Performance of Sustainable Flax Yarn Reinforced Polyester Laminate "Exploratory Study"

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***Abstract*- Green composites become very considerable in the new investigations and research because of its potential in replacing polymers and metals in some industrial applications. Replacing polymer parts with green composite in vehicle's interior parts is an important application. In this study, physical and mechanical efficiencies of using long flax yarns -made of short discrete fibers were used to produce natural yarn reinforced polyester (NYRP) laminate. Single-layer (lamina), samples made of polyester matrix and reinforced with flax-yarn fabric, was investigated in this study. In order to examine the manufacturing process effect, both hand layup and compression molding techniques -at different packing pressures- were used to produce different NYRP laminae. Tension and flexure testes were applied to measure the main mechanical properties of different produced NYRP laminae. In addition, two main fiber's orientation zero degree (0^0) and 45 degrees off axis (45^0) were considered during testing to investigate the fiber orientation's effect. Microscopic images showed good fibers distribution and resin-fibers impregnation across hand layup and compressed NYRP laminae for many specimens, while some fiber's impregnation/distribution defects were observed for other specimens in addition to few air bubbles in resin. Generally, stiffening of polyester is the main significant role of adding flax-yarn fabric to polyester reaching 3.3 folds under tension and 2.2 folds under flexure depending on the manufacturing process and fiber-loading directions. However, early premature mode's failure –due to the observed defects- lower bounded the strengthening, ductility and toughness gains of the NYRP laminates compared to pure polyester. As the possible defects have sensitive effect during the assessment of single-layer laminate's performance, further current study is considering multi-layer influence on the performance of NYRP composites. The initial results of the later further investigation show significant enhancement in stiffness, strength, maximum strain and accordingly modulus of toughness of eghit layers (0)8 NYRP laminate compared with the explored Single-layer (0).**

Keywords: ***Natural fibers; Flax; Unsaturated Polyester; Tensile and Flexural properties; Hand-Lay-Up; Compression Mold.***

1. INTRODUCTION

Many researches have used natural fiber composites in several applications, such as the automobile sector due to high strength to weight ratio and high resistance to impact, as well as low cost [1] [2] [3]. Moreover, natural fibers can be renewed, recycled and decomposed completely or partially, in addition to their satisfactory mechanical properties. The aforementioned advantages, make natural fiber composites an attractive environmental alternative to synthetic fiber (e.g. glass, carbon) composites [4]. In addition, many researchers have studied hybrid role of natural fibers in composites by adding natural fibers to synthetic fibers [5]. However, some researchers have tackled main challenges for the natural fiber's application.

For example, applying some chemical treatment on natural fiber was investigated to improve the surface adhesion properties against the fiber's surfaces waxy residue [6] [7]. While the effect of the yarn's twist angle -on their impregnation- is another significant point which was studied in some researches [8]. Many long natural fibers, such as flax, sisal, and kenaf, show good role for reinforcing thermosetting composites [4] [9] [10] [11] [12]. However, making use of the short discrete of natural fibers is an important challenge for sustainable source of natural fibers as some of the long continues natural fibers need special extraction process or have an alternative expensive use in textile industry (e.g. long flax fiber fabric).

The potential of using locally available natural short discrete fiber yarns for reinforcing polyester bars was explored [3]. Using sustainable flax yarn showed remarkable enhancement of the polyester bar's mechanical properties. However, infusion technique –used to produce NYRP bars- limited the fiber volume fraction and accordingly their reinforcing role [3]. In the present paper, fabric made of short discrete flax yarns was used to produce single-layer composite laminate. The flax fabric was used to reinforce polyester using hand lay-up technique and cold press compression technique under different compressive pressures to investigate the influence of manufacturing process on the fiber volume fraction and the corresponding mechanical properties of the composite laminate. Therefore, the main objectives of this study are summarized in the following points:

1. Determine the main properties of fabric made of locally available short flax fibers yarns.
2. Investigate the tensile and flexural performances the laminate made of natural flax yarn reinforced polyester (NYRP).
3. Asses the efficiency of using different manufacturing processes, for producing NYRP laminate.

2. EXPERIMENTAL WORK

The experimental work consists of the following consecutive procedures:

1- Preparation and testing of constituent materials.
2- Manufacturing of NYRP laminates.
3- Measuring the main properties of NYRP laminates.

2.1. Preparation and testing of constituent materials

2.1.1. Preparation of the reinforcing materials

Unidirectional flax yarn reinforced fabric – shown in Figure 1 - was used for manufacturing the composite laminate. The reinforcing fabric -made of locally available short flax fibers yarns- was cleaned and dried before manufacturing [13]. The cleaning process targeted the main dirt, wax and suspended materials may found from the fabrication process. The cleaning procedure started by immersing fabric in water for one hour, followed by washing until the water pass through the fibers shows no color change. At this point it is believed that the fabric becomes clean of dirt, wax and suspended materials. After cleaning, the fabric was dried in air and then ironed to get rid of moisture and wrinkles due to the washing process. Then the fabric was cut according to the dimensions and the direction required.

Fig. 1: Flax fiber fabric before preparation.

2.1.2. Resin Preparation

The resin used was an unsaturated polyester (ETERSET 2121 CL) Catalyzed by the addition of 1-2% of an organic peroxide catalyst (TURPEROX HQ) [14] [15]. The process of mixing polyester with the hardener was carried out using a mechanical stirrer for two minutes at low speed to prevent the bubbles formation.

2.1.3. Testing of reinforcing fabric and polyester matrix

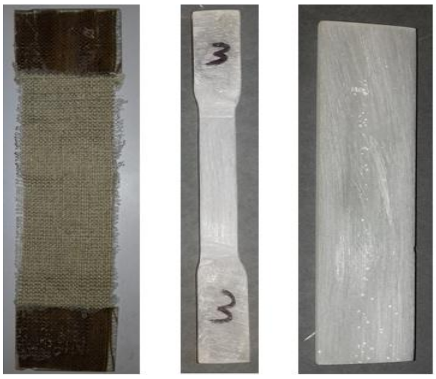
Even though the main properties were presented for the same flax yarn –by two of the co-authors- in separate research work [3], tensile test was applied on flax fabric specimen. In order to assure that applied tensile load reached all longitudinal fibers of the fabric, specimen was initially extended before the preparation of special pads for the specimen's ends. The end pads were prepared by impregnating the fabric with polyester resin to form composite lamina. On the other hand, specimens of pure polyester with enough thickness to make easy handling and testing (i.e. has thicker thickness than composite lamina). Figure 2 shows different fabric and unsaturated polyester specimens prepared for tensile and flexure testing and their testing setup.

