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Ultra-High-Performance Concrete: Development of On-Site Fresh Mix Rheology Test Methods

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ABSTRACT

Experimental investigations were conducted on the challenges that may be encountered in the industrial-scale production of ultra-high-performance concrete (UHPC). The rheological attributes of fresh UHPC mixtures were investigated, and a convenient set of tests were developed for field evaluation of the UHPC rheological attributes. These tests would allow for adjustment of the water content of the delivered UHPC to provide adequate workability characteristics, considering that the distinctly low water content of UHPC mixtures make them more prone to the adverse effects of the lack of control on the actual water content of concrete materials produced at industrial scale. The effects of water content on the fresh mix rheology and hardened UHPC compressive strength were evaluated. Distinctions were made between the fresh mix rheology of the UHPC paste versus normal Portland cement paste.

1. Introduction

Ultra-high-performance concrete (UHPC) is an advanced cementitious material comprising optimally graded granular constituents, distinctly high contents of cementitious materials (including a relatively high concentration of silica fume), relatively fine aggregates, and less than 0.25 water-to-cementitious materials ratio enabled by the use of high superplasticizer dosages [1-4]. UHPC materials are generally reinforced with discrete fibers in order to avoid brittle failure modes and also achieve higher strength levels [5-7]. There are distinctions between the fresh mix rheology of UHPC versus that of conventional concrete, that need to be considered in construction applications. The incorporation of high dosages of silica fume and superplasticizer in UHPC mixtures could alter their rheological characteristics in fresh state [6,8,9]. Successful introduction of UHPC to the mainstream construction applications would benefit from understanding and resolving the challenges associated with the distinct features of its fresh mix rheology [10-12]. Figure 1 shows the schematics of a (linear)

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relationship between shear stress and shear rate obtained by testing a liquid using a rheometer. The slope of the down-curve (when decreasing the shear rate) is the plastic viscosity of the liquid, and the intercept at zero shear rate is the yield stress.

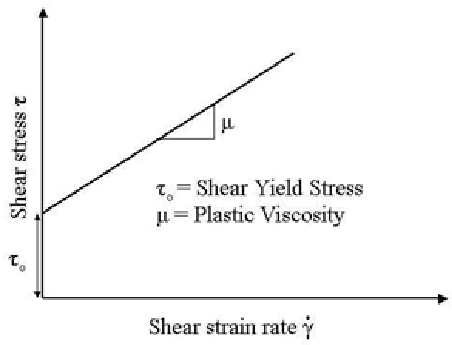


Fig. 1. Typical rheology curve for fluids

UHPC mixtures incorporate high dosages of superplasticizer for lowering their water-to-cementitious materials ratio while retaining viable fresh mix workability [10,13]. The addition of superplasticizer primarily lowers the fresh mix yield stress [14]; as a result, UHPC mixtures tend to be more viscous than normal-strength concrete [15]. Therefore, measurements such as slump which are influenced more by yield strength may not fully reflect the fresh mix workability of UHPC. Furthermore, the use of superplasticizer at high dosages could lead to a relatively high rate of workability loss after mixing.

Given the low water content of UHPC, the uncertainties with water content in industrial-scale production caused by, say, variabilities in the aggregate moisture content, could have pronounced effects on the fresh mix rheology of UHPC. This would require thorough assessment of the UHPC fresh mix rheology in field conditions [15]. The rheometers which can make such thorough measurements, however, do not suit filed applications [16,17]. UHPC mixtures also exhibit relatively high levels of surface adhesion which could, through interactions with formwork and reinforcing steel, challenge their field placement and consolidation [18]. There is thus a need for assessment of the surface adhesion attributes of UHPC in field.

The work reported herein focused on addressing the UHPC fresh mix qualities which challenge its transition to mainstream construction practices. In the work reported herein, an attempt was made to develop practical test methods that make a reasonable assessment of the UHPC fresh mix rheology in field conditions.

