REPORT ABOUT EXPERIENCES WITH CEMENT BASED CORRUGATED SHEETS VACUUM PROCESSING

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ABSTRACT

Combinations of components are currently undergoing research in order to get properties of the cement based tiles for roofing closely matching those of asbestos cement. Although several companies are trying to manufacture products that replicate corrugated sheets using similar processing to that followed by the asbestos-cement industry, right now there is not a satisfactory solution in terms of stability of mechanical properties of the tiles. This paper reports the experiences of investigations into fiber reinforced composites focusing on the role played by components of the cementitious matrixes as Portland cement, hydrated lime, siliceous sand, combinations of different types of polymeric and mineral admixtures, and reinforcement of Fique fiber - a vegetal natural fiber – and in some mixtures with the Fique fiber and PVA fibers forming hybrid reinforcement. Problems surged during a vacuum process- similar to the Magnani process – determine the fulfillment of the final properties of the tiles. These problems are related to the behavior of the fresh matrixes with respect to the process variables as transport of the slurry, vacuum intensity, corrugation action, sheets supporting while curing and curing procedure. The experimental program included the flexural testing of corrugated tiles with dimensions of 1830 mm long, 920 mm wide, 6 mm thick, and 57 mm crest height. The load rupture best result reported 3313 N/m at 28 environment curing days, which is higher than the value established by the Colombian standard for the cement-asbestos-cellulose high crest corrugated sheets for roofing. Corrugated sheets produced with asbestos fibers using the same variables of processing reported 2050 N/m. Although at the delivering time the corrugated sheets fitted the requirements of the Colombian standards, the tiles consumers presented claims about defects of the tiles once they were put in service. The main recommendation of this report is a calling to the responsibility of the producers about the necessity of introduction of their products to the market only when the management and durability properties of them have been rigorously proved by experimentation.

KEYWORDS:

Corrugated sheets; asbestos cement; fiber reinforced composites; fiber cement manufacturing; fique fiber.

INTRODUCTION

Ludwig Hatschek, an Austrian engineer made possible the manufacture of pre-formed asbestos-cement products in 1907, when the Hatschek machine, a wet transfer roller, was used to produce the initial asbestos-cement sheets, later other two manufacturing processes were developed, the Mazza process for pipes, and the Magnani semi-dry process for corrugated sheets (St John, 1998). Asbestos-cement was the first fiber reinforced cement composite manufactured in modern times and, up to now, has been the material more consumed due to the excellent compatibility between the asbestos and the Portland cementitious matrix. The asbestos crystalline fibers, which present high elasticity modulus a high strength, distribute effectively within the cement matrix being possible to add more than 10 % of fibers with respect to the total volume (Bentur, 1990). Asbestos-cement building products have highly desirable material characteristics, such as being lightweight, impermeable to water, durable, tough; resistant to rot, termites, soiling, corrosion, warping, and fire, and easy to clean and maintain. Additionally Asbestos-cement possesses low thermal conductivity and is therefore a good electrical insulator. However, the demand of this ideal material has been reduced in all over the world after the Environmental Protection Agency (EPA) implemented the initial ban on asbestos in 1973 (National Trust for Historic Preservation, 1993). The main reason, according to Bentur and Mindess (Bentur, 1990), is that “Some asbestos fibers, when inhaled, constitute a health hazard leading to asbestosis, a form of lung cancer. Health risks were shown to be greatest during mining and production processes, but minimal during installation and use of asbestos-cement products.” (Bentur, 1990). Some fiber reinforced materials have been manufactured to substitute asbestos-cement elements. Fibers that have been investigated include: steel, glass, polypropylene, wood, acrylic, akwara, alumina, carbon, cellulose, coconut, kevlar, nylon, perlon, polyethylene, PVA, rock wool, sisal, and fique. Particularly, vegetable fiber reinforced cementitious materials for corrugate sheets has been an investigation line of Savastano Research Group in the University of Sao Paulo for the last 21 years (Agopyan, 2005).

Several companies manufacture products that replicate asbestos-cement roofing and siding shingles, flat sheets, and corrugated sheets. Some of these manufacturers include: Supradur Manufacturing Company, Cement Board Fabricators, U.S. Architectural Products, Inc., Re-Con Building Products, and GAF Materials Corp (Woods, 2000). However, so far, there is not a material that conclusively develops the performance of asbestos-cement. The research about fiber reinforced thin cementitious corrugate materials moves on the seeking of low cost available chemical stable environmental friendly reinforcing fibers. One of the alternatives is the use of natural fibers, but their shortcomings have to be remedied. The Research Group of Composite Materials of the Universidad del Valle has been researched the fique fiber in connection with cementitious matrixes since 20 years ago. Essentially, its investigations has been devoted to developing of technology for production of materials for housing at low scale level. In this paper are relate the results of a low scale production size experience of manufacturing undulated sheets for roofing using a Colombian native fiber named Fique fiber or cabuya.

