SOLUTION FOR FRP PIPES: TECHNICAL AND ECONOMIC ADVANTAGES OF NATURAL FIBERS AND OF RTM PROCESSING

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SUMMARY

It was investigated the potential use of vegetable fibers as alternative of glass fibers for chemical plants pipes. Hemp, kenaf and sisal were evaluated for the study. The novel pipe with hemp mats as internal layer allows for a cost reduction and a weight saving compared to the commercial solution without any drawback in terms of the final performances.

Keywords: *fiber reinforced composites, natural fibers, hand lay-up, light-RTM, piping.*

INTRODUCTION

Since several decades fibers reinforced polymers (FRP) based on glass fibers are widespread in many industry fields when low cost and good mechanical properties are needed. An interesting use is in piping systems for chemical plants. Lower weight, increased resistance to aggressive fluid, easiness to build complex shapes [1] are among the advantages shown by FRP pipes than metal ones. Currently only glass fibers are used as reinforcement for these applications in union with cheap and simple techniques such as hand lay-up. During the last years it has been shown interest to more modern and automated techniques, such as Resin Transfer Moulding (RTM).

The use of plant fibers as reinforcements for polymer is a topical issue and is attracting increasing interest of industry. Fibers properties are influenced by many factors, including plant type and variety, growth conditions, and the method used to extract the fiber bundles. Among natural fibers for composites the bast fibers, extracted from the stems of plants such as jute, kenaf, flax, ramie and hemp, are widely accepted as the best candidates due to their very good mechanical properties. Hemp was shown to have very promising tensile properties for applications where mechanical properties are a requisite [2-5]. Some high-performance plant fibers have tensile properties quite close to those of glass fibers. Natural fibers are cheaper, lighter and more environmentally friend than glass fibers [2]. Natural fiber mats are already used in the automotive sector in interior and exterior components[6,7].

Currently most studies on natural fibers are concerned on the fundamental understanding of their behavior as reinforcement for FRP. The focus is on the study of the mechanical properties, the interface between fiber and matrix, the chemical modification of the fiber surface and the composite processing. In all these studies the composites manufactured contain only natural fibers as reinforcement. However, very few studies exist on the use of hybrid solutions with lay-up containing both glass and natural fibers [8-11]. None of this studies concerns the use of hemp fibers.

The aim of the present work was to study the replacement of glass mats with hemp mats in a typical fitting used in the pipeline of a chemical plant. The pipe for the study was a 90° curved fitting flanged at both ends, with a nominal diameter of 100mm, designed to withstand an internal pressure of 10 bar and in the presence of acid aqueous solutions.

The study was conducted at first performing mechanical analysis on each single ply lamina and then designing, on the basis of the results of the mechanical results, a novel lay-up for the fitting. Mechanical tests for the lamina with the final lay-up were also performed in dry conditions and after long exposure to acid solutions. The curved pipe designed was produced using the hand lay-up technique and tested under pressure to simulate the real in-use conditions. The cost reduction of the proposed design was investigated. Some natural fibres alternatives to hemp were also evaluated.

Economic evaluations have been conducted on the use of Hand lay-up and an alternative process technique based on the light-RTM.

EXPERIMENTAL

Materials

The epoxy vinyl ester resin Derakane MomentumTM 470–300 purchased by Ashland Italia SpA, Italy, was used as thermoset matrix. Cumene hydroperoxide and cobalt naphthenate were used as catalyst and accelerator respectively. The properties of the resin are summarized in Table 1. The catalyst and accelerator were purchased by Aldrich, Italy.

Table 1 Resin properties

Property	**Value**
Uncured Resin Density, 25°C	1.08 g/mL
Resin Density after curing	1.135 gr/cm^3
Shelf life[a], 25°C	10 months
Styrene Content	33%

[a] Without the addition of additives, catalyst or cure promoters.

Several glass fabrics were used varying from E-glass woven (code HP-P600E) to E-glass random mat (code HP_MP600E) and C-glass liner (code C-Glas Vlies T 1791C) that were all purchased from HP-Textiles (for E-glass woven and mat), Germany, and Mühlmeier GmbH, Germany, respectively. The hemp mat was purchased by Hempcore Ltd., United Kingdom. Kenaf and Flax mats were kindly offered by Sachseinleinen Gmbh. The properties of the natural fibers and of the fabrics used in the present study are summarized in Tables 2 and 3, respectively.

