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**ORGANOSOLV PULPED SISAL AS REINFORCEMENT FOR
CEMENT BASED COMPOSITES**

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ABSTRACT

Abstract: The present work describes non-conventional sisal (*Agave sisalana*) chemical (organosolv) pulp as reinforcement to cement based materials. Sisal field by-product from Brazilian industry of cordage was chemically characterized. Organosolv sisal pulp was produced with ethanol:water 1:1 solvent and post chemically and physically characterized. Cement based composites reinforced with organosolv pulp and combined with polypropylene (PP) fibres were produced by the slurry de-watering and pressing method as a crude simulation of the Hatschek process. Mechanical and physical performances of the composites were evaluated at 28 days of age, after exposition to accelerated carbonation chamber and after 100 soak/dry cycles. Carbonation promoted the densification of the composites reinforced with organosolv + PP fibres. There was a trend to composites reinforced with only sisal pulp to accomplish greater MOR and LOP than composites with hybrid reinforcement. This behaviour can be attributed to the better adhesion and packing between the cement matrix and cellulose fibres. The obtained results bring encouragement to the continuation of the ongoing research with the compromise between physical and mechanical performance of the composite and its cost of production.

KEYWORDS *Keywords: Fibre cement, cellulose pulp, sisal pulp, pulping, polypropylene fibre, ordinary Portland cement.*

INTRODUCTION

In several developed countries, cellulose fibres are used as reinforcement of cement-based materials and in order to provide an alternative for low cost buildings by adaptation of the former asbestos-cement production process [1].

Tropical countries present significant opportunities for the production of non-wood lignocellulosic fibres [2], especially if they are available from by-products of the main commercial agricultural activities (e.g., cordage). With the low cost of raw materials and simplified pulping methods, the resulting cellulose pulp has considerable potential for fibre-cement production at significantly lower costs than those associated with the use of conventional kraft wood pulps [3].

Alkaline kraft pulping is the dominant chemical pulping process today, but it presents some serious shortcomings, as air and water pollution and the high investment costs. These shortcomings have led to the development of several organosolv methods capable of producing pulp with properties near those of kraft pulp [4].

Diverse solvents, pure or in mixtures, can be used to promote delignification [5,6]. Amongst them, the process that involves ethanol is the most used, regarding the recovery facilities, the better impregnation of vegetal tissue by solvent, the easier recovery of lignin and polysaccharides from the pulping liqueur beyond the efficient delignification and favourable conditions of operation in alcohol producer's countries [7-9].

The lignin dissolution in the organosolv processes is a result of hydrolysis of ether bonds, as α -O-4 and β -O-4 bonds of lignin macromolecules [10]. Organosolv delignification also consists on the breaking of ether bonds between carbohydrates and carbon atoms from the lateral chains of lignin [11]. According to Aziz & Goyal [12] cleavage of alpha-ether linkages is the most important reaction in the lignin molecule breakdown during organosolv pulping. The bulk delignification in ethanol:water pulping is a phenomenon involving breakdown of the lignin with high molecular weight and solubilisation of its breakdown products [13]. Ethanol acts as a scavenger for the free radicals formed during pulping and reduces the extent of lignin condensation. Some side chain rearrangement and ethoxylation of benzyl alcohol groups occurs. This reaction prevents the lignin molecule from recondensing during the pulping process [14].

In the kraft process the lignin extraction from cell wall occurs at the initial stage of delignification, whereas the lignin from middle lamella is extracted at the final stage of delignification. In the organosolv processes, the lignin extraction occurs first at the media lamella and lignin from cell wall is poster dissolved [15,16]. According to Mohr et al. [17] this characteristic must be of great interest since it decreases the tendency of fibre interlayer debonding during the soak/dry cycling, and consequently prevents the reprecipitation of hydration products within the fibre cell wall, minimizing fibre mineralization.

This work reports on the investigation of an alternative chemical (organosolv) pulping process applied to sisal (*Agave sisalana*) strand fibres. The organosolv pulp is used as sole reinforcement of cement based composites and jointly with PP fibres as hybrid reinforcement.

EXPERIMENTAL

Materials

Sisal (*Agave sisalana*) field by-product was provided by Associação de Desenvolvimento Sustentável e Solidário da Região Sisaleira (Apaeb), Brazil. Sisal strand fibres originated from residues of the cordage industry were around 5 mm long and approximately 0.2 mm average diameter (around 360 MPa tensile strength [18], 15.0 GPa elastic modulus [19] and 5% strain at failure [18]). The raw material was first chemically characterized and then pulped under organosolv process.

Polypropylene (PP) fibres measuring 6 mm long and $83 \pm 8 \mu\text{m}$ diameter, with 300 MPa tensile strength, 3.3 GPa elastic modulus and 25% strain at failure (data furnished by Fitesa S/A), was used for mix-design with hybrid reinforcement.

Physical and chemical properties of ordinary Portland cement (OPC) and carbonate filler are summarized in Tables 1 and 2 respectively. Carbonate filler was used for partial substitution of OPC in order to reduce costs concerning the production of fibre-cement. Bentonite (specific surface area = $0.2152 \text{ m}^2/\text{g}$) was used to improve the water retention. Particle size distribution was evaluated by Mastersizer S long bed 2.19 version in a Malvern equipment and was depicted in Figure 1.

TABLE 1 – PHYSICAL, CHEMICAL AND MECHANICAL CHARACTERIZATION OF ORDINARY PORTLAND CEMENT (CP-IIE^(a)).

