Fresh and Hardened Behavior of Ultra-High Performance Concrete (UHPC) Prepared with Different Mix Design Parameters and Mixers

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Abstract:

Ultra-high performance concrete (UHPC) is a new class of concrete that has superior workability, as well as mechanical and durability properties that far exceed those of conventional concrete. To achieve these properties, a very dense internal structure and the very low water-to-binder ratio (w/b) are generally necessary. While particle packing theories are typically used to design UHPC, due to the complexity of UHPC composition interaction and characteristics, the "theoretical optimum particle packing" might not necessarily provide the best UHPC performance. A comprehensive study of the impact of different design parameters such as types and amounts of supplemental cementitious materials (SCMs), binder content, and w/b are needed for a more rational design of UHPC. Besides, the extensive amount of fine materials, together of the absense of coarse aggregate and the very low w/b often makes the mixing process of UHPC challenging. In this study, evaluations were performed with multiple series of mixtures prepared with different mix design parameters and considerations. In addition, this study included an evaluation of the impact of mixers on the fresh and hardened properties of UHPC.

Keywords: UHPC Mix Design, Particle Packing, Materials Selection, Water-to-Binder Ratio, Binder Volume, Type of Mixer, Mixing Procedure.

1. Introduction

Ultra-high performance concrete (UHPC) is a special type of concrete with superior workability, mechanical properties, and durability. The concept of having a very high strength and high-performance material initiated in the 1970s with a better understanding of hydration reactions, shrinkage, creep, and porosity along with the development of water reducers and advance in concrete treatment and curing processes (Graybeal, 2006; Naaman and Wille, 2012).The very low water-to-binder ratio (w/b), high binder content, and the absence of coarse aggregate make UHPC significantly different from conventional concrete in both fresh and hardened states.

UHPC's components are rigorously selected considering particles sizes and distributions to maximize particle packing density (El-Tawil et al. 2016). A high packing density is obtained when the particles are arranged so that the voids of the matrix are minimized. UHPC's design is generally based on the optimum particle packing so the materials in the matrix are combined in an optimum proportion minimizing the voids and ensuring high strength, up to 17,000 psi (117.2MPa), low permeability, and self-consolidating nature (Yu et al. 2015, Lowke et al. 2012).

Although particle packing theory is often being used to design UHPC, fine powders such as cement and SCMs are subjected to a strong interparticle force due to their high finesses, which is generally not accounted for in those models. On the other hand, the method does not account for the water and chemical admixtures used in the concrete. When liquid is introduced in the mix, the interaction force between fine particles (<0.004 inches (100µm)) is affected (Meng et al. 2017). Also, other factors that could affect the degree of particle packings, such as particle shape and surface condition are also not considered in most packing models. As such, while particle packing theory can serve as a general guideline, with the specific materials uses, experimental work is still necessary to determine the actual packing for optimum UHPC design. Besides, key parameters such as water-to-binder ratio (w/b), binder type and content, and type of mixer also play an essential role in UHPC performance. This study, therefore, aims to evaluate the impact of these key parameters on the characteristics of UHPC in fresh and hardened states.

2. Background

The terminology of high strength concrete was created in the 1980s when concrete with compressive strength up to 17.4 ksi (120MPa) was developed using supplemental cementitious materials (SCMs) and reducing the water-to-cement ratio (w/c). UHPC was introduced in the early 1990s with the application of particle packing theory, use of fine particles, low porosity, and lower w/c. The advance in the chemical admixture development and the introduction of different fibers in the concrete contributed to the progress of UHPC (Naaman and Wille, 2012).

