Overview of the Prestress Losses and Long-term Deflection Response of Ultra-High Performance Concrete Members

Madiha Z. Ammari, Ph.D. (corresponding author) – Formerly, Visiting Postdoctoral Associate at Michigan Technological University. Currently, NRC Postdoctoral Research Associate, Turner-Fairbank Highway Research Center, Federal Highway Administration, Mclean, VA, USA, Email: madiha.zahera.ammari@dot.gov

Theresa M. Ahlborn, Ph.D., P.E., FACI, FPCI – Professor, Michigan Technological University, Department of Civil, Environmental and Geospatial Engineering, Houghton, MI, USA, Email: tess@mtu.edu

Abstract

Ultra-High Performance Concrete (UHPC) is an innovative material due to its unique properties and performance compared to conventional concrete. UHPC provides a resilient infrastructure and advances systems for sustainable use due to its extreme strength and superior durability under variable loadings and exposures. Although UHPC is a promising construction material, it faces numerous challenges before widespread implementation in the U.S. There are currently no published design guides to use UHPC in different infrastructure applications in the U.S., and accordingly, engineers and owners lack confidence in system performance. This work will focus on some challenges facing implementing UHPC in large-scale projects in the U.S., including discussing the impact of thermal or steam treatment on prestress losses and the long-term deflection response of UHPC prestressed systems.

Keywords: UHPC, thermal treatment, prestress loss, deflection, time-dependent behavior, elastic shortening, creep, shrinkage

1. Introduction

Ultra-High Performance Concrete (UHPC) has significant improvements compared to conventional concrete. It has increased compressive strength, tensile strength, flexural strength, modulus of elasticity, and durability. Due to its high performance, UHPC has proved to be a competent material to other rapidly growing materials used in constructing bridges and buildings (Graybeal et al., 2020).

UHPC has performance characteristics that exceed conventional concrete. This performance is achieved by utilizing well-graded constituents in UHPC. UHPC is a rich mixture with high content of cementitious materials including cement and silica fume. Only aggregate in the fine sand size is used in UHPC, with no coarse aggregate content. It is a self-consolidated concrete with high content of admixtures to ensure good performance while in a fresh state. UHPC has also a high content of high-strength steel fibers of 2% by volume (Graybeal et al., 2019). El-Helou et al. (2022) summarized typical mechanical properties according to international recommendations including the range of compressive strengths, modulus of elasticity, cracking and localization stresses, and localization strains for structural-grade UHPC.

UHPC provides a resilient infrastructure and advances systems for sustainable use due to its extreme strength and superior durability under variable loadings and exposures. Although UHPC is a promising construction material, it faces numerous challenges before widespread implementation in the U.S. There are currently no published design guidelines to use UHPC in different infrastructure applications in the U.S., and accordingly, engineers and owners lack confidence in system performance (Ahlborn, 2015).

Other challenges include the lack of accepted standard definitions and specifications of UHPC, the lack of standardized testing methods for the performance of UHPC under different environmental conditions, and the lack of production standards in manufacturing facilities for quality control (Ahlborn, 2015). The U.S. Federal Highway Administration has been reporting tremendous efforts for better understanding UHPC behavior and the AASHTO-LRFD Bridge Design Specifications is in the review process for some of those efforts for the purpose of adopting some of the proposed models for the structural design guides for UHPC bridge elements. In addition, the ACI 239C Committee is accelerating its efforts to provide UHPC structural design guides.

The applications of UHPC worldwide range from minor field-cast closures to precast segments for long-span bridges to long bridge deck overlays. While UHPC has been utilized in large-scale applications in countries such as Switzerland, France, and Malaysia, applications in the U.S. are most of the time limited to secondary applications such as utilizing UHPC in connection systems for prefabricated bridge members (Graybeal et al., 2020). The structural design of the pre-tensioned concrete members is affected by the time-dependent behavior of concrete due to shrinkage and creep. A good understanding and estimation to prestress losses and camber in pre-tensioned UHPC members can facilitate the utilization of UHPC in construction.