Physical properties		Chemical properties											Mechanical properties	
Specific surface area (m^2/g)	Specific mass (g/cm^3)	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	P ₂ O ₅	K ₂ O	SrO	MnO	ZrO ₂	Loss of ignition	$\sigma_{c,7d}$ (MPa)	$\sigma_{c,28d}$ (MPa)
0.5211	3010	25.3	58.6	5.83	2.88	3.02	0.19	0.84	0.19	0.08	0.03	3.0	30.4	41.0
Retention # 200 ^(b) (%)		1.57												
Retention # 325 ^(c) (%)		9.9												

(a) Data provided by the supplier. Brazilian Standards NBR 11578 [20]: blast furnace slag = 6-34%; carbonate filler = 0-10%; (b) 200 mesh sieve (# 0.074 mm); (c) 325 mesh sieve (# 0.045 mm).

TABLE 2 – PHYSICAL AND CHEMICAL CHARACTERISTICS OF CARBONATE FILLER.

Physical properties		Chemical properties										
Specific surface area (m^2/g)	Specific mass (kg/m^3)	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	P ₂ O ₅	K ₂ O	TiO ₂	SrO	MnO	Loss of ignition
0.4298	2650	2.47	44.6	0.45	0.37	8.56	0.08	0.17	0.04	0.05	0.06	43.3
Present phases (DRX)		CaCO ₃ , CaMg(CO ₃) ₂ , Fe ₂ O ₃ , SiO ₂ , (K,Na)(Al,Mg,Fe) ₂ (Si _{3.1} Al _{0.9})O ₁₀ (OH) ₂										

Source: Laboratory of Technological Characterization, Escola Politécnica, Universidade de São Paulo.

According to Figure 1, 50% of the particles are smaller than 13.59 μm , 14.49 μm and 28.23 μm for OPC, carbonate filler and bentonite respectively. Most of particles (90%) are smaller than 41.75 μm , 50.08 μm and 71.92 μm respectively.

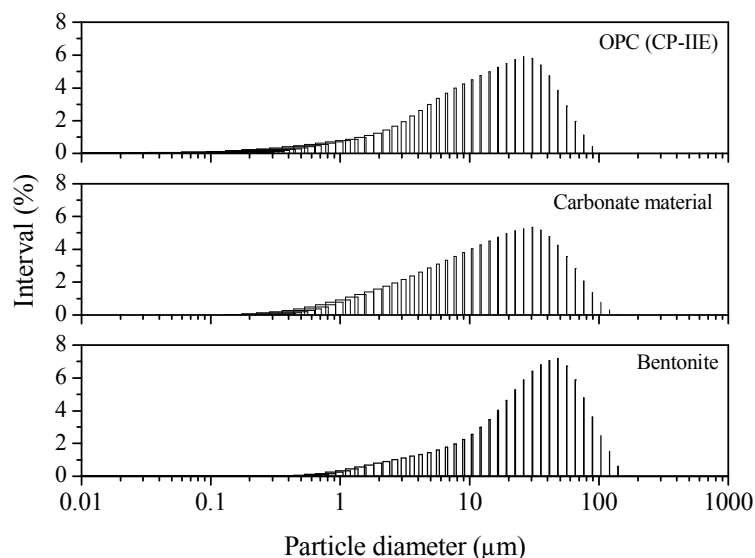


FIGURE 1 – PARTICLE SIZE DISTRIBUTION OF OPC (CP-IIIE), CARBONATE MATERIAL AND BENTONITE.

Fibre characterization

Determination of insoluble and soluble Klason lignin

Insoluble lignin - The content of insoluble Klason lignin was determined according to Tappi Test Method T222:88 [21]. Dry fibres (1 g) were solubilised with 15 mL of H₂SO₄ 72% under magnetic agitation during 2 h. After this, the mixture was placed in a 1 L glass balloon added to 560 mL of distilled water under reflux. The mass of fibres left after filtration was dried at 100°C until the constant weight was attained.

Reflux was performed during 2, 3, 4 and 5 h for the sisal strand fibres in order to determine the maximum dissolution. For the organosolv pulp it was used 4 h under reflux condenser. The content of Klason lignin was defined by Eq. 1:

$$\%R_l = \frac{m_l}{m_m} \cdot 100 \quad (1)$$

where m_m is the dry mass of fibres [g], m_l is the mass of dry Klason lignin [g] and $\%R_l$ is the content of insoluble Klason lignin [%].

Soluble lignin - The filtered solution after insoluble determination was diluted to 1 L with distilled water for Ultra Violet (UV) spectroscopy analyses in order to determine the soluble lignin. It was prepared a reference solution from 1.5 mL 72% sulphuric acid in 100 mL water. An aliquot was collected for the absorbance analyses at 280 and 215 nm. The amount of lignin [g/L] in the diluted samples was calculated using the Eq. 2:

$$C \text{ (g/L)} = \frac{4.53 \cdot A_{215} - A_{280}}{300} \quad (2)$$

where C [g/L] is the amount of soluble Klason lignin [g/L], A_{215} is the absorbance at 215 nm and A_{280} is the absorbance at 280 nm.

