DEVELOPMENT OF ULTRA-HIGH PERFORMANCE CONCRETE FOR SHEAR-KEYS IN PRECAST BRIDGES USING LOCALLY AVAILABLE MATERIALS

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ABSTRACT

The development and use of ultra-high performance concrete (UHPC) mixtures produced from local materials is gaining importance as highway agencies are increasingly adopting precast bridges as the standard structures for replacing the aging short-span bridges. Typically, an ultra-high-performance concrete/grout mixture is used for the shear key construction due to its superior mechanical and durability properties.

In this paper, the findings from an investigation conducted to develop UHPC using local materials will be presented along with cost considerations. Test results from this investigation showed that highly flowable UHPC mixtures can be produced with desired mechanical and durability properties. Compressive strength and MOE in excess of 150 MPa (22,000 psi) and 50 GPa (7.2 x 10^6 psi), respectively were obtained along with split tensile and flexural strengths exceeding 15 MPa (2,200 psi) and 25 MPa (3,625 psi), respectively. Also, these UHPC mixtures showed negligible chloride ion permeability values. The bond strength tests showed that the interface bond between the UHPC and precast concrete was superior. The pull-out tests using 13 mm (0.5 inch) rebar embedded in the UHPC showed excellent bond with short development length. Based on this study, it can be concluded that efficient and economical UHPC can be produced using local materials that meet the desired mechanical and durability performance.

Keywords: UHPC; Shear-key; Silica fume; Steel microfiber; Shrinkage reducing admixture; Development length

INTRODUCTION

Ultra-high performance concrete (UHPC) is a relatively new type of concrete that is characterized by its low water-cementitious materials ratio (w/c less than 0.25), high cementitious materials content, high dosage of high-range water reducing admixture (HRWRA), and reinforcing microfibers in the mixtures. These features provide UHPC with its superior workability, mechanical properties, and durability [1,2]. Typical 28-day compressive strength of UHPC is in excess of 150 MPa (21.7 ksi)[1]. Silica fume (SFU), a by-product of the production of elemental silicon or alloys containing silicon, is one of the widely used supplementary cementing materials (SCM) in UHPC formulations. Its super fine particles and pozzolanic reactivity improve compressive strength and densify the microstructure of hardened concrete significantly [3,4]. Silica flour (SFL), a finely ground quartz sand, is an inert form of silica which does not have chemical reactivity at ambient temperature; however, the fine particulate nature of the SFL physically improve the grading and packing of the aggregate and reduces the permeability of concrete [5]. SFL is usually used as filler material, substituting a portion of the fine aggregate. Steel microfiber (SMF) is another frequently used component in UHPC due to its ability to restrain crack propagation in concrete [4].

Several research studies have developed UHPC with desirable properties over last decade [1,2,6]. For instance, Wille et al. formulated several UHPCs having compressive strength over 150 MPa (21.7 ksi) without special treatment, such as heat curing or pressure curing [6]. If special treatments were applied, UHPC with compressive strength of 510 MPa (74 ksi) could be prepared[7]. Regardless of the remarkable properties of these UHPC, the commercially available UHPC products which are applicable for in-situ construction are still limited, and typically these patented products are expensive. If special treatments are required, the cost of UHPC would be even higher. UHPC with superior properties and relatively low cost continues attracting the interest of the concrete industry.

In the present study, the material and structural properties of UHPC developed using local materials from South Carolina with no special curing requirements were systematically studied. Materials-related variables explored in this study included varying dosages of a SFU, SFL, SMF, and shrinkage reducing admixture (SRA). The properties of UHPC investigated included workability, air content, density, time of set, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity (MOE), rapid chloride permeability (RCP), and drying shrinkage. The structural properties of UPHC investigated included bond strength between UHPC and precast concrete, and bond strength between UHPC and steel rebar. UHPC with compressive strength over 150 MPa (21.7 ksi) was prepared without any special curing treatments. The minimum development length for

13-mm (0.5-inch) diameter Grade 420 (60) rebar was also determined.

EXPERIMENTAL PROGRAM

MATERIALS USED

For this experimental study, a Type Ⅲ portland cement conforming to ASTM C150 specification was used. A very low loss on ignition (LOI < 0.5%) SFU was used in the UHPC as an additional cementitious material and not as a replacement to portland cement. A commercially available ground quartz (MIN-U-SIL ® 5 from U.S.. Silica Company) was used as SFL, a filler material substituting portion of the fine aggregate. Table 1 lists the physical and chemical properties of cement, SFU, and SFL.

