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Short-term tensile creep and shrinkage of ultra-high performance concrete

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ABSTRACT

The tensile creep and free shrinkage deformations of ultra-high performance concrete (UHPC) were examined through short-term testing to assess the influences of stress/strength ratio, steel fiber reinforcement, and thermal treatment. The use of fibers and the application of thermal treatment decreased 14-day drying shrinkage by more than 57% and by 82%, respectively. Increasing the stress-to-strength ratio from 40% to 60% increased the tensile creep coefficient by 44% and the specific creep by 11%, at 14 days of loading. Incorporating short steel fibers at 2% by volume decreased the tensile creep coefficient by 10% and the specific creep by 40%, at 14 days. Also, subjecting UHPC to a 48-h thermal treatment at 90 °C, after initial curing, decreased its tensile creep coefficient by 73% and the specific creep by 77% at 7 days, as compared to ordinarily cured companion mixes. Comparison of tensile creep behavior to published reports on compressive creep in UHPC reveal that these phenomena differ fundamentally and that further evaluation is necessary to better understand the underlying mechanisms of tensile creep in UHPC. Results from this study also showed that the effects of both thermal treatment and fiber reinforcement were more pronounced in tensile creep behavior than tensile strength results of different UHPC mixes. This emphasizes the importance of conducting tensile creep testing to predict long-term tensile performance.

1. Introduction

Compared to ordinary concrete, ultra-high performance concretes (UHPCs) – also sometimes called "reactive powder concretes" (RPCs) – generally possess a more homogeneous structure. This is derived from optimization of the dry-compacted density of its constituents, improvements in microstructure development (via materials selection and proportioning), and by enhancements afforded through special curing regimes, often at higher temperature and sometimes under pressure [1–8]. Densification with reactive micro- to nano-sized particles in UHPC is based on the concept of optimizing particle packing, in combination with selection of appropriate materials and proportions [7]. In a recent study, it was stated that most of the UHPC matrices are generally composed of fine sand, between 150 and 600 μm, cement with an average diameter of approximately 15 μm, crushed quartz with an average diameter of 10 μm, and silica fume that has a diameter small enough to fill the interstitial voids between the unhydrated cement grains and the crushed quartz particles [8]. Similar compositions were also reported by other studies [9–11]. In addition, very low water-to-cement ratios (i.e., <0.20) are typically used in UHPC mixes, allowing the particles to pack more uniformly, reducing the porosity of conventional concrete, and thereby increasing strength. As a result, significant amounts of superplasticizing chemical admixtures, typically based on polycarboxylate (PC) chemistry, are used to compensate for the low fluidity of these mixes.

Several studies have shown that further improvements to the cementitious matrix could be achieved via thermal treatment, as the reaction of silica fume and other phases may be activated, reducing the average pore size [3,6,8]. Mercury intrusion porosimetry conducted by Cheyrezy et al. [4] indicated negligible porosity in confined UHPC cured between 150 °C and 200 °C. Another study by Collepardi et al. [5] concluded that both shrinkage and swelling in UHPC were reduced upon steam curing, suggesting nano-to microstructural refinement. Similar trends were also observed where thermal curing at 90 °C was applied to UHPC mixes [3].

While UHPC shows substantially increased compressive strength and decreased porosity, UHPC matrices tend to be brittle. Short steel fibers of various dimensions and mechanical properties are commonly used in UHPC at various volume fractions to improve tensile and flexural strength, impact resistance or toughness, control cracking, and alter the mode of failure by increasing post-cracking ductility [7,12–28].

Recently, the use of UHPC for precast prestressed concrete highway bridge girders has been explored because of the potential for reduced maintenance costs relative to steel and conventional concrete girders. In addition, fiber reinforced UHPC girders may

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not require transverse shear reinforcement needed in conventional reinforced concrete because of the enhanced tensile behavior of the UHPC [29–34]. However, before specifying such girders without shear reinforcement, the tensile creep performance of the material must be characterized to ensure adequate long-term shear and tensile performance.

