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Comparative Evaluation of Sisal and Polypropylene Fiber Reinforced Concrete Properties

Samantha Acosta-Calderon [1], Pablo Gordillo-Silva [1], Natividad García-Troncoso [1,*], Dan V. Bompa [2] and Jorge Flores-Rada [3]

[1] Facultad de Ingeniería en Ciencias de la Tierra (FICT), ESPOL Polytechnic University, Guayaquil 09015863, Ecuador; smacosta@espol.edu.ec (S.A.-C.); pagordil@espol.edu.ec (P.G.-S.)
[2] Department of Civil and Environmental Engineering, University of Surrey, Guildford GU2 7HX, UK; d.bompa@surrey.ac.uk
[3] Centro de Innovación Holcim, Holcim Ecuador S.A., Guayaquil 090616, Ecuador; jorge.flores@holcim.com
* Correspondence: nlgarcia@espol.edu.ec; Tel.: +593-963804749

Abstract: This paper presents a focused comparative case study considering the influence of natural and synthetic fibers on the fresh and mechanical properties of concrete. Locally sourced 19 mm long sisal fibers from sisalana leaves and manufactured polypropylene fibers were incorporated in a normal strength concrete matrix with fiber volumetric contents of 1%. After describing the measured aggregate characteristics, mix designs, and fresh concrete properties, several destructive and non-destructive tests on hardened concrete were undertaken. The former included compression tests on cylinders and flexural tests on prismatic samples, and the latter included ultrasonic pulse velocity and rebound number tests. The workability of sisal-fiber reinforced concrete was generally lower than the nominal concrete and that provided with polypropylene fibers by about 20%, largely due to the hydrophilic nature of the natural fibers. Test results showed that the presence of sisal fibers can improve the compressive strength by about 6%, and the tensile strength by about 4%, compared with the non-reinforced counterpart. This was due to the sisal fibers storing moisture that was released gradually during hydration, helping with the strength development. The concrete with polypropylene had virtually identical properties to the reference concrete. In addition to fresh and mechanical properties, environmental impacts associated with the production of fiber and concrete were also identified and discussed. Based on the assessments from this paper, overall, from the two fibers investigated, the sisal fiber showed more promising results, indicating that natural fibers can be a more sustainable alternative to plastic fibers, providing a good balance between workability and strengths.

Keywords: fibers; sisal; polypropylene; fresh properties; mechanical properties

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1. Introduction

Concrete is the main composite material used in the construction and building industry. Though novel and more sustainable materials exist, concrete is irreplaceable due to its need to be used in foundations of buildings and large infrastructure projects [1]. The material performance is typically related to compression strength, although this property is also converted into other properties, such as flexural and tensile strengths. Concrete is inherently brittle, being characterized by sudden failure unless reinforced by rebars or fibers. Incorporating fibers as paste-like materials is a common procedure and was used in heritage structures in ancient times. This was largely done to reduce the brittleness of hardened rock-like materials. Fibers have been a viable option for concrete reinforcement for several decades now, and numerous studies and investigations have been performed to verify the benefits of fibers in terms of the mechanical properties of the composite.

The term fiber reinforced concrete (FRC) is defined as the resulting material with a random distribution of short discontinuous fibers [2] and, according to [3], there are four categories of concretes based on fiber material type, namely metallic, synthetic, carbon, and natural fibers. The steel fibers can be manufactured or recycled [4]. Common synthetics are polypropylene [5–7], polyethylene terephthalate [8,9], high-density polyethylene [10], and rubber [11], whilst natural fibers are jute, sisal, or coir, among others.

FRC is characterized by an enhanced ductility and post-cracking tensile residual strength or toughness, due to the fiber reinforcement mechanisms provided by fibers bridging the crack surfaces [12]. The mechanical performances of fiber-reinforced composites are strongly affected by the fiber volume, fiber geometry, and orientation within the matrix [13]. Tensile, bending, and compressive cracking stress, peak stress, strain at peak stress, toughness, and residual strength under cyclic loading are significantly improved with the increase in volumetric fiber content [14]. Besides enhanced ductility and spalling properties, there is a significant benefit of using steel fibers in concrete structures where brittle failures are a governing consideration in design [12]. Unsurprisingly, due to their wide application in slabs on grades, hydraulic structures, architectural panels, footings, and many more [15], there are several design procedures for steel-reinforced materials [3].

The versatility and applicability of polymers have permitted the development of a wide range of plastic materials [5]. As noted above, several studies were carried out on plastic-reinforced concrete. Typically, plastic or rubber fibers have poorer mechanical properties than steel, and both the compressive and flexural strengths of plastic-reinforced cement-based composites are reduced compared to their non-reinforced counterparts [11]. The reduction in strength is counterbalanced by an improved ductility, represented by a favorable post-peak response in tension and an enhanced flexural softening and post-cracking performance [5,11]. A specific polymeric fiber suitable for cement-based materials is polypropylene, a synthetic resin that is commonly used in ropes, clothes, objects, etc.

Although polypropylene is not a natural fiber, it can be an eco-friendly alternative when used from recycling. Plastic waste is a global problem, with the United States producing 35.7 million tons of plastic waste in 2018 [16], whereas Europe produced 61.8 million tons [17], of which 19.3% was polypropylene. Incorporating this material in concrete can contribute to recycling and reusing plastics, but also enhance the performance of the cement-based composite in terms of shrinkage, tensile properties, and post-cracking performance [18,19]. For example, 0.5% recycled polypropylene fiber mixes provided an increase in tensile strength by 19.6% and flexural strength by 19.5%, respectively, compared to the non-reinforced counterpart [6]. Moreover, 0.25%, 0.5%, 0.75, 1.0%, and 1.25% volume fractions of the same type of fibers enhanced the impact resistance and energy absorption by 71%, 189%, 239%, 318%, and 418%, respectively, compared with their conventional counterparts [20].

