# CORN STALK FROM AGRICULTURAL RESIDUE USED AS REINFORCEMENT FIBER IN FIBER-CEMENT PRODUCTION.

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## ABSTRACT

In the last few years an increasing high interest has been drawn to the potential use of agricultural waste as raw material to produce structural reinforcement fibers for building materials, due to environmental and economical aspects. Corn is the world's most produced cereal in terms of quantity, what entails the generation of large quantities of waste. Despite this fact, only a few research works concerned with the use of fibers from waste corn stalks in the production of fiber-cement have been published and there is a complete lack of data on the characterization of these fibers. The objective of this research is to study the feasibility of using fibers obtained from corn stalk as reinforcement fibers in the production of fiber-cement through new environmentally friendly cooking methods. This study encompasses the morphological characterization of the fibers and the study of the effects that the use of these fibers has on the flocculation, retention and drainage of the fiber-cement suspensions and on the mechanical and physical properties of the final product.

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The results obtained in the tests confirmed the high potential of the corn stalk as a source of fibers for the manufacture of a fiber-cement capable of meeting the requirements of demanding applications.

**Keywords:**

Drainage; Flocculation; Mechanical properties; Physical properties; *Zea Mays L.*

## 1. Introduction

The commercial use of asbestos fibers in cement paste matrixes began with the invention of the Hatschek process in 1898 (A.C.I.544.1R., 1996). However due to health hazards associated with asbestos, the use of alternative fibers have been investigated in the past years. Natural fibers are considered the most promising replacements for asbestos since they offer distinct advantages such as availability, renewability and low cost (Segetin et al., 2007; Tadas et al., 2011). In line with this argument it is worth mentioning that pine fibers are currently the most common fibers used in the manufacture of fiber-cement for roofing (Bart et al., 2004; Coutts, 2005; Isamail, 2007). As a result, in the last few years, the knowledge on the use of natural fibers as reinforcement in composites has made a relatively great progress (Savastano et al., 2009; Silva et al., 2010). On the other hand, there has never been such a large demand for fiber resources as the one experienced nowadays (Pappua et al., 2007).

Worldwide development growth has generated unprecedented needs for converted forest products, constituting also the cause of the generation of agricultural wastes from cereal crops in quantities never seen before. In view of this, it is clear that the use of these crops wastes as sources of fibers could be a way to reduce cost and increase the sustainability of many processes (Juárez et al., 2007). The composition and properties of agricultural waste fibers have a significant effect on the properties of cement e.g. hydration and stiffening of (Li et al., 2004).

Fiber-cement is mainly used in three major application areas: siding, roofing, and tile backerboard. Cereal straw is used in production of cement-bonded particleboard, which generally incorporates milled wood particles (Wu et al., 2005). Recent research efforts aimed at reinforcing fiber-cement boards with agricultural residues have been focused on preventing the adverse effects of the water soluble constituents of such residues on the hydration and the strength development of cement (Soroushian et al., 2004).

*Zea mays L.*, commonly known as corn, maize and millet is an annual grass plant. Corn is the most produced cereal worldwide (FAOSTAT, 2012), surpassing wheat and rice (Fig. 1). Furthermore, the production of this cereal increases almost every year. The large amounts of wastes generated in the production of this crop, justify the study of this material in different applications.

Corn stalks consist of a pithy core with an outer layer of long fibers. Currently, corn stalks are chopped and used for forage, left on the field, or baled for animal bedding (Youngquist et al., 1993). Research shows that corn stalks can be used in many applications including human consumption and as a source of industrial raw material for the production of oil, alcohol and starch (Muoneke et al., 2007; Yang et al., 2001). It can also be used to make reasonably good particleboard and fiberboard (Chow, 1974; Wu et al., 2005).

There is, however, a remarkable lack of knowledge on the use of wastes from corn stalk in the reinforced fiber-cement. With the purpose of contributing to building up this knowledge, the work described in this paper was aimed to study the effect of the use of the corn stalk as reinforcement fiber in the manufacture of fiber-cement for roofing and on the product properties taking into account the morphology of the fibers and their interactions with the cement suspensions.

## 2. Materials and methods

### 2.1. Materials

The corn stalk used for this study was coming from a culture of *Zea Mays L.* grown in Spain and supplied by the LEPAMAP group. The corn stalk was cooked to obtain corn pulp through two different methods, a semi-chemical process with NaOH and anthraquinone, and a chemical one (organosolv), employing ethanolamine as solvent. The cooking conditions are summarized in Table 1. The conditions applied are the ones resulting from a previous optimization study carry out by LEPAMAP group from University of Gerona.

Refined unbleached pine Kraft pulps (35 ºSR) (PR) were used as reference since these pulps are commonly used to provide cellulose fibers in the manufacture of fiber-cement by the Hatschek process.

The flocculant used to study the behavior of fiber-cement suspensions and to prepare the fiber-cement probes was an anionic polyacrylamide (APAM) with a molecular weight of $7.4 \cdot 10^6$ g/mol and a charge density of 13.4 %, commonly used in the industrial Hatschek process (Negro et al., 2006).

Flocculant was dissolved in distilled water to prepare solutions of APAM with a concentration of 1.5 g/L.

A Portland cement (type II / AV 42.5) containing 12% fly ash was used for the probes. It is a fine powder with a wide distribution of particle sizes, being the 80% of the particles in the interval from 2 µm to 50 µm.

