EFFECT OF FREQUENCY ON FATIGUE LIFETIME OF SBR AND NBR COMPOUNDS

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ABSTRACT

Fatigue behaviour of rubber is a very important characteristic due to its extensive use in many engineering applications. In most applications, rubber is commonly subjected to fluctuating loads, which often lead to failure due to the nucleation and growth of defects or cracks. Due to their viscoelastic behavior, rubbers have a high damping ability. Very often rubbers are subjected to different frequencies in the service, such as engine mounts. The effect of frequency on the fatigue lifetime needs deep investigations. In present work, the effect of frequency on the styrene butadiene (SBR) and nitrile-butadiene rubber (NBR) with 0,20,30,50 and 70 Phr of carbon black was investigated. It was found that the fatigue lifetime decreased with the increase of the frequency. Increasing carbon black (CB) contents in rubber improved the fatigue resistant and increased of the fatigue lifetime.

Keywords: Rubber, Fatigue lifetime, Carbon black and Frequency.

1. Introduction

Rubber materials are extensively used in industrial applications because of their large elastic deformation and great damping capabilities. Rubber parts, such as tires, seals, engine mounts and vibration isolators are often subjected to cyclic loading conditions in use. When these parts are subjected to fluctuating loads, they often fail due to nucleation and growth of defects or cracks. The main causes or factors affecting fatigue cracking in rubber are mechanical, thermal, environmental and chemical parameters [1-3]. Due to their viscoelastic behavior, rubbers have a high damping ability. However, rubber suffers from the fact that the energy lost as heat is small[4]. This results in heating of the rubber parts, which leads to premature failure of the parts. Therefore, fatigue analysis and effect of frequency on fatigue lifetime are very important in design procedure to assure the safety and reliability of mechanical rubber components.

The effect of loading frequency on the fatigue life depends on polymer structure. For rubbers that exhibit strain crystallization, frequency has little effect on fatigue life, while for amorphous rubbers, frequency is observed to have much effect[2]. Such effect has been attributed to time dependent steady crack growth, associated with viscoelasticity[1,5,6]. When the frequency of stressing is too high especially for a thick sample, generation of excessive heat results. The predominant cause of failure is now no longer mechanical fatigue but rather high temperature degradation. This type of failure, is often referred to as thermal runaway, these failures should not be confused with mechanical fatigue[1].

Fatigue lifetime is conventionally defined as the number of cycles to break a specimen into two pieces at a particular stress for stress controlled tests, or at a particular strain for strain controlled tests. Usually, for obtaining an average value of rubber fatigue life a large number of samples are necessary which are time consuming experiments. Two general approaches to

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fatigue analysis are available depending on the goals of the investigation, namely, fatigue crack nucleation and fatigue crack growth. The fatigue crack nucleation approach focuses on the life of a component until a crack is formed. The fatigue crack growth approach focuses on the growth of existing cracks or flaws in the material[7, 8]. In order to avoid large increase in temperature, Saintier et al. [6] performed fatigue test on vulcanized natural rubber (NR) filled with reinforcing carbon black at frequency (1–2 Hz). Le Cam et al. [9]set the strain rate to limit the rise of temperature at the sample surface under 20 ◦C in order not to superimpose thermal damage to mechanical damage; which corresponds to loading frequencies below 5 Hz. Zine et al. [10] performed the dynamic fatigue tests on Instron 8872 servo hydraulic testing device at room temperature under low frequencies from 1 to 4 Hz in order to minimize the hysteretic heating effect, the cyclic loading model was considered a sine wave function. Abraham et al. [11]used unfilled and filled ethylene propylene (EPDM) and styrene-butadiene (SBR) vulcanizates in the experiments under uniaxial cyclic tests, used dumbbell test specimens of 25 mm free length and 15 mm diameter. Dynamic fatigue tests have been made with a servo hydraulic test system (MTS 831.50) at room temperature with a sinusoidal load of 1 Hz. The frequency was chosen to induce failure due to the initiation and growth of cracks and to avoid large increases in temperature and consequent thermal breakdown. Woo et al.[12]used three-dimensional dumbbell specimen made of carbon-filled vulcanized natural rubber, for the fatigue life evaluation of the natural rubber. Fatigue tests were conducted in an ambient temperature of 70^{o}C and under the stroke controlled condition with a sine waveform of 5Hz and different mean displacements. Kim and Jeong [13] investigated experimentally and examined the effects of carbon black on the fatigue life, the hysteresis, the fracture surface morphology and the critical J-value of Natural rubber compounds filled with three kinds of carbon black N330, N650 or N990. The fatigue test was conducted at room temperature, 23 ^{o}C, and controlled displacement. The displacement was prescribed as a sinusoidal pulse at frequency of 1 Hz with maximum displacement of 16, 19 or 22 mm and zero minimum displacement.