2.2. Manufacturing of NYRP laminates

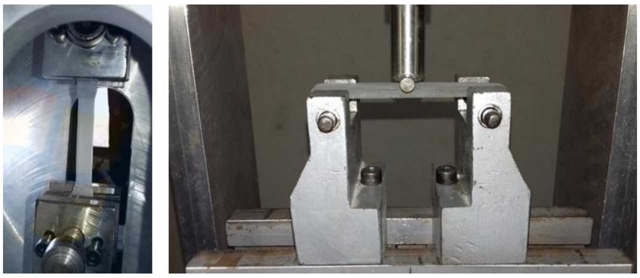
During this exploratory study, single layer of unidirectional fabrics was used to manufacture the natural flax yarn reinforced polyester (NYRP) laminates by two techniques, hand-lay-up and cold press.

2.2.1. Using Hand-Lay-Up technique

As normal sequence of hand-lay-up technique, it was started with cleaning the surface of the mold plate with acetone solvent to make sure of the surface is cleanness and smoothness. Thin layer of mold release was applied to the mold surface before start lamination process. The lamination process started with applying a small quantity of resin to the surface of the lamination mold plate followed by the cleaned flax placed above the resin layer.



a) Fabric and polyester specimens.



b) Tensile and flexure testing setup for fabric and polyester specimens.

Fig. 2: Prepared fabric and polyester specimens and their testing setup.

More resin was applied over flax fabric and distributed well –using hand roller brush- to ensure good impregnation of the fabric. Finally, special care should be paid to assure removing any excess resin and air bubbles during the hand roller application. The upper surface of the mold was placed above the impregnated layer and a weight of 40 kg was placed on it. This dead weight produced low pressure (i.e., about 0.06 bar) which was applied for straightening the samples. This sustained load was kept for 24 hours at room temperature till the composite plate was cured**.** The composite plate was then released and cut with different dimensions and orientation (0°, 45°) to apply the required tests according to the ASTM standard [16] [17] [18].

2.2.2. Using Cold press technique

During the Cold-press technique, the preparation steps of the NYRP laminate were similar to the steps of the hand layup techniques. However, after resin impregnation of fabric, instead of applying a constant weight, sample was exposed to different values of pressure by means of a Compression Molding machine. This machine contains two pneumatic cylinders which used to produce the compression force. Figure 3 shows the Compression Molding machine while the molding pressure is usually not greater than **0**.5 MPa ≈ 5 bar [19]. The compressed laminate samples were left under pressure for 24 hours at room temperature for curing. The NYRP laminate was then released from the compression molding machine and were cut to different shapes and dimensions for conducting the mechanical testing according to ASTM standards [16] [17] [18].

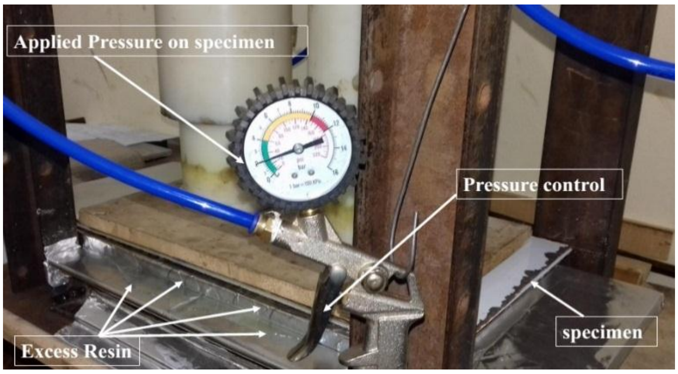


Fig. 3: The configuration of the compression machine.

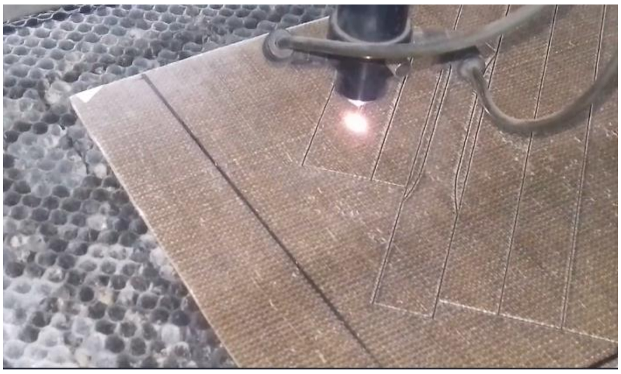


Fig. 5: Cutting test's specimens with laser CNC machine.

In order to get rid of the air bubbles and to investigate the influence of the fiber volume fraction (FVF) on the laminate's performance, two different pressures were applied (i.e., 0.25 and 0.5bars) during the production cycle.

2.3. Measuring the main properties of NYRP laminates

Tensile and Flexural tests were performed -on the NYRP laminates- according the ASTM standards [16] [17] [18] and in Polymer Lab, Faculty of Engineering - Tanta University. Universal Testing Machine was used for testing with a 98 kN load cell and at constant loading speed of 2 mm/min followed by ASTM standard as shown in Figure (4).

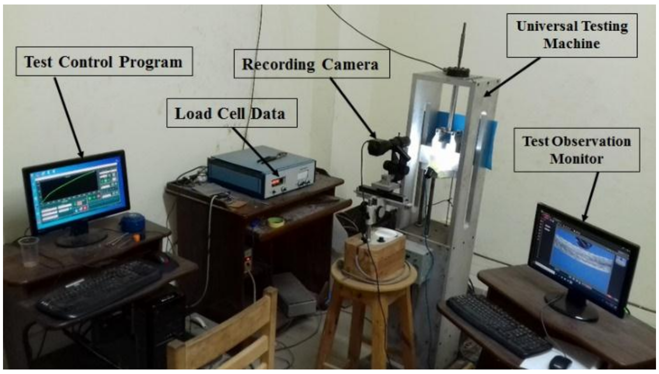


Fig. 4: Universal Testing Machine in Polymer Lab.

2.3.1. Specimen preparation

Initially, NYRP laminate's edges were trimmed to have straight-edge samples of 210 x 320 mm dimensions. Further, constant cross-sectional specimens were prepared for tensile and flexure tests in addition to dog-bone shape specimens only for tensile test. Trimming and cutting process were performed using a laser CNC machine as shown in Figure (5). Figure (6) shows the schematic patterns of the cutting the NYRP composite tensile test's specimens (i.e., 20x200mm constant cross section and dog-bone shape specimens) and flexure test's specimens (i.e., 13x100mm). All these specimens were cut on the direction of fiber's orientation (0) degree and (45) degrees as shown in Figure 6. To avoid the expected stress concentration due to the testing machine's grips, ends of the constant cross section tensile specimens were bonded with beveled composite tabs reinforced in bi-directions.