Determination of holocellulose content

Holocellulose content was determined by the use of sodium chlorite in acid solution, and it is designated chlorite holocellulose. The procedure is described in the literature [22]. The amount of 1 g of fibres was diluted in 60 mL of distilled water under magnetic agitation at $70 \pm 2^\circ\text{C}$ during 0.5 h. After thermal equilibrium 1.5 g of sodium chlorite and 2 mL of acetic acid were added. This procedure was repeated after 1 h and after additional 2 h, resulting in 3 h of reaction. Finally the resultant mass was filtered and dried at 100°C until constant mass. The content of holocellulose was calculated according to the Eq. 3:

$$\%R_{holo} = \frac{m_{holo}}{m_m} \cdot 100 \quad (3)$$

where m_m is the dry mass of fibres [g], m_{holo} is the dry mass of holocellulose [g] and $\%R_{holo}$ is the content of holocellulose [%].

Determination of cellulose and polyose

The filtered solution after the determination of insoluble Klason lignin was used for the determination of carbohydrates by high performance liquid chromatography (HPLC). The amounts of cellobiose, glucose, arabinose, formic acid, acetic acid, hydroxymethylfurfural and furfural were determined. The quantity of polyose and cellulose could be determined from the amount of each component in the solution.

Cellulose and polyoses contents were determined by HPLC, where the hydrolyzed pulp from Klason lignin determination was employed. The sample to be analyzed was prepared as cited by Pasquini et al. [23]. Determinations of cellobiose, glucose, xylose, arabinose and acetic acid, were performed in a Shimadzu, model CR 7A chromatograph equipped with Infrared Shimadzu R10-6A detector, column Aminex HPX 87H (300 mm×7.8 mm, Biorad), using H_2SO_4 , 0.005 mol L^{-1} as eluent and a flow rate of 0.6 m L min^{-1} . For the determinations of furfural and hydromethylfurfural, the same chromatograph was employed with a Shimadzu Ultraviolet detector (254 nm), model SPD-10A, column RP 18 (C18) Hewlett-Packard, using acetonitrile/water 1:8 (v/v) with 1% acetic acid (v/v) as eluent and flow rate: equals to 0.8 m L min^{-1} .

Organosolv pulping

Organosolv pulping was conducted along three periods of reactions, in order to observe the higher yield of the process. Pulping times were 1, 2 and 3 h of reaction from the moment in which the temperature of the reactor reached 190°C .

The quantity of 25 g of by-product sisal (around 5 mm long) was added in a blend of ethanol

and water in the range of 1:1 v/v at 190°C in a locked 1 L reactor. After each cooking time (1, 2 and 3 h), the reactor was cooled to no longer than 20 min and the pulp was filtered in a Buchner funnel. Pulp was triple washed with ethanol and dried at 100°C. The yielding was calculated according to Eq. 4:

$$\%R_o = \frac{m_o}{m_m} \cdot 100 \quad (4)$$

where m_m is the dry mass of the by-product sisal [g], m_o is the dry mass of the pulp [g] and $\%R_o$ is the pulp yield [%].

Physical characterization of fibres and pulp

The main physical attributes of the organosolv pulp were characterized by the particle size analyser Galai CIS-100.

The analysis with Galai CIS-100 consists in the evaluation of the attributes of the whole fibrous material present in the pulp. Average length and width, coarseness, number of fibres per gram and fines content were analysed and stored with the aid of the Wshape v.1.0 software.

Composite preparation

Cement based composites were moulded in plates measuring 200 mm x 200 mm and reinforced with sisal pulp (unrefined organosolv) and polypropylene fibres. They were prepared in laboratory scale using a slurry vacuum de-watering followed by pressing technique described in details by Savastano Jr. et al. [24].

Formulations in Table 1 were established based on prior studies published elsewhere [25,26]. They refer to the dry mass of the solid raw materials before mixing with water.

TABLE 1 – MIX-DESIGN OF THE FIBRE-CEMENT COMPOSITES.

Raw material	SO	SOPP
	w/w %	
Sisal pulp (SO = unrefined organosolv)	4.7 ^a	3.0 ^b
Polypropylene fibres (PP)	-	1.7 ^c
Ordinary Portland cement (CP-IIIE)	77.8	77.8
Carbonate filler	16.5	16.5
Bentonite	1.0	1.0

^a Equivalent volume fraction = ~5.0%; ^b Equivalent volume fraction = ~3.1%;

^c Equivalent volume fraction = ~2.6%.

Bentonite was previously dispersed separately in water during 10 min and post added jointly with the pulp, which was dispersed in water by mechanical stirring at 1,700 rpm during 1.0 h. The mixture formed with approximately 20% of solids was stirred at 1,700 rpm for 20 min. The slurry was transferred to the evacuable casting box and the vacuum was applied (~80 kPa gauge) until a solid surface formed. Three pads of each formulation were pressed simultaneously at 3.2 MPa for 5 min (final water/cement ratio ~ 0.3), then sealed wet in a

plastic bag to cure at room temperature for two days and immersed in water during twenty-six days. Pads were cut wet into four 165 mm x 40 mm flexural test specimens using a diamond saw cooled with water. Specimen thickness was approximately 6 mm. On completion of the cure, specimens were tested under saturated condition at 28 days after production.

Accelerated carbonation

Accelerated carbonation of the composites was carried out in a climatic chamber with carbon dioxide (CO₂) saturated environment and with controlled temperature and humidity (30°C and 80% RH respectively). The composites were submitted to the climatic chamber environment during two weeks until the complete carbonation of the samples. The carbonation degree was evaluated by the exposure to a solution with 2% of phenolphthalein diluted in anhydrous ethanol as described by Silva [27] and Agopyan et al. [28].