Consequently, according to above literature review the effect of frequency on rubber fatigue lifetime still needs more study and deep investigations. In present work, the effect of frequency on the fatigue lifetime of styrene butadiene (SBR) and nitrile butadiene (NBR) rubber will be investigated under different carbon black contents.

2. Experiments

2.1 Materials and specimen preparation

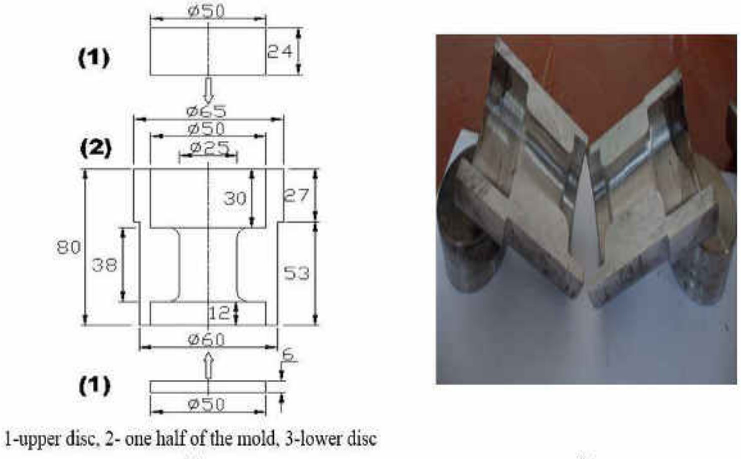
In present work, two types of rubber, namely, styrene butadiene (SBR-1502) and nitrile-butadiene rubber (NBR) are used in experiments. Styrene butadiene (SBR-1502) has styrene content of 23.5%, with specific gravity of 0.945±0.005 and Moony viscosity (ML4) of about 52 at 373K while nitrile-butadiene rubber (NBR) has acrylonitrile content of 33%, with specific gravity of 0.990±0.005 and moony viscosity (ML4) of about 45 at 373K. Different concentrations of N550 carbon black contents of 0, 20, 30, 50 and 70 phr (parts per hundred of rubber by weight) are used while the concentrations of the remaining additives were not changed to compose a rubber formulations namely S0, S1, S2, S3, S4 and N0, N1, N2, N3, N4 respectively. These rubbers were adopted through out the current tests. The formulation of rubber compounds used in this study are given in Table 1.

Table 1.
Composition of carbon black filled SBR and NBR systems.

Ingredients Phr.[a]	Formula No.									
	S_0	S_1	S_2	S_3	S_4	N_0	N_1	N_2	N_3	N_4
SBR-1502	100	100	100	100	100	-	-	-	-	-
NBR	-	-	-	-	-	100	100	100	100	100
ZnO	5	5	5	5	5	5	5	5	5	5
Stearic acid	2	2	2	2	2	2	2	2	2	2
Processing oil	10	10	10	10	10	10	10	10	10	10
Carbon black	0	20	30	50	70	0	20	30	50	70
MBTS	2	2	2	2	2	2	2	2	2	2
DPG	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sulfur	2	2	2	2	2	2	2	2	2	2

[a] Phr: Parts per hundred of rubber by weight.

All materials were provided from Marselleno Company for chemical industry and trade in Cairo, Egypt. Ingredients of the rubber compounds were mixed on a two-roll laboratory mill. The rubber compounds were vulcanized at 160 °C to provide diabolo specimen. The rubber test specimens were prepared in stainless steel molds, Fig. 1, inserted in a steel holder, Fig. 2. The molds are made split lengthwise in order to facilitate the removal of the specimens after vulcanization. The vulcanization process often was carried out on a screw press equipped with an upper and lower heating plates as shown in Fig. 3. Figure 4 (a) illustrates the main dimensions of diabolo test specimen, while Fig. 4 (b) shows isometric view of the specimen. To adjust the heater temperature, the temperature of lower and upper plates were measured by a thermocouple at different thermostat temperature valuses from this process it was found that the temperatures deviations were about ±5 degrees.



