Shrinkage of Steel-Fibre-Reinforced Lightweight Concrete

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Abstract. Long-term behaviour of steel fibre reinforced concrete remains rather unknown and to a large extent unquantified by equations and standards. This paper studies experimentally the free drying shrinkage of steel fibre reinforced lightweight concrete during the first 28 days using 100 × 100 × 500 mm beams. The coarse lightweight material tested (LYTAG) is recycled and offers an alternative to gravel and quarry resources which are subjected to depletion in the future. Also, this material can lead to reduction in the mass of the structure which results in economical designs. However, LYTAG aggregate can absorb up to 15% of its own weight in water. This makes it susceptible to drying shrinkage both at young age and long-term due to environmental diffusion. Shrinkage can have a detrimental effect on the concrete by inducing cracks, creating therefore weak zones in the concrete. It is thought that fibres can have a favourable effect on the reduction of shrinkage due to their ability to bridge cracks. This could be vital particularly in large concrete flat slabs, joints, beams and even columns. This project uses modern hooked-end DRAMIX 3D and 5D fibres with different dosages V_f and number of hooks and evaluates shrinkage for concrete with different characteristic strengths f_{ck}.

KEYWORDS: Lytag · Hooked-end fibres · Early-age shrinkage · Drying shrinkage · Shrinkage beams · Environmental diffusion · Cracks

1 Introduction

Shrinkage is the time-dependent change in volume of unrestrained concrete when tensile stresses due to contraction exceeds that of the concrete itself, although creep can play a factor in counter acting the latter due to stress relaxation in a restrained structure (Hossain, 2003; Havlasek 2014). Shrinkage can take place due to either internal reactions usually before concrete hardening, responsible for by autogenous, plastic and chemical shrinkage, or due to their surrounding environment responsible for by thermal and drying shrinkage that leads to water evaporation through concrete pores (Neville 2011). This leads to shrinkage cracking at the surface which can negatively affect the strength and integrity of the concrete from a young age to long-term (Mindess and Young 1981). Shrinkage can be affected by wind, humidity, temperature, cement fineness, water content and curing (Shoya 1979; Mehta 1994). The lightweight aggregate LYTAG used in this work is porous and capable of absorbing water of up to 15% of its weight. Besides, no pore size reducing materials such as silica fume are used

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for the concrete mixed. Hence, this makes it easy for the water to evaporate out of the concrete and act as a catalyst for drying shrinkage unlike the denser high strength concrete (Mehta and Monteiro 1993; Koenders 1997). The lower modulus of elasticity of lightweight concrete can also facilitate the shrinkage of concrete (Kayali et al. 1835). Therefore, lightweight concrete is more susceptible to shrinkage than normal weight concrete (Neville 2011). This however has been proven wrong in some other studies where lightweight concrete showed less shrinkage than normal weight concrete (Zhang et al. 2005).

Lightweight concrete is noted by its brittle nature in tension due to the absence of tension toughening aggregate interlock mechanism which causes micro- and macro-cracking. The incorporation of steel fibres in the concrete mix has been shown and proven to increase the tensile strength of the concrete by bridging the crack and maintain tensile stress flow in the concrete (Gao et al. 1997; Campione and La Mendola 2004; Abbas et al. 2014; Di Prisco et al. 2013; Grabois et al. 2016; Mo et al. 2017). Provided that shrinkage cracking only takes place if the contraction due to water dissipation to environmental diffusion or cement hydration is higher than the concrete tensile strength, steel fibre reinforcement can offer a control mechanism to shrinkage cracking at all ages. Previous studies on lightweight concrete agree with the latter (Tan et al. 1994; Zhang et al. 2001).

Since the current design codes such as the Eurocode 1992-1 use the drying shrinkage to calculate the long term shrinkage strain due to drying shrinkage, while as erroneous as it might be, autogenous shrinkage is assumed to be controlled in the choice of material mixing and curing conditions, this work focuses on the measurement of the free unrestrained drying shrinkage of SFRLC.

2 Experimental Study

2.1 Experimental Programme

The experimental program included 3 mixes with 3 different fibre dosages: $V_f = 0\%$, 1% and 2%. Each mix constituted of 3 specimens. The mixes also aimed to study the effect of different W/C ratios and type of fibre (Table 1). The latter was either 3D fibres regarded as the most commonly used in industry (Sadoon et al. 2018) or the 5D fibres with the highest tensile strength and most comprehensive hooking system which promises of being capable of primary reinforcement substitution.

