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Original Article

Fresh and Hardened Behavior of Self-Compacting Lightweight Concrete Reinforced with Sisal Fibers

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Abstract *- This study presents the results of a lightweight self-compacting concrete reinforced with sisal fibers. Lightweight aggregates such as expanded clay, pumice, and expanded polystyrene were used as lightweighting materials, replacing up to 30% of the coarse aggregate by volume. Different volumetric fractions and lengths of sisal fibers were added: 0.1%, 0.2%, and 0.3% by volume, and 2.5 cm, 5.0 cm, and 7.5 cm in length. To analyze their influence on workability, the slump test and T500 were used; mechanical behavior was determined through compression and tensile tests at different curing times. The results showed that in the slump test, all mixtures fell within a range of 70 to 80 cm, and the T500 values ranged from 4.3 to 7.2 seconds, including the specimens with sisal fibers. Replacing coarse aggregate with lightweight aggregate and adding sisal fibers negatively affects compressive strength regardless of curing time; however, the presence of the fibers improves tensile strength.*

Keywords *- Lightweight self-compacting concrete, Lightweighting material, Organic fibers, Compressive and tensile strength, Density.*

1. Introduction

Lightweight self-compacting concrete combines the properties of Self-Compacting Concrete (SCC)-which eliminates the need for external vibration-with those of lightweight concrete, which aims to reduce the density and, consequently, the weight of the material. This makes it a suitable choice for use in major structures. [1, 2]. The unique rheological properties of SCC are due to its viscosity and cohesion, which are sufficient to allow the mixture to flow into the formwork without mechanical vibration and without segregation of its components [3, 4]. Furthermore, the bulk density of concrete typically ranges from 2,200 to 2,500 kg/m³; reducing this property without compromising strength can offer design and construction advantages [5].

Concrete is generally made lighter by adding lightweight aggregates [6,7], which, in addition to reducing weight, offer other benefits such as sound and thermal insulation [8]. Among the most common lightweighting options are pumice [9,10], expanded polystyrene beads [11], and expanded clay [12], among others.

One of the aggregate options for lightweighting concrete is pumice stone. According to [10, 13], substituting between 10% and 30% of the coarse aggregate volume offers an optimal balance between mechanical behavior and density, recording a moderate reduction in compressive strength (between 4.8% and 22.6%) alongside an oven-dry density ranging from 1600 kg/m³ to 2000 kg/m³. Another lightweighting option is expanded polystyrene [11, 14], where replacements of 10% to 30% of the coarse aggregate volume report reductions in compressive strength ranging from 21.8% to 35.6%, simultaneously achieving a decrease in density between 1947 kg/m³ and 1870 kg/m³. Additionally, expanded clay can also function as a lightweight aggregate; [12, 15] reported that partial volumetric replacements of coarse aggregate by 25% and 50% can cause a reduction in strength between 14.4% and 23.5%, while decreasing density by 13.7% and 39.7%, respectively.

On the other hand, the behavior of concrete depends largely on the aggregates it contains, as these account for approximately 75% of its total volume. When lightweight aggregates are used, their intrinsic properties can alter the properties of concrete in both its fresh and hardened states [2].

One of the properties that draws attention is the high absorption capacity of most lightweight aggregates (due to their high volume of pores containing micrometric tubular channels that generate capillary forces and surface tension [16]). This can benefit the fluidity of self-compacting concrete due to the suction exerted by the porous aggregate on a fraction of the cement paste, which can generate a uniform coating layer around the lightweight particles that acts as a lubricant, allowing them to move more freely within the mix

[2]. However, this same characteristic can have a negative impact by absorbing mixing water that the paste needs to react, leaving a fraction of unhydrated cement precisely in the contact zone between the cement paste and the lightweight aggregate surface, which would affect the mechanical strength and durability of the concrete [16, 17].

The shape of the lightweight aggregate is another characteristic that must be taken into account; spherical or regular shapes can benefit the workability of self-compacting concrete by reducing internal friction forces within the mix, as the rolling effect is promoted, minimizing drag friction [18]. Regarding compressive strength, a regular morphology of the lightweight aggregate can be beneficial since, lacking sharp edges, stress concentration at the aggregate boundaries is avoided, which could otherwise cause premature cracking and lead to concrete failure [19].

Incorporating lightweight materials with water-repellent (hydrophobic) properties can solve water loss issues due to absorption; however, it transforms the rheological behavior mainly due to the water repulsion effect, causing segregation of this material and modifying the stability of the mix. Regarding mechanical performance, it can be diminished due to the lack of affinity with water, which prevents proper anchoring, causing adhesion defects and thus penalizing strength [20, 21].

However, due to the high porosity of lightweight aggregates, they have a low capacity to absorb energy under mechanical stress, leading to a variable stress distribution within the matrix and a loss of control over crack propagation, thereby reducing deformation capacity. The result is a material that is prone to brittle fracture [20, 22], a failure that must be avoided in structures due to its sudden and dangerous nature.

To mitigate the brittle nature of lightweight matrices, researchers have opted to incorporate fibers into the concrete, which has been shown to offer several benefits, such as: improved ductility due to the ability to undergo greater deformation, increased toughness, and higher tensile strength (properties that can be further enhanced in lightweight concrete), as well as delaying crack propagation, since the fiber can act as a bracing element to hold the crack together and distribute stresses more uniformly [23].

When discussing fibers, their inclusion in the mix can affect the behavior of concrete in its fresh state. Long fibers can cause particle interlocking, generating restrictions on movement, which produces a negative impact on workability [24,25]. Likewise, a higher fiber content in the mix can increase the solid fraction within a constant paste volume, which can increase the internal friction of the mix, thereby affecting its rheological behavior [26]. Consequently, controlling both fiber length and volume becomes a critical control parameter.

Now, when discussing hardened concrete, the curing time is important, since the low stiffness of the cementitious matrix can improve the compressive strength with long fibers at early ages, which promotes the appearance of microcracks, against which larger fibers act as bridging and local confinement elements, contributing to a more effective transfer of stresses[27]. However, at longer curing times, when the compactness of the matrix and the fiber-paste adhesion are already high, the rheological effect predominates, so long fibers can decrease the workability of the concrete, contributing to a heterogeneous distribution of fibers and an increase in the air content, thus reducing compressive strength [27, 28].