While such behavior in UHPC has not been previously examined, the use of short steel fibers as shear reinforcement in place of conventional stirrups in normal strength reinforced and prestressed beams has been investigated [35–40]. For example, Narayanan and Darwish [35] conducted some 36 shear tests on simply supported rectangular prestressed and non-prestressed concrete beams, containing steel fibers (0.3×30 mm) as web reinforcement with varying fiber volume fractions (0.91–4.47%,) variable shear-span to effective depth ratio (a/d), and type and extent of prestressing. Results from this study showed that increasing the fiber volume fraction from 0% to 2.0% increased the ultimate shear strength by 95%. In addition, significant shear strength was also observed after the first crack in fiber reinforced beams, unlike beams with no fibers. Imam et al. [36] studied the incorporation of steel fibers in singly reinforced high strength concrete (HSC) beams without stirrups failing under the combined effect of flexure and shear. Results from this study showed that the inclusion of steel fibers in high strength concrete beams without stirrups improved shear resistance and generally increased the ultimate flexural capacity and that steel fibers can successfully replace shear reinforcement. Furlan and Hanai [37,38] studied the influence of prestressing and fibers on the shear behavior of thin-walled I-section beams with reduced shear reinforcement ratio. Nine concrete beams were built (six with prestressing forces) with three different mixtures: without fibers, with $0.2 \times 2.3 \times 25.4$ mm steel fibers at 1% volume fraction, and with 0.05×42 mm polypropylene fibers at 0.5% volume fraction. Shear reinforcement ratios varied from 0% to 0.225% (geometric ratio). This study showed that the addition of steel fibers increased the tensile strength by 16% in some cases and also increased the shear strength, except in the beams without shear reinforcement. More importantly, upon comparing fiber reinforced concrete beams to those with no fibers, the former were characterized by: (1) smaller spacing between cracks, (2) slower development of cracks, (3) larger number of inclined cracks prior to collapse, (4) delayed appearance of inclined cracks and, consequently, delayed tensioning of the stirrups, and (5) a more ductile failure. The potential for use steel fibers as shear reinforcement instead of stirrups also was confirmed in other research [39,40].

However, none of these prior studies considered tensile creep and its potential to impact the long-term performance of flexural members where fibers have been substituted for stirrups as shear reinforcement.

In a beam, the design for shear must ensure that the shear strength equals or exceeds the flexural strength at all points in order to avoid any shear failure, which is frequently sudden and brittle. This is typically achieved through shear reinforcement. The main four functions of the shear reinforcement in flexural members are: (1) carrying a portion of external factored shear force, (2) restricting growth of diagonal cracks, (3) holding longitudinal reinforcement in place to provide the dowel capacity, and (4) providing confinement to the concrete in the compression zone if the stirrups are closed and closely spaced (less than 100 mm (4 in.)) [41,42]. In addition, the other portion of the external shear forces is resisted by the concrete itself through: (1) the dowel action of reinforcement bars, (2) shear in the compression zone, and (3) interlock between coarse aggregate particles (Fig. 1).

Now, as a result of the absence of both the shear reinforcement (as per the manufacturers recommendation), and coarse aggregates (typical for UHPC matrices), a significant portion of the traditional mechanisms for resisting shear crack propagation may be lacking in an UHPC beam. This, in turn, dictates that the long-term tensile performance of the material must be characterized to determine the material's ability to withstand shear-induced tension stresses in service.

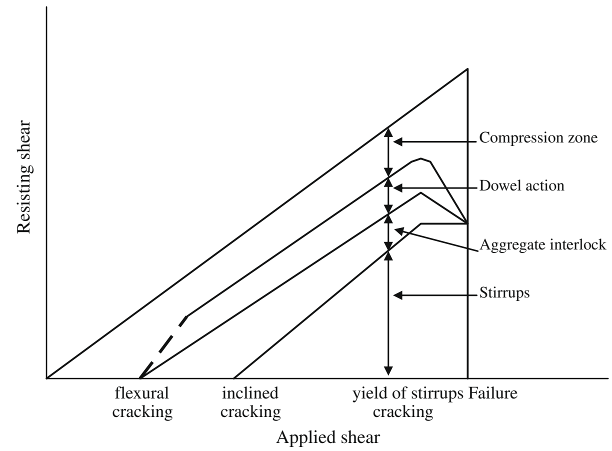

Fig. 1. Distribution of internal shears in a beam with web reinforcement (based upon [42]).

While some studies have examined tensile creep behavior in ordinary and high performance concrete [43–52], tensile creep in UHPC has not been characterized in the published literature. Therefore, the main objective of this research is to provide some preliminary data characterizing the tensile creep performance of UHPC and to define parameters to be investigated in a detailed, long-term investigation. In the overall research program, the effects of stress level at loading, the amount of short steel fiber reinforcement [53], and curing conditions will be examined. This overall program is necessary to develop a fundamental understanding of the tensile creep phenomena in UHPC so that design criteria can be developed for specifying UHPC for highway bridge girders.

2. Experiment

2.1. Materials

The UHPC mixes investigated were prepared from the ultra-high performance premix, Ductal®, provided by Lafarge North America and ultra-high strength steel fibers, Dramix 13/0.20, provided by Bekaert. The UHPC premix consisted mainly of Portland cement, silica fume, crushed quartz, and sand. The high strength steel fibers were 0.20 mm in diameter and 13.0 mm in length (aspect ratio = 65), and had a tensile strength of between 690 and 1000 MPa, according to the manufacturer. Also, commercially available high range water reducer (HRWR), Glenium 3030 NS, and accelerator, Rheocrete CNI, provided by BASF were also used. A typical UHPC mixture design is shown in Table 1.

