implies fiber segregation. Upon the discharge of fresh UHPC sample after the test, visual observation of fiber accumulation at the bottom of the cylinder was reported as VFS_{FB}, with "yes" indicating fiber segregation.

2.3.4. Penetration Test

The penetration test equipment consists of a plastic rod, a penetration head (with a combined mass of 1.8 oz or 30.8 grams), and a support frame. The penetration head is 3 in. (76.2 mm) in diameter and 2 in. (50.8 mm) in height, with the bottom portion hollow and the top part with small holes allowing air to pass through during its downward movement inside the concrete. With a support frame, the penetration head with the plastic rod was aligned in the center of a container with a minimum of 8 in. (203 mm) in diameter. During the test, fresh UHPC sample was loaded inside the container without any consolidation. The penetration head was then lowered onto the surface of the UHPC and released to allow it to penetrate freely into the fresh UHPC. The penetration depth was recorded after 30 seconds as P.

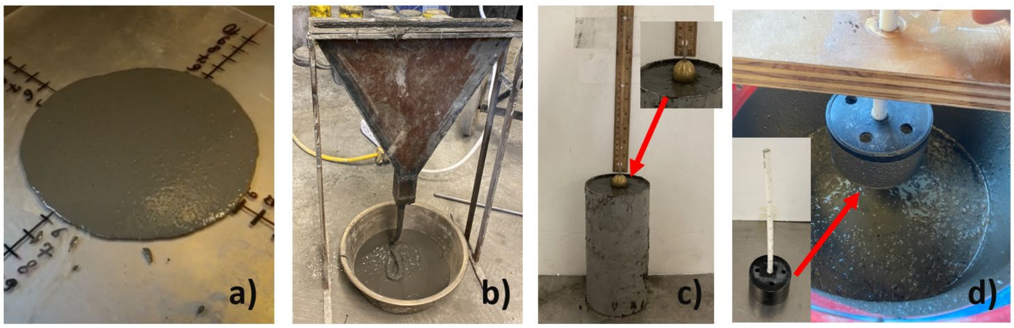

Figure 2. Fresh concrete tests for UHPC fiber stability (a. Flow and flow time, b. Mini-V-funnel, c. Falling ball, d. Penetration)

2.3.5. Hardened Visual Stability Index Test

Hardened Visual Stability Index (HVSI), as developed by Mendonca and Hu (2021), was used to quantitatively assess fiber stability in hardened UHPC based on the thickness of fiber-free or low-fiber content layer observed at the top of casted 3"x6" (76.2 mm x 152.4 mm) UHPC cylinder cross-sections. Similar to VSI, HVSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixture, respectively.

2.3.6. Wall Stability Test

In order to quantitatively assess fiber stability in hardened UHPC and simulate real-world conditions, a wall stability test was developed. Upon completion of mixing, UHPC sample was loaded into a form with 24 in. (609 mm) in height, 12 in. (304.8 mm) in width, and 1.5 in. in depth without any forms of consolidation, as shown in Figure 3. After 24 hours, the specimen (the wall) was de-molded and sawed 1 in. (25.4 mm) from the side to observe fiber segregation. Additionally, a surface resistivity test as per AASHTO R81 was conducted every 3 in. (76.2 mm) vertically from 3 in. (76.2 mm) from the bottom of the casted wall to determine ununiform fiber distribution along the wall based on inconsistent resistivity values.

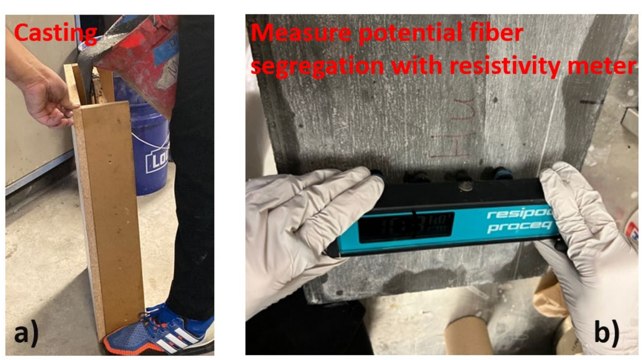

Figure 3. Wall stability test

3. Results and Discussion

Results from the fresh and hardened UHPC fiber stability test evaluation are summarized below in Table 3. As shown in the table, while results from different tests generally agreed with each other, the sensitivities of different tests in identifying fiber segregation are different.

