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Fatigue of swollen elastomers

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ABSTRACT

The compatibility of the properties of elastomer with conventional diesel fuel has made it favourable in many engineering applications. However, due to global energy insecurity issues, there is an urgent need to find alternative renewable sources of energy as replacements to conventional diesel. In this respect, biodiesel appears to be a promising candidate. Hence, research into the compatibility and fatigue characteristics of elastomers exposed to biodiesel becomes essential. The present paper introduces the first attempt to investigate the effect of different solvents on the fatigue of swollen elastomers. The filled nitrile rubbers are immersed in the palm biodiesel and conventional diesel to obtain the same degree of swelling prior to the application of uniaxial fatigue loading. Field Emission Scanning Electron Microscopy (FESEM) analysis is carried out to observe the fracture surfaces. Stretch-N curves are plotted to illustrate the fatigue life duration. These curves showed that the fatigue lifetime of rubber is the longest for dry rubber and the least for rubber swollen in biodiesel. FESEM micrographs reveal that the loading conditions have no effect on the crack initiation and propagation patterns regardless of the swelling state.

1. Introduction

Conventional petroleum-derived fuels are no longer seen as a futuristic source of fuel because of their ever increasing cost and the continuous diminution in supply. This condition has driven researchers to intensively explore the prospects of biodiesel as a renewable energy alternative for future substitution of current depleting energy resources [14]. Beside being eco-friendly, biodiesel's technical advantages have attracted the interest of researcher to comprehensively investigate its properties, potentials and applications. In Southeast Asia, countries like Malaysia and Indonesia are amongst the largest palm biodiesel producers in the world. Indeed, the production in these countries becomes even more favourable in view of the existing tropical climate [12,5].

The reported studies also confirm the influence of biodiesel on elastomers seeing that they have been exploited extensively in the sealing and automotive industries. These studies were motivated by the compatibility of elastomers and biodiesel, which remains a major challenge to date [15]. This concern arises especially when elastomeric components start to degrade in terms of mechanical properties even without any simultaneous imposed loading [31,15,2]. Undeniably, the degradation takes place with swelling [3] when biodiesel creates a hostile environment for elastomeric components.

During service, elastomeric components are usually subjected to cyclic loadings for long durations. For instance, vibration isolators, gaskets and seals are a few common components utilized for this condition. Elastomeric components which endure continuous cyclic loadings may experience fatigue failure [7]. Mars and his co-workers utilized the crack nucleation approach in their works [23–25] to investigate and to predict the appearance of a 1 mm fatigue crack length at the surface of rubber. It was explained that fatigue crack nucleation life can be interpreted as the growth period of pre-existing micro-cracks (smaller than 0.1 mm in size) [24].

Later, Le Cam et al. [21,18] affirmed this finding through a detailed description in their research on the mechanism of crack growth from microscopic flaws, which subsequently led to the appearance of macroscopic crack initiation under uniaxial and multiaxial fatigue loading conditions.

So far, investigations carried out into elastomer fatigue mainly focus on dry elastomers. The very few reported works on swollen elastomers under fatigue loading are dedicated to the effect of oil diffusion into elastomers. Cho et al. [11] discussed the variation of fatigue crack growth resistance of elastomer in the swollen state while Jerrams et al. [16] presented the Wöhler curves at failure obtained from equibiaxial loading conditions. No studies are reported for the fatigue of swollen elastomers by palm biodiesel to date.

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The current studies, which deal with the effect of palm biodiesel diffusion on the behaviour of rubbers, investigate the change of mass, volume, hardness and tensile strength of rubbers for different immersion durations [31,15,14,2]. Haseeb et al. [14] had immersed nitrile rubbers in diesel and biodiesel for 1000 h at room temperature prior to subjecting the specimens to tensile tests. They reported lower tensile strength values for the swollen biodiesel rubbers compared with the swollen diesel rubbers. Meanwhile, Alves et al. [2] conducted similar tests for the nitrile rubbers for a 100 h immersion duration. Their investigations contradict the results of Haseeb et al. [14]. In their research, the measured tensile strength values for the swollen biodiesel appeared to be higher. This contradiction highlights the importance of immersion duration which governs the final swollen state of rubber without disregarding other essential factors such as the compounding ingredients and specimen geometry.

The present paper proposes a first approach to investigating the response of elastomers swollen by palm biodiesel under fatigue loading conditions. For comparison, fatigue characteristics of elastomers swollen by conventional Malaysian diesel fuel are also investigated. For this purpose, the rubber specimens were immersed in these two different solvents in order to obtain swollen rubbers having the same degree of swelling. Moreover, the physical fatigue damage mechanism induced by the presence of biodiesel in the material at the macro and the microscale will also be probed.