Microsilica was also used to manufacture of the test probes. The type of microsilica employed was composed of ultra-thin amorphous spheres of $SiO_2$ with a particle size around 0.5 µm containing small amounts of crystalline quartz (less than 0.5%) as impurities.

The compositions of the fiber-cement slurries prepared in this study are summarized in Table 2.

Although the air curing process was used to prepare the probes, no synthetic fibers (PVA) were used in order to enhance the effect of the cellulose fibers in the properties of fiber-cement.

## 2.2. Methods

### *2.2.1. Canadian Standard Freeness (CSF)*

The degree of corn stalks pulps refining was measured using a Canadian Standard Freeness (CSF), according to ISO 5267/2.

### *2.2.2. Characterization by a scanning electron microscopy*

The morphological characterization of the fibers was carried out by a scanning electron microscope (SEM), JEOL, mod. JM-6400. Each sample was placed on a cylindrical slide and placed in a vacuum oven for 24 h to be dried. After drying the sample was coated with gold. Then, it was introduced in the SEM and was visualized with a magnification 500.

### 2.2.3. *Morphological characterization of fibers*

The fiber and pulp morphology analyzer, Morfi, V7.9.13.E (Techpap, France) was used for the morphological characterization of the different pulps considered in this research according to Jarabo et al., 2012a. The images are analyzed using a specific program to determine different parameters of the fibers and pulps: length weighted in length, average width, coarseness, microfibrills, fines number, etc (Jarabo et al., 2012b; Moral et al., 2010).

The samples for morphological characterization were prepared by adding 1 g of dry fibers to 600 mL of water and homogenizing the suspension in a lab disintegrator ENJO- 692. The characterization was done in duplicates. The variability of the morphological parameters (RSD) was determined by Equation 1.

$$RSD\ (\%) = [(X_i - X_{average}) / X_{average}] \cdot 100 \qquad [1]$$

Where, RSD is the variability of the parameter (%); $X_i$ represents the measured value; and $X_{average}$ represents the mean value of the two measurements.

### 2.2.4. *Flocculation of fiber-cement suspension*

A focused beam reflectance measurement (FBRM) M500L probe supplied by Mettler Toledo, USA, was used to monitor the flocculation process and to determine the floc properties.

The FBRM monitors the chord length distribution of the particles in suspensions in situ and on real time. The principle of the measurement and the details of the applied methodology have been described by the authors in previous references (Blanco et al., 2002; Hubbe, 2007; Jarabo et al., 2012a; Kerekes et al., 1992; Negro et al., 2006; 2007).

In a typical trial, the probe was immersed in to a 400 mL of fiber–cement suspension, prepared with water saturated in $Ca(OH)_2$, stirred at 800 rpm. After 10 min, stirring intensity was reduced to 400 rpm. 100 ppm of APAM was added 5 min later, to induce flocculation and the evolution of the flocs was studied at 400 rpm during 4 min. Then, the stirring intensity was increased to 800 rpm to break down the formed flocs (deflocculation) for 2 min, after which it was reduced again to 400 rpm to induce the reflocculation of the system (Jarabo et al., 2010).

#### 2.2.5. *Retention and drainage of fiber-cement suspension*

A vacuum drainage tester (VDT) was used to perform the retention and drainage tests. This equipment has two jars separated by a barrier: the upper jar keeps the fiber–cement suspensions stirred up to the addition of the flocculant dosage. The second jar contains a mesh at the bottom to carry out the dewatering of the suspension and it is connected to a vacuum pump and to a probe where filtrate is stored and weighted on real time and the final volume of filtrate is measured (Negro et al., 2005; 2006). In a typical trial, 400 mL of fiber–cement suspension, prepared with water saturated in $Ca(OH)_2$, were stirred at 600 rpm during 6 min in the upper jar. Then, stirring intensity was decreased to 300 rpm and after 5 minutes 100 ppm of APAM was added. After 15 s contact time between flocculant and mixture, the stirring was stopped, the barrier was removed and the suspension was drained to the second jar in which an 18 mesh wire was placed. The suspension was drained under vacuum (0.2 atm) through the filter and a computerized balance recorded the mass of drained water over time (drainage curve). Solids retention and cake humidity were determined by means of the gravimetric analysis of the formed cake (Fuente et al., 2010; Jarabo et al., 2012a).

### 2.2.6. *Preparation of fiber-cement probes*

Fiber reinforced cement probes were prepared in the laboratory through a slurry vacuum dewatering technique followed by the pressing technique described in details by Savastano Jr. et al., 2000. The cement based composites were molded in plates measuring 200 mm×200 mm and around 6 mm thick.  The matrix materials were added and dispersed in $Ca(OH)_2$ saturated water with a solids concentration of 20%.

Three pads were prepared for each formulation. After two days the pads were removed from the bags and placed in water. Twenty-six days later, the pads were removed from the water and four 200 x 50 $mm^2$ flexural test specimens were wet diamond sawn from each pad. Eight pads were prepared to provide sufficient specimens for the determination of mechanical properties and four pads were prepared for the determination of physicals properties (Jarabo et al., 2012a).

