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Elastomer Solubility and Stress Relaxation in Bio-Lubricants

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Abstract

This study presents novel results from in-situ stress relaxation tests using rubber O-ring seals immersed in bio-lubricant base oils (jojoba, soybean and palm oil), with a mineral base oil used for comparison. Little information is available on the interaction of bi-lubricants and elastomers.

The use of Hanson Solubility Parameter modelling methods was considered for assessing compatibility. Some correlation was found between experimental results for EPDM. Results were inconclusive for NBR and FKM.

EPDM immersed in palm and soybean oil suffered minor shrinkage, caused by stress relaxation. Swelling occurred with EPDM immersed in jojoba and mineral base oil, caused by diffusion. Results for nitrile showed shrinkage for all oils. Less than 1% change in mass occurred for all oils and FKM.

Key words: Bio-lubricants, Environmentally Friendly Lubricants, Elastomers, Hanson Solubility Parameters, HSP, Stress Relaxation, EPDM, NBR, FKM, Jojoba Oil, Palm Oil, Soybean Oil

1 Introduction

1.1 Degradation of Seals Exposed to Lubricants

Seals are a fundamental part of many engineering systems, acting as a barrier between materials, to prevent leakages or maintain system pressures. They are predominantly made up of synthesised elastomers, with varying polymers and chain lengths; for example nitrile rubbers are CH chains with CN (carbon-nitrogen) side groups, while fluorocarbon rubbers will be made up of CF chains (carbon-fluoride) (1). Synthetic rubbers will also contain various plasticisers to improve flexibility and promote easy processing, particularly for low temperature performance. These plasticisers are liquids of low molecular weight that form secondary bonds with the polymer chains. Cross linking with short chained sulphur atoms is also done to increase the hardness of the elastomers. Once cross links are formed, the shape of the material cannot be changed and the material cannot be completely dissolved in solvents, as the bonds formed are covalent (2).

Understanding the degradation of seals is vital for defining seal performance. Degradation could be due to the interaction with a lubricant, fuel or contaminant, as well as changes in temperature. In sealing applications particularly, stress relaxation can decrease performance. Stress relaxation is not necessarily caused by the seal itself, but can be caused by thermal expansion differences in the surfaces containing the seal, or from expansion of bolted joints (3).

Seals can be degraded (swell/shrink) to a large extent. Seal swell is acceptable up to a certain level as this can aid sealing performance. High levels of swell may however, lead to reduction in hardness, tensile and tear strength (4). With very high levels of swell, the seal may force itself into the clearance area between mating surfaces, causing misalignment. In static applications there are no defined acceptable levels of swell or shrinkage, it is application dependant. Some state that up to 50% swell is acceptable (3), others state 25-30% can be tolerated (5). Shrinkage of greater than 3-4% can cause leakages as the seal may no longer be in contact with both mating surfaces. Shrinkage may also increase hardness and reducing the flexibility of the seal.

Base oils used in lubricants have a dramatic effect on the amount of hardening that occurs in elastomers (6). While some additives may aid seal performance, others will degrade by, for example, promoting excessive crosslinking causing a reduction in seal flexibility (7).

The degradation of certain elastomers such as nitrile butadiene rubber (NBR) can be attributed to their polarity and the polarity of the fuels and lubricants they are in contact with. The polar bio-fuels/lubricants are more likely to defuse in to the polymer network, sitting among the polymer molecules causing polymer chains to relax. Haseeb et. al. (8) (9) , using static immersion tests, found that chloroprene (CR) and NBR degraded considerably, swelling more in a biodiesel in comparison to conventional diesel. Trends in hardness and tensile strength were similar, decreasing more in CR, NBR and ethylene propylene diene monomer rubber (EPDM) then in silicone rubber (SR) and polytetrafluoroethylene (PTFE), while FKM showed no change. FKM demonstrated very little weight or volume change. This result with FKM is also seen across literature with a variety of different fluids, this is due partly to its extremely low permeability to a range of fluids giving it high resistance to chemical degradation (10).