The practice of using natural fibers as secondary reinforcement in concrete provides an environmental-friendly alternative to synthetic fibers [21]. Sisal fiber is a natural fiber that comes from the leaves of the Agave sisalana plant and is commonly used in navy ropes, carpets, mats and many more [22]. These fibers were also used in in concrete and asphalt [23,24]. The maximum fiber length should be 50 mm. Otherwise, it can negatively affect the strength of the concrete [25]. Sisal fiber typically enhance the split tensile strength and elastic modulus of concrete, but it is unlikely that it can improve its workability and water absorption [26]. A considerable reduction in workability of cement concrete was reported because of moisture absorption by hydrophilic natural fibers [27]. Sisal fibers added in 3% per binder weight improved the split tensile strength by 14%, the flexural strength by 11%, and the modulus of elasticity by 6% [28]. However, long-term strength development may be impaired by the alkalinity of the concrete [29].

As noted above, a number of previous investigations have focused on the performance of mortars incorporating polypropylene or sisal fibers, indicating and improvement in mechanical performance but with inconclusive data. However, a direct comparison between the influence of natural and synthetic fibers the concrete performance seems to be lacking. Additionally, sisal fibers are typically locally sourced, implicitly having region-specific characteristics influencing the fresh and mechanical properties of the concrete. To assess the feasibility of incorporating polypropylene or sisal fibers from locally sourced materials, this study evaluates the properties of the fresh concrete and the mechanical properties of the hardened concrete, including resistance to compression, tension, bending, rebound number, and ultrasonic pulse velocity. The outcomes of this research work provide meaningful information concerning the fundamental properties of the concrete material using alternative fibers, and thus a potential way of reducing the environmental impact caused by the manufacturing of conventional concrete.

2. Materials and Methods

Materials

The cement adopted in the mixes from this paper is the Holcim premium type HE (high early-strength), manufactured to NTE INEN 2380 [30] that is the standard equivalent to ASTM C1157 [31] (Table 1). The cement clinker composition included on average: 3.5% Sulfate SO_3, <0.10% Chloride Cl, 0.6% Alkali Eq Na_2O, 55% Tricalcium Silicate C_3S, 20% Dicalcium Silicate C_2S, 10% Tricalcium Aluminate C_3A, and 8% Tetracalcium Aluminoferrite C_4AF [30].

Table 1. Chemical composition and physical properties of the cement adopted.

Chemical Composition *	Portland cement clinker up to 95% Calcium sulphate 0–5% Calcium Carbonate 0–5% Calcium Oxide 0–4% Magnesium Oxide 0–5% Crystalline Silica < 0.1%
Physical Properties	Change in length per autoclave: -0.04% Setting time, Vicat method: 150 min Air content of the mortar: 3% Minimum compressive strength • 1 day: 14 MPa • 3 days: 25 MPa • 7 days: 32 MPa • 28 days: 40 MPa

* Trace of chemicals could be detected during chemical experimentation.

Two types of fine aggregates were used, which were unified sand and shaken sand with the same grain size of 4.75–0.0015 mm. The reason why two types of fine aggregates are used is because one provides compactness and the other the required strength. Additionally, although it is evident that both have the same maximum grain size, their fineness modules differ, so the distribution of particles helps to complete the compact matrix of the mixture.

The coarse aggregate was only one type, and it was the No. 67 according to ASTM C-33, with grain sizes of 2.36–19 mm. A commercial superplasticizer was adopted to reduce the water's volume required (28%) and to improve the concrete workability [32].

Sisal fibers produced from leaves of the agave Sicilian plants were also considered as mix components in this paper (Figure 1a,b). These fibers were obtained from local sources in regions such as Quito and Cotopaxi. These are made using specialized equipment that crushes and scrapes the leaves to extract the fibers. The equivalent diameter is in the range of 0.1–0.2 mm and its density is low, approximately 1100 kg/m^3. The tensile strength is approximately 328.8 MPa and the percentage of elongation at fracture is between 2% and 2.5% [23]. For consistency in direct comparisons, the same fiber length of 19 mm was used for both sisal and polypropylene fibres.


(**a**) (**b**)

Figure 1. Sisal fibers (**a**) as received; (**b**) cut to length during mixing.

Polypropylene fibers were used to reduce shrinkage cracking and prevent crack propagation, improve flexural strength and impact resistance, as well as reduce brittleness. Polypropylene is a thermoplastic that is obtained by the polymerization of propylene, a gaseous by-product of petroleum refining. The fibres were added due to the small amount that is needed (0.6 kg/m^3 of concrete) and their good properties, such as the modulus of elasticity to tension being 15,000 kg/cm^2 and low density of 0.91 kg/L. The length of the fibers is precisely 19 mm. These fibers can admit a tension of 330 kg/cm^2 with an elongation of 25% as given by the manufacturer, and they possess a no water absorption feature (Figure 2a,b).


(**a**) (**b**)

Figure 2. Polypropylene fibers (**a**) as received; (**b**) during mixing.

The concrete mix design followed the ACI 211.1 procedures [33]. According to this method, the design strength was chosen at first. Then, the procedure was followed to obtain the constituents required for 1 m^3 of concrete containing both sand and coarse aggregate. The mix proportions are shown in Table 2.

Table 2. Concrete mix proportion for the reference concrete without fibres.

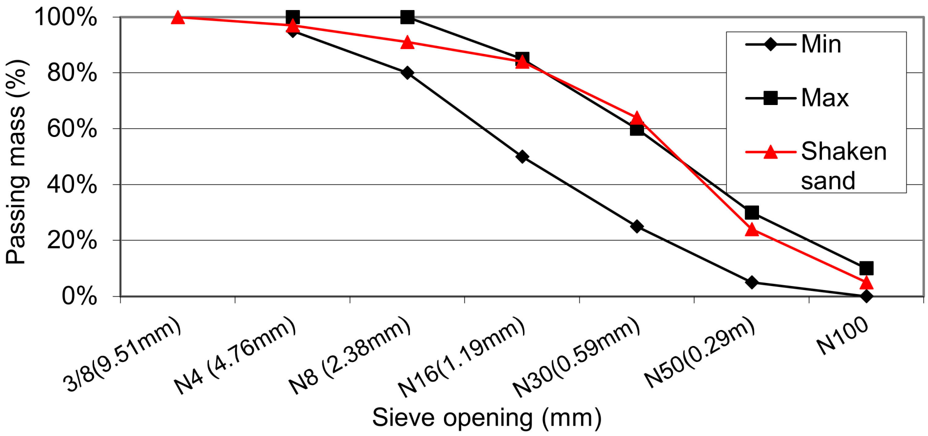
Materials	**Mass (kg/m^3)**
Cement	300
Coarse aggregate	895
Unified sand	567
Shaken sand	384
Water	149
Water reducer	2.70

