Effect of Different Curing Regimes on Strength and Transport Properties of UHPC Containing Recycled Steel Tire Wires as Micro Steel Fibers

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Abstract:

This paper presents the results of an ongoing research on the effect of different curing regimes on properties of Ultra high performance concrete (UHPC) containing recycled steel tire wires as micro steel fibers. Outstanding properties of UHPC as next generation of concrete make it a promising material for different structural applications. The effects of different curing conditions on the mechanical properties of UHPC have been investigated by many researchers. However, limited research works are available that investigates the effects of different curing regimes on transport properties of UHPC.

At this paper, different regimes of water curing (WC), air curing (AC), accelerated water curing (AWC) and autoclave curing (AUC) are applied on UHPC specimens containing 2 percents of recycled steel fibers (by total volume). The compressive strength and flexural strength are measured as mechanical properties. Water absorption, sorptivity (rate of water absorption) and pulse velocity tests were investigated on UHPC specimens in various curing regimes as transport properties and durability indexes. Results show that recycled fibers can be successfully used in UHPC mixes to produce an affordable and eco-friendly material. It has been found that both of strength and transport properties of UHPC can be significantly affected by applying the accelerated curing methods. Lack of attention on choosing an appropriate curing condition can lead to a significant increase in water absorption and sorptivity of UHPC.

Keywords: Curing regimes, Recycled steel fibers, UHPC, Strength properties, Transport properties

1. Introduction and Background

Ultra-high performance concrete (UHPC) is a new class of concrete that has been developed in recent decades. When compared with high performance concrete (HPC), UHPC tends to exhibit superior properties such as advanced strength, durability, and long-term stability (Graybeal 2006). UHPC represents a leap development in concrete technology. It’s very high strength and enhanced durability motivates its use in an increasing number of applications. UHPC can be achieved through enhancing homogeneity (for instance by eliminating coarse aggregates) (Holschemacher and Weie 2005), producing stronger and higher packing density microstructure through using very low water-to-cement ratio (w/c) (Schmidt and Fehling 2005), and incorporating high content of effective pozzolans.

Due to the better controlled conditions pre-cast plants are suited very well for the production of UHPC (Schmidt et al. 2003), (Rebentrost and Wight 2008). Although the heat-curing procedure of UHPC is mainly used in order to reduce curing time and increase early strength, this is not only energy-consuming and costly but also restricts the fabrication of UHPFRC products to a pre-casting factory (Yang et al. 2009). However, different curing conditions are applied and investigated by many researchers to improve the mechanical properties of UHPC in short time. Standard room temperature curing, heat curing under atmospheric pressure, and autoclave curing regimes are often used for production of UHPC. High temperature curing is beneficial to the pozzolanic reactions between CH from the hydration of cement and supplementary cementitious materials such as silica fume, which improves the microstructure, and hence results in higher strength. It also increases the chain length of C–S–H (Shi et al. 2015). Thermal curing has a strong effect on mechanical properties of concrete. Major effect is the development of a denser microstructure with the formation of calcium silicate hydrate (C–S–H) phases, which results in higher mechanical properties (Yazıcı et al. 2013). The effects of different curing conditions on the mechanical properties of UHPC have been investigated by many researchers. However, limited research works are available that investigates the effects of different curing regimes on transport properties of UHPC. UHPC is much more expensive than normal concrete. The only limiting factor in the application of UHPC is the cost (Vande Voort et al. 2008). Much of the cost of UHPC comes from its steel fiber reinforcement, so the cost of material is largely contingent on the cost of this component (Bonneau et al. 1996).

At this paper, beside investigating the mechanical and transport properties of UHPC under different curing regimes, feasibility of using recycled tire wires as steel micro fibers in UHPC mixes is studied. UHPC specimens containing 2% (by total volume) of recycled steel fibers, are tested and investigated for compressive and flexural strengths, water absorption, sorptivity and pulse velocity under different curing regimes of water-curing (WC), air-curing (AC), accelerated Water Curing (AWC) and autoclaving (AUC).

