Compressive properties of 3D braided flax fiber textile fabric reinforced PLA composites

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Abstract. In this study, fabric woven using 3D braided flax yarn is used to reinforce Poly Lactic Acid (PLA) composites. Solid braiding technique is used to convert the typical yarns into braided yarn and further these yarns are used to prepare woven fabric. Finally, composites are fabricated through layer stacking method using hot-press hydraulic compression moulding machine. Compression and shrinkage tests are performed on the braided composites. The braided flax fiber composite results are compared with the as received PLA polymer results. Results showed significant enhancement in the compression properties of PLA composites due to the braided fabric reinforcement. These properties are further increased with the increase in filler content respectively. Thermal shrinkage of the braided flax fiber composites is lower than the PLA polymer. This is due to the higher thermal sustainability property associated with the braided flax fiber.

1. Introduction

These days, fiber reinforced composites (FRC's) are generally utilized in car, aviation, military and building applications. Polymers are typically used in composites as a matrix material because of lower cost, simple processability, low density and strong mechanical properties comparable to metals and ceramics. Sadly, these polymers are based on petroleum and are non-biodegradable and non-regenerative polymers. Meanwhile, filler materials normally utilized are synthetic fibers (glass and carbon), which are non-degradable fibers. In this way, environmental-friendly composite material production has been an interesting research field [1]. Bio-composites fabricated with plant-fibers (for example flax, sisal, hemp, coir, bamboo and jute) reinforced thermoplastic biopolymers matrices (PLA, PHA, PCL...) are of great interest [2].

Poly (lactic-acid) (PLA) is a most promising reproducible resource based and bio-degradable thermoplastic matrix [3]. Over the past few decades its low production cost, facile availability and excellent mechanical properties received considerable attention [4,5]. Lactic acid is the basic monomer of the PLA derived by fermentation process from starch. Then lactic acid is polymerised by ring opening polymerisation or poly-condensation to poly (lactic acid) (PLA) [6]. The PLA polymer cost is high in contrast with regular thermoplastic-polymer and for certain applications these matrix materials are weaker. To lessen the matrix price and enhance the material characteristics without altering its "green-polymer" picture, analysts are attempting to get ready characteristic plant fiber strengthened bio-composites [7]. Recent research has examined the production of bio-degradable composites strengthened with natural-fibers for example hemp [8,9], flax [10], kenaf [11], jute [12]
and ramie [13] fibers. Some researchers are also used flax nonwoven fabric [14], woven flax fabric, bamboo fabric, cotton fabric, jute fabric [7,15–17] and knitted flax fabric [6] as filler materials for bio-composite fabrication. Natural fiber filled PLA composites mechanical characteristics are based on the volume of fiber in composites, fiber-matrix interfacial bonding and type of matrix, manufacturing conditions and reinforcement materials surface treatment.

Among the plant fibers, flax fibers are most popularly used as fillers for composite applications at present. Generally reinforcement of natural fiber (flax fiber) with polymer matrix enhances the composites mechanical characteristics. Oksman et al. [10] manufactured flax fiber filled PLA bio-composites using twin screw extruder with 30 and 40% of fiber content and then composites plates are prepared with compression-molding method. The Flax-PLA composites strength is 50% higher than the flax-PP composites, which are usually used for applications of automotive. Bodros et al. [18] showed that the tensile characteristics of the PLLA-flax and PLA-flax composites are high compared to PP-flax composites. Tensile characteristics (strength and modulus) of the PLLA-flax composites are nearer to the glass-fiber filled polyester-composites. Also, the PLLA-flax composites displayed better specific-strength compared to flax-fiber filled polyester composites. Kumar et al. [7] fabricated flax fabric reinforced PLA composites with montmorillonite clay (MMT) addition. Addition of MMT enriched storage modulus and mechanical characteristics of bio-composites. Duc et al. [19] conducted experimental study on the unidirectional and twill weave 2/2 flax-fiber filled with epoxy, polypropylene and poly (lactic acid) matrices with 40% of fiber volume and are compared with the glass fiber and carbon fiber filled composites. Damping and stiffness received with twill weave 2/2 flax-fiber filled PLA composites have best compromise.