Table 2 Composition of the natural fibers used (wt%)

Component	Hemp	Flax	Kenaf
Cellulose	65	56 – 63	53-57
Hemicelluloses	16	15 – 16	15-19
Lignin, Pectin	4	4 - 6	5,9-9,3
Wax	<1	<1	-
Proteins, minerals	2	4 - 10	6
Water	12	12	7-10

Table 3 Technical data of the fabrics used

Component	Cost [€/m^2]	Areal Weight [g/m^2]
E-glass Woven	2.80	600
E-glass Mat	2.13	600
C-glass Liner	0.50	30
Hemp Mat	0.31	600-650
Flax Mat	0.37	750
Kenaf Mat	0.33	630-650

Preparation of the lamina and of the fittings

The cumene hydroperoxide and the cobalt naphtenate were added to the epoxy vinyl ester resin with the percentage of 1.5wt% and 0.07wt% respectively. Once all the components were weighted together the resin was mixed by hand for about 10min. The lamina for mechanical testing were impregnated by hand lay-up and cured at room temperature for 48hr. The fittings were also manufactured by hand lay-up by wrapping the fabric onto a steel mandrel which is shown for reference in Fig.1.

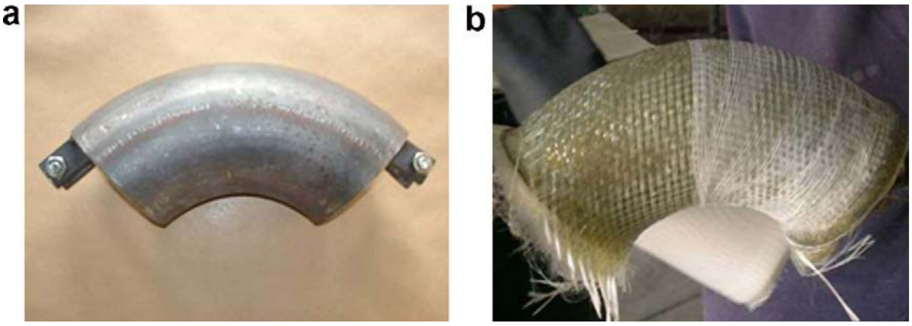


Fig.1 a) Steel mandrel; b) Fabric wrapping step.

Mechanical characterization

Tensile tests of single fibers were carried out with a Zwick Universal Testing machine (model Z050) equipped with a 2 kN load cell. The single fibers were manually extracted from each mat. The free fiber length was 15 mm. Forty-five replicas were tested for each fiber type to account for the variability of properties. The tensile test was carried out with a speed of 1 mm/min. The cured laminas were tested accordingly to EN ISO 527 and EN ISO 14125 for tensile and bending test respectively. Five replicas for each specimen were tested. The test was carried out with a Zwick universal testing machine (model Z050) equipped with a 50 kN load cell. The mechanical tests were carried out either on laminas obtained from a single fabric or on laminates obtained with a lay-up similar to those used for the fitting. Some laminate specimens were also conditioned in different HCl solutions with pH varying from 1 to 7. The specimens were immersed for 40 days and then tested to analyze the effect on mechanical properties. This test was designed to predict the mechanical behaviour of the specimens in real working conditions. All the specimens were wrapped with C-glass liner to simulate the real surface of the interior of the fittings which is usually exposed to acid solutions.

RESULTS AND DISCUSSION

Before using resin some rheological tests were carried out on a plate rheometer ARES by TA Instruments at room temperature with 25 mm (diameter) parallel plates and at 10 rad/s with various catalyst loadings. Increasing the level of catalyst a decreasing of gel time, available for processing resin, is obtained. Because of this result we opted to use a percentage of hydroperoxide of 1.5 wt%.