After weighing the constituents, these were placed in the container of a CF GUILCO 69,000–59,010 mixer with a volume of 30 L. Aggregates were placed first, which included the two types of sands and the coarse aggregate. Then the concrete mixer was turned on and aggregates were mixed for two minutes. In the next step, the cement was added and mixed with the aggregates for another two minutes. The mixer was hit with a rubber hammer several times, so that no material remained on the sides. Then, three-quarters of the amount of water was placed and mixed for 2 min again. When there was a homogeneous mixture, the additives were placed with the remaining one quarter of water. After that, the respective fiber was added, aiming for each fiber to be widely spread when looking for a homogeneous mixture. In the case of the sisal fiber, the fibers were previously saturated with water in order to prevent the fiber to absorb water from the mixture. On the other hand, the propylene fiber did not require saturation according to the manufacturer. Finally, the optimum percentage used for each design was chosen based on different research works that show the fiber percentages that can be used in the mix concrete design. Sohabia et al. (2018) [34] showed that the maximum recommended percentage that can be used in concrete is 1.5%. If this value increases, then the strength decreases. The work of Ramujee (2013) [35] highlighted that the fibers enhance the strength when is used in a range of 0.5 to 1.5%. They mention that beyond 1.5% the strength reduces, and the mix becomes difficult in terms of handling. In terms of the sisal fiber percentage, the researchers recommend that the fibre can be used in concrete within a range of 0.1–2%, where the recommended value in most of these studies is to use up to 1% [36–39]. Based on these studies and laboratory works developed by the authors, the optimum amount of fibers used in this research work for the mix proportion was 1% for both designs. The aim of using the same fiber content for both designs is to analyze performance in the same conditions. The mixing was carried out under ambient conditions. The room temperature was 22.6 °C, and the humidity was 65%.

It is indispensable to carry out the characterization of the aggregate since it corresponds to two thirds of the concrete volume and its properties directly influence the quality of the concrete [40]. It is also advisable to have a quality control of the material. This information can be collected by ASTM tests. The moisture content was assessed using ASTM C566 recommendations [41], and the moisture content obtained was 1.27%.

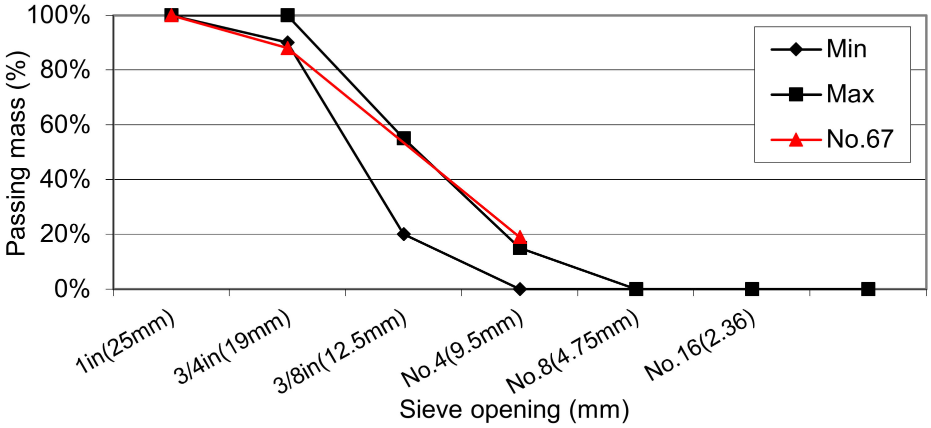
The absorption properties of the aggregates were assessed using guidance from ASTM C127 [42]. Absorption tests is used to identify how the aggregate changes its mass due to absorbed water. By direct comparison, the absorption properties were assessed, which were around 1.30%.

The granulometry test was used to determine the grading of the aggregates and their distribution. This was carried out using the ASTM C136 [43] guidance. These are shown in Figure 3.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Granulometric curve of (**a**) shaken sand; (**b**) aggregate No. 67.

After characterizing the fine and coarse aggregates, the fresh and hardened material properties were assessed through testing, to obtain an insight into how sisal and propylene fibers influence concrete properties. The fresh properties were assessed using ASTM C143 standard for measuring slump of hydraulic-cement concrete [44], the test method used to measure slump in concrete.

After assessing the slump of fresh concrete, the material from the slump cone and the mixer was placed in the molds. According to ASTM C31 [45] and C39 [46], in cylindrical molds of dimensions of 100 × 200 mm, the concrete was placed in two layers of the same volume, tamped with a rod for 25 times, and the mold was hit with a rubber hammer 15 times for each layer. The concrete in beams used for flexural testing must be placed in two layers of the same volume, tamped with a rod 54 times, and hit with the rubber mallet 12 times. After being placed in the mold and vibrated, the samples were kept in the molds for 24 h until the concrete hardened, as specified by ASTM C192 [47]. The samples were then removed from the molds and placed in high humidity curing environment.

After the cylinders (100 × 200) reached the age of 3, 7, and 28 days, they were tested to determine the compressive strength according to ASTM C39 [46]. As shown in Figure 4, this test method consisted of placing the cylinder in a hydraulic press for concrete testing and use unbonded caps according to ASTM C1231 [48] to guarantee the correct failure mode. Similarly, the tensile strength was determined in concordance with ASTM C496 [49] through indirect tensile testing. In the test, the cylinder was submitted to a compressive load at a constant rate of 1.6 MPa/min along the vertical diameter until failure, and the cylinders in splitting at 0.3 MPa/min.

