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FIBER REINFORCED HIGH-PERFORMANCE LIGHTWEIGHT CONCRETES: A LITERATURE REVIEW

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ABSTRACT

The use of steel fibers has become more popular in recent days due to their improvement in cracking resistance. When steel fibers are added to a concrete mixture, they reduce cracks width and create a ductility mode instead of a brittle one, witch improves the deformation capacity. Steel fibers has been added to high-performance lightweight concretes, and concretes with increased compressive and flexural strength has been produced. Moreover, the addition of 0.75% of steel fibers by volume, 15% of Fly-ash and 5% of silica fume has demonstrated to be an ideal amount to obtain high-strength concretes with great mechanical properties. Hence, this paper presents a literature review about High-Strength Fibre-Reinforced Lightweight Concrete pointing out its mainly mechanical properties.

Keywords: Literature review; Lightweight concretes; Fiber reinforcement.

1. INTRODUCTION

According to McCormac and Brown (2014), the interest in fiber reinforced concrete has increased in current days. The fibers used are made from steel, plastics, and glass. Moreover, the authors (2014) point out that research has shown that adding fibers by the quantity from 1 to 2% by volume have significantly enhanced the normal concrete properties.

Concretes with added fibers "are substantially tougher and have greater resistance to cracking and higher impact resistance" because the fiber "has increased the versatility of concrete by reducing its brittleness" and "randomly distributed fibers provide additional strength in all directions" (McCormac; Brown, 2014). Indira and Abraham (2007) note that "conventional concrete loses its tensile resistance after the formation of multiple cracks; however, fiber concrete can sustain a portion of its resistance following cracking to resist more cycles of loading".

One important use of fibers is with lightweight concretes (LWC). According to Rakocky and Nowak (2014), "structural lightweight concrete provides a more efficient strength-weight ratio in structural elements than NWC"; thus, due to this, the use of LWC for beams and slabs has enhanced. Sajedi and Shafigh (2012) emphasize that LWC "is known for its advantage of reducing the self-weight of the structures and areas of sectional members, thus making the construction convenient".

Using LWC presents other important characteristics for buildings. First, as mentioned before, "structural lightweight concrete has advantages of higher strength/weight ratio and better tensile strain capacity". Additionally, it presents a "lower coefficient of thermal expansion, and superior heat and sound insulation characteristics due to air voids in the lightweight aggregate" (SAJEDI and SHAFIGH, 2012; BARBOSA et al., 2012). Furthermore, "structural lightweight concrete provides a higher fire-rated concrete structure", and it has beneficial aspects for energy conservation because the lightweight aggregate "provides a source of water for internal curing of the concrete that provides continued enhancement of concrete strength and durability" (The National Ready Mixed Concrete Association, 2003).

Pelisser et al. (2012) point out that "with all the exceptions that may be between different studies and the specific properties of the materials used, a technically and economically vital point is the consumption of cement and the strength obtained, especially considering the application of lightweight concrete or aggregates, and the relation kg/MPa, is a performance index of the concrete with rubber that can be comparable between different studies".

Because the use of steel fibers in structural lightweight concretes has become more common, and there is not sufficient research about this subject, this paper presents a literature review about fiber reinforced high-performance lightweight concretes. Hence, the definition of high-strength lightweight concretes will be discussed, and their shear and flexural behaviours will be presented. Moreover, steel fibers (the most common type of fiber reinforcement) definition will be discussed, and then, mechanical properties of steel fiber-reinforced lightweight concrete will be provided.

2. HIGH-STRENGTH LIGHTWEIGHT CONCRETES

The structure of high-strength lightweight concretes (HSLWC) “depends on the hydration of cement, crystallization and formation of crystalline splice with cement blinder” (Inozemtce; Korolev, 2014). The most elevated strength can be obtained through the formation of “the solid object with most density of bonds and strength of single contact” with a very strong connection during hydration (Inozemtce; Korolev, 2014).

Moreno *et al*. (2014) comment, based on a literature review, that creating a HSLWC is problematic, considering that porous aggregate, water absorption and lightweight influence in an adverse way the mechanical properties and durability of concrete, but HSLWC very often contains added cementing materials that reduce the amount of water used, and they increase its mechanical properties and durability. Inozemtcev (2015) remarks the importance of factors such as “time and rate of mixing, parameters of vibro-compacting and mode of heat-humid treatment (HHT)” on the quality of concrete.

