International Journal of Fatigue 103 (2017) 216–222

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue behavior and life prediction of biodegradable composites of starch reinforced with date palm fibers

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ARTICLE INFO

Article history:
Received 9 December 2016
Received in revised form 27 February 2017
Accepted 5 June 2017

Keywords:
Composites
Bending strength
Residual strength
Fatigue
Damage index

ABSTRACT

This work studies the fatigue behavior of biodegradable composites of thermoplastic starch (TPS) reinforced with different amounts of date palm fibers (DPF) (20, 50, and 70 wt%). Composite with 50 wt% fiber content had higher static and fatigue strengths compared to other composites. The alternating stress at which the composites lasted for 10^7 cycles was about 16% of the flexural strength. Mathematical models following the assumptions of D'Amore et al. (1996) and Mao and Mahadevan (2002) were shown to give a good agreement with experimental results of the residual strengths under various fatigue cycles and of the fatigue damage index at different levels of stresses.

1. Introduction

Fatigue is one of the main reasons for failure in many structural materials [1]. Recently, a lot of research focused on studying the fatigue behavior of fiber reinforced composites due to their high specific strength and stiffness. Most of these studies investigate the fatigue behavior of composites reinforced with long synthetic fibers such as carbon, glass, and aramid, leaving the fatigue behavior for natural fiber-reinforced polymers less well understood because of the lack of systematic and detailed information available [2,3].

Fatigue behavior of homogenous materials differs from that of composites. In homogeneous material, an early crack occurs and dominates the damage development leading to the final fracture. While in composites, the fatigue behavior is characterized by crack initiation at multiple sites depending on the matrix ductility and modulus of fibers. In this case, many small cracks with no visible damage occur in the initial stages of fatigue. With the progress of fatigue loading, the cracks grow by crack bridging or debonding between fiber and matrix. Finally, a dominant crack appears and cause final fracture [2,4].

Most composites do not show endurance limit and residual properties like strength and stiffness are often used to quantify their fatigue behavior as the cyclic loading leads to degradation [4–7]. The fatigue life time of a composite in such cases is identified by number of cycles that cause a predetermined drop in a given property occurs. Several authors [4,5,7,8] presented their fatigue results as the loss fraction of the initial bending moment vs. number of fatigue cycles.

Wang et al. and Subramanian et al. [9,10] used a power law relationship to represent the relationship between the damage degradation rates and the corresponding applied stresses. The constants in the relationship were calculated from an S-N curve [10]. D'amore et al. [11] also used the power law to express the decrease in strength with fatigue cycle evolution.

The fatigue test in this study was conducted under bending loading conditions. Therefore, it was important to first investigate the flexural behavior of biodegradable composites of thermoplastic starch (TPS) reinforced with different amounts of date palm fibers (DPF). Mehanny et al. [12] studied the effect of fiber content on the flexural property of starch-bagasse composites. They showed that the optimum fiber content is 60% with flexural strength of 56.2 MPa. Mohanty et al. [13] also found that flexural strength of untreated jute–HDPE composites increased by approximately 45% from 0 to 30 wt% fibers then decrease by 25.6% from 30 to 45 wt% fibers.

In the present work, both the static properties and the fatigue behavior of thermoplastic starch (TPS) reinforced with short date

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http://dx.doi.org/10.1016/j.ijfatigue.2017.06.005
0142-1123/

palm fibers (DPFs) were investigated under bending loading conditions and the power law model was used to describe the fatigue damage behavior.

2. Experimental study

2.1. Study materials

Corn Starch was purchased commercially from Roquette company (batch E3593) with 24% amylose and 76% amylopectin and had particle size in the range between 4.9 and 33 μm with an average of 16 μm. Date Palm Fibers (DPF) were extracted from the mesh part in the palm-trees planted at the American University in Cairo with chemical composition (according to Van Soest method [14]) of 57.06, 16.97, 13.09, and 12.88 wt% for cellulose, hemicellulose, lignin, and dissolved materials like pectin and waxes, respectively. Chemicals used for matrix and fibers treatment were Glycerin with 99.5% purity, Sodium Hydroxide (NaOH) with molecular weight 40, and Acetic Acid Glacial with 99.5% purity. These chemicals were purchased from Morgan Specialty Chemicals Co.

