Durability properties of a generic ultra-high performance concrete mixed in the field

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Abstract: Most field applications of UHPC in the US have utilized proprietary materials. This study describes one of the earliest field applications of a generic blend of UHPC in the US. Material properties of the field-mixed material are described and compared to their lab-mixed counterparts. The durability resistance of the field mix and the family of mixes from which it originated is investigated by evaluating the presence and distribution of air voids, the ingress of chlorides, and the material's resistance to freeze-thaw cycling. It is shown that the mix, like its commercial counterpart, has extremely high resistance to freeze-thaw cycling and chloride penetration.

Keywords: mechanical properties; workability; field cast

1. Introduction

Ultra-high performance concrete (UHPC) achieves a compressive strength of at least 150 MPa, and it has self-consolidating properties. UHPC comprises component materials with particle sizes and distributions carefully selected to maximize packing density (El-Tawil et al 2016; Alkaysi and El-Tawil 2016) (constituent particles arranged as compactly as possible), which is the reason for the extremely high mechanical and durability properties of the material. Another key feature of UHPC is that it is reinforced with a small percentage by volume (typically 2%) of short steel fibers, which enhance the material's tensile behavior and energy dissipation (Wille et al. 2012, Russell and Graybeal 2013).

The use of UHPC as a field-cast material is not new, but most experience in the U.S. has been with proprietary materials (Hansen and Jensen 1999). Building upon previous work by the authors (El-Tawil et al 2016, 2018; Alkaysi and El-Tawil 2016, Liu et al. 2018, Wille et al. 2014), this research aims to address some of the hurdles facing broad adoption and implementation of generic UHPC. The study focuses on how various components of generic UHPC affect its short and long term response and the differences in properties between field- and lab-mixed versions of the same material.

2. Experimental program

2.1. Component Selection

The nonproprietary UHPC mixture was produced using Type I ordinary portland cement (OPC), ground-granulated blast-furnace slag (GGBS or slag cement), silica fume, two types of silica sand, and short steel fibers. To ensure workability, a high-range water-reducing admixture (HRWRA or superplasticizer) was used (El-Tawil et al 2016; Alkaysi and El-Tawil 2016). Four variants of the mixtures described in References 1 and 2 were considered good candidates for field application. The experimental variables were the amount of HRWRA and fiber length. The mixture proportions are shown in Table 1.

Table 1: Mixture proportions by weight (Portland cement + slag cement = 1.0)

Mixture No.	Water	Type I OPC	Slag cement	Silica fume	HRWRA	Silica sand		Steel fiber
						Sand A	Sand B	
1	0.22	0.5	0.5	0.25	0.02	0.30	1.21	0.2*
2					0.02		1.21	0.2
3					0.03		1.21	0.2
4					0.035		1.20	0.2

* The volume fraction of steel fibers to all the mixtures are 2.0%, the length used in mixture 1 was 19 mm (0.75 in), and the remaining three mixtures were 13 mm (0.5 in).

2.2. Effect of Mixing Process

When preparing UHPC, careful consideration should be given to mixing time, mixing speed, temperature, and mixing sequence to achieve the anticipated performance (Dils et al. 2012). Field mixing has two key restrictions that do not apply to lab mixing: (1) Large-capacity mixers used for field construction generally have mixing speeds that are lower than those achievable in smaller lab mixers, and (2) The powder materials and silica sands form lumps that can be quite large in field mixing applications, which hinder the mixing process. A new mixing protocol based on the work of de Larrard et al (de Larrard and Sedran 1994) and El-Tawil et al. (El-Tawil et al 2016) is evaluated in this research. The process entails the following steps: a) Dry mix cement, GGBS, silica fume, and a portion of the silica sands for 5 minutes; b) Add water and superplasticizer till turnover and formation of thick slurry; c) Incorporate remaining silica sands gradually and mix another 5 minutes; and d) Add fibers and continue to mix until fluidity is optimized (between 5 and 8 minutes).

Fig. 1 shows turnover time and spread of blends with different portions of silica sands. It can be observed that the fresh nature of UHPC is affected by the mixing method. When mixing UHPCs using the original mixing protocol in El-Tawil et al. (El-Tawil et al 2016), turnover occurs quickly, usually within two minutes. When the premixed material is free of silica sands, the turnover time exceeds six minutes, which demonstrates the importance of silica sands in facilitating mixing. Experiments conducted to evaluate the effect of the portion size of the premixed sands indicated that the spread was relatively independent of the premix portion (see Fig. 1).