Kılıc *et al*. (2003) comment on the research made by Al-Khaiat and Haque (1998). According to the authors (2003), Al-Khaiat and Haque “worked on the effect of initial curing on early strength and physical properties of lightweight concrete containing 500 kg/m^3 cement and 50 kg/m^3 condensed silica fume”, and they produced a HSLWC with 50 MPa and fresh density of 1,800 kg/m^3.

Dunbeck (2009) remarked three different studies with HSLWC. The first one was conducted by Meyer and Kahn (2002) that were investigating benefits of HSLWC. Concretes of 55 MPa (8000 psi), 69 MPa (10,000 psi) and 83 MPa (12,000 psi) “were considered using expanded slate lightweight aggregate” (DUNBECK, 2009).

The second study reported by Dunbeck (2009) was made by Buchberg (2002), who investigated over 75 different mixtures and “developed high-strength lightweight mix designs made with materials available in Georgia”. According to Dunbeck (2009), Buchberg recommended three mixtures of HSLWC of 55 MPa (8000 psi), 69 MPa (10,000 psi) and 83 MPa (12,000 psi). Thus, based on Buchberg study, Dunbeck (2009) concluded that silica fume was efficient “in increasing the early strengths of lightweight concrete as well as the late strengths” and the chloride permeability was very low.

Dunbeck (2009) ran her own study on the construction of the bridge “I-85 Ramp “B” Bridge over SR-34, Bullsboro Drive, in Cowetta County”, which was built using HSLW concrete girders. Dunbeck (2009) explained that “concrete samples were taken from every batch of concrete used in the construction of the girders”.

Dunbeck (2009) concluded that “silica fume must be closely monitored to ensure that it is mixed well within the batch and the moisture content of the lightweight aggregate should be frequently measured as well to ensure mixture consistency”. Moreover, the average concrete compressive strength was higher than the designed one, but the average modulus of elasticity was 2% lower than the predicted by ACI 363. According to Dunbeck (2009), “previous research showed that the elastic modulus was dependent on the type of lightweight aggregate used even when compressive strengths were the same”.

3. STEEL FIBERS

The most common material used are steel fibers (SF). Jang *et al*. (2015) remark that the first try of replacing reinforcement steel by steel fibers in RC beams was in 1970.

Ganesan, Indira and Abraham (2007) state that overall, the addition of fibers to concrete increase the “tensile strain in the neighbourhood of fibres”. Furthermore, “the cracking behaviour, ductility, and energy absorption capacity of the composite” will be improved (Ganesan, Indira and Abraham, 2007).

Kang and Kim (2010) remark that steel fibers tend “to improve mechanical properties and structural performance relative to conventionally reinforced concrete (with the same steel volume fraction)”. Furthermore, steel fiber-reinforced concrete (SFRC) members present improvements in shear and flexural behavior. Using SFRC contributes to “the degree and width of cracking”, so there is an improvement of SFRCs members’ behavior related to “the post cracking tensile strength” (Kang; Kim, 2010).

Casanova and Rossi, cited by Jang *et al*. (2015), conducted a study in 1997, showing that HSC beams without transversal reinforcement with the compressive strength of 90 MPa and 1.25% of steel fibers “could obtain equivalent performances of HSC beams with 1.1% conventional transverse reinforcements”.

Kwak *et al*. (2002) tested twelve beams: nine high-strength steel fiber-reinforced concretes (HS-SFRC) (65 MPa), with volume fractions (V_f) of 0, 0.5 and 0.75% and shear span over the distance from extreme tension fiber to the centre of the longitudinal bar (a/d) equals to 2, 3 and 4; and three beams (31 MPa) with 0.5% of steel fiber by volume fraction and a/d of 2, 3 and 4. Moreover, “the longitudinal bars were hooked upwards behind the supports and no stirrups were included within the shear span” (KWAK *et al*., 2002).