2. Prestressed Losses in Pre-tensioned Members

An estimation of the effective prestress force acting on a prestressed concrete section is required to determine concrete stresses and element deformations under service conditions. The total loss of prestressing is the difference between the stress in the strands immediately before force transfer to the prestressed concrete member and the stress at the end of the service life of the member.

There are two main sources of prestress losses not related to member loading: 1) initial losses due to elastic shortening immediately at prestress transfer due to prestressing and cambering of concrete, and 2) long-term losses due to relaxation of the strands, creep of the concrete under sustained prestressing stresses and shrinkage of the concrete.

Estimation of prestress losses is a critical aspect of the design of prestressed structural elements. Overestimating the prestress losses leads to an increase in the camber and may lead to cracks at the top of the prestressed member, on the other hand underestimating the losses will lead to cracks at the bottom concrete fibers under expected service loads.

Because UHPC has distinct properties compared to conventional concrete, the current provisions for calculating the losses in prestressed concrete elements due to creep and shrinkage cannot be considered reliable and need further investigation. Elastic shortening is affected directly by the modulus of elasticity of the UHPC. Another time-dependent prestress loss component is strands relaxation which is not considered in this review. Prestress losses due to strand relaxation can be estimated based on the relationship provided in the AASHTO LRFD Bridge Design Specifications.

When the concrete surrounding the prestressing strands shrinks it reduces the tensile prestressing stresses and then the prestressing efficiency is affected. Shrinkage and creep in concrete depend generally on the concrete mixture proportioning, curing conditions, shape and size of the girder (volume/surface ratio), and environmental conditions (temperature and humidity) (ACI 209.1R- 2005). The creep has a time-dependent effect and causes the concrete member to deflect under sustained load. Current AASHTO-LRFD (2020), ACI 423 (2016) and PCI Design Handbook (PCI, 2014) provide guidance to estimate prestress losses in conventional concrete but not in UHPC structural elements. AASHTO-LRFD will soon be providing predictive models to estimate creep and shrinkage and total prestress loss as an extension of the efforts of Mohebbi and Graybeal (2022).

Graybeal (2006) empirically measured prestress losses for AASHTO Type II girders. The strands were stressed up to 55% of ultimate strength. After 3 days of casting, the prestressing loads were transferred, and steam curing began. The stress level at transfer did not exceed 30% of the compressive strength of the UHPC at that time. At least 10 ksi (70 MPa) was achieved as the compressive strength of UHPC at transfer.

Mohebbi and Graybeal (2022) collected data and proposed models to estimate the behavior of creep and shrinkage of UHPC. Commercially available UHPCs were tested for creep and shrinkage under different service conditions. The specimens used were merely cured in ambient conditions. The study by Mohebbi and Graybeal 2022 also considered comparing the results of the predictive models with current AASHTO LRFD equations for conventional concrete, and with existing European recommendations for UHPC. The models proposed for creep and shrinkage were examined by calculating the total prestress losses and comparing the values with the actual prestress losses measured for seven full-scale pre-tensioned UHPC girders. The total prestress losses in the girders were empirically measured over time using vibrating wire gauges (VWG). The full-scale girders had similar diameter strands but different geometries and two commercially available UHPC products were used for their construction. The 0.7 in. (17.8 mm) strand size used was larger than the commonly utilized in the precast/prestressed industry. Using larger strands allowed for using a reduced cross-section and applying larger prestress forces to the girder. The compressive strength of UHPC at transfer exceeded 14 ksi (97 MPa). This research was part of a larger effort to assess the structural performance of the pre-tensioned UHPC girders.

Mohebbi and Graybeal (2022) provided measured data for prestressing loss in UHPC to be in the range of 12 percent to 23 percent of the effective prestressing (75% of the ultimate strength). As a comparison, ACI 423 (2016) and PCI (2014) provide an estimate of total losses of 12 percent to 25 percent for normal-weight concrete. In 2006, Graybeal reported a 14% loss for UHPC with compressive strength of 10 ksi (70 MPa) under 55% stress level.

