APPLICATION OF UHPC IN MITIGATION OF ASR DISTRESS IN EXISTING CONCRETE STRUCTURES

Li, Z.,
Rashidian-Dezfouli, H.
Rangaraju, P.R.*
Glenn Department of Civil Engineering, Clemson University, Clemson, SC, 29634

ABSTRACT

While many strategies exist to mitigate Alkali-silica reaction (ASR) distress in new constructions, few effective choices are available to mitigate ASR distress in existing structures. In this paper, the plausibility of using an Ultra-High Performance Concrete (UHPC) as an external restraining treatment to mitigate ASR distress in existing concrete elements was explored. Ultra-High Performance Concrete (UHPC), which exhibits superior compressive and tensile strength and strain capacity, was used as an external restraint on ASR-affected concrete test specimens. The test specimens consisted of prisms prepared using a normal-strength concrete containing alkali-silica reactive aggregates and high-alkali cement, to purposely induce ASR distress. When the concrete prisms reached a predetermined level of expansion (0.04%), a layer of UHPC was cast on the longitudinal faces of the ASR-affected concrete specimen on either 2 sides or 4-sides of the prism. Also, two different thicknesses of the UHPC layer were considered in this study. Results from this study showed that the thickness of the UHPC layer and the extent of coverage (i.e. on 2-sides or 4-sides) had a significant influence on the observed restraint in expansion. Overall, it was shown that UHPC cover with sufficient thickness could be potentially used as an external treatment technique to repair ASR deteriorated concrete structures.

Keywords: *UHPC; Alkali-Silica Reaction; ASR Mitigation*

INTRODUCTION

Alkali-silica reaction (ASR) is a chemical reaction that occurs between alkali hydroxides in the concrete pore solution, derived primarily from the portland cement and reactive silica (SiO_2) present in certain siliceous aggregates. The reaction produces a hygroscopic alkali-silica gel (ASR gel) which has a tendency to swell by absorbing moisture and exert pressure on the surrounding concrete. Under unrestrained conditions, the tensile stresses induced by the swelling of the ASR gel can exceed the tensile strength of concrete causing progressive cracking and associated deterioration. Several strategies have been developed to mitigate ASR distress in existing concrete structures. These strategies are external treatments which can either mitigate the symptoms of ASR or mitigate the causes of ASR of existing concrete structures[8]. Techniques to mitigate the symptoms include crack-filling to prevent water ingress, slot-cutting to relief stress and external restraint to prevent further expansion [1, 8]. Techniques to mitigate factors that promote ASR include reducing the internal relative humidity of the concrete below 80% to stop swelling of ASR gel and/or introduce lithium based compounds into concrete by methods such as vacuum impregnation or surface ponding to suppress further expansion due to ASR [1, 5, 8].

Ultra-high performance concrete (UHPC) is a new type of concrete. It is defined as a cementitious based composite with 28-day compressive strength in excess of 150 MPa (21.7 ksi), pre-and post-cracking tensile strengths above 5 MPa (0.72 ksi), and enhanced durability [7, 10]. The modulus of elasticity of UHPC is typically observed to be around 50 GPa (7233 ksi) [2-4, 6]. To achieve superior properties, UHPC is produced with low water-to-cementitious materials (w/cm) ratio (< 0.20), high cementitious materials content (>1000 kg/m^3 or 1689 lb/yd^3), and reinforcing fibers [4, 6, 7, 9-11]. Considering the high modulus of elasticity, superior tensile and bond strength and minimum permeability of UHPC, it is expected that UHPC can be used to mitigate the symptoms of ASR by restraining the expansion and preventing moisture penetration from external environment. This approach can be classified as a technique to mitigate the symptoms of ASR and can be achieved by simply casting UHPC on existing ASR-affected concrete. To the authors' best knowledge, the use of UHPC to mitigate ASR has never been explored and reported in the previous literature.

This study investigated the possibility of using ultra-high performance concrete (UHPC) as an external restraint (i.e. structural confinement) to mitigate ASR induced expansion of existing concrete structures. In a previous study, UHPC capable of achieving desired properties under ambient curing conditions was developed [4]. In the present study, the same UHPC composition was employed and fresh UHPC mixture was cast on the surface of a concrete prism that had undergone prior ASR deterioration. The ASR induced expansion of concrete prism before and after the application of UHPC as an external restraint was monitored. The parameters of UHPC treatment included the thickness and the extent of

UHPC cover over the concrete prism. Two levels of UHPC thicknesses – 6.4 mm (0.25 in.) and 12.7 mm (0.50 in.) were used in this study. Two patterns of UHPC coverage over the concrete prisms were studied – UHPC applied on all 4 sides of the prism, and UHPC applied on only two opposite sides of the prism.