(a) (b)

Fig. 1. Specimen mold: (a) main dimensions, (b) photograph of the parts of the mold

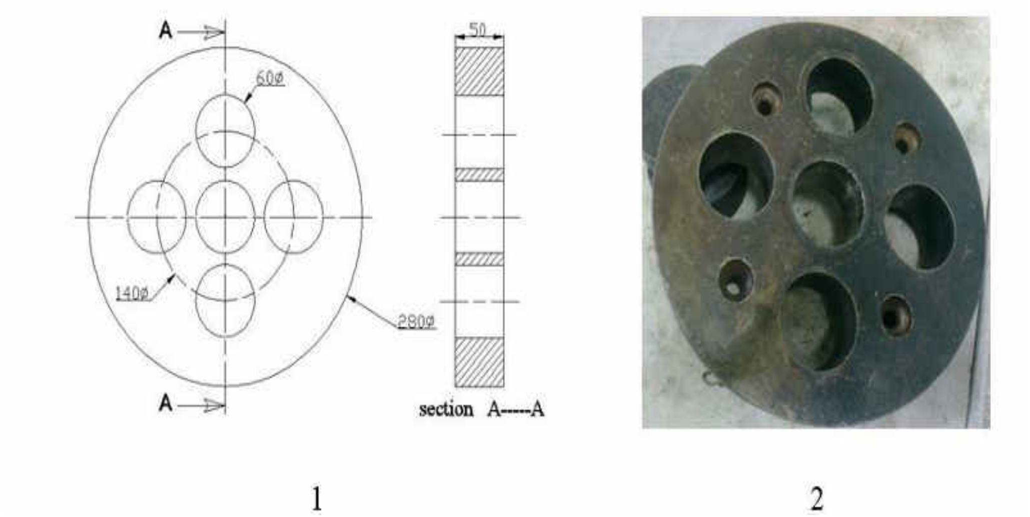


Fig. 2. Mold holder: 1- main dimensions, 2- photograph.

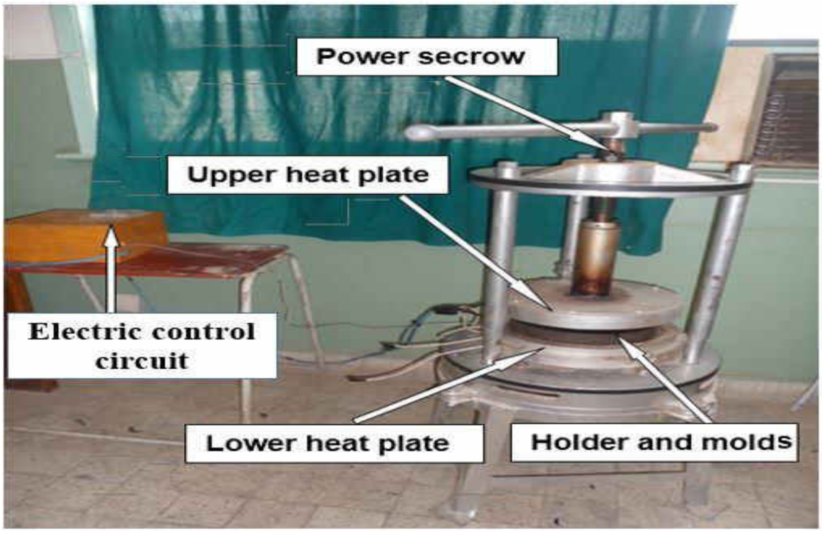


Fig. 3. A photograph of the screw press and heating system used in specimens preparation.

