14th International Conference on
AEROSPACE SCIENCES & AVIATION TECHNOLOGY,
ASAT - 14 – May 24 - 26, 2011, Email: asat@mtc.edu.eg
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Experimental Determination of Some Design Properties of Viscoelastic Solid Propellant Using Uniaxial Tensile Test

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Abstract: An experimental data treatment is introduced to manage with the tensile test responses of highly non-linear viscoelastic materials. This work investigates the effects of strain rate and temperature on the behaviour of solid propellant treated as non-linear viscoelastic material. The material investigated was rubber composite based on hydroxyl-terminated poly butadiene (HTPB).Viscoelastic design properties were derived from the experimentally measured tensile data. Design properties include isochronous stress–strain diagrams at different strain rates and temperatures.

Keywords: Solid propellant, Mechanical behavior, Non-linear viscoelastic, Strain rate.

1. Introduction

The mechanical behaviour of viscoelastic material has received great attention in recent years and has been studied in detail from both the theoretical and experimental points of view. Supported by the increasing power of the available numerical tools, the past decade has seen a tremendous development of viscoelastic models to describe the mechanical behavior of particle filled elastomers. These models have proved to be efficient in numbers of industrial applications ranging from tires conception to solid rocket propellant grains mechanical analysis. However, if a considerable literature addresses the theoretical and numerical aspects regarding these models, very few deal with the difficult path which has to be followed from the collection of the experimental observations to the identification of the model constants. The aim of this work is to propose an original method, based on the accumulated knowledge of solid propellants mechanical behavior, to build up from experimental data given from uniaxial tensile the type, and the behavior of the material from the response of solid propellant tests at various strain rates and temperatures.

2. Experimental Work

2.1 Test Machine

The Zwick Z050 universal test machine (figure 1) was used for carrying out all the mechanical tests. This machine has remote control software which could acquire record, analyze, store and print test data with minimum manual effort. The maximum permissible test load is 10KN, and the range of crosshead speed varies from 0.0005 to 1000 mm/min with

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Figure 1 Zwick Z050 universal test machine

accuracy 0.004 % of the set speed. The machine is provided with temperature chamber having a range varies from -70 to +250 ^{o}C.

2.2 Specimens

The used specimens in this work were produced according to JANNAF [1] (Joint Army-Navy-NASA-Air Force Propulsion Committee). Sample dimensions as shown in Figure (2).

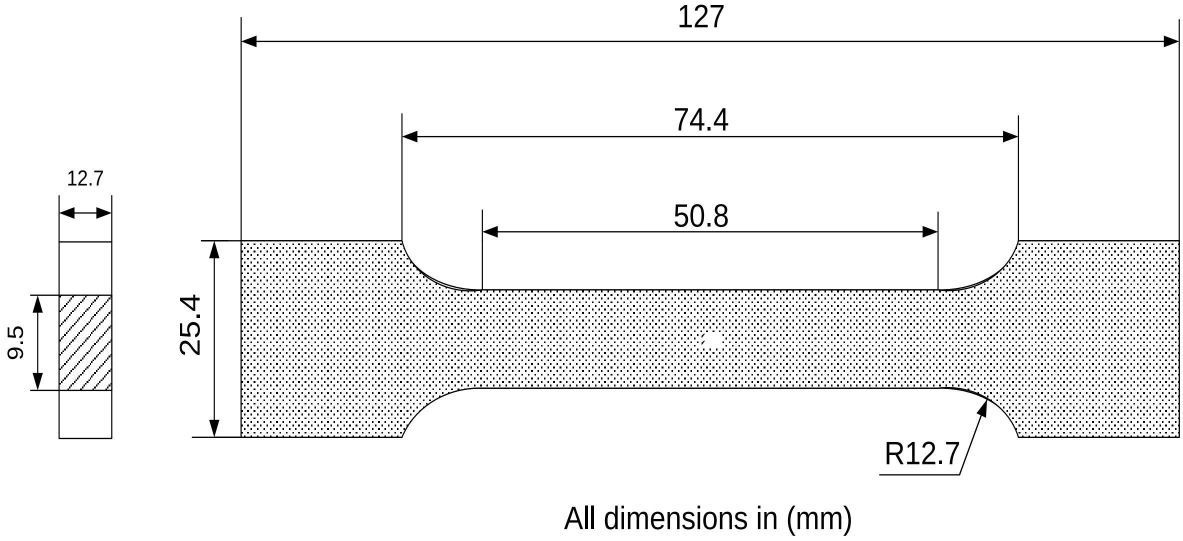

Figure 2 JANNAF standard sample

The test specimens were prepared by casting into carton boxes and placed in a large curing oven with the temperature controlled at 55^{o}C for a total curing time of 240 hours. Curing temperature was designed to accelerate the crosslinking reactions, i.e. harden the propellant rapidly. Then, they were checked for internal micro defects (like air bubbles-cracks-porosities-foreign materials) by using non-destructive X-Ray test as shown in Figure (3). After that, the accepted specimens were stored at ambient temperature in dry place as shown in Figure (4).