Table 1
UHPC composition.

Constituent	(kg/m^3)
UPHC premix	2194
Water	109
HRWRA	31
Accelerator	30
Steel fibers[a]	156[a]

[a] Dose recommended by the UHPC manufacturer (2% volume fraction).

Table 2
Different UHPC mixes, curing and loading conditions.

Mixture ID	Stress/strength at loading (%)	Curing temperature[a] (°C)	Fiber content
D-2f-90C-40	40	90	2% by vol.
D-2f-23C-40	40	23	2% by vol.
D-0f-90C-40	40	90	No fibers
D-2f-90C-60	60	90	2% by vol.

[a] All samples were cured at 100% RH.

2.2. Sample matrix

Four different conditions, designed to examine the influence of varying stress/strength ratio at the time of loading, fiber content, and thermal treatment temperature were considered (Table 2). The nomenclature used in this study was based on the type of UHPC used (i.e., Ductal® = D), fiber volume fraction (i.e., 2% volume fraction = 2f), maximum treatment temperature reached while curing (i.e., 23 °C or 90 °C), and the stress level maintained during the creep test (i.e., 40% means that the tensile stress-to-tensile strength ratio at the time of loading was 40%). For example, Mix "D-2f-90C-40" indicates that the premix was used with 2% steel fiber content, thermally treated at 90 °C, and loaded at 40% of its tensile strength at the time of loading.

2.3. Mixing and curing methodology

All specimens were cast according to procedures recommended by the UHPC manufacturer. First, the dry premix was mixed in an 85-l capacity high shear mixer (Erich Model R 08 W) at 30–35 rpm for 2 min to break apart any clumps that might exist in the dry mix. This mixing speed was maintained over the entire mixing process. Water and half of the HRWR mixed were then added slowly to the dry premix over a period of 2 min and allowed to mix with the dry premix for 1 min. The other half of the HRWR was then added over a period of 30 s, and mixing continued for another minute. The accelerator was then added over 1 min and mixing continued until the "turning point" was reached. The turning point is defined as the point at which the UHPC mix turns from clumps into a flowable, uniform paste. Finally, and once the turning point was reached, fibers were added over a 2 min period, and mixing continued for another 1–2 min until good fiber dispersion was visually evident. Once mixing was finished, flow table tests similar to ASTM C230 [54] were performed to assess the flowability of each mix and to decide whether vibration should be used while casting or not. Based on the flow table results and according to the mixing procedures recommended by the UHPC manufacturer, vibration was used to cast all specimens from all mixes.

After casting, all specimens were stored in a fog room at 23 °C and 100% RH for 48 h prior to demolding. Upon demolding, specimens were either stored in a fog room at 23 °C and 100% RH (D-2f-23C-40) or placed in an environmental chamber for thermal treatment (mixes D-2f-90C-40, D-0f-90C-40, and D-0f-90C-60) at temperature of 90 °C and 100% RH for the next 48 h. After initial curing or initial curing and thermal treatment, creep samples were wrapped in aluminum tape to minimize moisture loss during the following sample preparation period while shrinkage specimens were kept in the fog room for the same period before tests started at 7 days of age.

2.4. Test methodology

Tensile creep and free shrinkage deformations were measured on 100 × 380 mm cylinders, two loaded cylinders for tensile creep and two un-loaded companion specimens for free shrinkage (Fig. 2). Each cylinder was fitted with four sets of steel inserts located diametrically opposite on the surface of the specimen. Each set had a gauge length of 250 mm. For each creep specimen, two 38 mm thick steel plates were affixed, one on the top and one on the bottom using high modulus, high strength epoxy and left to cure for ~36 h under a pressure of 2.75 MPa (no rods were embedded in the concrete for affixing the plates to the specimens in this study). At an age of 7 days, creep samples were loaded at a constant rate of 0.0046 MPa/s until the desired load was reached. For each specimen, deformations were measured on each set of inserts using mechanical DEMEC gage with an accuracy of 0.00254 mm. The tensile creep test setup is shown in Fig. 2. Test conditions were kept at 23 ± 2 °C and 50 ± 3% RH for the whole testing period. Tensile creep and shrinkage deformations were measured initially at 1, 2, 4, 6, 12, and 24 h after loading. Subsequently, measurements were made daily for the rest of the 14-day testing period.