### 2.2.7. *Mechanical properties of fiber-cement probes*

The mechanical tests were performed in the universal testing machine Emic DL-30,000 equipped with 1 kN load cell. A four point bending configuration was employed in the determination of modulus of rupture (MOR), limit of proportionality (LOP), modulus of elasticity (MOE) and specific energy (SE) of the specimens which were obtained by following the calculations specified in Equations 2-5.

$$MOR\ (MPa) = (L_{max} / (b \cdot h^2)) \cdot (S_{down} - S_{up}) \qquad [2]$$

$$LOP\ (MPa) = (L_{LOP} / (b \cdot h^2)) \cdot (S_{down} - S_{up}) \qquad [3]$$

$$MOE\ (MPa) = tg\ \alpha \cdot (S_{down} - S_{up})^3 / (b \cdot h^3) \quad [4]$$

$$SE\ (\mathrm{kJ/m^2}) = Absorbed\ energy / (b \cdot h) \quad [5]$$

Where $L_{max}$ is the yield strength, $L_{LOP}$ is the stress at the upper point of the linear portion of the stress-strain curve, $(S_{down} – S_{up})$ is the support major span, $b$ and $h$ are the specimen width and thickness respectively measured at the nearest undisturbed location to the region of failure, $tg\alpha$ is the initial slope of the stress-strain curve corresponding to $L_{max}$.

A span of 100 mm and a deflection rate of 0.5 mm/min were used in the bending test (Savastano et al., 2000). Test data were digitally recorded and reduced using automatic data collection and processing facilities. Eight flexural specimens were tested for each composite formulation.

The absorbed energy is the area under the stress-strain curve to the point corresponding to a reduction in carrying capacity to the maximum stress (Tonoli et al., 2010). The mechanical properties of the probes were measured 28 days after the construction of the sheet (Jarabo et al., 2012a).

#### 2.2.8. *Physical properties of fiber-cement suspension*

Water absorption, bulk density and porosity values at 28 days were obtained from the tested flexural specimens following the procedures specified in ASTM C 948-81. Four specimens were used to determine these properties.

## 3. Results and Discussion

### 3.1. Effect of cooking condition on morphological characteristic of pulps

The results of the morphological characterization and the refining degree of corn stalk and pine pulps are shown in Table 3.

The fibers obtained by means of the semi-chemical process were longer than those obtained by means of chemical process compared with the same cooking conditions. In both process, a slight decrease in the value of length, width and coarseness was observed when cooking conditions were harsher (PA, PC).

The average width of the fiber in PB, PC and PD was higher than those in PA, and even higher than those in pine pulp. The low width of fibers in PA could indicate a chemical degradation of cellulose at harsher cooking conditions. This could also explain the value for PR. This chemical degradation seemed to be less significant when organosolv cooking process is used.

The use of organosolv process resulted in a higher percentage of microfibrills and fines number higher compared with the semi-chemical process. The percentages of microfibrills in the organosolv pulps (PC, PD) were similar to those in the pine pulps. The presence of microfibrills is a key for the interaction between fibers and matrix, while the high percentage of fines and the low length of fibers can result in a more homogeneous dispersion of the cellulose in the matrix.

A higher number of fines improves the retention of solids in the formation of fiber-cement but reduces the strength of the product (Fuente et al., 2010). The increase in the fines number and in the percentage of microfibrills may be due to the attrition experienced by fibers during the chemical process, and consequently, after the pulping a higher percentage of broken ends were measured and a higher refining degree volume CSF (less refined pulp).

Pulp refining produce an external fibrillation of the cells, what increases the flexibility and allows the formation of bridges with other fibers. In the case of PC and PD the refining stage could not be necessary, because the organosolv cooking combined with the defibrillation in the hydrapulper produced the same percentage of microfibrills than that in the pine fibers. This high percentage of microfibrills and broken ends very probably enhanced the cross linking of fibers, forming a more stable network for the formation of fiber-cement.

Fig. 2 shows photographs of corn stalk fibers obtained by image SEM with an increase of 500.

### 3.2. Flocculation of fiber-cement mixtures

Fig. 3 shows the evolution of the mean chord size of particles and flocs in cement suspensions.

After 600 s of stirring at 800 rpm, the value of the mean chord size was constant and the stirring was reduced at 400rpm. 900 s after starting the trial, the addition of 100 ppm of flocculant to the suspension caused a fast increase in the mean chord size due to the aggregation of particles to form larger flocs. A maximum value of this statistics was reached between ten and fifteen seconds after the addition of APAM. Then, the value of the mean chord size started to decrease due to the erosion and breakage of the flocs under the hydrodynamic conditions. The evolution of flocs during this stage depends on their stability and strength.

When the stirring increased to 800 rpm, part of the remaining flocs were broken decreasing the mean chord size due to the deflocculation process induced by the hydrodynamic forces. The reflocculation ability of the system is shown by the increase in the mean chord size when the stirring decreased to 400 rpm again.

The addition of APAM to cellulose fibers did not induce their flocculation; this is owing to the fact that fibers also present anionic character, thus indicating that APAM did not interact with fibers, or that its interaction did not induce flocculation (Jarabo et al., 2010). In this paper, however, it was possible to observe how the flocculation of the fiber-cement mixtures with different corn stalk fibers was affected by the morphology of the latter.