EXPERIMENTAL PROGRAM

MATERIALS AND PROPORTIONS

ASR Deteriorated Concrete Prism

Several conventional concrete prismatic specimens with dimensions of 50 mm x 50 mm x 285 mm (2 in. x 2 in. x 11.25 in.) were prepared and subjected to an aggressive environment as per AASHTO TP-110 procedure. These specimens were to simulate the existing ASR deteriorated concrete. The cement used for this concrete was a Type I cement with specific gravity of 3.15, and its alkali content was boosted up to 1.25% Na_2O_{eq} by mass of cement by adding reagent grade NaOH into the mixing water as per AASHTO TP-110. The coarse aggregate was a reactive rhyolitic gravel from Las Placitas gravel pit in New Mexico. The dry rodded unit weight, bulk specific gravity and absorption of the coarse aggregate were 1531 kg/m^3 (2581 lb/yd^3), 2.75 and 0.34%, respectively. The fine aggregate was an inert siliceous sand from Glasscock pit in Sumter, South Carolina. The bulk specific gravity and absorption of the fine aggregate were 2.67 and 0.30%, respectively. The mixture proportions used in fabrication of concrete prisms are presented in Table 1. These proportions were based on the guidance provided in AASHTO TP-110.

Table 1 Mixture proportions of conventional concrete (kg/m^3) for 1 m$^{3.}$

Cement	Water	Coarse aggregate		Fine aggregate	NaOH
		12.5-9.5 mm	9.5-4.75mm		
420	194.7	572.2	423.0	776.4	2.01

Note: 1 kg/m^3 = 1.69 lb/yd^3

The concrete prisms were subjected to an accelerated test conditions as per AASHTO TP-110 to induce ASR distress in the specimens. Once the ASR distress was trigged in the concrete specimens and the average expansion of three specimens reached 0.04%, external UHPC treatment was applied by casting a layer of UHPC of desired thickness and coverage.

Ultra-high Performance Concrete

The UHPC material used was a steel microfiber (SMF) reinforced cementitious mortar. The cementitious materials consisted of a Type Ⅲ portland cement conforming to ASTM C150 specification and a low carbon content silica fume (SFU) with a loss-on-ignition (LOI) of 1.34%. Table 2 lists the physical and chemical properties of cement and SFU.

Table 2 Physical and chemical properties of cementitious materials

Oxide/Property	Type Ⅲ Cement	SFU
Specific gravity	3.15	2.2
Specific surface area (m^2/kg)	540 [a]	20000 [b]
SiO_2 (%)	20.4	92.0
Fe_2O_3 (%)	3.5	-
Al_2O_3 (%)	6.0	-
TiO_2 (%)	-	-
CaO (%)	64.4	-
MgO (%)	1.0	-
Na_2O (%)	-	-
K_2O (%)	-	-
SO_3 (%)	3.5	-

Note: [a] Blaine surface area; [b] BET-Gas adsorption surface area; [c] Average 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 were 7.8 and 2000 MPa (290,000 psi), respectively. The fine aggregate used in the UHPC was a natural siliceous sand meeting ASTM C33 gradation specification. Its gradation is presented in Table 3. 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 the workability.

Table 3 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

The UHPC was formulated to achieve superior workability and compressive strength. The relative proportions of the component materials of UHPC were as follows:

w/cm: 0.20 by mass
HRWRA dosage: 1% by mass of cementitious materials
Sand-cementitious materials ratio: 1.25 by mass
SMF dosage: 2% by volume of total mixture.

The detailed mixing proportion of 1 m^3 UHPC is shown in Table 4

Table 4 Mixing proportions of UHPC (kg/m^3)

Cement	SFU	Water	Fine aggregate	SMF	HRWRA
803	160	193	1204	156	9.6

Note: 1 kg/m^3 = 1.69 lb/yd^3

SPECIMEN PREPARATION AND TEST METHODS

ASR Deteriorated Concrete

The ASR deteriorated concrete was prepared following the same procedure in AASHTO TP-110 (MCTP test method). The fresh concrete was prepared by a 0.04 m^3 (1.5 ft^3) rotating drum concrete mixer. The alkali content of the concrete was boosted by dissolving sodium hydroxide pellets in the mix water before adding it into the mixer. At first, the fine and coarse aggregates were dry mixed for about 2 min. Then one third of the mixing water was added and the mixing continued for about 1 min. Finally, cement and the rest of the mixing water was added sequentially, and mixing continued for about 3 min. The entire mixing process lasted for about 6 min.

