Analysis of the natural fiber reinforced polymer: composite fiber rods (FRPCY)

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Abstract. Fiber reinforced polymer composites (FRPC) can be used in new or repaired reinforced concrete structures. Fiber reinforced polymer composite yarn (FRPCY) can be formed as rods of different diameter and length to be used in the formation of concrete structures due to their superior light weight, corrosion resistance, the lack of material ductility and energy absorbing capabilities. The formation of these FRPCY rods using natural fibers yarns is tried in this work. Due to the variation of the fiber volume fraction of the yarn along its length, it will directly reflect on the fiber volume fraction of the formed composite. In this work, the relation between the yarn volume fraction and the composite fiber volume fraction were studied, taken into consideration its variation along the yarn length. The formation of these rods using flax yarns is tried in this work and their mechanical properties are investigated.

Keywords: Yarn volume fraction, Composite fiber rod, Natural fiber composites

1. Introduction
Replacement of the steel reinforcement in concrete structures with more corrosion resistant substitutes such as composites is rapidly becoming a more economical option for construction facilities worldwide [1, 2]. The fiber Reinforced Polymer (FRPCY) composite can be applied in repaired reinforced concrete structures. The fibers can be used in form of single, plied or braided yarns, with different sizes starts from 0.5 mm [3]. The combination of braiding and pultrusion processes has been also named pull-braiding, braided-pultrusion and braid-pultrusion [4-7]. Civil engineering applications, namely for concrete internal reinforcement, composite rods were produced, varying the type of fibers used as a core reinforcement of a polyester braided structure [8]. To improve the adhesion between the FRP rods and the concrete several types of ribs are designed on the outer layer of the rods [9]. During this process the internal architecture of the reinforcement material is susceptible to large structural changes as it is forced to deform to allow for the reduction in its volume [10, 11].

Natural materials have many advantages when compared to traditional materials and are less harmful to the environment. The formation of natural fiber reinforced composite rods present a solution to deterioration problem. In the case of staple fiber yarns, theoretically, the fiber volume fraction varied between 0.76 – 0.9, depending on the fiber arrangement. The fiber obliquity in the twisted yarns increases the compactness of the yarn, which in its turn depends on the spinning technology [3]. It was revealed that the packing density of the fibers in the yarn cross section varied from radios to another with its highest value at the center of the yarn. The average packing density of the yarn depends of several factors: yarn count, spinning system, fiber properties, twist factor and yarn diameter. The distribution of the fiber packing density along the yarn affects the mechanical properties of the yarns and the fabric [11]. Consequently, The FRPCY fiber volume fraction and their mechanical properties are discussed in this work.

2. Materials and methods
Formation of the fiber reinforced polymer composite rod using different counts of flax yarns with following specifications given in table (1). The yarn composite formation through the extortion of the polymer in a paper tube under pressure with the yarn located at the middle of the tube with an inner diameter of 4 mm. the pressure...
was adjusted to high enough to insure the production of rod composite with no defects. All the specimens' rods were dried and cured for seven days in standard atmosphere before applying the mechanical tests. Figure (1) illustrates the shape of the rods after formation. After the composite formation the paper tube was removed to leaving a solid.

| Yarn count Tex | Yarn diameter mm (CV%) | Yarn strength MPa | Young’s Mod. (E) GPa |
|----------------|------------------------|-------------------|----------------------|
| 271            | 0.851(10.66%)          | 178.9             | 4.21                 |
| 303            | 0.759(18.96%)          | 154.7             | 3.44                 |
| 385            | 0.649(14.65%)          | 115.7             | 2.57                 |
| 450            | 0.524(24.73%)          | 111.55            | 2.12                 |
| 500            | 0.447(17.04%)          | 99.14             | 1.21                 |

Figure 1. Composite Fiber Rods.

Figure 2. Various type of packing of spun yarns.

