Studies on Creep and Shrinkage in Normal and Heavy Density Concrete

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Abstract— In this research, there are lead to understanding on how and why lightweight concretes (LWC) may achieve similar or higher performance than their normal weight counterparts. The present paper reviews some of these aspects beginning with basic properties such as unit weight, compressive strength and specific strength (strength/unit weight). Stability and workability of LWC is discussed from rheological perspective. The volumetric stability of LWC in terms of shrinkage and creep are presented with some recent published data. Transport properties of the LWC in terms of sorptivity, water permeability and resistance to chloride-ion penetration are reviewed in comparison with normal weight concrete. Fire resistance of LWC and some current measures used to improve the resistance are discussed. With continual research and development, the performance of LWC is being enhanced to provide new opportunities for practical applications.

Key words: LWC, HPLWC, Heavy Density Concrete

I. INTRODUCTION

Lightweight concrete (LWC) has been used for structural applications for many years. In last two decades, there is significant development in high-performance lightweight concrete (HPLWC). Although some of the LWC may not have strengths as high as those of normal weight concrete (NWC), they have high specific strengths (defined as compressive strength/unit weight) similar to those of high-strength normal weight concrete (HSNWC). This paper reviews properties of HPLWC shrinkage and creep. These properties are critical for practical applications.

Structural lightweight aggregate concrete is an important and versatile material in modern construction. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world. Structural lightweight aggregate concrete solves weight and durability problems in buildings and exposed structures. Lightweight concrete has strengths comparable to normal weight concrete, yet is typically 25% to 35% lighter. Structural lightweight concrete offers design flexibility and substantial cost savings by providing: less dead load, improved seismic structural response, longer spans, better fire ratings, thinner sections, decreased story height, smaller size structural members, less reinforcing steel, and lower foundation costs. Lightweight concrete precast elements offer reduced transportation and placement costs.

II. LITERATURE REVIEW

Al-Khaja (1994) found similar results of reduced shrinkage, creep, and total deformation of high-strength concrete (HSC) using cementitious material SF. The study investigated the efficiency of SF in HSC, and it has reported that the concrete made with SF is useful for prestress concrete structural applications especially where prestress losses are primarily influenced by shrinkage and creep.

Nasser et al. (1986) investigated shrinkage and creep behavior of concrete using cementitious material FA, and the results were compared with reference concrete. It was observed that the shrinkage was almost the same with and without FA in concrete, but creep increased in the case of FA concrete.

Haque (1996) studied the drying shrinkage of HSC using SCMs like SF, FA, and GGBS. It was observed that SF in the range of 5–10% replacement of cement by weight in concrete reduced the influence of drying shrinkage of HSC. He further observed that with more than 20% replacement of cement by FA or GGBS increased the shrinkage strain substantially. Brooks (1999) assessed the long-term effects of concrete deformation without and with SCMs like FA, SF, and GGBS having the same mix proportion of concrete. He has reported that the GGBS and FA have potential to reduce creep in concrete, but no change has been observed in shrinkage. A small quantity of cement replacement with SF in concrete decreased the creep, but beyond 16% replacement creep increased.

Brooks (1999) has reported that the cementitious material SF does not appreciably affect the shrinkage behavior, but the predominant type of shrinkage observed is the autogenous and not the drying shrinkage.

Mokhtarzadeh and French (2000) studied the shrinkage and creep of HSC having 28 days compressive strength of mixes in the range of 52–128 MPa. The cementitious materials Class C FA 20% and SF 7.5% have been used as replacement by weight of Type I and III OPC (445 kg/m^3) with a w/=% ratio 0.3 and reported that the mix compositions having partial replacement of cement by cementitious materials, i.e., FA and SF had lower specific creep with reference to the standard mix using only OPC. Further, no significant effect on drying shrinkage has been observed in HSC using cementitious materials FA and SF.

Huo et al. (2001) performed experimental study on three different HPC mixes using cementitious materials FA and SF with OPC as a binder. The study shows that HPC shrinkage and creep are lower than of the conventional concrete and tends to develop rapidly in early age. Jianyong and Yan (2001) studied drying shrinkage and creep behavior of HPC using cementitious materials GGBS and SF, and the results of drying shrinkage and creep were compared with those of reference concrete that used only OPC. The test results show that drying shrinkage and creep behavior of HPC is significantly reduced by using GGBS and SF in concrete.

Mozloom et al. (2004) investigated the effects of cementitious material SF in HSC. The results show that concrete mixes having fixed w/b ratio 0.35, constant binder...
of 500 kg/m3 and different amount of SF as replacement of OPC in the range 0–15%, the autogenous shrinkage increased, and its drying shrinkage and specific creep decreased.