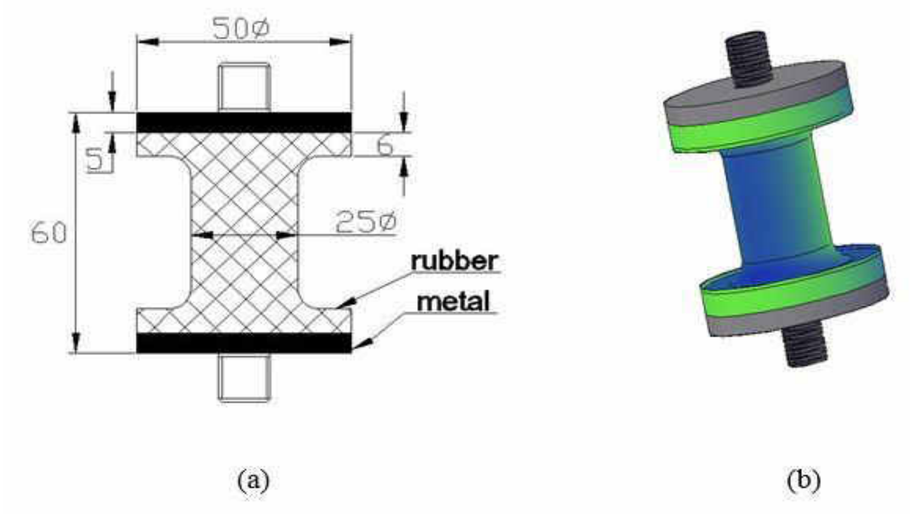


Fig. 4. Diabolo test specimen: (a) main dimensions, (b) isometric view.

2.2 Fatigue test rig

Fatigue tests were carried out on test rig shown in Fig. 5. This rig was designed and manufactured for testing the fatigue behaviour of rubber. It proved to be reliable and have good repeatability. Full descriptions of this rig and how it works as well as its dynamics are given in Ref. [14]. The main idea of the fatigue test apparatus is to generate a sinusoidal excitation (sine wave), which provides cyclic stress (tension, compression, or combination of both of them) on the rubber diabolo specimen up to its failure. Figure 5 shows a section elevation and section side view of the fatigue test apparatus. Two sheet metals are glued to the diabolo specimen at its ends by using cyanoacrylate glue. Then the specimen is fastened to the test rig by means of two bolts. One of them is connected to the movable plate (15) while the other is connected to the load cell (10), which is connected to the fixed plate on the base (1). Such arrangement provides a constant clamping force during the deformation of the sample, which is clamped between the two ends. Load cell type 546QDT-A5 with 220 kg full capacity, tension and compression, and 20V input is used to detect the load magnitude continuously. Figure 6 shows the calibration curve for the load cell. The load cell is connected to a 20V power supply and the output volt is indicated, monitored and recorded using a data acquisition system. The data acquisition consists of PC, a data acquisition board(National Instrument NI USB-6210 16 inputs, 16-bit, 250ks/s multifunction I/O), the Lab- View software and a stopwatch to record the elapsed time. The driving motor (3-phase, 360 V, 3 hp, 1440 rpm) was used to provide the desired speed, where the motor can be adjusted in the horizontal and vertical direction. A speed controller (IPM inverter model AS2-122 Adlee powertronic CO.LTD) is used to change the motor speed to a predetermined speed (frequency). To calibrate the speed controller, a digital speedometer tachometer (model

DT6235B) was used to measure the motor speed. From Fig. 7, it was found that the speed of the controller matches well the measured speed by the speedometer.

2.3 Experimental procedure

In order to study the effect of frequency on the fatigue behaviour of rubber the adopted rubber materials were subjected to cyclic tension/compression loading with constant strain amplitude and at different values of frequency. Tests were carried out at frequencies 3, 4 and 5 Hz with constant maximum strain of 0.471 (in tension) and minimum strain of 0.0816 (in compression). Each test was carried out several times and the number of cycles up to failure was recorded. The average of at least three repeated measurements was reported. All tests were carried out at room temperature, 25±3°C. The surface temperature of the specimen was measured by digital thermocouple for some specimens.