In order to monitor the length change of conventional concrete, MCPT specimens with dimensions of 50 mm x 50 mm x 285 mm (2 in. x 2 in. x 11.25 in.) were cast with a gage stud at each end. Rodding followed by mild external vibration was used to consolidate the concrete in the specimen molds. The concrete specimens thus prepared were demolded 24 hours after casting. Instead of following the curing condition described in AASHTO TP-110, the specimens were exposed to an environment with 100% relative humidity (RH) and 60 ^{o}C. Such environment was achieved by putting a layer of water at the bottom of a sealed box which was stored in a room maintained at 60°C. The specimens were seated on supports inside the box. For the entire period of exposure, the specimens were kept above the water level in the box, instead of being submerged under the water. The change in the length of the test specimens was monitored at selected periods of exposure. The expansion of the concrete was evaluated based on the average expansion of three concrete prisms. When the average expansion of a set of three concrete prisms reached 0.04%, the specimens were taken out of the 60 ^{o}C room and prepared for application of UHPC treatment.

Ultra-high Performance Concrete (UHPC)

Fresh UHPC was prepared by a UNIVEX M20 planetary mixer. Initially, cementitious materials, fine aggregate and the HRWRA powder were dry mixed for 2 mins at low-speed (100 RPM). The mixing water was added subsequently and the mixing was continued at low-speed for 5 mins until the mixture became flowable. At this time, the SMF was gradually added into the flowable UHPC mortar mixture and the mixing continued at low speed for additional 2 mins until the SMF was mixed thoroughly into the UHPC mixture. Finally, the UHPC mixture was mixed for another 2 mins at medium speed (300 RPM). The entire mixing process lasted for about 11 min.

Workability of UHPC

The workability of UHPC was measured immediately after the fresh UHPC was thoroughly mixed. The procedures described in ASTM C1437 were followed.

Mechanical properties of UHPC

The mechanical properties of UHPC monitored in this study include compressive strength, splitting tensile strength and flexural strength. The compressive strength of UHPC was determined using cube specimens with dimensions of 50 mm x 50 mm x 50 mm (2 in. x 2 in. x 2 in.) as per ASTM C109 procedure. The splitting tensile strength was measured by testing cylindrical specimens with diameter of 75 mm (3 in.) and length of 150 mm (6 in.), as per the ASTM C496 procedure. The flexural strength was investigated by testing prismatic specimens with dimensions of 40 mm x 40 mm x 160 mm (1.57 in. x 1.57 in. x 6.3 in.), as per the procedure described in ASTM C348 standard. The modulus of elasticity (MOE) of UHPC was measured by testing cylinders with diameter of 100 mm (4 in.) and height of 200 mm (8 in.) using the procedure described in ASTM C469 standard.

As the UHPC had a high flow, the test specimens were prepared by pouring the UHPC in to the molds and gently vibrating the molds to remove any unintended entrapped air bubbles. Immediately after casting, the specimens were kept in a moist room conforming to ASTM C511 specification. At the age of 24 hours, hardened UHPC specimens were demolded and stored in two curing conditions separately until test. These two curing conditions were:

(a) Normal Curing Conditions - 23^{o}C and 100% RH (ASTM C511)

(b) Accelerated Curing Conditions - 60^{o}C and 100% RH (AASHTO TP-110)

For each of the mechanical properties of UHPC evaluated, three specimens were tested.

Length change of UHPC

To investigate the length change of UHPC stored in environment with 60^{o}C and 100% relative humidity (i.e. accelerated conditions), three UHPC specimens with dimensions of 25 mm x 25 mm x 285 mm (1 in. x 1 in. x 11.25 in.) were cast with external vibration to remove any unintended entrapped air. Immediately after casting, the specimens were kept in a moist room conforming to ASTM C511 for a period of 24 hours. At 24 hours specimens were demolded and stored in a room with temperature of 60^{o}C and RH of 100%. After 24 hours being stored in 60^{o}C/100% RH conditions the zero-day length change readings of UHPC were taken. Subsequently, the length change behavior of UHPC specimens, subjected to 60^{o}C/100% RH exposure conditions, was monitored by taking readings at periodic intervals of 5, 19, 26, 47 and 54 days. All the length change readings were taken using a comparator and following the procedures described in ASTM C596.

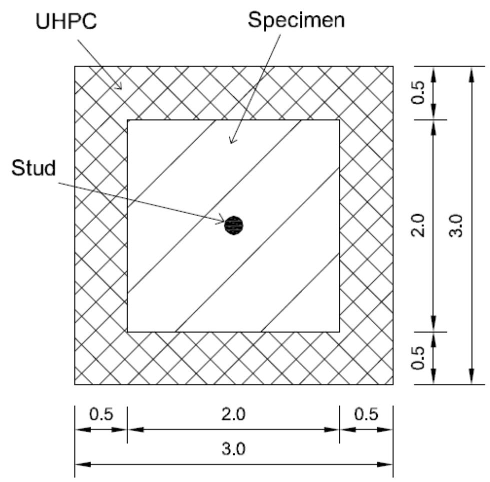
UHPC Treatment on ASR Deteriorated Concrete

When the average expansion value of conventional concrete prisms reached 0.04%, the concrete specimens were taken out of the 60^{o}C room. The surfaces of the specimens on which the UHPC was to cast were roughened using a rotating metal wire brush to create adequate surface texture to improve the bond. After completing the surface roughening treatment on the conventional concrete prisms and allowing the specimens to cool to ambient temperature, they were placed in the mold for application of UHPC layer on the surface of the concrete prisms.