Mullen (2013) analytically assessed the prestress losses and deflections of UHPC girders with three different sections: rectangular, modified bulb tee, and a pi-girder. In the study, the incremental time step approach was used, in addition to employing the material models proposed by Flietstra (2011). Flietstra (2011) conducted empirical testing on the modulus of elasticity, compressive creep, and unrestrained shrinkage on UHPC specimens that had different curing conditions: ambient curing, thermal treatment (TT) at 48 hours, and thermal treatment (TT) after 30 days.

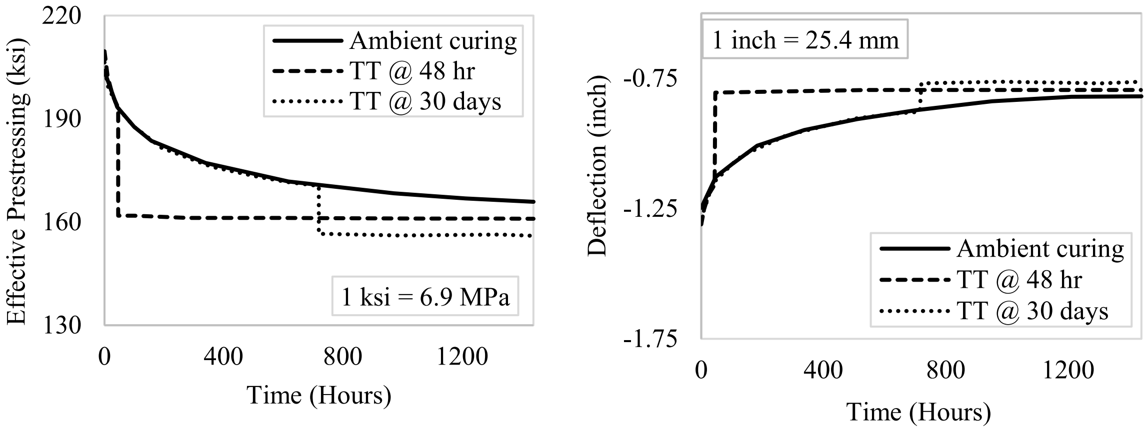


Figure 1. Analytical effective prestressing and deflection for rectangular girder, ambient cured and Thermally Treated (TT) (Mullen, 2013)

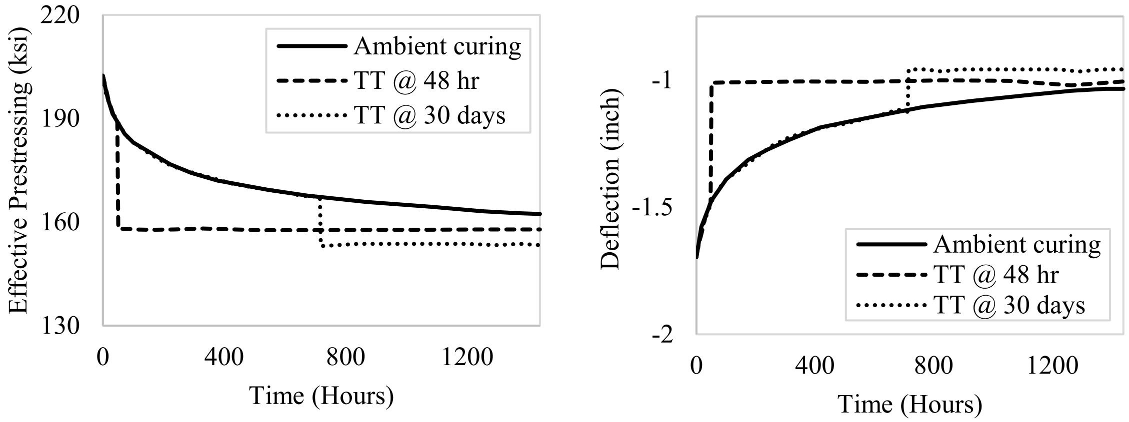


Figure 2. Analytical effective prestressing and deflection for modified bulb tee girder, ambient cured and Thermally Treated (TT) (Mullen, 2013)

