Construction and Building Materials 167 (2018) 205–215

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Creep and shrinkage of lightweight self-consolidating concrete for prestressed members

Arthur Wendling [1], Kavitha Sadhasivam [2], Royce W. Floyd *

University of Oklahoma, School of Civil Engineering and Environmental Science, 202 W. Boyd St. Room 334, Norman, OK 73019, USA

HIGHLIGHTS

- Creep and shrinkage were measured for lightweight and normalweight SCC.
- Lightweight SCC exhibited greater creep and shrinkage than normalweight SCC.
- Lightweight SCC and normalweight SCC exhibited similar prestress losses.

ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form 29 January 2018
Accepted 4 February 2018

Keywords:
Lightweight aggregate
Self-consolidating
Concrete
Creep
Shrinkage
Prestress losses

ABSTRACT

Creep, shrinkage, and prestress losses were measured for lightweight (LWSCC) and normalweight self-consolidating concrete (SCC). A slight expansion was observed for LWSCC at early ages (less than 24 h), but a 100–300 microstrain larger total shrinkage compared to SCC was measured at one year of age for measurements beginning at one day in all environmental conditions. Greater total creep, but a smaller creep coefficient was observed for LWSCC compared to SCC. The creep coefficients at one year for specimens loaded at one day were 2.0 for LWSCC and 2.9 for SCC. Experimentally measured creep, shrinkage, and prestress losses were compared to ACI and AASHTO provisions to assess the suitability of the current provisions for LWSCC.

1. Introduction

Lightweight self-consolidating concrete (LWSCC) has become increasingly common for use in prestressed concrete applications due to the possibility for reduced dead load, labor, noise, and time of construction, improved surface finish in difficult to vibrate areas, and lower formwork pressure than normalweight self-consolidating concrete (SCC). An understanding of creep and shrinkage behaviors of concrete used in prestressed applications is especially important due to the need for accurate prestress loss predictions. The composition of LWSCC has the potential to significantly affect these behaviors. The study described in this paper was focused on experimental measurements of creep and shrinkage for LWSCC and SCC taken for one year and prestress loss measurements taken for nine months.

Exact definitions may vary, but SCC should flow and fill forms under its own weight without vibration, remain homogeneous through long flow distances and vertical drops, and flow through congested areas without blockage or segregation [1]. LWSCC typically has a density between 110 lb/ft^3 and 125 lb/ft^3 (1760 kg/m^3 and 2000 kg/m^3), a compressive strength of at least 3000 psi (20.7 MPa) for conventional use and 7000 psi (48.3 MPa) for bridge beams, and fresh properties in the same range as for normalweight SCC [2–4]. The density is slightly higher than the typical equilibrium density range for structural lightweight concrete of between 105 lb/ft^3 and 120 lb/ft^3 (1680 kg/m^3 and 1920 kg/m^3) [5] due to the increased cement content. LWSCC for bridge girders and other precast members has garnered more study in recent years due to a desire for weight reduction in long span girders and to fit with the increasingly common production methods used in precast plants [3]. In contrast to the benefits provided by LWSCC, the ACI 318 Building Code [6] uses a modification factor based on concrete density to take into account the reduced modulus of elasticity, tensile

---

* Corresponding author.
E-mail addresses: arthur.wendling@live.fr (A. Wendling), sadhasivam.kavitha@gmail.com (K. Sadhasivam), rfloyd@ou.edu (R.W. Floyd).

[1] Present address: Cedeti Ingenierie, 4 Rue Gutenberg BP 159, 67723 Hoerdt, France.

[2] Present address: PTAC Consulting Engineers, 49 Pineville Road, Monroeville, AL 36460, USA.

https://doi.org/10.1016/j.conbuildmat.2018.02.017

strength, shear strength, and torsion strength of lightweight concrete in comparison to conventional concrete with the same compressive strength [6,7].

The magnitude of concrete creep is affected by the magnitude of the applied load and duration of loading among other factors. Creep is typically represented by the ratio of creep strain over time to the initial elastic strain, termed the creep coefficient. Concrete shrinkage can be classified into autogenous shrinkage resulting from the initial hydration reaction and drying shrinkage. Autogenous shrinkage is very small for most typical concrete mixtures, but can be more important for concrete mixtures with high cement contents such as SCC. Drying shrinkage results from capillary forces caused by loss of capillary and adsorbed water from the cement paste to the environment during drying [8]. Concrete shrinkage is affected by a number of composition and environmental factors, and total shrinkage (sum of autogenous and drying shrinkage) for conventional concrete varies with changes in these factors [8]. Concrete creep and shrinkage are particularly important properties for prestressed concrete. The compressive stress caused by the prestress force results in concrete creep and the combined change in volume from this creep and free concrete shrinkage will result in a decrease in prestress over time. The resulting loss in prestress further complicates the prediction of concrete creep since the applied compressive stress is not constant. A number of factors affect creep and shrinkage including: aggregate content and stiffness, water-cement ratio (w/c), cement content, compressive strength, volume to surface area ratio (V/S), temperature, relative humidity, curing time, and age at loading [8–10]. Aggregate volume and inherent aggregate stiffness play a major role in providing restraint against shrinkage and stiffness to resist creep [8,11,12] and higher compressive strength usually leads to smaller magnitude of creep [13]. These factors are included in the typical prediction methods [8,14].