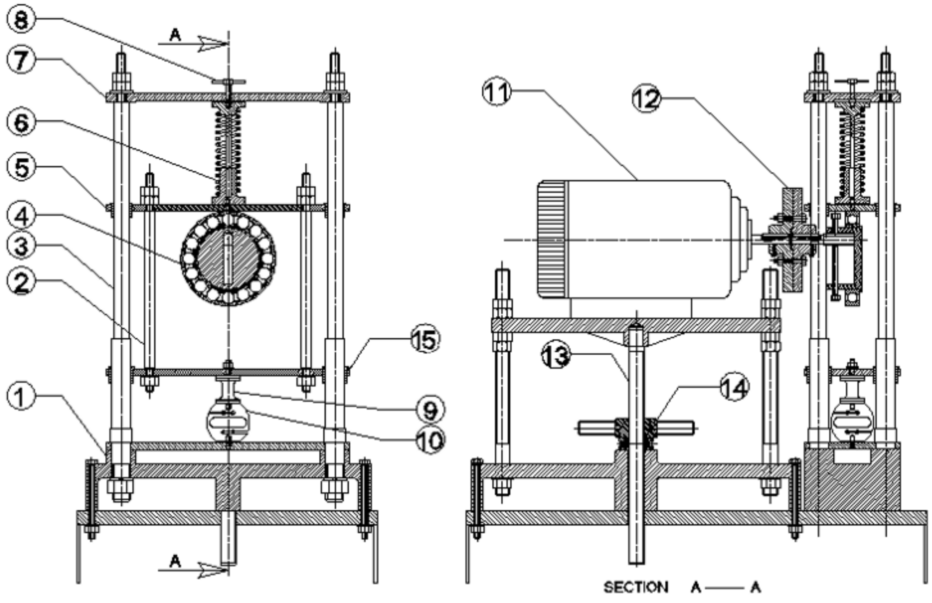


Fig. 5. Section elevation and section side view of rubber fatigue test apparatus (the specimen is in tension /compression): 1-base, 2-column, 3-main column, 4-ball bearing, 5-main plate, 6-cylindrical helical compression spring, 7-upper plate, 8-adjustin bolt, 9-rubber specimen, 10-load cell, 11-electric motor, 12-flange coupling, 13-power screw, 14-bronze nut, 15- lower plate.

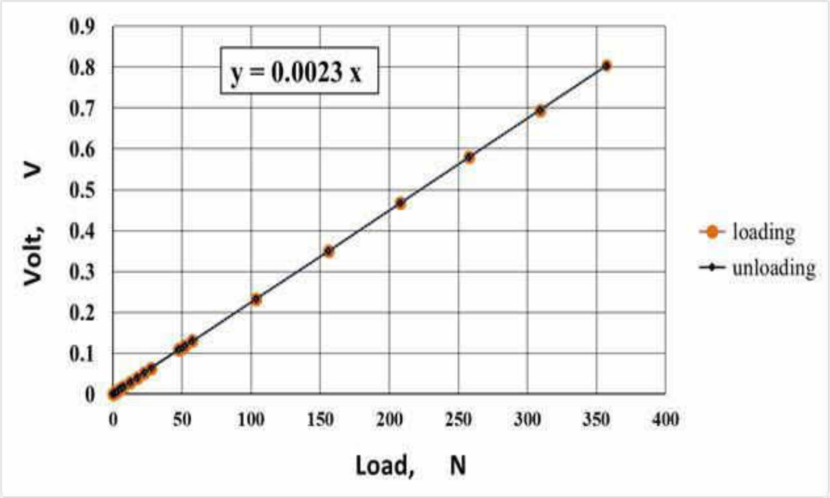


Fig. 6. Calibration curve of the load cell type 546QDT-A5.

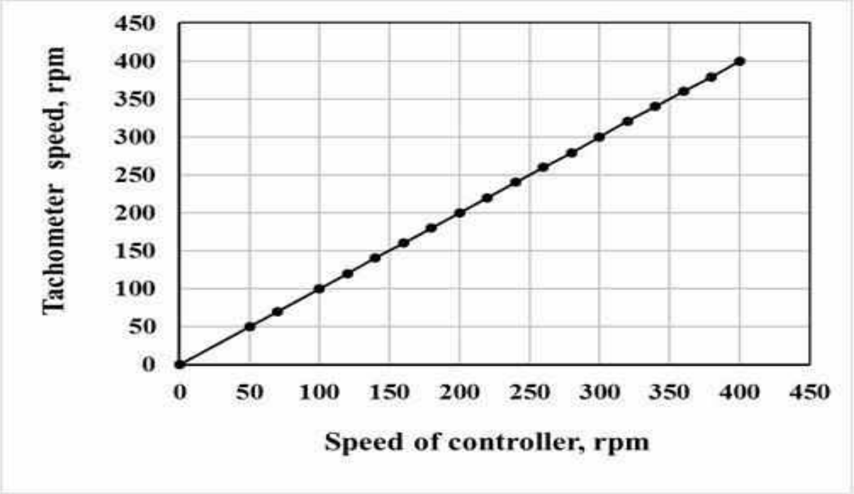


Fig. 7. Calibration curve of the speed controller.