PROPERTIES AND MICROSTRUCTURE OF THE FIQUE FIBER

The properties of the fique fibers are listed in Table 1. The Fique fiber or cabuya (*furcrae gender*) is a Colombian native natural fiber with similar characteristics to the sisal fibers.

It is clear that there is an important variation in fiber diameter among fique fibers of the same batch and along a fiber. The high standard deviation encountered indicates analogue lack of consistency in the geometry of natural fibers as found for sisal fibers by Torres et al (Torres, 2005) and Toledo et al (Toledo, 2003) also encountered similar variations in the coefficient of variation (CV) of the diameter for sisal and coconut fibers. The high variation in the fiber diameter and some variation in the mechanical properties along the length of a fiber due to the physical necessary response along the length of a leaf for supporting its weight determine the overall properties of the natural fiber.

A natural fiber changes its dimensions when its humidity varies. This is explained by the fact that the polymers that compose its walls contain hydroxyls and other chemical groups with Oxygen that attracts the water throughout the hydrogen bonds (Rowell, 1998). The hemicelluloses are responsible for the water absorption, although other components also play an important role. The process of water absorption is correlated with expansion and shrinkage of the fiber. Shrinkage happens when the humidity of the fiber falls below the water level of saturation. This reversible process is deleterious for a natural fiber reinforced based Portland cement composite because the fiber separates from the matrix, as it was observed in Figure 2.

Table 1 - Characteristics of the fique fibers

CHARACTERISTIC	FIQUE
Equivalent diameter, mm	0.16-0.42 0.236 (average) Coefficient of Variation: 27 %
Apparent density, kg/m^3	723
Specific gravity	1. 47
Water absorption, %	60.0
H_2O, %	12
Equilibrium relative humidity (Absorbency), %	8.12
Cellulose, %	70.0
Lignin, %	10.1
Tensile strength, MPa	43-571 132.4 (average) Coefficient of Variation: 40 %
Ultimate elongation, %	9.8
Elastic modulus, GPa	8.2 - 9.1

In the Figure 1 is presented a SEM micrograph done under cryogenic conditions. It is observed, the similarity between the microstructure of the fique fiber and those of the woods and the cellulose. The cells have hexagonal shape. It is visible the central channel or the lumen and the surface of the inner layer of the secondary wall of the fique fiber.

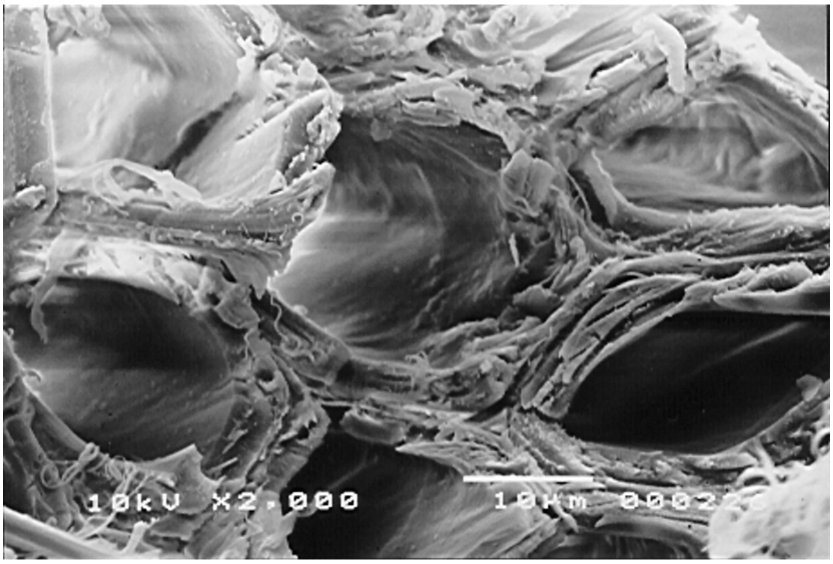

Figure 1 - Cross section of fique fiber filaments

FIQUE AS REINFORCING FIBER IN CEMENTITIOUS MATRIXES

The fique fiber has been disposed in matrixes of concrete, mortar and paste of Portland cement. In some cases, cement has been blended with pozzolanic additions. The observation of the interface, as presented in Figure 2, shows a fique fiber being separated from the matrix. (Delvasto, 1998a). The fiber had pulled out of the matrix. The white particles adhered to the fiber had a Calcium to Silicon ratio of 4 as determined by energy dispersive x-ray spectrometry techniques. The fiber structure of the natural fiber seems to be undamaged and there is not indication of fiber failure after six months of normal curing. Between the fiber and the cement matrix there is a separation of approximately seven micrometers. This separation is produced probably by a process of swelling and shrinkage of the natural fiber during the first stage of mix setting and indicated that bonding between fiber and matrix was mainly due to mechanical interlocking. This gap is responsible for the low shear strength at the interface during the friction stage after the adhesion resistance has been overcome, as was proved in a pull-out study (Delvasto, 2004).