As far as the authors know, Fafan-Cabrera et al. (11) published the only work found on the compatibility of bio-lubricants and elastomers. They used FKM, SR, CR and EPDM elastomers with jatropha oil in static immersion tests. Tests were conducted at 24 °C for 670 hours. Results showed that jatropha oil was highly compatible with all the elastomers, experiencing less than 10 % volume change. After immersion in a standard engine oil EPDM and CR increased in volume by approximately 55 and 85 % respectively. High levels of polar additives in the engine oil were said to have caused these high levels of swell. Fafan-Cabrera et al. suggested that the theory of 'like dissolves like' could not explain the interaction between the non-polar EPDM and the polar additives. Less than 2 % volume change occurred with FKM and SR. These results show that bio-lubricants have the potential to be more compatible with a range of elastomeric material.

The applied stress on an elastomer is an important factor in the swelling behaviour. If the elastomer is subject to extension, swelling will increase, if subject to compression the amount of swelling that occurs will decrease. This is due to the hydrostatic force component which, in extension is negative, and in compression it is positive (1). Therefore static tests may not be representative of the levels of swell or shrinkage a given seal material may experience in application.

1.2 Hanson Solubility Parameter

Seal degradation is dominated by diffusion. The likelihood diffusion will occur can be analysed through Hanson Solubility Parameter (δ). The lubricants and elastomers that have the closest solubility parameter values are most likely to swell.

The Hanson Solubility Parameter is a way of predicting and defining the solubility of substances, and can potentially be used to define the interaction of elastomers and fluids. Three parameters; dispersive forces, δ_D, dipolar forces, δ_P, and hydrogen bonding, δ_H, make up the Hanson Solubility Parameter, δ, as shown in Equation 1:

$$\delta^2 = \delta_D^2 + \delta_P^2 + \delta_H^2$$

(Eq. 1)

where, for each of the three parameters, δ_D, δ_P, δ_H, are equal to the cohesive energy, E, divided by the molar volume, V. $E = H_v - RT$, where H_v is the latent heat of vapourisation, R the universal gas constant and T the absolute temperature.

These values can go on to be used to define a relationship between two substances, in terms of Hanson Solubility 'space', a three dimensional representation of how the given substances may interact, known as the spheres of interaction. The 'distance' between the two substances in this space is defined by Equation 2.

$$(R_a)^2 = 4(\delta_{D2-}\delta_{D1})^2 + (\delta_{P2} - \delta_{P1})^2 + (\delta_{H2} - \delta_{H1})^2$$

(Eq. 2)

The Relative Energy Difference (RED), defined in Equation 3, is a useful parameter that can indicate how two substances will react. If the RED <1 then the two substances are likely to dissolve in each other, if RED>1 it is likely there will be little affect. R_o is the radius of interaction of one of the substances (generally the polymer) and is found experimentally. The Hanson Solubility Parameters in Practice (HSPiP) software is a tool that allows interaction parameters to be visualised and solubility parameters to be calculated, provided some information, such as solubility parameters or chemical structure is known.

$$RED = R_a/R_o$$

(Eq. 3)

The use of HSP is well documented for successfully assessing the miscibility of paints (12) and effectiveness of rubber gloves for Personal Protective Equipment (13). It is good for describing the solubility of simple chemicals with polymers.

The potential for correlation between experimental parameters and HSP predictions appears to dependant on the type of elastomer. Co-polymers such as NBR and FKM do not give a correlation when HSP values are derived for the elastomer interacting with fluids. As Nielson & Hansen (14) found with FKM, additionally to the co-polymer issue, a curing agent present in the elastomer can interfere with swell predictions. Heitzig et al. (15) also found this when comparing HSP data with that obtained from static immersion tests for NBR and FKM in a variety of biofuel candidates. There was not sufficient agreement between experimental results and predictions with HSP.