3. Results and discussion

3.1 Effect of frequency on the fatigue lifetime

Fatigue tests were carried out on specimens to study the effect of the frequency on the fatigue lifetime of the adopted rubber materials. It was found that the crack was initiated at the middle of the specimen or around its middle. Then the crack propagated and led to failure. At failure, the specimen was broken into two pieces. This is in agreement with the results published in literatures [9]. Figures 8 and 9 show the obtained relation between frequency and number of cycles that induced failure, (fatigue lifetime) for SBR and NBR respectively, at different carbon contents (0, 20, 30, 50 and70 Phr of CB). From these figures, it is clear that, the number of cycles decreases with increase of the frequency. This may be attributed to the fact that the increase in the frequency increases the temperature of the specimen. Consequently, the crack will initiate faster and this will lead to the decrease in the fatigue lifetime. From Fig. 8 and 9 one can also notice that the number of cycles up to failure (lifetime) increases with the increase of the carbon black (CB) content. In other words, the increase of CB addition increases fatigue resistance of the rubber. Comparing Fig. 8 and Fig. 9, it is clear that the number of cycles up to failure of NBR compound is greater than that of SBR.

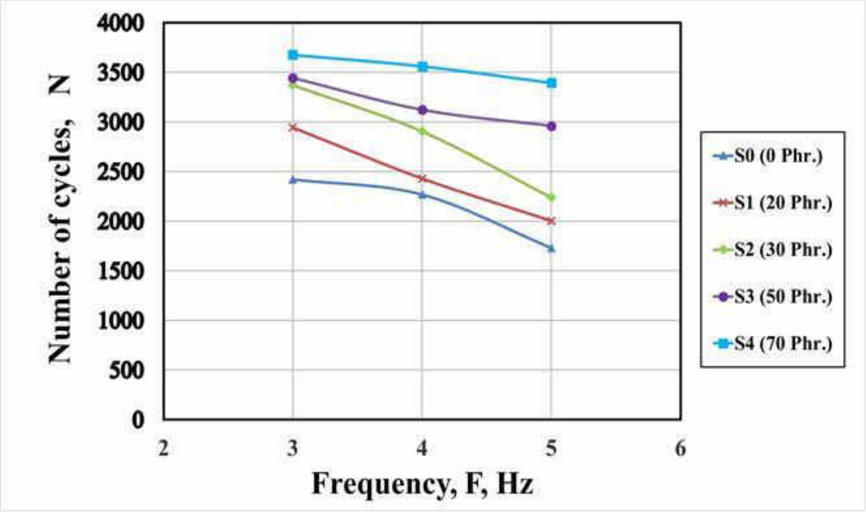


Fig. 8. Variations of number of cycles, N, versus the frequency, F, for SBR with different CB content.

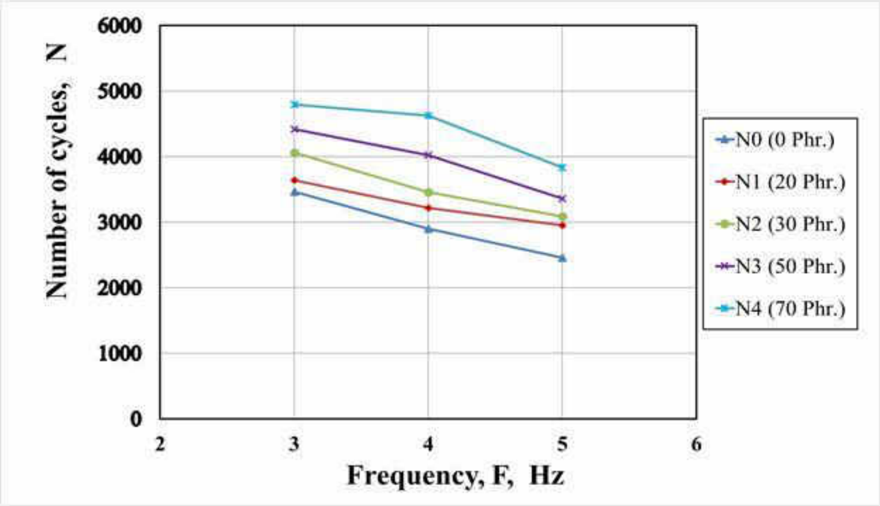


Fig. 9. Variations of number of cycles, N, versus the frequency, F, for NBR with different CB content.