2. Testing Methods

The UHPC considered here is prepared by the following ingredients: White cement; Natural River sand, silica fume (SF), a polycarboxylate-based superplasticizer (SP) and recycled steel tire wires in replacement of steel micro-fibers. The cement used in this study was white cement produced by Iran's Urumieh Cement Company. This cement has the specific gravity of 3.15 and blain fineness of 3820 cm^2/g (268650in^2/lb). Pumice powder was obtained from Eskandan regions located in North-east of Iran and has the specific gravity of 2.12. Silica fume with more than 95% sio_2 and specific gravity of 2.2 was used in all mixes. Chemical composition and physical properties of cement and pumice powder is presented in Table 1.Natural river sand with fineness modulus of 2.45, maximum size of 2.36 mm (No. 8), specific gravity of 2.69 and water absorption of 2% was used as aggregate in UHPC mixes. The grading curve of natural river sand is demonstrated at Figure 1. Random recycled steel micro fibers with about 4-20 mm (0.16-0.79 in.) long and 0.1-0.4 mm (0.004-0.016 in.) diameter were used in 2% by total volume of UHPC mixes. The superplasticizer used in this study was polycarboxylate-based and the total water/binder ratio was adjusted by taking into account the water content of the SP liquid.

The mix design of the UHPC is summarized in Table 2. The UHPC specimens containing 2% (by total volume) of recycled steel fibers were investigated under different curing regimes for strength and transport properties. These curing regimes and the specimens' designation are presented at Table 3. The cementitious materials and sand were first mixed at the low speed for 2 min. The water and superplasticizer were then gradually added and the fresh material was mixed at the high speed for 3 min. When preparing the UHPC, recycled fiber was added subsequently and another 2 min mixing was applied. The fresh UHPC was then transferred into steel moulds and compacted using a vibrating table. The specimens were then placed in curing cabin with about 23°C (73°F) temperature and relative humidity of more than 90 percents. After one day, they were demoulded and cured in different regimes. The freshly prepared mixtures were used to produce 4*4*16 cm (1.6*1.6*6.3 in.) prisms for flexural strength, water absorption and pulse velocity tests. The portions of prisms broken in flexure were used to obtain the equivalent compressive strength and sorptivity. The water absorption test was conducted to assess the water permeability characteristics of hardened UHPC specimens under different curing regimes. Only the water-cured specimens (WC-7 and WC-28) were heated at 110°C (230°F) until the constant mass was achieved and then were tested for water absorption and sorptivity. Performing the sorptivity test, the initial weight of the specimen was first measured and the specimen was then immersed in 3–5 mm (0.12-0.2 in.) deep water. The specimen was removed and weighed frequently according to the time duration. The flexural test was conducted by a displacement controlled testing machine with rate of 0.2 mm/min (0.008 in/min). The portions of prisms broken in flexure were used to obtain the equivalent compressive strength in conformity with (ASTM C 349, 2002). The pulse velocity test was performed according to (ASTM C 597, 2002).

Table 1. Chemical composition and physical properties of cement and pumice powder

Powder type	l.o.I %	SiO2 %	Al2O3 %	Fe2O3 %	CaO %	MgO %	SO3 %	K2O %	Na2O %	Blaine cm^2/g (in^2/lb)	Compressive strength kg/cm^2 (psi)		
											3	7	28
White cement	0.9	23.7	4.3	0.35	66.38	0.31	3	0.48	0.39	3820 (268650)	405 (5874)	530 (7687)	680 (9863)
Pumice powder	1.98	64.6	17.3	3.86	4.6	1.34	0.35	---	4.8	---	---	---	---

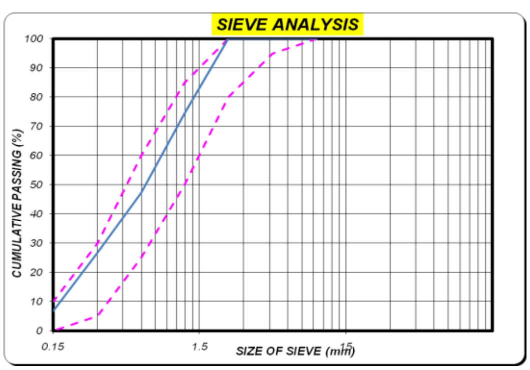

Figure 1. Grading curve of natural river sand

Table 3. Different curing regimes and the specimens' designation

Designation	Curing regimes
WC-7	Water-cured for 7 days
AC-7	Air-cured for 7 days
WC-28	Water-cured for 28 days
AC-28	Air-cured for 28 days
HC	Heat-cured at 90°C (194°F) for 48 hours
AWC	Accelerated water-cured at 90°C (194°F) for 48 hours
AUC	Autoclaved at 2 MPa (290 psi) pressure, 210°C (410°F) for 5 hours

Table 2. Mix design of the UHPC

Cementitious ingredients Kg/m^3(lb/yd^3)			Natural river sand Kg/m^3(lb/yd^3)	Water/binder ratio	Recycled steel fiber(% by total volume)	Superplasticizer (% solid by weight of binder)
cement	Pumice	SF				
757(1276)	300(506)	265(447)	789(1330)	0.2	2	0.73