Many different approaches have been used in designing UHPC. Wille et al. (2011) developed a UHPC using the flow table test as an indirect indicator of particle packing density of the UHPC paste, followed by the introduced aggregates and fibers. Similarly, Meng et al. (2017) proposed a UHPC mix design with the selection of binder candidates based on the flow characteristics, and then identify the appropriate w/c. For the aggregate gradation, the authors used the modified Andreasen and Andersen model or the bulk density test to determine the best proportion of two different aggregates. Then, the necessary paste volume was calculated using the excess thickness theory. Following, Meng et al. (2017) determined the fiber content based on the flexural load-deflection relationship. Finally, the w/c and HRWR were adjusted based on the performance of trial batches. Graybeal (2013)'s approach to developed UHPC was first to define the materials to be used based on experimental work and then to designate the type of material and proportions that delivers the best performance. First, the best performance paste was identified, followed by the introduction of two sizes of aggregates, and finally, fibers. Shi et al. (2015) presented a review showing the importance of reducing the porosity of UHPC to improve the microstructure and increase homogeneity and toughness. In addition, the authors showed that key parameters such as SCMs replacing cement and use of conventional river-sand could result in successful in the UHPC design. However, there is a lack of comprehensive study of the key parameters such as w/b, binder type and content, and type of mixer on UHPC performance.

3. Experimental details

3.1. Materials

In this research, Type I/II Portland cement that meets ASTM C150, class C fly ash that meets ASTM C618, ground granulated blast-furnace slag that meets ASTM C989, densified silica fume that meets ASTM C1240, and quartz powder was used as the cementitious materials and filler for the UHPC mixture. A polycarboxylate-based high-range water reducer (HRWR) that meets ASTM C494 Type F admixture specification was used to improve the flowability of the mixtures.

The aggregate used was a fine river sand (maximum grain size of No. 10 or 2.00mm) locally available in Nebraska, with specific gravity and absorption at 2.60 and 0.50% respectively, measured according to ASTM C128.

A straight steel fibers (SS), 0.5 inches (1.3 cm) long and 0.008 inches (0.02cm) of diameter, was selected for most of the UHPC mixtures. Selected mixes with other fibers, i.e. two twisted steel fibers, with different length, 0.5 inches (1.3 cm) (T13), and 0.9 inches (2.5 cm) (T25), both with 0.02 inches (0.05 cm) of diameters, and a synthetic glass fiber (SG), 0.74 inches (1.9cm) long and 0.02 inches (0.05 cm) of diameter, were also evaluated. The specific gravity of the steel fiber and glass fiber are 7.8 and 2.0 respectively.

3.2. Mixing Procedure

Another important factor is the UHPC's mixing procedure. Because of the very fine particle sizes and the elimination of coarse aggregate, together with the very low w/b, a higher mixing energy is generally needed, which results in a longer mixing time as compared to convention concrete to ensure good distribution of all the particles (Wille et al. 2011). As UHPC's ingredients are composed of very fine particles and they are likely to agglomerate forming chunks, mixing these particles in dry condition is crucial to reduce the shear force necessary to break the pieces.

The process of mixing UHPC can be very peculiar and specific for the different mixer used and volume of the material being mixed. In this study, three different mixers were used and results compared. A 20qt capacity Vollrath benchtop mixer (0.5 HP) with three different speeds was used for all the batches with $0.16ft^3$ ($0.0045m^3$) of UHPC (lab batch). For comparison, selected mixes were also prepared with a $3ft^3$ ($0.085m^3$) Imer Mortarman 120+ mixer (2 HP) for the batches with approximately $1.25ft^3$ ($0.035m^3$) (medium batch), and a $16ft^3$ ($0.45m^3$) capacity Imer Mortarman 750 mixer (5HP) for the batches with approximately $2ft^3$ ($0.06m^3$) (field batch). The mixing process can be generally separated into three main steps: (1) mix dry components (2) add water and superplasticizer (3) add fibers. The final product of UHPC should generally have a flowable and viscous consistency. Because of the different paddle configuration, dimension and spend, the mixing time will differ depending on the mixer and volume of the batch.

Figure 1 showed the procedures for the three different mixer and batch sizes that were developed based on the literature (Naaman and Wille, 2012, Graybeal and Hartmann, 2003, Alkaysi and El-Tawil, 2015) and trial mixes in the lab.

