USE OF ALTERNATIVE AGGREGATE FOR LIGHTWEIGHT CONCRETE PRODUCTION

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Abstract
The search for new material sources that meet the assumptions of sustainable development is constant, especially in the civil construction industry. Therefore, the objective of the present research was to develop and characterize physically and mechanically lightweight bio-concretes produced with an alternative lignocellulosic source. *Cereus jamacaru* (Cactus) wood was used as a bio-aggregate after washing in hot water (80 °C). Chemical and physical characterization of the aggregate were performed. A cement based matrix was developed using Portland Cement (CP V-ARI), a water-to-cement ratio of 0.4 and calcium chloride (3% bwc). Mixtures with two types of wood particles classified as green and brown were produced and for both cases several percentages of compensation water (100 and 200%) and cement / wood ratio (3, 4 and 7) were used. To characterize the mixtures in the fresh state a flow table test was performed. The mechanical characterization was performed by a uniaxial compression. The modulus of elasticity and density were determined. The density of the composites with the brown particles ranged from 892 to 1452 kg/m³ and the compressive strength of 3.38 to 10.51 MPa. The bio-concretes with green particles reached values between 872 and 1347 kg/m³ of density and between 1.72 and 8.94 MPa of compressive strength. The mixtures with higher cement/wood proportions and lower amount of compensating water reached higher compressive strength, as expected. The specimens with fixed consumption of 775 kg/m³ achieved better resistance/density ratio which is a property of great interest in engineering civil. The results showed that Cactus Wood can be used in the production of bio-concretes with good properties and varied applications in civil construction.

Keywords:
Lightweight concrete; Bio-concrete; Cactus Wood; Sustainability; Construction.

1 INTRODUCTION

According to [da Gloria 2015], the construction industry is one of the great generators of waste and a major consumer of natural resources, and therefore, the search for new resources and technologies able to cause less aggression to the environment is urgent. In this context, the use of alternative lignocellulosic sources for the development of materials is an option to cause less environmental impacts [Mesquita et al. 2015] [Soltan et al. 2017]. The main advantages of the lignocellulosic materials are carbon trapping, depending on the application, and the fact that they are renewable.

The cacti, family *Cactaceae*, are lignocellulosic materials that present themselves as an innovative source and of great competitive potential in the current market. They have great capacity for adaptation, being able to survive in regions of water stress that present high temperatures, low humidity and poor soil.

Currently, cacti are mainly used for ornamentation, animal feed and cosmetics production being underutilized in construction. There are records of the use of some species around the world as a "hedge" instead of conventional restraints and in some of the non-forested regions of Bolivia, Argentina and Venezuela, they are used for the construction of houses and also as firewood [Hewitt 1993].

The lack of knowledge about the materials and their potentials of use restricts and even prevents their use. It is therefore necessary and primordial to perform a characterization of the same so that their chemical, physical and morphological properties are known and the best destination is given.

The advances in the area of material characterization with the development of advanced techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetry (TGA) allow and facilitate a better understanding of macroscopic and microscopic structures of materials.

A sustainable alternative for lignocellulosic materials is a cement composites production. These products basically composed of mineral binders combined with vegetal aggregates and other additives [Beraldo 2011]. [Beraldo 2011], also states that the main advantages of using composites are the high availability of raw materials, which are renewable, the lightness of the final product, between 400 and 1500 kg/m³. Others advantages are the resistance to biodegradable agents, good dimensional stability the resistance to impact and the satisfactory mechanical, thermic and acoustic properties. According to [Beraldo 1997], in some applications, these materials can efficiently replace traditional materials in the construction.

A challenge in the production of cement composites with lignocellulosic materials, which may be called bio-concretes, is the chemical incompatibility between cement and vegetable biomass that can lead to retardation / inhibition of cement hydration reactions. According to [Simantupang et al. 1978], the extractives present in the wood are the main responsible for this impediment of cement solidification. [Beraldo 2011] explained that no vegetal species can be added in its natural state to the cement, since the chemical constituents of the plant are very sensitive to the alkaline environment of the cement matrix. The author also showed the importance and effectiveness of applying preliminary treatments in the biomass allied to the use of handle accelerators. In his studies he obtained satisfactory setting and hardening results by using the Brazilian Portland cement CPV-ARI, and 3% of calcium chloride, with biomass previously washed with hot water to reduce the extractives amount.

