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Mechanical and structural behavior of a swelling elastomer under compressive loading

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ABSTRACT

Swelling elastomers are a new breed of advanced polymers, and over the last two decades they have found increasing use in drilling of difficult oil and gas wells, remediation of damaged wells, and rejuvenation of abandoned wells. It is important to know whether an elastomer type or a certain seal design will function properly and reliably under a given set of oil or gas well conditions. This paper reports the results of an experimental and numerical study conducted to analyze how compressive and bulk behavior of an actual oilfield elastomer changes due to swelling. Tests were carried out on ASTM-standard compression and bulk samples (discs) before swelling and after different swelling periods. Elastic and bulk modulii were experimentally determined under different swelling conditions. Shear modulus and Poisson's ratio were estimated using derived isotropic relations. Cross-link chain density and number average molecular weight were obtained using predictive equations of polymer physics. Mechanical testing was also modeled and simulated using the nonlinear finite element package ABAQUS, material model being Ogden hyperelastic model with second strain energy potential.

Values of elastic and shear modulus dropped by more than 90% in the first few days, and then remained almost constant during the rest of the 1-month period. Poisson's ratio, as expected, showed a mirror behavior of a sharp increase in the first few days. Bulk modulus exhibited a fluctuating pattern; rapid initial decrease, then a slightly slower increase, followed by a much slower decrease. Salinity shows some notable effect in the first 5 or 6 days, but has almost no influence in the later days. As swelling progresses, chain density decreases, much more sharply in the first week and then showing almost a steady-state behavior. In contrast, cross-link average molecular weight increases with swelling (as expected), but in a slightly fluctuating manner. Very interestingly, Poisson's ratio approaches the limiting value of 0.5 within the first 10 days of swelling, justifying the assumption of incompressibility used in most analytical and numerical models. In general, simulations results are in good agreement with experimental ones. Results presented here can find utility in selection of swelling elastomers suitable for a given set of field conditions, in improvement of elastomer-seal and swell-packer design, and in modeling and simulation of seal performance.

1. Introduction

Many new and ground-breaking technologies are closely associated with advances made in the area of materials science and engineering. Swelling elastomer, a recently developed advanced polymer, is an apt example. Elastomers are highly elastic rubber-like materials that can stretch up to 500% of their original length [1]. Swelling elastomers swell when they interact with fluids like water or oil [2]. Swelling results in changes in volume, thickness, density, hardness and mechanical properties [3,4]. Swelling rate for a specific elastomer depends on the temperature and composition of the swelling medium. Water-swelling elastomers swell through absorption of saline water following the mechanism of osmosis, while oil-swelling elastomers swell by absorption of hydrocarbons through a diffusion process [5]. Elastomers have low modulus of elasticity (E) ranging from 10 MPa to 4 GPa (E-value for most metals is in the 50–400 GPa range), but very high elongation reaching up to 1000% (elongation for metals is always less than 100%).

Maintaining the profitability of old wells and economically exploiting new reservoirs (that were previously inaccessible) are two of the main challenges facing the oil and gas industry. Also, zonal isolation and optimization of the hole-size with economic production for both conventional and deep water wells are ongoing problems [6,7]. Swelling elastomers have found extensive use in highly sophisticated new well applications where other materials fail to work [8]. Their successful applications include solution of drilling problems in deep shelf high-pressure high-temperature

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Nomenclature

E	Elastic/Young's modulus (N/m^2)	N	chain density (mol/cm^3)
K	bulk modulus (N/m^2)	M_C	number average chain molecular weight (g/mol)
G	shear modulus (N/m^2)	k	Boltzmann constant (J/K)
ν	Poisson's ratio	T	absolute temperature (K)
σ	engineering stress (N/m^2)	n	number of crosslink chains
ε	engineering strain (normal)	m	mass (kg)
γ	engineering strain (shear)	V	volume (m^3)
τ	shear stress (N/m^2)	ρ	density (kg/m^3)
p	hydrostatic stress (N/m^2)	R	general gas constant (J/K-mol)
δ	volume dilatation (cm^3)	N_A	Avogadro's number (#/mol)

(HP/HT) wells [9]; use in conjunction with expandable tubular technology (SET) for improved well production [10,11]; water shutoff and other types of zonal isolation [12]; use in horizontal wells and in tandem with coiled tubing for better reservoir management [13,14]; optimization of multizone fractured wellbores [15]; etc.