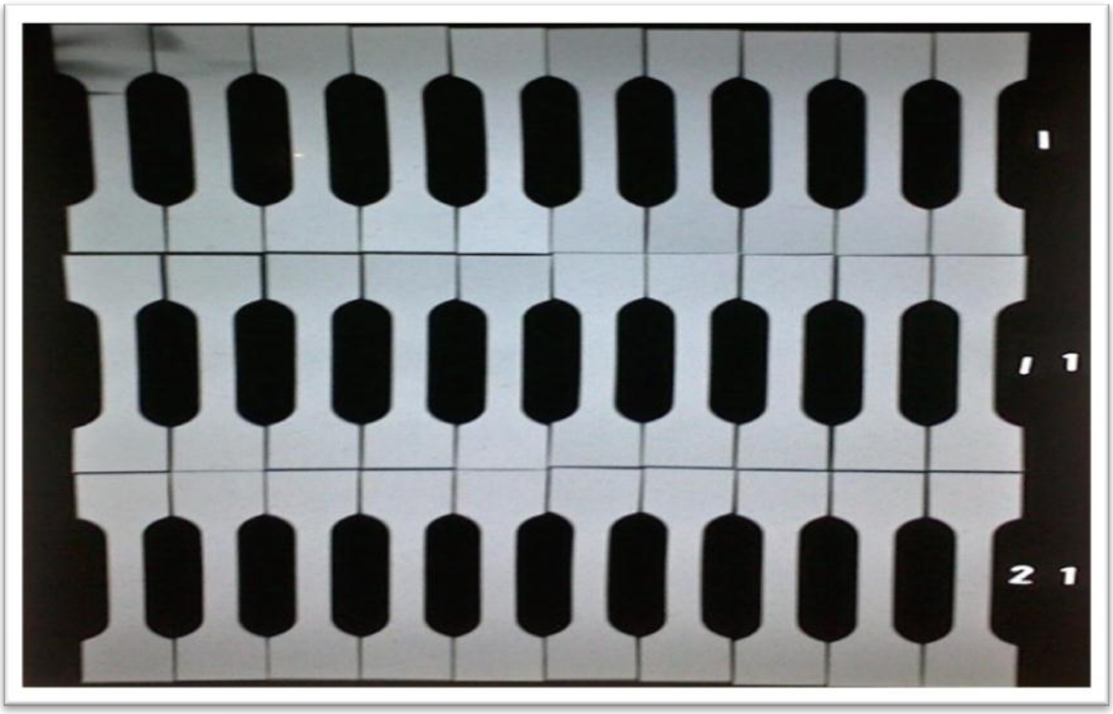

Figure 3 X-Ray film for JANNAF specimens

Figure 4 JANNAF specimens

2.3 Tensile Tests

The tensile tests are widely used for the analysis of the propellants behavior as well as for the manufacturing controls of these propellants [2,3]. However tensile tests alone are not sufficient to predict the complete behavior of the viscoelastic material. The following parameters can be identified from the tensile test that allows a better representation of the aspects of the experimental curves. These parameters are:

- Modulus of elasticity which defines the properties of a material as it undergoes stress, deforms, and then returns to its original shape after the stress is removed. It is a measure of the stiffness of a given material.
- Ultimate strength which is the maximum stress level reached in a tension test. In general the strength of a material is its ability to withstand external forces without breaking.
- Maximum strain is the strain at maximum stress.
- Break stress.
- Break strain.

The Young's modulus is determined in the straight line, starting part of the stress- strain curve. The available software of the testing machine offers the following algorithms for Young's modulus determination:

- Secants.
- Regression gradient.
- Tangent.
- Hysteresis.
- Automatic.
- Manual.

In this work it was found that the regression line is the best fitting line to the experimental test curves, the regression line is calculated in the range from the beginning of young`s-modulus determination at zero strain to the end of the first linear region (initial slope) on stress-strain curve [4] as shown in figure (5). Also figure (5) shows that the parameters can be identified from the tensile test