2. Materials and Methods

The granular raw materials used in the UHPC mix considered in this investigation can be divided into two categories: (1) cementitious materials and a fine filler (limestone powder); and (2) aggregates. The cementitious materials and the fine filler considered in this investigation were: (i) Type I Portland cement; (ii) un-densified silica fume with ~200 nm mean particle size, ~15 m^2/g specific area and >105% 7-day pozzolanic activity index; (iii) ground granulated blast furnace slag with specific gravity of 2.9 and bulk density of 1,200 kg/m^3, ground to less than 45 micrometer particle size; and (iv) limestone powder with 2 micrometers mean particle size. The particle size distributions of cementitious materials and limestone powder are presented in Figure 2. The aggregates used in UHPC mixtures included (see Table 1 for size distributions): (i) limestone coarse aggregate with 12.5

mm maximum size; (ii) coarse silica sand with mean particle size of 0.8 mm and specific gravity of 2.67; and (iii) fine silica sand with mean particle size of 0.4 mm and specific gravity of 2.65. A polycarboxylate-based superplasticizer (Chryso 150 supplied by Chryso, with 1.06 specific gravity and 30% solid content) and straight (brass-coated) steel fibers of 0.2 mm diameter and 12 mm length (supplied by Bekaert) were also used in UHPC mixtures.

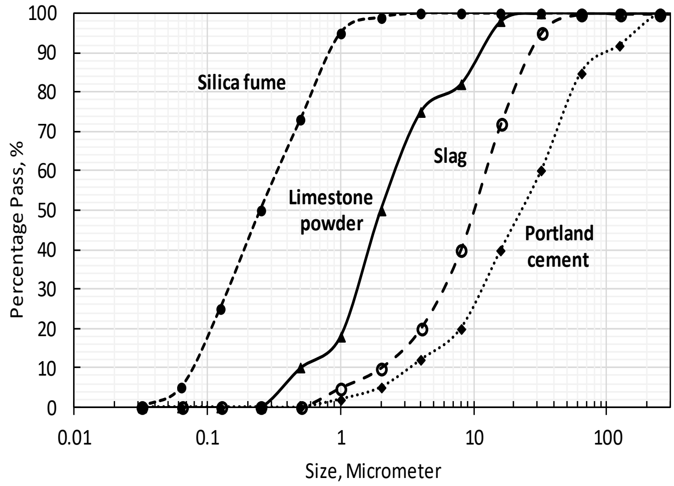


Fig. 2. Particle size distributions of cementitious materials and limestone powder

Table 1
Particle size distributions of aggregates

Sieve Size, mm	Percentage Pass, %		
	Coarse Aggregate	Coarser Sand	Finer Sand
0.15	0	0	0.05
0.18	0	0.1	0.3
0.30	0	0.3	6.8
0.60	0	6.7	86
1.18	0	86	100
2.0	0	100	100
2.36	0.9	100	100
4.75	3.8	100	100
9.50	54	100	100
12.50	98	100	100
19.50	100	100	100

The UHPC mix design considered in this investigation is presented in Table 2 together with the mix design of a normal-strength concrete used in the project for comparison purposes. A Portland cement paste with water/cement ratio of 0.42 was also used as control in viscosity tests applied to the paste content of UHPC.

Table 2
UHPC and normal-strength concrete mix designs

Material	Quantity, kg/m^3	
	UHPC	Normal-Strength Concrete
Coarse aggregate	612	1080
Coarser silica sand	500	960
Finer silica sand	500	-
Cement	604	360
Silica fume	268	-
Slag powder	120	-
Limestone powder	216	-
Water	144	151.2
Superplasticizer	57.6	-
Steel fiber	148	-

Ultra-high-performance concrete mixtures were prepared using a rotary drum mixer of 0.035 m^3 capacity. All aggregates and powders were added to the mixer in the following sequence: coarse aggregate, fine aggregates, and powders (cement, silica fume, slag and limestone powder), and were dry-mixed for two minutes. Water was then added with half of the superplasticizer over two minutes, and mixed for an additional half a minute. The rest of the superplasticizer was added to the mix over one minute, and mixing was continued (for about 7 minutes) until a homogenous fresh mix formed. Finally, steel fibers were added to the mix, and mixing was continued until a total mixing duration of about 15 minutes was reached.