Table 1 Physical and chemical properties of materials

Materials Name	Type Ⅲ Cement	SFU	SFL
Specific gravity	3.15	2.2~2.3	2.65
Specific surface area (m^2/kg)	540 [a]	15000~30000 [b]	5000 [b]
Particle size (μm)	-	0.15[c]	1.6[d]
Passing 325 mesh (%)	98.8	93.0	99.996
SiO_2 (%)	20.4	92.0	99.2
Fe_2O_3 (%)	3.5	-	0.035
Al_2O_3 (%)	6.0	-	0.3
TiO_2 (%)	-	-	0.02
CaO (%)	64.4	-	0.03
MgO (%)	1.0	-	0.01
Na_2O (%)	-	-	0.01
K_2O (%)	-	-	0.02
SO_3 (%)	3.5	-	-

Note: [a] Blaine surface area; [b] BET-Gas adsorption surface area; [c] Average particle size; [d] Medium particle size; 1 m^2/kg = 0.54 yd.^{2} /lb

The SMF were approximately 13 mm (0.5 inch) in length and 0.2 mm (0.008 inch) in diameter. Their specific gravity and ultimate tensile strength was 7.8 MPa (1131 psi) and 2000 MPa (290,000 psi), respectively. Fine aggregate used in this study was a natural siliceous sand meeting ASTM C33 gradation specification. Its gradation is presented in Table 2. The specific gravity, water absorption, and fineness modulus of the fine aggregate were 2.62, 0.3%, and 2.65 respectively. A polycarboxylic ester based high-range water-reducing admixture (HRWRA) in a powder form was used to improve workability. A liquid SRA with specific gravity of 0.93 was used for reducing drying shrinkage.

Table 2 Gradation of fine aggregate

Sieve	Percent Passing
9.5-mm (3/8 inch)	100.0
4.75-mm (No.4)	99.8
2.36-mm (No.8)	97.1
1.18-mm (No.16)	82.0
600-µm (No.30)	41.9
300-µm (No.50)	14.0
150-µm (No.100)	0.5
75-µm (No.200)	0.1

MIXTURE PROPORTIONS AND SPECIMENS PREPARATION

The proportions were designed to study the effect of SFU, SFL, SMF, and SRA on the material or structural properties of UHPC. SFU was used in addition to cement at two levels, 10% and 20% by weight of cement. SFL was studied as a substitution of fine aggregate at a level of 10% by weight of fine aggregate. The ratio of mass of fine aggregate (or fine aggregate and SFL) to cementitious materials was fixed at 1.25 throughout the study. SRA was studied at a dosage of 2% by weight of cementitious materials. SMF was used at a dosage of 2% by the volume of total mixture. For the study of plastic properties of UHPC, the dosage of HRWRA was kept constantly across all mixtures at 1% by weight of cementitious materials. For the rest of the study, the dosage of HRWRA was selected as long as the UHPC reached 150% flow in accordance with ASTM C1437. Table 3 lists the precise mixture proportions used for each of the UHPC mixtures studied.

Table 3 UHPC proportions

UHPC ID	Constituent (kg/m^3)								
	Cement	SFU	Water	Sand	SFL	SMF	SRA	HRWRA	
								F [a]	H [b]
C	1005	0	201	1257	0	0	0	10.1	10.1
SU1	903	90	199	1241	0	0	0	--	7.0
SU2	819	164	197	1229	0	0	0	9.8	7.2
SL	903	90	199	1106	123	0	0	--	7.4
SU2F	803	160	193	1204	0	156	0	9.6	9.6
SU2S	786	157	189	1179	0	153	19	9.4	4.7

Note: [a] Fresh state material properties; [b] Hardened state material and structural properties

Fresh UHPC was prepared in a 0.248 m^3 (9 ft^3) mortar mixer. If SRA was used, it was dispersed into the mixing water in advance. A sequential mixing procedure was followed so as to not overload the mixer at the initial stages when the UHPC mixture is highly viscous. As a first step, half of the dry material including cement, sand, HRWRA (powder) and where appropriate SFU and SFL, were mixed for 1 to 2 minutes. This was followed by adding half of the proportioned water. SRA was added along with water in mixtures where SRA was used. As long as the mixtures had enough ability to flow, the rest of the dry materials and liquid were gradually introduced into the mixer. When SMF was used, it was added into the plastic concrete mixture gradually and mixed thoroughly at the end of the mixing cycle. The total process of mixing took 15 to 20 minutes. After mixing, the fresh properties of UHPC were tested.

Even though the UHPC mixture was highly flowable, external vibration was applied to the molds to remove any unintended entrapped air during casting. Specimens cast for studying compressive strength, splitting tensile strength, flexural strength, MOE, and RCP, were kept in a moist room conforming to ASTM C511 specification. At the age of 24 hours, specimens were demolded and stored in the moist room until testing. For studying drying shrinkage of UHPC mixtures based on ASTM C596, specimens were stored in the moist room and de-molded at the age of 24 hours. Subsequently, the specimens were stored in saturated lime water for 2 days after de-molding, and then stored in an environmental chamber maintained at a temperature of 23±2 ^{o}C (73±3 ^{o}F) and a relative humidity of 50±4%, throughout the duration of the test. For studying bond strength between UHPC and precast concrete, a 25 mm (1 inch) thick layer of fresh UHPC mixture was placed on the roughened top surface of a precast concrete slab. Each of these specimens was stored in the lab under ambient conditions. For studying bond strength between UHPC and steel rebar, a series of specimens were cast, wherein, a Grade 420 (60) steel re-bar with diameter of 13 mm (0.5 inch) was embedded into UHPC at different embedment lengths. The specimens were stored in the lab under ambient conditions until pull-out tests were conducted.