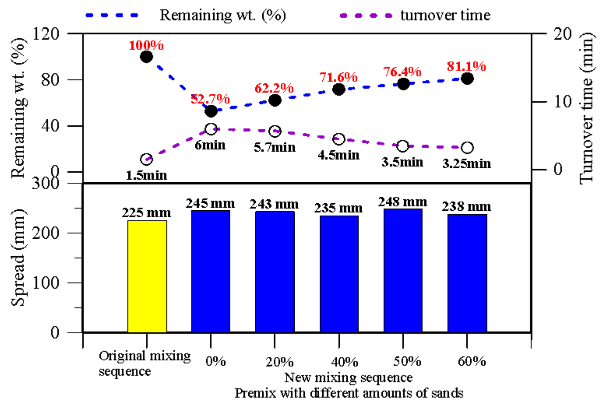


Figure 1 The weight variation of mixtures with different amounts of premixed silica sands

2.3. Laboratory Trial Batches

The rheology of the UHPC mixture was assessed by measuring spread according to ASTM C1437. Based on References 1 and 2, a mixture was considered appropriate for use if its spread ranged from 175 to 300 mm. The compressive strength was obtained from cubes tested per ASTM C109/C109M, while tensile strength was obtained using coupons tested per AASHTO T 132-87, Table 2 summarizes the properties of the four trial mixtures.

Table 2: Mechanical properties of laboratory and field batches

Mixture No. or ID	Spread, mm (in.)	Compressive strength, MPa (ksi)				Tensile strength, MPa (ksi)	Strain at peak tensile stress, %
		7-day	14-day	28-day	56-day		
1	214 (8.4)	121.3 (17.6)	149.1 (21.6)	175.7 (25.5)	196.2 (28.5)	12.9 (1.9)	0.41
2	215 (8.5)	118.2 (17.1)	147.8 (21.4)	169.2 (24.5)	187.4 (27.2)	11.1 (1.6)	0.17
3	235 (9.3)	118.8 (17.2)	143.5 (20.8)	159.0 (23.1)	176.4 (25.6)	9.5 (1.4)	0.18
4	238 (9.4)	113.4 (16.5)	137.1 (19.9)	151.9 (22.1)	—*	9.6 (1.4)	0.14
Field	238 (9.4)	108.9 (15.8)	127.0 (18.4)	148.1 (21.5)	—*	8.3 (1.2)	0.13

*Specimens not tested. Not enough were made due to an oversight

Table 2 shows the beneficial effects of the longer steel fibers. Mixture 1 (with 19 mm fibers) exhibited a larger strain at peak tensile stress and a larger peak tensile strength than the mixtures with 13 mm fibers. The longer fibers also led to a slightly higher compressive strength than the shorter fibers. The 28-day compressive strength decreased with increasing amount of superplasticizer, representing a 10% drop (Table 2). This was true also for tensile strength. The effects of using slag cement were also evident, as the strength kept rising substantially beyond 28 days. Comparing all the results, Mixture 3 provided a good compromise between flowability and strength, and it was selected for use in the field.

3. Durability test results

The durability of Mixtures 2 and 3 were investigated by performing air void analysis as well as rapid chloride penetration and freeze-thaw resistance tests. Details of the test methods and procedures can be found in Reference (Alkaysi et al. 2016).

3.1 Air void distribution

The air void size distribution as measured by the linear traverse method is shown in Fig 2. According to the test results, the most common air void size is between 500-1000 µm. If this is defined as the upper limit of the entrained air void, the distribution of finer air voids is almost identical in both mixtures and the cumulative air void content ranges from 4.1% to 4.7%.

3.2 Chloride penetration resistance

The RCPT results for both UHPC mixes are shown in Figure . The total charge passed for Mixture 2 and Mixture 3 is 33.0 Coulombs and 31.0 Coulombs, respectively. It can be seen from these results that UHPC specimens showed a very low chloride ion penetrability, well below 100 Coulombs. According to ASTM C1202, the test demonstrates that the UHPCs considered has low chloride ion penetration at 28-days, which could be classified as negligible. This is in contrast to regular concrete with a water-cement ratio of 0.4, which passes 5445.0 Coulombs.

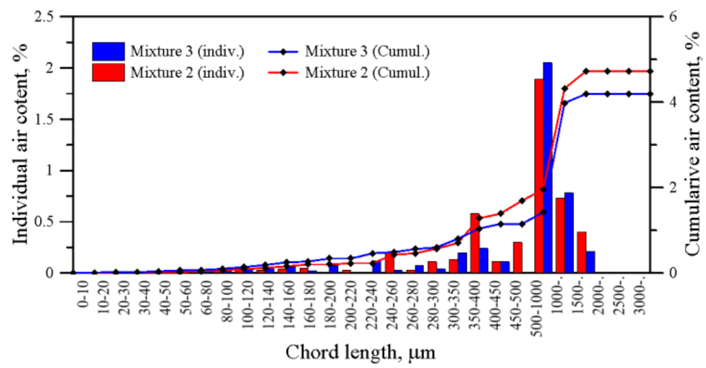


Figure 2 Air void size distribution based on the chord length from linear traverse method