Single fibers were tested in tensile mode in order to assess the mechanical properties of the fiber. The results of tensile testing on single fibers are summarized in Table 4 for each type of natural fibers used in the present study. High scatter is observed for each fiber type. The variability of mechanical properties for natural fibers is well known. In fact, the behaviour and properties of natural fibers depends on many factors, such as, the harvest period, weather variability, and the quality of the soil and the climate of the specific geographic location [12,13] as well as preconditioning [14,15]. To account for such variability we tested forty-five specimens for each fiber types. The hemp fibers used in the present study presented the higher properties in terms of mechanical properties compared to the other two types of fibers selected. This result supports the decision to adopt hemp fibers as substitute of glass fiber in the application interest.

The results of tensile testing on single ply lamina are summarized in Figs. 2 and 3 for the tensile strength and modulus respectively. The data of both graphs are normalized with respect to the density of each lamina.

Table 4 Results of tensile testing on single fibers

Fiber type	Stat. Param.	A [mm^2]	E [GPa]	σ_{max} [MPa]	ε_{max} [%]
Hemp	$\bar{x}$	0.008	19.40	1070	4.8
	s	0.002	12.60	442	1.5
Flax	$\bar{x}$	0.006	17.36	721	4.5
	s	0.002	13.35	334	2.5
Kenaf	$\bar{x}$	0.010	10.94	692	4.3
	s	0.004	11.06	315	2.2

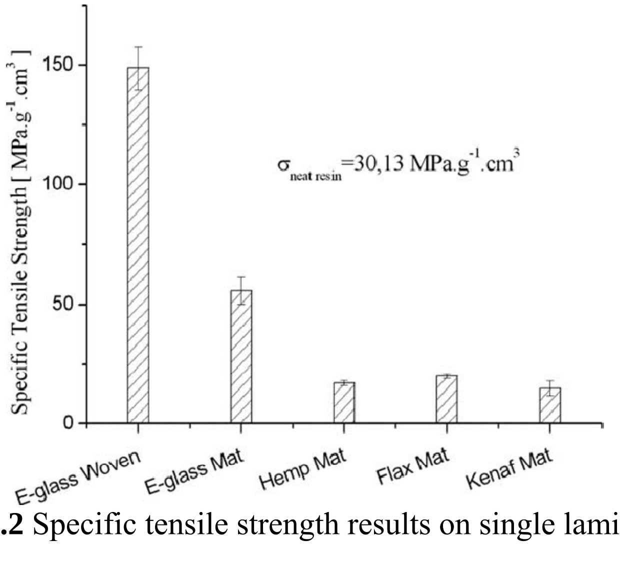


Fig.2 Specific tensile strength results on single lamina

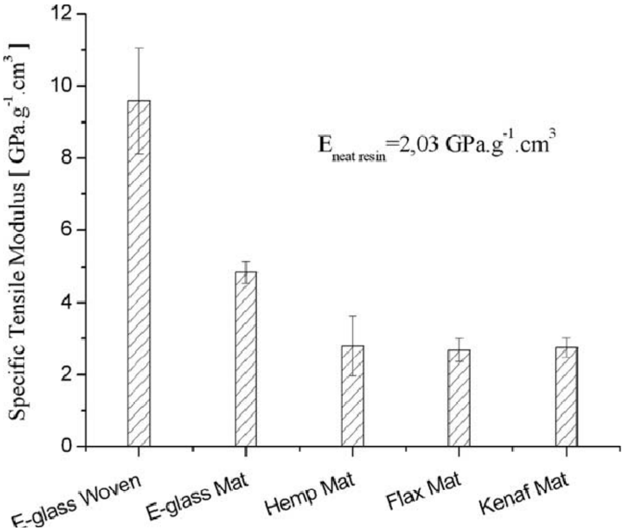


Fig.3 Specific tensile modulus results on single lamina.