In addition, the ASTM C78 was used to assess flexural strength of concrete using a four-point loading procedure [50]. The flexural strength on beams was only tested at the age of 28 days. The test method consisted of placing the beam in the apparatus on a side (with reference to the top side that it was molded with). The apparatus had two loading blocks at the top and two supports at the bottom, ensuring that the forces are perpendicular to the face of the specimen and there will be no eccentricity. The applied load causes a compressive strength on the top side and a tensile strength at the bottom side. This force was applied at a constant rate of 1.03 MPa per minute until the failure occurred. The force at failure and specimen geometry measured at three locations were used to determine the modulus of rupture of the concrete.

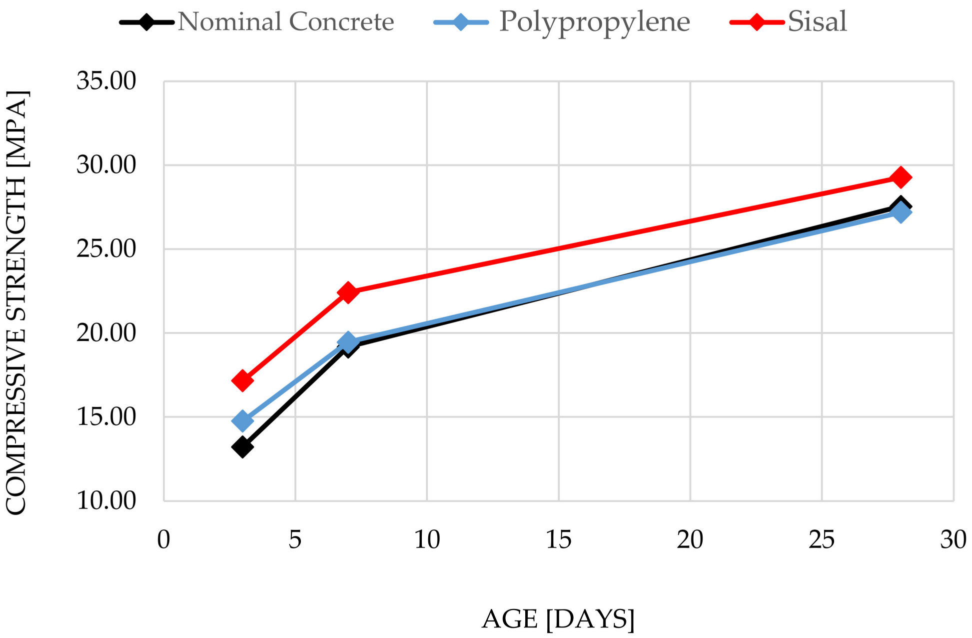


Figure 4. Compressive Strength ant the ages of 3, 7 and 28 days (1 kg/cm^2 = 0.0980665 MPa).

The ASTM C597 [51] was used as a reference to determine the ultrasonic pulse velocity of the concrete materials investigated here. Through this method, one can assess the quality of concrete, whether it has cracks or voids, as well as estimate the strength through direct correlations. A device provided with an electrical pulse generator, an amplifier, and an electronic timing circuit was used. The device had a set of transducers, which were placed at the bottom and the top of the cylinder. When in contact with the concrete sample, these transducers transform the electronic pulse into mechanical energy and vice versa in a range of frequency between 20 kHz and 150 kHz, measuring the time required for the pulse to travel between the two transducers. To assess the velocity, the length between the two transducers was divided by the measured time.

On the other hand, the ASTM C805 standard was used for the rebound number test of hardened concrete [52]. Through this test, one can identify variations in the quality of concrete and delimit between lower or higher density areas. It is also used to estimate (in place) the strength development of the concrete through correlations. This test cannot be carried out in specimens with thickness less than 100 mm. Therefore, in this study, a cylinder of 150 mm of thickness and 300 mm of height was used. A Schmidt hammer was used to impact perpendicularly the concrete at a horizontal angle to the specimen. A minimum of 10 readings at a 25 mm spacing were taken for each test.

3. Results and Discussion

3.1. Workability

The slump values obtained by performing the ASTM C143 [44] standard were 102 mm for nominal concrete design, 100 mm for de polypropylene design, and 80 mm for the sisal fiber design. It is shown that the concrete with fibers is less workable than the regular one. The concrete with sisal fibers showed the lowest slump, emphasizing that the polypropylene and the nominal design practically showed the same slump value. Polypropylene is not a natural fiber. In contrast, sisal fiber comes from the *Agave sisilana* plant, and vegetable cells tend to absorb water leaving less water to the mixture.

3.2. Compressive Strength

As mentioned, the compressive strength of the different types of concrete design were tested by the ASTM C-39 standard [46]. The mean compressive strengths determined in cylinders of 100 × 200 mm, at the age of three, seven, and 28 days are shown in Table 3 and

Figure 4. The results show a non-significant difference between every concrete design result in compressive terms, but also a non-delimited pattern because of the irregularity shown by the designs around the ages. It was expected that the concrete with polypropylene fibers would give the best compression strength, but sisal fiber concrete showed the best compressive performance at three, seven, and 28 days. This is probably due to the influence of the fiber type. The sisal fibers are hydrophilic, whist the polypropylene fibers are largely hydrophobic. The sisal fibers could have stored water that was released gradually during hydration, helping with the strength development. The polypropylene fiber reinforced concrete had nearly the same strength as the nominal non-reinforced concrete.

Table 3. Mechanical properties through destructive testing.

Property (-)	**Compressive Strength (MPa)**			**Splitting Tensile Strength (MPa)**			**Flexural Strength (MPa)**
Age (days)	3	7	28	3	7	28	28
Nominal	13.2 ± 0.1	19.2 ± 0.2	27.6 ± 0.8	2.1 ± 0.1	2.9 ± 0.6	3.5 ± 0.1	4.4 ± 0.1
Sisal	17.2 ± 0.1	22.4 ± 0.1	29.3 ± 1.1	2.2 ± 0.3	2.9 ± 0.2	3.7 ± 0.1	4.5 ± 0.4
Polypropylene	14.8 ± 0.2	19.5 ± 1.3	27.2 ± 0.8	2.0 ± 0.1	2.8 ± 0.1	3.6 ± 0.1	4.5 ± 0.3

However, finally, the increase of resistance showed that the best design in terms of compression was the sisal fiber concrete, somewhat in contrast with what was expected. Limited information available in the literature indicated that sisal fibers are likely to reduce compressive strength [53]. It was shown that a critical percentage of added sisal fiber exists, and keeping the quantity of fibers below that value, the strength is not reduced but rather increased. This conclusion holds for tensile strength, but it could be possible that this also occurs in compression. This critical percentage is around 0.5%.