It is evident from past studies that the effect of SCMs in concrete as partial replacement of cement has been studied by many researchers by measuring the secondary effects and creep strain. In fact, because of wide variation in characteristics of cement and cementitious materials used worldwide and guidelines for concrete mix design description differing from country to country, there is a need for more study especially for this geographic region. Nevertheless, owing to complexity of the problem and use of differently sourced ingredients, the extent of influence of SCMs like FA, SF, and GGBS on shrinkage and creep of HPC is still not fully known. Furthermore, the durability and sustainability aspect as microstructure changes need to be evaluated under local environmental and using indigenously sourced material has not been looked into especially under Indian conditions. Also, any gain in durability attributable to use of SCMs would improve the life cycle performance of built infrastructure. Therefore, an experimental investigation has been carried out in drying conditions to study the performance using three different SCMs, namely, FA, SF, and GGBS. This comprehensive experimental study focuses on change in permeability with time affecting durability and variation of secondary effects such as shrinkage, creep, and total deformation of HPC over a period of approximately 800 days.

Estimation of creep and shrinkage are critical in order to compute loss of prestress with time in order to compute leak tightness and assess safety margins available in containment structures of nuclear power plants. Short-term creep and shrinkage experiments have been conducted using in-house test facilities developed specifically for the present research program on 35MPa and 45MPa normal concrete and 25MPa heavy density concrete. Drying shrinkage and creep in concrete have been quantified for different strength grades of normal and heavy density concrete under controlled relative humidity, temperature, and age of loading. Summary and findings emerging from the study are:

Existing empirical models for creep and shrinkage prediction have been used to simulate the test results and found to make satisfactory predictions for short term data, in particular for heavy density concrete. Limited number of short term measurements of concrete creep and shrinkage, along with water loss estimates in shrinkage specimen has been used to effectively predict longer duration measurements of creep and shrinkage for both normal and heavy density concrete.

Extrapolation of theses models for very long term predictions of creep and shrinkage using Bayesian updating methods along with statistical sampling to account for parameter uncertainties has also been carried out. Scanning electron microscopy (SEM) images have shown differences in the extent of hydration in normal and heavy density concrete over the same period of time when cured under identical conditions. Higher levels of shrinkage and creep are present in heavy density concrete.

Long term creep prediction using short term data for normal and heavy density concrete. An analytical model accounting for the hygro-thermo-chemo-mechanical coupling (load levels, temperature, relative humidity, chemical composition and hydration rate) for creep and shrinkage prediction is under development. Nano- and micro-indenting of concrete samples used in creep studies is being undertaken to develop an understanding of the changes in the compliance of the hydrated concrete at different length scales across grain boundaries. Ongoing work on hygro-thermo-chemo-mechanical modeling of concrete to study creep and shrinkage will be extended to account for high temperature conditions, such as due to fires.

III. METHODOLOGY

A. Shrinkage and Creep

The entire study has been conducted in a creep and shrinkage laboratory under controlled environmental conditions having temperature 20 ± 2°C and relative humidity 60 ± 5%, maintained throughout the test duration. Because of constraints of creep setup in the laboratory and to maintain appropriate stress to strength ratio at prolonged duration, the creep specimens were loaded under uniaxial compressive stress such that stress to strength ratios were 0.30 0.02 for prisms and 0.20 0.02 for cylinders, where the strengths were obtained by the testing of three respective creep specimens at the age of 28 days. The companion shrinkage for unloaded specimens was simultaneously measured for all four HPC mixes under the same controlled environmental conditions. Three specimens each have been put under observation for shrinkage and creep measurement, and shortening of specimens was recorded at different time intervals. There was not much variation in the experimentally measured values of individual test specimens. The greatest percentage difference among the specimens was 3%, and hence average values are reported.

B. Scanning Electron Microscope (SEM)

The scanning electron microscopy (SEM) LEO 435 VP Instruments technique has been used to characterize pores, air voids, and hydration phase of all HPC mixes. To investigate the effects of SCMs in HPC, microscopic images have been taken from each concrete at age of 3, 28, and 110 days, respectively. The HPC cubic specimen of each mix was crushed at the age of 3, 28, and 110 days, and from the center portion small fragment samples were taken and analyzed using the SEM technique. The fragment samples ensure the conductive nature, and were coated with gold before using the SEM technique.

C. Mechanisms of Shrinkage and Creep

Consideration However, various terms of shrinkage and creep of concrete have been described differently in literature. Nevertheless, it is almost common in conventional practices to ignore the distinction between the autogenous shrinkage and the drying shrinkage, and the basic creep and the drying creep to find total shrinkage and creep in drying conditions (Buil and Acker 1985; Mehta and Monteiro 2006). Usually, total shrinkage is simply considered as stress free deformations (i.e., volumetric changes) of concrete specimen that is the sum of autogenous strain and drying strain, whereas creep is simply considered as the deformations of concrete specimen under constant uniaxial
sustained stress that is free from elastic strain and total shrinkage at drying conditions (Mehta and Monteiro 2006).