Metal, polypropylene, glass, and carbon fibers have been studied and used in the construction industry; however, natural fibers are attracting interest in materials development for their properties similar to those of commercial fibers [29]. When the analysis focuses on sisal, it has performed exceptionally well compared to other natural fibers due to its high cellulose crystallinity, which can improve interfacial bonding and delay fiber-matrix slippage [30]. Furthermore, when determining the volumetric content and length of natural fibers in concrete, it is based on a rheological-mechanical balance. Thus, [31] demonstrated that each fiber type (sisal, jute, hemp, pineapple, etc.) exhibits distinct mechanical responses, rendering generalization of dosages impossible. Tests by [32] with sisal and palm showed that, above 1.5% of cement volume, the strength gain stabilizes or declines due to increased paste demand. Micromechanical studies confirm that the critical length should be 20-40 mm to maximize stress transfer without compromising rheology [33-35]; mentioned that fibers work adequately when they present between 0.1 and 1.5% of the total volume of the mixture; however, this range must be adjusted to the type of natural fiber used. In lightweight concrete with coconut aggregate, [36] reported that a 3% addition of sisal fiber (by binder weight) increased compressive strength by 6% and tensile strength by 14%. At the same time, higher fractions lead to saturation and reduced performance.

Taking these considerations into account, sisal offers the construction industry an alternative with significant advantages, such as a lower environmental impact, reduced material costs, and the promotion of underutilized natural products.[37-40]. Ecuador produces approximately 1,771 tons of sisal annually, with production concentrated mainly in the Inter-Andean Valley, in the provinces of Chimborazo, Tungurahua, Imbabura, and Carchi. Although this fiber has traditionally been used to make yarn and sacks[41], its local availability presents an opportunity to incorporate it into lightweight self-compacting concrete.

Given the potential fragility of self-compacting concrete made lighter by the use of low-density materials such as expanded clay, pumice, and polystyrene, the addition of locally available natural fibers is being considered to assess their effects on the concrete's rheological and mechanical behavior.

2. Materials and Methods

2.1. Materials

The materials used in this study were: sisal fibers, solid paraffin to insulate the fibers from the cement paste, aggregates, cement, expanded clay (Arlita), and a superplasticizer additive for the production of self-compacting concrete.

The sisal fibers were purchased at the "Mercado Dávalos" in Riobamba, Ecuador. The twisted fibers had an average bulk density of 1,494.34 kg/m³, an average absorption rate of 235.64%, and a tensile strength of approximately 305 MPa. [29].

Its main chemical components are cellulose, lignin, and pentosans (73.8%, 11.3%, and 10.5%, respectively), and it also contains helical structures that give the fiber's elasticity [41]. (Figure 1) shows the dimensions and appearance of sisal fiber.

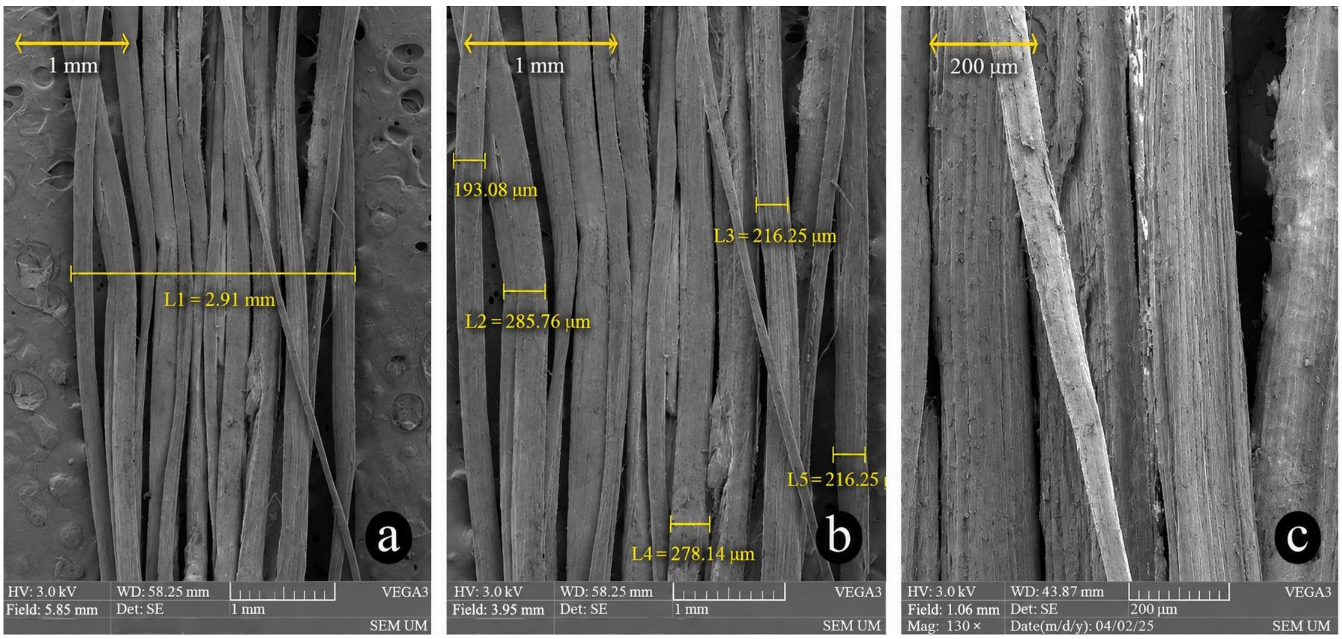

Fig. 1 (a) Total diameter of the twisted sisal fiber, (b) Reference diameter of each sisal fiber, (c) Appearance of the fiber under a 130x magnification.

The paraffin was purchased from the company "PRODUQUIMIC" in Quito, Ecuador. Its density in the solid state is 0.91 g/cm³, and its phase transition temperature ranges from 69°C to 84°C. This material was used as a coating on the sisal fiber to make its surface hydrophobic, thereby reducing its absorbency and acting as a barrier against the highly alkaline environment of the cementitious matrix [42].

The coarse aggregate is a river-derived material sourced from the "La Guadalupe" mine in the Chambo canton. The maximum nominal size of the coarse aggregate is 19 mm, and its particle size distribution falls within the limits established by ASTM C33 [43] for coarse aggregates with a particle size index of 6. The SCC mix design was developed using river gravel, as rounded aggregate promotes flowability [44].