3. Composites mechanical properties
Tensile and bending tests were applied on the composite specimens. The tests were performed on Mecmesin (MultiTest5-xt) testing machine with a uniaxial load with load cell 5KN and crosshead speed 1 mm/min. The tensile test was according to ASTM D3039. The gauge length for the tensile test was 40 mm. The tensile results were analyzed to calculate the strength (MPa), strain, Young's modulus, and the work of rupture. Bending tests were applied with the 4 – point bending test was according to ASTM C348-8. The readings of bending forces and deflections were recorded with Newton and millimeter respectively. Five specimens were test for each type of composite rods and the average readings were recorded for both test.

4. Results and discussions
Due to the variability of the yarn diameter and the variability of the fiber radial packing with maximum value at the center of the yarn, its value depends on the spinning system levels of twist and the fiber parameters [3]. The yarn diameter is varied from section to section along the yarn length as well as the packing density. Generally, yarn is not circular and closer to oval shape which represents the highest likely hood as shown in Figure (2) [11]. The open packing arrangement has $V_{fy} = 0.76$. The packing of the spun yarns may be classified as highly packed to very low packing [3, 11]. Assuming “a” is the major axis and “b” is the minor axis of the yarn cross section, then the equivalent diameter can be expressed as, $D_{yarn} = D_{measured} \times \alpha^{0.5}$, $D_{measured}$ is the yarn diameter measured by one dimensional sensor.

For ring spun yarns: assume the ratio $\alpha = (b/a), 0.67-0.89$, $D_{yarn} = 0.82 - 0.94 \times D_{measured}$. It was found that the average fiber volume faction in the yarn is given by [11], $V_{f, yarn} = 0.64 \times V_{max}$. In the case of FRPCY, the yarn is compressed during the composite formation.
The compactness of the yarn under the pressure will lead to the deformation of its cross section with increasing of the fiber packing density to reach its maximum value at the yarn center with reduction towards the outer layer [11]. In the case of rod type yarn reinforced polymer composite the outer diameter of the composite will be constant $D_c$ and formed by pressing the yarn radially and its diameter $D_y(i)$ at any cross section will squeezed radially to $D_m$. Limit packing density is defined from closest arrangement of fibers in cross section empirical limit of fiber packing density is about 0.7-0.8 at the core of yarn where fibers are squeezed by fibers in the adjacent fibrous layers. In the outer layers is packing density smaller and is decreasing towards the periphery. The average packing density $V_{yarn}$ is in close connection with the yarn diameter which is not the case of spun yarns then at any cross-section $i$.

$$V_{yarn}(i) = 4 \, \text{tex}_{y} / \pi \rho_f \, D_y(i)^2$$  \hspace{1cm} (1)

Figure (3) shows the change of the yarn diameter along the yarn length. In the case of apply pressure on the yarn during formation of natural fiber reinforced polymer composite rods the diameter is reduced according to the following equation:

$$\beta(i) = (D_y \text{, compact} / D_y \text{, initial}) = a \, P - b$$  \hspace{1cm} (2)

Where: $D_y \text{, initial}$ is the initial yarn diameter in free state at $i^{th}$ cross section, $a$, $b$ are constants, $P$ is the pressure on the yarn cross section. The experimental measurements indicated that, $a \approx 458861 \, \text{tex}^{-2.452}$, $b = 4 \, \text{tex}^{1.8856} \, 10^{-6}$ for flax yarns, which are used in this work. Figure (4) confirm the sounds of the calculation by equation (2).

5. The fiber packing density of the composite fiber rods

Based on the above, it can be assumed that measured mean diameter of the yarn $D_y$ cannot be used to determine FRPCY volume fraction. Assume that the final composite yarn has a constant diameter $D_c$, then the yarn at any cross section $D_y(i)$ and the fiber packing density at that section is $V_{yarn}(i)$. The fiber packing density of the composite yarn $V_{fc}$ will be:

$$V_{fc}(i) = (D(i)y / Dc)^2 V_{yarn}(i)$$  \hspace{1cm} (3)

Due to the compactness of the yarn the value of $V_{yarn}(i)$ at any cross section reaches its limited value $V_{yarn}(max)$ consequently,

$$V_{fc}(i) = (D(i)y / Dc)^2 V_{yarn}(max)$$  \hspace{1cm} (4)

This indicates that the variation of yarn diameter directly reflected on the fiber volume fraction of the composite yarn. The fiber volume fraction of compacted yarns varied along its length can be assumed to be normally distributed [11]. Figure (5) illustrate the variation of the yarn fiber volume fraction along the FRP rod with deferent ratio $\beta = Dc / Dy$.