The largest maximum mean chord size was reached in the MR suspension, although the flocs formed in the suspensions containing corn stalk fibers were more stable than those formed from MR (the decrease in mean chord size during the evolution of fibers and during defloculation stage was lower). Large flocs are more sensitive to hydrodynamic forces and, thus, they broke easily. Moreover, after the deflocculation and reflocculation stages, the mean chord size in MA, MB and MC remained larger than in MR.

The results indicate that the flocculation process and floc properties are affected by the morphology of the fibers and by the cooking process. The low maximum mean chord size in corn based pulps can be due to the shorter length of the fibers from corn stalk compared to those from pine pulps. The pulps cooked with ethanolamine presented a relatively low maximum size of the flocs formed when APAM was added to the fiber-cement pulp, but had an increased stability compared with the rest of suspensions. This is related to the higher percentage of microfibrills and fines which increase the area surface favoring the interaction of pulp with the cement particles to form more stable flocs.

### 3.3. Retention and drainage of fiber-cement suspensions

Fig. 4 shows the drainage curves of the fiber-cement suspensions considered in this research. Drainage took place in two steps: first, the suspension was filtrated and a cake was formed with a fast water removal, which corresponds to the first part of the drainage curves (linear part with a high slope); secondly, the cake was compressed and thickened and water removal rate decreases towards zero. During the first stage, only water among flocs was removed, while part of the water inside the flocs was removed during the compression stage. The loss of solids with the filtrate takes place mainly during the first stage, while the second stage determined the final humidity and the properties of the cake. Drainage time can be obtained as the time required to reduce the slope of the drainage curve to zero.

There are notable differences among the drainage curves of the fiber-cement suspensions containing corn stalk fibers and those of MR. During the first stage, all drainages curves have similar slopes. There is not an appreciable compression stage in the drainage curve of MC. The final weight of the recovered filtrate was higher in the case of MA, MB and MD. This weight was due to the mineral solids that were washed down and the drained water, not being therefore directly related with the humidity of the cake.

The deviation of the MC drainage curve in the compression stage with respect to the curves of the rest of mixtures can be owed to the morphology of the corn stalk PC. PC has the highest percentage of microfibrills, broken end and the lowest coarseness; these factors make the fiber interlock better than in the others cases, making the compression stage more efficient.

Table 4 shows that solids retention is very low in all suspensions containing corn stalk fibers in comparison to the pine suspension (MR). The lowest value observed when the cake was formed from MD, being appreciable the difference with respect to the other cakes. The addition of APAM to this fiber-cement suspension induced the formation of the smallest flocs (Fig. 3), with a poor interaction between them and with the fibers. Therefore, these flocs passed through the wire, as shown by the low retention of solids (Table 4). This is in accordance with the relationship between the solid retention and the maximum mean chord size reached in presence of APAM: Larger values of maximum mean chord size are related to higher solid retentions, because of the lower probability of large flocs to pass through the wire. This is the case in the flocculation of MA and MB, both mixtures reaching very similar maximum mean chord size and solid retention. The highest mean chord size and solid retention was reached with MR and the lowest values of mean chord size and solid retention were reached with MD.

The humidity of the cakes from MA and MB was higher than that of MR due to the higher cellulose content of these cakes and the high higroscopicity of this species.

Due to the high percentage of fines and microfibrills in PD pulp, the solid retention should be higher, consequently should have higher interaction between fibers and minerals in the case of MD. But the humidity of the MD cake was the lowest although most of mineral particles of the suspension were not retained. This is probably due to the high contents in lignin of PD, which is covering the cellulose surface and it affects its interaction with the APAM and minerals. Values of kappa number in PA, PB and PC were very similar and between 4 and 6 mL/g; the value for PD was 17 mL/g, three times higher (Table 2).

Fibers must interact with the mineral particles in the fiber-cement suspension to make possible the manufacture of a composite sheet with the required properties.

### 3.4. Mechanical and physical properties of the probes

Fig. 5 shows the stress-strain curves of the specimens after 28 days. All the curves have similar tendency to that for MR, except the curve MC. The probes obtained from MR presented highest values of yield strength and ultimate strength. This mechanical behavior, high strain and stress reached, and the large area under the curves can be associated with a good array of fibers and solid particles inside the composite (Roma et al., 2008). Among the probes prepared from the corn stalk pulps, MB presented the highest ultimate strength, but all of them, except probes prepared from MA presented similar yield strengths. The probes MC were the most rigid, as their short strain hardening regions indicate. The area under the curve for MB was higher than that for MA, MC and MD. The probes prepared from MB can therefore be the considered the ones with the best mechanical properties among the fiber-cement probes prepared with corn stalk fibers.

Fig. 6 shows the results of the following mechanical properties: modulus of rupture, limit of proportionality, elastic modulus and specific energy of the probes of fiber-cement made of corn stalk pulps with the two applied processes.

These figures show that, among the mixtures prepared with corn stalk fibers, MB yielded the probes with the highest modulus of rupture and specific energy, although these values were lower than those obtained with MR. It is worth noticing that the fibers used in MR are refined fibers. Refining increases the presence of microfibrills and degrade fiber surface, which enhances the interaction among fibers and matrix. Furthermore, pine fibers are notably longer than the fibers obtained from corn stalk and this also affects to the mechanical properties of the probes.

MA and MC were the probes with the lowest MOR. PA and PC were obtained applying the harshest cooking conditions (Table 1) and these have the lowest values of microfibrills and coarseness.