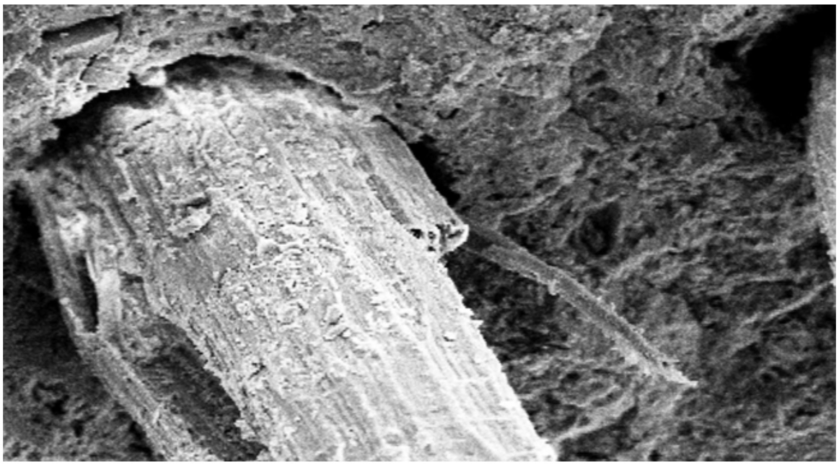

Figure 2 - Fique fiber pulling out from the cement Portland matrix (200 magnifications).

As it is seen in Figure 3, a groove of a fique reinforced cementitious composite presented at the interface a shape of smooth surface wrinkles following the outline of each fiber contour. It is seen the smooth surface of the surface matrix wrinkles, which indicates that the fiber was weakly attached to the matrix interface. Calcium hydroxide as portlandite is observed deposited on the face of the matrix in contact with the fique fiber. The process of petrification observed elsewhere (Bentur, 1989), seems to be arrested when the portlandite plates impede the progression of the tobermorite (hydrated calcium silicate) lying under the portlandite coating as is seen in the SEM micrograph (Figure 4). (Delvasto, 1998b).

Pull-out behavior of fique fibers

In a previous research [Delvasto, S. Gutiérrez, R. de., Váldez, Y., "Comparative study of the pull-out behavior of fique fibers in mortars of portland cement". Brazilian Conference on Non-Conventional Materials and Technologies: Affordable Housing and Infrastructure Brazil-NOCMAT 2004. Pirassununga, SP, Brazil, October 29th - November 03th 2004.], mixes with cement: sand ratio of 1:0.5 and water/cement ratio of 0.34 were prepared. A fiber embedded axially through the center of a specimen with the shape of a figure "eight" was used. This type of specimen has exactly the measurements of the mould utilized by ASTM C 190 to test hydraulic cement mortars for tensile strength. The top half of the mould was filled with matrix and compacted. The specimen was supported during handling with two aluminum plates connected by a steel bolt to press the specimens shortly after matrix compacting. The filled mould was stored under wet conditions at 24 ^{o}C for one day. It was then removed from the mould and kept under water with pH around 12 (to prevent steel fibers corrosion) at normal curing conditions (24 ^{o}C, 1 atm.) until testing. The mould was divided in two parts by a relatively stiff plasticine sheet, approximately 0.5 mm thick, taped to its middle section. The cementitious matrix was poured to fill more than half of the height of the mould, just deep enough to cover the embedded fiber and compacted before this fiber was inserted through a small hole in the center of the sheet of plastic. Fibers were embedded with lengths: 10, 15, and 20 mm. The fiber reinforced mortars were cast in and cured in water for 28 days following standardized procedures. The pull-out testing reported a maximum adhesional strength of 0.75 MPa as can be seen in Table 2. The highest frictional strength reported 0.50 MPa and the maximum value of the shear modulus at the interface (G_m) was 8.76. These values were obtained when the embedded length of the fiber was 10 mm. Longer values of the fiber reported smaller results in maximum adhesional shear bond stress, τs, and in frictional shear bond strength, τ_i. After the maximum adhesional shear bond stress, τs, is exceeded, debonding of the fiber initiates. In this point the fiber will stretch or the interface matrix crest will break catastrophically in small fragments. Here, the main energy dissipation will depend on the magnitude of the frictional shear bond strength, τ_i; afterwards, development of the fiber pull - out along the complete fiber length will continue. The probability of fiber failure is reduced as was observed.