This contradicts work by other researchers, who found correlation between experimental results and HSP predictions. There was an overall correlation between volume swell and solubility parameters in work done by Nielson & Hansen (14) and Graham et al. (16). Nielson & Hansen (14) found correlation with increasing RED and decreasing swelling with two types of EPDM. Interestingly, two of the four types of EPDM tested had noticeably different molecular weights and branching, yet this had little effect on the resulting experimentally derived HSP values.

Interestingly, Graham et al. (16) made the link between swell in NBR increased with increasing polar and hydrogen bonding values, for various aromatics found in aviation fuel, when using static immersion methods and calculating HSP values. Graham et al. also employed volume additive rules in order to construct a mixture within HSPiP (discussed further in Section 3.1). It was, however, considered that this may underestimate the polar characteristic of the NBR copolymer.

HSP values are dependent on the structure of the elastomer or fluid in question and Zhu et. al. (17) made the link with carbon chain length and interaction between fatty acids and elastomers. With increasing chain length of saturated fatty acids, swelling of NBR decreased. For unsaturated fatty acids higher swell occurred. For the six fatty acids tested by Zhu et al., the HSP dispersive forces were similar, while the polar and hydrogen values decreased with increasing carbon chain length. The polar and hydrogen values were noticeably higher for the C18:1 unsaturated fatty acid in comparison to the C18:0 saturated fatty acid. The relationship between chain length and chemical interaction with NBR extends to change in mechanical properties as well, for example change in tensile strength, elongation, tear strength, and hardness. All decrease with increasing carbon chain length.

Finally, no previous work has been found that considers the interaction of bio-lubricant base oils and elastomers in dynamic testing, only one study specifically investigated elastomer degradation with bio-lubricants, and limited data is available from industrial sources. The work presented here aims to overcome those deficiencies.

2   Experimental Method

Stress relaxation tests were carried out using an Elastocon Relaxation Tester EB 02. The aim of this was to assess the compatibility of bio-lubricants, compared with mineral base oil, with various common elastomer materials. This apparatus was selected because it is capable of continuous

dynamic data acquisition of sealing force that avoids the need to stop a test, remove the seal and then take static readings. It comprises a compression rig, made of parallel plates, immersed in oil, with a load cell and gauge attached. The O-ring seal was placed between the plates, the gauge was used to measure the thickness of the O-ring before it was then compressed by 25% of its original size. The average thickness of the O-ring was 1.92 mm +/- 0.1 mm. The change in force required to keep the plates in place was continually measured during tests. The rig was then placed in an oven and held at a constant temperature of 80˚C for the 168 hour test duration, as per ISO 3384-1:2011 (18). The O-ring seals were weighed before and after testing. O-rings were blotted dry with lint free cloth and left to air dry for an hour before being weighed.

Elastomers tested were EPDM, NBR and FKM (type 1), properties of these O-rings is given in Table 1. All were immersed in common potential bio-lubricant base oil candidates, palm, soybean and jojoba oil, properties of which are given in Table 2. Shell HVI 60 base oil was used for comparison.
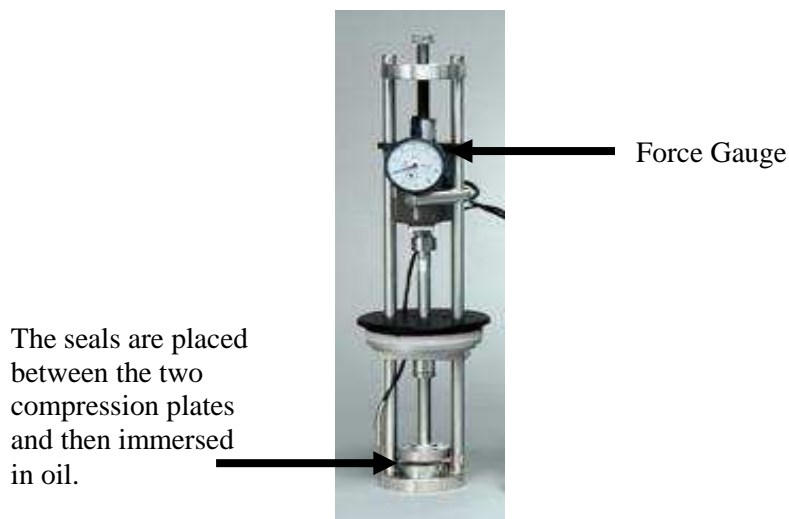
Force Gauge

The seals are placed between the two compression plates and then immersed in oil.