Kwak *et al*. (2002) observed that steel fibres remarkably reduced the crack width and size, increased deformation capacity, and contributed to creating a ductile mode instead of a brittle one. Moreover, the failure mode varied according to the V_f and a/d variations. For a/d equal to 2, two different types of failure occurred: for $V_f = 0\%$, the beam failed in shear; for $V_f = 0.5\%$ and $V_f = 0.75\%$, it failed in shear-flexure. For a/d equal to 3 and 4 and $V_f = 0\%$, the beam failed in shear; for $V_f = 0.5\%$ and $V_f = 0.75\%$, it failed in flexure (Kwak *et al*., 2002). Failing in flexure means that “the applied load at failure is not equal to the shear strength” (Kwak *et al*., 2002). Regardless, beams with the smallest a/d ratio (a/d = 2) had a huge increment in their shear strength from 69 to 80%. On the other hand, beams with larger a/d ratios had smaller shear strength improvement (22 to 38%) (Kwak *et al*., 2002).

Jang *et al*. (2015) reported another study, which was conducted by Cucchiara *et al*., in 2004, in which they tested hooked-end SFRC beams “with different amount of shear reinforcement, shear-to-span ratio, and fibre volume fraction”. Results demonstrated that adding “hooked-end steel fibres in the shear-dominant RC beams can transform the brittle behaviour characterized by shear failure into a ductile one by flexural failure” (Jang *et al*., 2015). Jang *et al*. (2015) reported other research done by different people, and all of them observed improvements in the cracks development.

Jang *et al*. (2015) conducted a study to investigate “the influence of steel fibre contents on the mechanical properties of HPC” of beams with compressive strength of 60 MPa and 100 MPa. Steel fibers tested quantities were 0, 0.5, 1.0 and 1.5% by volume, and they presented the following conclusions. First, there were no problems in mixing and casting up hooked-end steel fibres with a volume fraction of 1.5%. By increasing the amount of SF, the air content (AC) increases and the slump values decrease, which makes it less workable (Jang *et al*., 2015). Second, using 1.5% of steel fibers by volume led to an increment of 42.3% in the modulus of rupture of 60 MPa concrete beam, and 30.0% in the 100 MPa (Jang *et al*., 2015). Third, the “replacement of minimum shear reinforcement with deformed steel fibres” is 1.2% by volume to 60 MPa and 1.5% by volume to 100 MPa (Jang *et al*., 2015). Fourth, “aspect ratio (length over diameter ratio of hooked-end fibers) of 2.0 is effective to inhibit the crack development and decrease the increasing rate of shear span” Jang *et al*., 2015). Fifth, a high-strength steel fiber-reinforced concrete (HS-SFRC) beam with 1.5% of SF in a 60 MPa concrete (with no transverse reinforcements) demonstrated similar shear resistance of conventional beams with transverse reinforcements full confined (Jang *et al*., 2015).

Another field of application of SF can be found in LWC members. Kang and Kim (2010), Kang *et al*. (2011) and Campione (2014) point out that even though ACI 318-08 establishes the minimum of 0.75% of steel fiber fraction by volume, there are not sufficient studies that explain mechanical properties and shear and flexural behavior of steel fiber-reinforced lightweight concrete (SFRLWC).

Kang and Kim (2010) and Kang *et al*. (2011) remark a study made by Swamy et at., in 1993, who tested I-section beams. Their test results indicated that SFRLWC with "a steel fiber volume fraction of 1% showed significantly greater shear strength (by 60% to 210%) than equivalent beams without steel fibers".

Kang *et al*. (2011) performed a study with twelve concrete beams (six SFRLWC, three SFRC, and three LWC) "without stirrups", and they "were simply supported and loaded with two equal concentrated loads using a spreader steel beam". Three volumes of SF (V_f) were tested, 0, 0.5 and 0.75%, and three different a/d ratios, 2, 3 and 4. Unit weights of normal and lightweight concrete tested were 2,194 and 1,800 kg/m^3, the water-cement ratio was 0.33, for all beams, and the compressive strength of concrete varied from 39.6 to 57.2 MPa (Kang *et al*., 2011).