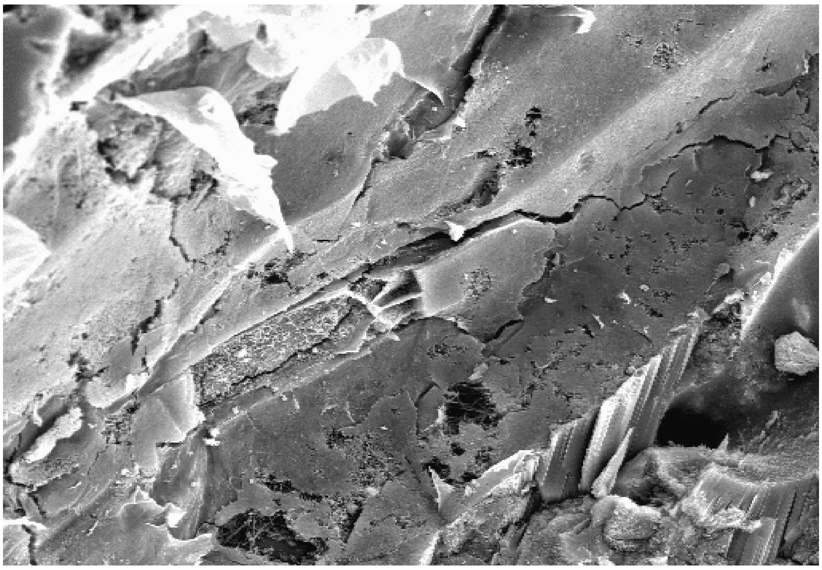

Figure 3 – Face of the cementitious matrix in contact with the Fique fiber (1000 magnifications).

Table 2 - pull-out results for specimens embedded with fique fiber

l_c mm	**τ_s (MPa)**	**τ_i (MPa)**	**G_m** MPa	$\frac{\tau_i}{\tau_s}$
10	0.75	0.50	8.76	0.66
15	0.37	0.20	4.80	0.55
20	0.42	0.18	5.34	0.43

Densification of a fique fiber cementitious interface

In order to improve the performance of the fiber reinforced material, silica fume (SF) could be used. In a research done by the Composites Group (Gutiérrez, 2000) an addition of 15% of silica fume generates 23 % higher compressive strength at 90 days than a reference mortar prepared to compare the effect of the pozzolan. Complementary absorption properties were determined (Gutiérrez, 2005) following the method proposed by Fagerlund (Fagerlund, 1982), that is called the capillary suction technique. The specimens tested, aged 45 days, were conditioned by drying them at 50°C prior to their testing. It was observed that the incorporation of a superplasticizer and 15% of silica fume do decrease the capacity of water absorption in the capillary pores of a mortar due to the densification of the matrix which reduces its permeability. The water absorption of specimens exposed to water for 24 hours, reported 9.2, 6.4, and 2.1 kg/m^2 for the plain mortar, mortar with superplasticizer, and mortar with the superplasticizer and silica fume respectively. The coefficient of capillary absorption was reduced and the resistance to water penetration was increased because of the silica fume addition to the mortars. Cylindrical specimens were specially made for the rapid chloride permeability test according to ASTM C1202. This test method provides a rapid indication of the resistance to the penetration of chloride ions. The relation between the total charge (coulombs) of the fiber reinforced mortar and the charge of the matrix without fiber was calculated. For the reinforced mortars with 15% SF the charge is reduced remarkably. This performance has been attributed to a reduction in the permeability resulting from a finer and discontinuous pore structure because the SF addition (Saricimen, 1999).

MANUFACTURE OF CORRUGATED SHEETS

Undulated tiles or corrugated sheets for roofing were being manufactured by a local plant. Sheets of standard Number six dimensions of 1830 mm long, 920 mm wide, 6 mm thick, and 57 mm crest height were obtained during 115 series of trials to adjust the variables of the process of production. Typically, 21.3 Kg of slurry was necessary to obtain 1 unit of corrugated sheet and 1 bag of Portland cement (50Kg) was necessary per batch to produce 6 corrugated sheets. The developed technology (Delvasto, 1998c) uses elements of the Magnani process. By this process a cementitious slurry is partially drained up by vacuum suction to the point when the material has a plastic consistency, similar to that of clay before the process of extrusion to produce green bricks. The capacity of production of this small plant is about 300 corrugated sheets. The technology works with different formulae of the material including asbestos (Chrysotile, 5R - 450, from Quebec, Canada).