Soak/dry accelerated ageing cycles

The soak/dry accelerated ageing cycles involved comparative analysis of the physical and mechanical performance of the composites before and after this test. Specimens were successively immersed in water at 20°C ± 5°C during 170 min, followed by the interval of 10 min, and then exposed to the temperature of 70°C ± 5°C for 170 min in a ventilated oven and with the final interval of 10 min. This procedure was based on recommendations of the EN 494 [29] Standards. Each soak/dry set represents one cycle and was performed for 100 times (i.e., 100 cycles).

Physical and mechanical characterization

Water absorption (WA), bulk density (BD) and apparent void volume (AVV) values were obtained from the average of ten specimens for each design, following procedures specified by the ASTM C 948-81 [30] Standards.

Mechanical tests were performed in a universal testing machine Emic DL-30,000 equipped with 1 kN load cell. A four-point bending configuration was employed for the determination of the values of modulus of rupture (MOR), limit of proportionality (LOP), modulus of elasticity (MOE) and toughness. A span of 135 mm and a deflection rate of 1.5 mm/min were adopted in the bending test. Eq. 5 and Eq. 6 define MOR and MOE respectively:

$$MOR = \frac{P \cdot L_v}{b \cdot h^2} \quad (5)$$

$$MOE = \frac{276 \cdot L_v^3}{1296 \cdot b \cdot h^3} \cdot \left(\frac{P}{\delta} \right) \quad (6)$$

where P is the maximum load, L_v is the major span between the supports, b and h are the specimen width and depth respectively, and δ is the deformation of the composite.

The limit of proportionality (LOP) was described as the stress corresponding to the upper point of the linear portion of the stress-strain curve.

Toughness (Eq. 7) was defined as the energy absorbed during the flexural test and divided by

the specimen cross-sectional area. The absorbed energy was calculated by integration of the area below the load-deflection curve.

$$Toughness = \frac{\text{absorbed energy}}{b \cdot h} \quad (7)$$

where b and h are the specimen width and depth respectively.

Scanning electron microscopy (SEM) was applied for the characterization of fibre-matrix interface on a fractured surface of specimens undergone to mechanical tests. Samples were gold coated before being analysed in a Zeiss LEO 440 microscope.

RESULTS AND DISCUSSION

Sisal strand fibres characterization

A preliminary study for the determination of the optimal time of reflux with sulphuric acid was performed in order to reach maximum carbohydrates degradation, during periods of time shown in Figure 2. Figure 2a represents the content of soluble, insoluble and total Klason lignin according to the time of reflux.

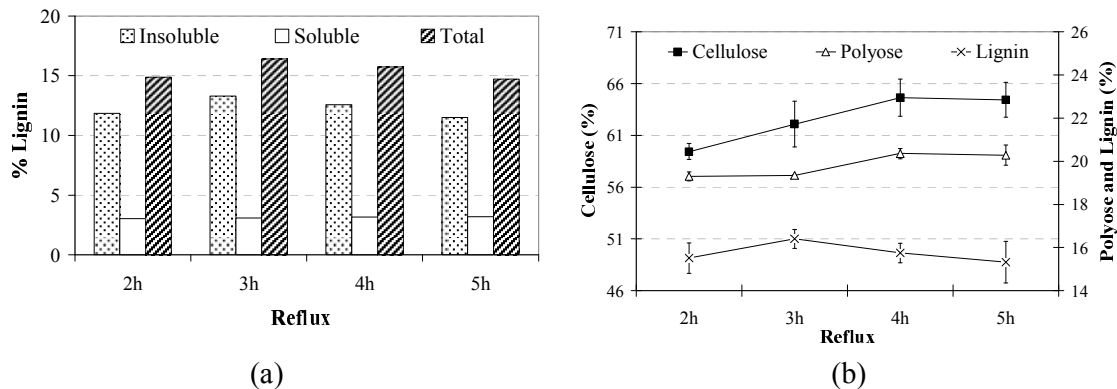


FIGURE 2 – (A) RESULTS OF INSOLUBLE, SOLUBLE AND TOTAL KLASON LIGNIN FOR DIFFERENT TIMES UNDER REFLUX CONDENSER. (B) CHEMICAL CHARACTERIZATION OF SISAL STRAND FIBRES.

In Figure 2a it can be seen that the content of Klason lignin decreases with the time of reflux, after 3 h. The higher the time of reflux, the higher the hydrolysis of the fibre, with a consequent removal of the constituents of the fibre that are not insoluble Klason lignin.

The Figure 2b depicts the content of cellulose and polyoses achieved by liquid chromatography. The values obtained for cellulose and polyoses are in accordance with the literature [31]. It was considered that 3 h of reflux was enough to reach complete hydrolysis of the carbohydrates.

Characterization of organosolv pulps

It can be observed in Figure 3 that the yield for 1 h pulping was the higher. It is attributed to the low removal of lignin, resulting in a higher mass of dry pulp. This fact indicates that 1 h

was not enough to get a satisfactory removal of lignin.

Figure 3 shows the yield and the content of pulp constituents for each time of pulping.