Table 1. The specimens cast

Mix	f_{ck} (MPa)	V_f (%)	Fibre type
1	30	0, 1, 2	3D
2	40		5D
3	30		5D

It should be noted that the specimens were kept in an environmental chamber with unrestrained supports.

2.1.1 Materials

Portland-Limestone cement (CEM 11) according to the specification supplied in EN 197-1 was used. Coarse aggregate Lytag, also known as Sintered Pulverised Fuel Ash Lightweight Aggregate (LYTAG) was provided by LYTAG Ltd. The loose dry density of LYTAG was calculated in the lab to be approximately 760 kg/m^3 while the water absorption was estimated to be around 15% per mass of LYTAG. For this reason the aggregates were pre-soaked for 24 h before mixing. This was proven to help reduce shrinkage. Natural river sand with a 4.75 mm maximum size was used as the fine aggregate of the concrete. The sand had a water absorption coefficient of 0.09% and specific gravity of 2.65 complying with BS EN 12620. The properties of the fibres used are summarized in the table below. It should be noted that to prevent the possibility of balling, fibres were collated from the manufacturer (Table 2).

Table 2. Properties of fibres

Fibre type	σ_u (MPa)	l_f (mm)	d_f (mm)
3D 65/60	1160	60	0.9
5D 65/60	2300	60	0.9

2.1.2 Mix Design

The mix designs used are summarized in Table 3 below. The mix design of the Lytag concrete for the characteristic cylinder and cube compressive strengths used are summarised below. These were directly adopted from Lytag (2011) manuals.

Table 3. Mix design used

(f_{ck}/$f_{ck,cube}$)	Cement (kg/m3)	Sand (kg/m3)	Loose bulk Lytag (kg/m3)	Effective water (kg/m3)
LC30/33	370	592	668.8	175
LC40/44	480	485	668.8	175

Calculating the water content of Lytag was of high importance as Lytag aggregates were found to absorb water of approximately 15% of their weight which is also confirmed by Lytag manual. For this reason and as suggested by Lytag manual 5 (2011), excess water to saturate Lytag aggregates was added 30 min before mixing (Fig. 1).

Fig. 1. Mixing process for plain and fibrous lightweight concrete

2.2 Experimental Tests

To measure the free axial early age and drying shrinkage, 100 × 100 × 500 mm beam specimens designed according to the European standard UNI 6555 with steel inserts fixed into both ends of the specimens were cast and the method of measuring shrinkage was identical to UNI 6555. This relatively large specimen was preferred to other smaller specimens such as the more conventional 75 × 75 × 280 mm specimen according to BS ISO 1920-8:2009 in an attempt to avoid any possible favorable orientation of fibres in the shrinkage direction i.e. orthogonal to crack plane for the SFRLC beams.

The specimens are required to be housed in a measuring apparatus with a digital displacement guage for the duration of the test with a constant relative humidity of (50 ± 5)% and temperature of (22 ± 2) °C (Fig. 2). To measure shrinkage strain, simply

Fig. 2. Concrete specimen about to be housed in the measuring apparatus

the digital readings of the displacement are taken and divided by the total length of the specimen. Shrinkage strains from repeated specimens are averaged. The drying shrinkage is assumed to start from day 2 following early age shrinkage which is recorded 24 h after concrete hardening.

3 Results and Discussion

Figure 3 below shows the recorded free drying shrinkage for the 2 different W/C ratios chosen. Throughout the duration of the test, the mix with the higher W/C ratio (f_{ck} = 30 MPa) seemed to shrink more than that with the lower W/C ratio (f_{ck} = 40 MPa). Both the readings reduced in gradient as the days of testing were increased. It should be noted that while the shrinkage of the mix with the low W/C ratio relatively plateaued at the end of the test, that of the mix with the high W/C ratio continued to increase (75% more shrinkage).

Figure 4 below studies the effect of hook geometry on drying shrinkage for 2 fibrous beams with V_f = 1%. It can be seen that while the free shrinkage of the fibrous beam reinforced with the stronger bonded 5D was slightly higher during the first 14 days, the free shrinkage of the fibrous beam reinforced with 3D fibres became higher during the remaining days of the test.