The process comprehends the steps of proportioning a slurry, mixing in a vessel with agitation by means of a conical spindle working at 750 RPM, pouring the slurry to forming the plastic mass on a canvas lined hollow steel rotating cylinder with distributed perforations on its surface while vacuum is applied, throwing the cementitious plate on a belt conveyor, cutting to the desired sizing, corrugating, mounting the sheet on an undulated mold, and finally curing the tile. The first day after forming, the sheet rest on the undulated steel mold in a humid environment, then thermal curing is done and finally curing at room environmental conditions up to delivery the corrugated sheets to the market.

The experimented fibrecement undulated tiles basically were composed of a fiber cement product consisting essentially by weight of a Portland cement binder in the amount of between about 30% and 75%, a Silicious sand (maximum size = 0.6 mm) in an amount of between about 0% and 25%, limestone powder (> 97 % $CaCO_3$, D_{50} = 6 μm) in an amount of between about 0% and 30%, Tap water in an amount of between about 34% and 59%, Fique fiber in an amount of between about 0% and 4%, Asbestos fibers (Chrysotile, 5R – 450) in an amount of between about 0% and 10%, PVA (Kuralon RECS7 x 6mm) synthetic fibers in an amount of between about 0% and 4%, bentonite in an amount of between about 0% and 4%, kraft pulp in an amount of between 0% and 4%, Hydrated lime in an amount of between about 0% and 10%, and a high water reducer superplasticizer in an amount of between about 0.25% and 2%. The product may also contain Silica Fume in an amount of between about 0% and 5% by weight. Sand was added to reduce early shrinkage and also to achieve an economical material, as also has been tried by other researchers (Shao, 2001). The average Apparent density in Kg/l was 2.28. Limestone powder and bentonite were used as mineral viscosity enhancing admixtures.

The short discontinuous Fique fiber was treated by inmersion into a boiling lime solution for 5 minutes previously to be embedded into the matrix. The calculated critical volume of fiber was 0.5 % and the critical length of fiber was 1.5 mm. Its length varies between 3 and 10 mm with medium length of 6 mm.

The best result from the point of view of mechanical resistance was reported by a mix containing 3.3 % by volume of fique fibers. This best average result for flexural load to failure reported 2875 N/m at 14 curing days, including a three days thermal curing at 50 Celsius degrees. This is higher than the value established by the Colombian Standard for the cement-asbestos free-cellulose high crest corrugated sheets for roofing (2000 N/m). Corrugated sheets produced with asbestos fibers using the same variables of processing reported 2050 N/m while the specified flexural strength for a commercial asbestos-cement corrugated sheet is 425 daN/m. Greater than 4% of the natural fiber did diminish the flexural strengths because of balling observed during the mixing procedure. The flexural strength of three of the 18 series of mixes is presented in figure 4.

The forming process was satisfactory for 18 of the 115 in total series. It was observed that a reduction below 2% in the fique fiber content causes problems during forming. Indeed, the fique fibre behaves more as an aid molding than as reinforcing material. Without the incorporation of fiber and bentonite is not possible to get the undulated shape of the corrugated sheet. It should be noted that the permeability test for each of these 18 series of sheets was satisfactory.

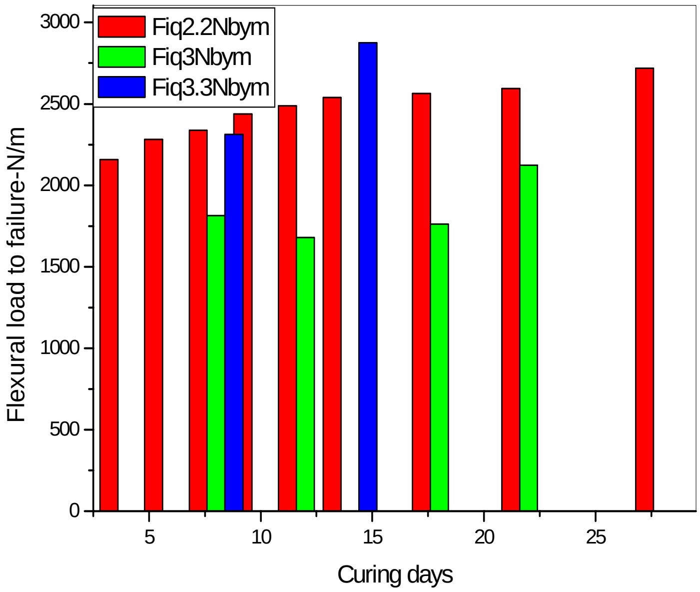

Figure 4 – Variation of the Flexural load to failure for mixes reinforced with different contents of Fique fiber.