On the other hand, the fine aggregate was extracted from the same "La Guadalupe" mine; it has a fineness modulus of 3.53, and its particle size distribution falls within the limits established by ASTM C33 [43] for fine aggregates. The filler was obtained from the company "COVIPAL" and is produced by crushing river material; it has a fineness modulus of 1.76, with 99.8% passing through a 2.38-mm sieve.

Among the lightweight aggregates analyzed are Arlita, which was purchased from Hidroponía Ecuador - La Huerta Honfleur, located in Quito and dedicated to hydroponics; its actual density is 0.86 g/cm³ with an absorption rate of 16.8%; and the pumice purchased from the 'Profuturo' mine, located in the city of Latacunga, Cotopaxi province, its actual density is 1.03 g/cm³ with an absorption rate of 20.3%, and expanded polystyrene purchased from Lastex, located in Quito, Ecuador; its actual density ranges around 0.05 g/cm³ with an absorption rate of 4.2%.

The Portland cement used was Holcim Fuerte type GU, which complies with the standard [45]. Its density is 2.93 g/cm³, which is equivalent to the value specified in ASTM C150 [46]. It is a Type I cement. The high-performance water-reducing admixture used was the Sikament N-100 superplasticizer, which contains a high proportion of synthetic resins [47]. (Figure 2) shows the materials.

Fig. 2 Materials: (a) Sisal fibers, (b) AG, (c) AF, (d) Filler, (e) Superplasticizer, (f) Paraffin, (g) Arlite, (h) Pumice, (i) Polystyrene.

2.2. Methodology

Self-Compacting Concrete (SCC) was chosen because it is a high-performance material that flows into the formwork with uniform properties without requiring vibration or reinforcement, unlike conventional concrete. It can be a good solution for fibers, as it reduces segregation and improves their orientation. [48,49], and for lightweight aggregates, it reduces the likelihood of segregation in the event of excessive vibration [50,51]. The design of this type of concrete was based on ACI 237 [52].

For the selection of lightweight materials, several lightweight aggregates were analyzed based on their properties and availability in Ecuador, from which three alternatives were selected: arlite (expanded clay), pumice, and expanded polystyrene [53-56]. Based on research conducted using these lightweight aggregates, it was decided to replace them in varying percentages relative to the volume of the coarse aggregate [10-12], Table 1 shows the dosages used for SCC with lightweighting materials per cubic meter (m^3).

Table 1. SCC mix designs with lightweight aggregates per cubic meter (m^3)

Replacement Coarse aggregate (%)	Portland Cement (kg)	Water (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Filler (kg)	Additive (kg)	Pumice stone (kg)	Expanded polystyrene (kg)	Expanded clay (kg)
0%	500	250	794.40	405.48	455.13	15	[-]	[-]	[-]
10%	500	250	714.96	405.48	455.13	15	55.28	[-]	[-]
20%			635.52				71.28	[-]	[-]
30%			556.08				87.28	[-]	[-]
10%	500	250	714.96	405.48	455.13	15	[-]	0.6	[-]
20%			635.52				[-]	1.2	[-]
30%			556.08				[-]	1.8	[-]
10%	500	250	714.96	405.48	455.13	15	[-]	[-]	23.3
20%			635.52				[-]	[-]	46.6
30%			556.08				[-]	[-]	69.9

To prepare the lightweight SCC, the process began by mixing cement with fine aggregate, followed by the addition of coarse aggregate, and then the lightweighting material. Water was gradually added to this mixture, and the superplasticizer additive was dissolved in the final 25% of the water, mixing until a homogeneous, fluid paste was obtained. To evaluate the properties of the concrete in its fresh state, the slump test and T500 test (ASTM C1611) were performed [57] and in the hardened state, compression tests were conducted in accordance with ASTM C39 [58], after 7 days of curing at a temperature of 19°C ± 2°C and a relative humidity of 70%.

Once the lightweighting material was selected based on the results of the compression, creep, and T500 tests, the sisal fibers were added to the mixture in accordance with the recommendation by Ahamed et al.[31] who state that the determination of the quantity and length of natural fibers depends on a rheological-mechanical balance, for which the following was used as a reference [30,34,35,59,60], The dosages are shown in Table 2.

Regarding the production of the lightweight SCC reinforced with sisal fibers, the fibers were first coated with paraffin and added to the mixture at the end to minimize damage to their structure. The sisal fibers were coated by immersing them in molten paraffin at a controlled temperature (69-84°C) for 15 minutes. After drying, the outer clumps were manually removed, and the fibers were cut to the dimensions required for the research.

Regarding the properties of the fresh mixture, slump and T500 tests were conducted in accordance with ASTM C1611 [57].

In addition, the compressive strength of the hardened specimens was determined in accordance with ASTM C39 [58], at 7 and 28 days of curing at a temperature of 19°C ± 2°C and a relative humidity of 70%, as well as the indirect tensile strength at 28 days of curing at the same temperature and relative humidity, using the test described in ASTM C496 [61] . (Figure 3) presents the research process diagram in three stages.

Table 2. Mix proportions for lightweight SCC with 20% expanded clay and jute fibers per cubic meter (m³)