The compressive strength using fibre is highly dependent on the amount used. Figure 5 shows the impact in the compression strength of different mix designs according to the fiber percentages.

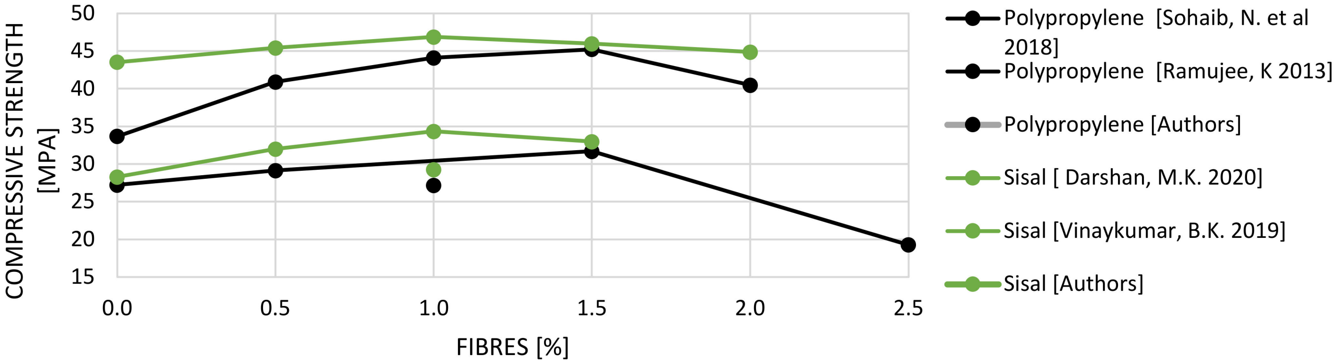


Figure 5. Impact in the compression strength of different mix designs according to the fiber percentages.

3.3. Flexural Strength

Based on Table 3 that shows the results obtained from the flexural strength test on the beams, it is evident that the sisal concrete is the one with the highest flexural strength. The three mixes follow the same pattern of results, as those of nominal concrete and polypropylene concrete only have a difference of 1.4% and 0.5% compared with the sisal concrete, respectively. The slight difference between the sisal and the polypropylene concrete is due to the type of fiber used, because both concretes had the same amount of fiber with the same size. As already mentioned, the three results are very similar, because the presence of fibers normally does not decrease the flexural strength of concrete, which is the case of the results obtained. Such behavior has also been observed in other research studies [54–56]. Despite the fact that the strength of the sisal fiber concrete was slightly higher than the other two materials, this is modest and cannot be taken as an improvement in the strength.

3.4. Tensile Strength

Figure 6 shows the changing trend in the tensile strength for the concretes at different ages, whilst Figure 7a,b depicts samples after testing. The trend obtained is similar to the one obtained in the flexural strength test. The sisal concrete presents higher values, then the polypropylene concrete and finally the nominal concrete at the age of 28 days. On the other hand, the polypropylene concrete obtained at three and seven days provided values 2.55% and 1.88% lower than the nominal concrete, which does not follow the same trend as the age of 28 days, but this is within expected experimental variations.

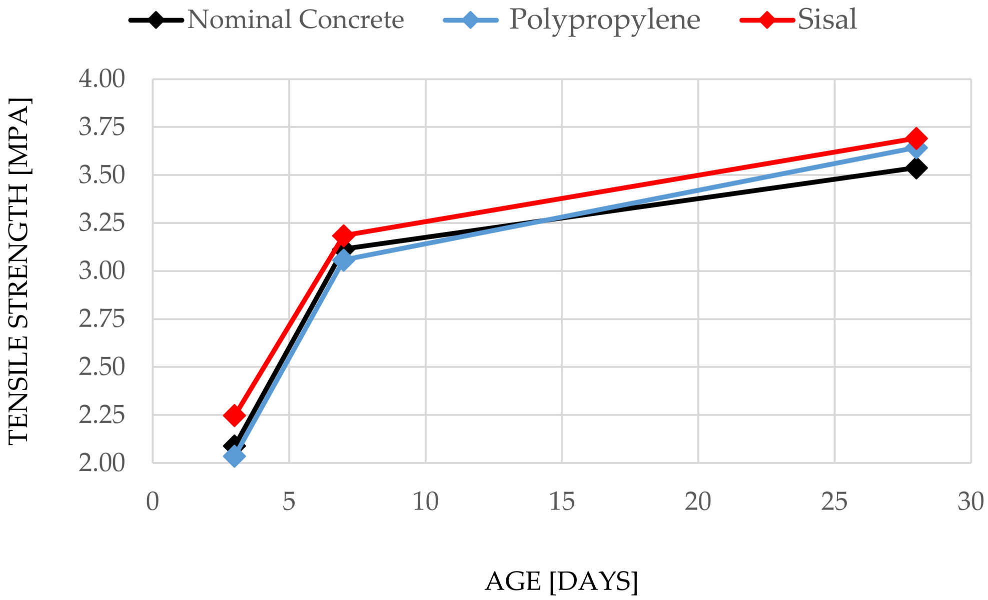


Figure 6. Tensile strengths at the ages of 3, 7 and 28 days (1 kg/cm^2 = 0.0980665 MPa).


(**a**) (**b**)

Figure 7. (**a**) Beam tested in flexure after failure; (**b**) Splitting tensile strength tested cylinder after load.

The addition of natural sisal and polypropylene fibres improved the tensile strength depending on the amount of fibres (Figure 8).