Figure 1, Compression Rig for the Elastocon Relaxation Tests

	EPDM	FKM	NBR
Inner Diameter, mm	15		
Thickness, mm	2		
Hardness, Shore A	70	75	70
Tensile Strength, MPa	10	10	10
Temperature Range, ℃	-57 to 149	-26 to 205	-34 to 121
Hanson Solubility Parameters, MPa$^{1/2}$			
Dispersive, δ_D^2	18.6	11.6	17.5
Polar, δ_P^2	3.4	23	2.3
Hydrogen Bonding, δ_H^2	4.4	5	3.4

Table 1, Properties for the Elastomer O-rings Tested

	Palm Oil	Jojoba Oil	Soybean Oil	Mineral Oil
Molecular Weight, KgKmol^{-1}	846	610	920	
Viscosity, cSt	24	25.2	33.5	23.1
Fatty Acid	Percentage, %			
C8:0	1.7			
C10:0	2.3			
C12:0	40.8			
C14:0	15.4			
C16:0	12.4	1.2	10.7	
C18:0	20.2	0.1	4	
C18:1 (trans)	1.5			
C18:1 (cis)		8.4	23.9	
C18:2 (cis)		0.1	52.9	
C18:3 (alpha)			5.9	
C20:1	0.1	72.2		
C22:1	0	15.3		
C24:1		1.8		
Other	5.6	0.9		
Level of Saturation	g/100g			
Saturated Fatty Acids	89.3	1.7	15.2	
Monounsaturated Fatty Acids	4.1	93.5	23.4	
Polyunsaturated Fatty Acids	0.6	0.3	56.3	
Hanson Solubility Parameters	MPa$^{1/2}$			
Dispersive, δ_D^2	15.48	15.7	16.1	17.4
Polar, δ_P^2	3.5	2.7	3	3
Hydrogen Bonding, δ_H^2	6.4	5.2	6	5.3

Table 2, Useful Properties for the Bio Base Oil Candidates

Three repeats of each test were carried out and the test sequence was randomised. Blinding was not performed and all O-rings came from single production batches. A control test was carried out with each elastomer material in air for the 168 hour test duration to take into account any stress induced by compression that causes the elastomer molecules to move.

HSP values for the HSPiP software were derived through volume additive rules using HSP values for the fatty acids that make up each bio-base stock, rather than experimentally determining them. This has shown to be a valid method for determining values (18), although it may underestimate the polar HSP element (14) (16). The fatty acid composition of the vegetable oils tested were performed by a

certified external laboratory using gas chromatography, results are shown in Table 2. HSP values for all fatty acids, apart from stearic acid, were available in the software database.

The HSP values for stearic acid were obtained using the DIY HSP function in the Y-MB solver. The Y-MB solver uses a combination of a Neural Network method and an automatic molecule breaking programme to fit data entered by the user to know data on HSP. The international chemical identifier for stearic acid was obtained via the Royal Society of Chemistry's chemical database (19). The values obtained from this method should be used with caution, on the advice of the software developers, who state an understanding of approximately what the HSP values are is important (18). The values obtained for stearic acid were in line with those for other fatty acids, therefore it was felt to be a fair approximation.

3 Results and Discussion

3.1 Mass Change

Figure 3 shows averaged percentage mass change of the elastomer seals tested in the base stocks, error bars represent the experimental spread of results and these results can be explained through chemical and physical mechanisms for diffusion.