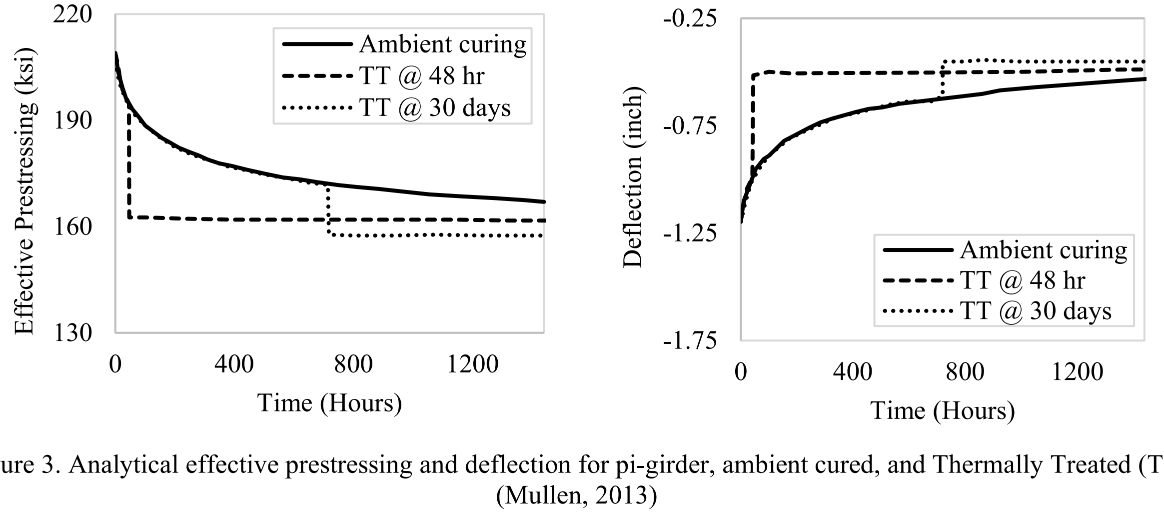


Figure 3. Analytical effective prestressing and deflection for pi-girder, ambient cured, and Thermally Treated (TT) (Mullen, 2013)

Results of the analytical study by Mullen (2013) are shown in Figures 1 through 3 for effective prestressing and deflection up to 60 days (1440 hours) with no considerations for results after deck replacement that was applied on some girders.

Results by Mullen (2013) showed the importance of thermal treatment for prestressed UHPC girders to "lock in" material properties (Ahlborn, 2015). However, timing of the thermal treatment was found to have a negligible effect on long-term deflections. Depending on the analytical study by Mullen (2013) for up to 10 years, the average prestress losses for the girders was found to be 33% for ambient cured girders, 28% for thermally treated girders after 48 hours, and 30% for thermally treated girders after 30 days, showing similar prestress losses after a very long time of service regardless of the curing conditions. However, the results showed negligible difference in prestress losses for the thermally treated girders between 60 days and 10 years while the ambient cured girders had a 20% increment in the prestress losses between those times. This difference for ambient cured girders is reflected as a difference of 45% in deflection between 60 days and 10 years (long term deflection) which can have an adverse effect on the serviceability and the non-structural elements at the top of the girder over time.

3. Elastic Shortening

Elastic shortening, also known as initial prestress loss, is a one-time loss that takes place at force transfer and contributes a significant amount of prestress loss. Heat treatment was found to improve the early modulus of elasticity of UHPC because of the enhanced compressive strength (Ahlborn et al., 2008; Graybeal, 2012), see Figure 4. Elastic shortening can be determined using different approaches including the gross-section approximation method similar to conventional concrete, presented in the PCI (2014).