<table>
<tr><th>Denomination</th><th>Cement (kg)</th><th>Water (kg)</th><th>Coarse Aggregate (kg)</th><th>River sand (kg)</th><th>Fine sand (kg)</th><th>Additive (kg)</th><th>Expanded clay (kg)</th><th>Fiber 2.5cm (kg)</th><th>Fiber 5cm (kg)</th><th>Fiber 7.5cm (kg)</th></tr>
<tr><td>SCC Base</td><td>500</td><td>250</td><td>635.52</td><td>405.48</td><td>455.13</td><td>15</td><td>46.60</td><td>[-]</td><td>[-]</td><td>[-]</td></tr>
<tr><td>SCC 0.1%-2.5cm</td><td rowspan="3">500</td><td rowspan="3">250</td><td rowspan="3">635.52</td><td rowspan="3">405.48</td><td rowspan="3">455.13</td><td rowspan="3">15</td><td rowspan="3">46.60</td><td>1.49</td><td>[-]</td><td>[-]</td></tr>
<tr><td>SCC 0.2%-2.5cm</td><td>2.98</td><td>[-]</td><td>[-]</td></tr>
<tr><td>SCC 0.3%-2.5cm</td><td>4.47</td><td>[-]</td><td>[-]</td></tr>
<tr><td>SCC 0.1%-5.0cm</td><td rowspan="3">500</td><td rowspan="3">250</td><td rowspan="3">635.52</td><td rowspan="3">405.48</td><td rowspan="3">455.13</td><td rowspan="3">15</td><td rowspan="3">46.60</td><td>[-]</td><td>1.49</td><td>[-]</td></tr>
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<tr><td>SCC 0.1%-7.5cm</td><td rowspan="3">500</td><td rowspan="3">250</td><td rowspan="3">635.52</td><td rowspan="3">405.48</td><td rowspan="3">455.13</td><td rowspan="3">15</td><td rowspan="3">46.60</td><td>[-]</td><td>[-]</td><td>1.49</td></tr>
<tr><td>SCC 0.2%-7.5cm</td><td>[-]</td><td>[-]</td><td>2.98</td></tr>
<tr><td>SCC 0.3%-7.5cm</td><td>[-]</td><td>[-]</td><td>4.47</td></tr>
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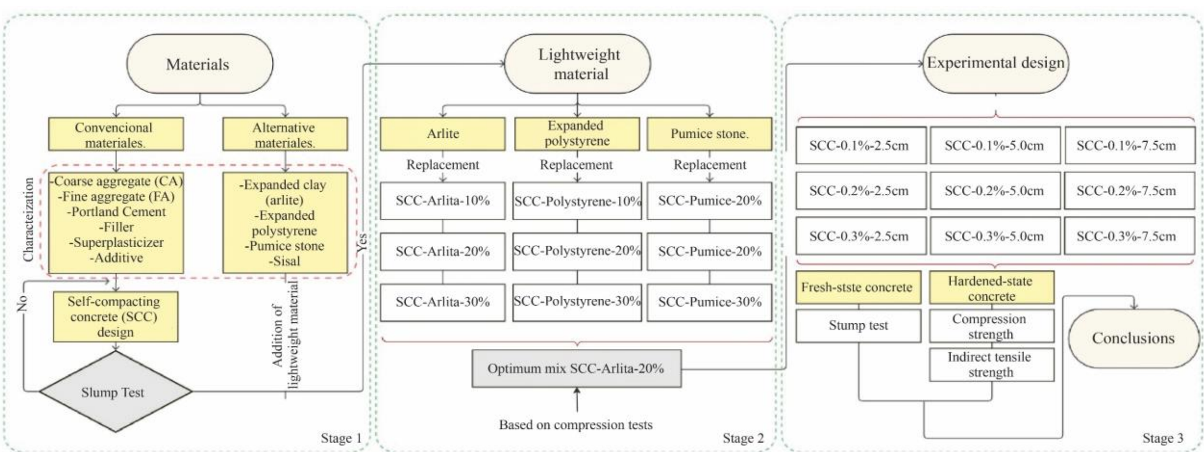


Fig. 3 Research process diagram

3. Results and Discussion

3.1. Lightweight Materials

Table 3 shows the slump test and T500 flow time for SCC mixtures with lightweight aggregates, to assess the influence of these materials on the rheological behavior of the concrete.

Table 3 shows that the type of lightweight aggregate affects the drainage test results. When considering the flow diameter and sorting the data in ascending order, the following sequence is observed: polystyrene < Arlita < pumice. This behavior may be due to the absorption rate of the lightweight aggregate; this trend is similar to that reported by [2], where a higher absorption percentage promotes the even distribution of aggregates within the cementitious matrix, resulting in improved mix flow. (Absorption percentage values: Polystyrene = 4.2%; Arlite = 16.8%; and Pumice = 20.3%).

Table 3. Analysis of drainage test results for SCC with lightweight aggregates

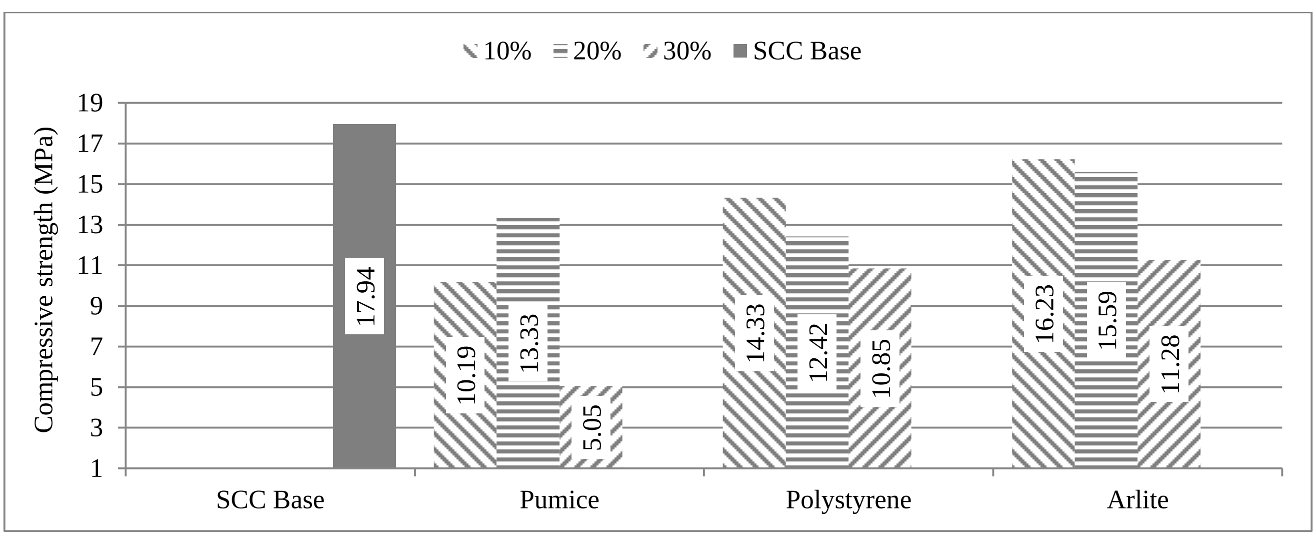
REPLACEMENT RATE	SCC-BASE		SCC-PUMICA		SCC-POLYSTYRENE		SCC-ARLITE	
	Df (cm)	T (sec)	Df (cm)	T (sec)	Df (cm)	T (sec)	Df (cm)	T (sec)
Base	77.5	7.21	[-]	[-]	[-]	[-]	[-]	[-]
10%	[-]	[-]	78.50	4.84	74.00	6.31	77.50	6.87
20%	[-]	[-]	73.50	4.55	72.50	5.84	76.00	6.11
30%	[-]	[-]	75.00	4.36	71.50	5.01	74.00	5.60

It should also be noted that the mixtures fall within the slump categories established by EFNARC [62], where SCC-Base, SCC-expanded clay, and SCC-pumice fall within the SF2 (660–750 mm) and SF3 (760–850 mm) class limits; on the other hand, polystyrene is classified as SF2.