(a) Lab batch (b) Medium batch (c) Field batch

Figure 1. Batching and mixing procedure flow charts of different batch sizes

4.Testing Methods

4.1. Mixture Design

In this study, the UHPC design was developed based on a systematic plan in evaluating the impact of key parameters such as binder type and content, w/b, and mixer types. The material proportions were selected based on the modified Andreasen and Andersen particle packing theory model. The model was used as a guideline to roughly determine the materials proportions. However, the impact of different parameters on the flowability and compressive strength was evaluated by experimental work.The study of the impact of different parameters on the flowability and compressive strength were evaluated by dividing the mixes into seven series presented in Table 1. Series 1 evaluated the impact of silica fume content, with the mixes prepared with silica fume content ranging from 5% to 19% by volume of binder. Series 2 evaluated the impact of using slag in the UHPC, with the fly ash in a selected mixture from series 1 totally replaced by slag, and then gradually increase the slay content from 23% to 46% by volume of binder. Series 3 examined the impact of fly ash in the UHPC. Again, a mixture from series 1 was selected and then gradually reduce the fly ash from 22% to 9% by volume of binder by replacing fly ash with cement. Series 4 was focused on the impact of quartz powder in the UHPC, which consisted of replacing fly ash form series 3 mixes with quartz powder. Even though the quartz powder is not considered a pozzolanic or hydraulic cement material, it is accounted here as binder due to its finesses. Series 5 studied the impact of w/b in the mix with two groups of mixes prepared with different w/b (0.190 and 0.170 respectively). Finally, the impact of the binder volume was analyzed in series 6, with the gradual increase of the binder content of a selected mixture from series 1 from 1600-1900 pcy (950-1127 Kg/m^3).

Additionally, series 7 was prepared to evaluate the impact of difference mixers on the UHPC mixing process and performance. Four mixes were prepared with both lab batch and field batch. The four mixes consist of the same mix design but different fiber types. However, the impact of fiber types was not presented in the paper due to the limit of time. Moreover, two of series 2 mixes

(SF11:FA0:S23:QP0 and SF11:FA0:S47:QP0) were parped in the medium batch to analyze the difference between lab batch and medium batch.

Detailed design of the different series of UHPC mixes are shown in Table 1. The mix identification was based on the name of the four types of binder evaluated, namely SF, FA, S, and QP stand for silica fume, fly ash, slag, and quartz powder respectively, followed by a number that indicates the percentage of that material based on the volume fraction out of the whole binder. As an example, SF19FA16S0QP0 has 19% of silica fume and 16% of fly ash in the total volume of binder; the mix does not contain slag or quartz powder. For series 5 mixes, 'WB' was added standing for w/b followed by the actual value. Mixes in series 6 have an additional letter of 'B', representing the binder content rounded to the nearest 50pcy. In series 7, mixes for the comparison between mixers had different fibers, and in the mix identification, the type of fiber used is showed with SS, T13, T25, and SG stand for straight steel, short twisted, long twisted and synthetic glass fiber respectively.

All the mixtures except for those in series 7 herein presented has 2 % of straight steel fibers, (by volume) and prepared in lab batches volume. The w/b in the following table accounts for the water in the admixture, which has 30% of solid in its composition. Air-dried fine aggregate was used in batching, the difference of moisture content as compared to saturated-surface dried condition was compensated for each batch.

Table 1. Design of different series of UHPC mixes (pcy)