Figure 5 below illustrates the effect of increasing the fibre volume fraction V_f on shrinkage. It is clear that the higher the fibre dosage, the lower the shrinkage as the tensile strength of fibres prevent cracking of the concrete beams. The axial shrinkage strain of the beam reinforced with V_f = 1% was about 56% of that of the plain lightweight concrete beam, while that reinforced with V_f = 2% was only 23%.

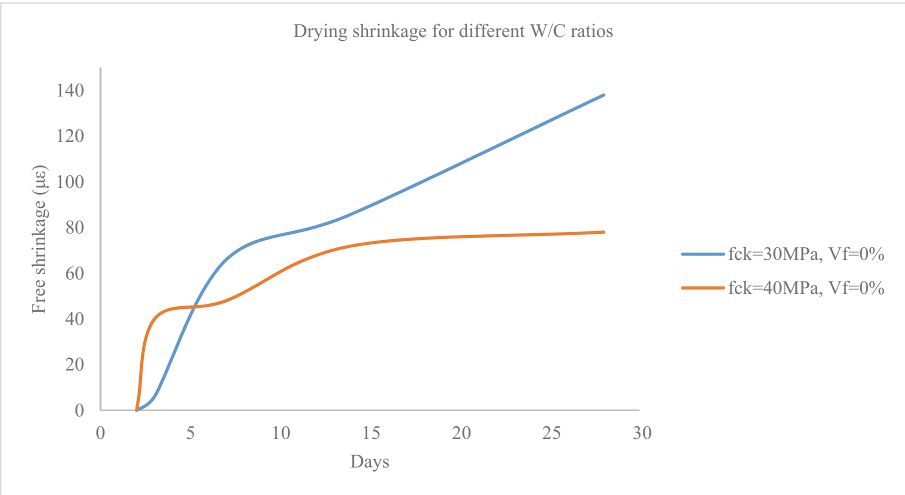

Fig. 3. Effect of W/C ratio on shrinkage

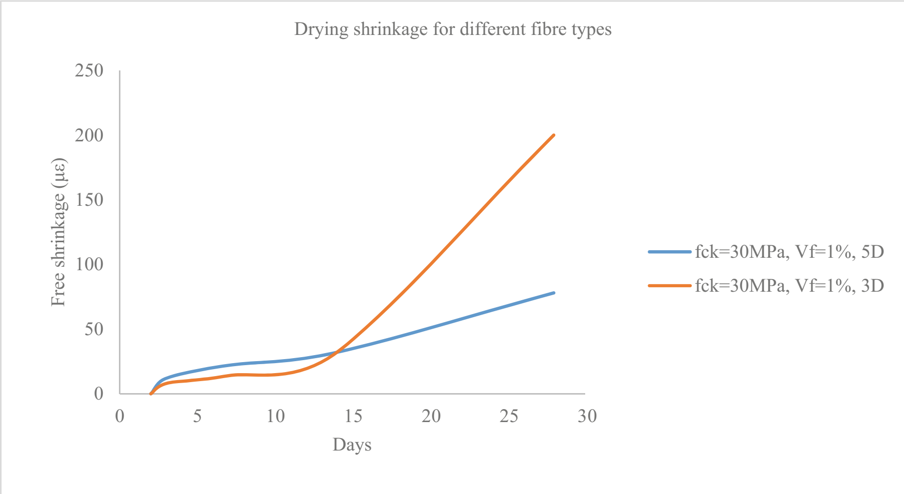

Fig. 4. Effect of fibre type on shrinkage

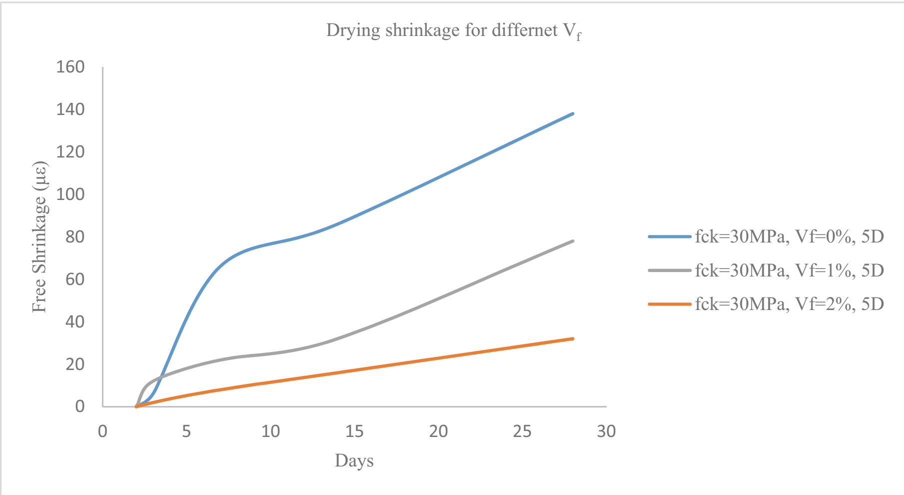

Fig. 5. Influence of increasing fibre dosage on the drying shrinkage of lightweight concrete