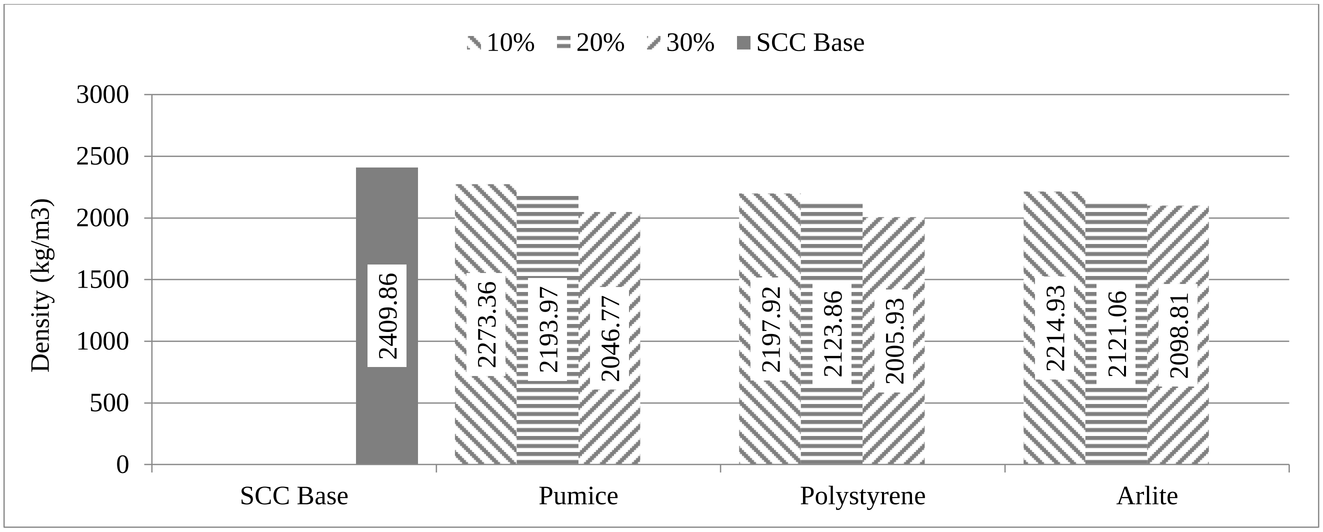
On the other hand, when analyzing the effect of variations in the amount of lightweight aggregate on flow time, it was found that flow time is inversely proportional to the amount of lightweight aggregate; this may be due to the rounded shape of the lightweight aggregates. This effect is similar to that observed in [63], where a higher proportion of rounded lightweight aggregate leads to greater lubrication between particles, resulting in greater flowability in the resulting mixture.

A general analysis of Table 3 shows that pumice exhibits better rheological behavior, as it has flow diameters ranging from 73.5 cm to 78.5 cm-values very close to those of the SCC-base—and flow times that are more than 2 seconds shorter than those of the SCC-base. This behavior could be explained by the absorption rate of the pumice, which may result in an even distribution of the aggregate in the mortar, leading to improved rheological properties of the mixture [2]. However, this increased fluidity does not necessarily imply better mechanical performance, as high absorption can alter the effective water-to-cement ratio and reduce strength at advanced stages of curing [16, 17].

(Figure 4) shows the compressive strength and density of SCC specimens after 7 days of curing with different lightweight aggregates. It is evident that as the proportion of lightweight aggregate increases, the compressive strength of the SCC decreases proportionally. These results are consistent with studies [64-66], which report a decrease in the density and compressive strength of the concrete as the amount of lightweight aggregate increases.



(a)



(b)

Fig. 4 Materials: (a) Compressive strength of lightweight SCC samples after 7 days of curing, (b) Density of lightweight SCC samples after 7 days of curing.

When analyzing the density of SCCs with different lightweighting materials, SCC–POLYSTYRENE stands out; however, its impact on compressive strength is significant (the greatest among the lightweight aggregates analyzed). If the density of SCC-BASE is compared with that of SCC-POLYSTYRENE-30%AG, there is a 20.1% reduction in density; however, when considering its compressive strength, a 65.3% loss stands out. This considerable decrease could be explained, first, by the hydrophobic nature of polystyrene, which leads to inefficient adhesion to the cement paste; and second, by a significantly lower stiffness than the cement paste, which causes a distribution of variable stresses within the concrete. This finding is confirmed in the following studies [20,21] this reason, the compressive strength of polystyrene-lightened concrete is reduced, falling below that of structural concrete as specified in the standard [67], making this weight-reduction method inefficient.

When focusing on viable lightweighting alternatives, Figure 4 shows that expanded clay offers the best performance: at a 20% replacement rate, it achieves a compressive strength of 15.59 MPa, representing 86.9% of the SCC-base, whereas pumice reaches 10.19 MPa, representing 56.8% of the SCC-base. On the other hand, when analyzing densities at the same 20% replacement rate, pumice reduces the density from 2409.86 kg/m³ in the SCC base to 2193.97 kg/m³, representing a 9.0% reduction in weight, while expanded clay (2121.06 kg/m³) represents a 12.0% reduction in weight. This density difference can be considered minimal, but when evaluated in terms of compressive strength, it becomes clear that expanded clay is the lightweighting material with the best performance in the study.

In terms of specific strength, the samples containing 20% expanded clay remain similar to the SCC-base, as they have values of 7.35 and 7.44Mpa·m^3/t respectively. In contrast, pumice, at the same replacement rate, has a lower efficiency of only 4.64Mpa·m^3/t. Therefore, it could be said that expanded clay provides effective weight reduction without unduly compromising the concrete's strength, which is crucial for structural applications. This pumice behavior may be due to its high absorption rate (20.3%), which would increase the amount of unhydrated cement in the contact zones between the matrix and the pumice, thereby affecting the compressive strength of the analyzed samples. This fact is evidenced in other studies such as [16,17].