Table 3. Results from fresh and hardened UHPC fiber stability tests

Tests	Flow			Mini V-Funnel				Falling-ball			Penetration	HVSI
Mixture ID	Flow	T_{10in}	VSI	T_{V0}	VFS_{V0}	T_{V2}	VFS_{V2}	T_{FB}	L_{FB}	VFS_{FB}	P	HVSI
Mix 1	10.0" (254mm)	37"	0	145"	No	187"	No	35"	8.0" 203mm)	No	0.875" (22.2mm)	0
Mix 2	11.0" (279mm)	15"	1	84"	No	135"	No	15"	7.5" (191mm)	Yes	1.50" (38.1mm)	2
Mix 3	11.5" (292mm)	10"	2	51"	No	60"*	Yes	7"	7.5" 191mm)	Yes	1.75" (44.5mm)	3

* Flow stopped due to fiber clogging

As expected, for the stable mix (Mix 1), a VSI value of 0 was obtained, which means no evidence of fiber separation or agglomeration can be observed. On the other hand, Mix 3 and 2 both showed fiber segregation. Mix 3 showed severe bleeding and fiber separation with the highest flow value of 11.5 inches (292mm) and VSI value of 2. In addition, results confirmed that, as suggested by Mendonca and Hu (2021), UHPC mixtures with T_{10in} less than 20 seconds (flow reach 10 inches (254 mm) under 20 seconds) could have a high potential for fiber segregation.

Results from the mini-V-funnel test showed that neither Mix 1 nor Mix 2 exhibited fiber blockage. However, the apparent difference in flow time between those two mixes implies the higher flowability and much lower viscosity of Mix 2, which could lead to the tendency of fiber segregation—in the case of Mix 3, a 2-minute settling time caused the stoppage of flow at 60 seconds due to fiber stuck in the neck, which clearly demonstrates fiber instability.

With the falling ball test, it is evident from the full-depth immersion that Mix 1 presented a stable behavior without any fiber accumulation at the bottom of the container. On the other hand, an L_{FB} at 7.5-in (191 mm) was reported in Mix 2 and Mix 3, which indicated a 0.5-in (13 mm) fiber piling at the bottom of the container. Although the difference between Mix 2 and Mix 3 cannot be distinguished by L_{FB}, the T_{FB} of Mix 2 is twice that of Mix 3, which indicates a lower viscosity and a high chance of fiber segregation of Mix 3. The results showed that the falling ball test is not only an easily performed test but also could be a good indicator of fiber instability in UHPC mixtures based on fiber accumulation at the bottom of the cylinder and the sink time of the brass ball.

Results from the penetration test showed that even though the depth of penetration increased with increasing instability of the fibers in the mixtures, the obtained values cannot provide comprehensive information regarding the fiber segregation resistance in UHPC. While the stable mix (Mix 1) had a penetration depth of 0.875 inches, the difference in penetration depth results between Mix 2 (1.50" or 38mm) and Mix 3 (1.75" or 44mm) is not significant despite the considerable difference in terms of fiber stability by other test methods, which can also demonstrate the inadequacy of this test. The weight of the penetration head with the plastic rod might be too heavy for the UHPC without coarse aggregates and was not sensitive enough to access fiber stability in UHPC.

Results from HVSI showed that, as expected, Mix 1 provided uniform fiber distribution without any sign of a fiber-free zone. In contrast, Mix 2 and Mix 3, with HVSI values of 2 and 3, respectively, established a low fiber content layer with 1.0 inches (25 mm) inches and 2.5 inches (64 mm) of thickness, respectively.