TEST METHODS

The temperature of fresh UHPC for all mixtures was measured between 70 ^{o}F and 80 ^{o}F (21 ^{o}C and 27 ^{o}C). The workability (flow), density, fresh air content, time of set, compressive strength, splitting tensile strength, flexural strength, MOE, RCP, and drying shrinkage were conducted in accordance with standard ASTM specifications. The corresponding test methods are listed in Table 4, along with test age and specimen dimensions.

Table 4 Standard test method

Properties	ASTM	Tested Ages	Specimen Dimensions

	Specification	(day)	(mm)
Workability	C1437	0	--
Fresh density	C138	0	--
Fresh air content	C231	0	--
Time of set	C403	0	--
Compressive strength	C109	1,3,7, 28	50×50×50
Splitting tensile strength	C496	28	∅75×150
Flexural strength	C78	28	75×75×300
MOE	C469	28	∅100×200
RCP	C1202	28	∅100×50
Drying shrinkage	C596	Up to 177	25×25×285

Note: 1 mm = 0.0394 inch

The bond strength between UHPC and precast concrete was evaluated by pull-off test, in accordance with ASTM C1583. At least three shallow cores with diameter of 57.2 mm (2.25 inch) were drilled into the UHPC overlaid precast concrete surface for each testing age. The drilling bit was controlled to penetrate into the slab with a depth of 50.8 mm (2 inch). So, the core specimen consisted of 25.4 mm (1 inch) thick UHPC and 25.4 mm (1 inch) thick precast concrete. A high strength epoxy was used to glue the aluminum disc on the top of core specimen for loading. Pull-off test was conducted at the ages of 7 and 28 days.

For testing bond strength between UHPC and steel rebar, a cylindrical UHPC specimen of dimensions 150 mm (6 inch) diameter and 300 mm (12 inch) long with a 13-mm (0.5-inch) diameter Grade 420 (60) re-bar embedded in it was cast as shown in Fig. 1a.

(a) Specimens (b) Steel jacket (c) Splitting crack in specimens without steel jacket

Fig. 1 Test setup for rebar pull-out test

Several specimens with various rebar embedment lengths were cast for the pull-out test. During the test, UHPC cylinder was placed inside a split cylindrical steel jacket as shown in Fig. 1b. The longitudinal slit could be closed by tensioning the two side bolts to close the slit and keep the cylinder wrapped on all sides. The purpose of the steel jacket was to provide sufficient confinement to prevent the cylinder from splitting (Fig. 1c) and at the same time not provide excess confinement stress that would artificially increase the pull out strength. The tests were conducted on two UHPCs, SU2 and SU2F, at the age of 7 days.

RESULTS AND DISCUSSIONS

FRESH CONCRETE PROPERTIES

The workability, density, air content, and time of set of UHPC mixtures C, SU2, SU2F, and SU2S are shown in Table 5. All the UHPC mixtures employed HRWRA at the dosage of 1% by weight of the cementitious materials.

Table 5 Properties of freshly prepared UHPCs

UHPC ID	Flow (%)	Density (kg/m^3)	Air Content (%)	Time of Set (hour)	
				Initial	Final
C	150	2416	3.5	5.58	7.06
SU2	150	2374	3.2	7.43	8.71
SU2F	150	2459	2.6	7.30	8.42
SU2S	150	2453	3.1	14.93	16.40

Note: kg/m^3=1.69 lb/yd^3

The flow values of all the UHPC mixtures were equal to 150%, the maximum measurable value on an ASTM C1437 flow table. However, with the material proportions employed in this investigation, the effects of SFU, SMF or SRA on the workability of UHPC could not be captured using this test method. For instance, some of the UHPCs reached 150% flow with the flow table being dropped less than 25 times, while some of the UHPCs reached 150% flow only when the flow table was dropped all the way up to 25 times. The method in ASTM 1437 could not tell the difference in workability of high-flow UHPCs in this study.

