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Material Behaviour

Rupture of swollen styrene butadiene rubber

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ABSTRACT

Elastomers have recently been explored to make swellable packers in the oil industry, which have many advantages over traditional cement packers. In the applications, the elastomers absorb solvent and swell against the confinement, which can seal zones in the borehole. In addition, swollen elastomers are usually subjected to a large pressure difference, which can cause fracture of the elastomer. In this article, we conduct experimental studies of the rupture behavior of an oil-swellable elastomer, styrene butadiene rubber (SBR), swollen in hexadecane. This combination of elastomer and swelling agent can be considered representative of oilfield applications. Pure-shear tests are used to measure the stretch at rupture and fracture energy of swollen SBR with different swelling ratios. It is found that swelling can significantly reduce both the stretch at rupture and the fracture energy of the swollen elastomer. Using the measured fracture energy, we have also successfully predicted the stretches at rupture of SBR for a simple extension test with different volume swelling ratios.

1. Introduction

Crosslinked elastomers can absorb solvent and swell. Recently, swellable elastomers have been widely explored in a myriad of engineering applications. For example, swelling elastomers have been developed as self-regulating valves in microfluidics [1–4]. Swellable elastomers have also been explored to make swellable packers in the oil industry to replace traditional cement packers [5–8]. In these applications, swollen elastomers may rupture when the deformation is large with a sufficiently large flaw size in the material [9,10].

Although rupture of dry elastomers has been intensively studied over several decades [11–17], few systematic investigations of fracture in swollen elastomers have been conducted. It is known that the viscosity of an elastomer can be dramatically decreased by solvent-induced swelling which, consequently, can cause a reduction in the fracture energy of the elastomer. It has also been shown that threshold fracture energy of an elastomer can be measured in its swollen state with low strain rate and high temperature [15–17]. The measured threshold fracture energy of elastomers agrees reasonably well with the predictions from classical Lake-Thomas theory [18]. Such agreement has provided important insights into the rupture of elastomers. Nevertheless, the rupture process of swollen elastomers in engineering applications usually greatly deviates from threshold conditions. Therefore, it is practically important to study rupture of swollen elastomer under various loading conditions and swelling ratios. Moreover, it is critical to verify if the fracture energy of swollen elastomer measured in one loading condition can be used as a material parameter to predict its rupture in other loading conditions.

In this article, we focused on the rupture of swellable elastomers used in oilfields. During the last decade, swelling of elastomers has been widely used in oilfield to seal the fluid flow in well bores [19–21]. Fracture in swollen elastomers has been recognized as one important failure mechanism for seals [10]. To study rupture of swollen elastomers, we carried out experiments on styrene butadiene rubber (SBR) swollen in hexadecane by following the “pure-shear” method first proposed by Rivlin and Thomas [14]. From these experiments, we found that both the fracture energy and the stretch at rupture decrease with increase of the degree of swelling and decrease of loading rate. Furthermore, using the measured fracture energy, we successfully predicted the stretch at rupture of elastomer for simple extension tests with different swelling ratios.

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2. Experiments

An oil-swellable elastomer, styrene butadiene rubber (SBR) (purchased from the website: http://www.rubbersheetroll.com/sbr-commercial-grade.htm), was used to swell in hexadecane at room temperature of about 20 °C. Following our previous work [6], this combination of elastomer and swelling agent can be considered representative of oilfield applications.

2.1. Preparation of SBR sheets with different swelling ratios

In the swelling experiments, a dry SBR sheet with length $L = 60$ mm, height $H = 6$ mm and thickness $B = 1.5$ mm was immersed in hexadecane. The length, width and thickness of the swollen sample were measured at different times until it reached equilibrium state. The weight of the swollen sample was also measured at the same time. We then calculated the volume swelling ratio (VSR) and weight swelling ratio (WSR), which are defined as the ratio between the increase of the volume/weight and the initial volume/weight of the dry SBR sheet, respectively. Fig. 1(a) and (b) plot VSR and WSR as a function of time, respectively. It can be seen that the sample reached equilibrium state within 40 h.

To prepare SBR sheets with different swelling ratios, we immersed the sheets in solvent for different periods of time. Then, the swollen sheets were removed from the solvent and sealed in soft impermeable plastic films for 24 h for homogenization. It is noted that the weight of swollen sheets measured before and after the application of the impermeable films ensured that no evaporation occurred during homogenization. For tests with a pre-cut, a 10 mm long pre-cut was introduced freshly by using a sharp knife after the sample was homogenized.