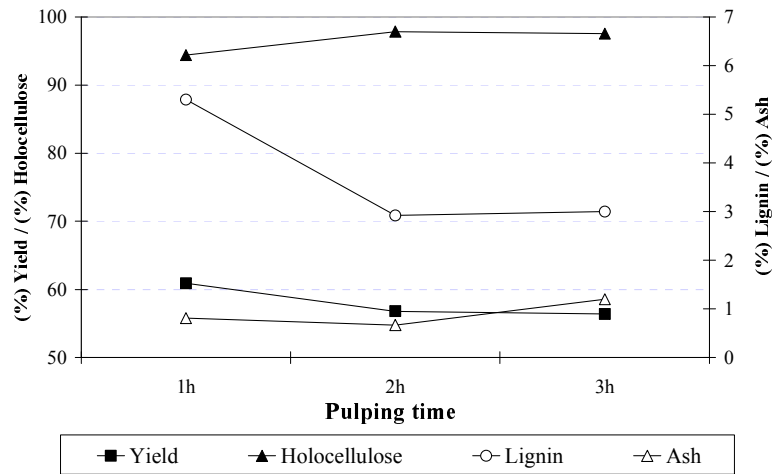


FIGURE 3 – RESULTS OF CHEMICAL CHARACTERIZATION OF PULPS AT DIFFERENT PULPING TIMES.

Results obtained for the yield, holocellulose and lignin contents after 2 and 3 h (Figure 3) indicated no significant variations in these properties. The period of 2 h of pulping was sufficient to extract the maximum lignin possible of the by-product sisal. This fact would represent an economy of energy by the adoption of 2 h of reaction instead of 3 h.

The physical characterization of the fibrous material, i.e., entire plus damaged fibres performed in Galai equipment gives a precise idea of the actual morphology of the pulp. Results follow in Table 2.

TABLE 2 – SISAL PULP AND FIBRE PHYSICAL PROPERTIES^a.

Pulp	Average length (mm)	Average width (μm)	Aspect ratio	Coarseness (mg/100 m)	Fibrous material (10^6 fibres/g)	Fines content (%)
Organosolv (unrefined)	1.10 ± 0.04	26.4 ± 0.2	42	11.5 ± 1.7	8.1 ± 1.6	25.8 ± 2.2
Kraft (unrefined) ^b	1.66 ± 0.02	22.2 ± 0.5	75	12.8 ± 0.1	4.7 ± 0.1	27.2 ± 1.2

^a Pulp and Paper Laboratory, Department of Forestry Engineering of the Federal University of Viçosa, Brazil.

^b Tonoli et al., [26].

In a previous study, Tonoli et al. [26] evaluated commercial sisal kraft pulp at different intensities of refinement (CSF 680, 220 and 20 mL). The Canadian Standard Freeness test (CSF) is a widely recognized standard measure of the drainage properties of pulp suspensions. Low freeness values (less than 300 mL) are indicative of high degrees of external fibrillation and/or shortage of the fibres, leading to long drainage periods during the test. The refinement greatly improves the manufacturing processes based on slurry dewatering techniques followed by pressing [24]. The physical properties of the unrefined kraft pulp (CSF 680 mL) are presented in Table 2. Comparison with the properties of the unrefined organosolv pulp shows similar amount of fines. The definition of fines is related to the fibres with less than 75 μm of length [32]. The average length of organosolv pulp was lower and average width was higher in the present work, which gives a considerably lower aspect ratio. The reduction of the average length and coarseness over the unrefined kraft pulp is probably a consequence of the

chemical intensity of the organosolv process. The coarseness expresses the amount of mass by length unity and its decrease is due to the external layers of the fibre have been removed by the treatment of the pulp. Comparing unrefined pulps, the organosolv process increased the amount of fibrous material per gram present in the pulp. On the other hand, the sisal source from residues of the cordage production should also be taken in consideration in the evaluation of these figures.

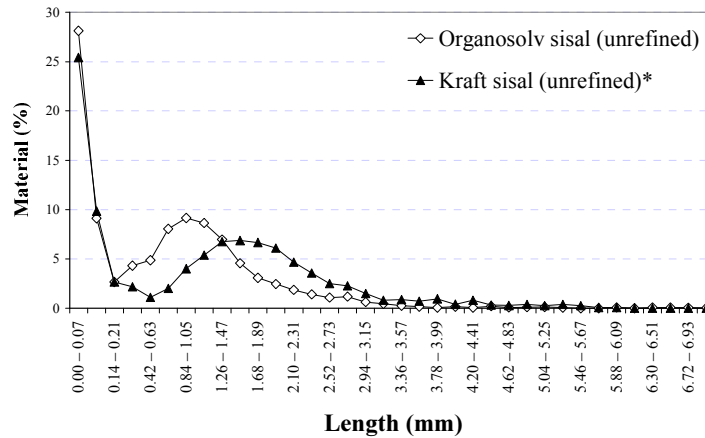


FIGURE 4 – LENGTH DISTRIBUTION OF THE FIBROUS MATERIAL. (*) TONOLI ET AL. [26].

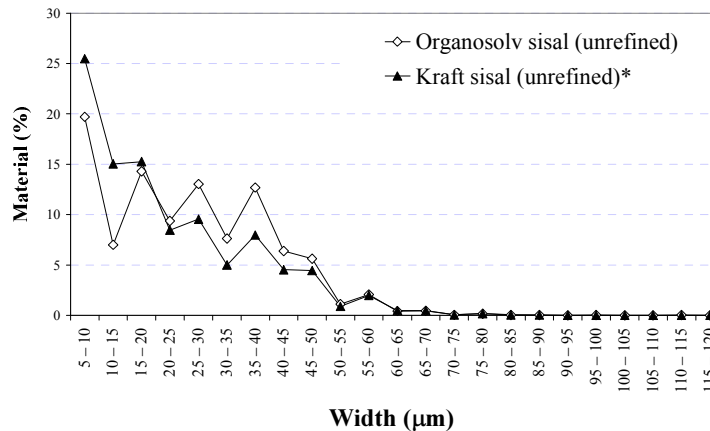


FIGURE 5 – WIDTH DISTRIBUTION OF THE FIBROUS MATERIAL. (*) TONOLI ET AL., [26].