The column chart below (Fig. 6) displays the early age shrinkage due to drying shrinkage and cement hydration process of the concrete. Overall, it is evident that the early age shrinkage is responsible for the majority of the shrinkage at the end of the 28 day test which makes it impactful. This agrees with findings reported by Holt (2001).

For example, during the first day after hardening for the specimen with f_{ck} = 30 MPa and V_f = 0%, shrinkage strain was recorded to be 742 microstrains which is 542% higher than that recorded at the end of the testing at 28 day. This is due to the porous nature of the lightweight concrete and the ability of the aggregates to absorb 15% of their weight in water which makes water loss due to environmental diffusion more likely. Another observation that can be made is with regards to fibre geometry. It appears that the more complicated anchorage system of the 5D fibres created more air voids in the concrete lattice making it more easily for the water to dissipate as compared to the specimens reinforced with the less complicated hook-ended 3D fibres. Similarly, the higher fibre fraction led to higher early age shrinkage. Hence, it can be deduced that a better vibration process, smaller fibres, less extended hooks or high humidity curing process is recommended for better shrinkage control.

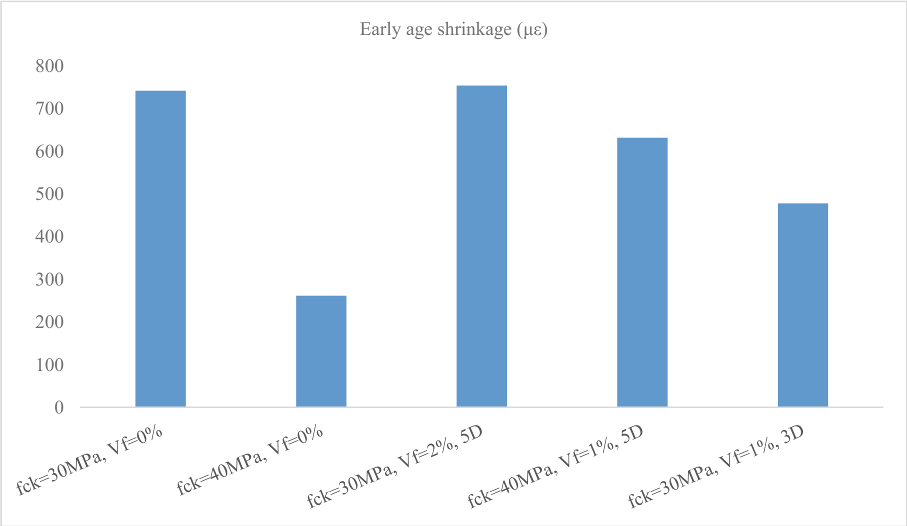

Fig. 6. Early age shrinkage for SFRLC beams

4 Conclusions

- The methodology adopted in this work was successful at measuring the early age and drying shrinkage for fibrous lightweight concrete beams.
- The higher the water cement ratio, the higher the drying shrinkage measured.
- The higher the fibre dosage, the lower the drying shrinkage recorded.
- The more extensive the hook anchorage system is the less the drying shrinkage. However, it was seen that the extensive 5D hooks lead to a more pronounced increase in early age shrinkage as compared to the more conventional 3D fibres.

- For the duration of the test and the material used, the early age shrinkage during the first day after hardening appeared to be 300% to 500% higher than the drying shrinkage by the end of the test.
- The porous nature of lightweight concrete and the ability of its aggregate to absorb up to 15% of their weight in water make the concrete more susceptible to shrinkage.
- The addition of fibres creates more voids in the lightweight concrete, making it likely to shrinkage especially during early age.
- Therefore, to control early shrinkage, a better compacting process, smaller fibres, less extended hooks or 99% humidity curing is recommended during early age.

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