The diffusion behaviour of mineral and jojoba oil in EPDM is similar. Jojoba oil has the lowest molecular weight of all the oils tested, at 610 KgKmol^{-1}. This means it has a greater potential to defuse in to the polymer network, the size of which is dictated by the size of the cross links. Chemically, 93.8% of jojoba oil's fatty acids are unsaturated, therefore have significant areas of enhanced reactivity which can drive the diffusion process. While soybean oil also has high levels of unsaturated fatty acids, 79.7%, the lower rate of diffusion is attributed to the high molecular weight of 920 KgKmol^{-1}, this is apparent from the low change in mass compared to mineral and jojoba oil. Palm oil has very low levels of saturated fatty acids, 4.7% and a higher molecular weight then jojoba oil, at 846 KgKmol^{-1}, the mass change results for palm oil and EPDM are similar to soybean oil, demonstrating low levels of diffusion.

As highlighted in Section 1.1, Fafan-Cabrera et al. (11) found high levels of swell in static emersion tests with EPDM and mineral based engine oil and low levels for jatropha oil. The molecular weight of jatropha oil is 866 kg/kmol (23), this is close to the molecular weight of palm oil, at 846 kg/kmol (24), so they should possess a similar diffusion quality. Jatropha oil is also made up of similar fatty acids to soybean oil (oleic and linoleic), so they should possess similar solubility parameters. Therefore, a fair estimate would be that EPDM would exhibit a similar stress relaxation profile for these three oils. The discrepancy in results is most likely due to the elastomers being under compression during stress relaxation tests, which would reduce swell compared with static immersion tests.

If the experimental spread of results is considered for percentage mass change of FKM and NBR in Figure 3, there is no measureable difference in results. This is because, in the case of FKM, there is little change of physical diffusion because it has low levels of permeability. Chemically it has high resistant to degradation due to being relatively 'inert' compared with other elastomers (10). The industry chemical resistance data validates the results, reporting it as a '1', which is defined as minor degradation with little swelling, between 0-5%, for all the fluids tested here.

The dominant process in the degradation of NBR was the extraction of plasticisers, which are needed for low temperature flexibility and performance. They are relatively easily extracted at elevated temperatures, as they leach into both polar and nonpolar liquids (25). The rate of this leaching is a function of temperature and plasticiser concentration. The plasticisers are found in the amorphous parts of the polymer and can be attached to the polymer chains or free among the polymer network (2); either way they can still be extracted. Fatty acids are replacing toxic conventional plasticisers. If polymers with these types of plasticisers come into contact with bio-base stocks, it is more likely they will be extracted, in line with the principles of the 'like dissolves like' theory.
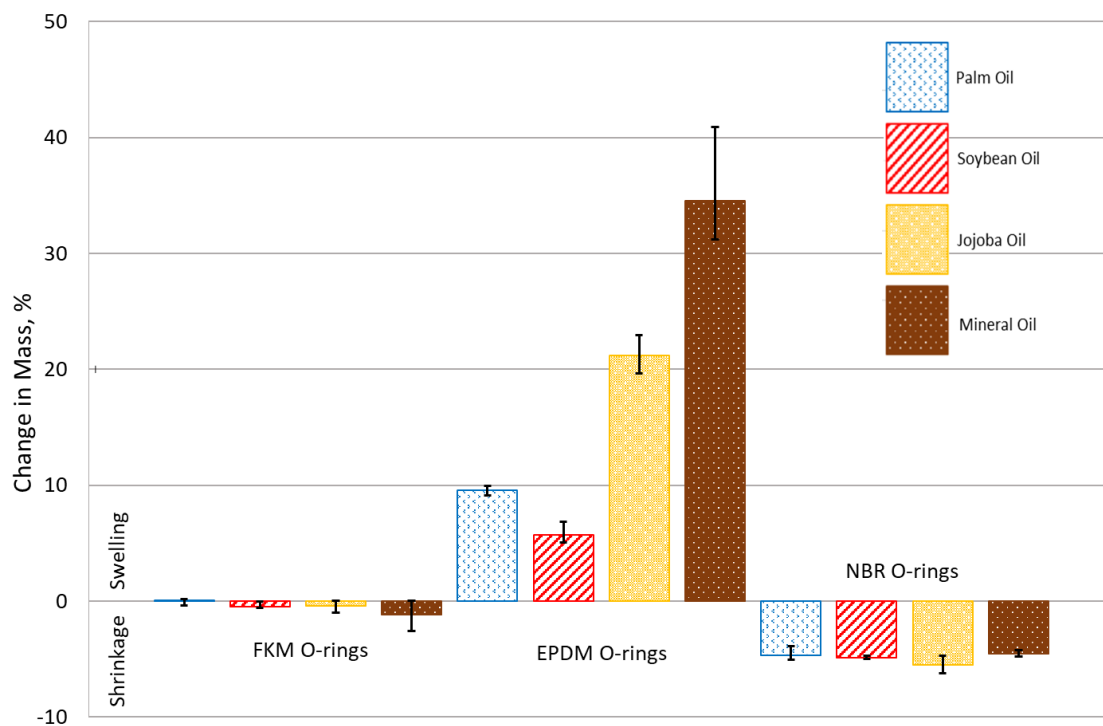
Figure 2, Percentage Mass Change after Stress Relaxation Tests