Based on tests results, Kang *et al*. (2011) presented certain conclusions. First, the compressive strength of SFRLWC increased with the increasing of volume of added fibers (by 13% for V_f = 0.5% and 20% for V_f = 0.75%). Moreover, the tensile strength of SFRLWC was also increased by 40% for V_f = 0.5%, and approximately 70% to 100% for a V_f of 0.75% (Kang *et al*., 2011). Second, SFRC material properties demonstrated huger values than SFRLWC, "compressive strength ($f_{c'}$) by 28%, splitting tensile strength (f_{sp}) by 33%, modulus of rupture (f_r) by 14%, and modulus of elasticity (E_c) by 20% on average". Thus, SFRC had a larger shear capacity than SFRLWC (Kang *et al*., 2011). Third, by adding steel fibers (comparing with no fibres), the resistance to structural derange, ductility and shear capacity enhanced, and increasing the volume of fibers led to "a change in the failure mode from brittle to ductile" (Kang *et al*., 2011). Fourth, Kang et al. (2011) advocates that "the ACI 318-08 minimum requirement of 0.75% appears to also be reasonable for steel fiber-reinforced lightweight concrete beams" because SFRLWC with V_f = 0.75% or V_f = 0.5% and a/d =2 to 3 "performed well without any signs of brittle failure" (Kang *et al*., 2011). Fifth, as the a/d ratio increased, the shear stress at diagonal crack and peak decreased. It is important to note that the current equations of SFRLWC do not consider a/d influence, so they should be incorporated (Kang *et al*., 2011).

4. MECHANICAL PROPERTIES OF STEEL FIBER-REINFORCED LIGHTWEIGHT CONCRETE

In this section, results of five different studies performed from 1997 until 2015, which used fibers in the concrete, will be discussed.

The first study was conducted by Gao, Sun and Morino (1997), who tested five different mixtures of high strength concrete, reinforced with steel fibers. Rectangular fibres with lengths of 20, 25 and 30 mm, aspect ratios (l/d) of 46, 58 and 70, respectively and the volume of fibres (V_f) used were 0, 0.6, 1.0, 1.5 and 2.0%, with water-cementing ratio of 0.28. According to Gao, Sun and Morino (1997), "the compressive strength ($f_{c'}$) and the splitting tensile strength (f_{sp}) were measured on 100 x 100 x 100 mm cubes, the flexural strength (f_r) was tested on 100 x 100 x 400 mm specimens with four-point flexural loading". Moreover, "the modulus of elasticity (E_c) was calculated, based on the stress corresponding to 40% of ultimate strength and the longitudinal strain produced by this stress" (Gao; Sun; Morino, 1997).

According to Gao, Sun and Morino (1997), results are the following. First, the compressive strength ($f_{c'}$) demonstrated a very small increase with increasing of V_f, from 70.2 to 85.4 MPa, and it can be explained, according to authors (1997), due to "the ultimate strength of concrete be controlled by the strength of lightweight aggregates" (Gao; Sun; Morino, 1997). Second, the splitting tensile strength (f_{sp}) increased significantly, from 4.95 to 8.88 MPa (19-78%), "depending on the various fibre volume and aspect ratio", but to have an effective impact in f_{sp}, the volume of fibres must be over 1% by volume (Gao; Sun; Morino, 1997). In addition to this, Gao, Sun and Morino (1997) remark that "the splitting strength increases linearly with the addition of fibres and is linear functions of V_f and l/d. Third, the flexural strength (f_r) strongly enhanced from 6.2 to 11.8 MPa (9.6 to 90%) according to V_f and aspect ratio (Gao; Sun; Morino, 1997). Gao, Sun and Morino (1997) explain that added fibres will carry the load, and they will bond the cracks, thus "the deflection corresponded to ultimate load increases with the increase of fiber volume and aspect ratio". Fourth, the modulus of elasticity (E_c) is significantly affected by the lightweight aggregates used, which are porous, so E_c tends to be lower using lightweight aggregates than normal ones. On the other hand, steel fibres have elevated $E_{c,}$ which contributes to enhancing the E_c of the concrete mixture, so the E_c varied from 23.1 to 27.9 GPa depending on V_f and aspect ratios (Gao; Sun; Morino, 1997).

