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HIGH-STRENGTH HIGH-PERFORMANCE LIGHTWEIGHT CONCRETE – A REVIEW

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Abstract

In the last two decades, there are developments that lead to greater 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.

1. 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 such as unit weight, compressive strength, specific strength, workability, stability, shrinkage, creep, permeability, and fire resistance. These properties are critical for practical applications. Focus will be on HPLWC with unit weight of < 2000 kg/m^3 and specific strength of $\geqslant 0.025$ MPa/kg/m^3.

2. DENSITY, COMPRESSIVE STRENGTH AND SPECIFIC STRENGTH

With advances in concrete technology, particularly the development of high-range water reducing admixtures, high-strength concrete (HSC) with low w/c (below 0.35) can be produced with satisfactory workability. With low w/c, cement pastes (or mortars with natural sand) in LWC are often stronger than LWA particles. Thus the strength of LWA particles can be critical in the strength of LWC. This is the same as in HSNWC.

Because of various sizes and amounts of voids in LWA, there are strength ceilings for each type of the LWA above which it is difficult to achieve increased strength without significant increase in the strength of cement paste or mortar matrix. Nevertheless, even with a porous LWA, HSLWC with 28-day cube compressive strength of 102.4 MPa was obtained and reported [1]. This LWC had fresh concrete unit weight of 1865 kg/m^3, which gives a specific strength of 0.055 MPa/kg/m^3. For more homogeneous materials, such as ceramics, strength is closely related to the total porosity and pore size. However, this may not be the case for a composite material like LWC. Use of a high-strength and dense matrix will result in a much higher total strength than would be expected considering the porous aggregate alone. When LWC is subjected to a uniaxial compressive load, the aggregate is subjected to lateral confinement of the surrounding matrix which may lead to higher strength of the LWA.

In addition to HSLWC with unit weight of around 1800-2000 kg/m^3, efforts have also been made to obtain structural LWC with unit weight as low as possible. Some of them are intended for applications in floating structures. Table 1 gives some examples of HPLWC developed since early 1990. High-performance LWC has also been used more and more in practice since that time. Table 2 lists some examples of structures using HPLWC.

3. STABILITY AND WORKABILITY FROM RHEOLOGICAL PERSPECTIVE

In practice, as lightweight aggregates often have lower particle densities than the density of the mortar matrix in concrete, upward movement of the coarse aggregates and thus segregation may take place when the workability of the fresh concrete is not appropriate. This is in contrast to the normal weight aggregate concrete (NWC) where coarse aggregates may sink to bottom if the workability is not appropriate.

There is considerable evidence [2] that the behavior of fresh concrete can be reasonably approximated by Bingham model as follows

$$\tau = \tau_0 + \eta_p \dot{\gamma} \qquad (1)$$

where τ is shear stress, τ_0 is yield stress, η_p is plastic viscosity, and $\dot{\gamma}$ is shear rate. As concrete is a viscoplastic material, it behaves as a solid below its yield stress, and flows like a liquid above the yield stress. Plastic viscosity governs the flow once the yield stress is overcome. With the two parameters - yield stress and plastic viscosity - the flow of concrete can be described quantitatively. Development in the area of concrete rheology has gained pace in the last decade, although most studies are concentrated on normalweight concretes [3, 4].

Fresh concrete may be considered as a two-phase composite material with coarse aggregate particles in a continuous mortar matrix. Beris et al [5] predicted that a spherical particle would settle in a fluid with Bingham plastic behavior only when the dimensionless parameter Y_g (referred to as the yield stress parameter) defined below is less than 0.143, assuming the spherical particle has a higher density than the fluid.

$$Y_g = \frac{3\tau_0}{2R(\rho_s - \rho_f)g} \tag{2}$$

where R is radius of a sphere, τ_0 is yield stress of fluid, $(\rho_s - \rho_f)$ is the density difference between the sphere and fluid, and g is the acceleration due to gravity. Once the settlement starts, the movement of a spherical particle in a Bingham fluid may be derived from Stokes drag [6],

$$U = \frac{2R^2(\rho_s - \rho_f)g}{9\eta_p C_s} \tag{3}$$

where U is its velocity of movement in the fluid, η_p is plastic viscosity of the fluid, and C_s is the Stokes drag coefficient.