3.2. Lightweight SCC with Added Fibers

Table 4 presents the results of the slump test and the T500 flow time for mixtures of 20% SCC arlite and different amounts and lengths of jute fiber, to assess their influence on the rheological behavior of the concrete:

Table 4. Results of drainage tests on 20% SCC arlite, with varying amounts and lengths of sisal fiber

Fiber Quant. Fiber Length	Lightweight base		0.10%		0.20%		0.30%	
	Df (cm)	T (sec)	Df (cm)	T (sec)	Df (cm)	T (sec)	Df (cm)	T (sec)
[-]	76.00	6.11	[-]	[-]	[-]	[-]	[-]	[-]
2.5cm	[-]	[-]	76.00	5.84	76.50	6.01	77.00	6.65
5.0cm	[-]	[-]	76.00	6.14	75.50	6.65	76.50	6.94
7.5cm	[-]	[-]	75.00	6.55	77.00	6.98	77.00	7.12

An analysis of the effect of fiber length in Table 4 shows that the flow diameter varies minimally, ranging from 75 to 77 cm. However, when focusing on flow times, clear differences emerge: as fiber length increases from 2.5 cm to 7.5 cm, flow time tends to increase. This effect can be explained by the fact that longer fibers have a larger surface area, which could promote particle entanglement and impose greater restrictions on matrix movement, leading to poorer workability. Similar results can be seen in [24, 25]. If the flow diameter results are compared with the ranges established by EFNARC [62], SCCs reinforced with sisal fiber are classified as SF3 (760–850 mm).

An analysis of the influence of the amount of sisal fiber on flow diameter yields only a slight variation. However, regarding flow times, a direct relationship is observed: for 2.5 cm-long fibers with a content of 0.1%, the flow time is 5.84 seconds, whereas with 0.2% and 0.3%, the times are 6.01 seconds and 6.65 seconds, respectively. The same applies to fibers 5.0 cm and 7.5 cm long.

The reduced workability of lightweight SCC with higher fiber content may be due to the incorporation of additional solids into a constant volume of paste, which alters the internal friction and interactions between the particles that make up the concrete; this change can significantly alter the packing of the aggregates and influence their rheological properties [30].

When comparing flow time results with natural fibers such as abaca [68] or the areca nut [69], the behavior is similar, as the flow time increases proportionally as the length and amount of the fiber increase; for example, the 3% configuration with 12 mm fibers showed a 36% increase compared to the 1% configuration with 8 mm fibers. This delay in flow time may be due to increased friction from the fiber in the mixture.

Table 4 shows that the mixture with the best rheological behavior is the 0.10% SCC mixture with 2.5 cm fibers, as it has a flow diameter of 76 cm and the shortest flow time of 5.84 seconds. On the other hand, mixtures with 7.5cm fibers have the longest flow times, reaching 7.12 seconds.

To determine the mechanical properties of SCC reinforced with sisal fibers, three cylinders were subjected to compression testing at 7 days for each mix design; the average results are shown in Figure 5.

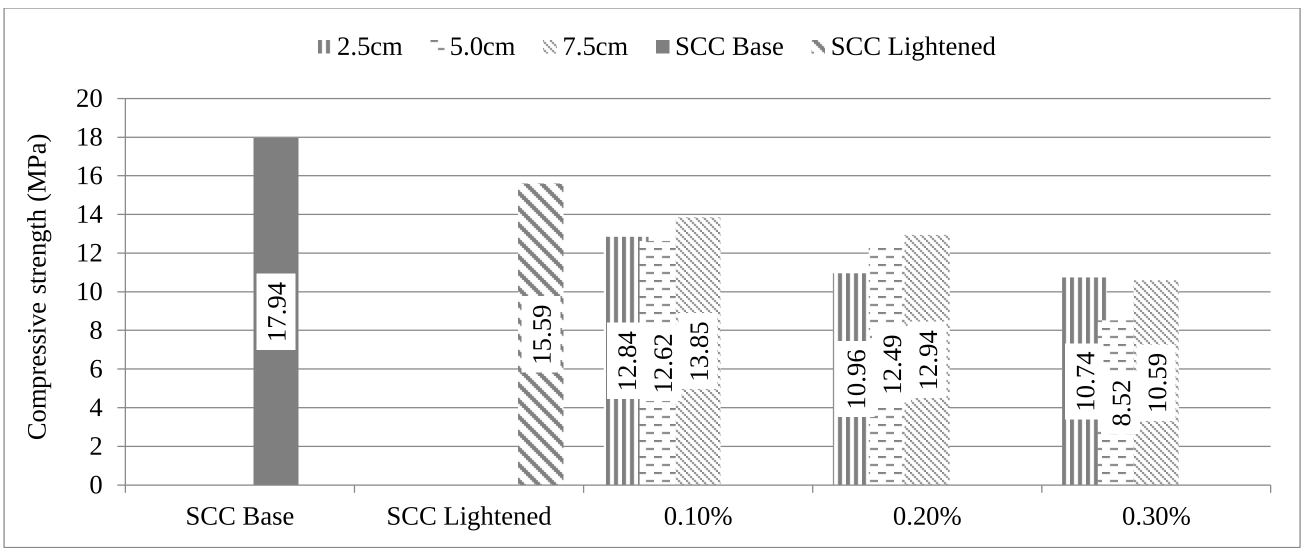


Fig. 5 Compressive strength of fiber-lightened SCC specimens (7 days of curing)

Figure 5 shows that the specimens containing sisal fibers exhibit a clear trend toward a decrease in compressive strength as the amount of fibers in the mixture increases; which could be related to a reduction in workability observed in Table 4, due to the addition of extra solids to a constant volume of paste, which may lead to an increase in voids and internal defects, causing an uneven distribution of the fibers and thus contributing to a reduction in the final strength of the hardened concrete [24, 25].

When analyzing the effect of sisal fiber length on compressive strength after 7 days of curing, it is noted that the 7.5 cm fibers exhibit the best performance, achieving an average compressive strength of 12.46 MPa with 7.5 cm fibers-8.0% higher than the mixture with 2.5 cm fibers and 10.5% higher than the mixture with 5.0 cm fibers.

This behavior could be related to the early curing age at which the compression test was conducted; at this stage, the cementitious matrix is still low in stiffness, making it prone to microcracking. It is here that the longer fibers act as a local bridging and confinement system, limiting crack propagation and enhancing stress transfer. Thus, incorporating long sisal fibers can increase compressive strength. The same behavior was observed in [27].