Series	Mix ID	Cement	Fly ash	Slag	Silica Fume	Quartz powder	Water	Sand	Fiber	HRWR	w/b
1	SF5:FA22:S0:QP0	1108	295	0	58	0	247	2130	251	46	0.192
	SF8:FA22:S0:QP0	1076	294	0	87	0	257	2115	248	48	0.200
	SF11:FA22:S0:QP0	1044	293	0	117	0	243	2123	250	51	0.192
	SF13:FA:22:S0:QP0	997	287	0	143	0	233	2081	246	46	0.186
	SF16:FA22:S0:QP0	987	293	0	175	0	236	2119	252	63	0.192
	SF19:FA22:S0:QP0	928	288	0	215	0	230	2098	250	66	0.193
2	SF11:FA0:S23:QP0	1064	0	299	119	0	248	2164	255	52	0.192
	SF11:FA0:S34:QP0	906	0	438	120	0	245	2185	273	52	0.192
	SF11:FA0:S46:QP0	711	0	603	121	0	241	2200	274	52	0.193
3	SF19:FA16:S0:QP0	1086	233	0	233	0	262	1988	257	48	0.191
	SF19:FA11:S0:QP0	1157	154	0	231	0	260	1977	256	54	0.193
	SF19:FA09:S0:QP0	1183	130	0	232	0	261	1980	256	54	0.193
4	SF19:FA0:S0:QP16	1075	0	0	230	230	259	1968	254	48	0.191
	SF19:FA0:S0:QP11	1159	0	0	232	155	261	1980	256	54	0.193
	SF19:FA0:S0:QP09	1202	0	0	236	132	265	2021	260	55	0.193
5	SF11:FA20:S0:QP0:WB19	1098	308	0	123	0	252	1959	251	54	0.190
	SF20:FA20:S0:QP0:WB19	1167	368	0	292	0	302	1587	253	64	0.190
	SF30:FA20:S0:QP0:WB19	1016	367	0	437	0	301	1580	252	64	0.190
	SF11:FA20:S0:QP0:WB17	1155	324	0	129	0	230	2060	264	56	0.168
	SF20:FA20:S0:QP0:WB17	1202	380	0	301	0	270	1635	261	66	0.168
	SF30:FA20:S0:QP0:WB17	1020	368	0	438	0	262	1587	253	64	0.168
6	SF11:FA22:S0:QP0:B1600	1155	324	0	129	0	230	2060	264	56	0.168
	SF11:FA22:S0:QP0:B1700	1214	341	0	136	0	242	1919	262	59	0.168
	SF11:FA22:S0:QP0:B1800	1292	363	0	145	0	258	1780	263	63	0.168
	SF11:FA22:S0:QP0:B1900	1366	383	0	153	0	272	1651	263	67	0.168
7	SF8:FA22:S0:QP0:SS	1076	294	0	87	0	257	2115	248	48	0.200
	SF8:FA22:S0:QP0:T13	1074	293	0	87	0	244	2107	229	48	0.191
	SF8:FA22:S0:QP0:T25	1080	295	0	87	0	243	2134	249	48	0.189

	SF8:FA22:S0:QP0:SG	1070	292	0	86	0	243	2109	64	47	0.191

Note: all valuates (except for w/b) are in pcy (1pcy = 0.59Kg/m^3)

5. Results

The workability of UHPC was measured using a standard flow table specified with diameter of 10 in (254 mm) as specified in ASTM C230; the test followed ASTM C1856. Specimens were prepared using 3 in (76.2mm) diameters by 6 in (152.4mm) height cylinders molds. After 24-hours the concrete was removed and cured in saturated lime water at 73°F (23°C) until testing. The compressive strength of the mixtures was also tested following ASTM 1856. Figure 2 presents the impact of different design parameters on UHPC performance.