The distributions of length and width for the fibrous material (obtained with the particle size analyser) can be visualized in Figures 4 and 5 respectively. According to Figure 4, most of the filaments (around 65%) are lower than 1 mm. Organosolv pulping generates shorter fibrous material than unrefined kraft pulp [26]. For the width distribution (Figure 5) most of the fibres (84%) lie in the 5-40 µm region.

Physical results of the composites

According to the results shown in Figure 6, water absorption and apparent void volume have decreased significantly for composites fast carbonated and aged. Water absorption of the unaged composites with organosolv + PP fibres was less influenced by 100 ageing cycles.

Bulk density increased significantly with the accelerated carbonation for composites

reinforced with only sisal and with sisal + PP fibres. Results for bulk density were not significantly different for composites at 28 days when compared to those at 100 ageing cycles.

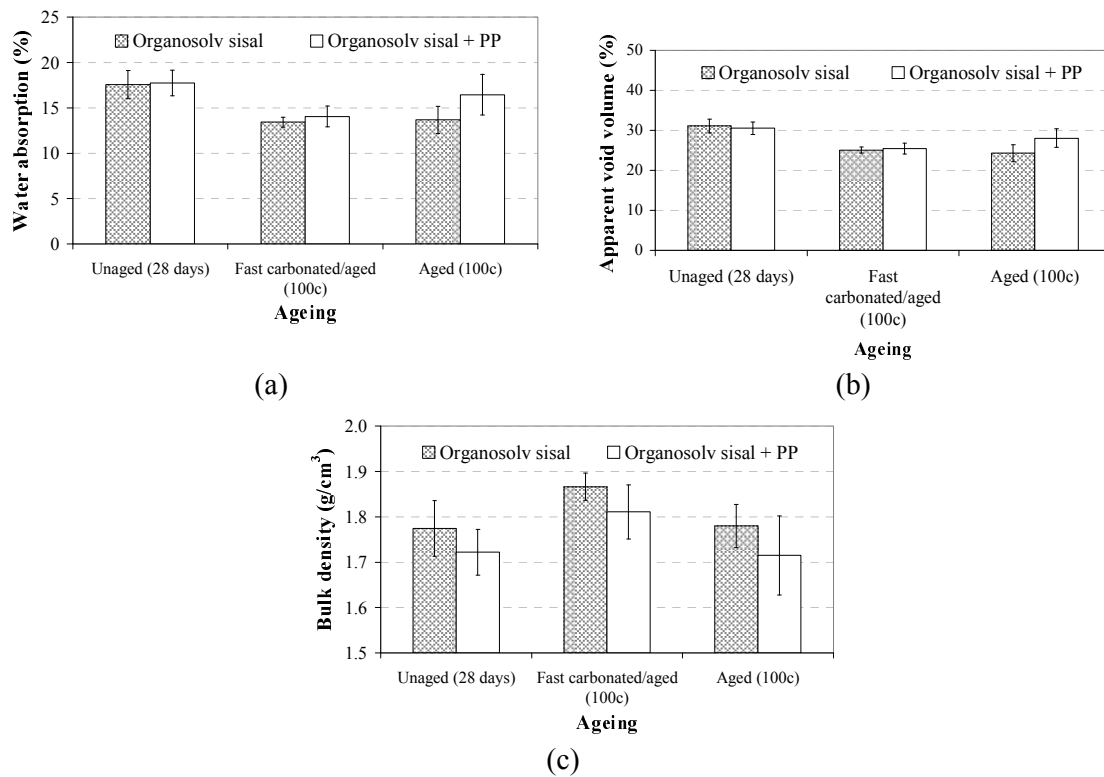


FIGURE 6 – (A) WATER ABSORPTION, (B) APPARENT VOID VOLUME AND (C) BULK DENSITY OF THE COMPOSITES.

Composites with organosolv pulp and PP fibres as reinforcement presented higher water absorption after 100 ageing cycles over composites only reinforced with organosolv pulp. This behaviour can be attributed to deficient distribution of long and hydrophobic synthetic fibres in the matrix, which can have caused higher void content also after ageing, as a probable consequence of capillaries associated to the poorer packing. Another fact that could contribute to lower values of water absorption in the sisal aged composites is the probable formation of hydration products around and into the cores of the cellulose fibres after the ageing cycles. According to ongoing research, composites with only organosolv sisal presented lower water absorption than composites with only kraft sisal at 28 days and after the 100 ageing cycles. These results will be present in a forthcoming paper.

The higher bulk density of the formulations containing only sisal pulps in comparison with composites with polypropylene fibres is directly related with the substitution of the fraction of the matrix (density~2.6 g/cm³) and cellulose fibres (density~1.5 g/cm³) by polypropylene fibres (density~0.9 g/cm³).