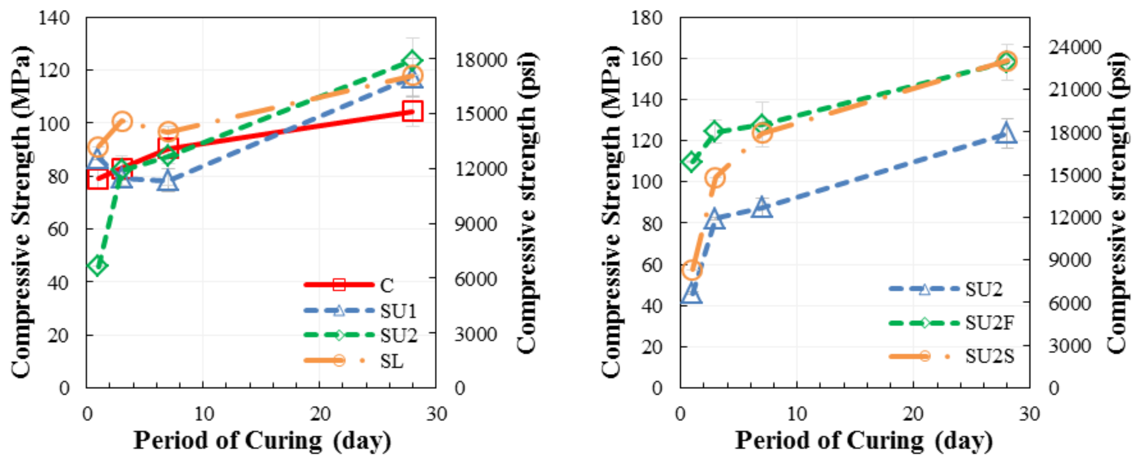
The test results of density, air content, and time of set showed a general picture of the effect of SFU, SMF, and SRA. The addition of SFU at 20% dosage level reduced the density and air content by 2% and 9%, respectively compared to the control mixture (C). The time of initial and final set in SU2 mixture were delayed by 33% and 23%, respectively, when compared with control mixture C. In the comparison between UHPC SU2 and SU2F, it was observed that the addition of SMF increased the density by 4%, but decreased the air content by 19%. It did not have significant effect on the time of set. The addition of SRA slightly reduced the density by 0.2%, but increased the air content by 19%, when compared with UHPC SU2F. However, the addition of SRA significantly delayed the time of initial and final set by 105% and 95%, respectively, compared with UHPC SU2F. The abnormal long time of set of UHPC SU2S appeared to be influenced by the combination of HRWRA and SRA in the study. The values presented in this study were for a HRWRA dosage of 1% and an SRA dosage of 2% by weight of the cementitious materials. In other studies (not reported here), the authors used a lower HRWRA dosage of 0.5% and SRA dosage of 2%, with similar proportions of other components in the UHPC mixture. The time of initial and final set for the SU2S with lower dosage of HRWRA was observed to be 7.5 hour and 9.28 hour respectively, which were significantly shorter than the values obtained in this study.

COMPRESSIVE STRENGTH

The effect of SFU and SFL on the compressive strength of UHPC is shown in Fig.2a. The addition of SFU tended to decrease the compressive strength of UHPC at early ages. It can be observed that the compressive strength of both UHPCs containing 10% and 20% of SFU were lower than UHPC without SFU at the ages of 1, 3, and 7 days, except the compressive strength of UHPC with 10% SFU was 10% higher than UHPC without SFU at the age of 1 day. However, SFU significantly improved the compressive strength at the age of 28 days. A comparison of the 28-day compressive strengths revealed that 10% and 20% addition of SFU improved the compressive strength by 12% and 18%, respectively, compared with 0% addition of SFU. Similar phenomenon had been observed and reported by other researchers previously, wherein the influence of SFU on compressive strength of concrete was characterized as a combination of filler and pozzolanic effects [4, 22, 23].

The addition of SFL improved the compressive strength at early ages (1, 3, and 7 days). When comparing the UHPC SU1 with SL, it was found that 10% of fine aggregate replaced by SFL increased the compressive strength at the ages of 1, 3, and 7 days by 5%, 27%, and 23%, respectively. However, SFL did not have significant effect on the compressive strength at later ages (28 days). It was found that that the use of SFL only increased the 28-day compressive strength by 0.7% which was negligible. The effect of SFL can be explained by the fact that the fine particulate nature of SFL provides a large amount of substrate surface for the nucleation of $Ca(OH)_2$, which accelerates the hydration of cement at early ages[5]. Considering that SFL had little influence on the later age compressive strength, this material was not considered further in the UHPC formulations to evaluate other mechanical and durability properties.

The effect of addition of 2% microfibers can be assessed by comparing the compressive strength of UHPC SU2 with UHPC SU2F. As is shown in Fig. 2b, the compressive strength of UHPC SU2F was significantly higher than the SU2 at all curing periods. For example, at the ages of 7 and 28 days, the percentage increase in compressive strength due to microfiber addition was 46% and 28%, respectively.



(a) Effect of SFU and SFL (b) Effect of SMF and SRA

Fig. 2 Compressive strength of UHPC

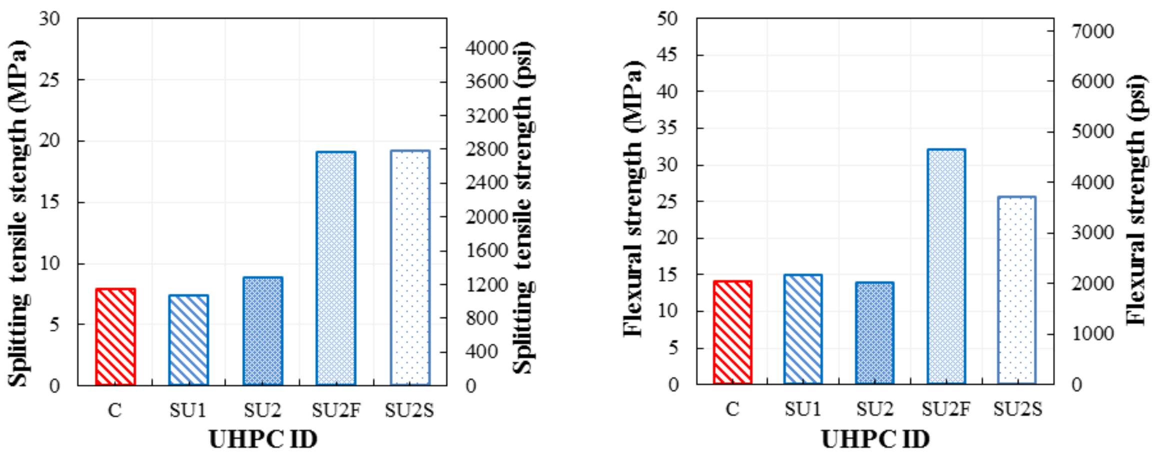
The effect of addition of 2% SRA can be assessed by comparing the compressive strength of UHPC SU2F with UHPC SU2S. As shown in Fig. 2b, the compressive strength of SU2S mixture was significantly lower than the UHPC SU2F mixture, especially at the age of 1 day. The percentage decrease in the compressive strength due to addition of SRA decreased with age from 1 day to 7 days. At the age of 7 days, this percentage decrease in strength due to SRA addition was only 3%, compared with 91% decrease at the age of 1 day. The compressive strengths of UHPCs with and without SRA were almost identical at the age of 28 days. From these results it appears that the addition of SRA at 2% has a tendency to lower early age compressive strength with no significant negative effect at later ages.