The water-to-cement ratio is a variable of extreme influence on the resistance of the bio-concrete and according to [Andreola 2017] the cement hydration will occur completely only if this ratio is greater than 0.38. Because of the high water absorption of the biomass, it is important to have enough water to keep the biomass saturated, to allow the cement hydration and also to guaranty the consistence of the bio-concrete. Another important factor to be analysed in the production of bio-concrete is the granulometry of the lignocellulosic material that will be used as well as the particle format. [Beraldo 1997] verified the lack of adhesion between bamboo and cement paste when whole stems of large diameter bamboos, which do not present side shoots, were used. [Latorraca 2000] concluded that granulometry has a significant influence even in cement pickling and solidification time.

In view of the above, the present research aimed at the cactus wood chemical characterization and the physical-mechanical characterization of lightweight bio-concretes produced through the use of cactus wood, an innovative lignocellulosic source, as bio-aggregate in order to verify the possibility of use as an alternative material in civil construction.

2 MATERIALS AND METHODS

2.1 Cactus wood precedence

The cactus wood used was of the species *Cereus jamacaru* from Barueri - São Paulo, Brazil. The samples were obtained by manual cutting from the base of three years age tree.

2.2 Chemical characterization

Chemical analysis

The cactus wood presented different external aspects depending on the stem position which they were extracted. For the chemical analysis and the preparation of the cementitious composites these different fragments were separated in two groups: green coloration (dark fragments with greater proximity to the leaves of cactus) and brownish coloration (clear fragments coming from a more internal region of the trunk).

Fig. 1: Comparison of the brownish cactus wood fragments (left) of the more greenish fragments (right).

The material was milled and sieved to obtain particles with nominal size between 0.25 and 0.40 mm. The quantification of the total extractives was made from an adaptation of the norm NBR 14853 (ABNT 2010). The NBR 13999 (ABNT 2003) and NBR 7989 (ABNT 2010) standards were used to determine the content of ash and insoluble lignin.

Holocellulose content was obtained following the procedure described by [Browning 1963] and starting from dry holocellulose the cellulose content and hemicelluloses were determined following the procedure described by [Kennedy et al. 1987].

Thermogravimetric analysis

Also, to obtain an approximate chemical quantification the thermogravimetric analysis (TGA) of the wood was performed on a SDT Q600 V20.9 Build 20 (Universal V4.5A TA Instruments). Particles with a maximum particle size of 0.074 mm were subjected to a heating rate of 10 ° C / min starting from 25 ° C to 1000 ° C in a liquid nitrogen atmosphere at 50 mL / min. The degradation temperature was determined from the inflection of the baseline in the differential thermogravimetric curve (DTGA).

Fourier-transform infrared spectroscopy

Fourier-transform infrared spectroscopy of attenuated total reflectance (ATR-FTIR) was performed using a Spectrometer Varian 600-IR FTIR series equipped with a Gladiator from Pike Technologies for ATR-FTIR measurements. The sample of cactus wood was scanned from 4000 to 400 cm -1 with 32 scans on average for each spectrum with an intensity of 4 cm -1.

2.3 Lightweight bio-concrete production

Preparation of cactus wood (bio-aggregate)

The fragments were reduced to smaller size with a hammer mill and all the generated particles whose length exceeded three times the diameter value were discarded due to the possible adhesion damage that they can generate in the final composite. With the remaining particles, particle size analysis was performed.

To determine the amount of washes required to reduce the extractives, a wash cycle experiment was performed with a Magnetic Stirrer, an Electronic Contact Thermometer, and two beakers with a capacity of 500 ml. First, 5 g of cactus particles and 300 ml of distilled water were added to the beaker. The water was kept at 80 °C for one hour, its final color was recorded and then a new cycle started. The cycles were repeated until it was noticed that the final water was clear.

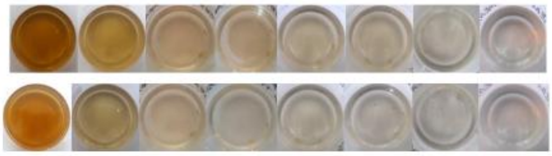

Fig. 2: Comparison of the water coloration at the end of each washing cycle (ordened from left to right) for the greenish (top) and browned (botton) particles.