The lamina reinforced with glass woven fabric showed the best performances in terms of tensile strength and modulus. This result is the consequence of the presence of long and aligned continuous glass fibers. The glass mat showed better mechanical properties compared to the natural fiber mats. The decrease of tensile strength compared to neat resin was observed for the lamina obtained from natural fiber mats. However, slight improvements of tensile modulus were observed compared to neat resin for the same samples. This behaviour can be explained as a consequence of the low fiber volume fraction (V_f) achieved for the lamina reinforced with the natural fibers and of the scarce adhesion between fiber and matrix [16]. The latter and matrix were due to the absence of surface treatment on the fibers used in the present study. The natural fiber surface was not treated because this choice avoids to increase the price of the natural fiber. Measurements of V_f were performed on the natural fiber mat samples and an average of 8–11% was obtained. The reason for such low V_f are twofold: the hand lay-up method does not allow to achieve high compaction pressure and poor control on resin quantity is obtained; the natural fibers have a porous structure that increase the amount of resin adsorbed when lamina are impregnated. Moreover, the architecture of the natural fiber mats is quite open and thus higher percentages of resin are allowed to impregnated the mat. If liquid molding techniques like RTM (Resin Transfer Moulding) were employed for the manufacturing a V_f of 30% could be achievable [17]. Table 5 reports the mechanical data of Fig. 3 after normalization to a V_f of 30%. The data clearly show that natural fibers can compare to glass fibers also in terms of mechanical performances if higher volume fraction of natural fibers are achieved.

The original laminates for fittings are currently manufactured with the following ply sequence:

$$[C/C/M/W/M/W/M/M/W/M/W/M] \qquad (1)$$

Where C stands for C-glass liner, M for E-glass mat and W for E-glass woven. The laminate sequence (1) leads to a thickness of 12mm and a cost for the fittings of 15.74€ (in terms of raw materials cost) with a weight of 2.97kg. The resistance of the laminate sequence was verified applying the Tsai–Hill criterion and the maximum tension criterion for each single ply using the data from single lamina testing for the calculations.

Table 5 Mechanical properties of single lamina after normalization to V_f to 30%

Material	V_f (%)	Tensile Strength (MPa g^{-1} cm^3)	Tensile Modulus (GPa g^{-1} cm^3)
E-glass woven	35	127.64	8.22
E-glass mat	20	83.78	7.26
Hemp mat	12	42.95	7.00
Flax mat	10	60.24	8.04
Kenaf mat	9	49.50	9.17

The results (Table 6) showed that one lamina made of the glass woven fabric could easily sustain the pressure load of 16 bar (safety factor = 1.6) justifying glass fiber mats replacement with natural fiber mats despite the lower mechanical properties of these materials.

Table 6 Application of Maximum tension and Tsai-Hill criterions for each ply.

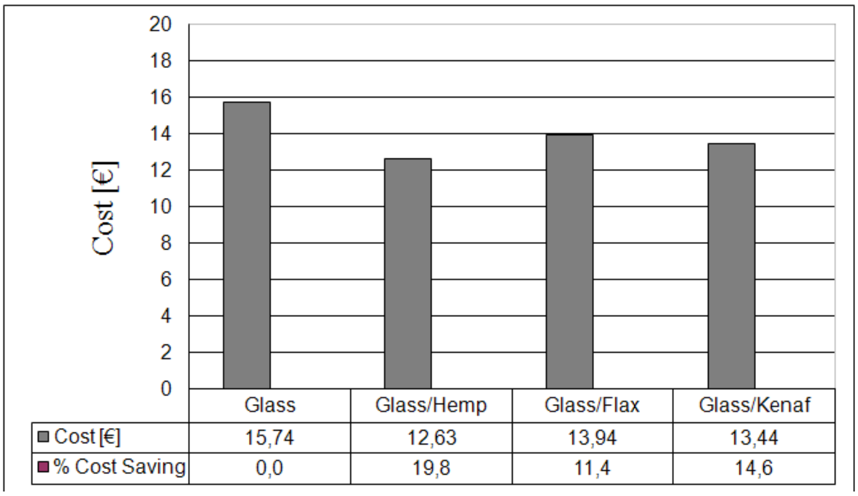
			Maximum tension criterion			Tsai-Hill criterion			
Ply	R	t	σ	Res. σ	Verify	σ	Res. σ	R	Verify
	mm	mm	MPa	MPa		MPa	MPa		
Liner	50	-	-	-	-	-	-	-	-
L1	50	1,54	51,9	74,8	Yes	51,9	74,8	0,36	Yes
L2	51,54	0,67	123,1	240,2	Yes	123,1	240,2	0,20	Yes
L3	52,21	1,54	54,2	74,8	Yes	54,2	74,8	0,39	Yes
L4	53,75	0,67	128,4	240,2	Yes	128,4	240,2	0,21	Yes
L5	54,42	1,54	56,5	74,8	Yes	56,5	74,8	0,43	Yes
L6	55,96	1,54	58,1	74,8	Yes	58,1	74,8	0,45	Yes
L7	57,5	0,67	137,3	240,2	Yes	137,3	240,2	0,25	Yes
L8	58,17	1,54	60,4	74,8	Yes	60,4	74,8	0,49	Yes
L9	59,71	0,67	142,6	240,2	Yes	142,6	240,2	0,26	Yes
L10	60,38	1,54	62,7	74,8	Yes	62,7	74,8	0,53	Yes
	mm	11,92							