TENSILE STRENGTH (SPLIT TENSILE STRENGTH AND FLEXURAL STRENGTH)

The effects of SFU, SMF, and SRA, on the split tensile strength of UHPC at the age of 28 days are shown in Fig. 3a. The results indicated that the addition of SFU did not have significant effect on the split tensile strength. The split tensile strength values of UHPCs with SFU dosage of 10% and 20% were 6% lower and 13% higher than UHPC without SFU, respectively. Comparing the split tensile strength values for the UHPC SU2 and SU2F, it was observed that the addition of SMF increased the tensile strength substantially by 115%. The split tensile strength of UHPC SU2S, which contains SRA, was almost identical to that of SUSF, but significantly higher than UHPCs C, SU1, and SU2 by 140%, 160%, and 116%, respectively.

The flexural strength of UHPC at the age of 28 days is shown in Fig. 3b. As the results show that the addition of SFU did not have significant effect on the flexural strength either. The 28-day flexural strength of UHPCs with SFU dosage of 10% and 20% was 6% higher and 1% lower than UHPC without SFU, respectively. Comparing the flexural strength values for UHPCs SU2 and SU2F at the age of 28 days, it was observed that the addition of SMF increased the flexural strength by 131%. The addition of SRA decreased the flexural strength of the UHPC SU2S specimen by 21%, which was evident by comparing the test results of SU2F and SU2S mixture. But the flexural strength of UHPC SU2S was still higher than UHPC C, SU1, and SU2 by 81%, 71%, and 83%, respectively.

Based on the test results of split tensile strength and flexural strength, it can be concluded that the use of SMF was the most effective way of improving the tensile strength of UHPC. This observation was similar to that reported in previous studies, and the crack restraining ability of microfibers was believed to be the reason[4]. In these studies, the impact of using SFU alone on the tensile strength of the UHPC was not apparent at any dosage level. The effect of SRA on the tensile strength of UHPC was not conclusive. Further studies are needed.



(a) Split tensile strength

(b) Flexural strength

Fig. 3 Tensile Strength

MODULUS OF ELASTICITY (MOE)

The MOE of UHPC at the curing age of 28 days is shown in Fig.4. By comparing the 28-day MOE values of UHPCs C, SU1 and SU2, it was found that the addition of SFU would increase MOE. The addition of SFU at 10% increased the MOE by 9%, compared with UHPC without SFU. However, only 0.6% decrease in MOE was found as the SFU content went from 10% to 20%. Similarly by comparing the MOE values of UHPCs SU2 and SU2F mixture, it was observed that the addition of SMF decreased the MOE by 2%. The addition of SRA reduced the MOE of UHPC by 5%, which was evident by comparing the test results of SU2S and SU2F mixture.

Similar effect of SFU and SMF on MOE has also been observed in other studies [24]. Koksal et al found that MOE of high strength concrete increased as the SFU content increased up to 15%, but it decreased as the SFU content further increased [24]. They attributed this phenomenon to the brittle structure of high strength concrete caused by SFU. It was also found that SMF decreased the MOE of high strength concrete, which was attributed to the ductility of SMF [25].

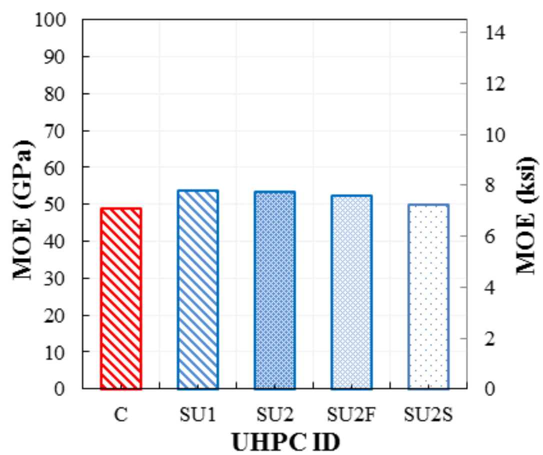


Fig. 4 MOE of UHPC

RAPID CHLORIDE ION PERMEABILITY (RCP) TEST

The RCP test results of UHPC at the age of 28 days are shown in Fig. 5. A comparison among test results of C, SU1 and SU2 mixture indicated that the 10% and 20% addition of SFU decreased the charge passed substantially by 86% and 89%, respectively. Addition of SFU at 10% reduced the chloride ion permeability rating of UHPC from “very low” to a “negligible” level. Further addition of SFU beyond 10% was not very effective in lowering the chloride ion permeability. By comparing the RCP of the SU2 and SU2F mixture, it was observed that the addition of SMF significantly increased the RCP value of concrete by about 14 times. A comparison of UHPC SU2F and SU2S mixture revealed that the addition of SRA reduced the charge passed by 80%.