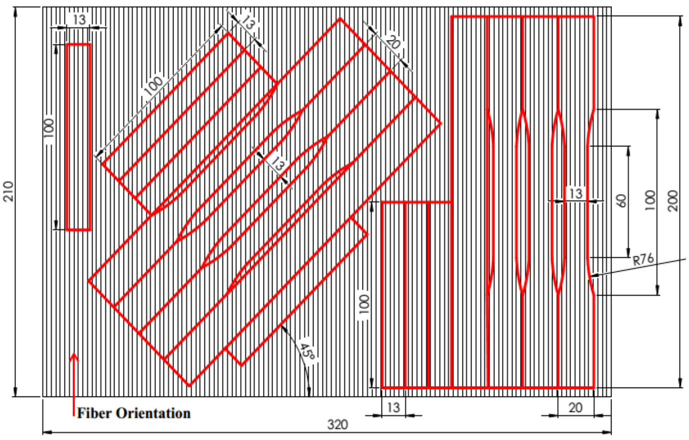


Fig. 6: Schematic cutting patterns of preparing NYRP composite specimens for tensile and flexure tests.

2.3.2. Tensile Test

The tensile tests were conducted according to ASTM D638, ASTM D3039 [16] [17]. However, tensile strength (σ_T), tensile modulus (E_T) and strain (ε_T) at brake are the main tensile properties which were targeted during the tensile performance evaluation. Uniaxial tensile force was applied along the test setup with crosshead speed of 2 mm/min followed by ASTM standard.

2.3.3. Flexure Test

ASTM D7264 [18] was followed to determine the flexural properties of the NYRP specimens, such as flexural strength (σ_F), flexural modulus(E_F) and flexural strain ($\boldsymbol{\varepsilon_F}$). These values were calculated using the following formulas:

$$\sigma_F = 3PL / 2bh \tag{1}$$

$$\varepsilon_F = 6\delta h / L^2 \tag{2}$$

$$E_F = L^3 m / 4bh^3 \tag{3}$$

Where:

P = applied force (N).
δ = mid-span deflection (mm).
L = support span (mm).
b = width of beam (mm).
h = thickness of beam (mm).
m = slope of the secant of the force-deflection curve.

During the flexure test, three-point bending mode was applied -with a crosshead speed of 2 mm/min - along 80 mm loading span (L) according to ASTM standard [18].

3. RESULTS AND DISCUSSIONS

3.1. Raw materials

Main physical and mechanical properties of flax yarns were tested, by the co-authors [3], in different research as shown in Table 1. In addition, the main physical and mechanical average properties of the flax-yarn fabric and the polyester specimens are shown in Table 2 and figures 7 through 9. Figures are showing samples of the observed performances for both materials. The expected brittle behavior of pure polyester is clear under tension and flexure, while more ductile behavior is shown for the flax fabric under tension. On the other hand, stiffness and strength values nominate flax fabric to strengthen pure polyester as a composite material.

Table 1: Main physical and mechanical properties of flax yarns [3].

Yarn Type	Nm (Km/kg)	Humidity %	Load (kg)	Tenacity (cN/tex) (km)	Elongation %
Flax	2.5	10.68	4.0168	9.84	2.1

Table 2: Main physical and mechanical average properties of flax fabric and pure polyester.

Properties	Pure polyester	Flax fabric
Density	1.11 g/cm^3	0.044 g/cm^2
Water absorption %	0.1	152
Tensile strength (MPa)	36.6	103
Modulus of elasticity using tensile test (GPa)	1.5	4.3
Max tensile strain (%)	3.7	5.3
Tensile modulus of toughness (MPa)	0.98	1.6
Flexure strength (Modulus of rupture) (MPa)	65	-
Modulus of elasticity using flexure test (GPa)	2.5	-
Max flexural strain (%)	2.25	-
Average flexural modulus of toughness (MPa)	1.62	-

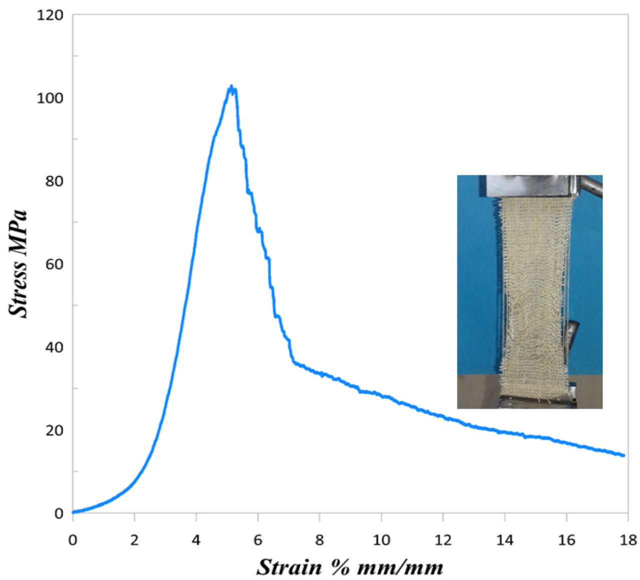


Fig. 7: Stress-strain behavior in tensile test of non-impregnated flax fabric.

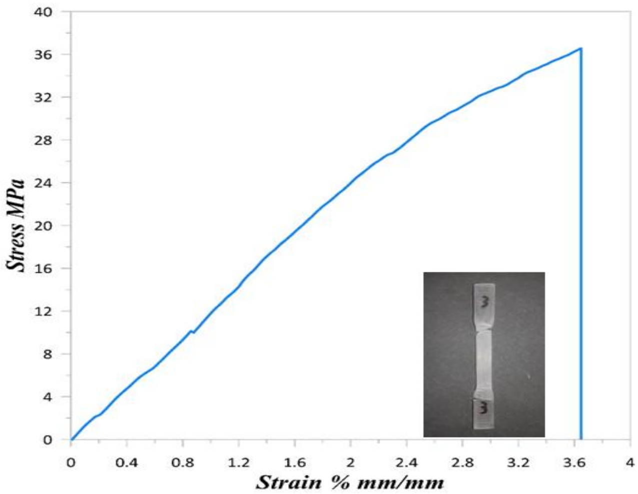


Fig. 8: Stress-strain behavior under tension for pure polyester.

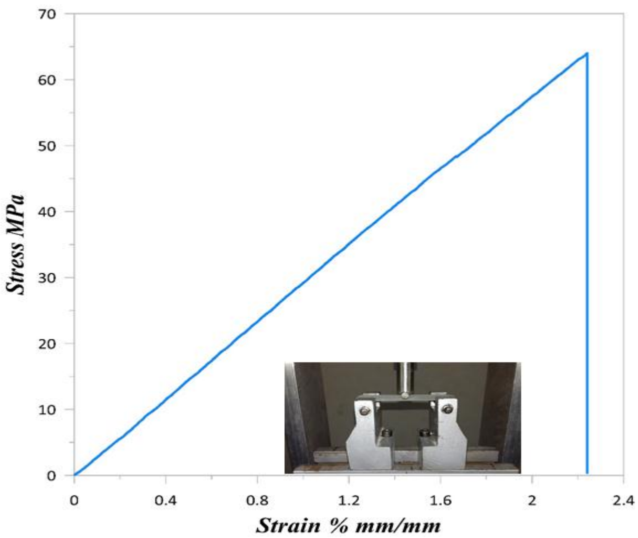


Fig. 9: Stress-strain behavior under flexure for pure polyester.