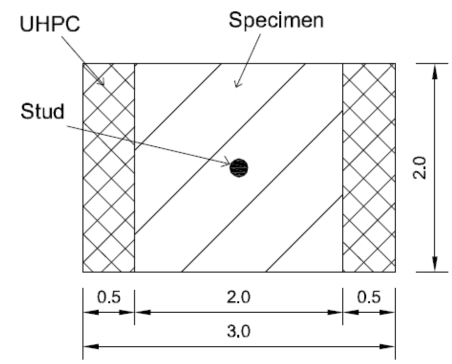
After the UHPC was thoroughly mixed, fresh UHPC was cast on ASR deteriorated concrete specimens. The two UHPC-related variables investigated in this study included the thickness of the UHPC cover (6.4 mm (0.25 in.) and 12.7 mm (0.5 in.)), and the location of UHPC cover on the concrete prisms (covering all 4-sides along the length of the prism, and covering only on two parallel sides of the prism). Thus, the effect of UHPC cover on the ASR induced expansion was studied under four configurations which were:

(a) UHPC covering 4 sides with a UHPC thickness of 12.7 mm (0.5 in.)
(b) UHPC covering 2 sides with a UHPC thickness of 12.7 mm (0.5 in.)
(c) UHPC covering 4 sides with a UHPC thickness of 6.4 mm (0.25 in.)
(d) UHPC covering 2 sides with a UHPC thickness of 6.4 mm (0.25 in.).

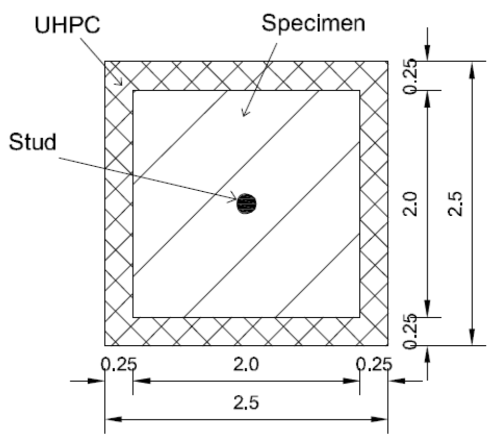
The four configurations are shown in Fig. 1.



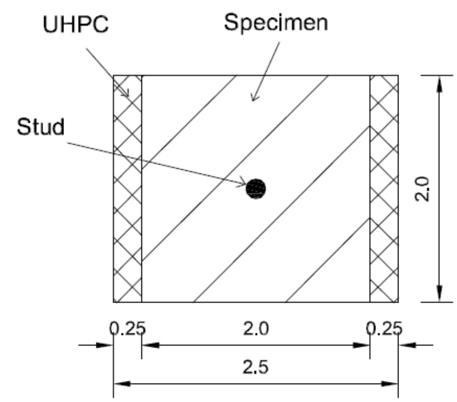
(a) 0.5 in. UHPC covering 4 sides



(b) 0.5 in. UHPC covering 2 sides



(c) 0.25 in. UHPC covering 4 sides



(d) 0.25 in. UHPC covering 2 sides

Fig. 1 Configurations of UHPC treatment (Unit: inch; 1 in. = 25.4 mm)

Two methods of applying UHPC cover over the concrete prisms were used. For the first method, concrete specimens were placed horizontally into a mold with internal dimensions of 50 mm x 50 mm x 285 mm (3 in. x 3 in. x 11.25 in.). This set was used for casting 12.7 mm (0.5 in.) thick cover on all four sides of the concrete prism (see Fig. 2a).

For the second method, concrete specimens were placed vertically into wooden molds with corresponding internal dimensions which can form 12.7 mm (0.5 in.) thick cover on two sides, 6.4 mm (0.25 in.) thick cover on all four sides and 6.4 mm (0.25 in.) thick cover on two sides of the concrete prism (see Fig. 2b).