Given the high cost of UHPC, and the desire in this work to develop UHPC mixtures that can be prepared in a ready-mixed concrete (rotary drum mixer), an attempt was made to develop a convenient test method that could be implemented before UHPC exists truck. This test method comprises three elements that can be performed simultaneously from the charge hopper of the truck as concrete is moved up the drum, but before it exists to the collection hopper towards the discharge chute (Figure 3).

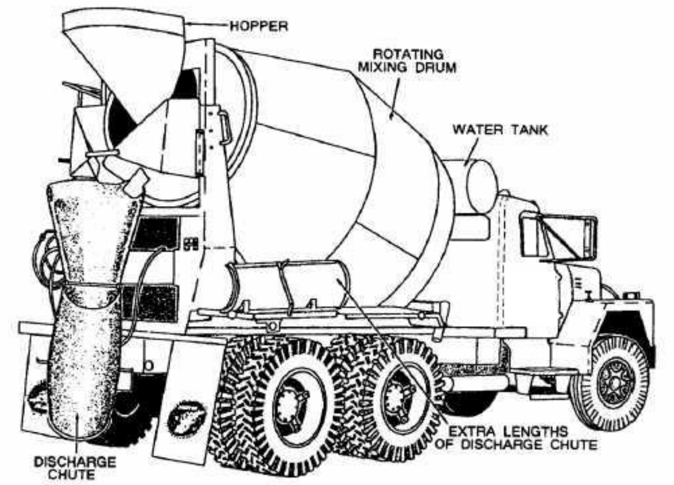


Fig. 3. Schematics of a concrete ready-mixed truck

The three elements of the tests were devised to produce measurements relating to the fresh UHPC mix viscosity, yield stress and surface adhesion capacity. In this investigation, tests were performed at room temperature (22±2ºC) and 50±5% relative humidity. While the three tests can be performed simultaneously, they were performed separately in this development work.

The three elements of the test are shown in Figure 4; all three tests use rectangular Ti-Al alloy steel plates with No. 6 surface roughness (ASTM C480). The plate used in the surface adhesion test (Figure 4a) is 9cmx11cm, with a thickness of 2mm. The one used in push-in test (Figure 4b, that provides an indication of viscosity) is 10cmx15cmn with 2mm thickness. The plate used for pull-out test (Figure 4c) that provides a measure relating to the fresh mix yield stress had dimensions similar to that use in push-in test.

The locations of holes used for anchoring the plates for the purpose of surface adhesion and push-in/pull-out tests are shown in Figure 5. The surface adhesion test (Figure 4a), inspired by a research reported in the literature [19], involves pushing the plate onto the fresh concrete surface until a full contact (including at all four corners) is established between the plate and the concrete surface. The plate is then moved away from the concrete surface at a speed of 1 cm per second. The maximum force required for separating the plate from the surface is recorded as an indication of the surface adhesion qualities of the fresh concrete mix. Figure 6 shows the separation mechanism of the plate from the mass of fresh concrete in the surface adhesion test. The force required to separate two objects that are not permanently bound together is a measure of tack. Tackiness is often used to characterize the surface adhesion of sticky materials. The pull resistance between two surfaces reflects the contributions of cohesion, surface tension and viscosity to tackiness. A material is sticky when the energy required to break its bond with a surface is as large as the interfacial energy dissipation during the separation process, which in turn causes deformation and friction in the contact film.

In the push-in test (Figure 4b), which provides an indication of the fresh mix viscosity [20], the plate is pushed vertically into concrete at a speed of 1 cm per second, and the maximum force required for pushing the plate into concrete (until the hole shown in Figure 4b reaches the concrete surface) is recorded. The resistance to push-in action is provided by the glazing of aggregates against the plate and also the flow friction produced by the finer constituents of the mix. These phenomena relate mostly to the yield strength of the fresh concrete mix. A fresh concrete mix with good consistency has a low viscosity. The rise in coarse aggregate and fine contents, which compromise consistency, would also raise the resistance to push-in by raising the glazing of aggregates against the plat wall and the flow friction, respectively.