From the above, it is apparent that in fresh NWC the start of settlement of coarse aggregate particles depends on the yield stress of the mortar, the density difference between the aggregate particles and the mortar, and the size of the coarse aggregate. Once movement occurs, the velocity of the settlement is affected by the plastic viscosity of the mortar in addition to the density difference between the coarse aggregate particle and the mortar, and the size of the coarse aggregate. Although the movement of particles in LWC is upward, the principle parameters that affect the stability of the fresh concrete is the same as discussed above. For given mixture proportion, LWC with denser LWA is more stable to segregation compared with LWC having less dense LWA [7, 8] partly due to lower density difference between the LWA and mortar. Furthermore, LWC with lower yield stress and plastic viscosity had lower stability in segregation, although the effect was more pronounced for the decrease in yield stress. The trends agree well with the Equations (2) and (3).

In practice, air entrainment is known to produce more cohesive concrete with lower tendency to segregate. This is also true for self-compacting LWC [9]. However, the stability of air entrained LWC decreased as air entrainment content increased, possibly due to lowering of the plastic viscosity [7, 8]. For given slump, an air entrained LWC (6% air) used less superplasticizer and has better stability than corresponding non-air entrained LWC (4% air) [10].

From rheological viewpoint, air entrained LWC had higher yield stress but lower plastic viscosity than non-air entrained LWC at similar slump, implying that the former requires a higher shear stress to initiate flow but flows with less resistance, compared with the latter [11]. On the other hand, for given superplasticizer dosage, the air entrained LWC had lower yield stress and plastic viscosity but higher slump than the non-air entrained LWC. However, the extent of the increase in slump with increasing entrained-air content was not significant, compared to the initial introduction of air entrainment in the concrete.

Although reducing yield stress and plastic viscosity in concrete produces the undesirable effect of lower resistance to segregation, this change will lead to higher workability from a flow perspective. Thus, in design of LWC mixtures there is a need to strike a compromise to achieve the required workability and stability of the concrete. Regular chemical admixtures such as superplasticizers and air-entraining admixtures improve the workability differently from rheology perspective, although both affect the rheological parameters of LWC in some similar ways as NWC [12]. Increase in superplasticizer content in LWC reduced the yield stress but did not have a significant effect on the plastic viscosity. On the other hand, yield stress of air entrained LWC was lower than that of non-air entrained LWC with the same mixture proportion and superplasticizer dosage. However, the yield stress was not affected by the change in air content in the range of 6 to 17%. Plastic viscosity, on the other hand, was reduced with an increase in entrained air content.

For production of LWC, the LWA is often selected based on its availability and particle density to achieve specified strength and unit weight of concrete. 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 superplasticizers and air entraining admixtures in order to reduce potential segregation of fresh concrete. In design of LWC mixtures with a specified slump, air entrainment is recommended for improvement of both the workability and the stability of fresh concrete even when the concrete is not subjected to repeated freezing and thawing cycles. However, for concrete with a given maximum aggregate size, the amount of air entrainment should be limited based on considerations of stability and mechanical properties.

4. ELASTICITY, SHRINKAGE, AND CREEP

4.1 Elastic modulus

Elastic modulus of LWC is generally lower than that of concrete made with normal weight aggregates. Elastic modulus of normal weight aggregates is typically within a range of 70 - 140 GPa, whereas LWA may have elastic moduli of 14 to 35 GPa [13]. Actual E value of the LWC depends on pore structure and relative proportion of LWA used as well as characteristics of cement paste/mortar matrices. For a given coarse LWA, lightweight concretes with natural sand have higher modulus of elasticity than those with lightweight sand. For a given mortar matrix of LWC, higher porosity of coarse LWA usually leads to lower E-modulus of concrete. Because of the lower elastic modulus of LWC, long term deformations such as drying shrinkage and creep of concrete may be affected.

4.2 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 [14].

Table 3 summarizes 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 has lower shrinkage rates and values at early age, but the ultimate shrinkages are higher than those of normal weight concrete [15, 16] (Figure 1). Lower shrinkage of LWC at earlier age is also reported by other researchers [14, 17, 18]. Approximately the same 500-day total shrinkage for NWC and LWC with prewetted

LWA was reported by Lopez [14]. However, if dry LWA was used, total shrinkage of the LWC was higher than that of the NWC at 500 days [14].

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 [19, 20] and drying shrinkage [14] 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 [21-23].