The color change (Fig. 2) was noticeable in each cycle and can be explained by the reduction of extractives of the biomass. It is also possible to observe that the removal of the extractives happens mainly during the first three washing cycles since the color difference between the third and the fourth waste water was not significant. So it was established that the particles would be submitted to 3 cycles of washes before being used for the bio-concrete production.

The water absorption of solid wood and the apparent specific mass of the bio-aggregate (greenish and browned particles) were characterized according to the standards [NBR 11491 / ABNT 2003] and [NM 52/2009], respectively. The results are on Table 1.

Tab.1: Physical properties of cactus wood

Water absorption of solid wood (%)	Apparent specific mass (kg/m³)
199	250

The apparent specific mass for the two types of particles (greenish and brownish) was the same.

Blinder and additives

The Brazilian Portland Cement CP V - ARI (cement of high initial strength) was used as binder. The chemical composition and density of the cement can be verified in [Andreola et al., 2016]. To accelerate the cement hydration, 3% (based on the cement mass) of calcium chloride ($CaCl_2$) was added to the blends.

Bio-concrete production

Table 3 shows the relations cement mass:cactus wood used for the production of cactus bio-concretes (BC). The letters L and F indicates the type of particle used, where L is for brownish and F for greenish. For all mixtures the water -to-cement ratio (w/c) ratio was 0.4.

The composition of these bio-concretes was set as follows: for cement mixtures BCL 100, BCL 200 and BCF 200 the cement consumption and the volume of wood were set following [Andreola 2017]. The variation in compensating water had the objective to evaluate the necessity of its placement in front of the wood's absorption obtained (almost 200% based on wood mass) and the desired workability. For the mixtures BCL 3, BCF 3 and BCL 4 were fixed the cement: wood ratio following the results obtained by [da Gloria 2015]. Numbers 3 and 4 indicate the ratio cement mass: wood mass.

The cactus bio-concretes (BC) were produced in a planetary mortar, with a 5-liter capacity vat and stainless steel beater. The water was initially mixed with the calcium chloride in a reserved container forming a homogeneous solution. The cement and wood particles were also mixed separately and were placed first in the equipment. At low rotational speed (136 rpm), during the first minute was added gradually to the dry materials. After the first minute of mixing the turning of the mortar was interrupted for manual release of the material that was attached to the vats. Next the mix continued until reach 05 min of total time.

Cylindrical specimens of 5 x 10 cm (diameter x height) were produced. The molds were filled in three layers and the type of compaction was varied: manual with 15 strokes per layer (BCL / BCF 200 and BCL 100) and vibrating table (BCL 3, BCF 3 and BCL 4). The specimens were protected against moisture loss until demolding, which happened 24 hours later. Finally, the specimens were placed in a humid chamber at 20 °C (± 2 °C) and 95% (± 2%) humidity until they reached the 28 days age.

During the production of the bio-concretes it was observed that there was no segregation or exudation between the blends and that the adhesion between the wood and the other components was ideal (Figure 3).

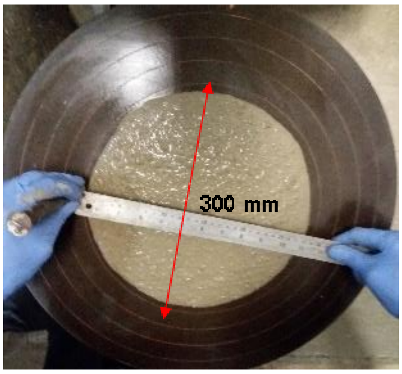

Fig 3. Flow table test.

At fresh state, the property evaluated was the spreading through the flow table test. The consistence index of each mixture was obtained from the average of the diameters reached. Based on the Brazilian standard [NBR 5739 (ABNT 2007)], the compressive test was performed after 28 days in a Shimadzu-1000 kN universal test machine, at a speed of 0.3 mm/min.

Tab.2: Blend Compositions.

Blend	Cement comsumption (kg/m³)	Wood volume (%)	Ratio (in mass)				
			Cement	Wood	Water	Compensation water	$CaCl_2$
BCL 100	775.0	45.0	1	0.145	0.4	0.145	0.03
BCL200/BCF 200	775.0	45.0	1	0.145	0.4	0.290	0.03
BCL3/BCF 3	488.1	65.1	1	0.333	0.4	0.667	0.03
BCL 4	582.9	58.3	1	0.250	0.4	0.500	0.03

The vertical displacements were obtained from the average reading of two linear variable differential transformers LVDTs. For each mixture, four cylindrical specimens were tested. The modulus of elasticity was determined according to the requirements of standard [NBR 8522 (ABNT 2008)].