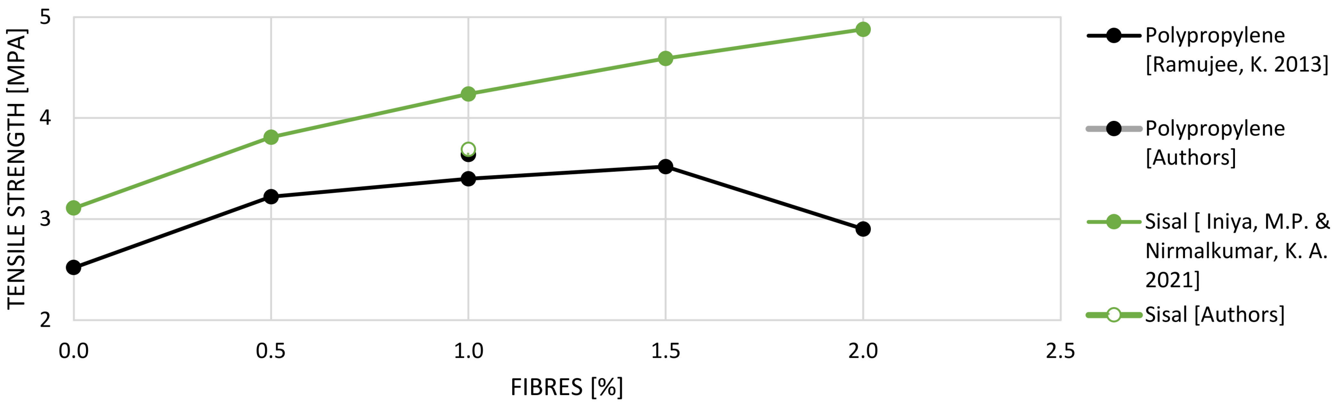


Figure 8. Impact in the tensile strength of different mix designs according to the fiber percentages.

3.5. Pulse Velocity

A study to correlate the concrete's strength applying non-destructive test was performed [57]. The mean values of time and velocity of the ultrasonic pulse for a cylinder with measurements of 150 × 300 mm at the age of 28 days are shown in Table 4. The values obtained are similar to each other. However, the one with the shortest time range and consequently the highest wave speed was the sisal fiber concrete, which indicates that of the three, it is the one with the best quality. On the other hand, conventional concrete has around 7.25% and 9.68% discrepancy with polypropylene and sisal, respectively. This may be due to inhomogeneity within the specimen. According to Yahya et al. [58], if the pulse velocity is between 3.5 and 4.5 km per second, the quality of the concrete is considered good, but slight porosity may exist, which is the case of the three concrete specimens.

Table 4. Ultrasonic pulse velocity (m/s) and Compressive strength (MPa).

Property	Ultrasonic Pulse Velocity (m/s)	Compressive Strength (MPa)
Nominal	4000	28.5
Sisal	4400	33.6
Polypropylene	4300	38.2

3.6. Rebound Number

Table 5 shows the correlation obtained from the ten rebounds that were made in the vertical position in each 150 × 300 mm sample, at the age of 28 days, these being the minimum value, the maximum, the average, the standard deviation, and finally the compressive strength for each respective design. According to the general guideline for concrete quality based on rebound number [41], if the rebound number is between 20 and 30, the quality of the concrete is considered fair. The results obtained were kind of contradictory according to the values and the quality of the concrete obtained in the pulse velocity test. For this test (same as the velocity pulse test), the surface infers a lot in the results obtained. Since the surface is in direct contact with the rebound hammer, when the surface is hard and smooth, higher numbers of rebound will be obtained. On the other hand, if the surface is rough with much irregularity, lower numbers of rebounds will be obtained, as was the case, similar in the standard [41]. Despite the results of the quality of the concrete, the compressive strength obtained for the three samples exceeds the value of the design resistance. Although this value cannot be used as a basis for acceptance, it can be used as reference.

Table 5. Concrete Rebound and Compressive strength (MPa).

Property	Rebound Number	Compressive Strength (MPa)
Nominal	25.0	25.3
Sisal	27.7	28.2
Polypropylene	27.3	29.3

Based on the experimental findings, it can be concluded that sisal fibers can be effectively used in concrete design. Such fibres typically enhance the strength and may also be suitable in structural elements. However, there are several challenges that need to be addressed to enable the reliable application of sisal fibers in practice, including: (i) microstructural investigations of the behavior of sisal fibres in the matrix; (ii) influence of the sisal fibres of storing moisture and gradual release; (iii) threshold of maximum fibre content.

4. Environmental Aspects

It is important to note the environmental impact caused by the construction industry. The extraction processing and transportation of raw materials is responsible for high levels of pollution and energy consumption [59]. The sisal and polypropylene materials used in this research go through an industrial process to obtain the final product, leading to additional environmental impacts in addition to those associated with the production of conventional concrete. Details of various environmental impacts for fibers and fiber reinforced concrete structures are listed in Table 6.

Table 6. Environmental factor and impact.

Stage	Activities	Environment	Environ-Mental Factor	Environmental Impact Identification
Extraction	Polymer extraction	Natural	Ground	Soil contamination due to compound residues.
			Atmosphere	Propylene is a combustible gas that arises from the thermal reaction between different fuels.
		Human	Health	The harmful effects on the health of workers by toxic gases.
Application and use	Preparation of fiber reinforced concrete	Natural	Water	The consumption of drinking water is showed in the production of the concrete, in the curing of the structures and in the washing of machinery used in the construction process.
			Ground	Surplus stone resources, including the used polymer similar to plastic, as well as liquid residues that remain in the preparation of the concrete that seep into the ground.
			Atmosphere	Dust that is produced in construction from the concrete mixer, from the movement of materials and gases emitted from the machines.
End-of-life disposal	Construction demolition	Natural	Ground	The residues generated by the demolition of the concrete pollute the ground mostly because of the fiber polymer.
		Human	Ground	Common waste sites can proliferate disease vectors.
Extraction	Sisal fiber extraction	Natural	Water	Exhaustive use of the resource for watering the plant.
			Ground	The exploitation of the ground is common, due to the plant takes 2 to 7 years to produce the fiber.