Therefore, the factors affecting the autogenous and drying shrinkage and basic and drying creep of HPC and separate determination of these experimentally is outside the scope of the present research work. Only common conventional practices to find shrinkage and creep of HPC have been followed in drying conditions, and the results were used for a comparative study.

D. Shrinkage
Shrinkage refers to the reduction of the volume of a concrete associated with the evaporation of the water contained in the concrete. It is composed of two simultaneous effects, drying shrinkage and carbonation shrinkage.

1) Drying Shrinkage
Drying shrinkage occurs when internal water is lost through evaporation. Drying shrinkage occurs only in the cement paste. Long term deflection of concrete element under sustained load, and depends on several factors associated with the cement paste. The major factors affecting drying shrinkage are cement factor, stiffness of the aggregates, water content, type of cement, curing and storage conditions and the size of the concrete member.

2) Carbonation Shrinkage
Carbonation shrinkage occurs due to the interaction of the internal water and CO2 in the air. As a result, the calcium hydroxide in the cement paste (Ca(OH)z) is converted to calcium carbonate (CaC03). The new CaC03 forms in the voids of the hardened paste, thereby decreasing its volume. The schematic chemical reaction is as follows: The water produced from the reaction fills the voids and must diffuse out of the concrete for carbonation shrinkage to occur.

E. Definition of Creep
According to ACI Committee 2005, the main mechanisms which describe creep are:
- Viscous flow of the cement paste caused by sliding or shear of the gel particles lubricated by layers of absorbed water,
- Consolidation due to seepage in the form of absorbed water or the decomposition of interlayer hydrate water,
- Delayed elasticity due to the cement paste acting as a restraint on the elastic deformation of the skeleton formed by the aggregate and gel crystals, and
- Permanent deformation caused by local failure (microcracking and crystal failure) as well as recrystallization and formation of new physical bonds.

This research study does not involve the study of the mechanisms of creep, but rather of the overall creep characteristics of concrete containing fly ash. In a simplistic definition, creep is the internal strain associated with the effects of a constant applied stress.

F. Definition of Creep Recovery
The designation creep recovery is given by analogy to creep; however, the two phenomena are different. The mechanisms proposed for creep recovery are as contradictory as the ones proposed for creep; nevertheless, they agree on the fact that it is caused by the reentry of the water to the concrete matrix and the slipping back of the broken bonds to the original position. In this study creep recovery refers to the partial recovery of the total deformation created by a constant sustained load.

IV. RESULTS AND DISCUSSION

A. Shrinkage
Shrinkage of LWC depends on water-to-cement ratio (w/c), type of cement, degree of cement hydration, characteristics, amount, and elastic modulus of aggregate used, and water content in the aggregate. When exposed to a dry environment after an initial moist curing, total shrinkage of concrete may be divided into two components – drying shrinkage and autogenous shrinkage. The autogenous shrinkage is a consequence of the withdrawal of water from the capillary pores by the hydration of cement, a process known as self-desiccation.

For HPC, the autogenous shrinkage may consist of a significant portion of the total shrinkage at early age due to their low w/c. However, after 28 days of moist curing, any subsequent autogenous shrinkage should be nearly negligible relative to drying shrinkage total shrinkage of HPLWC published in recent years in comparison to that of HPNWC. These data were obtained from concrete specimens after initial moist curing of various lengths, thus the data are a combination of drying and autogenous shrinkage. Lightweight aggregate concretes generally have lower shrinkage rates and values at early age, but the ultimate shrinkages are higher than those of normal weight concrete. Lower shrinkage of LWC at earlier age is also reported by other researchers. Approximately the same 500-day total shrinkage for NWC and LWC with prewetted LWA was reported by Lopez. However, if dry LWA was used, total shrinkage of the LWC was higher than that of the NWC at 500 days.

The lower shrinkage of LWC at early age may be attributed to water absorbed inside the LWA which contributes to “internal curing” of concrete and compensates for water loss when concrete specimens are exposed to dry environment. This “internal curing” contributes to reduced autogenous shrinkage and drying shrinkage of LWC in comparison with NWC. Numerous papers on the use of pre-soaked LWA to reduce shrinkage and improve concrete performance were published in recent years. Higher ultimate shrinkage of LWC may be explained by the lower modulus of elasticity of the LWA that have less restraint effect on the shrinkage compared with the normal weight aggregate (NWA) particles.