As shown in Figure 4a, while the vertical cross-sections of the wall prepared with mix 1 showed a uniform fiber distribution, clear fiber segregations were observed in the walls casted with mix 2 and 3. As expected, the measured surface resistivity shown in Figure 4 in the specimen prepared with mix 1 was fairly consistent throughout the different heights. On the other hand, apparent changes in the measured resistivity along the specimens were observed in both Mix 2 and Mix 3, with a lower surface resistivity (compared to the stable mix) and a significant increase when reaching the low-fiber zone. As the high fiber content zones or fiber agglomeration areas led to higher conductivity or lower surface resistivity, fiber segregation led to lower resistivity at the bottom, while the top portions of the specimens exhibited higher surface resistivity. The consistent results, compared to different fresh stability tests, demonstrated that the surface resistivity test could effectively identify fiber instability in different UHPC mixtures in cast-in-place or precast concrete elements.

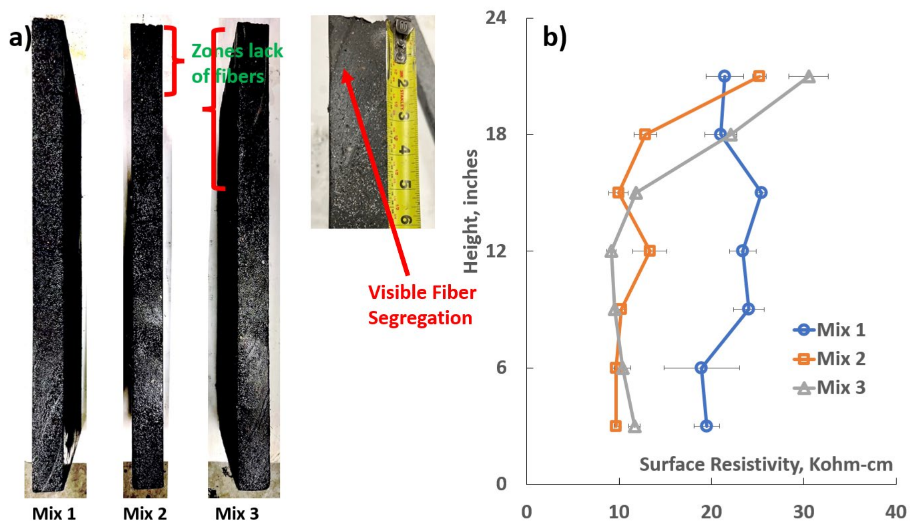

Figure 4. Results from wall-stability test (a. Visible fiber segregation; b. Change of measured surface resistivity along different heights)

4. Conclusions

A preliminary experimental study was carried out to evaluate if the different fresh and hardened concrete tests can effectively identify fiber segregation before or after the casting of UHPC. The following are the main conclusions that were drawn from this study:

- A high amount of water and/or HRWR can lead to fiber segregation in UHPC, which can be observed in both fresh and hardened states;
- While methods such as VSI and HVSI can be used to access fiber stability, the two parameters are relatively subjective and might not be sensitive enough to identify fiber segregation;
- The newly developed mini-V-funnel and falling ball tests are objective measures that could be used to identify fiber-stability issues in fresh UHPC;

- Flow time, which reflects the viscosity of UHPC, could be a good indicator of fiber stability; however, more data is needed to develop an acceptance range for QA/QC.
- The current setup of the surface resistivity test might not be sensitive enough to identify fiber stability of UHPC; however, it has the potential to identify fiber stability in deep components;
- Surface resistivity test can potentially be used for in-situ evaluation of fiber distribution in hardened UHPC products.

As only limited data were included in this study, a more comprehensive investigation is needed to evaluate correlations among promising tests and the workability of UHPC on a wide range of UHPC mixtures. In addition, further effort is necessary to incorporate different test methods in real construction jobs to establish a database to make recommended criteria for practitioners.

5. Acknowledgments

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