3 RESULTS AND DISCUSSION

3.1 Chemical composition

The chemical analysis showed that the samples with the leafiest appearance had a higher content of lignin, cellulose hemicelluloses and extractives in relation to the woody ones that presented a very high content of ashes reaching almost 40% of its total mass (Table 3). The high ash content can be a harmful factor for possible industrial applications.

The cellulose content is representative mainly for the hardwoods, being favorable since the structure of the cellulose exerts great influence on the physical and mechanical properties of the fibers [Fonseca et al. 2013], as elasticity and tensile strength, desirable properties for elements constructive Hemicelluloses, whose content is considerable and quite close to hardwood and woody, can cause disadvantageous properties such as hygroscopy, swelling and plasticity.

The lignin content was the lowest for both woody and hardwood. This chemical structure acts as a natural reducer of susceptibility to wood degradation. The low concentration presented by *C. Jamacaru* can therefore entail higher costs with treatments and products that avoid this degradation

The thermogravimetric analysis resulted in the curves shown in figure 4. The constituent molecules of a material degrade at specific temperatures. This means that significant falls in the weight decay curve show the disintegration of a given compound. By deriving the weight curve these falls are converted into easily identifiable characteristic peaks.

Peaks prior to 100 °C are due to evaporation of free water, the peak at temperatures of 330 °C to 360 °C refer to degradation of the cellulose, around 290 °C of the hemicelluloses and around 367 °C of the lignin. What remains at the end of the process is carbon, that is, it is mainly the ashes [Martin 2010] [João Filho et al. 2010].

Based on the thermogravimetric analysis, it was possible to obtain an approximation for the chemical composition of *C. Jamacaru* (Table 3) using the TA Universal Analisys © software.

Tab.3: Chemical composition.

Components (%)	Chemical analysis		Weight loss
	Greenish	Brownish	
Lignin	7.4	1.7	8.8
Cellulose	30.0	21.4	44.2
Hemicellulose	17.8	16.2	21.8
Ashes	19.3	36.4	16.9
Total extractives	29.1	18.2	8.3*

**Extractives are diverse substances whose disintegrations happen along the whole curve and their peaks are "hidden" in others. The value in question was obtained by a difference of 100%.*

3.2 Fourier-transform infrared spectroscopy

The FTIR spectra of cactus wood showed some characteristic peaks, such as those in the 1595 cm^{-1} and 1030 cm^{-1} band (Fig. 5). These peaks are representations of C=C elongation bonds, aromatic rings and also compounds such as flavonoids (compounds that make up the tannins) and stretches =C-O-C=, oxo-aromatic components, respectively.

These data corroborate with the chemical analyzes performed since they also indicate a high presence of extractives.

The band corresponding to the O-H binding represented by the peak of 3280 cm^{-1} was well defined, with a band well representative of the amount of water present in the sample.

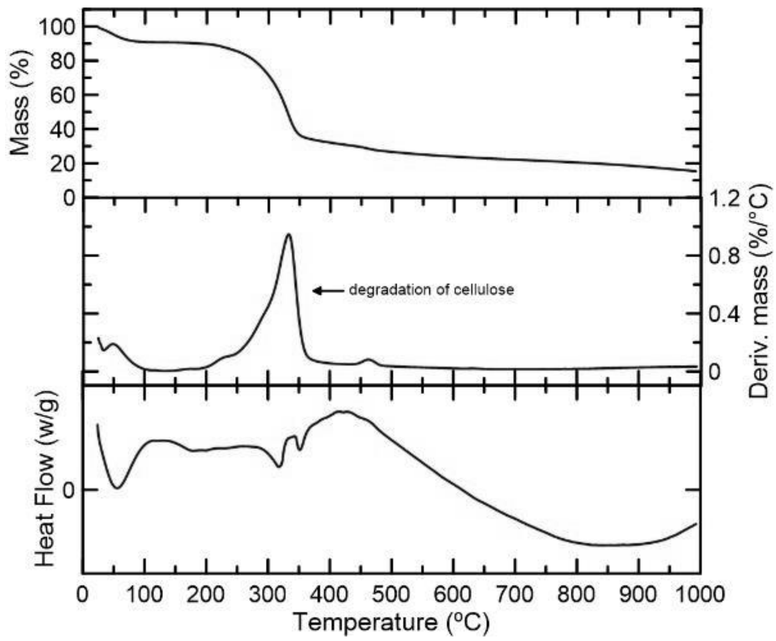

Fig. 4: Thermogravimetric analysis of cactus wood.