3.2. NYRP laminate made by different techniques

3.2.1. Physical properties

The average density, microscopic examination, water absorption and the fiber weight/volume fractions were evaluated for all NYRP laminate. Table 3 shows different prepared laminate's specimens and the corresponding measured properties during this experimental testing program. Performance of 1-layer specimens, prepared with Hand lay-up (HLU) and cold press (CP) techniques, were compared in both 0^0 and 45^0 directions with respect to the pure polyester resin specimen. Referring to Tables (2) and (3), the following observations can be pointed:

- The maximum reached fiber weight fraction, using the explored manufacturing techniques and pressures, is 32.5%.
- Adding flax fibers has minor impact on the polyester density with maximum increment of 3%.
- Polyester resin reduces the water absorption of flax-yarn fabric significantly in NYRP laminates (i.e. reaching less than 3%) having good composite nominated for several applications of water/humidity exposure conditions.

Table 3: Different prepared specimens and the corresponding measured properties.

Prepared specimens*	Physical properties**			
	Fiber weight fraction Wf %	Fiber volume fraction Vf %	Average density g/cm3	Average water absorption %
Pure polyester	---	----	1.11	0.1
HLU (0^0)	27.3	24.7%	1.145	2.66
HLU (45^0)	27.3	24.7%	1.145	2.66
CP 0.25 bar (0^0)	28.6	26.8%	1.131	2.34
CP 0.25 bar (45^0)	28.6	26.8%	1.131	2.34
CP 0.5 bar (0^0)	32.5	30.1%	1.139	1.36
CP 0.5 bar (45^0)	32.5	30.1%	1.139	1.36

*HLU = Hand Lay-Up technique, CP=Cold Press technique, (0^0) & (45^0) = Fiber orientation with respect to longitudinal direction of the specimen, Physical properties** of (45^0) is the same as (0^0) (the same plate).

3.2.2. Microscopic examination

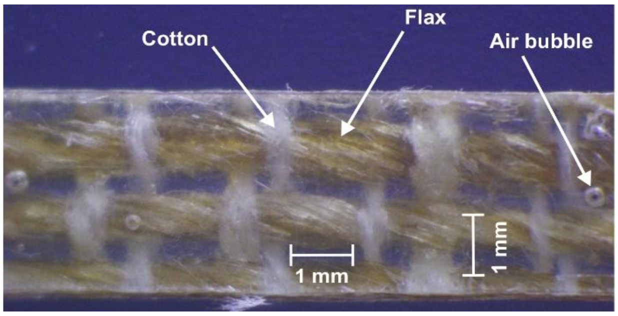
Figure 10 shows examples of the optical micrographs of NYRP laminates –with different scales- showing the fiber distribution, yarn-polyester interface and some physical defects such;

- Polyester crakes and air bubbles.
- Not complete fiber impregnation.
- Bleeding of polyester resin leading to bad distribution of fibers across the lamina section.

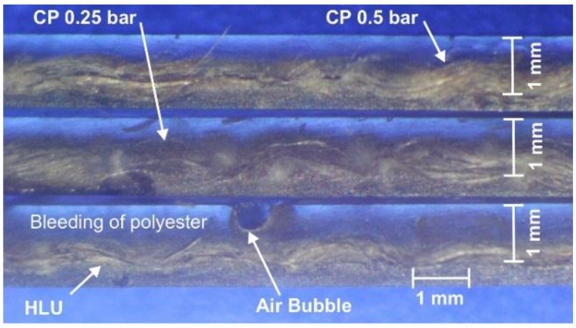
Even though these defects were observed on specimens made by different techniques, the more uniform applied pressure the fewer defects were observed with better fiber impregnation. Applying suitable cold pressure for multi-layered composite can enhance the fiber impregnation and correspondingly increases the fiber weight/volume fraction measured during this exploratory study.

3.2.3. Tensile properties

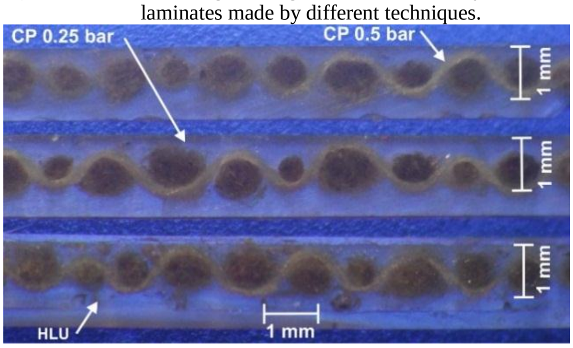
Table (4) and Figure (11), (12) show the tensile performances and main properties of NYRP laminates made by different techniques (i.e., hand layup Vs cold press) and fiber direction (0 and 45) with respect of the tensile load direction. Tensile behavior of pure polyester is added to the composite's behaviors in figure (11) for comparison. In addition, figure (13) shows the common modes of failure observed for different NYRP laminates under tensile test.



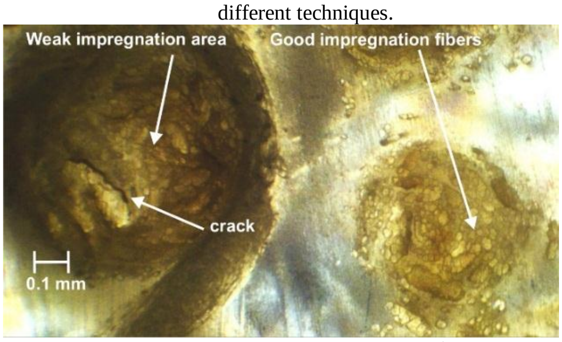
a) General image in longitudinal direction of yarns.



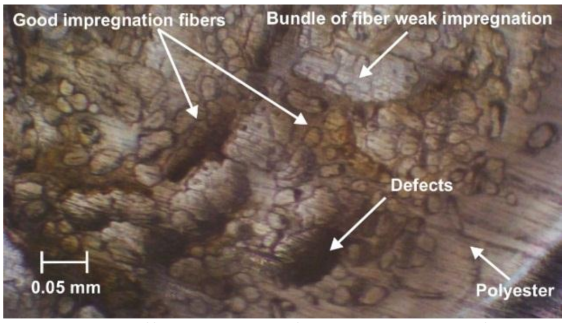
b) Cross-sectional image in longitudinal direction of yarns for NYRP laminates made by different techniques.



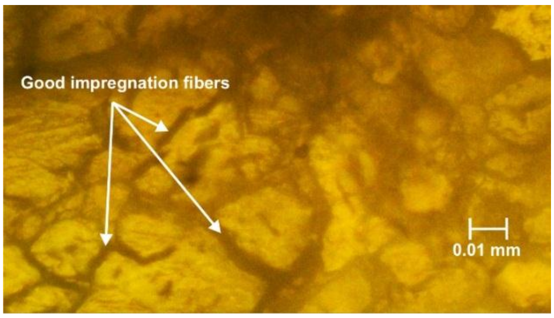
c) Cross-sectional image across yarns for NYRP laminates made by different techniques.



d) Close image showing yarn-polyester interface condition.



e) Different qualities of impregnation and defects.



f) Case of good impregnated fibers.