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 [16].

4.3 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 is summarized in Table 4. A brief literature review for creep of HPLWC was presented in a paper by Lopez et al. [24].

Berra and Ferrara [15] investigated creep behaviour of LWC with 28-day compressive strength of 47.6 – 59.4 MPa (cured in 95% RH) and 49.2 – 61.4 MPa (cured in 50% RH). They reported specific creep of the LWC twice that of NWC of the same strength.

Lopez et al. [24] investigated creep behavior of LWC stored at 50% RH and 21 ^{o}C for a period of 620 days. Compressive strength of the LWC at 56 days was from 68.5 to 75.4 MPa. 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 24 hrs 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 24 hrs 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 75.4 MPa was 22% lower than that of a LWC with 56-day strength of 68.5 MPa. 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 [25] 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 eta al. [14]. 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 the 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 prewetted 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.

5. WATER ABSORPTION, PERMEABILITY, AND CHLORIDE-ION PENETRATION

Lightweight aggregates generally have higher porosity than NWA. However, the permeability of LWC may not necessarily be higher than that of NWC. Lightweight aggregate concrete differs from NWC in a number of aspects such as increased porosity, improved interfacial transition zone, improved cement hydration due to internal curing, and reduced microcracking that may affect the transport of water and chloride-ions in the concrete. The actual transport properties of the LWC in comparison to those of the NWC depend on which of these factors are dominant. The connectivity of the pore system is of primary importance. Quality of the paste matrix in LWC is generally more important in controlling the transport properties of the concrete [26, 27].

According to Nyame [28], mortars incorporating lightweight sand and with a water-to-cement ratio (w/c) of 0.47 were about twice as permeable as those made with natural sand. Bentz [29], however, found that the chloride ion diffusivity estimated from the chloride penetration depth of the mortar with 31% lightweight sand was at least 25% lower compared with the mortar with normal weight sand. He attributed the reduced chloride ion diffusivity to reduced interfacial transition zone (ITZ) percolation and enhanced cement hydration due to internal curing effect from the lightweight sand. For LWC, Al-Khaiat and Haque [30] found that the concentrations of chloride penetrated into the LWC with both coarse and fine LWA were somewhat higher than that in normal weight aggregate concrete of the same 28-day compressive strength of 50 MPa.

Water absorption, permeability, and resistance to chloride-ion penetration of concretes with different cumulative LWA contents were investigated systematically by Liu et. al. [31]. The experiments included four LWCs with increased LWA from about 50 % (only coarse LWA) to 100% by volume of total aggregate (all LWA) in comparison to a control NWC with similar w/c of 0.38 and a control NWC with similar 28-day strength (w/c of 0.54). They found that although the total charge passed, migration coefficient, and diffusion coefficient of the LWC were not significantly different from those of NWC with the same w/c of 0.38, the resistance of the LWC to chloride-ion penetration decreased with the increase in the cumulative LWA content in the concrete. The water penetration depth under pressure and water sorptivity showed, in general, similar trends. The LWC with only coarse LWA had similar water sorptivity, water permeability coefficient and resistance to chloride-ion penetration compared to NWC with similar w/c. The LWC had lower water sorptivity, water permeability and higher resistance to chloride-ion penetration than the NWC with similar 28-day strength [31].

By comparison of coarse aggregates of different porosities, it was found that the incorporation of coarse LWA in concrete increased the water sorptivity and permeability slightly compared to NWC of similar w/cm [26]. This is related to increased porosity of the concrete due to pores in coarse LWA. Resistance of the sand-LWC to chloride-ion penetration depends on the porosity of the coarse LWA. Performance of the LWC with a less porous coarse LWA was similar to that of NWC, whereas a more porous coarse LWA tends to reduce resistance of the LWC to chloride-ion penetration [26].

Effective w/c of LWC is affected by the water absorption of LWA, which in turn directly influences the resistance to water and chloride-ion penetration in concrete. Thus, the water absorption of LWA, especially those fine crushed particles, needs to be carefully determined, and trial mixes are recommended for structures exposed to severe environments [31].