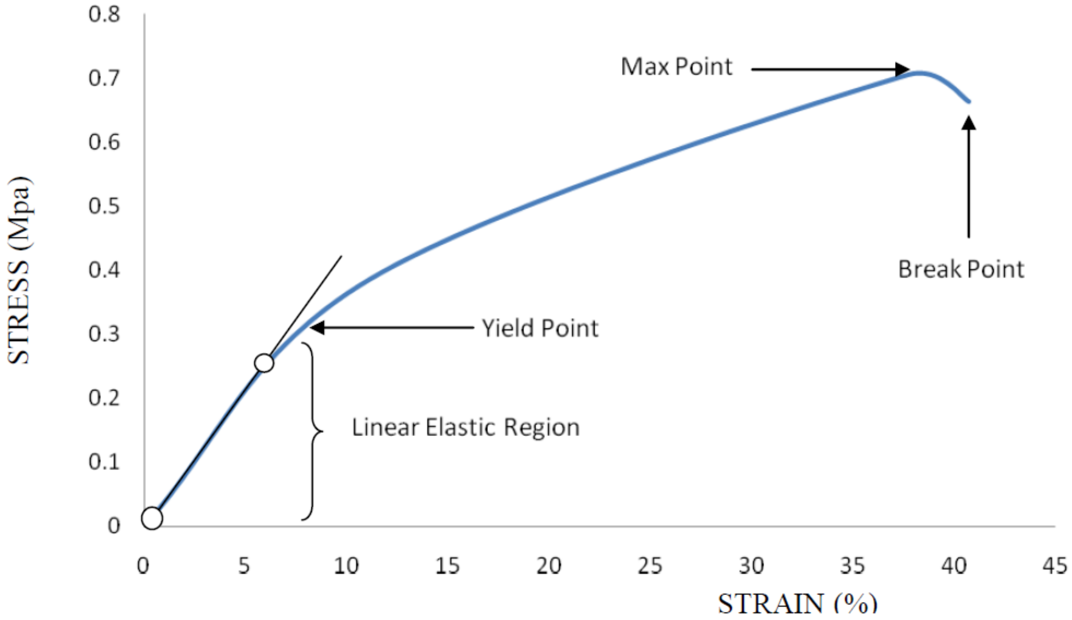

Figure 5 The parameters identifiable from the tensile test

Values of these parameters vary with each propellant type, pressure, temperature, and strain rate. Also, aging and humidity are common factors which affect these parameters. Composite propellants consist of small particle size solids in a polymeric matrix. The bonding surfaces between the binder and the fillers are very important. During the tensile test the physical nature of the propellant results in an increase of the volume of the specimen, caused by the occurrence of vacuum holes around some crystalline fillers [2]. In general, during the tensile test there is failure of the bonding between some fillers and the binder, failure of the binder close to a solid particle. Vacuum holes are created, and their size increases with the stress/strain increase. When these vacuum holes reach a significant size (several microns) they cause micro failures initiating small cracks in the binder, and causing failure of specimen. Figure (6) shows that the results of tensile test at different strain rates at ambient temperature (20 ^{o}C) .The usual test crosshead speed is 50 mm/min [5], also we use 0.5mm/min and 5mm/min for slow strain rate response measurements, and 150mm/min, 300mm/min, 500mm/min, and 1000mm/min for high strain rate response. Note that every experimental test was carried out on three specimens and the mean value of these three results is used for the analysis, also for every test the specimens were pre-conditioning at least for three hours in external conditioning chamber with humidity (20 - 25) %. During each test the specimen was maintained at the desired temperature by specially test chamber.