There were prepared hybrid fiber reinforced mixes containing Fique and Asbestos fibers using the same parameters of process. The reference mix was one with 10% by weight of the cement. This mix, that reported 2400 N/m, was composed only of portland cement, water and asbestos. The results, presented in figure 5, show that the hybrid mixes (green colored mixes) did not behave as well as the only reinforced with fique fibers.

In the proccess of production of corrugated tiles, the slurry is prone to segregation, since low of viscosity accelerates the sedimentation of the particles (Kong, 2003). In this sense, bentonite was successfully employed and proved to be efficient in the production of an economical mix without the use of any viscosity enhancing chemical admixtures. Although a better rheological behavior of the mix is enhanced by the incorporation of the bentonite, however the bentonite reduces the mechanical strengths, as can be observed in figure 6. This fact should be considered when the mixes are tailored. A similar behavior was observed when kraft pulp was used. The sand and the ground limestone reduce the shrinkage tendency at early curing ages. The plasticity and the permeability are favored by an small amount of hydrated lime, although the incorporation of lime reduces the strengths at early ages. Replacement of 5% of the hydrated lime by 2.5% of silica fume did reduce the strength from 2875 N/m to 2750 N/m probably due to problems related to silica fume dispersement within the cementitious mix. However by using 0.75% of silica fume instead of the lime was generated the best result (2875 N/m). The use of a high range water reducer superplasticizer is important to obtain the slurry with low viscosity at very low water/binder ratio.

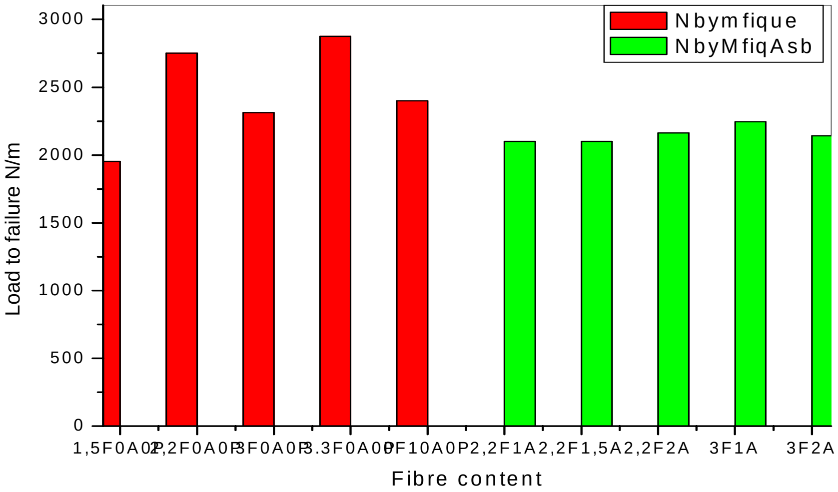

Figure 5 – Variation of the Flexural load to failure for hybrid mixes reinforced with Fique (red colored) and Asbestos fibers. A letter represents the type of fiber (F for Fique and A for asbestos) and the number after it the % of fiber by weight with respect to the portland cement content.

Because of claims of customers about cracking of the corrugated sheets at the time fixing the roofing, it was decided to incorporated PVA fibers. The results manufacturing the hybrid composite with PVA did not show relevant improvements as can be observed in figure 7.

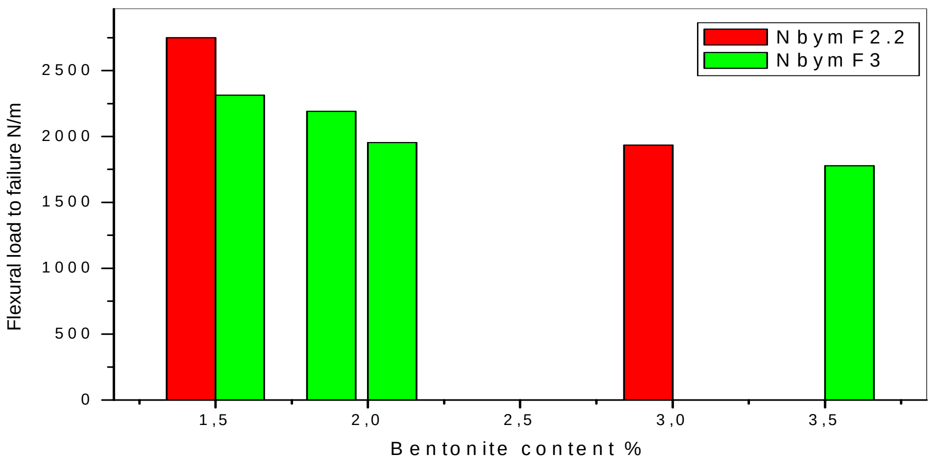

Figure 6 – Variation of the Flexural load to failure for mixes added with bentonite. Red colored columns represent the mixes reinforced with 2.2% of Fique fibers while the green columns represent the mixes with 3% of fiber.