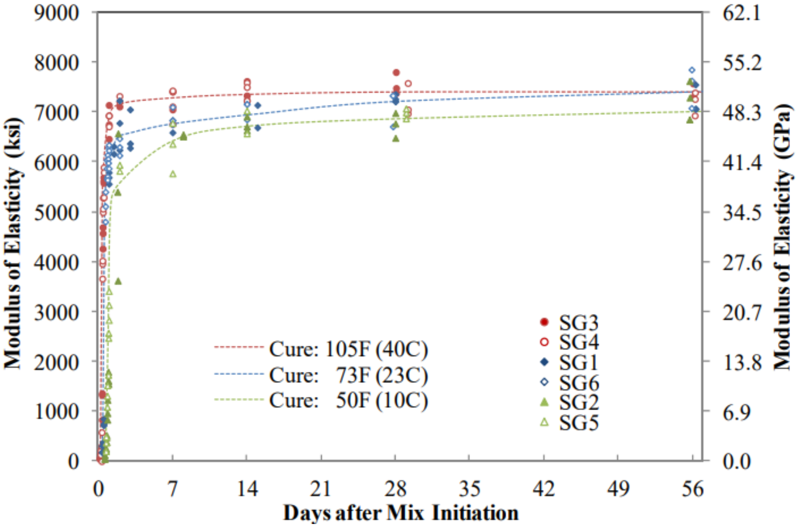


Figure 4: Modulus of elasticity of UHPC cured under different conditions (copied from Graybeal, 2012)

The modulus of elasticity equation for conventional concrete published in the American Concrete Institute (ACI 318, 2019) was found to overestimate the modulus of elasticity of UHPC when superimposed with the experimental data, while the AASHTO LRFD equation for conventional concrete showed a good fit with the data and found to be applicable for UHPC (El-Helou et al., 2022). The average compressive strength of UHPC at force transfer should be used to estimate the modulus of elasticity for the purpose of estimating the initial prestress loss. Generally, the modulus electricity of conventional concrete is found to be in the range of 2000 – 6000 ksi (14 to 41 GPa) compared to UHPC which can be between 6500 – 9400 ksi (45 to 65 GPa) (Ahlborn et al., 2008; El-Helou et al., 2022).

The experimental study for the full-scale girders conducted by Mohebbi and Graybeal (2022) resulted in a measured initial prestress loss in the range of 64% - 88% compared to the total prestress losses (sum of elastic shortening, creep, shrinkage, and strand relaxation). This leads to the conclusion that a good estimation of the modulus of elasticity would greatly enhance the prediction of the total prestress losses. The predicted prestress loss in the study was a good fit with the measured prestress loss. The elastic shortening was calculated using the directly measured compressive strength of 3 in. x 6 in. (75 mm x 150 mm) cylinders at the time of force transfer. The results also revealed that the time-dependent prestress losses in UHPC girders will be small within the range of 12% to 38% of the total prestress losses.

Mohebbi et al. (2022) suggested that secondary curing of the pretensioned girders after force transfer may not reduce creep in the girders because most of the creep occur within a short time after strand release. This suggestion can also apply to elastic shortening.

4. Unrestrained Shrinkage in UHPC

Shrinkage in concrete causes its volume change and must be evaluated. It is a stress independent element. There are three main types of concrete shrinkage: chemical, autogenous, and drying. Chemical shrinkage results when cement reacts with water. A reduction in the volume of both cement and water due to this reaction causes an internal volume reduction in concrete (Tazawa et al., 1995). Chemical shrinkage is directly related to the degree of hydration of concrete. Autogenous shrinkage is different from chemical shrinkage in that it causes external microstrain volume reduction of concrete. It takes place even if the concrete is totally closed and sealed with no transfer of moisture to the surrounding environment. It starts at an early age while the concrete is still workable and continues to take place after concrete hardening.

Drying shrinkage is defined as shrinkage caused because of water loss after concrete hardening. The drying shrinkage occurs when mixing water, not consumed in cement hydration, evaporates once the concrete is exposed to dry environmental conditions with low relative humidity. Some other factors affecting shrinkage in concrete include cement content, water-binder (w/b) ratio, silica fume content, the geometry of concrete members, coarse aggregate content, fiber content, and curing conditions (ACI 209.1R, 2005).

Because of the high cementitious content of UHPC and reduced aggregate content compared to conventional concrete, the total shrinkage is relatively increased. UHPC has a low w/b accompanied by the increased amount of silica fume leading to increased autogenous shrinkage. The admixtures used in UHPC can also affect the size, distribution, and chemistry of the pores in the paste.