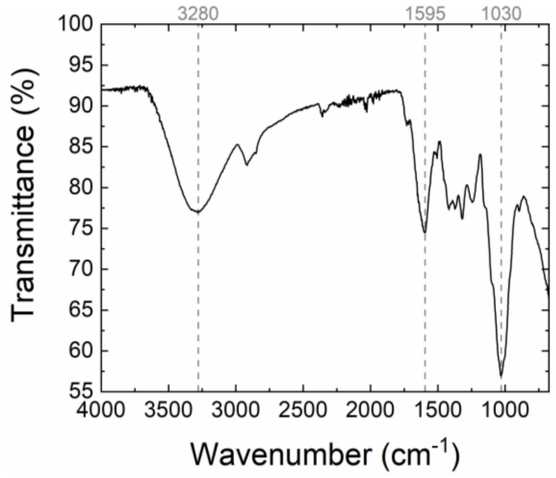

Fig. 5: FTIR spectra of cactus wood.

3.3 Lightweight bio-concrete

During the production of the bio-composite no segregation or exudation occurred and the mixtures achieved good workability as can be seen by analyzing the results in Table 4 (column 1 – Blend Workability).

The BCF 200 and BCL 200 with 200% of compensating water and fixed cement consumption and the BCL 4 achieved better workability; the spreading values were between 282.5 and 298.5 mm. This result indicates that the higher quantity of wood in the mixtures negatively influenced the workability.

The composites with cactus wood and cement studied were demoulded with one day of age indicating that the treatments of washes used, as well as the addition of calcium chloride and the use of cement CP V- ARI were effective in preventing delay / inhibition of cement hydration reactions.

The specimens presented a good homogeneity of the particles in the cementitious matrix (Figure 6).

Fig. 6: Homogeneity of bio-concretes. Top view (left) and tangential section (right) of one of the specimens.

After 28 days of age the BC were then submitted to the uniaxial compression test, and the stress vs strain curves are presented in the Figure 7.

The values of maximum strength as well as the modulus of elasticity and density of the bio-concretes studied are shown in Table 4.

The bio-concretes with greenish particles reached bulk density between 872.5 and 1347.1 kg/m³ while the density of the bio-concretes with the brown particles ranged from 997.4 to 1451.6 kg/m³. According to [Rilem 1978], they can be classified as lightweight materials, since they have a density of less than 1800 kg/m³. The determinant variables on density were the amount of water and cactus wood (more water and more cactus wood resulted lower densities), and there are indications (analysis BCL 200 versus BCF 200; BCL 4 versus BCF 4) that for similar mixtures with different types of particles, bio-concretes with greenish particles results in a composite with higher densities.

With the stress versus strain curve generated, it was possible to observe that the bio-concretes presented an initial elastic linear behavior, followed by a region of marked nonlinearity until reaching the maximum tension. The rounded aspect of the curve can be explained by microcracking pre-rupture of the bio-concrete that increases the deformations recorded by the LVTDs.

The blends with greenish particles (BCF-x) reached between 1.72 and 8.94 MPa of compressive strength while the browned (BCL-x) strength were between 3.38 and 10.51 MPa.

The specimens with fixed consumption of 775 kg/m³ (BCL 100, BCL 200 and BCF 200) achieved better resistance / density ratio and higher stiffness. Analyzing the results of the BCL 100 and BCL 200 mixtures, it was observed that by reducing the compensating water in half the bio-concrete had a small gain of density, increase of the MOE, a significant gain of resistance and a great loss of workability.