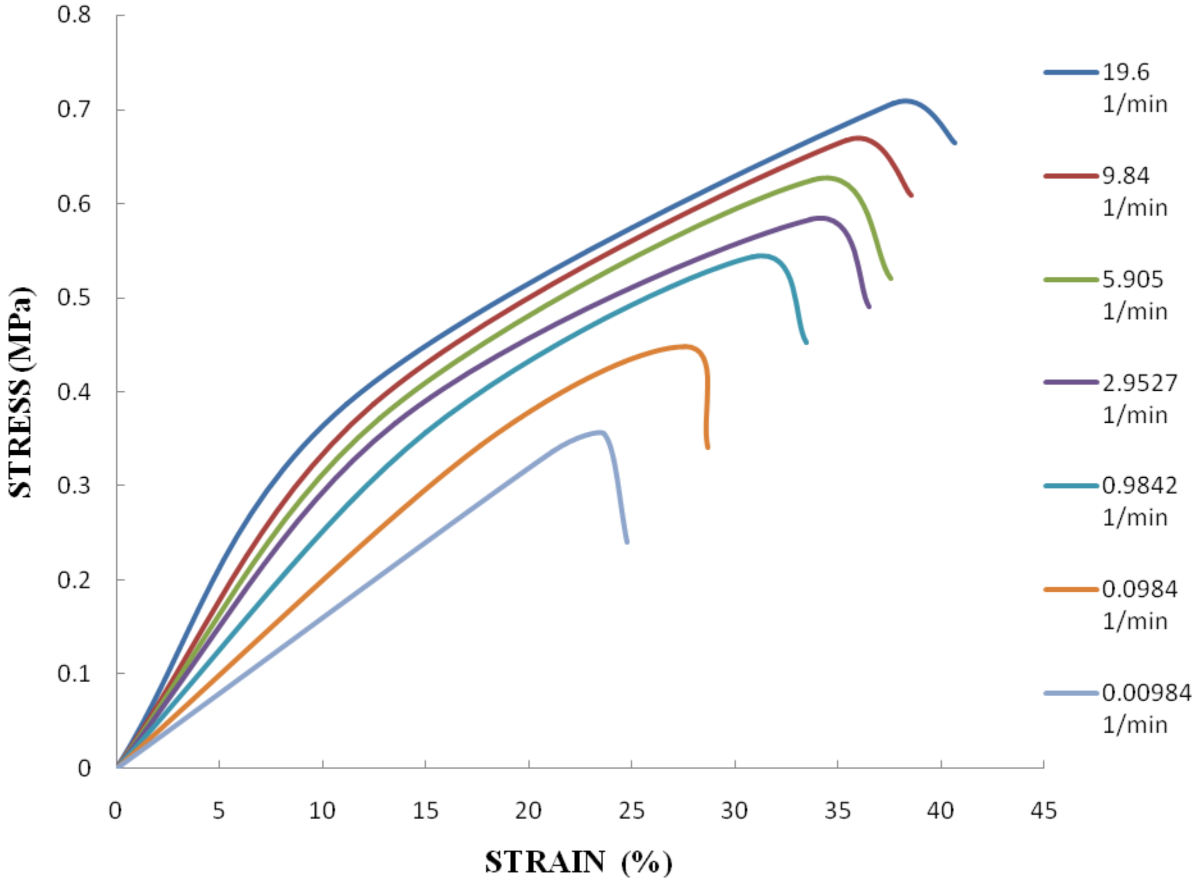

Figure 6 Effect of strain rate on stress-strain curves

From Figure (6) it can be noted that the material has viscoelastic behavior because the strain rate or the rate of loading modifying the response of the material, while in elastic material the strain rate plays no role. Also it can be show that at small strain rates (0.5 - 5 mm/min) the material behave in a linear viscoelastic manner where the solid particles effectively reinforce the binder [6], but at high strain rates (150 -300 – 500 -1000 mm/min) the bond between the oxidizer and binder breaks down and effectiveness of the reinforcement is reduced so the material behave in non-linear viscoelastic behavior. It is necessary to distinguish the following actions:

- Quick stimulus (which simulates high strain rate)
    - Ignition.
    - Vibrations.
    - Accelerations.
- Slow stimulus (which simulates small strain rate)
    - Long-time storage in the same position.

In other words it can be treated the solid propellant as linear viscoelastic material in analytical solutions or in computational analysis in case of slow stimulus, but in case of quick stimulus the solid propellant must be treated as nonlinear viscoelastic material. If the temperature is constant the increasing strain rate tends to increasing the young`s modulus, which increases the maximum strain, and increasing the maximum stress as shown in figures (7), (8), and (9).

Vacuum holes are created and their size increases with stress\strain increases. This phenomenon generates a dissipation of energy resulting in a viscous nature inherent to the binder [2] .Also we can calculate the work done from the start of the test until break by using the following integration:

$$W = \int_{l_o}^{l_f} F(t)dl$$

where W is the work done in Joules, F is the applied force in Newton l_o is the initial sample length, and l_f is the final sample length in meters. The area under the curve of the tensile test represents the work done until the break. Figure (10) shows that when the strain rate increases the area under the curve increase that mean the work need to break increase.