Although the pulps PA and PB were cooked by using the semi-chemical process, MOR of MB was better than those for MA. Therefore, the low values of MOR for MA and MC could be related to the strenght of the cooking conditions which damaged the cellulose, decreasing the reinforcing ability of fibers.

Fig. 6 shows that the elastic modulus of the probes prepared with corn stalk fibers had similar values to those obtained for the reference probes (MR); the figure also shows that the values of LOP of the probes containing corn stalks fibers were similar too, but lower than the value of this parameter in MR probes.

Fibers are keys for an adequate ductile performance of fiber-cement. In this case, the larger length and high percentage of microfibrills of the pine fibers increased their effect on the ductility as shown by the larger values of the specific energy and the larger value of the strain at the ultimate strength. Therefore, the use of corn stalks as a source of cellulose did not have a significant effect on the elasticity of the material, but it reduced the stress required to cause its permanent deformation. This is related to the effect on the yield strength.

Fig. 7 shows physical properties of the probes, namely water absorption, bulk density and porosity. The bulk densities measured in corn fibers prepared through the semi-chemical process presented the same values as those measured in MR probes.

The probes made of MA presented the lowest water absorption, what can be related to the lowest value of permeable void volume of the probes. These effects are related to the low value of the average width of the fibers in PA (Table 3). This value is notably lower than that for the other corn stalk fibers, which indicates that the lumen could collapse during the pulping and defibrillation processes. This affected the absorption of water.

One of the drawbacks of using cellulose in fiber-cement is the ability of this polysaccharide to absorb moisture from the environment through hydrogen bonding. This causes a dimensional change of the fibers through swelling that has a negative effect on the composite durability. From this point of view the reduction of water absorption by cellulosic from corn stalks fibers would be an advantage.

## 4. Conclusions

The effect of using corn stalk pulps in fiber-cement manufacture and properties is directly related to the fibers morphology and chemical composition which depends on the cooking conditions.

Mechanical and physical tests confirmed the feasibility of the use of corn stalk as a source fibers as reinforcement fibers for fiber-cement production to obtain a product capable of meeting stringent requirements in demanding applications. However, in order to reach the same mechanicals properties as those achieved when the product is manufactured with pine pulps, the combination of corn stalk fibers and with pine or synthetic fibers would be required.

Although it seems that the best results were obtained using the semi-chemical process, specifically the MB mixture, cooking the corn stalk in NaOH at 10% at 140ºC during 30 minutes was the optimal pulping process among the studied options for corn stalk pulping.

Mild cooking conditions in the semi-chemical process favor the obtaining of longer fibers, which result in a final product with better mechanical, physical and solid retention properties.

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**Table 1**

**Table 1. Cooking conditions of corn stalks using semi-chemical and chemical processes.**

| Semi-Chemical Process | | | |
|---|---|---|---|
| **Pulps** | **T (ºC)** | **Time (min.)** | **NaOH (%)** |
| PA | 180 | 90 | 20 |
| PB | 140 | 30 | 10 |
| **Chemical Process (Organosolv)** | | | |
| **Pulps** | **T (ºC)** | **Time (min.)** | **Ethanolamine (%)** |
| PC | 185 | 90 | 60 |
| PD | 155 | 30 | 40 |

**Table 2**

Table 2. Composition of fiber-cement slurries, yield and kappa number.

| Slurries | MA | MB | MC | MD | MR |
|---|---|---|---|---|---|
| Source of fibers | PA | PB | PC | PD | PR |
| Cellulose (%) | 5 | 5 | 5 | 5 | 5 |
| ASTM II cement (%) | 91 | 91 | 91 | 91 | 91 |
| Microsilica (%) | 4 | 4 | 4 | 4 | 4 |
| Yield (%) | 43 | 69 | 54 | 75 | -- |
| Kappa (mL/g) | 5.2 | 4.4 | 4.4 | 16.8 | 25.4 |

**Table 3**

Table 3. Morphological characterization and CSF of corn stalks and pine pulps.

| **PROCESS** | **NaOH** | | **Ethanolamine** | | **Kraft** |
|---|---|---|---|---|---|
| **PULPS** | **PA** | **PB** | **PC** | **PD** | **PR** |
| Canadian standard freeness (CSF) (mL) | 456±2 | 476±4 | 687±8 | 696±10 | 192±1 |
| **FIBERS** | | | | | |
| Length weighted in length (µm) | 677±3 | 777±8 | 650±4 | 705±5 | 1130±7 |
| Average width (µm) | 22.8±0.1 | 29.1±0.3 | 29.4±0.2 | 30.8±0.5 | 25.5±0.02 |
| Coarseness (mg/m) | 0.17±0.01 | 0.19±0.02 | 0.14±0.01 | 0.18±0.03 | 0.19±0.02 |
| Microfibrills (%) | 1.04±0.03 | 1.18±0.05 | 1.66±0.02 | 1.64±0.6 | 1.63±0.09 |
| Break end (%) | 37.9±0.5 | 44.5±0.8 | 47.2±0.9 | 46.3±0.7 | 39.3±0.6 |
| **FINES** | | | | | |
| Fines number | 17903±895 | 28278±1414 | 30081±1504 | 30574±1529 | 49192±2460 |

**Table 4**

Table 4. Solid retention and humidity of cake.

| Fiber-cement suspension | Source of fibers | Retention (%) | Humidity (%) |
|---|---|---|---|
| **MA** | PA | 38.4 ± 3.6 | 65.2 ±0.6 |
| **MB** | PB | 40.1 ± 2.5 | 60.1 ± 1.3 |
| **MC** | PC | 34.9 ± 1.7 | 57.8 ± 3.0 |
| **MD** | PD | 16.6 ± 1.5 | 54.4 ±1.3 |
| **MR** | PR | 57.3 ± 2.3 | 57.9 ± 1.2 |

# FIGURE CAPTIONS

Fig. 1. Mundial production of main cereals.