![Figure 3. Measured yarn diameter versus its length.](image-url)
Figure 4. Measured and calculated (D_{compact}/D_{yarn}).

Figure 5. Fiber packing density of the composite rods $V_c$ along its length.

The change of the average value of fiber volume fraction of the yarn will result in changing final FRPCY rod average fiber packing density as shown in figure (6). Figure (7) illustrated the relation between the average composite fiber volume fraction ($V_c$) and that of the yarn ($V_y$), for different values of ($\beta$).

Figure 6. $V_c$ of FRPCY versus $V_y$. 
Due to the variation of the fiber volume fraction of the yarn along its length, it will directly reflect on the fiber volume fraction of formed composite. In this work, the relation between the yarn fiber volume fraction and the composite fiber volume fraction was studied, taken into consideration its variation along the yarn length. The effect of the rod /yarn diameter ratio $\beta$, yarn fiber volume fraction variation was studied, taking into consideration the variability of yarn diameter. The relation between the average composite fiber volume fraction $V_{fc}$ and that of the yarn ($V_{fy}$), for different ratio $\beta$, indicated that the $V_{fc}$ is inversely proportional to $\beta^2$ and the range of $V_{fc}$ variation reduced as $\beta$ increased. The value of average $V_{fc}$, in the case of $V_{fy}$ 0.7, reaches 0.37 for $\beta$ 1.5 and 0.048 for $\beta$ 4. These values are function of yarn diameter variability. Moreover for the value of $\beta$, the yarns compression during formation of the rod should take into consideration.

6. Mechanism of failure of the fiber reinforced polymer composite yarns
The FRPCY rods using different counts of flax yarns (271,303,385,450, 500 tex) were formatted through the extrusion of the polymer in a paper tube under pressure with the yarn located in the middle of the tube with an inner diameter of 4 mm. The pressure was adjusted to be high enough to insure the production of rod composite with no defects. Results on mean tensile strength, presented in Figure (8) show in most cases starts with the failure of the polymer matrix followed with the straining of the core yarn till it breaks under the increasing loads as illustrated in figure (8). It was found that the pull off strength is given in figure (9).
It was revealed that the strength of the rods increased as the yarn count (tex) increases due to the better anchoring of the finer in the matrix that increase the interfacial shear forces. The effect of the variation of count of the yarns used on the final FRPCY are given in figures (10-11).

The work of rupture of the composite rods are found to be increased as yam count (tex) increase as shown in figure (12). It is well known that the bending stiffness of the yarns is very low. However, when the composite rod was tested it was revealed that the maximum deflection of the rod in 4-point bending test increased as a
function of the yarn count (tex), which indicates that the FRPCY become more flexible with the increase of the yarn count (tex), figure (13).

![Figure 12. FRPCY work of rupture versus yarn count.](image)

It was found that the mechanical properties of the flax yarn reinforced polyester polymer composite were improved by using yarns of coarse counts even at the low values of fiber volume fraction.

7. Conclusions
To enhance the resistance to bacterial and enzymatic degradation of flax fibers, a protection by low molecular weight polyester matrix was applied for its physical protection and bacteriostatic properties. The fabrication of FRPCY rod of flax yarns gives the possibilities to be used in concrete mixture. The effect of the rod /yarn diameter ratio, yarn fiber volume fraction on the FRPCY rod was studied, taking into considerations the variability of yarn diameter. The mechanical properties of the flax yarn reinforced polyester polymer composite was improved by using yarns of coarse counts even at low values of fiber volume fraction. Also, the enhancement of bending resistance of FRPCY makes it possible to be used for new or repaired reinforced concrete structures.

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