Accordingly to this finding and taking into account the cured ply thickness of the hemp mat the following alternative design was proposed for the fittings in order to achieve a pipe thickness similar to the original pipe construction.

$$[C/C/M_n/W/W/M_n] \qquad (2)$$

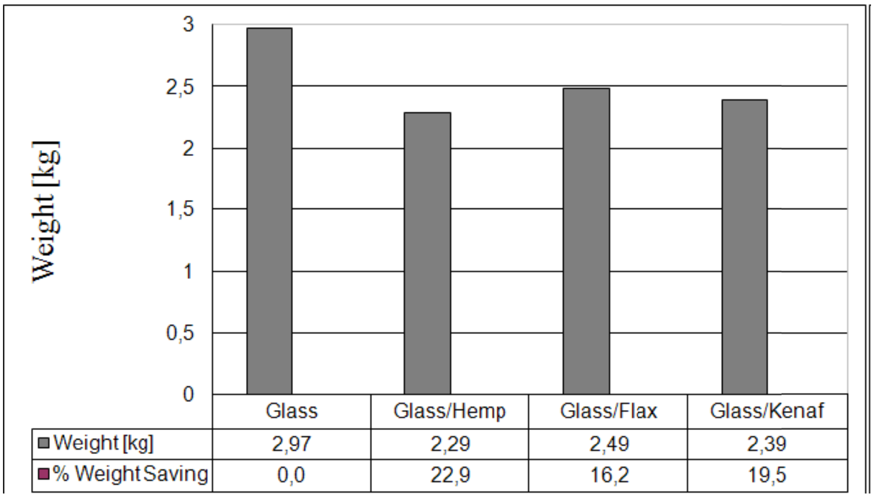
Where M_n stands for the natural fibre mat.

The novel hybrid lay-up has been used to predict the cost (raw material) and the weight of the fittings produced using natural mat as replacement of glass mat. The results are summarized in Figs. 4 and 5 where the data for the original lay-up (named Glass) is reported for comparison purposes. The comparison shows that the novel lay-up allows for the reduction of cost and weight for all the types of the natural fibers selected. The best performances were obtained with the hemp mat.



	Glass	Glass/Hemp	Glass/Flax	Glass/Kenaf
■ Cost [€]	15,74	12,63	13,94	13,44
■ % Cost Saving	0,0	19,8	11,4	14,6

Fig.4 Cost comparison for different lay-up solutions.



	Glass	Glass/Hemp	Glass/Flax	Glass/Kenaf
■ Weight [kg]	2,97	2,29	2,49	2,39
■ % Weight Saving	0,0	22,9	16,2	19,5

Fig.5 Weight comparison for different lay-up solutions.

A prototype of the fitting was build with the laminate sequence (2) using the hemp mat and it was tested under pressure up to 16 bar with the set-up showed in Fig. 6.

Fig.6 Fittings build with hybrid glass/hemp lay-up.

The fitting with the hemp mat showed to withstand up to 16 bar of internal pressure without any significant deformation or fluid leakage.