Mechanical results of the composites

Figure 7 presents the results of mechanical properties of the composites before and after the ageing for both series subjected or not to fast carbonation. Fast carbonated/aged composites presented higher MOR, LOP and toughness than those only aged composites (without fast carbonation) reinforced with organosolv pulp + PP fibres. Unaged composites with

organosolv pulp did not present significant differences of MOR in relation to those ones reinforced with organosolv + PP fibres.

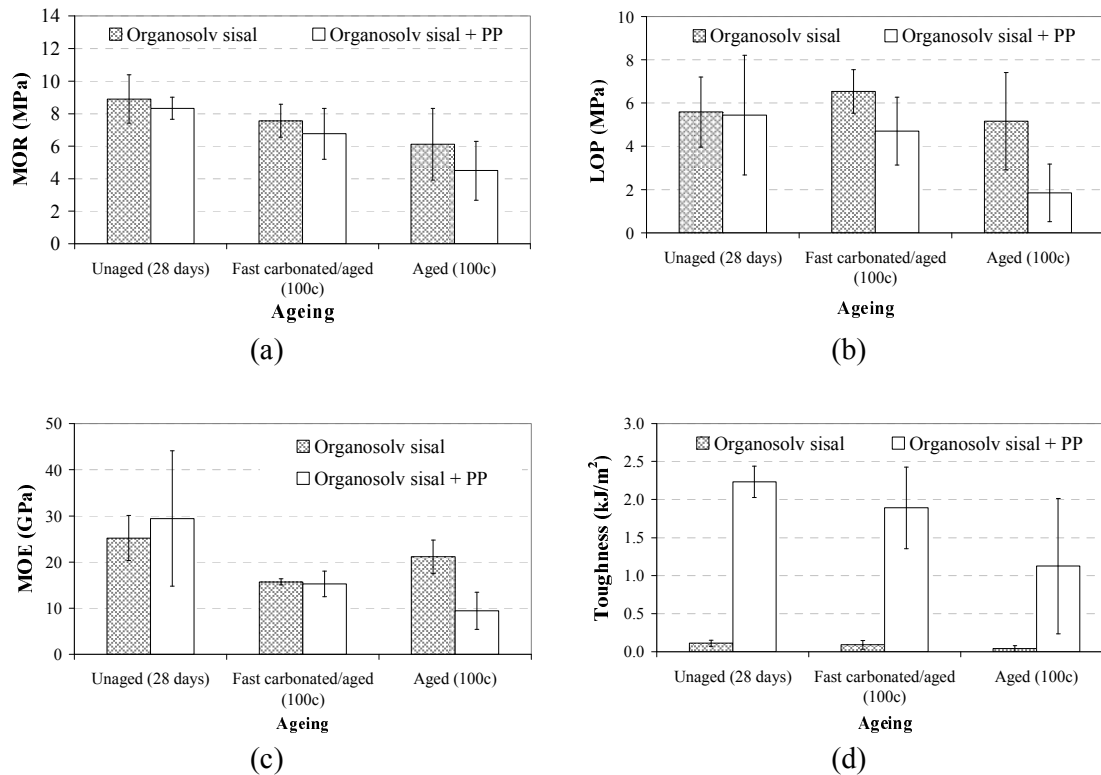
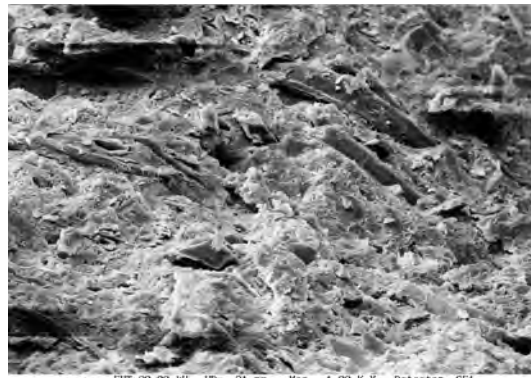
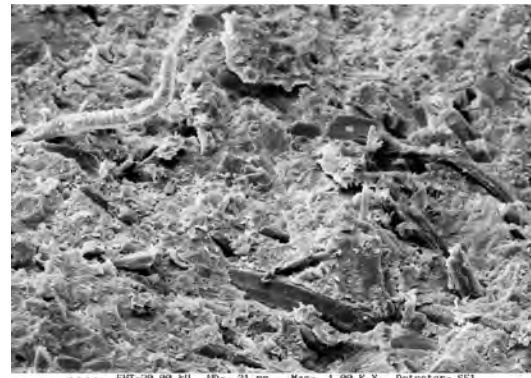


FIGURE 7 – (A) MOR, (B) LOP, (C) MOE AND (D) TOUGHNESS OF THE COMPOSITES REINFORCED WITH ORGANOSOLV AND PP FIBRES AT 28 DAYS, FAST CARBONATED/AGED AND AGED.

Toughness is often related to the length of reinforcing fibre especially in the case of short fibre (with length below the critical length). As the stress is transferred from the matrix to the fibre, debonding can take place at the interface and the fibre may be pulled out through the matrix, generating considerable frictional energy losses, which contribute to toughness [3]. Composites reinforced with only organosolv sisal provided lower toughness than composites reinforced with unrefined kraft pulp, according to previous work [26]. Organosolv fibres seem to be weaker than kraft fibres as the pull-out of the organosolv fibres was decreased. According to Young [33], in general, the strength properties of organosolv pulps are inferior to those of corresponding kraft pulps, which may be related with the great amount of solubilized polyoses [34]. There may be significant contribution to the decay of the reinforcement capacity with the consequent fragile behaviour of the composite.