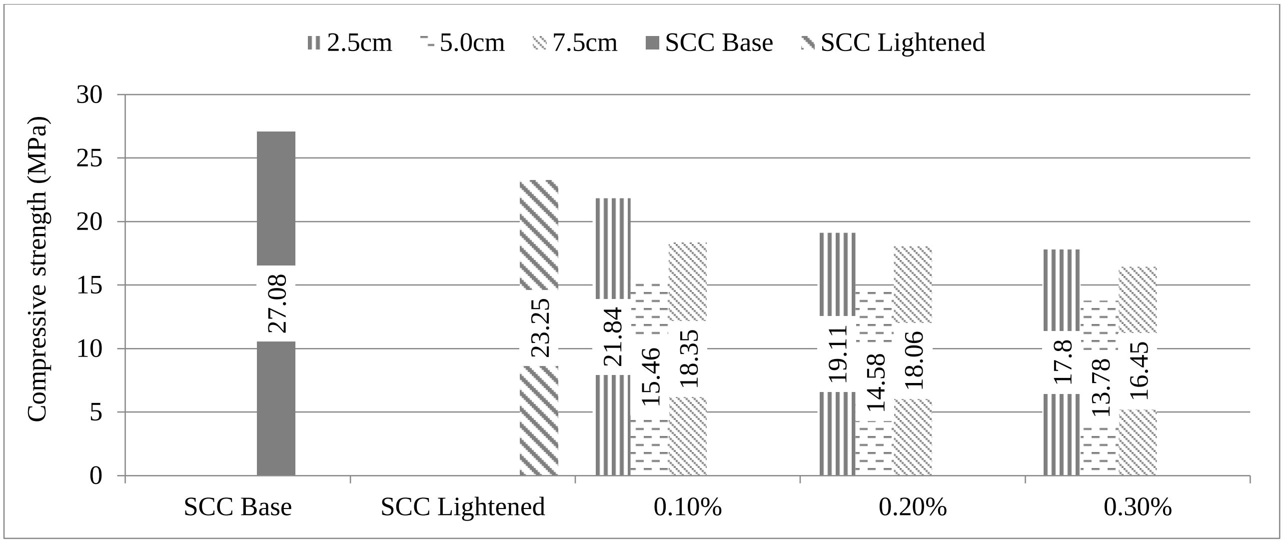


Fig. 6 Compressive strength of fiber-lightened SCC specimens (28 days of curing)

Furthermore, the 0.1%-7.5 cm SCC mixture achieves the highest compressive strength; however, it shows a 11.2% reduction compared to the lightweight SCC mixture. On the other hand, the SCC-0.3%-5.0 cm mixture has the lowest compressive strength, showing a 45.3% difference compared to the lightweight SCC.

(Figure 6) shows the average compressive strength of three concrete cylinders after 28 days of curing, accounting for variations in the length and quantity of sisal fibers.

Figure 6 highlights the trend in the data, as an increase in the number of fibers leads to a decrease in compressive strength. This decrease could be attributed to the same phenomenon observed at 7 days (the fibers may increase voids in the concrete) [24,25,70]. In addition, the test demonstrates the bond between the concrete and the sisal fibers, as the concrete remained intact.

When evaluating the influence of sisal fiber length on 28-day compressive strength, 2.50 cm fibers achieve the highest values. This result contrasts with the result recorded at 7 days; this behavior could be explained by the increased curing time. At early ages (7 days of curing), the matrix is still not very rigid and susceptible to microcracking. On the other hand, at 28 days of curing, when compaction is high and fiber-matrix adhesion is already strong, the rheological effect begins to dominate compressive strength (as shown in Table 4). long fibers impair workability, which could lead to a heterogeneous fiber distribution and an increase in the air content of the mixture, thereby contributing to poorer results. Similar behaviors have been observed in previous studies [27, 28, 71].

Furthermore, the 0.1%-2.5% SCC mixture exhibits the highest compressive strength; however, it shows a 6.1% decrease compared to the lightweight SCCS. On the other hand, increasing the proportion of SCC fibers to 0.3%–5.0% yields the lowest compressive strength, a 40.7% reduction relative to the lightweight SCC.

When comparing the results with natural fibers, such as areca nut fiber [69], coconut or jute [72], The behavior is similar, since increasing the length and number of fibers affects the compressive strength; for example, a 1% configuration with 8 mm fibers has 7.5% higher compressive strength than a 3% configuration with 12 mm fibers, this decrease in strength may be since a greater quantity and length of fibers can disrupt their uniform distribution, creating voids and areas of internal weakness. To analyze the effect of the quantity and length of sisal fibers on compressive strength, a statistical analysis was conducted at 28 days (because this represents the point at which the chemical hydration reactions of the cement have matured sufficiently to consolidate the internal structure of the concrete) [73], The Shapiro-Wilk test yielded p-values greater than 0.05 for all groups, so the assumption of normality was not rejected. Levene’s test showed a p-value of 0.034, indicating a lack of homogeneity of variances among the evaluated dosages. For this reason, Welch’s ANOVA was used as the test for comparing means:

Welch's ANOVA confirmed statistically significant differences among the formulations analyzed ($p<0.01$). Using the Games-Howell post hoc test, the most significant differences were observed between the mixtures containing 2.5 cm and 5.0 cm fibers. The results suggest that both the length and the amount of jute fiber directly influence the compressive strength of concrete, with shorter fibers in lower proportions favoring more efficient performance.

To determine the contribution of the fibers to tensile strength, Figure 7 shows the relationship between tensile strength and compressive strength, expressed as a percentage, for specimens that have cured for 28 days.