6. FIRE RESISTANCE

Fire resistance of HPC with low w/c has been of concern due to explosive spallings of concrete surface layers observed in laboratory tests [32-36] and in structures [37]. Such failure pattern is not generally observed in ordinary concrete [38]. The extent of spalling and damage of HPC is affected by a number of factors such as heating rate, specimen size, concrete permeability and moisture condition [39]. Main mechanism of the explosive spalling is believed due to the buildup of high pressures within the HPC as a result of liquid-vapor transition of water in capillary pores at high temperatures. Polypropylene fibers have been used to overcome this problem [33-35, 40].

Bentz [41] presented a comprehensive review and study on fibers, percolation, and spalling of HPC exposed to fire. He applied a three-dimensional model for fiber-reinforced concrete to examine the spalling phenomena of HPC. Hypothesis that the percolation of the interface transition zone (ITZ) between aggregate and cement paste matrix in concrete is of paramount importance to spalling is supported by simulations and experimental results. Efficiency of fibers to percolate ITZ has been clearly demonstrated in his study. His study also suggests that at temperatures where most of the water vapor is generated in a HPC, the polypropylene fibers are softened and adsorbed by the surrounding cement paste matrix, thus providing channels for vapor escape.

Because of the extensive use of HPC in offshore oil and gas platforms since 1970s, many published data are obtained from tests that simulate hydrocarbon fires which have much higher heating rates than those encountered in ordinary building structures. A hydrocarbon fire is characterized by a linear temperature development up to 750 ^{o}C in one minute and a maximum temperature of 1100 ^{o}C after approximately 20 minutes [36]. It has been reported that HPLWC have more spalling than their normal weight counterpart when exposed to hydrocarbon fire [35].

Bilodeau et al [35] tested non-air entrained LWC, modified normal density concrete (MND), and normal density (ND) concrete with or without polypropylene fibers (20 mm) with w/c of 0.33 exposed to hydrocarbon fire. The LWA used was expanded slate with a specific gravity of 1.56 and absorption of 5.2%. The specimens were 1000x1000x500-mm reinforced blocks tested about 11 weeks after casting. The test was performed at about 1100^{o}C for 2 hrs. They reported that the amount of spalling increased with the increase of the amount of LWA in the concrete. However, the properties of the concrete in the middle of the blocks were not significantly affected by the fire exposure.

According to Hoff [33], not all LWA particles perform in the same manner under the hydrocarbon fire test conditions. The susceptibility of the concrete to spall increases with the degree of absorption of the LWA used, and additional moisture can be a major contributor to explosive spalling when the concrete is exposed to a fire with rapid increasing temperature [33, 40, 42].

Residual strengths of HPC at 100, 200, 300, 500, 700, 900, and 1100 ^{o}C were evaluated by Hoff et al. [40] with the intension to determine the effect of hydrocarbon fire on the residual strength. However, average heating rate for the test was 0.35 ^{o}C/min, which was much lower than that in typical hydrocarbon fire tests. The temperature was held at the maximum levels for 2 hrs and decreased slowly to room temperature. The study included three types of concretes – LWC, MND, and ND concretes - with 28-day compressive strengths of 49.3-63.9 MPa, 62.9-68.4 MPa, and 74.5 to 83.3 MPa, respectively. Two lightweight and two normal weight aggregates were used in these concretes. Each concrete made with specific type of aggregate was made with and without polypropylene fibers. With the lower heating rate used, there was no spalling of the concretes because the vapor could gradually escape from the concrete during the heating. This indicates that the heating rate has significant influence on the spalling. For the three types of concrete, they observed a slight improvement in residual strength at 200 ^{o}C compared to 100 ^{o}C exposure. At exposure temperature of 300 ^{o}C and higher, there is a significant loss of strength. At temperature of 900 ^{o}C and higher, all the concrete essentially had no structural integrity. The residual strengths of the HSC at exposure temperatures of 300 ^{o}C or higher are not significantly different from those of NSC. The addition of polypropylene fibers to HSC to reduce explosive spalling in a fire with rapid temperature rise has virtually no beneficial or adverse effect on the residual strength.

The use of a small amount of polypropylene fibers reduced spalling of concrete significantly when exposed to hydrocarbon fire [32, 34, 35], even when the concrete was relative immature and was essentially fully saturated [33]. According to Bilodeau et al. [42], a low w/c LWC made with silica fume blended cement requires more polypropylene fibers than a higher w/c concrete. The finer 12.5-mm fibers are significantly more efficient than the 20-mm fibers for preventing the spalling of concrete exposed to fire. Lightweight concrete containing polypropylene fibers was used in Heidrun tension leg offshore platform in portions of the hull where there is a potential for fire exposure and some other parts.