3. Results and Discussion

3.1. Compressive strength:

Compressive strength for UHPC mixes in different curing regimes is illustrated in Table 4 and Figure 2. The strength values are the average of six test specimens and the standard deviation of strengths is shown in table 4. Compressive strength in the range of 1218-2027 kg/cm^2 (17666-29399 psi) was obtained applying different curing conditions. It is obviously seen that different accelerated curing regimes has considerable effects on compressive strength of UHPC. The all of accelerated curing regimes including AWC, HC and AUC led to an increase in compressive strength of UHPC in comparison with UHPC specimens under 28 days of standard water curing. However, autoclaved specimens have the maximum compressive strength within all UHPC mixes cured in different conditions. At this research, autoclaving the specimens has resulted in increase of about 66% and 35% in compressive strength compared with those of WC-7 and WC-28 specimens, respectively. It seems that under autoclaving condition, other hydration phases and micro structures are formed, which may improve the overall material performance. While other accelerated conditions increase reactivity of ingredients, autoclaving leads to development of different phases (Yazıcı 2007). There was no considerable change in compressive strength of UHPC specimens cured at normal water (WC) in comparison with that of the ones under air-cured condition at all ages.

Table 4. Compressive and flexural strength values and the standard deviations

Designation	Compressive strength Kg/cm^2(psi)								Flexural strength Kg/cm^2(psi)							
	1	2	3	4	5	6	Average	SD[a]	1	2	3	4	5	6	Average	SD[a]
WC-7	1162 (16853)	1247 (18086)	1112 (16128)	1228 (17811)	1290 (18710)	1272 (18449)	1218 (17666)	68 (986)	236 (3423)	191 (2770)	264 (3829)	229 (3321)	277 (4017)	270 (3916)	244 (3539)	32 (464)
AC-7	1225 (17767)	1243 (18028)	1293 (18753)	1343 (19479)	1321 (19159)	1290 (18710)	1286 (18652)	45 (653)	230 (3336)	219 (3176)	256 (3713)	265 (3843)	296 (4293)	279 (4047)	257 (3727)	29 (421)
WC-28	1406 (20392)	1425 (20668)	1606 (23293)	1524 (22104)	1520 (22046)	1520 (22046)	1500 (21756)	74 (1073)	223 (3234)	208 (3017)	196 (2843)	273 (3959)	244 (3539)	292 (4235)	240 (3481)	38 (551)
AC-28	1654 (23989)	1598 (23177)	1583 (22959)	1494 (21669)	1490 (21611)	1558 (22597)	1563 (22669)	63 (914)	265 (3843)	230 (3336)	230 (3336)	265 (3843)	266 (3858)	290 (4206)	258 (3742)	24 (348)
HC	1612 (23380)	1662 (24105)	1765 (25599)	1734 (25150)	1697 (24613)	1747 (25338)	1703 (24700)	58 (841)	289 (4192)	263 (3814)	304 (4406)	232 (3365)	289 (4192)	268 (3887)	274 (3974)	26 (337)
AWC	1580 (22916)	1610 (23351)	1612 (23380)	1731 (25106)	1610 (23351)	1622 (23525)	1627 (23598)	53 (769)	312 (4525)	281 (4076)	266 (3858)	249 (3611)	259 (3756)	279 (4047)	274 (3974)	22 (319)
AUC	1959 (28413)	2061 (29892)	2204 (31966)	2086 (30255)	1950 (28282)	1900 (27557)	2027 (29399)	112 (1624)	247 (3582)	270 (3916)	265 (3843)	258 (3742)	224 (3249)	260 (3771)	254 (3684)	17 (247)

a: standard deviation

3.2. Flexural strength:

Flexural strength for UHPC mixes in different curing regimes is illustrated in Table 4 and Figure 2. The strength values are the average of six test specimens and the standard deviation of strengths is shown in table 4. At this paper, all types of accelerated curing regimes including AWC, HC and AUC have resulted in improvement of UHPCs flexural strength, relatively in comparison with 28 days standard water curing. The maximum increase in flexural strength of UHPC mixes of about 14% can be seen in specimens under AWC condition. Flexural strength of autoclaved specimens was generally very close to the 28 days water cured (WC-28) series. This shows that although autoclaving increases the compressive strength significantly, improvement in flexural behavior is not in the same extent as other results. This is probably due to the weaker bond between the fibers and matrix under these curing regimes. The rate of hydration and strength gain of UHPC in both WC and AC regimes is very high till the age of 7 days .The specimens gain their whole flexural strength only after 7 days of water and air cured regimes. Flexural strength in the range of 240-274 kg/cm^2(3481-3974 psi) was obtained in different curing conditions. It shows that flexural strength is less affected by different curing conditions compared with compressive strength. However, the mentioned flexural strength range of UHPC specimens presents a successful use of recycled steel tire wires as micro fiber replacement in UHPC mixes under different curing regimes.