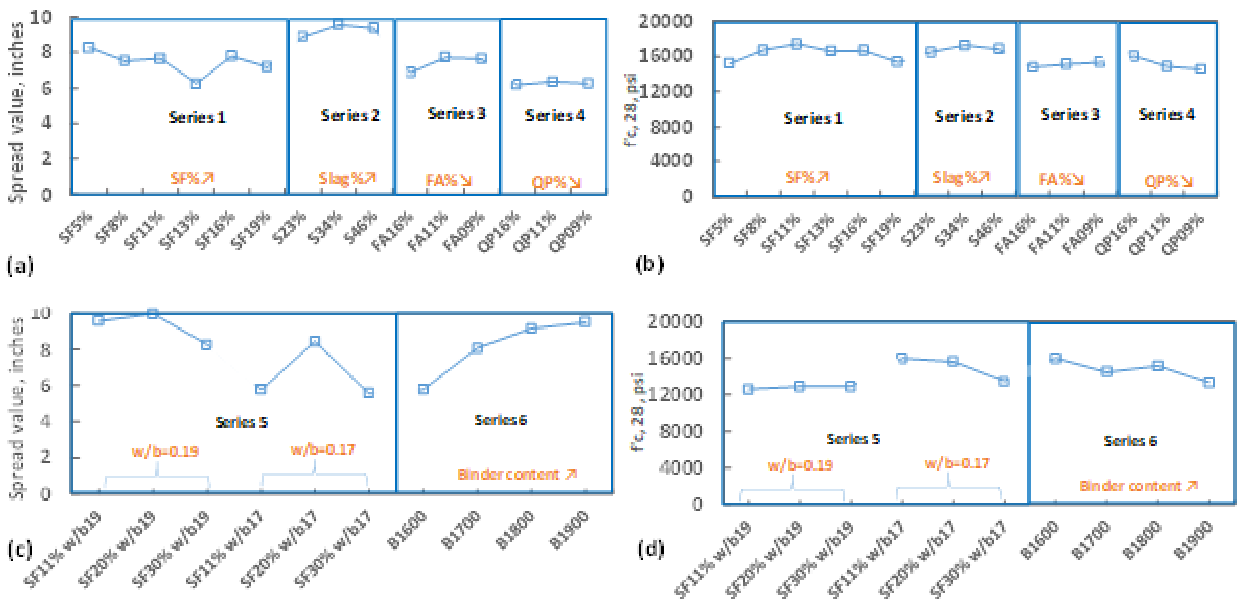

Figure 2. Impact of SCMs types and contents (a and b) and w/b and binder content (c and d) on fresh and hardened concrete properties (1 inch = 2.54cm; 1 psi = 0.0069 MPa)

The spread value and compressive strength of mixes mixed in different mixers are shown in Table 3.

Table 2. Fresh and hardened concrete properties of mixes prepared with different mixers

Mix ID	Property	Lab batch	Medium batch	Field batch
SF8:FA22:S0:QP0:SS	Spread value (in.)	7.52	-	8.05
	f'$_{c, 28}$ (psi)	16,729	-	15,050
SF8:FA22:S0:QP0:T13	Spread value (in.)	7.70	-	9.54
	f'$_{c, 28}$ (psi)	9,317	-	11,387
SF8:FA22:S0:QP0:T25	Spread value (in.)	7.13	-	9.81
	f'$_{c, 28}$ (psi)	11,657	-	11,777
SF8:FA22:S0:QP0:SG	Spread value (in.)	8.40	-	9.23
	f'$_{c, 28}$ (psi)	12,101	-	11,387
SF11:FA0:S23:QP0	Spread value (in.)	8.89	8.64	-
	f'$_{c, 28}$ (psi)	16,513	15214	-
SF11:FA0:S46:QP0	Spread value (in.)	9.39	8.50	-
	f'$_{c, 28}$ (psi)	16,830	15,530	-

6. Discussion

6.1. Impact of types of binder

As shown in series 1 in Figure 2, when silica fume content increased, the spread decreased, and the compressive strength increased until an optimum value. While it is generally believed that silica fume helps to provide denser particle packing, which in term leads to strength increase, it will also negatively impact the flowability due to its finesses. Low flowability can result in entrapped air formation on the casting process, which will negatively affecting the compressive strength. Thus, the amount of silica fume should be well controlled. Based on the results, the optimum dosage of this material for the matrix analyzed is 11% of the volume of the total binder. This result is later confirmed with series 5 mixes, which showed a reduced lower compressive strength in two different w/b, with the increase of silica fume content.

Comparing the results from series 1 and 2, when fly ash was replaced by slag, the flowability was improved, which indicated an optimized packing when slag is introduced.

Results from series 3 mixes showed that with the decrease of fly ash content, the spread and the compressive strength both increased. This result can indicate that the quantity of fly ash selected initially (22% by volume) is disturbing the particle packing.

Series 4 results should be analyzed in two ways, first within the series, then correlating it with series 3. As can be seen, within series 4, the reduction of quartz powder did not influence the overall flowability of the concrete. On the other hand, the strength dropped as the quartz powder amount decreased. This result leads to the conclusion that the packing density was affected. Since the decrease of its amount resulted in a drop of the mixes compressive strength, it is presumed that with a decrease of the quartz powder filler, the packing density is disturbed. Moreover, it can be observed that the spread value of series 4 was reduced when compared to series 3. This drop was expected, considering that fly ash particles have a spherical shape, which helps concrete to flow. Furthermore, quartz powder is a very fine material, thus with a high surface area. Regarding the compressive strength, quartz powder did not show much improvement when replace fly ash.