‘In braiding three or more number of yarns are cross-linked along the axis and length of the thread, to obtain a thick and strong thread’ [20]. These are used in composites, ropes and biomedical applications. Rajesh and Pitchaimani [21] fabricated basket type woven-fabric with flat-braided yarn filled polyester-composites and they proved that the flat-braided yarn composites mechanical characteristics are greater than short fiber and conventional woven fabric composites. Also, they showed that the braided composites have greater storage modulus compared to knitted fabric and conventional woven fabric filled composites [22]. Kanakannavar and Pitchaimani [23] are produced fabric with solid 3D braided flax yarn filled PLA bio-composites and the buckling at thermal load study revealed that the addition of braided yarn fabric enriched the thermal buckling sustainability and decreased deflection for applied temperature load compared to pure PLA. Also, the addition of woven fabric with flax braided yarn improved the wear resistance quality of PLA [24].

Present research aims to find the effect of 3D braided flax fiber woven fabric reinforcement with PLA on compressive strength and modulus. Braided yarns are prepared by solid braiding method and braided yarn is interwoven to prepare fabric. The prepared fabric is used as filler material with PLA matrix. Composites are fabricated with film stacking and compression-molding methods. On these composites compression and shrinkage tests are performed and then composites results are compared with the pristine PLA.

2. Methodology

2.1. Materials

PLA is procured from Nature Tech India Private Limited, Chennai, India. Simply twisted flax yarn is supplied by The Matrix Enterprises, Tiruppur, India. Dichloromethane (DCM) solvent is purchased from Sri Durga Laboratory Equipment Suppliers, Mangalore, India.

2.2. Preparation of Braided-yarn and woven fabric with plain architecture

Purchased four simply twisted yarns are used to manufacture solid 3D braided flax yarn on a braiding machine. The prepared braided flax yarn is interlaced in warp (longitudinal) direction and weft (transverse) direction to manufacture the plain woven fabric using handloom weaving machine. Figure 1 and Figure 2 represents the sample of 3D braided flax yarn and natural-fiber 3D braided-yarn plain woven-fabric (NFBF).
2.3. Fabrication of composites

In this study, composites are prepared by using two processes. Firstly solution casting is used to manufacture the PLA and flax braided fabric PLA sheets. The solution of PLA/DCM is prepared by dissolving PLA matrix in DCM (dichloromethane). Then this solution is poured in the aluminium square trays, for pure PLA sheet only PLA solution is poured. For braided yarn fabric/PLA (PLA/NFBF) sheet, a known quantity of PLA/DCM solution is poured, on this solution fabric layer is laid by hand layup method. Then another known quantity of PLA/DCM solution is poured above this fabric. To evaporate DCM from pure PLA and braided yarn fabric/PLA trays are kept in room temperature for 48 hours. Secondly the composites are fabricated by film sequencing and hot-press compression method. For this neat PLA and PLA/NFBF sheets are stacked such that PLA sheet comes to p and bottom of the PLA/NFBF sheet. Then these laminas are compressed in hydraulic compression molding machine with 5 MPa pressure at 180° C temperature for 15 minutes as shown in Figure 3. After room temperature cooling for 6 hours (or below 40° C temperature), composite laminates are taken out from the machine and coupons are cut as per testing standards. The composites are fabricated with various natural fiber weight fractions ($W_F$) using following equation.

$$W_F = \frac{W_{NFBF}}{W_{NFBF} + W_{PLA}} \times 100$$

where, ‘$W$’ represents the weight and suffixes ‘NFBF’ and ‘PLA’ represents the natural fiber braided yarn fabric and poly (lactic acid) matrix respectively.
2.4. Compressive test
Compressive test is carried out as outlined in the ASTM D695 standard on a universal testing machine (H75KS, 50KN load cell capacity, Tinius Olsen make, UK) at 1 mm/min cross head velocity. For each fiber loading, five specimens with size of $20 \times 20 \times 3$ mm$^3$ [25] are used and calculated average results are presented. Braided bio-composites results are compared with the virgin PLA.

2.5. Shrinkage test
Thermal stability of the bio-composites are characterised by placing the PLA/NFBF composite specimens and pure PLA specimens in an vacuum oven at 80° C and the thermal shrinkage of the specimens are measured as the function of time [26]. This study is conducted on the coupons of size $20 \times 20 \times 3$ mm$^3$. From each composition 3 specimens are used for the testing and average values are calculated. Finally the results of composite are compared with pure PLA.

3. Results and discussion
In the present study, composites are prepared by reinforcing 1, 2 and 3 layer of braided yarn fabric and these are having weight fraction of 11, 22 and 33% respectively. According to their weight percentage these are named as NFBF11, NFBF22 and NFBF33 respectively. Pure PLA is shown as NFBF0.