2.2. Measurement of fracture energy of swollen SBR sheets

We adopted pure-shear tests to measure fracture energy of swollen SBR sheets. The tests were carried out in a mechanical testing machine (Zwick/Z010). During the test, to avoid possible slip of the samples in the grips, SBR sheets were firmly glued to two acrylic plates. Then, the acrylic plates were firmly clamped in the testing machine. During the test, the samples were stretched in the direction along its height at a constant extension rate. In our experiments, three extension rates were selected as 0.2/min, 2/min, and 20/min. It is noted that these extension rates were defined relative to the initial height of the sample. For instance, if the initial height of the specimen was $H = 6$ mm and the extension rate was 2/min, the stretching speed was then set to be 12 mm/min. The tensile force and displacement were recorded automatically by the testing machine. Tests were made in triplicate.

Fig. 2 is the photographs of dry SBR specimen during a “pure-shear” test. Fig. 2(a) shows the undeformed state of a pristine sample. During the extension test of the pristine sample, an arc-shaped edge was observed when the stretch was relatively large (Fig. 2(b)). Eventually, the specimen ruptured (Fig. 2(c)).

The undeformed state of the specimen with a pre-cut is shown in Fig. 2(d). During the test of the specimen with a pre-cut, with the increase of stretch, the crack-tip was first blunted, as shown in Fig. 2(e). At a certain stretch, the crack started to propagate, as shown in Fig. 2(f). The critical point at which the crack started to propagate can be clearly seen with the naked eye. The stretch corresponding to this critical point is defined as the stretch at rupture [22].

Figs. 3 and 4 show the nominal stress-stretch curves for the specimens without and with a pre-cut. The specimens were swollen in hexadecane with different volume swelling ratios, 0.0% (dry state), 12.3% (swollen in hexadecane for 1 h), 33.9% (swollen in hexadecane for 5 h) and 71.8% (fully swollen state). Three stretch rates 0.2/min, 2/min and 20/min were adopted in the pure-shear test.

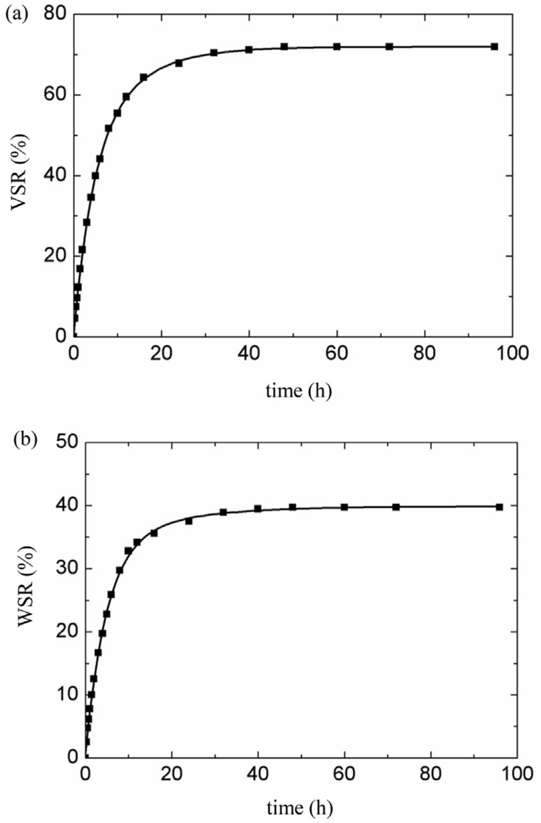

Fig. 1. Experimental measurements of swelling ratio of SBR in hexadecane as function of time. (a) Volume swelling ratio (VSR) as a function of time. VSR is defined as the ratio between the increase of volume and the initial volume of an SBR sample. (b) Weight swelling ratio (WSR) as a function of time. WSR is defined as the ratio between the increase of weight and the initial weight of an SBR sample.

Based on the “pure-shear” test, the fracture energy Γ of the SBR sheet can be calculated as

$$\tau = W(\lambda_{rup}) \cdot H \tag{1}$$

where H is the height of the specimen in the undeformed state and $W(\lambda_{rup})$ is the area under the nominal stress-stretch curve of a specimen without a pre-cut between 1.0 to λ_{rup}. Here λ_{rup} is the stretch at rupture of the pre-cut specimen.

2.3. Simple extension of SBR sheets with edge crack

Simple extension tests of SBR sheets were also carried out in the same mechanical testing machine (Zwick/Z010). The stretch rate in the simple tension test was set as 2/min. The geometry of the sample was taken as: length: $L = 100$ mm (in loading direction) and width: $H = 20$ mm. Simple extension tests were performed for SBR samples with four different volume swelling ratios which were VSR = 0.0%, 12.3%, 33.9% and 71.8%. To compare the theoretical predictions with the experimental measurements in the simple extension test, pre-cuts of four different lengths were introduced into the samples, which were $c = 1.5$ mm, 2.5 mm, 5 mm and 8 mm. It is noted that pre-cuts were also introduced freshly in the sample just before the mechanical tests.