(a) Surface Adhesion Test (b) Push-In Test (c) Pull-Out Test

Fig. 4. The three tests devised for thorough measurement of the fresh UHPC mix properties

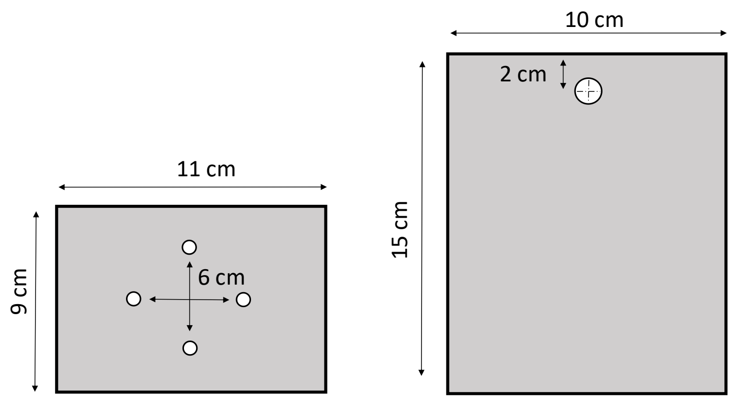


Fig. 5. Locations of the holes used for anchoring the plates in surface adhesion (left) and push-in/pull-out (right) tests

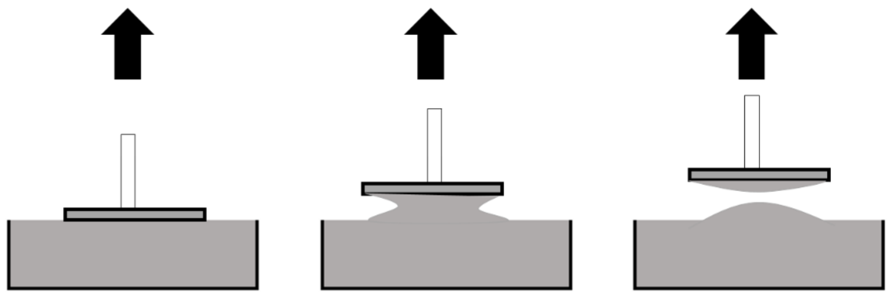
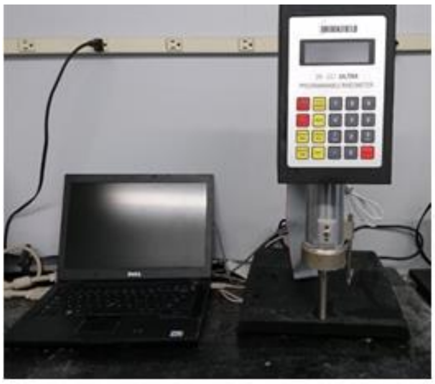
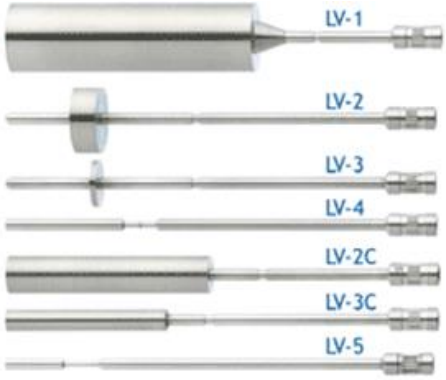


Fig. 6. Separation mechanism of the plate from the mass of fresh concrete in the surface adhesion test

The pull-out tests (Figure 4c) provides an indication of the fresh mix yield stress [21]. The high fine content of UHPC provides for a non-Newtonian behavior in fresh state. The shear stress at which the material starts flowing is called yield stress [22,23]. In the pull-out test, a steel plate is first pushed vertically into the fresh concrete at a rate of 1 cm per second until the hole (in plate) reaches the concrete surface. After waiting for 5 seconds, the plate is pulled out of the fresh concrete at a speed of 1 cm per second, and the maximum force required for complete removal of the plate from concrete is recorded. To obtain the true yield stress, the shearing action should be within the material and not between the material and an object (plate). Ideally, a virtual plane of material should be moved inside the suspension and the material-material shearing stresses measured. This option, however, is not available in a simple test for field applications.