Table 6. *Cont.*

Stage	Activities	Environment	Environ-Mental Factor	Environmental Impact Identification
Application and use	Fiber preparation	Natural	Water	The manufacture of commercial natural fiber is done through an industrial process that requires washing the fiber.
			Atmosphere	The machinery for the processing, washing and combing of the fiber emits polluting gases.
End-of-life disposal	Construction demolition	Natural	Ground	Despite the existence of contamination in the ground because of the concrete, using natural fiber is a benefit, since it is biodegradable.

Sisal fibers, materials of natural origin, require a low degree of industrialization for their processing, which means that they have a low amount of embodied energy in comparison to synthetic fibers [60]. Sisal fibers are extracted through a process known as decortication, where the leaves of the plant are crushed and beaten by a set of rotating wheels with dull blades. The next process where energy is consumed is in the dried section. This is done by industrialized machines instead of in the open air because the fiber quality depends on the moisture content. Finally, the fibers are brushed.

On the other hand, as polypropylene fibers are synthetic materials, their manufacture goes through a complex industrialized process, which involves high-end chemical processes and therefore requires a high amount of energy. According to the technical sheet from Sika, 80% of the raw material (propylene and ethylene) is imported, and is obtained during the thermal cracking of different fuels, such as naphtha and liquefied petroleum gas [61]. This material is pumped to storage spheres at a low temperature to preserve the liquid state of the material. The remaining 20% of the raw material is national propylene, which is sent to a separation plant to separate the propane from the propylene.

In the production process, all the raw material goes to through a purification system to eliminate impurities that may affect the quality and stability of the process. Once purified, the reactors where the polymerization reaction occurs, the result of which powers polypropylene, are fed. Then, the polypropylene is sent to degassing to remove the remaining hydrocarbons and conduct extrusion. In this process, the mixing and melting machines intervene to combine the powered polypropylene in additives to melt, to produce pallets. Finally, the process ends once the material is ready to be distributed to its consumers. To achieve the fiber shape of the material, it goes through an industrialized machine, which is responsible for giving it the shape and size necessary for use.

During the useful life of a structure, when the fibers are inside the concrete, no greater environmental impact is generated. However, once the structure reaches its end-of-life status, an environmental impact may be generated. At this stage, components are recycled through crushing by separating the concrete from the steel rebars [62]. Hence, the waste concrete can be used as an aggregate in concrete [63,64]. This is typically implemented in various construction works, especially on pavements [65]. For the sisal fiber concrete, as the fibers are 100% biodegradable, there will be minimal environmental impact at the end-of life [66,67].

The above results show that the incorporation of sisal fibers in concrete can lead to similar or enhanced mechanical performance, whilst for the same fiber ratio, the polypropylene fibers had a minor effect. The improvement in compressive strength due to presence of sisal fibers was in the range of 6%, whilst in tension it was around 4%. Although this increase is relatively small, it shows that the sisal fibers have generally a beneficial influence on the short-term strength development. This is likely to be due to their hydrophilic nature maintaining moisture during mixing, releasing it slowly and helping with the cement hydration. An increase in mechanical performance comes at the expense of lower workability, which could possibly be enhanced by a higher amount of admixtures.

This remark is similar to other results from the literature noting that some improvement in strength is possible, but workability is normally reduced [26]. It is worth pointing out that due to the high alkaline environment of the cement-based matrix, the long-term performance of sisal fibers be limited, and short-term strength enhancement can be offset by this [27]. The use of polypropylene fibers had virtually no influence on the fresh and short-term mechanical performance of the concrete, though they are typically used to control shrinkage successfully [20]. A direct comparison between the use of a nature-based solution (sisal) and a thermoplastic (polypropylene) suggests that the former can be an effective solution for the dispersed reinforcement of concrete, yet more in-depth tests are required to validate both short- and long-term properties.

Life Cycle Assessment (LCA)

The functional unit defined for our system was 1 m^3 of concrete for each fiber implemented. The scope of the life cycle covers the comparison between a nominal concrete and the concretes reinforced with the fibers (sisal, polypropylene). The raw material used to produce the established functional units is considered within the processes.

The life cycle assessment was evaluated using the software SimaPro (Version 9.2, Pré-Sustainability, Amersfoort, The Netherlands). The method ReCiPe Midpoint H [68] was used to change the parameters in the inventory to environmental impact scores. The Ecoinvent database [69] was used for the background information needed for the system, using a market perspective and consequential approach. The inventory included data from the library: cement, ordinary Portland, water (natural resource), gravel (crushed), river sand (coarse and fine), and polypropylene fiber. The superplasticizer and the sisal fiber inventories in software were created based on published data [70,71].

The LCA for the concrete mixes reinforced with fibers is shown in Table 7. The impact indicators analyzed were global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), freshwater eutrophication (FE), and water consumption (WC). The indicators show a difference that does not exceed 1% compared to the nominal concrete. The changes in variation are not considerable when including fibers into the matrix.

Table 7. ReCiPe Midpoint H method results for 1 m^3 of concrete mix.

Mixes	GWP [kg CO_2]	ODP [kg CFC11]	AP [kg SO_2]	FE [kg P]	WC [m^3]
Nominal Concrete	313.717464	6.2375×10^5	0.55660589	0.05117901	2.47942288
PP Fiber—Concrete	315.08268	6.2712×10^5	0.56086763	0.05116763	2.48008645
Sisal Fiber—Concrete	313.736294	6.2444×10^5	0.55714865	0.05119341	2.4792952

Fiber inclusion in the concrete matrix has no significant impact on the above categories. The contribution of each process, including the fiber, can be seen in Figure 9 for the GWP indicator. The three main contributors are cement, gravel, and sand, as the main components of concrete. One study [72] shows that the inclusion of carbon fiber has a significantly greater impact on the climate change indicator while the reinforcement with steel is slightly higher than the polypropylene fiber. The use of steel had a 2.43 kg CO_2 impact on the concrete, which is 68% higher than the score for the PP fiber for this study [72].