Comparing lightweight and normal weight concrete of similar 28-day strength, the lightweight concrete would probably have lower risk of shrinkage cracking under the same restraint conditions at early age due to its lower shrinkage and modulus of elasticity. Incorporation of 5% silica fume reduced the total shrinkage of concrete significantly, and its effect on HPLWC is more substantial than that on the HPNWC.

B. Creep
Creep Similar to shrinkage, creep behaviour of LWC is also affected considerably by elastic properties of aggregates and their relative proportions in concrete. Due to length of testing, there is less information available on creep behaviour of HPLWC. Some limited information available from literature.
A brief literature review for creep of HPLWC was presented in a paper by Lopez et al. Berra and Ferrara investigated creep behaviour of LWC with 28-day compressive strength of 47.6 – 59.4MPa (cured in 95% RH) and 49.2–61.4MPa (cured in 50% RH). They reported specific creep of the LWC twice that of NWC of the same strength. Lopez et al. investigated creep behavior of LWC stored at 50% RH and 21°C for a period of 620 days. Compressive strength of the LWC at 56 days was from 68.5 to 75.4MPa. One half of the specimens were loaded to 40% and the other half to 60% of the compressive strength. Within each group of specimens, some were loaded at 16 hrs and the rest at 24hrs after casting. They found that time under load and compressive strength at the age of loading are significant parameters for the creep.

Difference in creep coefficient between loading at 16 and 24hrs were 2.5% and between loading to 40 and 60% of initial strength was 1.5%. The 620-day creep coefficient of a LWC with 56-day strength of 75.4MPa was 22% lower than that of a LWC with 56-day strength of 68.5MPa. The former had a specific creep similar to that of a NWC of the same grade but less cement paste and significantly lower specific creep than a NWC of the same grade and similar paste content. Malhotra investigated creep behaviour of HPLWC with or without fly ash and silica fume moist cured for 1 year. After 370 days under loading, the concretes with fly ash and silica fume had lower creep strains than the reference Portland cement concretes. He attributed the lower creep strains of the former to large amount of residual unreacted fly ash which would act as aggregate and provide restraint to deformation. Effect of internally stored water in LWA on creep of HPC with w/cm of 0.23 was investigated by Lopez et al. The experiments included a concrete with prewetted coarse LWA (LWW), a concrete with dry coarse LWA (LWD), and a reference concrete with NWA. Natural sand was used for all three concretes. They found that LWW mixture showed lowest specific creep among the three concretes after 500 days under load. However, without internally stored water in the LWA, the LWD mixture had higher creep than the reference NWA mixture.

It was also found that basic creep was much higher than drying creep for all these concretes. They attributed the reduction of creep in the LWC with pre wetted aggregate to three mechanisms: enhanced cement hydration, expansion of microstructure, and water seepage inhibition due to the internally stored water in LWA. Comparing the results from these three concretes, they concluded that a higher compressive strength did not necessarily ensure lower creep because compressive strength and creep did not depend on the same factors to the same extent.

V. CONCLUSIONS
From the above review on high-strength high-performance LWC, some of the significant conclusions are summarized as follows:

1) High strength high-performance LWC (compressive strength workability, mechanical properties, and durability can be produced by using quality LWA, low w/c, silica fume, and chemical admixtures in the concrete. Such concrete has been used in structures in practice.

2) If the difference between the particle density of LWA and the density of mortar matrix is relatively large, caution should be exercised to avoid overdoses of super plasticizers and air entraining admixtures in order to reduce potential segregation of fresh concrete.

3) Lightweight aggregate concretes generally have lower shrinkage rates and values at early age, but the ultimate shrinkages are higher than those of normal weight concrete. The lower shrinkage of LWC at early age may be attributed to water absorbed inside the LWA which contributes to “internal curing” of concrete and compensates for water loss when concrete specimens are exposed to dry environment.

4) Reported results on creep of HPLWC in comparison to that of HSNWC do not always agree. It is found that LWC with pre-wetted LWA has lower specific creep after 500 days under load than NWC. However, the LWC with dry LWA has higher creep than the NWC. The reduction of creep in the LWC with pre wetted aggregate is attributed to enhanced cement hydration, expansion of microstructure, and water seepage inhibition due to the internally stored water in LWA.

5) Lightweight concrete had lower water sorptivity, water permeability and higher resistance to chloride-ion penetration than the NWC of similar 28-day strength. The LWC with only coarse LWA had similar transport properties compared to NWC of similar w/c. However, the resistance of the LWC to chloride-ion penetration decreased with the increase in the cumulative LWA content in the concrete.

6) High-performance LWC has more spalling than their normal weight counterpart when exposed to hydrocarbon fire. However, the properties of the concrete in the middle of the testing blocks were not significantly affected by the fire exposure. Low w/c LWC made with silica fume blended cement requires more polypropylene fibers than for a higher w/c concrete.

REFERENCES