Fig. 2. Corn stalk image by SEM with magnification 500. Fibers from: (a) pulp A, (b) pulp B, (c) pulp C, and (d) pulp D.

Fig. 3. Evolution of the mean chord size during the flocculation, deflocculation and reflocculation of the fiber-cement suspensions.

Fig. 4. Drainage curves of the fiber-cement suspensions.

Fig. 5. Stress-Strain curves of the composite reinforced with corn stalk.

Fig. 6. Effect of the corn stalk on: a) modulus of rupture, b) limit of proportionality, c) modulus of elasticity and d) specific energy.

Fig. 7. Effect of the corn stalk on: a) water absorption, b) bulk density and c) permeable void volume.

**Figure 1**

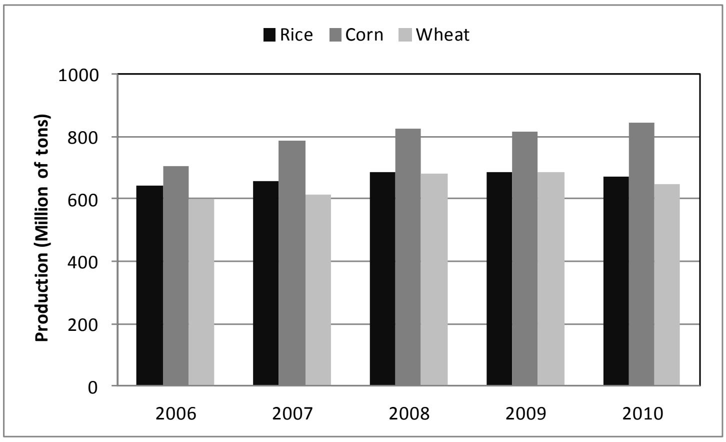
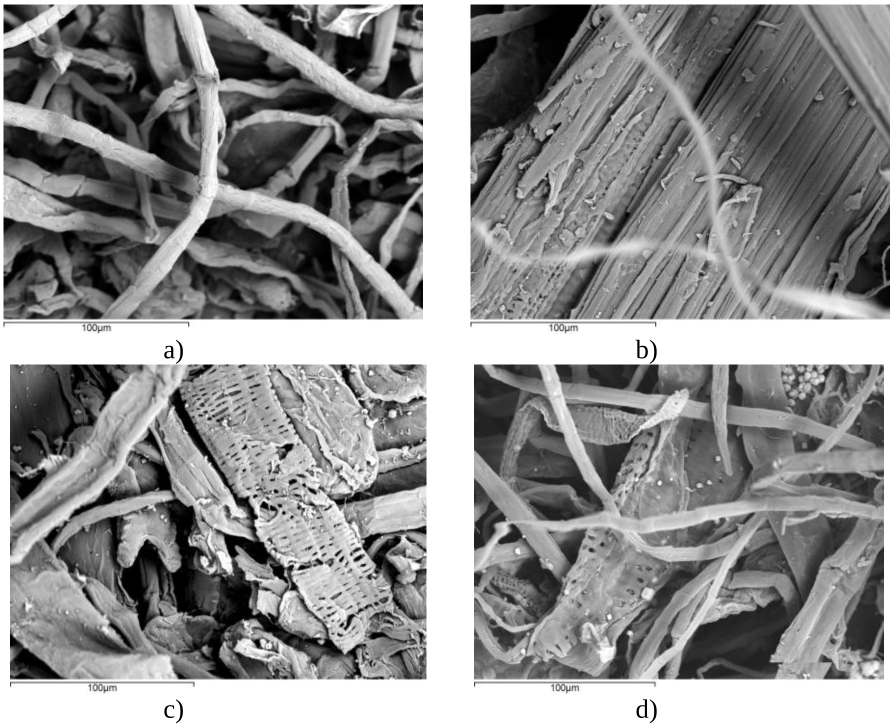


**Fig.1. Mundial production of main cereals.**

**Figure 2**



a) b) c) d)

**Fig. 2. Corn stalk image by SEM with magnification 500. Fibers from: (a) pulp A, (b) pulp B, (c) pulp C, and (d) pulp D.**