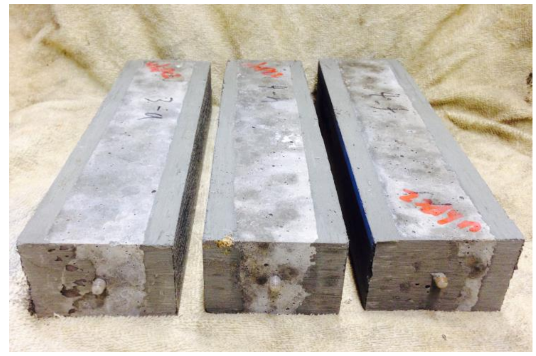
(a) Treatment cast method 1

(b) Treatment cast method 2

Fig. 2 Cast methods of UHPC treatment

Immediately after casting UHPC, the specimens were stored in the moisture room (23 ^{o}C). The UHPC covered specimens were demolded after 24 hours. The UHPC covered specimens are shown in Fig. 3. Upon demolding, while a consistent and uniform UHPC cover was observed for specimens with 12.7 mm (0.5 in.) thickness, some consolidation problems were observed for specimens having a UHPC thickness of 6.4 mm (0.25 in.), as shown in Fig.4. Based on the quality of the UHPC cover over the concrete prisms, only limited number of specimens could be used in the testing. The number of samples included in this study for each UHPC cover configuration is shown in Table 5. After demolding, all the specimens were subjected to accelerated curing conditions (i.e. 60^{o}C and 100% RH) to promote further occurrence of ASR-induced expansion in the specimens.

(a) 0.5 in cover thickness, 4 sides



(b) 0.5 in cover thickness, 2 sides

(c) 0.25 in cover thickness, 4 sides

(d) 0.25 in cover thickness, 2 sides

Fig. 3 Finished specimens of UHPC treatment (Unit: inch; 1 in. = 25.4 mm)

Fig. 4 Consolidation problems in specimens covered with 0.25 inch thick UHPC

Table 5 Number of ASR deteriorated concrete specimens with UHPC treatment

Configurations	Number of specimens
12.7 mm (0.5 in.) cover, 4 sides	3
12.7 mm (0.5 in.) cover, 2 sides	3
6.4 mm (0.25 in.) cover, 4 sides	1
6.4 mm (0.25 in.) cover, 2 sides	2

RESULTS AND DISCUSSION

ASR INDUCED EXPANSION OF ASR DETERIORATED CONCRETE

The average expansion observed in ASR deteriorated concrete subjected to accelerated curing (i.e. 60°C and 100% RH) is shown in Fig. 5.

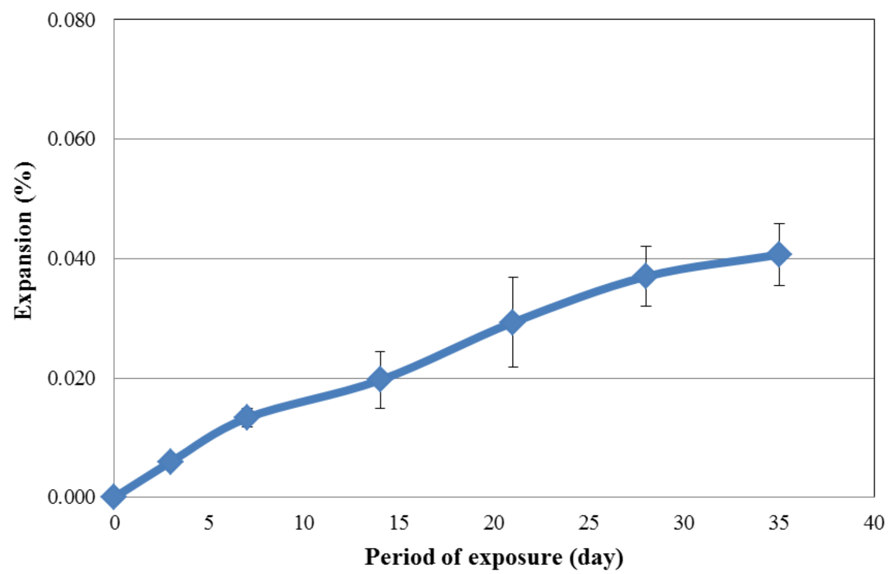


Fig. 5 ASR induced expansion of ASR deteriorated

As shown in Fig. 5 the ASR induced expansion in precast concrete prism reached 0.04% at 35 days, which is when the external UHPC treatment was applied. The reason for choosing a threshold expansion value of 0.04% in concrete prisms before UHPC is that, it is typically considered as an expansion level in concrete when cracking due to ASR is considered as deleterious[12].

MATERIAL PROPERTIES OF UHPC

The material properties of UHPC cured in the normal curing conditions (i.e. 23°C and 100% RH) and the accelerated curing conditions (i.e. 60°C and 100% RH) are shown in Table 6 and Fig. 6.