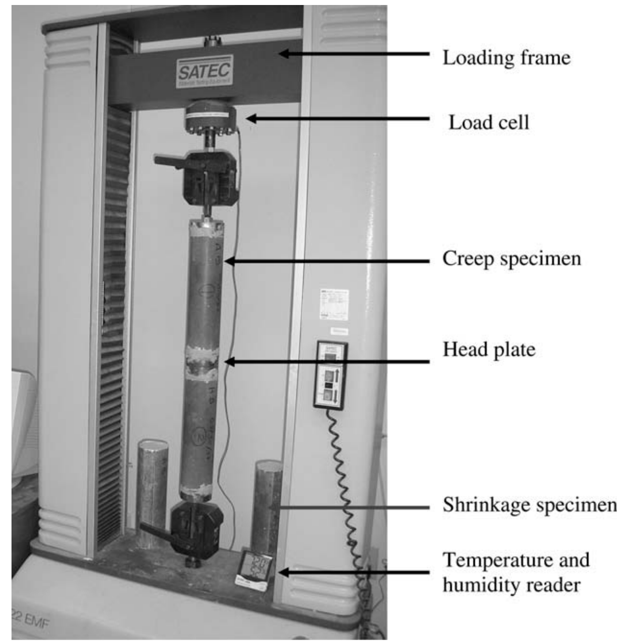

Fig. 2. Tensile creep test setup.

3. Results and discussion

Figs. 3 and 4 show the measured free shrinkage and tensile creep for over 14 days where the influence of stress/strength, fiber

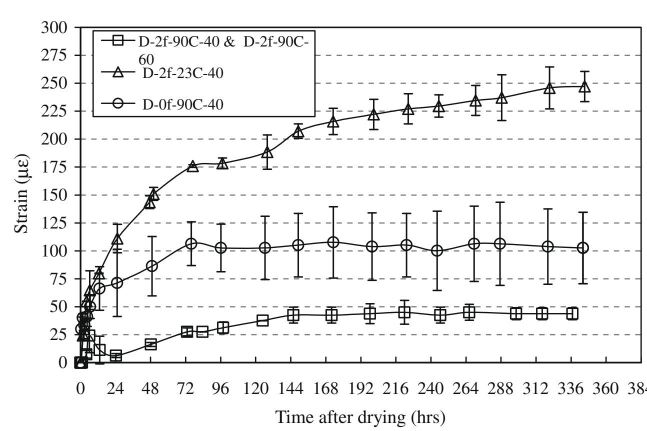

Fig. 3. Free shrinkage of different UHPC mixes; drying started at 7 days of age.

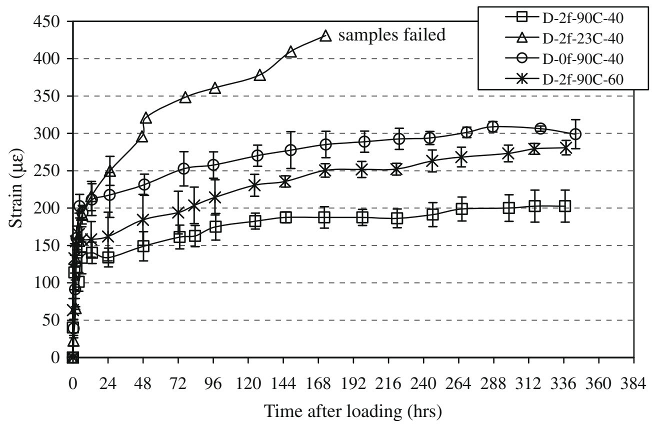

Fig. 4. Tensile total creep of different UHPC mixes loaded at 7 days of age.

reinforcement, and thermal treatment are examined. Only one of the mixes – the non-thermally treated mix (D-2f-23C-40), failed during this short-term tensile creep test; as a result, tensile creep data for this mix are only available up to 7 days.

Table 3 summarizes for each sample type the average tensile strength at the time of loading, tensile creep coefficient and specific tensile creep at 7 and 14 days of loading, and the 7 and 14-day free shrinkage strains. It is worth noting that the 7-day tensile strength among the mixes did not vary considerably. The maximum difference in strength was about 8%, when comparing mixes D-2f-90C-40 and D-0f-90C-40 (Table 3). These results also show that eliminating fiber reinforcement has a slightly more pronounced effect on the reduction of 7-day tensile strength than eliminating thermal treatment.

3.1. Free shrinkage

As shown in Fig. 3 and Table 3, the incorporation of short steel fibers limited free shrinkage. Results at 14 days of drying show that the free shrinkage of mix D-0f-90C-40, with no steel fibers, was about 135% more than that of mix D-2f-90C-40 in which 2% fibers by volume was incorporated. This suggests that the fibers offer some restraint to deformation, as would be expected when the fibers are well-dispersed in the matrix.

Fig. 3 and Table 3 also show that after 14 days of drying, the free shrinkage of mix D-2f-23C-40 (i.e., where no thermal treatment was applied) was about six times that of the mix D-2f-90C-40 which was thermally treated at 90 °C for 48 h. In addition, results in Fig. 3 also show that mix D-2f-23C-40 continued to shrink for the whole testing period, while mix D-2f-90C-40 reached an asymptotic shrinkage strain value of about 45 με after about 6 days of drying. Similar results for UHPC were reported by Graybeal [8], where specimens thermally treated at 90 °C for 48 h did not show any measurable free shrinkage after thermal treatment, while air-cured specimens continued to shrink with time. Both microstructural refinement and consumption of most of the mix water due to the accelerated hydration associated with thermal treatment likely contribute to the reduced shrinkage in the thermally treated samples.