Finally some laminates, according the original and the novel designs, were tested after immersion in aqueous acid solutions for 40 days. This construction of the test lamina allows reproducing the conditions of the internal layer of the pipe which is usually exposed to the acid solution. The results of the exposure on the tensile strength are summarized in Fig. 7 for the tensile strength. Similar trends were showed for the tensile modulus. The mechanical test showed that only small variations of the mechanical properties after immersion were obtained. The resistance to acid solution is a consequence of the barrier effect of the liner wrapping.

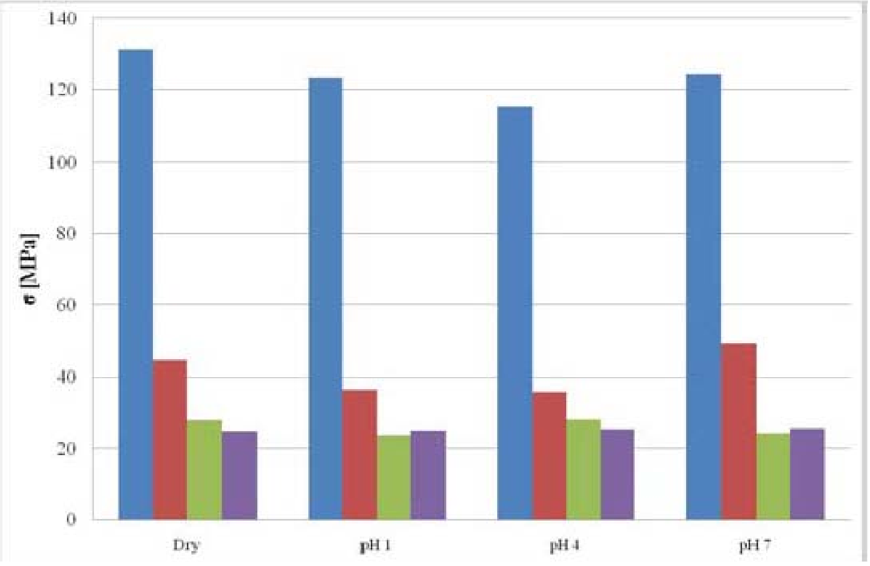


Fig.7 Laminates tensile strength after 40 days immersion in acid solution.

Light-RTM solution

The excellent results obtained in the study of the fiber / hemp hybrid solution made with manual techniques have stimulated the search for further production costs reductions. This aim has been pursued by developing a modified RTM version, called “light”, based on the use of lightweight fiberglass mold. Furthermore, the sealing mold system is usually based on the use of vacuum and, optionally, low cost manual screws. In this case, the geometry of the 90° curved tube required a further development of the technique in order to eliminate demolding problems. In particular, the most important difficulty is the mandrel extraction from the cross-linked component. The manual solution is based on the use of metal mandrels which are extracted from the cured component by reducing the diameter by means of screws placed inside the mandrel itself. A novel solution has been adopted for light-RTM in order to facilitate the mandrel extraction. It is based on a silicone mandrel inserted on a PVC base (Fig.8). Once inflated, the silicone mandrel is sufficiently rigid to allow the deposition of plies.

The injection point choice was supported by FEM analysis of different solutions. The chosen solution was to use a single line injection in the lowest base.

Fig.8 Silicone mandrel setting

Finally, the fiberglass external mold was realized by hand lay-up technique using traditional glass mats (Fig.9).

Fig.9 Mold for Light-RTM process

Taking advantage of the developed system some injection tests were made to verify the molding and extraction easiness of the rigid pipe. The evaluation of costs production by light-RTM showed a reduction of about 25% than the manual technique due to the reduction of waste.

CONCLUSIONS

In the present paper a novel use of natural fiber mats as been proposed. The materials selected were fully characterized in terms of their mechanical properties. The data obtained on the single lamina showed that natural fibers have poor properties when compared to glass fabrics. However, a proper design of the laminate sequence of the part allowed to keep the desiderate resistance even if natural fiber mat were used. A prototype fitting was produced and tested with an experiment simulating the real work conditions. The test confirmed that the proposed fitting can withstand the real work condition. Notably the proposed laminate sequence allows for a cost reduction of about 24% and a weight reduction of 23% when hemp mat are used. In addition, as part of research was developed an innovative light-RTM technique for the construction of curved tubes. This solution has resulted in a further reduction in production costs.

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