Fig. 10: Exemplary optical micrographs of NYRP laminates showing fiber distribution, size and some physical defects (voids).

As seen in figure 13, fibers fracture was the common cause of failure for specimens with fiber aligned in the direction of the applied load, while polyester fracture –on the fiber interface- was the main cause of specimens having fibers on 45^0 off the loading direction. However, whitening was observed on both cases of failure, highlighting the role of polyester either in initiation failure or at the breakage stage of the specimens. Aforementioned defects (e.g. incomplete fiber impregnation) have a role of the observed whitening and corresponding polyester cracks appearance at failure.

Base on the data deduced from figures and tables, the following observations can be pointed:

- ***Considering stiffening effect of flax-yarn fabric***

  - Generally, adding flax-yarn fabric to polyester –for the purpose of producing composite laminate- shows remarkable stiffening impact compared to the tensile behavior of the pure polyester.
  - The tensile stiffness of the composite lamina was ranged between 1.3 to 3.3 folds of the pure polyester depending on the manufacturing technique, applied pressure and orientation of fiber with respect to the loading direction.
  - Enhancement of tensile stiffness increased by applying cold pressure rather than using hand layup technique which can be related to the expected increase in the fiber volume fraction, better fiber impregnation and fewer defects which may affect the composite strength. However, doubling the applied pressure showed limited enhancement in the tensile behavior of the composite laminate. So, it is recommended not to increase the pressure over 0.5 bar for manufacturing the composite lamina explored in this study.
  - Stiffening reduction was observed –by range of 30-48%- for specimens having aligned fibers 45^0 off the direction of the applied tensile load. Even though this reduction is expected due to the off-axis effect of the fibers, but the reduction range increased with increasing pressure during manufacturing as a result of the higher stiffing impact related to application of higher pressure.

- ***Considering strengthening effect of flax-yarn fabric***

  - Similar to stiffening, the role of strengthening -due to adding flax-yarn fabric to polyester- is remarkable in case of applying load in the direction of fiber's alignment. However, strength reduction –over pure polyester- for the specimens loaded 45^0 off the fiber direction can be related to premature failure either due to defects (e.g., bubbles) or the low role of fibers incase of the off axis loading in addition to the expected interface failure which is usually initiate unreliable early failure. Such premature failure lowers the limits of strength, maximum strain, and the corresponding modules of toughness.
  - Tensile strength of the unidirectional composite lamina found to be between 1.3 to 2 folds of the pure polyester depending on the manufacturing technique and applied pressure, while the strength of HLU (45) specimen reached only 30% of the pure polyester due the premature failure.
  - Enhancement of tensile strength increases by applying cold pressure rather than using hand layup technique, while doubling the applied pressure showed only 12% enhancement in the tensile strength of the composite lamina.

- ***Considering ductility effect of flax-yarn fabric***

  - Having maximum strain as ductility reference, less than 30% enhancement was observed with adding flax-yarn fabric to polyester. This unexpectedly low ratio of ductility enhancement in addition to the observed reduction in other cases is indication of the premature failure's role on the tensile behavior on general.
  - While the manufacturing technique and applied pressure had no clear effect on the observed maximum strain values, all the specimens loaded 45^0 off the fiber direction showed clear reduction of these values. On contrary to the expected behavior with adding the fibers, reduction of ductility highlights again the premature failure impact on the composite specimen's tensile behavior.

- ***Considering toughness effect of flax-yarn fabric***

  While the tensile modules of toughness of all composite specimens loaded in direction of the fibers showed good enhancement over pure polyester (e.g. reached 2.2 fold), remarkable reduction was observed for specimens loaded 45^0 off the fiber direction. In addition, the manufacturing technique and applied pressure had no clear effect on the measured modules of toughness. Again, the premature failure affecting the strength and the maximum strain surly will affect the modules of toughness.

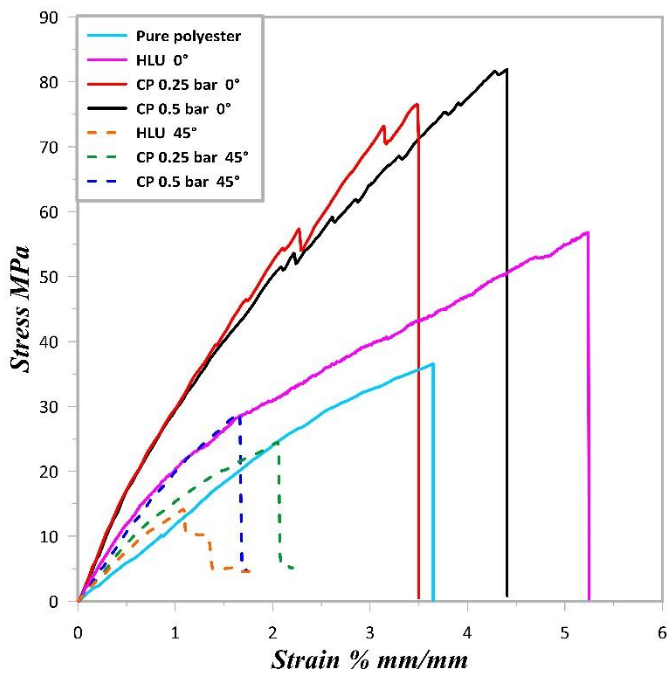
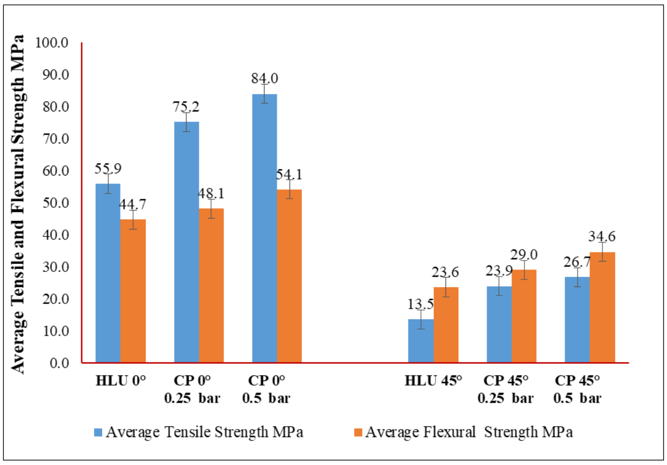


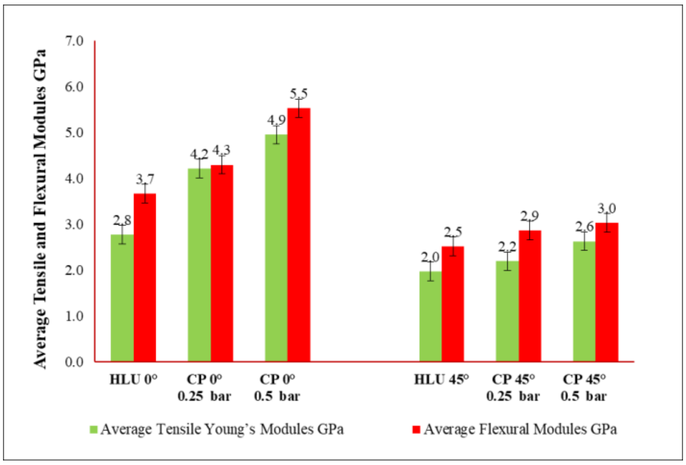
Figure 11: Stress-strain behavior of different NYRP laminates under tensile test.