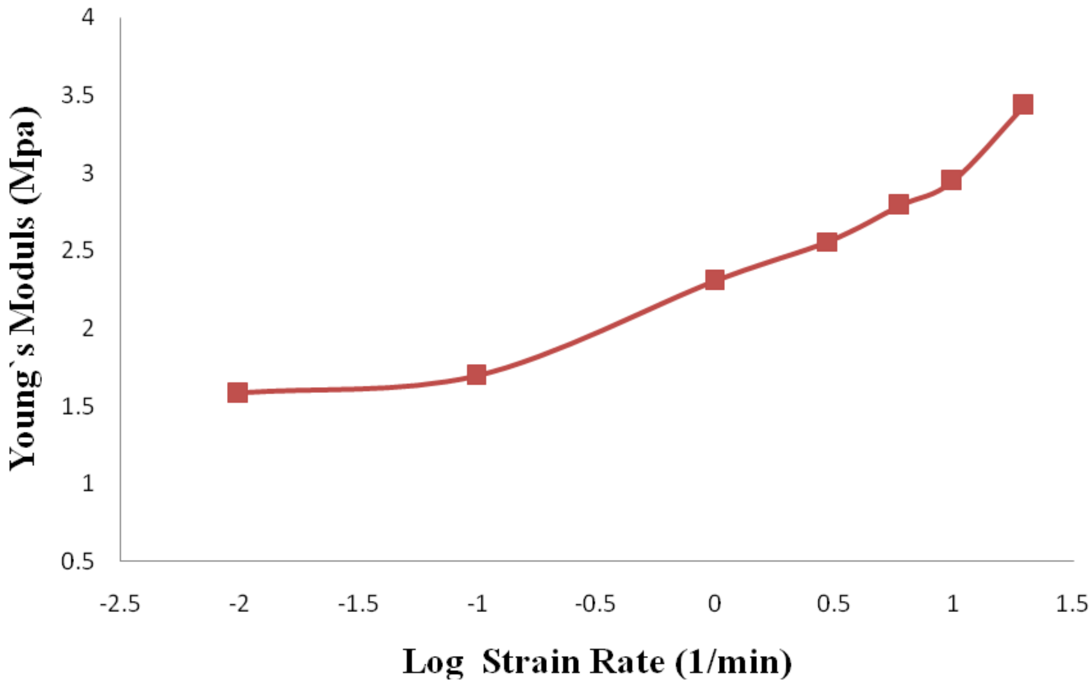

Figure 7 Young`s modulus vs. log strain rate

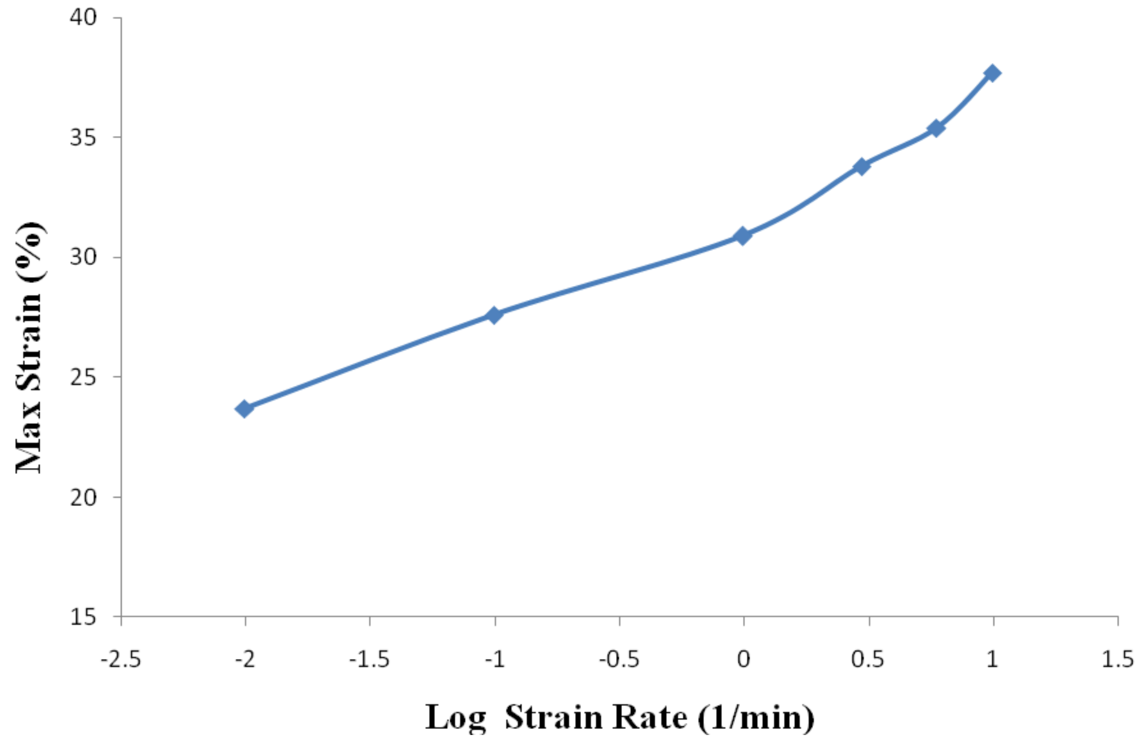

Figure 8 Maximum strain vs. log strain rate

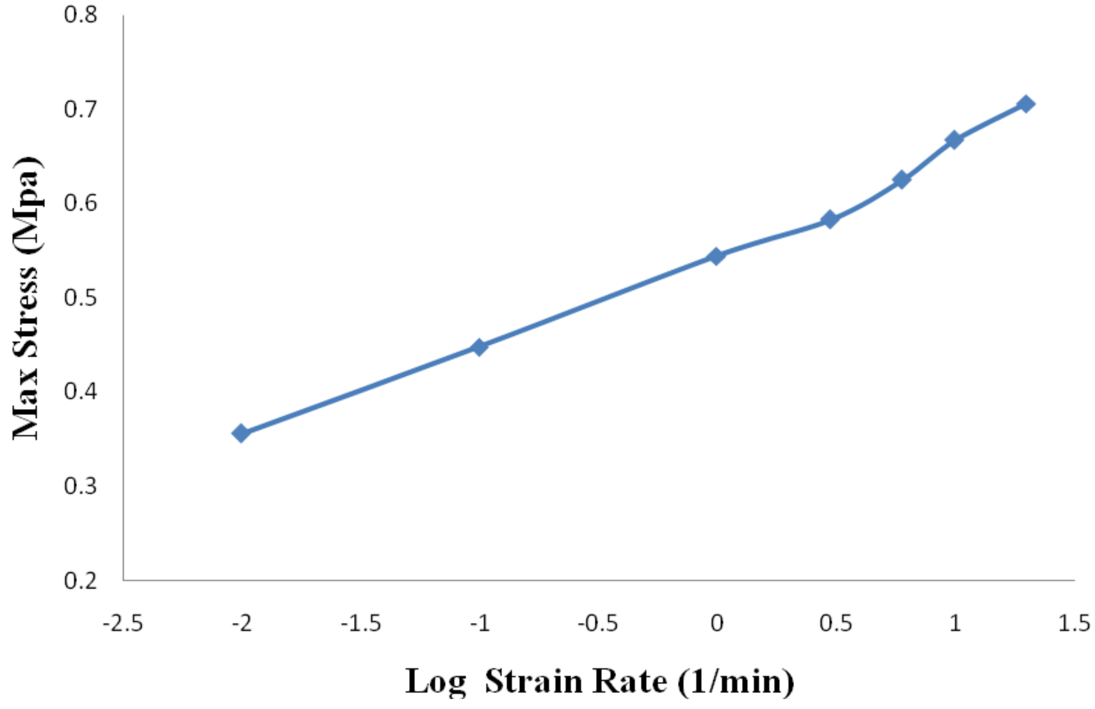

Figure 9 Maximum stress vs. log strain rate

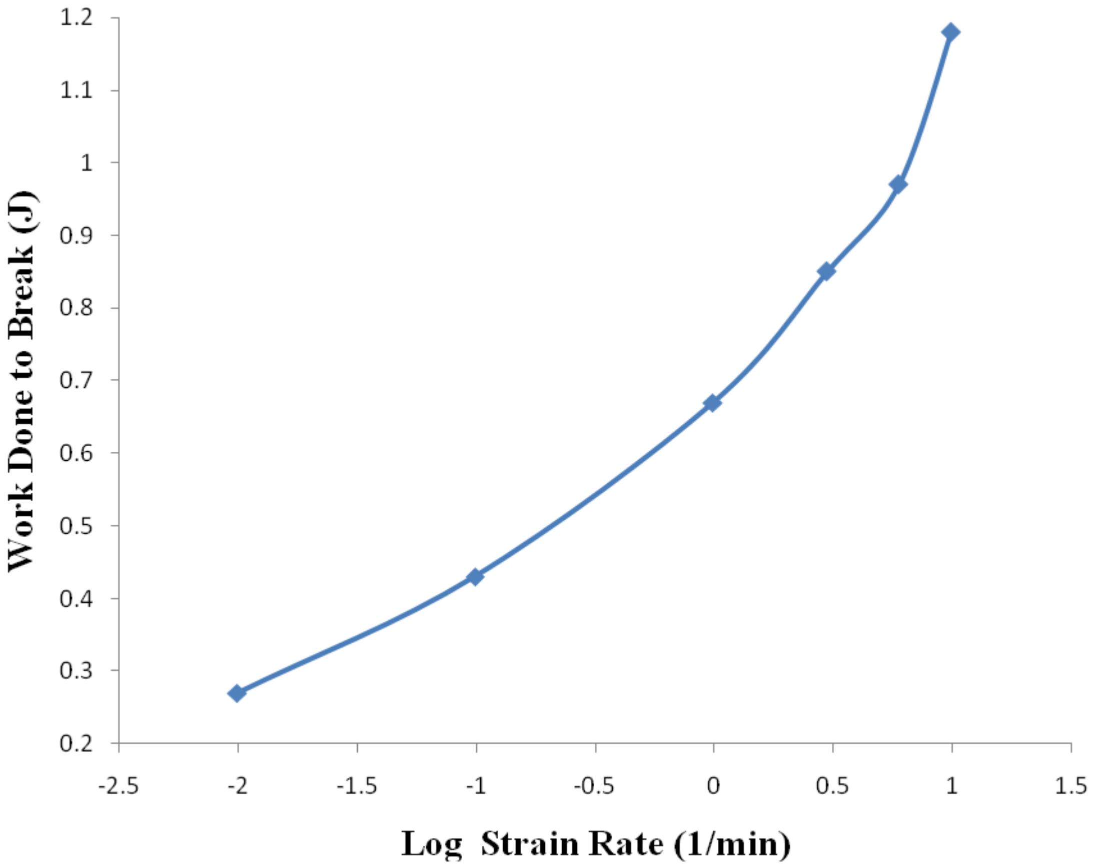

Figure 10 Work done to break vs. log strain rate.

Figure (11) shows that the tensile tests at constant crosshead speed and different isothermal temperatures conditions ranging from the crosslinking temperature (60:80)^{o}C down to the glass transition temperature (-40:-70) ^{o}C to show the effect of temperature in the behavior of the material [1].

The mechanical behavior of propellants may be altered at low temperature because of structural changes in the binder. An important modification of the mobility of the polymeric chain that occurs when the temperature decreases and goes through a phase called (glass transition). The physical and mechanical properties of the polymer are greatly modified, as shown in figure (11) when the temperature decreases the elastic modulus in particularly increases significantly and the capability of elongation at certain level of stress becomes very small. But it can be note that at high temperature the crosslinking chains between the polymers going to break which result decreases in elastic modulus and the capability of elongation at certain level of stress becomes too high. In other words at constant crosshead speed the increasing in temperature tends to decreasing in young`s modulus, decreasing in maximum strain, decreasing in maximum stress as shown in figures (12), (13), and (14) respectively.