The addition of SFU appeared to be the most effective way of reducing the permeability of UHPC. The micro-filler and pozzolanic effects of SFU resulting in the densification of microstructure of UHPC is believed to be the main reason for the observed reduction in the RCP values [4, 22, 23]. The reason for higher RCP value of SU2F mixture is likely due to an interconnected network of SMF in the concrete with little to no insulation between the individual fiber strands. However, in the presence of SRA, the UHPC mixtures containing SMF showed reduced RCP value. Although the precise mechanism is not clear at the present time, the presence of SRA in the mixture may have produced a better separation of the fibers, therefore increasing the insulation between the individual steel fibers. This would likely reduce the RCP values of mixtures with SMF. More studies are needed to confirm these effects of SRA.

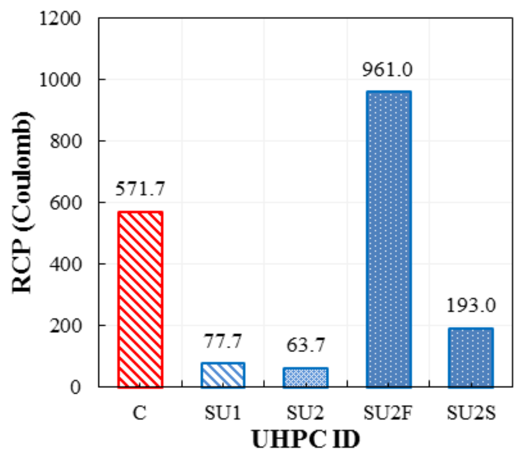
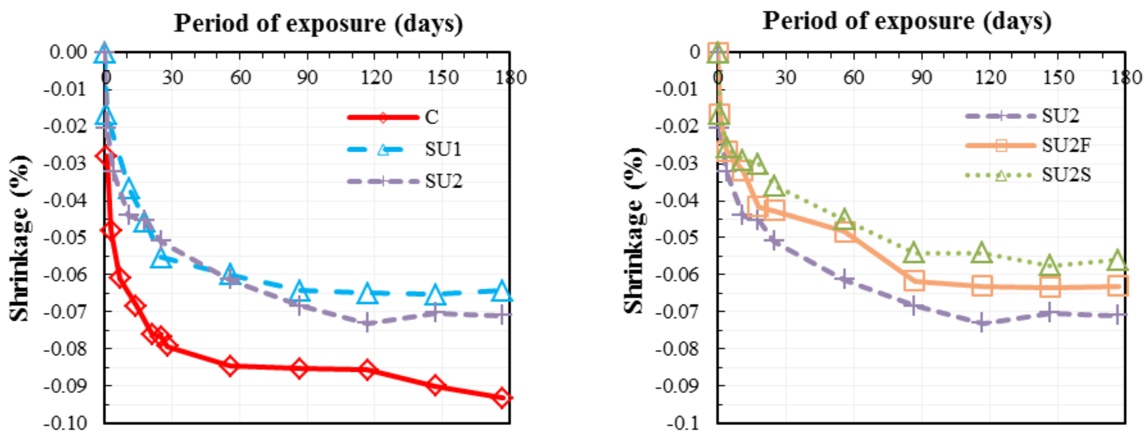


Fig.5 RCP of UHPC

DRYING SHRINKAGE TEST RESULTS

The drying shrinkage test results of the UHPCs are shown in Fig. 6. The drying shrinkage at the period of exposure of approximately 6 months (177 days) is listed in Table 6. The test results show that the use of SFU was helpful in reducing the drying shrinkage. At 6 months, the addition of SFU at 10% and 20% reduced the drying shrinkage by 31% and 20%, compared with UHPC C mixture. Similar phenomenon of reduced drying shrinkage with the addition of SFU was observed in previous studies [25].

The use of SMF and/or SRA reduced the drying shrinkage of UHPC. At 6 months, it was observed that the drying shrinkage of SU2F was 11% less than that of SU2. The main reason for the reduced drying shrinkage in the presence of SMF would be that the fibers restrain the shrinkage of cementitious paste in the UHPC[4]. A comparison between UHPCs SU2F and SU2S showed that 2% addition of SRA reduced the drying shrinkage by 8%. The reason of reduced drying shrinkage in presence of SRA is likely due to the reduced surface tension of pore fluid [26]. The rather minimal reduction of shrinkage of UHPC mixtures in presence of SRA suggests that the performance of SRA in very low w/c mixtures may not be all too effective.