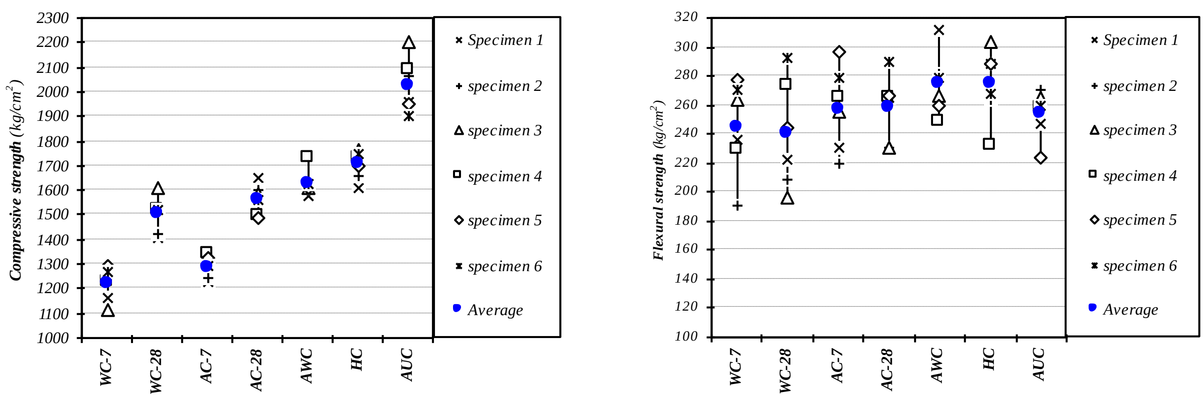

Figure 2. Compressive and flexural strength for UHPC mixes in different curing regimes

3.3. Water absorption:

Water absorption of all UHPC mixes under different curing regimes is presented in Figure 3. Water absorption in the range of 0.894-2.917 percent were obtained applying all curing conditions on UHPC specimens. This wide range in results demonstrates that different curing regimes have different effects on water absorption of UHPC. UHPC specimens cured at 90°C (194°F) in water (AWC) resulted in lower water absorption compared with those of other curing conditions while the specimens that were heat–treated (HC) at 90°C (194°F) led to the highest water absorption. The same trend can be observed in WC and AC regimes. Water absorption of autoclaved specimens (AUC) was generally very close to those of the 28 day air-cured (AC-28) series. It seems that presence of humidity and moisture in both of normal and accelerated curing conditions has significant effect on water absorption of UHPC. It is clearly found that lack of attention on choosing an appropriate curing condition can lead to a significant increase in water absorption of UHPC.

3.4. Sorptivity:

The results of initial water sorption of UHPC mixes under different curing regimes are presented in Figure 4.Sorptivity is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of material (Hall 1989). Sorptivity of the concrete is obtained by linear regression from the slope of the sorption graph versus the square root of time that is presented in Figure 3. Sorptivity in the range of 0.0008-0.0039 mm/s0.5 ($3.1*10^{-5}$-$15.3*10^{-5}$ in/s0.5) was obtained applying different curing conditions on UHPC specimens. This wide range in results demonstrates that different curing regimes have different effects on sorptivity of UHPC. Similar to the above mentioned manner at water absorption part, UHPC specimens cured at 90°C (194°F) in water (AWC) exhibited lower sorptivity compared with those of other curing conditions while the specimens that were heat–treated (HC) at 90°C (194°F) exhibit the highest sorptivity. This behavior can also be observed in WC and AC regimes, as the same story. Sorptivity of autoclaved specimens (AUC) was generally very close to the 28 days water-cured (WC-28) series. It can be seen that the presence of humidity and moisture in both of normal and accelerated curing conditions has significant effect on sorptivity of UHPC. Both of water absorption and sorptivity, as the main indicators of transport properties, are significantly affected by different curing conditions. Accelerated curing regimes in presence of humidity, sound to be more beneficial in improvement of transport properties.