Table 6 Material properties of UHPC cured in normal curing and accelerated curing conditions

	Curing condition	
	Normal Curing	Accelerated Curing
Workability (%)	150	150
Compressive strength (MPa)	153	155
Split tensile strength (MPa)	19	25
Flexural strength (MPa)	33	28
MOE (MPa)	52500	--

Note: 1 MPa = 145 psi

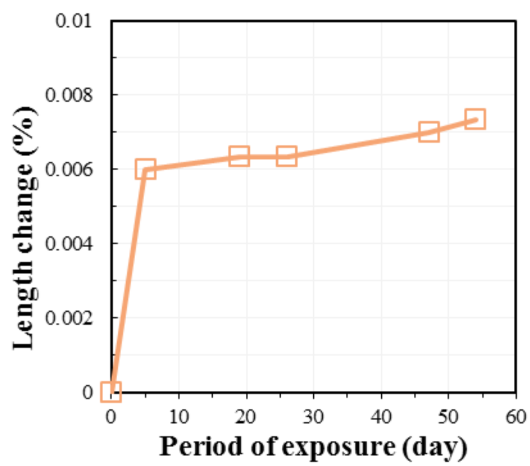


Fig. 6 Length change behavior of UHPC under accelerated curing conditions.

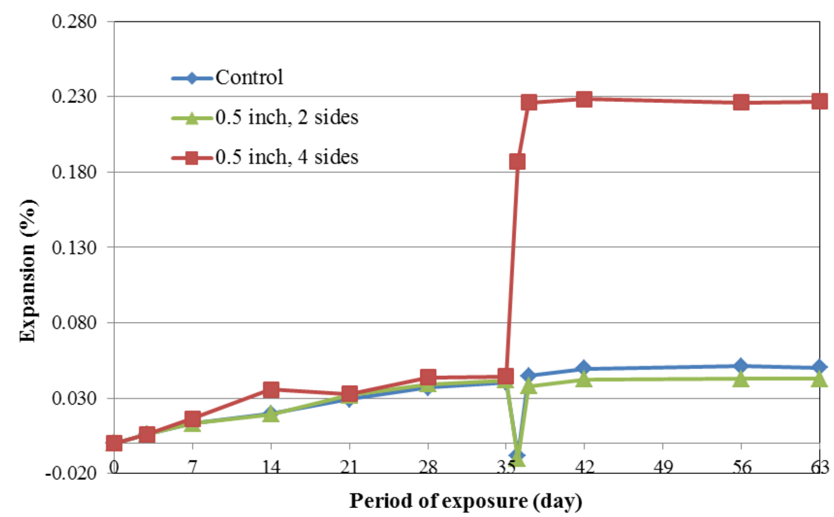
As shown in Table 6, the 28-day compressive strength of UHPC cubes cured in either the normal curing conditions (23ºC, 100% RH) or the accelerated curing conditions (60ºC and 100% RH) are all higher than 21.7 ksi (150 MPa). The elevated temperature in the accelerated curing procedure improved the 28-day compressive strength, compared to the normal curing condition. It can also be observed from Table 6 that UHPC specimens cured under both curing conditions yield high splitting tensile strength and flexural strength at 28 days. The splitting tensile strength of UHPC cured in accelerated curing is 40% higher than that of UHPC cured under normal curing conditions. However, the flexural strength of UHPC cured under accelerated conditions is 15% lower than that of UHPC cured under normal conditions. The MOE of UHPC is 52.5 GPa which is much higher than that of conventional concrete which is around 30 GPa under normal curing conditions.

As shown in Fig. 6, the length change of UHPC under accelerated curing conditions was observed to be very minimal even after 56 days of exposure. Therefore, it can be concluded that UHPC does not cause any expansion on its own when subjected to accelerated curing conditions.

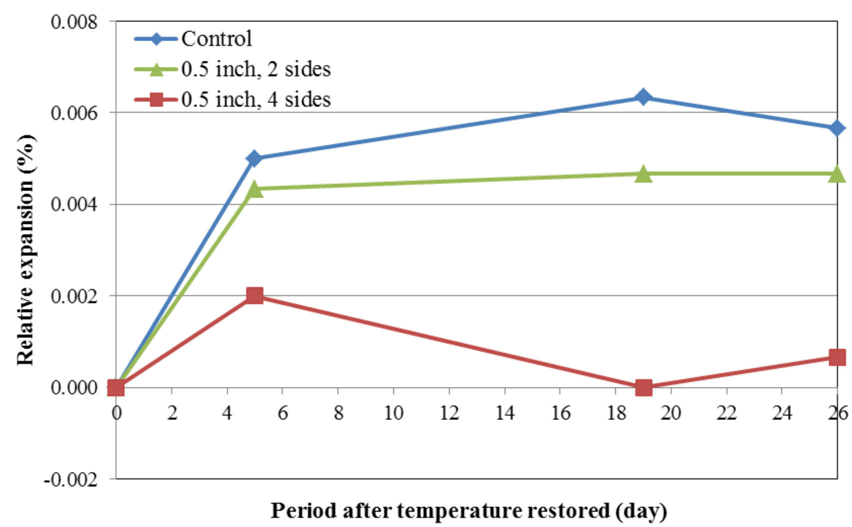
UHPC TREATED ASR DISTRESSED CONCRETE

UHPC Treatment: Thickness 12.7 mm (0.5 in.)