3.2. Tensile creep

This section presents the effects of varying the stress-to-strength ratio, incorporating short and randomly-dispersed high strength steel fibers in mix, and thermal treatment prior to loading on the tensile creep of UHPC. Results in Fig. 4 show tensile creep increasing steadily with time for each of the four mix types examined. First, both the tensile creep coefficient and the specific tensile creep increased upon increasing the stress–strength ratios. However, both parameters decreased in the presence of steel fibers and with the application of thermal treatment prior to loading. The effect of steel fibers in this study is of particular importance since the creep behavior is contrary to published reports [46,52], which indicate an increase in tensile creep with fiber reinforcement in NSC and HPC. (This difference is discussed in further detail below.) Generally, these results show the tensile creep of UHPC to be lower than tensile creep results reported in the literature for normal strength and high performance concretes [46,52]. However, the tensile creep measured here in UHPC is also significantly higher than the compressive creep previously reported [8] for UHPC.

First, increasing the stress-to-strength ratio from 40% (D-2f-90C-40) to 60% (D-2f-90C-60) increased the creep coefficient by 44% and increased the specific creep by 11% at 14 days of loading (Fig. 4 and Table 3). These results in tension agree with the compression results of Graybeal [8] who reported increasing compressive creep with increasing stress-to-strength ratio for the same steel fiber reinforced UHPC material. Similar results have been also reported by Bissonnette et al. [52] where the tensile creep of normal and high strength concretes have shown a dependence on the stress-to-strength ratio.

As for the effect of steel fiber reinforcement, comparing the tensile creep results for mixes with (D-2f-90C-40) and without steel fibers (D-0f-90C-40) in Fig. 4 and in Table 3 shows that the tensile creep coefficient decreased by 10% and the specific creep decreased by 40% with the addition of 2% fibers at 14 days. It is noted that the UHPC examined here was optimized based upon the use of 2% steel fibers by volume; hence, structure and performance were designed to be enhanced by the presence of fibers. These results, however, are opposite to those reported by Bissonnette and Pigeon [46] and by Bissonnette et al. [52] which investigated the influence of steel fiber reinforcement in normal and high strength concretes undergoing tensile creep. In both of these previous studies, an increase in tensile creep was typically associated with the use of steel fibers. The variation between the prior and current results could be related to the differences in the material composition (e.g., particle packing, heterogeneity), material structure (e.g., lower strength, less microstructurally dense NSC vs. higher strength, lower micro/nano porosity UHPC), and processing (e.g., ordinary moist curing vs. thermal treatment). In particular, the application of thermal treatment to the fiber reinforced samples warrants further examination.

Table 3
Summary of the results of the short-term study.

Mixture	Tensile strength (standard deviation) at loading (MPa)	Tensile creep coefficient		Specific tensile creep (με/MPa)		Free shrinkage strain (με)	
		7-day	14-day	7-day	14-day	7-day	14-day
D-2f-90C-40	6.50 [0.29]	0.65	0.78	28.44	34.22	43	44
D-2f-23C-40	6.09 [0.40]	2.38	N/A	124.66	N/A	216	247
D-0f-90C-40	6.04 [0.30]	0.78	0.87	51.78	57.44	108	103
D-2f-90C-60	6.50 [0.29]	0.89	1.12	30.2	38.00	43	44

As previously noted, the application of thermal treatment was found to significantly affect tensile creep of UHPC. Thermally treating fiber reinforced UHPC at 90 °C for 48 h prior to loading resulted in a 73% decrease in the creep coefficient and 77% decrease in specific creep when comparing the behavior of D-2f-23C-40 and D-2f-90C-40 at 7 days of loading (due to the premature failure of the D-2f-23C-40 mixture). It is proposed that this thermal treatment may result in refinement in the cementitious matrix nano- and microstructure, especially around the fibers. This proposed improvement in the structure and properties at the fiber/matrix interface may be viewed similarly – although occurring likely at the nanoscale in UHPC – to refinements by thermal curing at the microscale, interfacial transition zone (ITZ) around coarse aggregate [25,52]. For non-thermal treated UHPC, the possibility of formation of water films around fibers during casting might have resulted in a higher local water-to-cementitious materials ratio. Mondal et al. [55] monitored similar phenomenon around fine aggregates (1.18–2.36 mm in size). The proposed porous interfacial zone around fibers might have been improved due to thermal treatment. Thermal treatment could have promoted further reaction of the cementitious paste, leading to a reduction in the porosity around fibers and minimization of the weakness in the fiber–matrix interfacial zone.