**Figure 3**

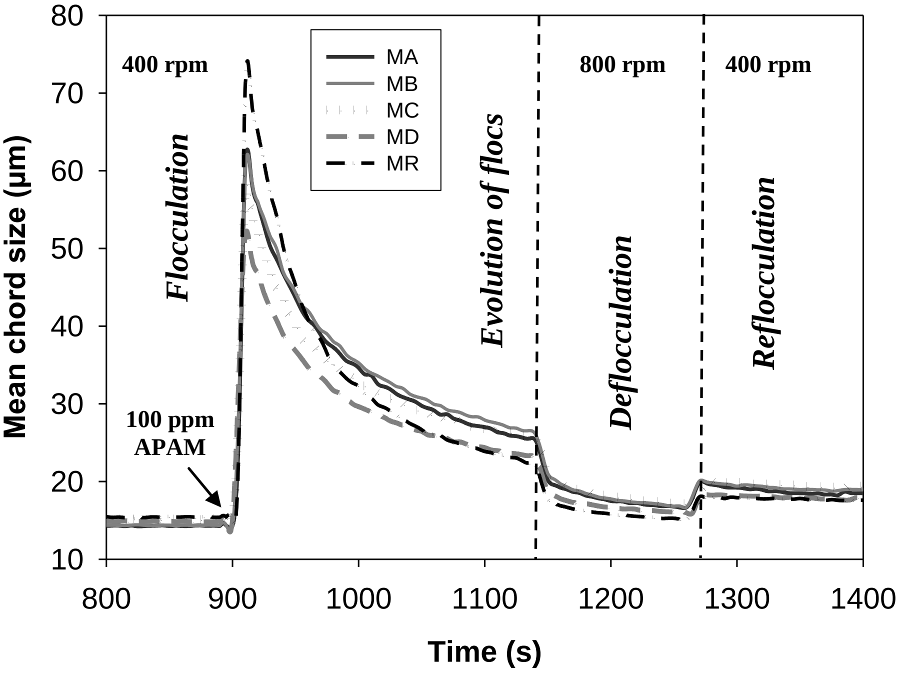


**Fig.3. Evolution of the mean chord size during the flocculation, deflocculation and reflocculation of the fiber-cement suspensions.**

