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# Fresh and hardened-state properties of self-compacting lightweight concrete reinforced with steel fibers

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## HIGHLIGHTS

- Self-compacting lightweight concrete was produced with steel fibers.
- Structural efficiency factor for self-compacting lightweight concrete was assessed.
- Thermal characterization was performed to characterize self-compacting lightweight concretes.
- The use of lightweight and porous expanded clay aggregates was essential to obtain low values of autogenous shrinkage.

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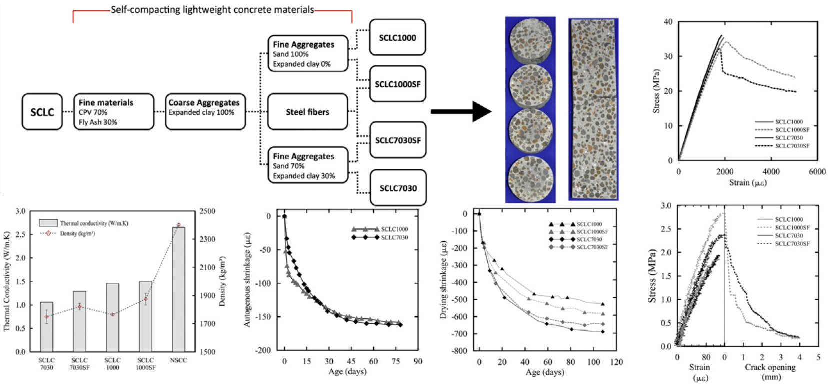
## GRAPHICAL ABSTRACT



## ABSTRACT

This paper presents the results of a comprehensive experimental characterization on the fresh and hardened state of self-compacting lightweight concrete (SCLC) reinforced with steel fibers. Two classes of SCLC were produced containing either coarse or coarse and fine lightweight aggregates. Steel fibers were used as reinforcement in fiber volume fraction of 0.5%. Slump flow, inverted slump flow and "V" funnel tests were performed to characterize the self-compacting behavior of the concretes. The mechanical behavior was evaluated by means of compression, tensile and flexural tests. Thermal characterization was performed by specific heat, thermal diffusivity and conductivity tests. Autogenous and drying shrinkage tests were also carried out in the study. The results showed slump flow within 600–700 mm without segregation even for fiber reinforced SCLC mixes. All mixes have shown 28-day compressive strength above 30 MPa and density within 1700–1900 kg/m$^3$. The fiber reinforcement has increased the mechanical properties under direct tensile and bending tests. Adequate thermal insulation properties were verified when compared to normal-weight concrete. Moreover, autogenous shrinkages were around 150 microstrain. Finally, concretes containing coarse and fine lightweight aggregates presented higher drying shrinkage than those only coarse lightweight aggregate.

## 1. Introduction

Lightweight concrete (LC) has been increasingly adopted in several structural applications due to its economic and technical potentials, such as reduced dead weight of components, low handling costs combined with good mechanical and durability properties [1]. In the early 90s, the development of self-compacting concrete (SCC) enabled the execution of concrete structures without the need for vibration due to its flowability and self-consolidating capabilities [2].

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The development of self-compacting lightweight concrete (SCLC) may allow to couple the advantages of both LC and SCC concrete types. Therefore, SCLC may bring advantages to the design of structures due to self-weight reductions and total load over foundations, thermal properties enhancement by reduction in thermal conductivity, and reducing costs of transportation in case of precast structural components. In addition, the use of steel fiber reinforcement improves the material mechanical response under direct tensile and bending loads increasing the strain capacity, toughness and post-cracking behavior by reducing its brittleness [3,4]. Therefore, steel fibers can be used as a supplementary reinforcement allied to traditional steel bars, in thin plate structures and in structural rehabilitation.

Research focusing on the characterization of self-compacting lightweight concrete is relevant due to the still insufficient knowledge about its properties. A few relevant studies have been conducted to experimentally characterize SCLC in fresh and hardened states. All of these studies address to the workability and compressive strength properties [5–15]. However, some authors have been also focusing on mix-design procedures [5–8,14], durability [5,6] and shrinkage [6]. The literature about fiber reinforced SCLC still has a lack of information to be fulfill. Mazaheripour et al. [12] showed that polypropylene fibers had no influence on the compressive strength behavior and elastic modulus of SCLC. Nevertheless, their results indicated splitting tensile and flexural strengths enhancements due to the presence of polypropylene fibers. In another study, Klein et al. [13] presented different compositions of SCLC reinforced with polyester or steel fibers and obtained an optimal polyester fiber reinforced SCLC with 1665 kg/m$^3$ density, 605 mm slump flow and 22.3 MPa 28-day compressive strength for rehabilitation of a real structure.

This work aims to contribute in fulfilling the gap about the fiber reinforced SCLC properties discussing an experimental characterization. Firstly, detailed information regarding fresh and physical properties (slump flow, inverted slump flow, "V" funnel, density and water absorption) was assessed. After that, a mechanical characterization including compressive and tensile stress–strain behavior, load–deflection and post-cracking performance in bending, and structural efficiency was performed. Finally, the experimental program was completed by thermal and shrinkage (autogenous and drying) results. To attain these objectives two types of structural SCLCs were produced with 28 days compressive strength of 35 MPa and density lower than 1920 kg/m$^3$ using expanded clay as lightweight aggregates and steel fibers as reinforcement.