In addition, the D-2f-23C-40 specimens, which were not thermally treated, failed at the epoxy interface after one week of loading with the fracture occurring in the concrete. Substitute specimens were cast later but failed at the same location while loading. This failure may be related to the inadvertent introduction of defects into all the creep samples during the grinding of the specimen ends before applying the epoxy adhesive to attach the steel loading plates. Premature failure occurred only in the non-thermally treated samples and never in the various thermally treated samples. This behavior suggests that some self-healing of any defects induced during grinding may have occurred during thermal treatment where water was available at the surface to aid the self-healing process.

Tensile creep results for mix D-2f-90C-40 in the current study were compared to compressive creep results for steel fiber reinforced (2% by vol.) UHPC specimens thermally treated at 90 °C and loaded at 40% of the compressive strength by the time of loading reported by Graybeal [8]. At the age of 14 days of loading, this comparison shows that both the tensile creep coefficient and specific creep are about 12 times higher than the corresponding values during compressive creep. While the mechanisms of tensile creep behavior in UHPC have not been thoroughly examined, this significant difference in the magnitude and rate of development between compressive and tensile creep of UHPC, with the later being about an order of magnitude higher and faster at early age, suggests that tensile creep occurs phenomenologically quite differently than compressive creep in thermally treated, fiber reinforced UHPC. This may be, in part, due to the magnified effect of microcracking during tensile creep as compared to compressive creep, as well as the potential contributions of several other factors. Specifically, it is proposed that further investigation should examine the influence of fiber restraint of compression creep, fiber/matrix debonding particularly during tensile creep, and deformation of the fiber reinforcement. This observation is of significant importance as it emphasizes that tensile creep should be fundamentally and fully investigated prior to specifying this material for use where tensile capacity is of primary importance.

Finally, another important result of this study is that both thermal treatment and fiber reinforcement affected tensile creep significantly more than these factors affected early (7-day) tensile strength. That is, while the increase in the 7-day tensile strength was about 8% upon incorporating short steel fibers, the corresponding decrease in the tensile creep coefficient and the specific tensile creep at 14 days of loading was about 10% and 40%, respectively. Also, while the increase in the 7-day tensile strength was about 7% upon applying thermal treatment, the corresponding decrease in the tensile creep coefficient and the specific tensile creep at 7 days of loading was about 73% and 77%, respectively. The observed differences between tensile creep and tensile strength among the various mixtures examined emphasizes the importance of conducting tensile creep testing to predict long-term tensile performance. It is proposed that, the more ability of cracks to coalesce and propagate during a tensile creep test rather than a tensile strength test may likely play an important role in describing the observed differences between the two sets of results.

4. Conclusions

Short-duration, 14-day tests were used to provide an initial understanding of the influence of varying the stress-to-strength ratio at time of loading, incorporating short steel fibers, and thermal treatment on the tensile creep behavior of UHPC, with a complementary examination of drying shrinkage in these same mixtures. From this examination, the following observations can be made:

(1) While the maximum variation in 7-day tensile strength among the different conditions examined measured just 8%, tensile creep behavior varied by up to ~70% when the influence of fiber reinforcement and curing conditions were compared. These results emphasize the importance of conducting tensile creep testing rather than tensile strength tests to predict long-term tensile performance.
(2) The use of fibers and the application of thermal treatment decreased 14-day drying shrinkage by more than 100% and by 600%, respectively.
(3) As expected, an increase from 40% to 60% in the tensile stress-to-strength ratio at time of loading resulted in a 44% and 11% increase in the tensile creep coefficient and specific tensile creep after 14 days of loading.
(4) In contrast to tensile creep results provided literature for NSC and HPC, reinforcement with short straight steel fibers decreased the tensile creep of UHPC. It is proposed that this is, in part, due to the enhancements at the fiber/matrix interface during thermal treatment.
(5) Thermal treatment of UHPC at 90 °C for 48 h decreased both the tensile creep coefficient and specific tensile creep at 7 days of loading by 73% and 77% when compared to companion concrete subjected to ordinary moist curing.

Overall, this research suggests that the combined effect of thermal treatment and incorporation of short steel fibers act to limit tensile creep and shrinkage in UHPC, with thermal treatment having the most pronounced effect. Furthermore, results from this study suggest that the tensile creep phenomenon in UHPC occurs differently than compressive creep in UHPC. This emphasizes the importance of further study of the tensile creep behavior of UHPC, particularly for applications where satisfactory long-term tensile performance is required.