Lightweight aggregates have a high absorption capacity and are typically prewetted before mixing to ensure no water is lost from the mix. The water stored in the aggregates is gradually released over time after the concrete has set, which allows cement and supplementary cementitious materials to continue to hydrate after external curing is terminated, as long as water remains inside the aggregates. This process is called internal curing. Internal curing results in a reduction of plastic shrinkage and can entirely eliminate autogenous shrinkage [15,16]. It has been suggested that the internal curing will decrease the permeability of the concrete, which will reduce creep, but the reduction in the proportion of unhydrated cement will increase creep since these particles typically provide additional restraint [17].

Previous research related to lightweight concrete has indicated an expansion occurs at very early ages [18–21], but the concrete will have a higher final shrinkage [13,17,18,21–24] than conventional concrete. Lower shrinkage at early ages and a reduced shrinkage rate have been observed in multiple studies [13,17]. The lower early age shrinkage can be at least partially attributed to a reduction of autogenous shrinkage due to internal curing [25] which can be important for concrete mixtures with high cement contents. Larger final creep values have been observed [22,26] with some reduction at early ages [18]. Other researchers have observed similar creep coefficients for both lightweight concrete and normalweight concrete at later ages [20,23]. When considering SCC compared to conventional concrete, larger drying shrinkage and creep have been observed due to increased cement content [27]. Recent studies comparing LWSCC and SCC have indicated that LWSCC has lower shrinkage values [28,29] and a smaller creep coefficient [24,28]. In general it is expected that SCC and lightweight concrete will have a higher total shrinkage than their normalweight counterparts in spite of a small expansion at early ages and reduction of autogenous shrinkage due to internal curing. It is also expected that they will have higher creep values than their normalweight counterparts, but a smaller creep coefficient due to a reduced modulus of elasticity and corresponding increased elastic strain. Vincent et al. [26] compared the creep and shrinkage performance of a high strength lightweight concrete to the ACI 209 [8] prediction methods appropriate for lightweight aggregates. They found that the ACI 209 method provided the best prediction when accelerated curing was used and the GL2000 model was best for standard curing [26].

Larger prestress losses have been measured for lightweight concrete and SCC. The elastic shortening of lightweight concrete members is expected to be greater due to the reduced modulus of elasticity from the less stiff lightweight aggregates [16,29]. The reduced coarse aggregate content used for SCC also tends to reduce the modulus of elasticity [30]. Larger long-term losses have been measured for lightweight concrete and LWSCC due to increased creep in spite of reduced prestress force from the larger elastic shortening and increased shrinkage for LWSCC compared to normalweight SCC [28,29]. Holste et al. [28] measured total losses that were very similar for SCC and LWSCC. High performance lightweight concrete has in some cases exhibited smaller losses than conventional concrete [17].

A deeper understanding of the effects of LWSCC composition on long-term behavior is needed as the benefits of using LWSCC make its use more widespread. The composition of SCC, and specifically LWSCC, has the potential to affect the time dependent deformation leading to prestress losses. An accurate estimate of prestress losses for LWSCC is important for serviceability concerns including camber, deflection, and service load stresses. In the study described in this paper, laboratory tests for creep and shrinkage were conducted on SCC specimens cast with both expanded shale lightweight aggregate and conventional limestone, and prestress losses were measured for LWSCC and SCC beams. The main objective of this study was to compare LWSCC creep and shrinkage behavior to normalweight SCC, existing code provisions, and previous research.

2. Materials and methods

The coarse aggregates used throughout the project included limestone and expanded shale lightweight aggregate both with a particle size distribution ranging from a nominal maximum size of ¾ in. (19 mm) to a No. 4 sieve (4.75 mm). The specific gravity and the absorption capacity of the expanded shale were measured after 24 h of soaking using Appendices A and B of ACI 211.2-98 [31]. Aggregate samples both oven dried before soaking and taken directly from the stockpile were tested. The lightweight aggregates were soaked for 24 h prior to casting for all batches in order to reduce absorption of free mixing water during mixing. The fine aggregate used throughout this project was a locally available concrete sand. Table 1 gives a summary of the properties of each aggregate. Type I cement was used for all concrete mixtures.

SCC and LWSCC mix designs used for testing are presented in Table 2. Concrete workability was assessed using the slump flow and T_{50} and segregation resistance was evaluated using the Visual Stability Index (VSI), all as specified by ASTM C1611 [32]. Passing

Table 1
Fine and coarse aggregate properties.

Property	Sand	Limestone	Expanded Shale
Specific Gravity	2.63	2.68	1.46 (Wet Condition) 1.47 (Dry Condition)
Absorption Capacity (%)	0.86	0.86	18.0 (Wet Condition) 15.0 (Dry Condition)