2. Experimental setup

2.1. Material and specimen geometry

The material used here was of a commercial grade of carbon black-filled nitrile rubber. It was filled with 25 wt% of carbon black and its hardness was 60 shore A. It is denoted as F-NBR in the rest of the paper. Following Ch́ng et al. [10], the rubber specimens used in the study corresponded to a hollow-diabolo having a height, outer diameter, and wall thickness of 55 mm, 25 mm, and 6 mm, respectively. The detailed features of the specimen and chemical compositions of the palm biodiesel (B100) used in he study are provided in Fig. 1 and Table 1.

The swollen rubber specimens were obtained by immersing initially dry F-NBR in conventional diesel (B0) and palm biodiesel (B100) with the assigned immersion durations in Table 2. The percentage of volume change of the swollen rubbers were calculated using the following equation in accordance to the ASTM D471 standard:

$$\Delta V\% = \frac{(M_3 - M_4) - (M_1 - M_2)}{M_1 - M_2} \times 100 \tag{1}$$

where ΔV is the change in volume, M_1 is the initial mass of specimen in air, M_2 is the initial mass of specimen in water, M_3 is the mass of specimen in air after immersion, M_4 is the mass of specimen in water after immersion.

In the following sections, the swelling in rubber specimens is described in terms of the degree of swelling, J_s, defined by the ratio between the volume of swollen specimen and that of a dry specimen. In order to achieve a certain degree of swelling of F-NBR, it is worth noting that the required immersion duration will be different when different solvents are used.

No standard is followed regarding the choice of the specimens and immersion durations. The hardness and mass value of swollen rubbers were measured before and after fatigue testing. Later, the percentage of hardness and mass change were calculated using the following equations to investigate the effect of solvent type on the hardness and on the degree of swelling during the specimens undergoing fatigue testing:

$$\Delta H = \frac{H_i - H_s}{H_s} \times 100 \tag{2}$$

$$\Delta M = \frac{M_i - M_s}{M_s} \times 100 \tag{3}$$

where ΔH is the percentage of change in hardness, H_i is the hardness value of the swollen rubber after testing, H_s is the hardness value of the swollen rubber before testing, ΔM is the change in

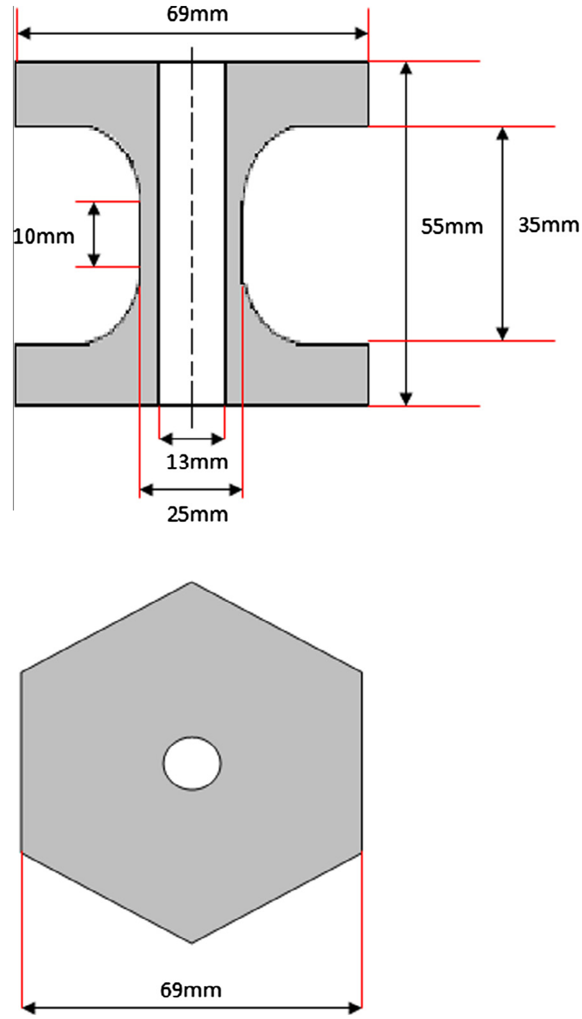

Fig. 1. Geometry of rubber specimen.

Table 1
Properties of B100 palm biodiesel.

Test	% Unit	Methods	Results
Ester content	% (m/m)	EN 14103	96.9
Density at 15 °C	kg/m^3	EN ISO 12185	875.9
Viscosity at 40 °C	mm^2/s	EN ISO 3104	4.667
Flash point	°C	EN ISO 3679	168
Cetane number	–	EN ISO 5165	69.7
Water content	mg/kg	EN ISO 12937	155
Acid value	mgKOH/g	EN ISO 3679	0.38
Methanol content	% (m/m)	EN 14110	<0.01
Monoglyceride content	% (m/m)	EN 14105	0.67
Diglyceride content	% (m/m)	EN 14105	0.2
Triglyceride content	% (m/m)	EN 14105	0.2
Total glycerine	% (m/m)	EN 14105	0.25