The length change of ASR deteriorated concrete before and after the 12.7 mm (0.5 in.) UHPC treatment is shown in Fig. 7.



(a) Length change of ASR deteriorated concrete before and after UHPC treatment



(b) Relative length change after the specimens' temperature restored at 60 °C

Fig. 7 Effect of 12.7 mm (0.5 in.) UHPC treatment on the ASR distress of concrete

As shown in Fig. 7a, at the period of exposure of 36 days which is the age of demolding, the length readings of the UHPC covered specimens show two different phenomenon. The decrease in the length is observed for the control and the specimens with 2 sides cover by UHPC. This is attributed to the reduced temperature, considering the UHPC covered specimens were cured in the moisture room with temperature of 23 ^oC instead of in the room with 60 ^oC before demolding. However, one day after stored in the 60 ^oC room (37 days of exposure), the temperature of the UHPC covered specimens went back to 60 ^oC, and the length value was about the same as the value just before the UHPC treatment (35 days of exposure).

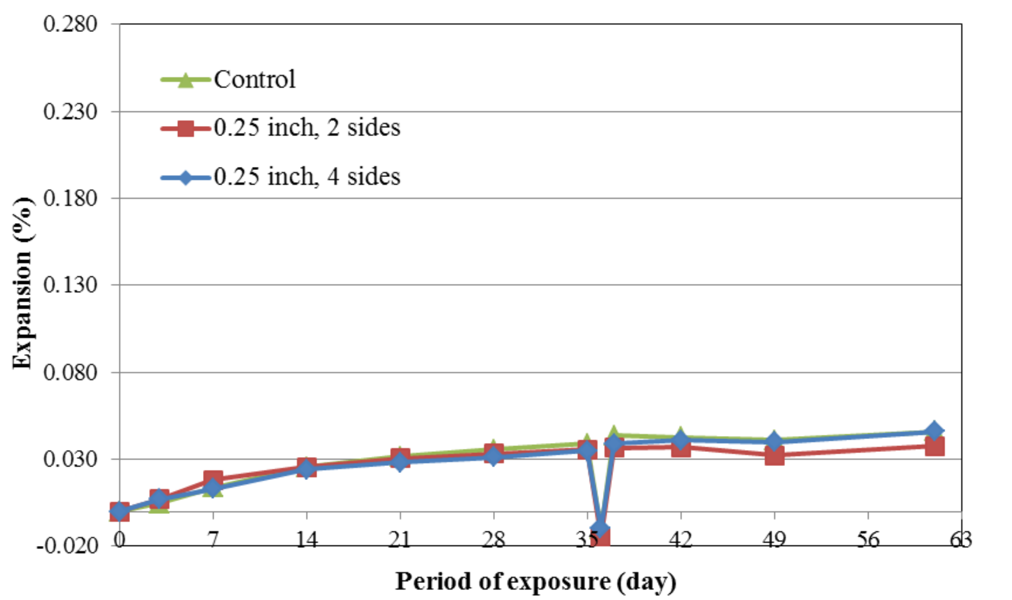
The sudden increase in the length is observed for the specimens with 4 sides cover by UHPC. This is likely attributed to the method of applying UHPC treatment on specimens with 4 sides covered. Noticing that the ASR deteriorated concrete specimens were placed horizontally in the molds before casting UHPC, which is shown in Fig. 2a, it is possible that the hydraulic pressure of the fresh UHPC mixture exhibit tensile force on the concrete specimens by pushing the end plates. Also, it is likely that the heat of hydration of UHPC on all four sides is significantly more than that of UHPC on two sides.

It is noted that, Fig. 7a cannot give clear understanding of the effect of UHPC treatment on the ASR induced expansion. Thus, the relative expansion after UHPC treatment is given in Fig. 7b to have a close look at the length change of UHPC covered specimens. The relative expansion is calculated by subtracting the length value at the period of exposure of 37 days from the length values of period of exposure after 37 days. Remembering that at the period of exposure of 37 days, the UHPC treated concrete specimens have been kept in the 60 ^oC room for 24 hours, the length at the period of exposure of 37 days is the zero point of ASR induced expansion after specimens' temperature restored at 60 ^oC, and the relative length change after the period of exposure of 37 days is purely due to the ASR distress.