6.2. Impact of binder content

In UHPC, cement paste is used to fill the voids of the aggregate matrix and to coat aggregate particles and fibers, thus to minimize the friction between aggregate and fiber, especially when rigid fibers are used as the particles tend to interact and often make the flow more difficult (Naaman and Wille, 2010). The paste used to coat particles and fibers is called excess paste. According to Hu (2005), as the paste is the only phase inside a mortar that can provide flowability, the excess paste helps the flowability due to the reduction of friction between particles and fibers. As binder content increases, the excess paste is consequentially increased. As can be seen in Figure 2c, the spread value of the mixtures increased as the binder content increased. Unlikely the spread value, the compressive strength slightly reduced with the increase in the binder content, except for one mix. It can be concluded that, despite the increase in the flow, the particle packing was disturbed with the binder increased, resulting in a less dense UHPC.

6.3. Impact of w/b

Water in the fresh state of the concrete is essential to provide flow and hydration of the cement. However, UHPC's w/b is significantly lower comparing to conventional concrete. Therefore, admixtures such as high range water reducer are introduced in the mix to provide sufficient flowability to ensure good compaction during casting. Concrete with high w/b will present high flowability. However, the portion of water that not used for the hydration process will be later evaporated, leaving voids on the matrix. Voids will reduce the compressive strength. Thus, the amount of water should be well controlled with the desired properties.

The very low w/b is one of the responsible factors for the high strength attributed to UHPC. However, as mentioned before, it is important to have a flowable UHPC, otherwise entrapped air can be formed, negatively influencing the strength. According to Wille et al. (2011), the increase in the strength can only be associated with the reduction of w/b if the flowability is improved, implicated by a better packing density. As can be observed in Figure 2c, the spread value decreases when the w/b decreases. However, the strength increases in the same series when w/b dropped from 0.19 to 0.17, meaning the decrease in the w/b could have led to a denser packing, which in term improve the strength.

6.4. Impact of mixer

Mixer energy is important to properly disperse UHPC materials, especially the fine ones. Since HRWR is used to in UHPC, a longer time compared to conventional concrete is generally necessary to achieve the desired concrete consistency, defined by visual examination of the fresh material. As shown in Table 3, although the mixers have different input energy, UHPC mixed in lab, and field mixers resulted in similar compressive strength. However, results also showed that mixtures prepared with the lab mixer and the field mixer resulted in different spread value even with the same mix design, with large batch mixes presented an average of 1.5 inch (3.81 cm) higher flow, likely due to the higher mixing energy associated with the much larger travelling distances of large mixing paddles. Mixtures prepared with the medium batch, on the other hand, presented lower spread values along with lower compressive strength values. This result is likely due to the insufficient dispersion of materials from mixers, as a much lower paddle rotating speed was observed in the mixer.

7. Conclusions

Based on this comprehensive study that evaluated key design parameters including types and contents of binder, w/b, and mixer on the performance of UHPC, the following conclusions can be drawn:

- While particle packing theory is a useful tool to guide the design of UHPC, it can be complemented with test results to adjust and refine the optimum mixture design.
- Although silica fume is widely used in UHPC for denser packing, when used more than an optimum amount, it can prejudice the flowability and consequently reduce the strength.
- Quartz powder used in this study did not improve the UHPC performance when replaced fly ash. However, the replacement of fly ash with slag resulted in a UHPC with better performances.
- Low w/b is essential to ensure high strength UHPC, with the amount of water should be just sufficient to ensure appropriate flowability and cement hydration.
- Different mixers do not necessarily influence the mechanical properties of UHPC as long as they provide sufficient energy to disperse all fine particles of UHPC design. However, compared with lab-mixer, the field-scale mixer was found to result in UHPC with slightly higher flowability, likely due to the higher mixing energy employed.

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