Table 4:Tensile test results of different NYRP specimens.

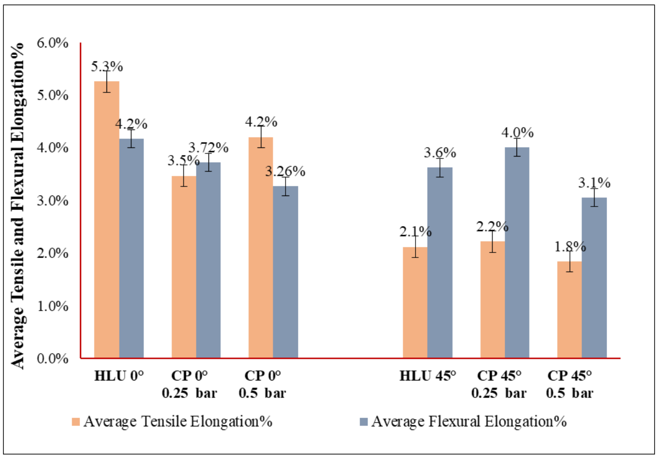
Specimen description	Fiber weight fraction $Wf\,\%$	Average Tensile Strength σ_T MPa	Average Tensile Stiffness E_T GPa	Max Tensile Strain $\varepsilon_T\ \%$	Tensile Modules of Toughness T_T MPa	σ_T / W_f MPa	E_T / W_f MPa
Pure polyester	--	36.6	1.5	3.7	0.98	--	--
HLU (0^0)	27.3	55.9	2.8	5.3	1.82	205.0	10.2
HLU (45^0)	27.3	13.5	2.0	2.1	0.17	49.6	7.2
CP 0.25 bar (0^0)	28.6	75.2	4.2	3.5	1.56	263.2	14.7
CP 0.25 bar (45^0)	28.6	23.9	2.2	2.2	0.29	83.7	7.7
CP 0.5 bar (0^0)	32.5	84.0	4.9	4.2	2.12	258.7	15.2
CP 0.5 bar (45^0)	32.5	26.7	2.6	1.8	0.23	82.4	8.1



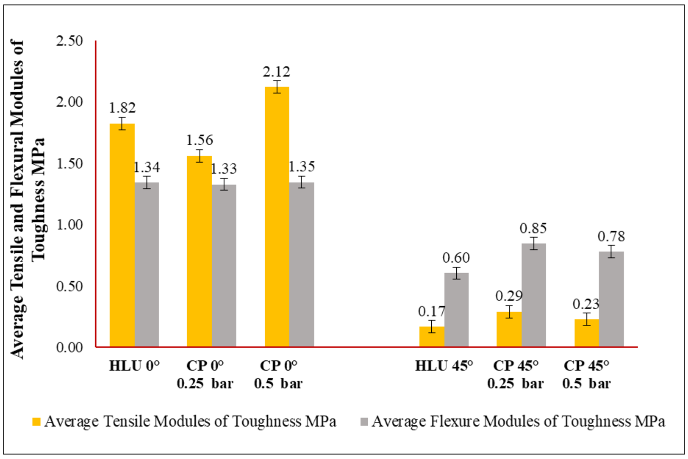
a) Average tensile and flexural strengths



b) Average tensile and flexural modules of stiffness GPa



c) Average tensile and flexural elongation %

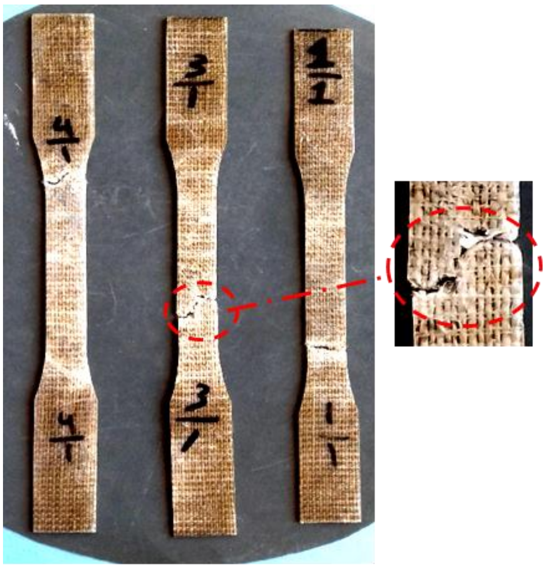


d) Average tensile and flexural modules of toughness MPa

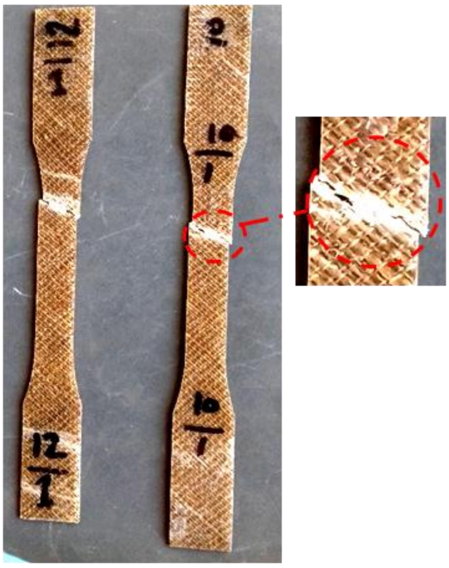
Figure 12: Main properties of the tensile and flexural tests for different NYRP laminates by different techniques.

Table 5: Flexure test results of different NYRP specimens.