In order to measure the rheological features of fresh UHPC pastes (and also those of the control Portland cement paste), a digital rheometer (DV-III ULTRA) with stress control and data acquisition capabilities was used (Figure 7a). This apparatus measures the shear yield stress and plastic viscosity of fresh cementitious paste mixtures. The fresh mix is placed in a sample holder comprising an external sleeve and an internal rotator (spindle). The dimensions of the internal rotator and the external sleeve can be selected based on the rheological properties of the fresh mix. The container used in this investigation had 600 ml capacity with a working volume of 500 ml. A standard LV-5 spindle (Figure 7b) was selected for use in this investigation after preliminary trials. A stress controller was used in this test to control the torque of the internal rotator (spindle). If the relationship between torque and rotational speed is linear, then the linearity coefficients are proportional to the Bingham constants of the fluid.





(a) Rheometer (b) Spindles

Fig. 7. The rheometer and the spindles used in this investigation (the LV-5 spindle was selected after preliminary trials)

The fresh mix flow test was also conducted per ASTM C1611. In addition to the tests conducted in fresh state, compression tests were also conducted on UHPC. For this purpose, 50 mm cube specimens of UHPC were cast into molds and consolidated via external vibration. The specimens were demolded after 24 hours of storage in sealed condition, and were subjected to steam curing at 90°C for 48 hours. The cured specimens were then stored at 50% relative humidity and room temperature, and subjected to compression tests per ASTM C109 at 7 days of age.

3. Results and Discussion

Figure 8 shows the variation of viscosity with shear rate for the UHPC and Portland Cement pastes. Viscosity of the UHPC paste is observed to be much higher than that of the Portland cement paste especially in the lower rage of shear rate. For both pastes, viscosity decreases with increasing shear rate. The shear stress-shear rate relationships shown in Figure 9 indicate that shear stress increases with shear rate at a significantly higher pace for UHPC than for normal Portland cement paste.

The resultant values of plastic viscosity and yield stress are presented in Table 3 for the UHPC paste and the normal Portland cement paste. The yield stress of UHPC paste is observed to be two orders of magnitude greater than that of the normal Portland cement paste, and the viscosity of UHPC is one order of magnitude greater than that of normal Portland cement paste. Fresh mix workability tests that mostly reflect the yield stress of fresh concrete mixtures (e.g., slump) could thus produce misleading results in application to fresh UHPC mixtures. The high silica fume content of the cementitious paste in UHPC, its strong reliance on a large dosage of superplasticizer to achieve workability in spite of the very low water content, and the high packing density of the UHPC paste have produced a fresh mix rheology that is significantly different from that of a normal cement paste.

The rheology test results presented above indicate that one test (e.g., flow) may produce misleading results in application to fresh UHPC mixtures. The simple set of three tests introduced earlier would produce three measurements that could provide a more thorough assessment of the fresh UHPC mix rheology. A preliminary experimental work was conducted in order to use these three simple tests for evaluating the effects of water content of the fresh UHPC mix rheology.

The simple surface adhesion, pull-out and push-in tests were used to investigate the effects of water content on the UHPC rheology. These tests are developed to enable adjustment of the water content of UHPC prior to field placement. The measured value of surface adhesion force (Figure 10a) seems to peak at an intermediate value of water content, while the pull-out force (correlating with yield stress) and the push-in force (relating to plastic viscosity) exhibit, as shown in Figures 10b and

10c, respectively, general trends towards lower values with increasing water content. There are variabilities in these trends (especially in push-in tests) that point at the need for establishing the variances of test results and specifying a minimum number of replicated tests to be performed on the fresh mix.