3.2 Effect of frequency on surface temperature of specimen

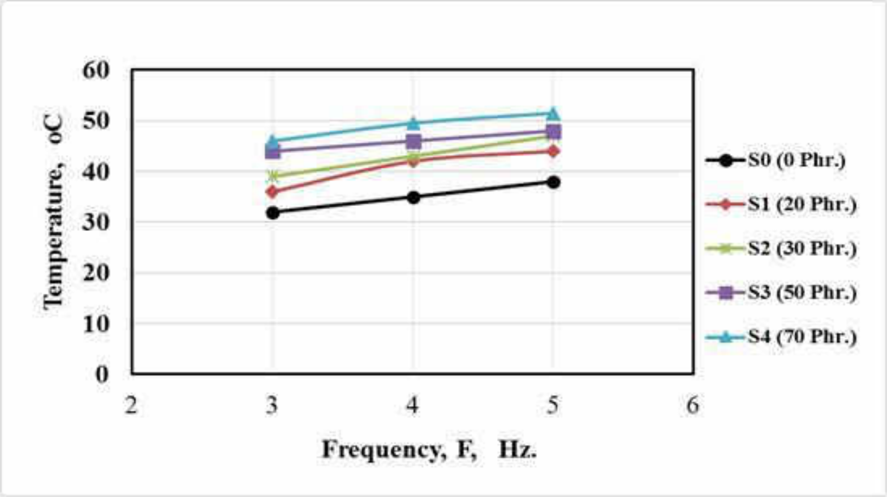


Fig. 10. Variation of surface temperature versus frequency, F, for SBR specimens.

Figures 10 and 11 show the relations between frequency and surface temperature of the specimens at failure. In these figures, it is clear that the surface temperature of specimen increases with the increase of the frequency. In addition, the surface temperature increases with the increase of the CB content in rubber.

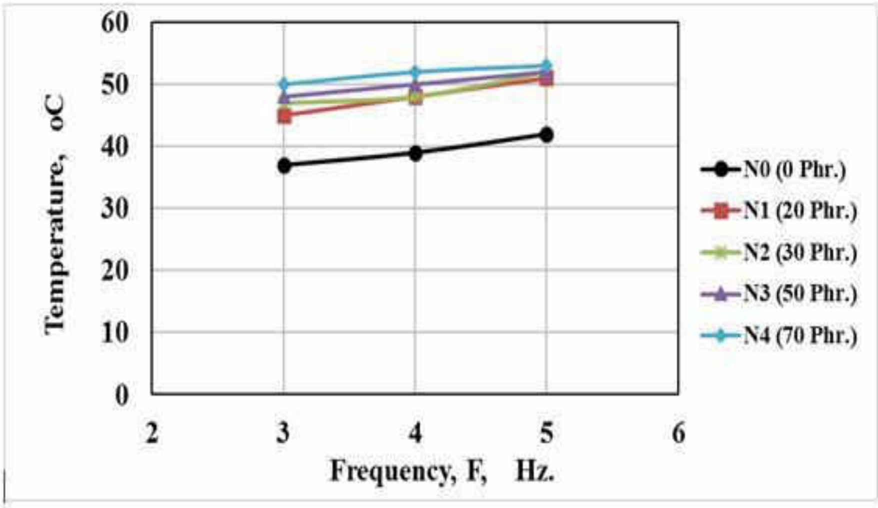
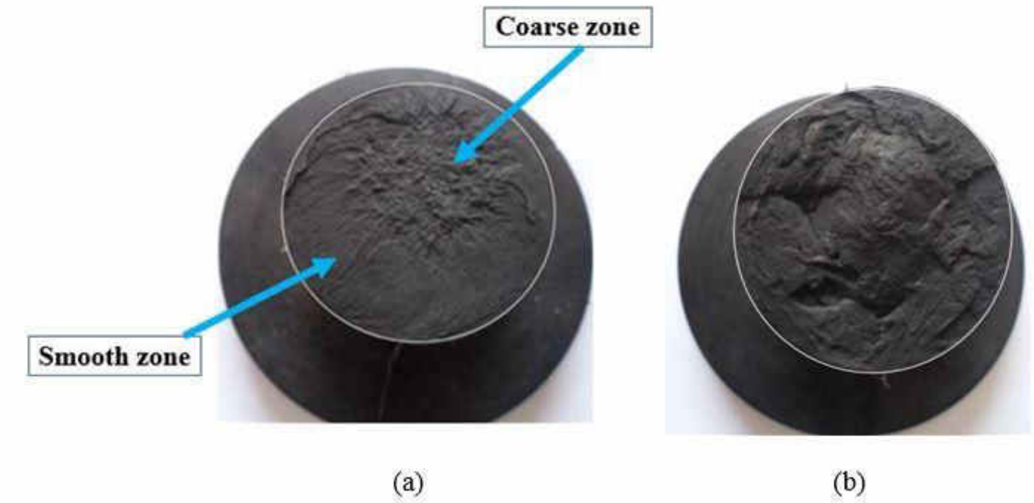