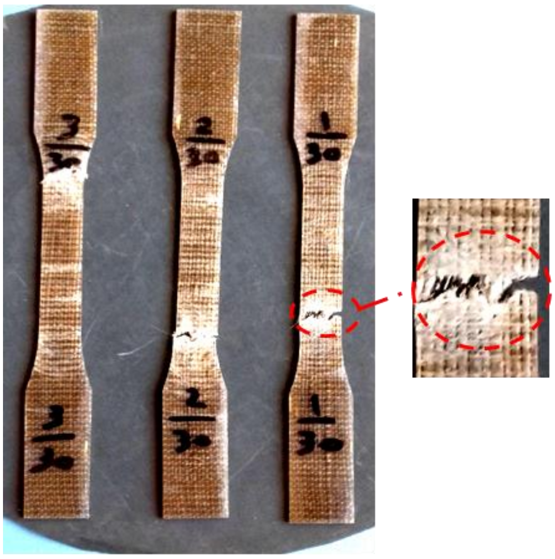
Specimen description	Fiber weight fraction $Wf\,\%$	Average Flexure Strength σ_F MPa	Average Flexure Stiffness E_F GPa	Max Flexure Strain $\varepsilon_F\ \%$	Flexure Modules of Toughness T_F MPa	σ_F / W_f MPa	E_F / W_f MPa
Pure polyester	--	65	2.5	2.25	1.62	--	--
HLU (0^0)	27.3	44.7	3.7	4.2	1.34	164.0	13.5
HLU (45^0)	27.3	23.6	2.5	3.6	0.60	86.6	9.2
CP 0.25 bar (0^0)	28.6	48.1	4.3	3.72	1.33	168.4	15.0
CP 0.25 bar (45^0)	28.6	29.0	2.9	4.0	0.85	101.5	10.0
CP 0.5 bar (0^0)	32.5	54.1	5.5	3.26	1.35	166.8	17.0
CP 0.5 bar (45^0)	32.5	34.6	3.0	3.1	0.78	106.6	9.3



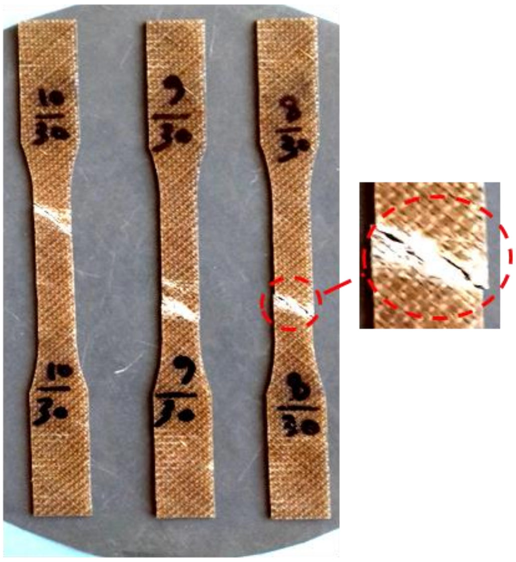
a) HLU (0^0)



b) HLU (45^0)

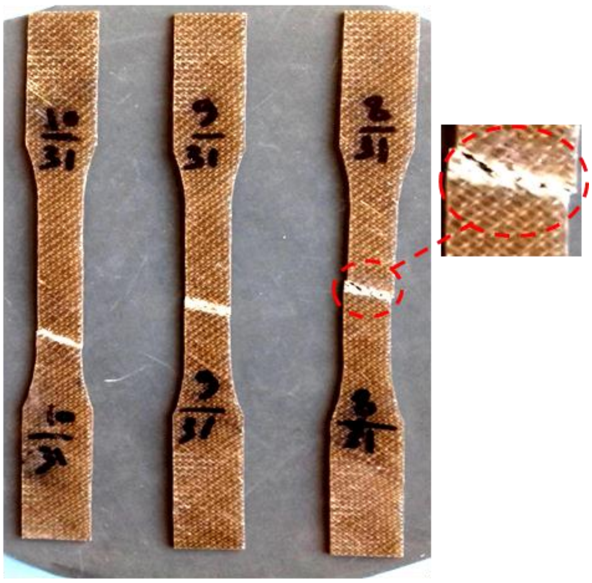


c) CP 0.25 bar (0^0)



d) CP 0.25 bar (45^0)

e) CP 0.5 bar (0^0)



f) CP 0.5 bar (45^0)

Fig. 13: Common modes of failure observed for different NYRP laminates under tensile test.

3.2.4. Flexural properties

Figures 12, 14 and Table 5 show the flexural performances and main properties of NYRP laminates made by different techniques (i.e., hand layup Vs cold press), various applied pressures (i.e., for cold press technique) and fiber direction with respect to specimen's unidirectional direction (0^0 and 45^0). Flexural behavior of pure polyester is added to the composite's behaviors in figure 14 for comparison.

Based on the figures above and tables, the following observations can be pointed:

- ***Considering stiffening effect of flax-yarn fabric***
  - Generally, remarkable flexural stiffening was observed for the flax- fabric-polyester composite compared to pure polyester.
  - The flexural stiffness of the composite lamina reached 2.2 folds of the pure polyester depending on the manufacturing technique, applied pressure and orientation of fiber with respect to the loading direction.
  - Enhancement of the stiffness -under flexure- increased by applying cold pressure rather than the hand layup technique.
  - Stiffening reduced –by range of 30-45%- for specimens having aligned fibers 45^0 off the specimen's unidirectional direction which is expected due to the off-axis effects of the fibers.
- ***Considering strengthening effect of flax-yarn fabric***
  - On contrary to stiffening effects, strengths of all specimens decreased due to adding flax-yarn fabric to polyester which can be related to premature failure which is due to aforementioned defects (e.g., bubbles). Such premature failure is the possible cause for lowering the limits of strength, maximum strain, and the corresponding modules of toughness. Therefore, further investigation is needed in monitoring the failure's mode effect under microscopic level which was not performed during this exploratory investigation due to irregular nature of the fracture surface of the NYRP laminates test specimens.
  - Flexural strength of the unidirectional of the NYRP composite lamina was ranged between 69% to 83% of the pure polyester depending on the manufacturing technique and applied pressure, while the strength of HLU (45) specimen reached only 36% of the pure polyester due the aforementioned premature failure.
  - Enhancement of flexural strength was observed by applying cold pressure rather than using hand layup technique, while doubling the applied pressure showed only 13% enhancement in the flexural strength of the composite lamina.
- ***Considering ductility effect of flax-yarn fabric***
  - The maximum strain of composite lamina under flexure test showed narrow range of 1.4 to 1.9 folds of the pure polyester.
  - In the manufacturing technique the applied pressure and fiber direction have no clear influence on the maximum strain of NYRP composite lamina. In lightening of the expected premature failure on the flexure tests due to the defects (e.g., bad distribution of fibers across the lamina section, air bubble, and other's).
- ***Considering toughness effect of flax-yarn fabric***
  - On contrary to maximum strain, modulus of toughness of all specimens was –unexpectedly- reduced to reach 37-83% of the pure polyester due to adding flax-yarn fabric. This reduction can be related to the reduction of strength which can be originated to the premature failure due to aforementioned defects (e.g. bubbles).