(a) Effect of SFU (b) Effect of SMF and SRA

Fig. 6 Drying shrinkage behavior

Table 6 Drying shrinkage at the period of exposure of 177 days

UHPC ID	Average (%)	Coefficient of Variance (%)
C	-0.093	1.6
SU1	-0.064	7.7
SU2	-0.071	3.7
SU2F	-0.063	2.7
SU2S	-0.058	0.0

PULL-OFF BOND STRENGTH

Test results from pull-off bond strength tests are shown in Table 7. The results indicated that the control UHPC C mixture did not have good bond with the precast concrete at the ages of both 7 and 28 days. For the UHPCs containing 20% SFU and mixtures containing both 20% and 2% SMF, had bond strength higher than the tensile strength of the precast concrete, as the failure occurred in the precast concrete. The beneficial effect of SFU can be characterized by the formation of a denser interface between the precast concrete and newly poured UHPC [27]. The SU2S mixture performed equally well compared to SU2F mixture in the pull-off bond strength test.

Table 7 Ultimate load of slab pull-out test specimens of UHPC

UHPC ID	Period of Curing					
	7 Days			28 Days		
	Average (kN)	COV (%)	Failure Location	Average (kN)	COV (%)	Failure Location
C	1.7	29.4	Bond [a]	4.3	2.3	Bond [a]
SU2	3.9	5.1	Concrete [b]	4.8	2.5	Concrete [b]
SU2F	4.6	6.5	Concrete [b]	5.9	12.1	Concrete [b]
SU2S	6.0	0.0	Concrete [b]	6.2	6.8	Concrete [b]

Note: [a] Failed at the interface; [b] Failed in the concrete portion; 1 kN =220 lb

REBAR PULL-OUT TEST

The test results are shown in Table 8. The explanation of failure modes are listed in Table 9.

Table 8 Maximum stresses obtained during the pull-out testing of the rebar

UHPC ID	Embedment Length (mm)	Average Max Tensile Stress in Re-bar (MPa)	Steel Jacket	Failure Mode [c]
SU2	76	685.3	Y [a]	Cone or Split
	102	841.5	Y [a]	Yld
	127	863.2	Y [a]	Yld
SU2F	76	774.4	Y [a]	Yld
	76	735.8	N [b]	P-O or Split

Note: [a] Steel jacket applied; [b] Steel jacket not applied; [c] Failure Mode listed in Table 9; 1 mm = 0.0394 inch; 1 MPa = 0.145 ksi

Table 9 Descriptions of the failure modes

Mode	Description
Yld	Rebar yielded and test was stopped prior to or after fracture of rebar
P-O	Rebar pulled out and load was dropping (rebar may have also yielded)
Cone	Concrete shear cone developed at tip of rebar (rebar may have also yielded)
Split	Splitting cracks radiated out from rebar (rebar may have also yielded)

Regardless of the mixture, depth of embedment or use of the jacket, the stress in the rebar during the testing of every specimen exceeded the minimum specified yield stress of the steel. The rebar pull-out test results of UHPCs SU2 and SU2F indicated that 102 mm (4 inch) and 127 mm (3 inch) was the minimum embedment length for 13-mm (0.5-inch) diameter Grade 420 (60) re-bar, respectively. That is, a development length of only six times the rebar diameter or greater is likely to be enough to develop the strength of rebar surrounded by

UHPCs SU2 and SU2F, respectively. Such short development length would be an advantage for minimizing the dimensions of the in-situ poured shear-key. Also, the shorter embedment length is advantageous for utilizing straight rebar, which is easier to construct, than U-shaped rebar as reinforcement extending out from the precast deck.

By comparing the failure modes of specimen using UHPC SU2F with and without steel jacket, it was obvious that sufficient confinement from the steel jacket had significant effect on the test result of the testing setup used in this study. If steel jacket was not applied, the UHPC cylinder might probably split before rebar being pulled out or yield. However, in reality, the concrete from which rebar is pulled out is confined by the adjacent rebars and the concrete, and therefore the steel jacket confinement used in this study is considered appropriate.

A rebar embedment length of six bar diameters for development appeared to be sufficient for UHPC SU2F which presented the best mechanical properties among the studied UHPCs. However, a decision to only use six bar diameters for development is not suggested given normal construction tolerances and the negative consequences of not developing the strength of the reinforcement.

COST ANALYSIS OF UHPC PRODUCED USING LOCAL MATERIALS

The unit cost of materials and the cost of the UHPC mixtures are shown in Tables 10 and 11, respectively.

Table 10 Estimated unit cost of materials

Ingredient	Cost ($/kg)	Cost ($/lb)
Cement	0.11	0.05
SFU	0.52	0.26
Water	0	0
Sand	0.033	0.015
SMF	5.15	2.34
HRWRA*	11	5
SRA	11	5

*Powdered polycarboxylate ester based HRWRA was used.