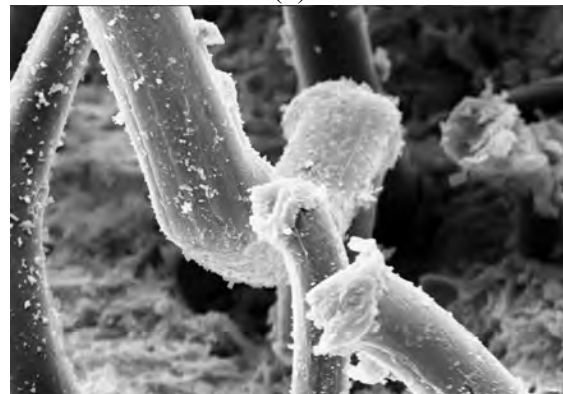
(a)



(b)



(c)



(d)

FIGURE 8 – SEM OF FRACTURE SURFACE OF COMPOSITES AFTER 100 SOAK/DRY CYCLES: (A) AND (B) ORGANOSOLV PULP; (C) AND (D) ORGANOSOLV PULP + PP FIBRES.

After ageing, since the cellulose fibres are more adhered to the matrix, the fracture prevails (Figures 8a and 8b) over the pull out inasmuch as the toughness decreases for samples with only sisal pulp.

Figure 9 presents the stress-strain curves of the composites according to the use of organosolv sisal pulp for samples without and with polypropylene respectively. The area below the stress-strain curves is related to the absorbed energy by the composites.

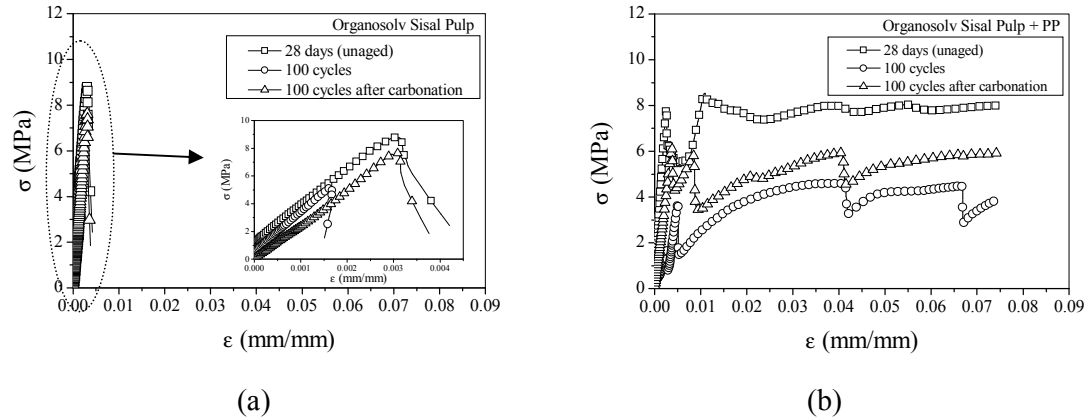


FIGURE 9 – STRESS-STRAIN CURVES FOR COMPOSITES WITH DIFFERENT REINFORCING FIBRES AT 28 DAYS AND AFTER 100 CYCLES WITH/WITHOUT FAST CARBONATION: (A) ORGANOSOLV SISAL PULP; (B) ORGANOSOLV SISAL PULP WITH POLYPROPYLENE FIBRES.

Toughness was greatly improved with the addition of PP fibres. The intrinsic properties of the PP fibres (tensile strength = 300 MPa and modulus of elasticity = 3.3 GPa), which do not adhere very well to the matrix in the initial ages, contribute to the enhancement of the composite toughness. The improvement of toughness with the addition of PP fibres is also related with the absence of fibrillation, favouring poor anchoring to the matrix and considerable incidence of pulled out fibres (Figures 8c and 8d). Accelerated carbonation seems to be effective in the maintenance of the toughness of the composites with organosolv pulp combined with PP fibres after ageing.

CONCLUSION

This experimental study has been developed in order to evaluate an alternative pulping process for natural fibres, aiming to make viable the use of cellulose fibres as a suitable reinforcement in low-cost fibre-cement application.

Organosolv pulp composites after 100 ageing cycles (without fast carbonation) presented lower water absorption and apparent voids volume than composites reinforced with organosolv + PP fibres. Also, the density of the polypropylene (PP) fibres provide lower density to the ensuing composites. Despite the good mechanical performance of the composites reinforced with organosolv pulp, these results are not definitive and one can expect improvements, once the process is not well adapted for the production of this kind of material, differently of the fibre-cement with kraft pulp, which has been extensively studied. Accelerated carbonation promotes densification of the composites and has maintained the resistance of the composites reinforced with organosolv + PP fibres.

The highest toughness was associated with the addition of polypropylene fibres in the mixture. It can be understood by the fact that polypropylene fibres poorly adhere to the cement matrix, favouring insufficient anchorage and considerable incidence of pull out.

This work is part of a more comprehensive project dedicated to the development of asbestos free formulations applied to fibre-cement products to meet the needs of emerging countries. The tailoring of these non-conventional composites includes not only the optimization of the cellulose pulp from available raw materials but also the selection of adequate formulations

and processes in the fibre-cement production. The obtained results bring encouragement to the continuation of the ongoing research with the compromise between physical and mechanical performance of the composite and its cost of production.

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