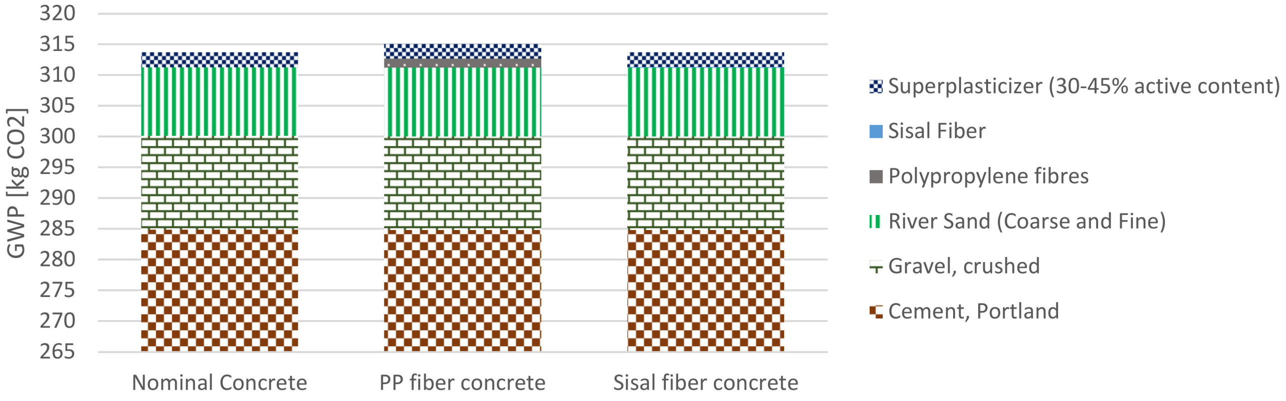


Figure 9. Process contribution for 1 m^3 of the concrete mixes.

Pillai et al. [73] showed the life cycle assessment scores for different mixes, with an average of 300 kg CO_2. This situates the scores obtained by the study in the ranges found in literature considering the use of fibers as reinforcement. Similar results in GWP score and process contribution were reported in the literature [74,75]. For instance, the superplasticizer contribution to GWP was calculated to be around 0.4–0.6% in the literature [75], but its contribution found in this study is ~0.7%. This serves as a reference to check the variability and sensitivity of the system created in the LCA.

Figure 10 shows the normalized values for the categories found in this study. This additional step allows for better interpretation of the results by using fixed values and proportional scores relevant to the world [76].

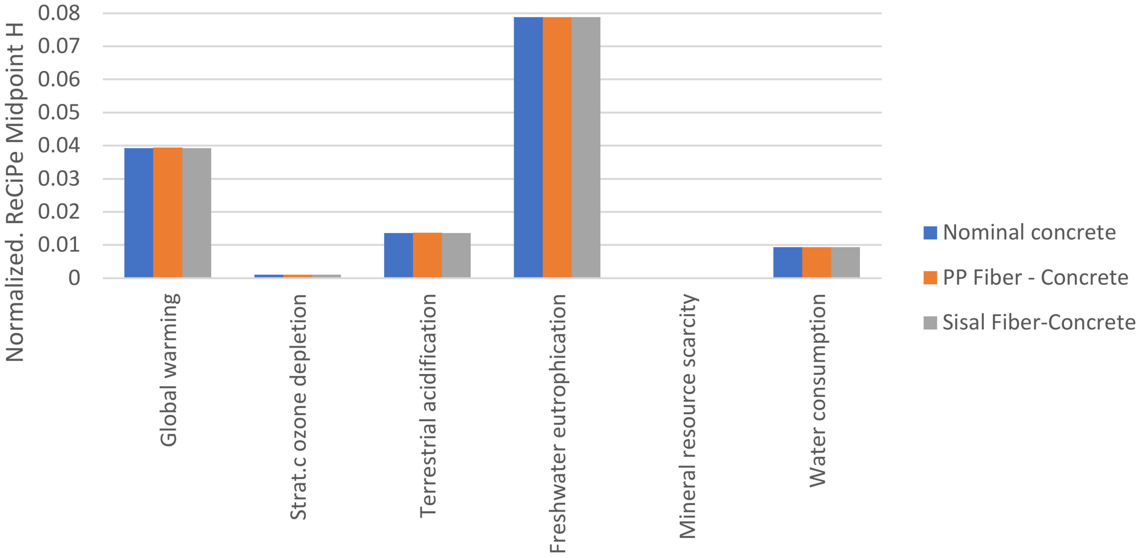


Figure 10. Normalized values for 1 m^3 of the concrete mixes.

Normalized scores show the tendency of the system that shows no significant variability between the different mixes, as seen in Figure 10 The low contribution of the fibers to the concrete mix accounts for a stable enough system. In terms of sustainability, the inclusion of these fibers is green enough not to cause a significant impact on the environment. One additional category was added to Figure 10, namely mineral resource scarcity, because Portland cement is a finite resource. Almost no considerable impact was found for the system under study for this indicator. However, further research should be implemented regarding the effect on environmental indicators, e.g., the different ecotoxicity indicators included in the abovementioned method.

5. Conclusions

This paper examined the experimental response of concrete materials incorporating sisal or polypropylene fibers. Fresh and mechanical properties through destructive and non-destructive testing were presented. The latter included compressive, splitting, and flexural tests as well assessments of the ultrasound pulse velocity and rebound number. Based on the experimental results, the following remarks can be made:

- The workability of the polypropylene fiber reinforced concrete was virtually identical to that of the nominal non-reinforced materials. On the other hand, the presence of sisal fibers reduces the workability by about 20% due to this fiber absorbing the added water, leaving less water in the mixture.
- The presence of sisal fibers in the concrete tends to improve the compression by around 6% compared with the nominal concrete, whilst the polypropylene fibers had minimal or no influence. Ultrasonic pulse velocity and rebound hammer tests largely confirm these results.
- For the flexural strength, the three mixes follow the same trend, but some improvement is obtained for both sisal and polypropylene fiber reinforced concrete. The increase in strength is likely to be associated with enhanced fracture toughness, providing ductility in tension, making these materials feasible for avoiding spalling under extreme loading.
- Based on the assessments from this paper, overall, from the two fibers investigated, the sisal fiber showed more promising results, indicating that natural fibers can be a more sustainable alternative to plastic fibers, providing a good balance between workability and strengths.

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