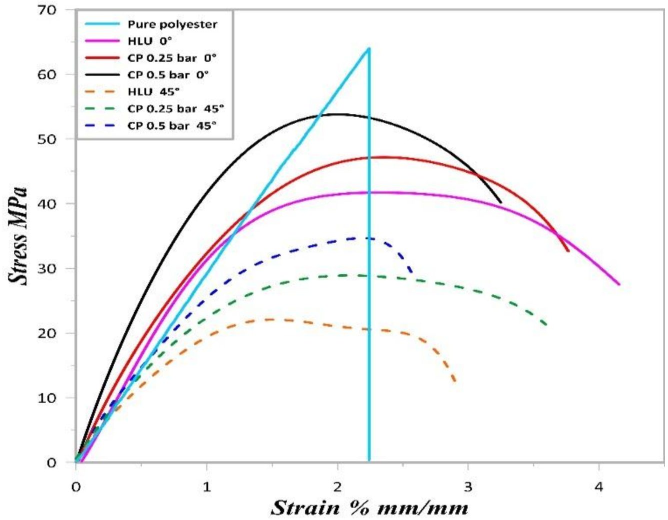


Fig. 14: Stress-strain behavior of different NYRP laminates under flexure test.

4. ON GOING STUDY

In order to extend this exploratory work for engineering applications and for clarifying some of the unexpectedly observed findings, further study is currently implemented. The followings are some considered parameters during the extend study:

1- Behavior of multi laminae flax fabric reinforced polyester and the influence of the fiber's off axis orientation.

2- Different manufacturing techniques and applied pressure.

3- Performance of the multi laminae flax fabric reinforced polyester under impact loading test.

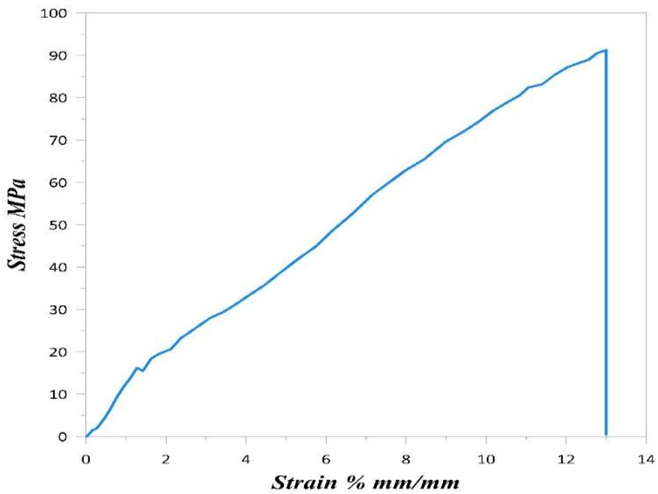


Fig. 15: Stress-strain behavior of (0)8 NYRP laminate under tensile test.

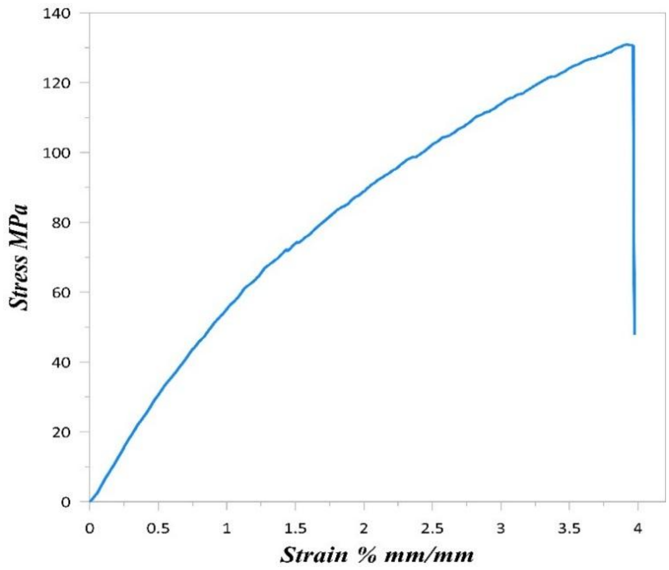


Fig. 16: Stress-strain behavior of (0)8 NYRP laminate under flexure test.

Figures 15 and 16 show the tensile and flexural stress-strain behavior of undirection flax fabric reinforced polymer laminate manufactured by hand layup technique. Significant enhancement is observed in stiffness, strength, maximum strain and accordingly modulus of toughness if compared with the (0) one layer investigated in this exploratory study.

5. CONCLUSIONS

Generally, this exploratory study shows that recycling short discrete residual flax fibers –in the form of fabric- has promising results for producing natural yarn reinforced polyester (NYRP) laminates. Accordingly, the following points can be initially concluded for the explored NYRP laminates:

1- In case of using polyester as matrix the water absorption ratio of the laminates is significantly reduced with respect to the original ratio of the flax fabric with no remarkable effect on the density of polyester.

2- Some physical defects were observed -under microscope- in NYRP specimens such as air bubbles and incomplete impregnation as well as bad distribution of fibers. Manufacturing process is the main cause of these defects in addition to the possible influence of using natural twisted-form yarns.

3- Remarkable tensile and flexural stiffening was observed for the flax-fabric-polyester composite compared to pure polyester. This stiffening reached 3.3 folds under tension and 2.2 folds under flexure depending on the manufacturing process and/or the direction between the applied load and the fiber alignment.

4- Even though tensile strength, ductility and toughness enhancement were clear in tension of the explored NYRP laminates compared to pure polyester. However, in case of single layer laminate the premature failure of the NYRP specimens is the reason for this lowering the flexure strength. This premature failure can be related to either the aforementioned defects- and/or loading-fiber directions influence. It’s expected that the sensitivity of single-layer laminate has a significant role on the very early premature failure cases; therefore, current further study is concentrating on the performance of the multilayered NYRP laminate.

5- Ductility under flexure was clearly enhanced by adding flax fabric to polyester. However, the maximum flexural strength and the corresponding modulus of toughness -of the explored NYRP laminates- reached 83% of the pure polyester sample.

6- As expected, higher fiber weight/volume fraction accompanied with replacing hand layup by cold press manufacturing process leads to a remarkable effect on the performance of the NYRP laminates. However, increasing the applied pressure -during cold press- from 0.25 to 0.5 bar has limited enhancement in mechanical performance. Therefore, no effort was considered during this exploratory study to increase the applied pressure over 0.5 bar.

7- Having the fiber’s direction off the applied tensile force or flexure moment axis showed significant reduction of the NYRP specimen’s stiffness, strength, and modulus of toughness. However, the unexpected reduction of ductility during tensile tests in case of the off-axis alignment between the applied load and fibers can be related again to the premature failure.

8- The preliminary results of the current investigation show significant enhancement in stiffness, strength, maximum strain and accordingly modulus of toughness of eight layers (0)8 of unidirectional fibers NYRP laminate compared with the explored (0) single layer for both cases. This enhancement highlights the sensitivity influence of the one-layer lamina on the behavior of the NYRP laminate.

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