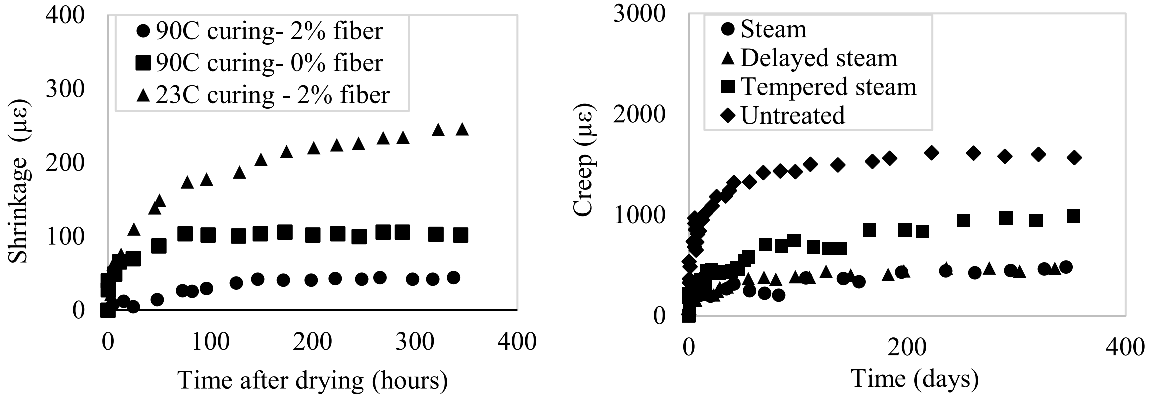
Recent studies reported that UHPC exhibits higher autogenous shrinkage and lower drying shrinkage compared to conventional concrete due to the high content of binder and low amount of water in the mixture, even though the increased steel fiber content in UHPC led to a significant reduction in autogenous shrinkage (Meng and Khayat, 2018).

Researchers who conducted shrinkage testing on UHPC using different curing conditions noticed a more stable behavior for UHPC with negligible drying shrinkage after the thermal treatment (Ahlborn, 2015; Flietstra, 2011; Garas et al., 2009). Most of the shrinkage was early high autogenous and found to take place during the thermal treatment. Ahlborn (2015) expressed this behavior as a "locked-in" property. Garas et al. (2009) conducted experimental free shrinkage testing to find out that thermal treatment in UHPC has more effect to limit shrinkage than fiber content, see Figure 5(a).

5. Compressive Creep in UHPC

Creep is the time-dependent increment in the strain of the hardened concrete under sustained load and in the case of prestressed concrete elements, it results in prestressing force losses. The creep recorded in UHPC was found to be less than that for conventional concrete (Haber et al., 2018). Drying shrinkage and creep most of the time take place simultaneously.

Factors that influence the creep rate of concrete include the age of concrete at loading, degree of hydration, pore water content, temperature, humidity, curing condition, and stiffness of concrete (Bazant and Wittmann, 1982). Other factors affecting creep in concrete are the strength of the concrete and stress level and its duration. Since the moisture movement in UHPC is negligible, the effect of the specimen size on creep results is no longer significant (Mohebbi and Graybeal, 2022). The creep coefficient (creep strain/elastic strain) for UHPC can vary depending on the maturity of the concrete and the curing treatment that has been applied. A creep coefficient of 0.3 was reported for UHPC after steam treatment, while the creep coefficient was as high as 0.78 for untreated UHPC at the same stress level (Graybeal, 2006), see Figure 5(b).



(a) (b)

Figure 5. Curing conditions effect on (a) shrinkage of UHPC (Garas et al., 2009) and (b) compression creep of UHPC (Graybeal, 2006)

6. Conclusion

Thermal treatment of UHPC produces a more stable behavior of material over time with "locked-in" properties. Early thermal treatment before load transfer can eliminate drying shrinkage, reduce compressive creep, and increase the modulus of elasticity which overall affects the time-dependent behavior of UHPC and reduces the total prestress losses. This leads to the importance of considering the time-dependent behavior of thermally treated UHPC members in the structural design guidelines of UHPC specifically related to prestress losses. Long term deflection was found to considerably change over time for ambient cured members which can adversely affect the serviceability and cause damage for the non-structural elements at the top of the girder.

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