Fig. 11. Variation of surface temperature versus frequency, F, for NBR specimens

3.3 Effect of frequency on surface fracture appearance

In general, when a rubber component filled with carbon black is subjected to loading, the rubber matrix around carbon black is strained more than the rest. If a large or repeated force is applied, carbon black is separated from the matrix nucleating microcracks [13]. Also, there are other sources of microcracks in rubber including contaminants or voids in the matrix, imperfectly dispersed compounding ingredients and surface flaws. Figure 12 illustrates the photograph of specimen surface fracture appearances of NBR with 20 and 70 Phr of CB contents. In Fig.12 (a), it is clear that the surface of fracture for NBR with 20 Phr of CB consists of two zones, namely, smooth and coarse zones. The smooth zone was formed due to stress concentration in one crack (or more). Then, the crack (or cracks) propagated during loading producing a smooth surface. The crack propagation continued until the remaining surface area became unable to sustain the applied load. At this moment, brittle fracture took place forming a coarse zone. Figure 12 (b) illustrates the specimen surface area at fracture for NBR with 70 Phr of CB. From this figure, it is clear that the whole surface area is coarse. This may be attributed to the increase of CB content. As explain above the number of points at which crack may be nucleated is large due to increase in CB content, i.e. due to large number of cracks induced in the specimen a sudden brittle fracture took place leaving a coarse surface area. Thus, the amount of CB addition has noticeable effect on the surface fracture appearance. Careful examination of the surface area at fracture at different values of frequency, it was noticed the there was no significant effect of frequency on the surface fracture appearance for the same CB content.



(a) (b)

Fig. 12. Specimen surface facture appearance of NBR: (a) 20 Phr, (b) 70 Phr of CB.

4. Conclusions

From the current investigation of the effect of frequency on fatigue lifetime of SBR and NBR compounds, the following points can be concluded:-

1- The increases in the frequency led to an increase in the surface and internal temperature of specimens resulting in premature failure.
2- The increase of CB content in rubber results in an increase of the surface temperature of the specimens.
3- The fatigue lifetime of rubber decreased with increase of the frequency.
4- Fatigue lifetime of rubber can be improved by increasing of the carbon black additions.
5- The number of cycles up to failure (fatigue lifetime) of NBR compound is greater than that of SBR compound.
6- The surface fracture appearance is dependent on CB content and independent on the frequency.

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تأثير التردد على مقاومة الكلال لمركبات الستايرين بيوتاديين والنيتريل بيوتاديين المطاطية

الملخص العربى

يعتبر سلوك الكلال في المطاط من الصفات والسمات الهامة نظراً للإستخدامات الواسعة له في التطبيقات الهندسية المختلفة. حيث يتعرض المطاط، في هذه التطبيقات، لأحمال متكررة بشكل مستمر مما يؤدي الى إنهياره نتيجة لتكون وإنتشار الشروخ فيه. يستخدم المطاط في كثير من التطبيقات التي يتعرض خلالها الى ترددات مختلفة ومتنوعة ولذلك فان دراسة تأثير التردد على مقاومة الكلال مهم جدا. وفي هذا البحث تم دراسة تأثير التردد على مقاومة المطاط للكلال حيث أجريت الدراسة على مركبات الستايرين بيوتاديين (SBR)، والنيتريل بيوتاديين (NBR) المطاطية بنسب كربون 0, 20, 30, 50, 70 أجزاء من الكربون لكل مائة جزء من الوزن للمطاط. وقد تم إختبار العينات تحت ترددات 3, 4, 5 هرتز. ووجد انه كلما زاد التردد قلت مقاومة المطاط للكلال. وكلما زاد نسبة الكربون في المطاط زادت مقاومته للكلال بإختلاف التردد. كما أظهرت النتائج تأثير التردد على درجة حرارة سطح العينة, ولا يوجد تأثير مهم يذكر للتردد على مظهر سطح الفشل (الإنكسار).