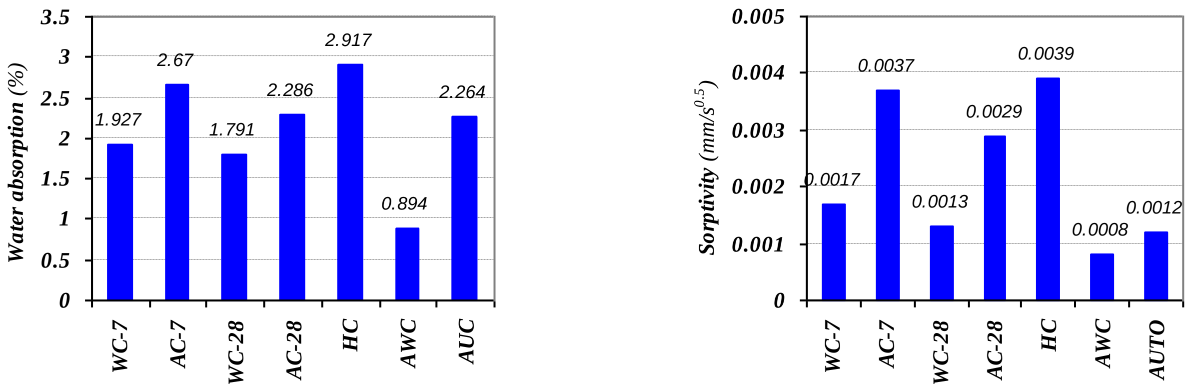

Figure 3. Water absorption and sorptivity of UHPC mixes

3.5. Pulse velocity:

The ultrasound pulse velocity tests (UPV) were carried out by a non-destructive ultrasonic testing utility (PUNDIT). This test is based on the theory of ultrasound transfer inside the material and is generally used to provide information about the porosity of material in concrete application (Vasconcelos et al. 2008). Ultrasonic method is a common technique employed for analyzing the porous structure of concrete to detect the internal defects (voids, cracks, delaminations, etc) (Lafhaj et al. 2006). All UHPC specimens under different curing regimes were tested for ultrasonic pulse velocity and the results are shown in Figure 6. As it can be seen, pulse velocity of WC-28 is higher than that of the other specimens under different curing regimes. On the other hand, pulse velocity value of AWC is very close to that of the WC-28. It means that AWC is an admissible accelerated curing method when compared with other regimes. However, it seems that lack of adequate humidity in accelerated curing regimes leads to a decrease in pulse velocity values.

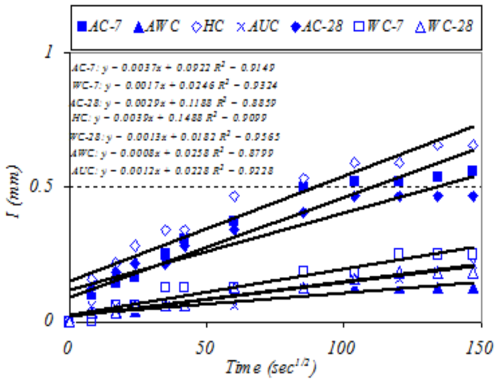

Figure 4. Initial water sorption of UHPC mixes

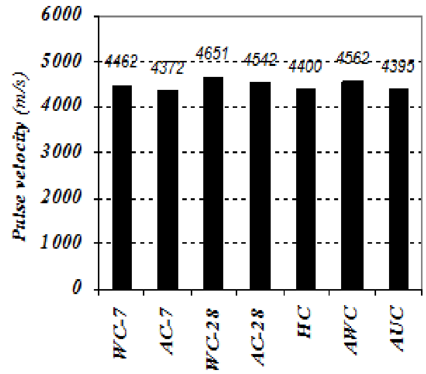

Figure 5. Pulse velocity of UHPC mixes

Conclusions:

Analyses of UHPC mixes containing recycled steel tire wires as micro fibers under different curing regimes allowed concluding that:

- Strength range of UHPC specimens presents a successful use of recycled steel tire wires as micro fiber replacement in UHPC mixes under different curing regimes.
- It is obviously seen that different accelerated curing regimes has considerable effects on improvement of compressive strength of UHPC.
- At this research, autoclaving the specimens has resulted in an increase of about 66% and 35% in compressive strength compared with WC-7 and WC-28 specimens, respectively.
- All types of accelerated curing regimes including AWC, HC and AUC have resulted also in improvement of UHPCs flexural strength, in comparison with 28 days standard water curing.
- It seems that presence of humidity and moisture in both of normal and accelerated curing conditions has significant effect on sorptivity of UHPC. Accelerated curing regimes in presence of humidity, seems to be more beneficial in improvement of transport properties.
- It is clearly found that lack of attention on choosing an appropriate curing condition can lead to a significant increase in water absorption and sorptivity of UHPC.

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