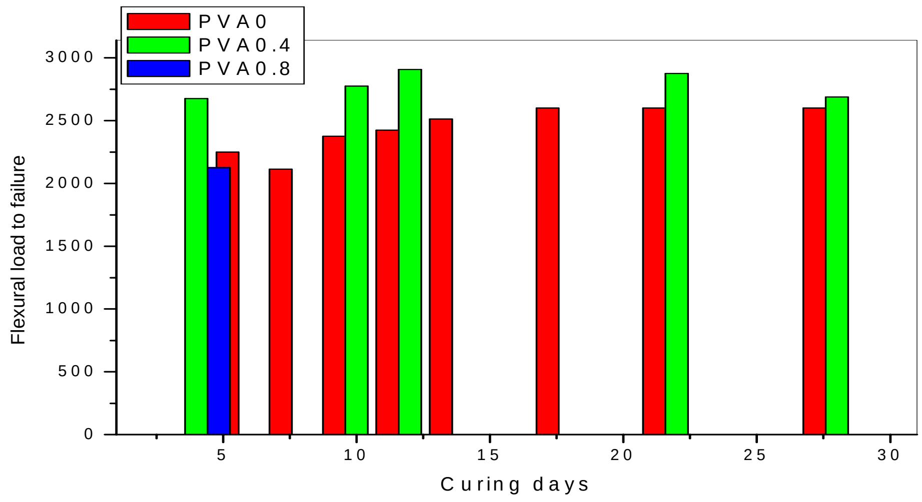

Figure 7 – Variation of the Flexural load to failure for hybrid mixes reinforced with PVA and fique fibers. Fique fibers amount was fixed at 2.2%.

Problems of encrypted fissures that reveals at the time of exerting stressing during the roofing lifting operation of the sheets could arise of management problems during the process of production. Some of the probable causes of failures that could explain the observed differences between the reinforced material plane sheets (boards) and the corrugated sheets are:

- The thickness of the slurry was not uniform when it was pouring on the surface of the cylinder. Also, the texture of the surface and distribution of the fibers were irregular.
- Fissures appeared when the vacuum exceeded a certain level. This level varied between one mixing batch and another. The fissures were related to the dryness of the material.
- Water accumulated in the reverse face of the material plate when the forming process of the sheet ended affected the throwing of the plate to the belt conveyor. This originated tears in the sheet.
- The process of cutting the plate laying on the conveyor by means of a disk was difficult by the opposition of the fiber to be cut. Also, the belt had to be replaced frequently.
- Tearing in the plate happened sometimes because of lack of synchronization between the velocity of plate falling and the velocity of the belt conveyor.
- The fiber oriented in the same direction of the forming cylinder rotation. The bridging of the fiber in the fresh state of the matrix is affected because there in not sufficient volume of fiber across the orthogonal direction to resist the stressing when the sheet is undulated.
- It was difficult to standardize the water content of the plate in its plastic consistency. The excess or lack of humidity caused problems of fissures during the management and the undulation of the sheet.
- Generally, there was not matching between the curvature of the fresh corrugated sheets and the steel mold to support them during the first day after mixing. This causes stressing in the weak material during the first hours of strengthening.
- The curing procedure was not consistent and not appropriate, especially during the first hours when shrinkage of the cementitious material is important.
- There were not used pallets to manage the endured sheets.

CONCLUSIONS

- There are several alternatives to obtain appropriate compositions of the cementitious mixes for corrugated sheets. However, the effect of each compound on the final properties should be accounted when the corrugated sheets are going to be tailored.
- It is necessary to strengthen the improvement of small scale friendly environmental low cost technologies that does not need skilled labour. The vacuum cylinder forming process for manufacture of corrugated sheets is promissory in this direction and also because the raw materials are available and comparatively cheap.
- The machinery used in the vacuum cylinder forming process is simple and could be built locally in developing countries.
- Corrugated sheet manufacture technologies as the vacuum cylinder forming process would be appropriated for small scales of production. However, the formulae, dimensions and morphology should be different to those of the Hatschek process.
- It is recommendable to increase the thick of the corrugated sheets produced by the vacuum cylinder forming process in order to impart a security factor that compensates their losing of strengths with the time.
- All the processing factors which could affect cracking have to be controlled in order that the products manufactured using the vacuum cylinder forming technology could have chance to compete properly in the market.
- Fique fiber is a fiber that behaves properly as an aid forming compound.
- The producers must be responsible for the introduction of their products to the market only when the management and durability properties of them have been rigorously proved by experimentation.