For the same trace of BCF 3 - in which it was possible to obtain 1.72 MPa of resistance, 2.30 GPa of MOE and 872.5 kg/m³ of density, [Da Gloria 2015] obtained, using wood sawdust, 15.97 MPa of resistance, 4.03 GPa of MOE and 1250 kg/m³. [Andreola et. al. 2017] studied bio-concrete with bamboo particles and obtained 12.01 MPa of resistance, 4.03 GPa and 1157 kg/m³ of density. These data show that for this ratio the bio-concretes with cactus wood although less resistant have as main differential the low density that they can achieve and the fact of maintaining a relatively high stiffness. The comparison with the results of the study by [Beraldo 1997], which also deals with the production of a cementitious composite with bamboo particles, corroborates with the previous analysis.

The traces BCL 200 and BCF 200 are similar to those of [Andreola 2017] who use bamboo particles as bio-aggregate, obtained maximum resistance of 4.20 MPa, MOE of 2.35 GPa and 788.47 kg/m³ of density and 285 mm of spreading. These results show that in cement matrix fixation the cactus bio-concrete obtained better properties than the bamboo, which is probably due to the large amount of fine particles present in the mixture, which reduced the amount of voids, densifying the mixture and consequently increasing mechanical properties.

4 CONCLUSION

The potentiality of *Cereus Jamacaru* was verified for possible industrial applications due to the advantages presented by analyzing its chemical characterization.

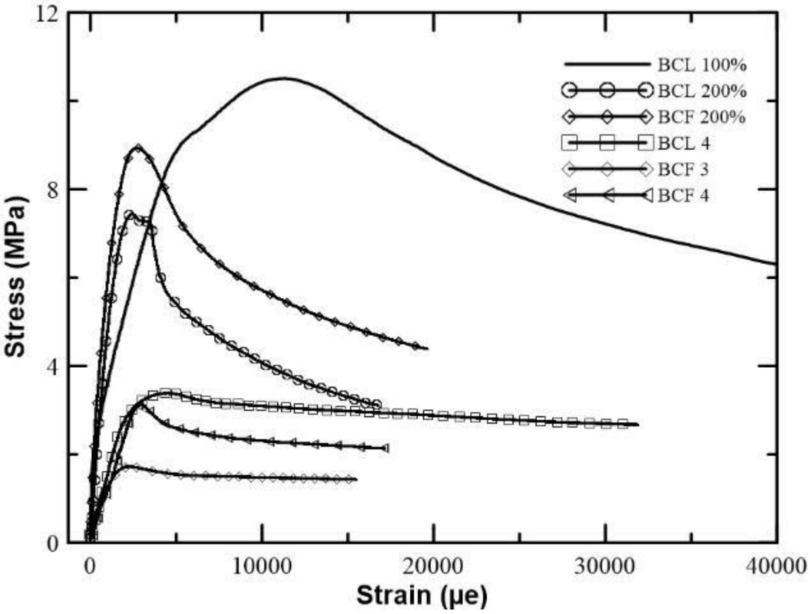

Fig. 7: Typical stress-strain curves of bio-concretes submitted to compression test

Tab. 4: Physical and mechanical properties of the bio-concretes.

Blend	Fresh state	Hard state			
	Blend Workability (mm)	Compression Strength (MPa)	Strain (µe)	E (GPa)	Density (kg/m³)
BCL 100	225.0	10.5	66499.2	11.5	1451.6
BCL 200	282.5	7.4	16764.0	10.3	1284.0
BCF 200	298.5	8.9	19618.8	12.0	1347.1
BCL 4	287.5	3.4	31901.4	2.6	997.4
BCF 3	212.5	1.7	15471.6	2.3	872.5
BCF 4	257.5	3.1	17135.5	2.0	999.6

The washing treatment on the cactus wood particles together with the use of the Portland cement CPV-ARI and the addition of calcium chloride were effective in guaranteeing the cement hydration and in the hardening of the bio-concretes.

The mixtures with the highest cement consumption and with 200% of compensating water presented better workability than the others.

The specimens with fixed consumption of 775 kg/m³ reached a better resistance / density ratio and higher stiffness and in general it was observed that the bio-concretes with higher strength presented higher MOE values.

Finally, the objective of producing light bio-concretes was reached given the low final density of the products. In addition, good physical, mechanical and workability properties (properties of interest in construction) have been reached and it can be concluded that cactus wood can be used as an alternative lignocellulosic source in the production of bio-concretes for use in various purposes in the construction industry.

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