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References

[1] Powers TC, Brownyard TL. Studies on the physical properties of hardened portland cement paste. In: Bulletin 22 of the Portland Cement Association, Chicago, IL, USA; 1948.
[2] Dodson VH. Concrete admixtures. New York: Van Nostrand Reinhold; 1990.
[3] Richard P, Cheyrezy M. Reactive powder concretes with high ductility and 200–800 MPa compressive strength. In: Mehta PK, editor. Concrete technology: past, present, and future. ACI SP 144; 1993. p. 507–18.
[4] Cheyrezy M, Maret V, Frouin L. Microstructural analysis of RPC (reactive powder concretes). J Cem Concr Res 1995;24(7):1491–500.
[5] Collepardi S, Coppola L, Troli R, Collepardi M. Mechanical properties of modified reactive powder concrete. In: Malhotra VM, editor. Superplasticizers and other chemical admixtures in concrete. ACI SP 173; 1997. p. 1–21.
[6] Feylessoufi A, Crepin M, Dion P, Bergaya F, Van Damme H, Richard P. Controlled rate thermal treatment of reactive powder concretes. Adv Cem Based Mater 1997;6(1):21–7.
[7] Shah SP, Weiss WJ. Ultra high strength concrete; looking toward the future. In: ACI special proceedings from the Paul Zia symposium, Atlanta, GA, USA; 1998.
[8] Graybeal BA. Characterization of the behavior of ultra-high performance concrete. PhD thesis, University of Maryland, USA; 2005.
[9] Goldman A, Bentur A. Properties of cementitious systems containing silica fume or nonreactive microfillers. Adv Cem Based Mater 1994;1(5):209–15.
[10] Chung DDL. Review: improving cement-based materials by using silica fume. J Mater Sci 2002;37(4):673–82.
[11] Chan Y, Chu S. Effect of silica fume on steel fiber bond characteristics in reactive powder concrete. J Cem Concr Res 2004;34(7):1167–72.
[12] Hannant DJ. Fibre cements and fibre concretes. New York: John Wiley & Sons; 1978.
[13] Potrzebowski J. The splitting test applied to steel fibre reinforced concrete. Inter J Cem Compos Lightweight Concr 1983;5(1):49–53.
[14] Rossi P, Coussy O, Boulay C, Acker P, Malier Y. Comparison between plain concrete toughness and steel fibre reinforced concrete toughness. J Cem Concr Res 1986;16(3):303–13.
[15] Kormeling HA, Reinhardt HW. Strain rate effects on steel fibre concrete in uniaxial tension. Inter J Cem Compos Lightweight Concr 1987;9(4):197–204.
[16] Banthia N, Yan C, Mindess S. Restrained shrinkage cracking in fiber reinforced concrete: a novel test technique. J Cem Concr Res 1996;26(1):9–14.
[17] Gao J, Suqa W, Morino K. Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete. J Cem Concr Compos 1997;19(4):307–13.
[18] Krstulovic-Opara N, Malak S. Tensile behavior of slurry infiltrated mat concrete (SIMCON). ACI Mater J 1997;94(1):39–46.
[19] Pigeon M, Cantin R. Flexural properties of steel fiber-reinforced concretes at low temperatures. J Cem Concr Compos 1998;20(5):365–75.
[20] Li VC, Matsumoto T. Fatigue crack growth analysis of fiber reinforced concrete with effect of interfacial bond degradation. J Cem Concr Compos 1998;20(5):339–51.
[21] Chunxiang Q, Patnaikuni I. Properties of high-strength steel fiber-reinforced concrete beams in bending. J Cem Concr Compos 1999;21(1):73–81.
[22] Karihaloo BL, DeVriese KMB. Short-fibre reinforced reactive powder concrete. In: Reinhardt HW, editor. Proceedings of the third international RILEM workshop on high performance fiber reinforced cement composites HPFRCC3, Mainz, Germany; 1999. p. 53.
[23] Nataraja MC, Dhang N, Gupta AP. Stress–strain curves for steel–fiber reinforced concrete under compression. J Cem Concr Compos 1999;21:383–90.
[24] Zhang J, Li VC. Simulation of crack propagation in fiber-reinforced concrete by fracture mechanics. J Cem Concr Res 2004;34(2):333–9.
[25] Mehta PK, Monteiro PJ. Concrete microstructure, properties, and materials. 3rd ed. McGraw-Hill; 2005.
[26] Lu X, Hsu CT. Behavior of high strength concrete with and without steel fiber reinforcement in triaxial compression. J Cem Concr Res 2006;36(9):1679–85.
[27] Banthia N, Sappakittipakorn M. Toughness enhancement in steel fiber reinforced concrete through fiber hybridization. J Cem Concr Res 2007;37(9):1366–72.
[28] Juárez C, Valdez P, Durán A, Sobolev K. The diagonal tension behavior of fiber reinforced concrete beams. J Cem Concr Compos 2007;29(5):402–8.