Thomas and Ramaswamy (2007) made an experimental program in which they tested the influence of steel fibers in three different types of concrete: normal-strength concrete (35 MPa, w/c = 0.48), moderately high-strength concrete (65 MPa, w/c = 0.35) and high-strength concrete (85 MPa, w/c = 0.28). Steel fibres used had 30 mm of length and aspect ratio of 55 and V_f of 0, 0.5, 1.0 and 1.5%. The compressive strength was tested in two different specimens: cube (150 x 150 x 150) and cylinder (150φ x 300); the splitting tensile strength with a cylinder of 150φ x 300; the modulus of rupture was tested using a prism with 100 x 100 x 100; and the modulus of elasticity using a cylinder of 150φ x 300.

Thomas and Ramaswamy (2007) remarked the following conclusions. First, the increase of compressive strength was not symbolic. Using the cube compressive strength, from 0 to 1.5% by volume of fibres, it was observed an increment of "3.65% in normal-strength concrete, 2.65% in moderately high-strength concrete, and 2.59% in high-strength concrete", and the cylinder compressive strength was "8.33% in normal-strength concrete, 6.10% in moderately high-strength concrete, and 4.60% in high-strength concrete" (Thomas and Ramaswamy, 2007). Second, split tensile strength enhanced largely, by 38.2% in normal-strength concrete, 41.2% in moderately high-strength concrete, and 38.5% in high-strength concrete (Thomas and Ramaswamy, 2007). Third, the modulus of rupture had a considerable increment by using fibres: 46.2% in normal-strength concrete, 38.8% in moderately high-strength concrete, and 40.0% in high-strength concrete. On other words, those results mean a remarkable enhancement in post-cracking response "with fibres dosages across the different concrete grades" (Thomas and Ramaswamy, 2007). Fourth, the modulus of elasticity was not somewhat affected by the addition of fibres once it increment was 8.3% in normal-strength concrete, 9.2% in moderately high-strength concrete, and 8.2% in high-strength concrete (Thomas and Ramaswamy, 2007).

Wang and Wang (2013) report a study in which "five groups of SFLWC specimens with different steel fiber volumes including 0.0%, 0.5%, 1.0%, 1.5% and 2.0% were tested to investigate the effect of steel fiber content on the static mechanical properties and the impact resistance of lightweight aggregate concrete". The compressive strength, at 28 days, of LWC was 60.4 MPa and the water-cement ratio of 0.42 (Wang; Wang, 2013). The compressive strength and the splitting tensile strength were tested using specimens of 150 x 150 x 150 mm, and the flexural strength was tested "on 150 x 150 x 550 mm specimens with four-point flexural loading" (Wang; Wang, 2013).

Wang and Wang (2013) come up with certain conclusions. First, "test results show the compressive strength varied from 60.4 MPa to 74.8 MPa (23.8%), corresponding to the age of 28 days for the various fiber volume fractions" (Wang; Wang, 2013). Like it was mentioned by Gao, Sun and Morino (1997), in LWC, lightweight coarse aggregates control the ultimate strength of concrete. However, "the incorporation of steel fiber into matrix serves to increase the ultimate compressive strength by the resultant arresting growth of cracks based on the bond of steel fiber and cement paste" (Wang; Wang, 2013). Second, the splitting tensile strength demonstrated a largely enhancement, from 3.99 to 7.6 MPa (92.5%) (Wang; Wang, 2013). Third, the flexural strength also increased due to "the influence of fibre arresting cracking" (Wang; Wang, 2013). In addition to this, Wang and Wang (2013) observe the way that LWC and SFLWC discs failed: "the SFLWC discs failed largely by the two-piece break, whereas the LWC discs failed mostly by the three-piece break shown" (Wang; Wang, 2013). Moreover, in SFLWC breaking pieces were connected with fibers, and in LWC (with no fibres), the broken parts were separated (Wang; Wang, 2013).

Iqbal *et al*. (2015) made a study to investigate "mechanical properties of steel fiber reinforced high-strength lightweight self-compacting concrete (SHLSCC)". Compressive strength, splitting tensile strength and modulus of elasticity were tested using cylinder specimens of 100 mm (diameter) x 200 mm (height), at the age of 28 days. Flexural tests were made using small prisms of 80 x 80 x 400 mm, also at the age of 28 days. Steel fibers with length of 13 mm and aspect ratio of 65 were used, and by the volume fraction of 0, 0.5, 0.75, 1.0 and 1.25%. Water-cementing ratio was 0.46 for V_f of 0, 0.5, 0.75 and 1.0%, and it was 0.48 for V_f 1.25% (Iqbal *et al*., 2015).