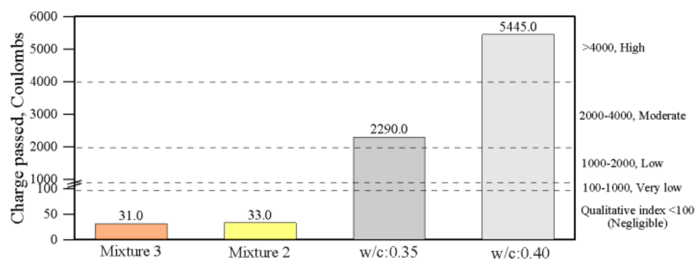


Figure 3 Total charge passed for UHPC and regular concrete

3.3 Freeze-thaw resistance

Specimens were subjected to fast freeze-thaw testing in 3% sodium chloride (NaCl) salt solution. In such testing, the relative dynamic modulus (RDM) provides a reliable measure for evaluating internal frost damage as discussed in (Alkaysi et al. 2016). The RDM result are shows in Fig 4(b). The RDM values of the specimens did not show an obvious drop during the freeze-thaw cycles and they always varied from 97 to 100 % of the initial value. This is attributed to the optimal particle packing density in UHPC, which can strongly decrease the void connectivity within the concrete matrix.

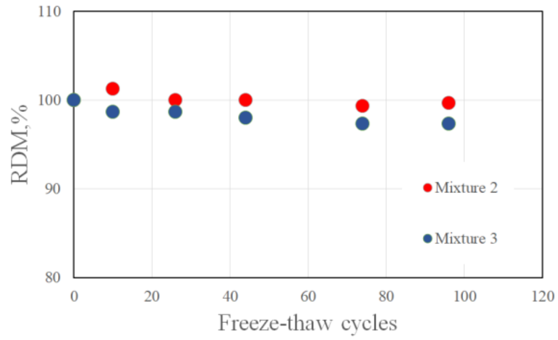


Figure 4 Effects of freeze-thaw cycling on RDM

4. Field Application of UHPC

The bridge repair project was located on Kilgore Road over the Pine River, Kenockee Township, MI, see Fig. 5(a). The bridge is 13.6 m (44.7 ft) long and 6.5 m (21.4 ft) wide (Fig. 5(b)).

(a) (b)

Fig. 5 Bridge repair site: (a) location in Michigan; and (b) close up view

4.1. Mixing

Mixing used two Mortarman 360 MBP pan mixers, each with a capacity of 8 ft^3 (0.23 m^3). The first batch of the day was mixed at an ambient temperature of 23.9°C (75°F). The mixture temperature peaked at 26.7°C (80°F), and the spread was 238 mm (9.4 in.). The ambient temperature for the second batch was 25.0°C (77°F), but the mixture temperature rose to 35.0°C (95°F). The increased mixture temperature caused a marked reduction in spread, decreasing to 200 mm (8 in.) for the second batch from 238 mm (9.4 in) for the first batch. As shown in Table 3, turnover time increased a little with increasing ambient temperatures and the spread dropped significantly as the mixture temperature increased.