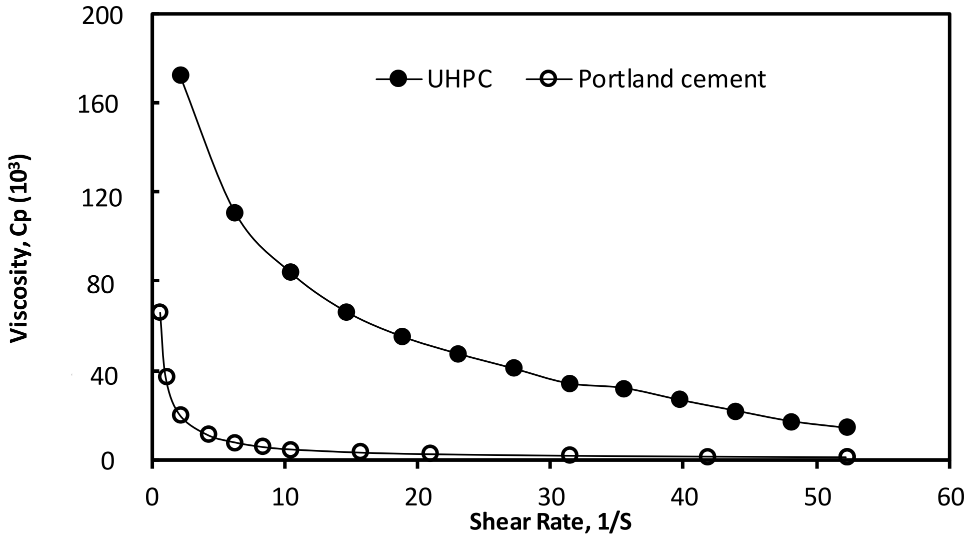


Fig. 8. The viscosity-shear rate relationships for UHPC and normal cement pastes

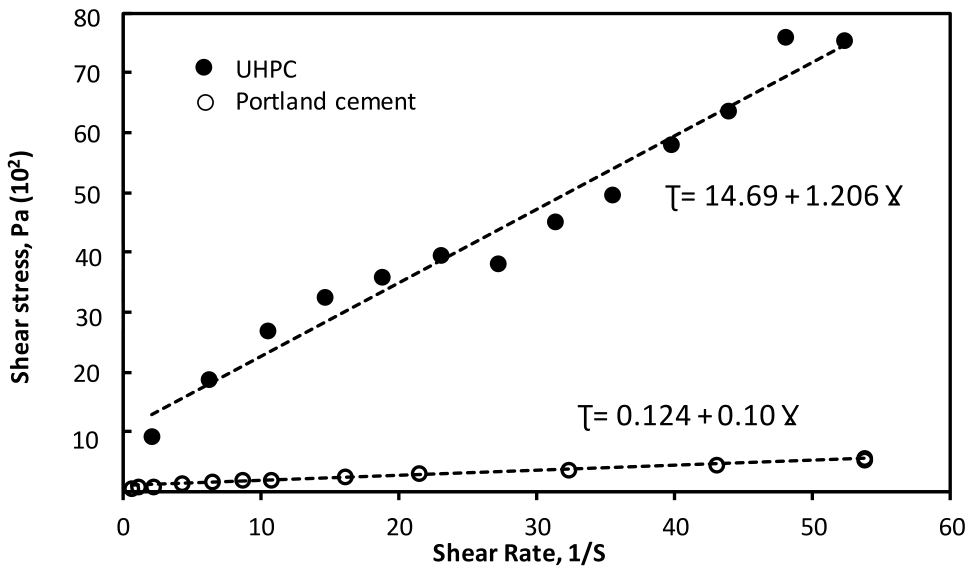
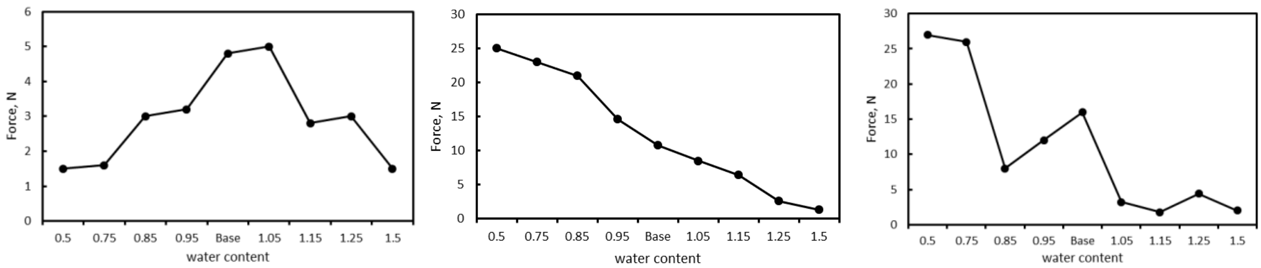