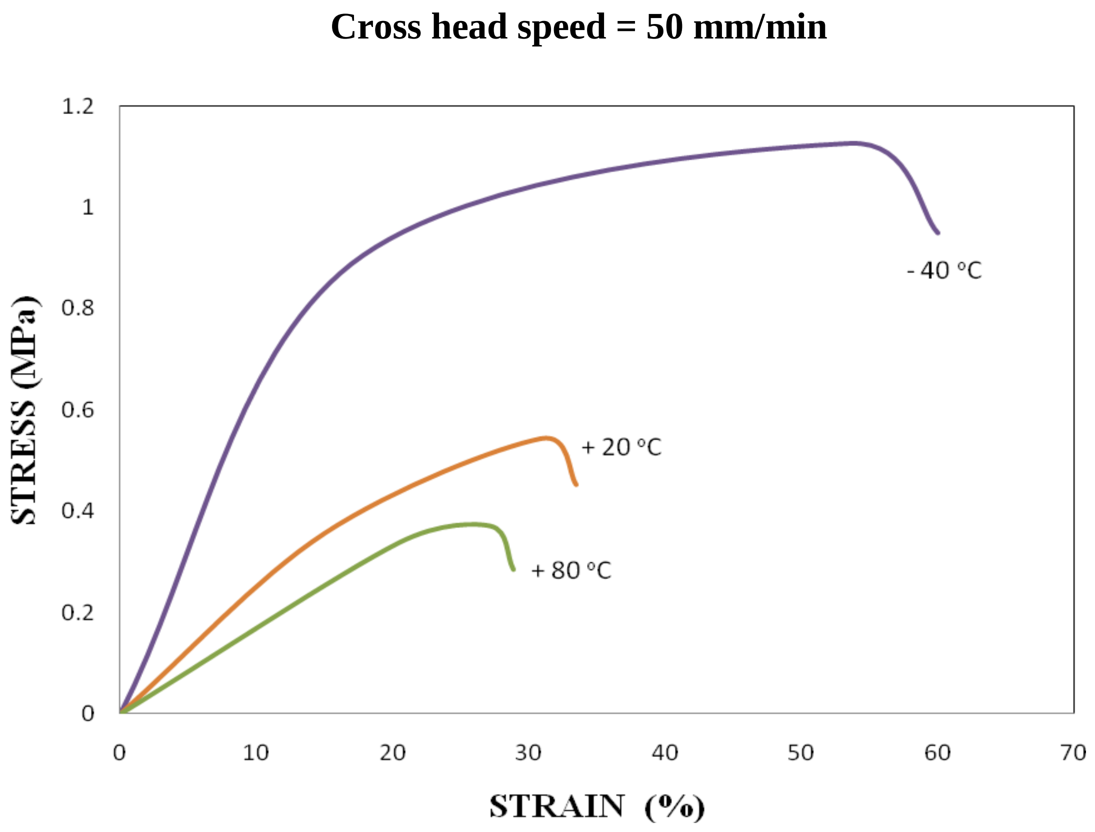

Figure 11 Effect of temperature on stress-strain curves.