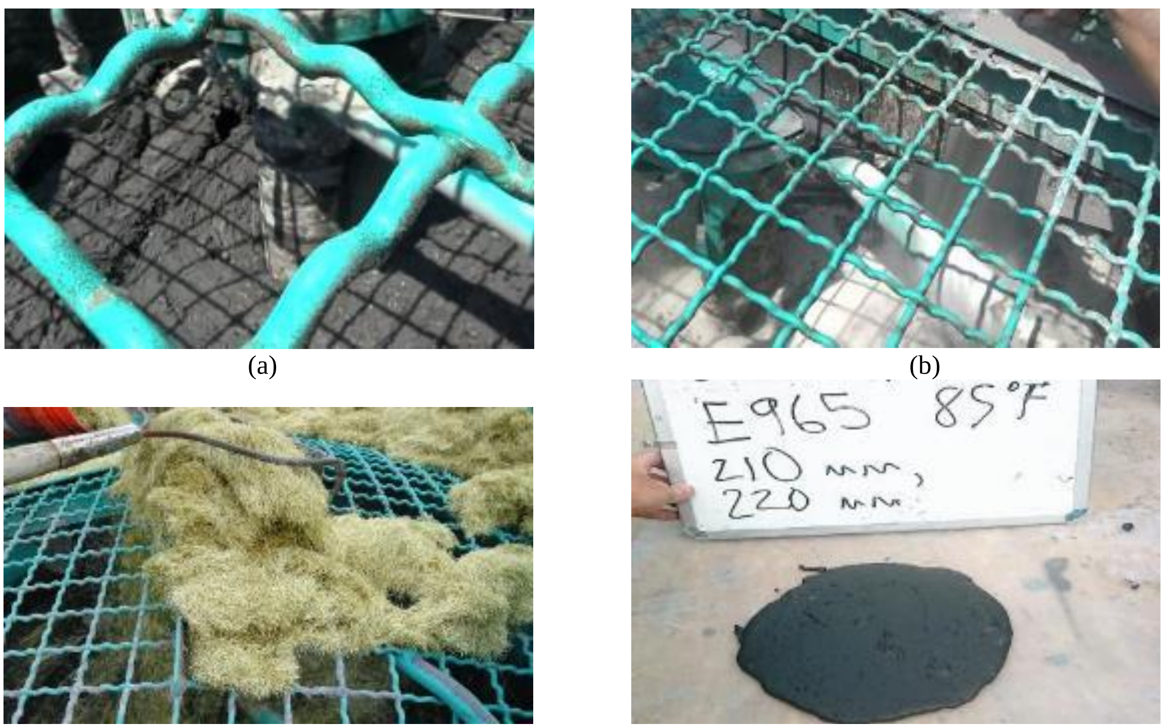
Table 3: UHPC fresh test results

Batch	Turnover time	Ambient temperature, °C (°F)	Mixture temperature, °C (°F)	Spread, mm (in.)
1	1 minute, 30 seconds	23.9 (75)	26.7 (80)	238 (9.4)
3	2 minute, 5 seconds	25.0 (77)	35.0 (95)	200 (8.0)
4	2 minute, 30 seconds	25.6 (78)	30.0 (86)	231 (9.1)
7	2 minute, 45 seconds	26.7 (80)	29.4 (85)	220 (8.7)

Cubed ice was added as a replacement for some of the mixing water as recommended in Reference 7 to reduce the temperature of the mix. On-site experimentation showed that a 40% replacement yielded good results and kept the mixture temperature below about 29.4°C (85°F), a point beyond which test showed that the spread drops quickly. Figure 6 shows the steps of the field mixing procedure and testing.

4.2 Casting process

The forms were pre-wetted to ensure that they did not absorb water. The surface of the existing concrete and the reinforcing bars were also pre-wetted to prevent the mixture from losing water to the dry surfaces (Fig. 4(a)). UHPC was cast at a rate that did not allow it to flow too far during placement in order to minimize preferential alignment of the fibers in the direction of flow. This was done by starting the casting process at one end of the joint and proceeding to the other end at a speed comparable to the flow speed of the fresh mixture. Once casting was carried out, top forms were installed to reduce surface dehydration (Fig. 4(b)).



(a) (b) (c) (d)

Fig. 6 Field mixing procedure and testing of UHPC mixture: (a) after turnover, thick slurry is formed; (b) incorporate remaining silica sands and continue mix to disperse and homogenize; (c) addition of steel fibers; and (d) flow test

(a) (b)

Figure 7 Casting of UHPC into a joint between beams: (a) placement; and (b) top forms installed

4.3 Comparison of Field and Lab Properties

Cubes and coupons were made during field mixing in order to compare field properties to lab values. The results are listed in Table 2. The 28-day compressive strength of the field mixture was about 10 MPa (1500 psi) lower than the lab Mixture 3. The tensile properties of the field mixture were also lower than those of Mixture 3. The differences are attribuetd to the hot weather, which caused mixing water to evaporate rapidly, and the mixer, which likely was unable to provide sufficiently uniform mixing.

5. Conclusions

The research discussed in this paper suggests that the proposed mixing protocol can reduce the burden on field mixers. As such, larger mix loads can bs used in the field. It was shown that the 28-day compressive strength of all mixtures in the laboratory were higher than 150 MPa (21.7 ksi), fulfilling the minimum requirements for UHPC. However, the the 28-day compressive strength of the field-mixed material was slightly lower, at 148.1 MPa (21500 psi). Although this is below the 150 MPa mark, the material is expected to continue to gain substantial strength at later ages due to the use of slag cement. Finally, mixing during warm days can cause the mix to become too hot, adversely affecting the effectiveness of the high range water reducer and significantly decreasing the workability of mix. However, those effects can be alleviated by replacing some of the mix water with cube ice.

6. References

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7. Acknowledgements

This research was funded by MDOT. The authors would like to acknowledge the ideas and intellectual contributions of Dave Juntunen and Steve Kahl of the Field Services Research Administration at MDOT.