REFERENCES

Agopyan, V. Savastano Jr. H. John, V. Cincotto, M.A. 2005. “Developments on vegetable fibre–cement based materials in Sao Paulo, Brazil: an overview”. Cement & Concrete Composites 27 (527–536).

Bentur, A. and Akers, S. A. S. 1989. “The microstructure and ageing of cellulose fibre reinforced cement composites cured in a normal environment,” The Int. J. of cement composites and lightweight concrete, V. 11 (2). 99-109.

Bentur, A., and Mindess, S. 1990. “Fibre Reinforced Cementitious Composites”. Elsevier Science Publishers Ltd.

Delvasto *et al.* 1998a. “The Microstructure of the Interfacial Zone between a Portland Cement Matrix and Fique Fiber Reinforcement”. Sixth International Symposium on Ferrocement – Lambot Symposium Ferro 6. Ann Arbor, Michigan, USA.

Delvasto *et al.* 1998b. “Investigation of the Mechanisms of Toughness Generation in Natural Fiber Cementitious Composites”. Sixth International Symposium on Ferrocement-Lambot Symposium Ferro 6. Ann Arbor, Michigan, USA.

Delvasto, S., Mejia de Gutierrez, R., Rodriguez, C., Oliveros. 1998c. “Producción al Vacío de Tejas Fibrorreforzadas con una Fibra Natural”. Materiales Compuestos Aplicados en Arquitectura y Construcción, ARQUIMACOM 98. Burdeos, Francia, Octubre de 1998.

Delvasto, S. Gutiérrez, R. de., Váldez, Y., 2004. "Comparative study of the pull-out behavior of fique fibers in mortars of portland cement". Brazilian Conference on Non-Conventional Materials and Technologies: Affordable Housing and Infrastructure Brasil-NOCMAT 2004.

Fagerlund, G. 1982. "On the Capillarity of Concrete". Nordic Concrete Research No. 1, Oslo. (Paper No. 6) 1-20.

Gutiérrez, de R. Delvasto, S. Talero, R. 2000. "Degradation of Fiber Reinforced Mortar in a Marine Environment" *In* Marine Corrosion in Tropical Environments, ASTM STP 1399, A. B. Smith and C. D. Jones, Eds., American, 190-196.

Gutiérrez, de R. Diaz, L. N. Delvasto, S. 2005. "Effect of pozzolans in the performance of fiber-reinforced mortars". Cement and Concrete Composites. Amsterdan: (27) 593 – 598.

Kong, H., Bike, S., Li, V. 2003. "Constitutive rheological control to develop a self-consolidating engineered cementitious composite reinforced with hydrophilic poly(vinyl alcohol) fibers". Cement and Concrete Composites (25) 333-341.

National Trust for Historic Preservation. 1993. "Coping with Contamination: A Primer for Preservationists". Information Bulletin No. 70, 12.

Rowell, R.M. 1998. "Property enhanced natural fiber composite materials based on chemical modification, Science and Technology of Polymers and Advanced Materials", ed., P.N. Prasad *et al*., Plenum Press, New York, 717-732.

Saricimen, H. 1999. "Research to Improve Durability of Reinforced Concrete in Agressive Environments". Controlling Concrete Degradation. Dhir R. K. and Newlands M. D., Eds., UK.

Shao, Y., Qiu, J., Shah, S,. 2001. "Microstructure of extruded cement-bonded fiberboard". Cement and Concrete Research (31) 1153-1161.

St John D.A, Poole A.B, and Sims, I. 1998. "Concrete Petrography: A Handbook of Investigative Techniques". Arnold Publishers, London, 320-322.

Toledo, R. Filho, Ghavami, K. England, G. Scrivener, K. 2003. "Development of vegetable fibre–mortar composites of improved durability". Cement & Concrete Composites (25)185–196.

Torres, F.G. Cubillas, M.L. 2005. "Study of the interfacial properties of natural fiber reinforced polyethylene", Polymer Testing (24) 694–698.

Woods, A.L. 2000. "Keeping a Lid on It: Asbestos-Cement Building Materials" Preserving the Recent Past 2, National Park Service, Conference Proceedings, Philadelphia.