[29] Bierwagen D, Abu-Hawash A. Ultra high performance concrete highway bridge. In: Proceedings of the PCI national bridge conference (CD proceedings), Atlanta, GA, USA; 2004.
[30] Graybeal B. Fabrication of an optimized UHPC bridge. In: Proceedings of the PCI national bridge conference (CD proceedings), Atlanta, GA, USA; 2004.
[31] Bierwagen D, McDonald N. Ultra high performance concrete highway bridge. In: Proceedings of the PCI national bridge conference (CD proceedings), Palm Springs, CA, USA; 2005.
[32] Graybeal B, Hartmann JL. Experimental testing of UHPC optimized bridge girders: early results. In: Proceedings of the PCI national bridge conference (CD proceedings), Palm Springs, CA, USA; 2005.
[33] Perry V. The use of UHPC for precast bridge decks: the technology, applications and challenges facing commercialization. In: Proceedings of the PCI national bridge conference (CD proceedings), Palm Springs, CA, USA; 2005.
[34] Steinberg EP, Ahlborn TM. Analysis of UHPC bridge girders. In: Proceedings of the PCI national bridge conference (CD proceedings), Palm Springs, CA, USA; 2005.
[35] Narayanan R, Darwish IYS. Shear in prestressed concrete beams containing steel fibres. Inter J Cem Compos Lightweight Concr 1987;9(2):81–90.
[36] Imam M, Vandewalle L, Mortelmans F, Gemert DV. Shear domain of fibre-reinforced high-strength concrete beams. J Eng Struct 1997;19(9):738–47.
[37] Furlan S, Hanai JB. Shear behaviour of fiber reinforced concrete. J Cem Concr Compos 1997;19(4):359–66.
[38] Furlan S, Hanai JB. Prestressed fiber reinforced concrete beams with reduced ratios of shear reinforced. J Cem Concr Compos 1999;21(3):213–21.
[39] Lim DH, Oh BH. Experimental and theoretical investigation on the shear of steel fibre reinforced beams. J Eng Struct 1999;21(10):937–44.
[40] Cucchiara C, Mendola LL, Papia M. Effectiveness of stirrups and steel fibers as shear reinforcement. J Cem Concr Compos 2004;26(7):777–86.
[41] Anderson BG. Rigid frame failures. ACI J 1957;53(7):625–36.
[42] MacGregor JG, Wight JK. Reinforced concrete, mechanics and design. 4th ed. Prentice Hall; 2005.
[43] Umehara H, Uehara T, Iisaka T, Sugiyama A. Effect of creep in concrete at early ages on thermal stress. In: Springenschmid R, editor. Thermal cracking in concrete at early age E&FN Spon, London, RILEM; 1994. p. 79–86.
[44] Gutsch A, Rostasy FS. Young concrete under high tensile stresses, creep, relaxation and cracking. In: Springenschmid R, editor. Thermal cracking in concrete at early age E&FN Spon, London, RILEM; 1994. p. 111–8.
[45] Kovler K. Testing system for determining the mechanical behavior of early age concrete under restrained and free uniaxial shrinkage. J Mater Struct 1994;27(6):324–30.
[46] Bissonnette B, Pigeon M. Tensile creep at early ages of ordinary, silica fume and fiber reinforced concretes. J Cem Concr Res 1995;25(5):1075–85.
[47] Kovler K. Interdependence of creep and shrinkage for concrete under tension. J Mater Civil Eng 1995;7(2):96–101.
[48] Kovler K, Igarashi S, Bentur A. Tensile creep behavior of high strength concretes at early age. J Mater Struct 1999;32(5):383–7.
[49] Kovler K. A new look at the problem of drying creep of concrete under tension. J Mater Civil Eng 1999;11(1):84–7.
[50] Altoubat SA, Lange DA. Tensile basic creep: measurements and behavior at early age. ACI Mater J 2001;98(5):386–93.
[51] Tao Z, Weizu Q. Tensile creep due to restraining stresses in high-strength concrete at early ages. J Cem Concr Res 2006;36(3):584–91.
[52] Bissonnette B, Pigeon M, Vaysburd AM. Tensile creep of concrete: study of its sensitivity to basic parameters. ACI Mater J 2007;104(4):360–8.
[53] Garas VY, Kahn LF, Kurtis KE. Preliminary investigation of the effect of steel fibers on the tensile creep and shrinkage of ultra-high performance concrete. In: Tanabe T et al., editors. Proceedings of the eight international conference on creep, shrinkage and durability of concrete and concrete structures, Ise-Shima, Japan; 2008. p. 741–4
[54] ASTM C230. Standard test method for flow table for use in tests of hydraulic cement. Philadelphia, Pennsylvania: American Society for Testing and Materials; 1998.
[55] Mondal P, Shah SP, Marks LD. Nanoscale characterization of cementitious materials. ACI Mater J 2008;105(2):174–9.