3.1. Compressive properties
The compressive test is carried out to analyze the effect of NFBF (natural fiber braided yarn woven fabric) reinforcement on the compressive characteristics of PLA composites. Neat PLA and PLA/NFBF composites compressive load and displacement curves are showed in Figure 4. Average maximum compressive load and compressive modulus of neat PLA and PLA/NFBF composites are indicated in Figure 5. From Figure 4 it can be observed that the behavior of the compressive load versus displacement curves are linear for PLA and PLA/NFBF composites up to 0.7 mm displacement. After 0.7 mm displacement curves shows nonlinearity and it represents the crack initiation in the PLA and PLA/NFBF composites. The virgin PLA showed average maximum compressive strength of 71.74 MPa and average compressive modulus of 1.63 GPa. From Figure 5, it can be seen that for braided yarn woven fabric reinforcement, composite showed the increased compressive strength and modulus.

Figure 3 Composites fabrication flow chart
as compared to neat PLA and these are further enriched with the filler content increase. The fiber content of 33 weight percentage showed the maximum compressive strength of 83.61 MPa and compressive modulus of 1.92 GPa and these values are 16.54% and 17.17% higher than the virgin PLA.

![Figure 4](image-url)  
**Figure 4** Force versus displacement curves for pure PLA and PLA/NFBF composites

![Figure 5](image-url)  
**Figure 5** Compressive strength and compressive modulus of pure PLA and PLA/NFBF composites

Kain et al. [27] carried out compressive study on 3D printed wood fiber reinforced PLA composites and they noticed that for 25% of fiber reinforcement the compressive strength of the composites is 68 MPa. Chen and Lin [17] fabricated composites reinforcing jute fabric with PLA using hot press compression molding and the compression study of these composites revealed that the maximum compressive strength of the composites is 59.8 MPa. Baba and Ozmen [28] performed a compressive study on long chicken feather fiber filled PLA composites and short chicken feather fiber filled PLA composites. These composites fabricated by extrusion and injection molding methods. Neat PLA sample showed compressive strength of 56.70 MPa. The compressive strength of PLA is diminished with the reinforcement of chicken feather. These results are further decreased with the fiber content increase for both short and long chicken feather fiber reinforcement. Compared to these available literature results the present NFBF reinforced PLA composites results are better.
3.2. Shrinkage properties

Figure 6 Shrinkage of the neat PLA and PLA/NFBF composites over time at 80° C

Additional to the compressive study of the natural fiber braided yarn strengthened PLA composites thermal stability of the composites are also analyzed experimentally. Figure 6 represents the shrinkage behavior of virgin PLA and PLA/NFBF composites for 80° C of fixed temperature. The percentage shrinkage of virgin PLA and PLA/NFBF composites are increased with time period respectively. From Figure 6, it is observed that the neat PLA sample has higher shrinkage percentage with 1.207%. Reinforcement of the natural fiber thermal shrinkage value of the composites is decreased. Because, natural fibers are porous structures and bad conductors of heat [29]. Hence, filling these fibers with PLA resists the shrinkage of composites. Due to this reason composites shrinkage percentage diminished. Also, Kanakannavar and Pitchaimani [23] thermal deflection study showed that the reinforcement of the natural fiber braided yarn woven fabric with PLA enhances the thermal sustainability of the composites. Due to improved thermal sustainability of these composites required higher temperature to shrink. Further the composites shrinkage percentage is decreased with the fabric content. The composites filled with 33% of fabric showed lowest shrinkage value of 0.403%. Similar trend is noticed by Jang et al. [26] for coconut fiber filled PLA composites. This shrinkage study results confirms that the thermal stability of the composites is high compared to virgin PLA.

4. Conclusions

The biodegradable composites are produced by solution casting and hot-press compression molding methods using braided yarn fabric as filler material and PLA as matrix with different fabric weight percentage. The compressive characteristics and thermal shrinkage results of the PLA composites are investigated experimentally. The investigation shows that compressive properties of the composites are enriched with the braided yarn fabric addition compared to virgin PLA and these values are further enhanced with the filler content respectively. Composites with 33 weight percentage addition of fabric with PLA showed highest compressive strength and modulus, which are 16.54% and 17.17% greater than the pristine PLA. The shrinkage study revealed that the reinforcement of the fabric with flax fiber braided yarn enhanced the thermal stability of PLA/NFBF composites.

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