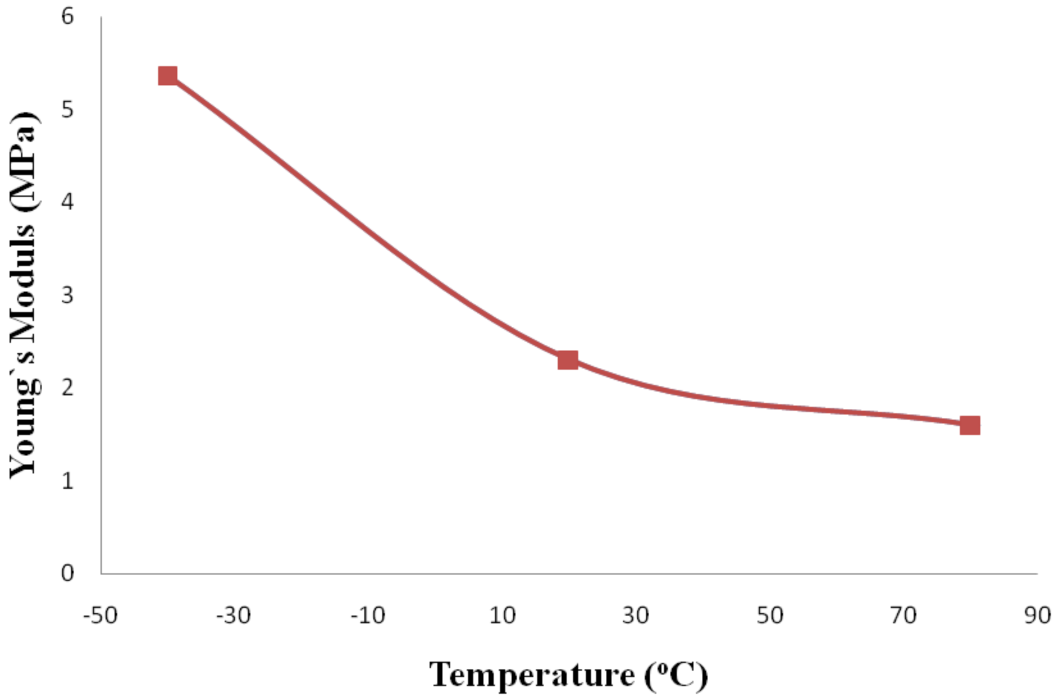

Figure 12 Young`s modulus vs. temperature

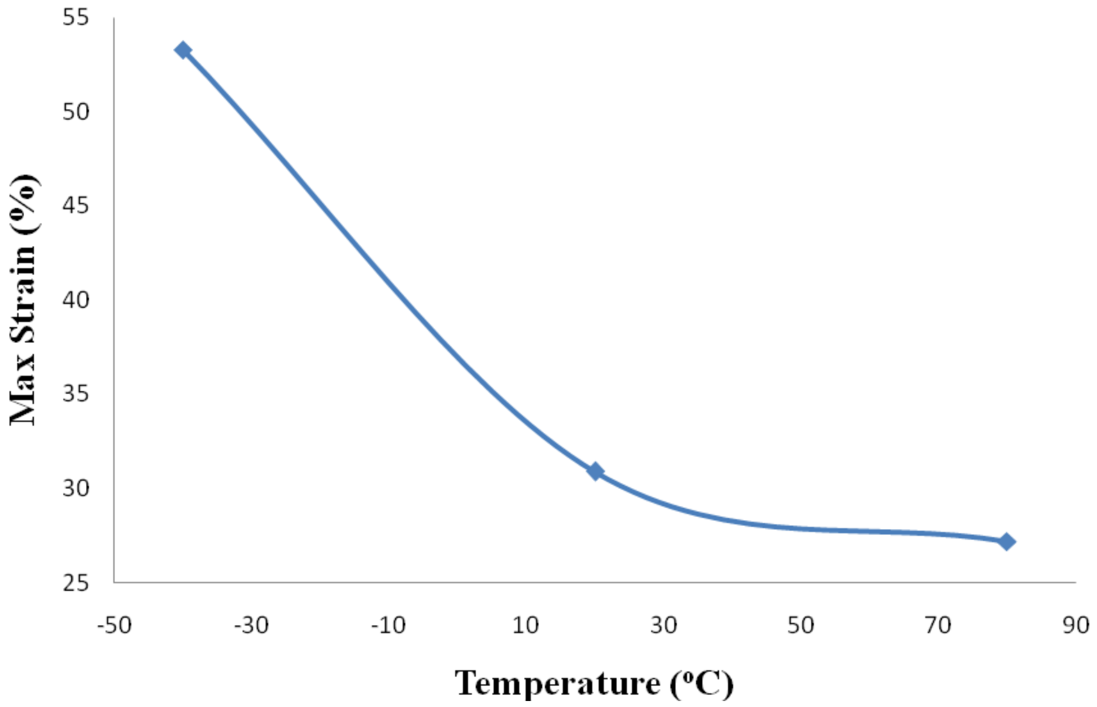

Figure 13 Maximum strain vs. temperature

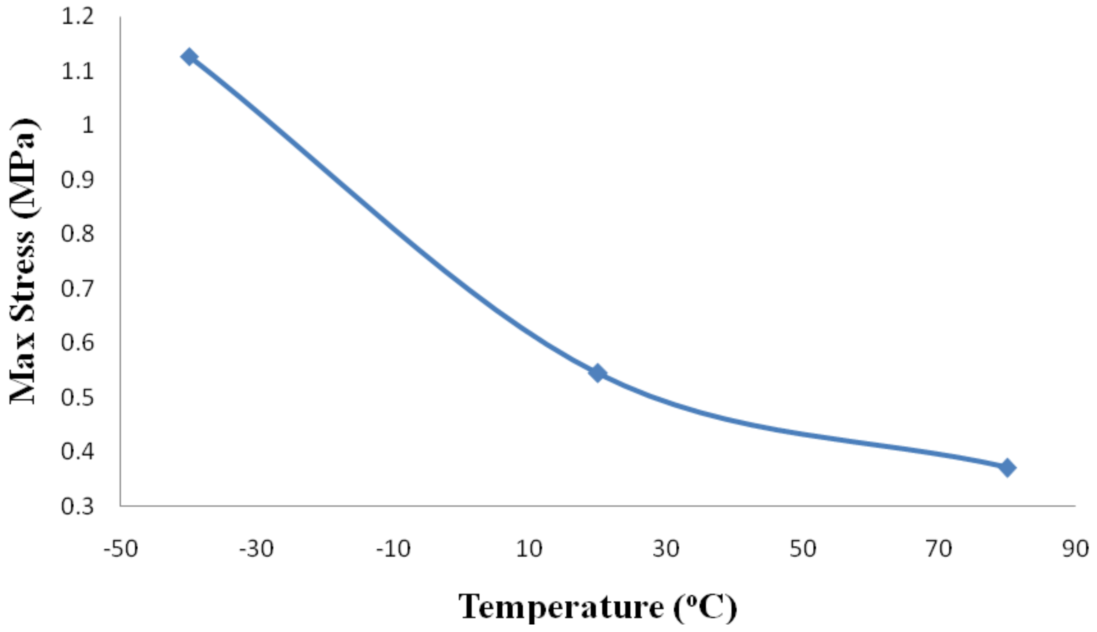

Figure 14 Maximum stress vs. temperature

3. Conclusion

The mechanical characteristics of the propellant are not obtained as straight forward as those for steel or other material, since the propellant is viscoelastic material, i.e. the material remember all the stresses even if these stress happen in different times, so both temperature and strain rate must be taken into consideration. For propellant, which are times and temperature dependent and have non-linear stress-strain curves, the definition of the young`s or elastic modulus depends on the type of the method used during the tensile test. For the propellant being time and temperature dependent, they have a different mechanical behavior when changing the temperature and strain rate. From experiments we have the following results:

1. Young`s modulus, maximum stress, and strain at maximum stress increase proportionally as the strain rate increases.
2. In general, for a solid propellant, decreasing temperature has the same effect behavior of increasing the strain rate.
3. Both the break strain and strain at maximum stress follow a non-monotic behavior.
4. The viscoelastic effects in solid propellant arise from the binder, as a viscous material, and from the friction between particles and binder during the debonding process.
5. The non-linear behavior is related to the dewetting process which is also known to be time-temperature dependent.
6. The non-linear response depends strongly on the storing conditions of time (aging) and temperature.

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