Based on their study, Iqbal et al. (2015) present following results. First, the compressive strength demonstrated a small reduction (12%) when the $f_{c'}$ (at 28 days) of concrete without fibers (67.80 MPa) was compared with $f_{c'}$ (at 28 days) of concrete with 1.25 % of fibres volume fraction (59.74 MPa). According to Iqbal et al. (2015), this reduction is "due to the increase of air content" with increasing of steel fiber content (Iqbal *et al*., 2015). Second, the splitting tensile strength increased with increasing of steel fibers volume, from 4.1

to 5.64 MPa (37%) (Iqbal *et al*., 2015). Third, the flexural strength also increased from 3.7 to 7.62 MPa, and "the first crack load increases by around 32% while there is an increase of around 110% in peak load, once the fiber content is increased from 0% to 1.25%, once the fibers start bridging the cracks increasing the ultimate load" (Iqbal *et al*., 2015). Fourth, even though the modulus of elasticity reduces if compare the concrete without fibers with those that have fibers, Iqbal *et al*. (2015) state that "the modulus of elasticity remains unaffected by the addition of steel fibers".

As it was mentioned in the previous section, Jang *et al*. (2015) conducted a study to investigate "the influence of steel fibre contents on the mechanical properties of HPC" of beams with the compressive strength of 60 MPa and 100 MPa. Steel fibers tested quantities were 0, 0.5, 1.0 and 1.5% by volume, and the average length of the fibers are 30 mm, and aspect ratio of 60. Prismatic specimens of 100 x 100 x 400 mm were used for flexural strength test, and cylindrical specimens of 100 x 200 mm were used for compressive strength test. Furthermore, "to investigate the feasibility of replacing stirrup and additional transverse reinforcement with hooked-end steel fibres for the shear-dominant short coupling beams, two specimens were designed, constructed, and tested up to failure" (Jang *et al*., 2015). Each beam is 1300 mm long, and they have the cross section of 200 x 300 mm.

According to the study, Jang *et al*. (2015) present following conclusions. First, increasing the volume of added steel fibres, the compressive strength reduced in 60 MPa and 100 MPa samples, if compared those without and with steel fibres. Jang *et al*. (2015) remark that "the presence of hooked-end steel fibres had little effect on the compressive strength of HP-SFRC with specific compressive strength of 60 and 100MPa" (Jang *et al*., 2015). Second, the modulus of rupture had significant increment with the increasing of steel fibers by volume. Jang *et al*. (2015) observe that "the addition of 1.5% steel fibres to the 60MPa and 100MPa HPC caused a maximum increase of 42.3% and 30.0% compared with the modulus of rupture of HPC without steel fibres, respectively". Third, using 1.5% of steel fibers by volume, in the 60 MPa concrete is sufficient to create a ductility behavior in the tested beams (Jang *et al*., 2015).

5. CONCLUSIONS

This literature review paper presented information regarding High-Strength Fibre-Reinforced Lightweight Concretes, and their mainly mechanical properties were demonstrated through different and well conducted researches. It was possible to observe that structural lightweight concrete has benefits when compared to normalweight concretes due to higher strengthens-weight ratio and improves tensile strain capability. Moreover, even thought it was demonstrated that the shear behavior of LWC are reduced when compared with NWC, more studies about shear behavior in LWC beams need to be done. Regarding the flexural behavior, LWC has bigger ultimate deflections, and elastic flexural theory proposed by ACI 318 code somewhat underestimates the actual deflection for LWC.

Another aspect investigated in this paper was the addition of steel fibers. Studies analyzed in this paper have shown that steel fibers increase shear and flexural behaviour. Adding 0.75% of fibers by volume demonstrated a huge improvement in shear and tensile strength. Furthermore, SF extraordinarily reduced the crack width and size, enhanced the deformation capacity, and contributed to creating a ductile mode instead of a brittle one.

Although all studies presented here have publicised remarkable improvements in shear and flexural behaviours of High-Strength Fibre-Reinforced Lightweight Concretes, it is fundamental that new research projects be conducted. These prospective studies will contribute to a better understanding, and they will contribute to change current codes and create innovative ones.

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