Fig. 9. The shear stress-shear rate relationships for UHPC and normal cement pastes

Table 3
Measured values of viscosity and yield stress for UHPC paste and normal cement pastes

	Portland cement paste	UHPC paste
Viscosity, Pa	10.40	120.60
Yield stress, MPa	12.40	1469.0



(a) (b) (c)

Fig. 10. Effect of the UHPC water content of (a) the surface adhesion force; (b) the pull-out force and (c) the push-in force

Images captured from the top surfaces of UHPC mixtures with different water contents indicate that excessively high-water contents (20% more than that in the base UHPC mix) lead to settlement of coarse aggregates (Figure 11a) while excessively low water contents (20% less than that in the based UHPC mix) challenge uniform dispersion of the coarse aggregates (Figure 11b). The base UHPC mix produced a compressive strength of 224±5 MPa. Increasing and decreasing the water content by 20% (Figures 11a and 11b, respectively) lowered the compressive strength to 182±4 MPa and 208±4 MPa, respectively. This observation reinforces the concept that a specific UHPC mix would have an optimum water content; water contents higher or lower than the optimum level would lower the compressive strength of the UHPC mix.

(a) Excess water (b) Base mix (c) Insufficient water

Fig. 11. Surface appearances of UHPC mixtures with different water contents

4. Conclusions

- The rheology of fresh concrete mixtures can be defined using two values: yield stress (the stress needed to start moving the concrete) and plastic viscosity (the characterization of the low of the concrete one the stress in higher than yield stress). The combination of yield stress and rheology for ultra-high-performance concrete (UHPC) are distinct from that for conventional concrete. Therefore, fresh mix workability tests (e.g., slump) that reflect primarily the yield stress of fresh concrete mixtures could produce misleading results in application to UHPC. In this work, a set of convenient tests were developed for field assessment of the fresh mix rheology of UHPC. These tests quantify three aspects of the fresh UHPC mix performance that relate to its viscosity, yield stress and surface adhesion. These tests can be feasibly performed on fresh concrete mixtures inside the mixer (including the ready-mixed concrete truck) prior to discharge.

- Investigations into the rheological attributes of a UHPC paste versus a normal Portland cement paste indicated that the yield stress of the UHPC paste was two orders of magnitude greater than that of the normal Portland cement paste, and the plastic viscosity of the UHPC paste was one order of magnitude greater than that of normal Portland cement paste. Correlations were drawn between the water content of UHPC and the results of the three simple tests developed in the project. The measured value of surface adhesion force seems to peak at an intermediate value of water content, while the pull-out force (correlating with yield stress) and the push-in force (relating to plastic viscosity) exhibit general trends towards lower values with increasing water content. These correlations would allow for adjustment of the water content of the delivered UHPC prior to discharge. The tests are rapid, and are designed for field application. They would allow for resolving the uncertainties with water content of UHPC mixtures that are produced using industrial-scale concrete batching and production facilities.
- Compressive strength test results performed on UHPC mixtures with different water content indicated that there is an optimum water content for a UHPC mix. Raising or lowering this optimum water content tends to compromise the compressive strength of UHPC. Hence, adjustment of water content after a reasonably thorough assessment of the fresh mix rheology for producing a workable mix would not necessarily compromise the compressive strength of UHPC.

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