## 2. Materials and methods

### 2.1. Materials

Brazilian high-early strength Portland cement (40 MPa-strength class) and fly ash (104% pozzolanic activity index [16]) were used in this research. Coarse (AE1506) and fine (AE0500) expanded clay fractions, natural river sand, polycarboxylate-based superplasticizer, viscosity modifier agent, Dramix 65/35 hooked-shape steel fibers, and water were also used to produce the concrete mixes. Dramix 65/35 has a 35 mm length, 0.55 mm diameter, 1.1 GPa tensile strength, 210 GPa Young's modulus, and 7.85 kg/m$^3$ density. Particle size distributions and physical and chemical characteristics of the SCLC materials are shown in Fig. 1 and Table 1, respectively.

Fig. 2 shows the water absorption as a function of time for both coarse and fine lightweight aggregates. Water absorption rapidly increase when the grains were submersed in water, e.g., from time 0 to 5 min, fine aggregates reached more than 2% of absorption and the coarse ones reached values around 4%. At about 30 min, the fine aggregates has already absorbed 3.9% while the coarse absorbed 9.1% (around 60% and 65% of the total absorption in 24 h, respectively).

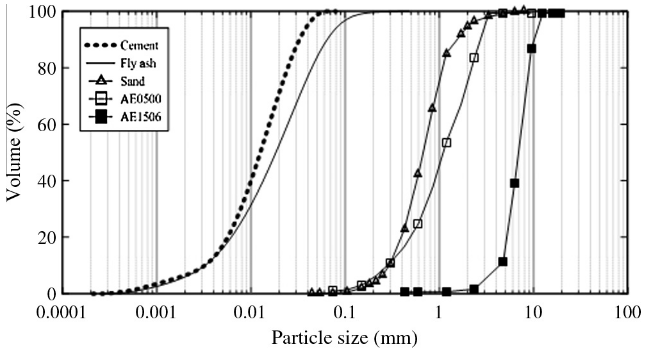

**Fig. 1.** Particle size distributions of SCLC materials.

**Table 1**
Physical characteristics and chemical composition of the SCLC materials.

| Materials | Density (kg/m$^3$) | Absorption-24 h (%) | $D_{max}$ (mm) | $D_{50}$ (μm) |
|---|---|---|---|---|
| Cement | 3209 | – | – | 12.55 |
| Fly ash | 2405 | – | – | 18.98 |
| Natural sand | 2668 | 1.40 | 2.36 | – |
| AE0500 | 1541 | 6.45 | 4.75 | – |
| AE1506 | 956 | 13.95 | 12.5 | – |

| | Oxide composition by mass (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | CaO | SiO$_2$ | SO$_3$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | K$_2$O | TiO$_2$ |
| Cement | 70.86 | 13.10 | 5.75 | 4.30 | 4.28 | 0.94 | 0.25 |
| Fly ash | 1.94 | 51.58 | 1.51 | 32.65 | 5.80 | 3.39 | 1.30 |

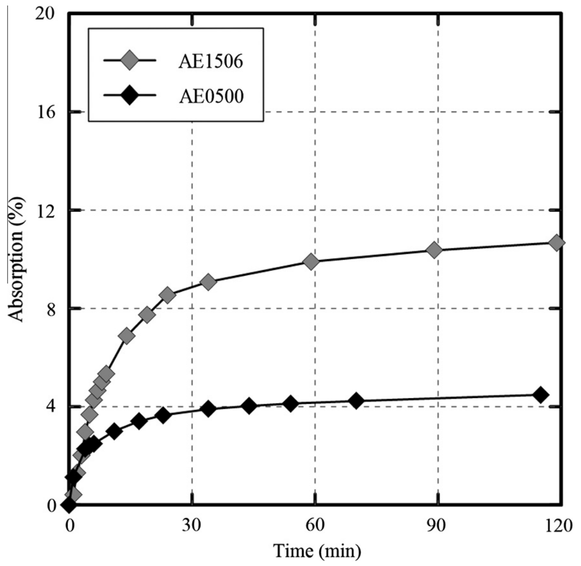

**Fig. 2.** Mass variation *versus* immersion time for both lightweight aggregates.

### 2.2. Mix design and procedures

Concrete mixes were designed with cement (70% in mass) and fly ash (30% in mass) as cementitious materials. For both classes of SCLC, the coarse aggregates used were expanded clay denominated AE1506. The first concrete class (denominated SCLC1000) was made with 100% of river sand as fine aggregate. For the second class (SCLC7030), 70% of sand and 30% of fine expanded clay were used. The water–cementitious materials ratios (w/cm) of mixes SCLC1000 and SCLC7030 were 0.36 and 0.42, respectively. Considering the 24-h water absorption of lightweight aggregates (Table 1), the effective water–cementitious materials ratios (w/cm) of mixes SCLC1000 and SCLC7030 were 0.29 and 0.32, respectively. A fiber volume fraction of 0.5% (39 kg/m$^3$) was used considering the replacement of the same volume of coarse aggregate. In these cases, the suffix SF was added to the mix names (SCLC1000SF and SCLC7030SF). Table 2 presents the concrete mix-designs.

The concretes were produced in a vertical-axis planetary mixer under lab-conditions with a controlled temperature of 21 ± 1 °C. The mixing process predicted that all aggregates pass through a dry mix process for 1 min and then, according to