7. SUMMARY

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 ≥ 60 MPa) with good 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 superplasticizers 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 prewetted 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.

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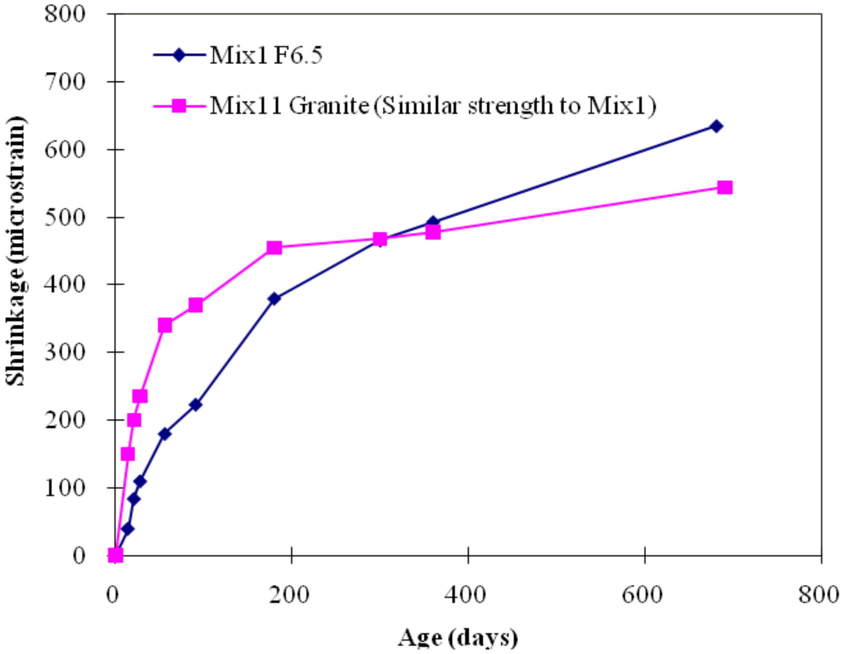

Figure 1 – Shrinkage of lightweight concrete in comparison with that of normal weight concrete of similar compressive strength. (28-day cube compressive strength of the concretes ~50 MPa) [16]

Table 1 – Unit weight, compressive strength, and static modulus of LWC in comparison to those of NWC (some examples)

References	Unit weight, kg/m^3	28-day cube compressive strength, MPa	28-day cylinder compressive strength, MPa	Specific strength MPa/kg/m^3	Static E-modulus, GPa	Remarks
[1]	1865	102.4	-	0.055	25.9	
[17]	2085	-	90.5	0.043	29	
[36]	1480	49.9	52.4	0.035	17.5	
[43]	1270		30.8	0.024	-	
[44]	1000	14		0.014		SCS sandwich composites
[45]	1430	64.0		0.045	16.8	
[17]	2450 (NWC)	117.8 (91d)		0.048	40	

Table 2 – High-performance lightweight concretes used in practice (some examples)

References	Structures	Year	Unit weight, kg/m3	Specified strength, MPa	28-day cube compressive strength, MPa	28-day cylinder compressive strength, MPa	Static E-modulus, GPa
[46]	Bank of America Corporate Center, Charlotte, USA	1992	1890			47	
[46]	Nordhordaland Bridge, Norway	1993	1881	55	69.9		21
[46]	Heidrun tension leg platform, North Sea	1995	<2000 in slipform, <1950 for cast in place	60	79		
[47]	New Benicia-Martinez Bridge, California, USA	2008	1920 – 2000	45		73.5 (35 days)	26.6