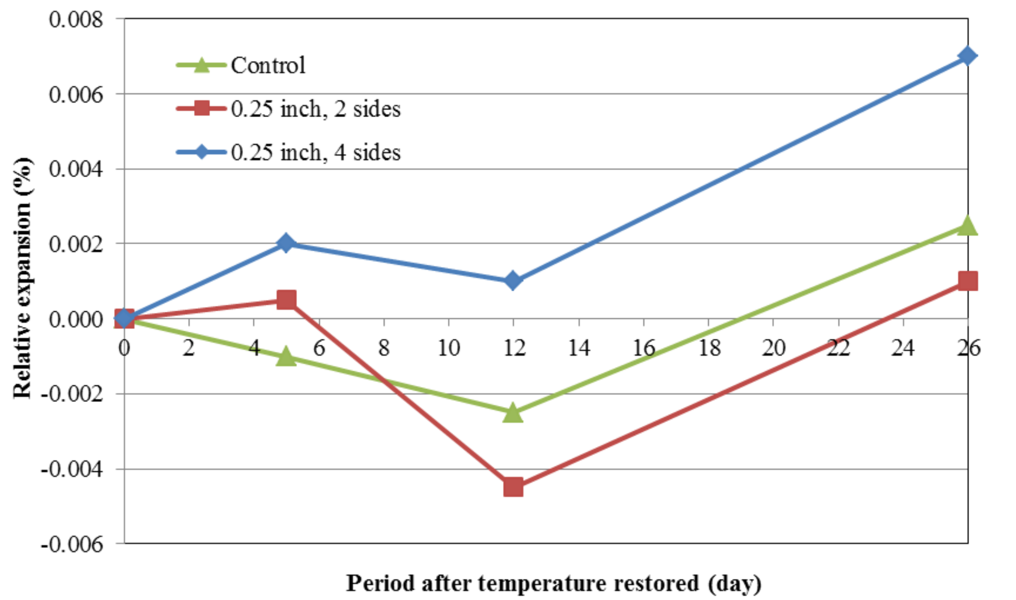
As Fig. 7b shows, at the period of exposure from 0 to 37 days after temperature restored the control specimens present the highest expansion, followed by specimens with 2 sides covered by UHPC. The specimens with 4 sides covered by UHPC present the lowest expansion. The observed phenomenon likely support the expectation of this study that UHPC treatment can restrain the ASR induced expansion. The possible explanations may include the high modulus of elasticity and high tensile strength of UHPC which restrain the expansion of substrate concrete, and the low permeability of UHPC which limit the moisture from penetrating into the substrate concrete.

UHPC Treatment: Thickness 6.4 mm (0.25 in.)

The length change of ASR deteriorated concrete before and after 6.4 mm (0.25 in.) UHPC treatment is shown in Fig. 8a. Similarly, the relative length change after specimens' temperature restored at 60 ^{o}C is calculated and shown in Fig. 8b.



(a) Length change of ASR deteriorated concrete before and after UHPC treatment



(b) Relative length change after the specimens' temperature restored at 60 ^{o}C

Fig. 8 Effect of 6.4 mm (0.25 in.) UHPC treatment on the ASR distress of concrete

As shown in Fig. 8a, at the period of exposure of 36 days which is the age of demolding, the decrease in the length is observed for all the specimens. This is attributed to the decreased temperature, considering the UHPC covered specimens were cured in the moisture room with temperature of 23 ^{o}C instead of in the room with 60 ^{o}C before demolding.

As Fig. 8b shows, at the period after applying UHPC treatment of 24 days, the specimens with 4 sides covered by UHPC present the lowest expansion, followed by the control specimens. The specimens with 2 sides covered by UHPC present the lowest expansion. It looks like that 6.4 mm (0.25 in.) UHPC cover did not show significant effect on restraining the ASR induced expansion. However, reminding that there was only one specimen available for evaluating the expansion of specimen with 4 sides covered by UHPC, it is likely that the observed phenomenon from one specimen is not reliable.

The effect of 6.4 mm (0.25 in.) UHPC treatment on the ASR induced expansion needs further study. The poor consolidation under such small dimension is the problem need to be solved.

CONCLUSION

This study investigated the ASR induced expansion of existing ASR distressed concrete before and after the external UHPC cover applied. The UHPC materials used exhibit 28-day compressive strength above 150 MPa (21.7 ksi) both at ambient temperature curing and at 60 ^{o}C curing. Based on the materials and proportions used, the following conclusion are drawn:

- 12.7 mm (0.5 in.) UHPC cover is effective in mitigating ASR induced expansion. Concrete specimens with all four sides covered by UHPC exhibit lower expansion than control specimen and specimens with two sides covered. Externally covering the existing ASR distressed concrete with UHPC is a potential technique for the repair of concrete structures.
- 6.4 mm (0.25 in.) UHPC cover did not show clear behavior in mitigating ASR induced expansion in this study. More research work is needed on the effect of 6.4 mm (0.25 in.) thick UHPC cover. The effect of UHPC cover thickness is another topic which needs further study.

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