Investigation of the swelling and mechanical behavior of these elastomers is essential in resolving application and design issues. When an elastomer seal is positioned in the well, environmental conditions initiate the swelling and the material may continue to swell throughout its life. Swelling results in the alteration of mechanical properties and sealing response. If elastomer seals are put into use without thoroughly studying these changes, resulting seal failure may cause loss of time, money, and other resources. Rework is not only time consuming but at times not possible at all. Failures may even cause the oil or gas production from the well to stop.

One critical aspect of good design is appropriate material selection. This cannot be done without reliable knowledge of how the material will behave when exposed to different loads, temperatures, and other environmental conditions. As swelling elastomers are basically used as sealing elements in petroleum applications, and as seals are under compressive loading, investigation of the mechanical behavior of elastomers under compression is very important.

Contemporary elastomer seal design is usually based on laboratory tests and trial-and-error method. To test all possible combinations of field parameters (elastomer material, water salinity, oil type, temperature, pressure, etc.) in the laboratory is almost impossible, especially for extended swelling periods. Numerical modeling and simulation of seal design, validated by experimental results, may provide answers for all possible scenarios, which cannot be attempted experimentally. Numerical simulations (FEM based, for example) can shorten the lead time for development of robust sealing applications in difficult or new oil and gas wells, offering an accurate and cost effective alternative to extensive testing.

This paper discusses four key mechanical properties of swelling elastomers (elastic modulus E, bulk modulus K, shear modulus G, and Poisson's ratio ν) and two polymer characteristics (cross-link chain density N, and average molecular weight M_C) needed for design improvement and performance analysis of elastomer seals. These parameters were experimentally determined for an elastomer being currently used by the petroleum industry, before and after various stages of swelling. To strengthen the experimental results, compression and bulk tests were also simulated using a commercial FEM package. After rigorous evaluation, the most appropriate hyperelastic material model (currently available in FEM packages) was used for these simulations. Simulation results are generally in good agreement with experimental values.

2. Theoretical background

As mentioned above, the paper discusses the effect of swelling on four mechanical properties that describe the macroscopic-level behavior of the elastomer, and on two microscopic-level characteristics that are related to polymer structure. Brief theoretical background and inter-relationships of these quantities are presented in this section.

2.1. Macroscopic behavior: isotropic relationships

Once the values of E and K are established experimentally, shear modulus (G) and Poisson's ratio (ν) can be determined using the isotropic relations derived below. The elastic behavior of any isotropic material is completely described by Hooke's law [16]:

$$\varepsilon_x = \frac{1}{E}[\sigma_x - \nu(\sigma_y + \sigma_z)], \quad \varepsilon_y = \frac{1}{E}[\sigma_y - \nu(\sigma_z + \sigma_x)], \quad \varepsilon_z = \frac{1}{E}[\sigma_x - \nu(\sigma_z + \sigma_y)], \tag{1}$$

where σ is the engineering stress and ε is the strain. Being in the elastic region, engineering shear strain (γ) is obviously proportional to shear stress (τ):

$$\gamma_{yz} = \frac{1}{G}\tau_{yz}, \quad \gamma_{zx} = \frac{1}{G}\tau_{zx}, \quad \gamma_{xy} = \frac{1}{G}\tau_{xy}. \tag{2}$$

Fig. 1 shows a body under a state of pure shear and its Mohr circle representation giving the principal stresses:

$$\sigma_1 = \tau_{xy} \quad \sigma_2 = -\tau_{xy} \quad \sigma_3 = 0 \quad \tau_{12} = 0. \tag{3}$$

We can use Eq. (1) (Hooke's law) to find the principal strains:

$$\varepsilon_1 = \frac{\tau_{xy}(1+\nu)}{E}, \quad \varepsilon_2 = \frac{\tau_{xy}(1+\nu)}{E}. \tag{4}$$

Shear strain γ_{xy} can also be expressed in terms of the principal strains:

$$\gamma_{xy} = \varepsilon_1 - \varepsilon_2 = \frac{2\tau_{xy}(1+\nu)}{E}. \tag{5}$$

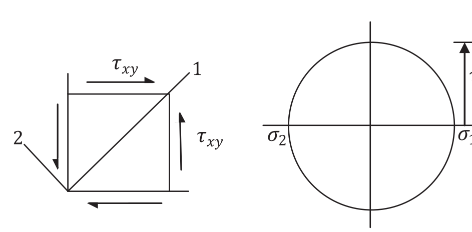

Fig. 1. A body under a state of pure shear, and its Mohr circle representation.