Table 3 – Total shrinkage of HPLWC in comparison to that of HPNWC

Reference	Unit weight, kg/m^3	28-d Compressive strength, MPa	28-d E-modulus, GPa	Curing and exposure	Total shrinkage, με	Total shrinkage, με	Remarks
[14]	1918	80.2 (56d)	33.3	28-day moist curing		299 (500d)	Prewetted LWA
	1918	77.0 (56d)	31.2			~370 (500d)	Air-dry aggregate
[16]	1915 (fresh)	49.2 (cube)	24.4	Moist curing 7 days, exposure 65% RH and 30 °C	223 (91d)	635 (681d)	No silica fume
	1940 (fresh)	52.3 (cube)	24.2		125 (91d)	450 (758d)	With silica fume
[24]	1875 -1905 (fresh)	52.6-67.3 (24h), 68.5-75.4 (56d)	24.9-27.5 (24h), 27.2-28.5 (56d)	16 hrs, 24 hrs moisture curing, exposure 50% RH and 21 °C	430-565 (100d)	610-818 (620d)	
[32]	1850-1990 (fresh)	48.1 – 68.5 MPa (10-mm cylinder)	20.4 – 28.0	7-d (cured in saturated lime water)		518-667 (448d)	Based on 5 different LWA
[25]	1920-1976 (1d wet)	42.6 – 56.5 (28d) 53.6 –66.0 (1y)	24.8-25.7 (28d)	Moist curing 28 days	489-539	581-632	No FA & SF
	1886-1946 (1d wet)	50.1-62.1 (28d), 59.7-69.3 (1y)	25.2-25.9 (28d)		372-415 (112d)	440-517 (360d)	With FA & SF
[17]	2020-2085 (wet)	73.8 – 90.5 (cylinder)	26-29	7-d water curing	156-406 (128d)		
[14]	2334				240 (~100d)	312 (500d)	
[16]	2370 (fresh)	80.5	30.7		360 (91d)	580 (772d)	No silica fume
	2370 (fresh)	87.7	32.3		290 (91d)	466 (765d)	With silica fume
[24]	HPNC	80.1-94.0 (56d)				504-539	
[17]	2450 (wet)	96.7 (cylinder)	40	7-d water curing	393 (128d)		

Table 4 – Creep of HPLWC in comparison to that of HPNWC

Reference	Unit weight, kg/m^3	Compressive strength, MPa	E-modulus, GPa	Loading age	Loading level, % of strength	Elastic strain, με	Exposure environ-ment	Specific creep, με/MPa	Creep coefficient	Creep strain, με	Remark
[14]	1918	80.2 (56d)	33.3 (28d)	28 d			50% RH, 23 ^{o}C	17.3 (500d)			Prewetted LWA
	1918	77.0 (56d)	31.2 (28d)	28 d				26.4 (500d)			Air-dry LWA
[24]	1875 (fresh , HPLC2)	52.6 (24h) 68.5 (56d)	24.9 (24h) 27.2 (56d)	16 hrs, 24 hrs (moisture cured)	40%, 60%		50% RH, 21 ^{o}C	67 (250 d), 69.5 (1 y), 75.5 (620 d)	0.842 (16 d), 1.684 (620d)		
	1905 (fresh, HPLC3)	67.3 (24h) 75.4 (56d)	27.5 (24h) 28.5 (56d)		41%	1092		53.8 (ultimate)	0.572 (16 d), 1.143 (620d)	1484	
					62%	1638				2227	
[47]	HPLWC	28 (3d)	21 (3d)	3 days (cured in molds)	40%	619	50% RH	88.5 (91d)	1.58 (91d)		
		58 (28d)	27 (28d)	28 days (14d moist, 14d air dry)	30%	643		36.3 (91d)	0.96 (91d)		
		69 (91d)	27 (91 d)	91 days (14d moist, 14d air dry)	27%	673		26.1 (91d)	0.96 (91d)		
[15]	1674-1749 (28-d)	47.6-59.4 (28d)	17.8-20.4 (28d)	28d curing, 20 ^{o}C, 95% RH				~58-81 (200d)			
[25]	1920-1976 (1d wet)	42.6 – 56.5 (28d) 53.6 –66.0 (1y)	24.8-25.7 (28d)	1 y (moist cured)	30 – 33%	557-574		27-30		642 – 686 (370d)	No FA & SF
	1886-1946 (1d wet)	50.1-62.1 (28d), 59.7-69.3 (1y)	25.2-25.9 (28d)		27-31%	552-597				457-508 (370d)	With FA & SF
[14]	2334	104.3 (56d)	34.7 (28d)	28 d				19.5 (500d)			
[24]	HPNWC (HPNC3)	80.1 (56d)		16 hrs, 24 hrs (moisture cured)	34.4%			53.2 (ultimate)		1467	
					51.7%					2200	
	HPNWC (HPNC6)	94.0 (56d)			29.4%			94.3 (ultimate)		2599	
					44.0%					3898	