2.2. Study methods

2.2.1. Fibers preparation

Fibers treatment was performed to remove lignin and hemicellulose from the fibers, first by soaking in water for two days, then washing and drying at room temperature. The fibers were then cut into 20–30 mm length and mechanically treated by stirring them in water in a home use blender four times each for 10 s. The blended fibers were then dried at 120 °C for 3 h. Chemical treatment was then performed by placing the fibers in 5% NaOH solution at 90 °C for 3 h before being stirred for 30 min using magnetic stirrer. The NaOH treated fibers were then washed several times in cold water followed by dipping in 5% acetic acid solution to remove any excess NaOH from the fibers surface. Finally, fibers were washed again then dried at 120 °C for 3 h.

2.2.2. Thermoplastic starch preparation

Native corn starch was mixed with 30% w/w glycerin for 10 min. Then, 20% w/w distilled water was added and the mixing process continued for another 5 min at the 60–80 °C. Thermoplastic starch (TPS) was left in plastic bag overnight to enhance its flow properties.

2.2.3. Composite preparation

Composite plates of 120 mm length, 80 mm width and 3 mm thick were prepared by compression molding at 130 °C under 5 tons for 60 min. The fiber content was 0, 20, 50, and 70 wt%. In this process, fibers were added into the mold and carefully distributed, then an emulsion of TPS in water was poured on them. The TPS-water emulsions had ratios of 1:1, 1:2, 1:3, and 1:4 TPS to water for the 0, 20, 50, 70 wt% fibers respectively.

2.3. Material characteristics

2.3.1. Bending test

The bending test samples (Fig. 1) were cut from the composite plates with a size of 120 mm × 10 mm × 3 mm using Laser cutter. The flexural strength and modulus were tested under three-point bending using Instron universal testing machine according to ASTM D790 – 10. The support span length was 48 mm. At least six samples were tested for each condition and an average value was recorded.

Fig. 1. Photograph of the bending sample.

The machine results were expressed in stress strain curves where the flexural stress and strain were calculated using the following two equations:

$$\sigma_f = \frac{3PL}{2bh^2} \tag{1}$$

$$\varepsilon_f = \frac{6\delta h}{L^2} \tag{2}$$

where (σ_f) is the flexural stress at midpoint in outer surface, (ε_f) is the flexural strain in the outer surface, (P) is the load at the given point, (L) is the support span, (b) is the sample width, (h) is the sample height, (δ) is the deflection of the center of the beam.

2.3.2. Fatigue test

Fatigue tests were carried out using alternating bending fatigue machine (HSM20) applying tension compression stresses (stress ratio of R = −1) with constant amplitude deflection. The test was performed using motor of 20 Hz frequency and driven at half of the motor speed via reduction pulleys at room temperature. The stress applied on the sample was calculated using the following equation:

$$\sigma = \frac{1.5Et\delta}{l^2} \tag{3}$$

where (σ) is the maximum alternating stress (MPa), (E) the modulus of elasticity (GPa), (t) thickness of samples (3 mm), (δ) the deflection measured, (l) the effective length of sample (50 mm).

The flexural modulus obtained from the bending test was used in determining the parameters of the fatigue test.

The samples used for the fatigue test (Fig. 2) were of dimensions 80 mm × 10 mm × 3 mm. A hole of 4 mm diameter was drilled 5 mm from the end of the sample to fix it to the clevis of the machine. Samples with different fiber content (0, 20, 50, and 70 wt%) were tested in order to study the effect of fiber content on the fatigue behavior.

Each composite was tested at different number of cycles (10^2, 10^3, 10^4, 10^5, 10^6, and 10^7) after which the sample was tested in tension to measure the residual tensile strength. The relation between the number of cycles and the residual strength was plotted to determine beginning of failure (decrease in residual strength) for the different fiber contents. Further investigation was conducted on the composites with optimum fiber content at δ (2, 4, and 12 mm) to obtain S-N curve. Six samples were tested for each condition.

Along with the experimental work, a model following the assumptions of D'Amore et al. [11] was applied, where the relationship between the material strength reduction and number of cycles was expressed in terms of power law as follows:

$$\frac{d\sigma_r}{dn} = -a.n^{-b} \tag{4}$$

where (b) depends on the material type as well as condition of loading, while (a) is assumed to increase linearly with the stress amplitude according to ($a = a_o \cdot \Delta\sigma$) such that ($a_o$) depends on the material type and loading condition. The stress amplitude $\Delta\sigma$ is expressed as ($\Delta\sigma = \sigma_{max} - \sigma_{min}$). Where, σ_{max}, σ_{min} are the maximum and minimum stresses applied during fatigue cycles, respectively.