**Figure 4**

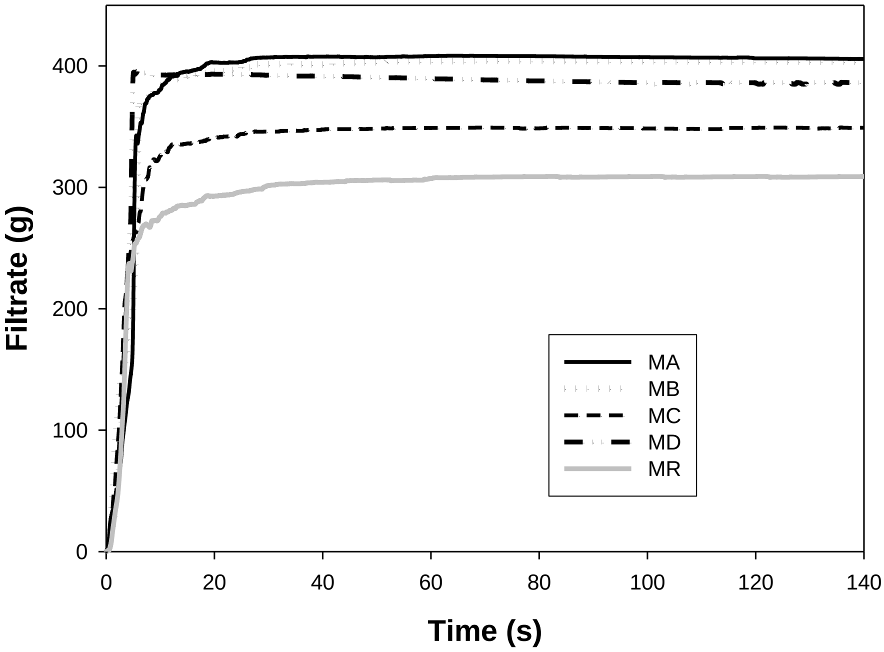


**Fig.4. Drainage curves of the fiber-cement suspensions.**

**Figure 5**

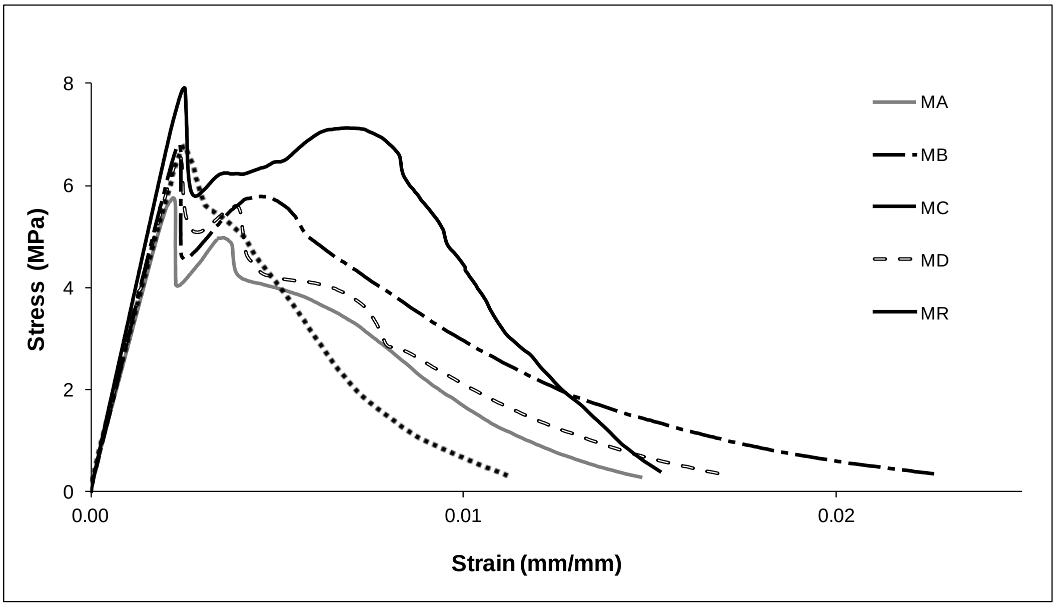
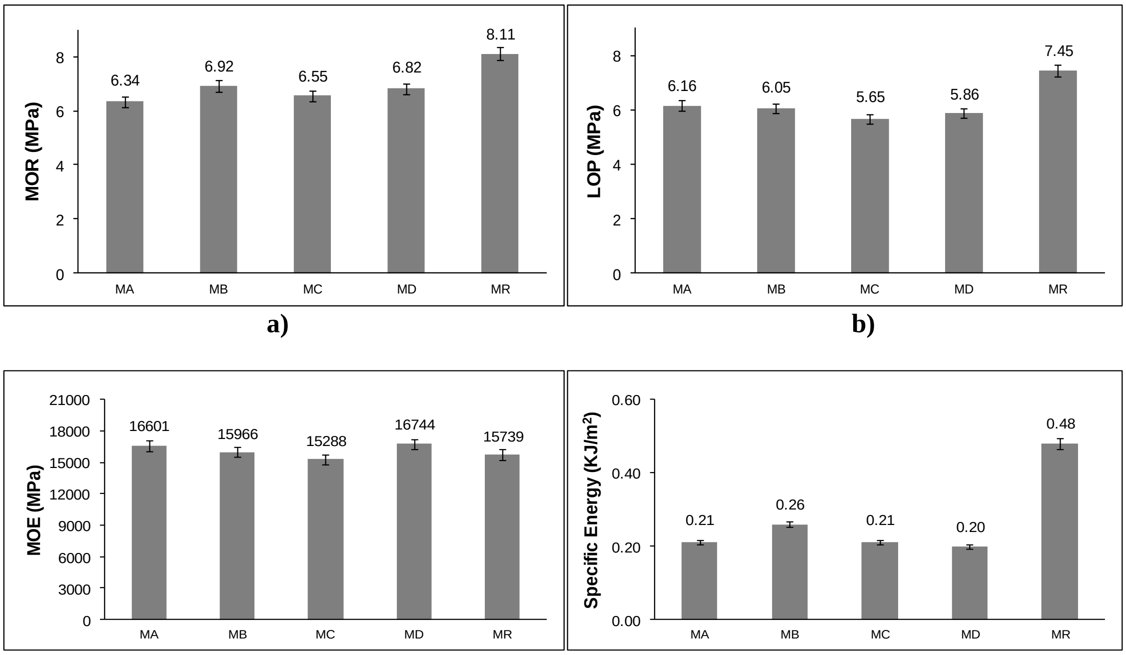


**Fig.5. Stress-Strain curves of the composite reinforced with corn stalk.**

**Figure 6**



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

**c)** **d)**

**Fig.6. Effect of the corn stalk on: a) modulus of rupture, b) limit of proportionality, c) modulus of elasticity and d) specific energy.**

**Figure 7**

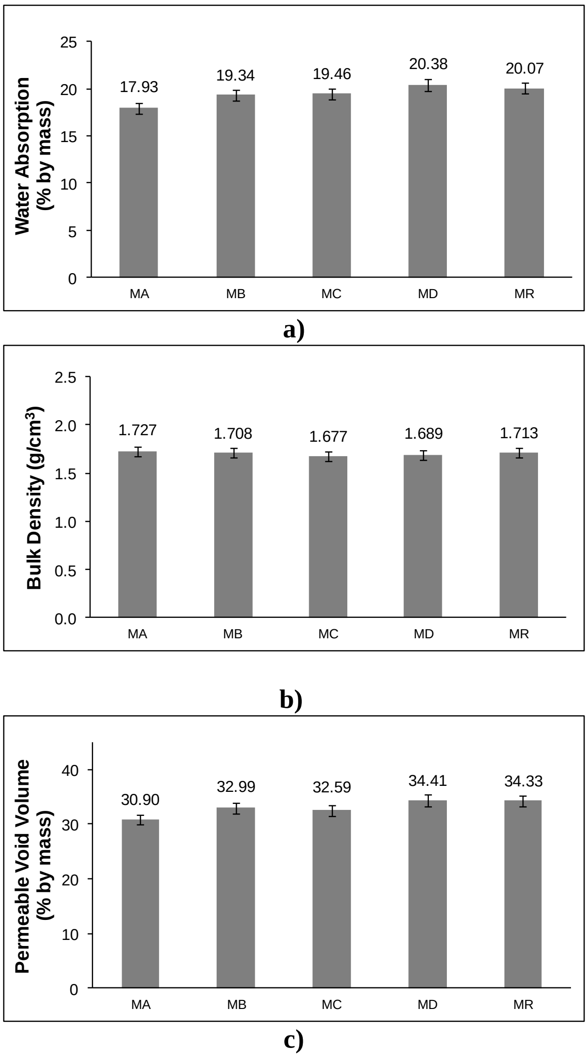


**Fig.7. Effect of the corn stalk on: a) water absorption, b) bulk density and c) permeable void volume.**