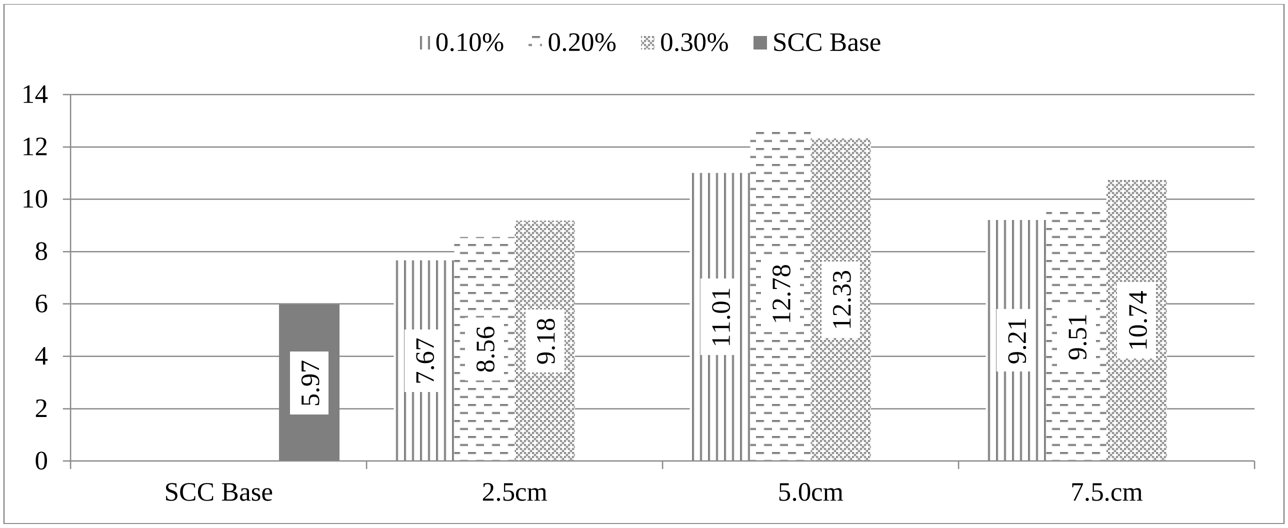


Fig. 7 Percentage ratio of concrete tensile strength to compressive strength after 28 days of curing

In Figure 7, the base SCC has a percentage ratio of tensile to compressive strength of 5.97%; this low performance may be related to the shape required of the coarse aggregate to promote the flow of self-compacting concrete, where the rounded shape can create small contact interfaces; when subjected to tensile stresses, these small contact areas are prone to damage and cause the rounded aggregate to detach [74].

Furthermore, it is observed that mixtures containing sisal fibers exhibit tensile strengths higher than those reported for the SCC-Base. The results obtained are consistent with previous experiments showing that the fibers improve the tensile strength of concrete, as applying a tensile load induces microcracks in the cementitious matrix; when these cracks encounter the fibers, the fibers help prevent rapid propagation of the cracks [75]. This coincides with [72], which states that fibers have a positive effect on tensile strength; it also notes that this effect depends on the strength of the fibers added to the concrete, which, in the case of sisal fiber, is approximately 305 MPa [29].

The results in Figure 7 show that increasing jute fiber content improved the tensile-to-compressive strength ratio of fiber-reinforced concrete at 28 days. For example, for fibers with a length of 5.0 cm, the ratio increases from 11.0% with a fiber content of 0.1% to 12.8% with 0.2%, demonstrating that a higher amount of sisal fibers increases the concrete's ability to resist tensile stresses. This behavior may be due to higher fiber content, which allows the fibers to be positioned closer together, providing a larger fiber-matrix interface area and leading to more efficient control of crack propagation, consistent with the findings of [76].

On the other hand, it was found that the length of the sisal fiber has a significant influence on the tensile behavior of the lightweight SCC; for example, 5.0-cm fibers at a concentration of 0.2% exhibit the highest tensile-to-compressive strength ratio, reaching a value of 12.8%, while 2.5 cm and 7.5 cm fibers at the same content yield 8.6% and 9.5%, respectively. This behavior is similar to that reported by [77], where, although longer fibers can provide better crack bridging and stress distribution to a certain extent, excessively long fibers can reduce workability, leading to uneven fiber distribution and poor adhesion. Therefore, the optimal fiber length depends on factors such as fiber type, volume fraction, and mix design.

It should be noted from the results in Figure 7 that the 0.2%-5.0 cm SCC dosage yields the highest percentage ratio of tensile strength to compressive strength, exceeding the ratio of the SCC-Base by more than double; in contrast, the lowest values in the series are obtained with the 0.1%-2.5 cm SCC dosage, which is 1.3 times higher than the ratio presented by the SCC-Base.

When comparing the results with natural fibers such as areca nut [69], coconut, or jute [72], a similar pattern is observed: the maximum and minimum results do not occur at the extremes of the configurations but rather at 1% with 12 mm. This behavior can be explained by the fact that insufficient fiber quantity and length limit the reinforcement effect. In contrast, excessive amounts and lengths of fiber can affect the uniform distribution of concrete constituents.

4. Conclusion

The following conclusions were drawn from this study:

Replacing coarse aggregate with lightweight materials and adding sisal fibers to self-compacting concrete mixtures alter their behavior in both the fresh and hardened states; these changes can be positive or negative depending on the type and amount of lightweight material, as well as on the size and amount of sisal fiber.

The positive effect of replacing coarse aggregate with lightweight aggregate in the T500 slump test for self-compacting concrete was pronounced when pumice was added to the mixtures at a rate of 30%, in addition to the inverse relationship between the amount of lightweight aggregate and the T500 slump test results.

The negative impact of including sisal fiber in terms of both quantity and length on the T500 slump test of self-compacting concrete was pronounced in mixtures containing 7.5 cm fibers at 0.30%, in addition to a direct relationship between the quantity and length of the sisal fibers.

Compressive strength was affected to varying degrees by the type and amount of lightweight aggregate. The self-compacting concrete lightened with 30% pumice had the lowest compressive strength among the mixtures, due to the negative impact caused by a higher replacement of coarse aggregate with lightweight aggregate, demonstrating an inverse relationship between the amount of lightweight aggregate and compressive strength.

Density was influenced by the type and amount of lightweighting material; the self-compacting concrete lightened with 30% expanded polystyrene has the lowest density of the mixtures, due to a greater replacement of coarse aggregate with lightweight aggregate.

Compressive strength was affected by the amount and length of the sisal fiber added; the mix with the lowest compressive strength at 7 and 28 days of curing was the lightweight self-compacting concrete reinforced with 0.3% sisal fiber and 5.0 cm in length.

Tensile strength is enhanced by the inclusion of sisal fiber in terms of both quantity and length; the lightweight self-compacting concrete reinforced with 0.2% sisal fiber and 5.0 cm in length exhibits the highest tensile-to-compressive strength ratio at 28 days of curing.

For future research on SCC, the use of other lightweighting materials, such as expanded vermiculite, expanded perlite, or hollow glass spheres, is recommended to obtain relatively low-density concrete with minimal impact on mechanical performance.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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