Table 11 Quantity of materials and cost to produce one cubic meter (1 m^3) of UHPC

Ingredient	UHPC C		UHPC SU2		UHPC SU2F		UHPC SU2S	
	Mass, (kg)	Cost ($)	Mass (kg)	Cost ($)	Mass (kg)	Cost ($)	Mass (kg)	Cost ($)
Cement	1005	110.6	819	90.1	803	88.3	786	86.5

SFU	0	0.0	164	85.3	160	83.2	157	81.6
Water	201	0.0	197	0.0	193	0.0	189	0.0
Sand	1257	41.5	1229	40.6	1204	39.7	1179	38.9
SMF	-	-	-	-	156	803.4	153	788.0
HRWRA	10.1	111.1	7.2	79.2	9.6	105.6	4.7	51.7
SRA	-	-	-	-	-	-	19	209.0
TOTAL COST	2473	263.1	2416	295.1	2526	1120.3	2488	1255.7

* 1 m^3 = 1.307 yd^3; 1 kg = 2.2 lb

From this cost analysis it can be observed that approximate cost of recommended UHPC (i.e. SU2F and SU2S) is approximately $1120.3 and $1255.7 per cubic meter ($861 and 961 per cubic yard, respectively). From Table 11, it can be observed that the significant cost of the recommended UHPCs is predominantly due to the cost of the SMF. In this investigation, effort to optimize the proportions of the ingredients, particularly SMF dosage, was not conducted. It is likely that the cost of the UHPC mixtures can be further reduced by optimizing the proportions without significantly sacrificing the properties of UHPC.

CONCLUSIONS

In this study, the development of UHPC for shear key construction in precast bridges using locally available materials was explored. The influence of SFU, SFL, SMF, SRA and polycarboxylic ester based HRWRA on the fresh and hardened properties of UHPC were studied. Based on the findings from this study the following conclusions are derived:

1. In presence of adequate dosage of HRWRA, fresh properties of UHPC such as workability, air content, density and time of set are not significantly influenced by the use SFU or SFL in the mixture. However, the use of SMF increased the density of the UHPC. The use of SRA in the UHPC mixtures significantly increased the time of set, particularly at higher dosage levels of HRWRA.
2. In this study, UHPC mixtures with 28-day compressive strengths in excess of 150 MPa (22,000 psi) were produced using material combinations containing SFU, SMF and SRA. To achieve this level of strength, the use of SFU and SMF were found to be the most influential factors. Although, the use of SRA reduced early-age compressive strengths, the later-age strength was not affected.
3. The UHPCs containing SFU, SMF and SRA produced in this study achieved split tensile strength and flexural strength exceeding well above 15 MPa (2,200 psi) and 25 MPa (3,625 psi), respectively. Of all the components of the UHPC, the use of SMF had the most significant influence in improving the split tensile and flexural strength

of UHPC.

4. The MOE of UHPC was not significantly influenced by the presence or the absence of SFU, SMF or SRA. However, compared to control mixture, UHPCs containing SFU, SMF and SRA produced higher MOE values.
5. SFU was the most effective material in improving the durability of UHPC. It significantly reduced the charge passed in the RCP test, and lowered the drying shrinkage. Although the use of SMF by itself increased the RCP value of UHPC, in presence of SRA the UHPC mixture containing SMF showed significantly lower RCP value. SMF reduced the drying shrinkage of UHPC likely by restraining the shrinkage of the paste. SRA was helpful in reducing drying shrinkage of UHPC.
6. With exception of control UHPC mixture, the other UHPC mixtures (i.e. SU2, SU2F, and SU2S) showed adequate bond strength with precast concrete.
7. The rebar pull-out test indicated that a rebar embedment length of eight times the rebar diameter or greater was sufficient for UHPC mixtures without SMF (i.e. SU2). However, in the presence of SMF (i.e. SU2F), a rebar embedment length of only six times the rebar diameter was sufficient to develop bond strength.
8. From the cost analysis of UHPC mixtures studied in this investigation, it can be concluded that the predominant cost component of UHPC mixture is steel microfiber.

RECOMMENDATIONS

Although this study was successful in developing UHPC that meet the desired properties using specific dosage levels of SFU, SMF SRA and HRWRA, additional studies should be conducted to optimize their dosage levels in order to achieve a more economical UHPC mixture. Also, the use of supplementary cementitious materials other than silica fume should be explored to improve durability properties such as drying shrinkage and resistance to alkali-silica reaction. In addition, the influence of SRA in reducing the chloride ion permeability in the presence of SMF should be explored further.

ABBREVIATION OF UHPC IDs USED

C	UHPC Control without any of the SFU, SFL, SMF, or SRA.
SU1	UHPC with SFU in addition to cement at the level of 10% by weight of cement, but without any of the SFL, SMF, or SRA.
SU2	UHPC with SFU in addition to cement at the level of 20% by weight of cement, but without any of the SFL, SMF, or SRA.
SL	UHPC with SFU in addition to cement at the level of 10% by weight of cement, and 10% of fine aggregate replaced by SFL, but without either of the SMF, or SRA.
SU2F	UHPC with SFU in addition to cement at the level of 20% by weight of cement, and

SMF at the level of 2% by volume of total mixture, but without either of the SFL, or SRA.

SU2S UHPC with SFU in addition to cement at the level of 20% by weight of cement, SMF at the level of 2% by volume of total mixture, and SRA at the level of 2% by weight of cement, but without SFL.

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