3.2 Performance of EPDM seals

Figure 3 shows averaged results from stress relaxation tests with EPDM and base oils. Force readings were normalised, removing any variation that might be caused through error induced in measuring the initial thickness of the seal. The cyclic fluctuations, which occurred over the soybean oil test particularly, were caused by variation in ambient room temperature. The stress relaxation for the control test followed a similar trend to results obtained with palm and soybean oil. This would suggest that palm and soybean oil have little interaction with EPDM. EPDM and mineral oil on the other hand demonstrated swelling behaviour. This was apparent early on in the test where F/F_o, was greater than 1. Stress relaxation begin to occur at around 72 hours. Figure 3 also shows that the rate of absorption of oil into the elastomer is faster than the rate of desorption of elastomer into oil. This can be seen by observing the relatively quick rate of swell in the mineral and jojoba oil tests, within the 24 hours of testing. The rate of shrinkage is much slower, over 48-72 hours.

These results contradict industry defined chemical resistance data (22). The interaction of EPDM with soybean oil, 'vegetable' and mineral oils are all rated at '3', which is defined as moderate to severe swell (10-20%), only suitable for static applications. The experimental data in Figure 3 clearly shows that EPDM does not act similarly with soybean, palm, jojoba and mineral oil. The mass increase of EPDM samples tested in mineral oil was in the range of 31-38.5%, the average is shown in Figure 3, where the error bars represent the experimental spread of results from 3 tests. Jojoba oil in a narrower range of 20-23%, while EPDM samples in palm and soybean oil were in the range of 9-10% and 5-7.5% respectively. Discrepancies in test method are likely the cause of this. The industry standard tests are performed at room temperature, while tests in this work were carried out at 80℃, this should have accelerated aging. Industry defined chemical resistance is based on volume swell, compression set and aging resistance test methods, rather than a single test method. The stress relaxation tests are

however felt to offer a good insight into material interaction, as the test has the ability to dynamically measure samples under compression, giving an indication of the level of swell and in service behaviour, but not necessarily towards end of life, where a rapid drop off in material properties may be expected, therefore not necessarily fiving a full view of aging behaviour. It is felt that chemical resistance data, in this instance, gives a particularly cautious overview in terms of jojoba, palm and soybean oil, particularly as no specific data is available for palm and soybean oil. While they come under the class of vegetable oil, vegetable oils have a wide range of chemical structures, which will cause varying results on contact with elastomers. Figure 3 also shows that the rate of absorption of oil into the elastomer is faster than the rate of desorption of elastomer into oil. This can be seen by observing the relatively quick rate of swell in the mineral and jojoba oil tests, within the 24 hours of testing. The rate of shrinkage is much slower, over 48-72 hours.
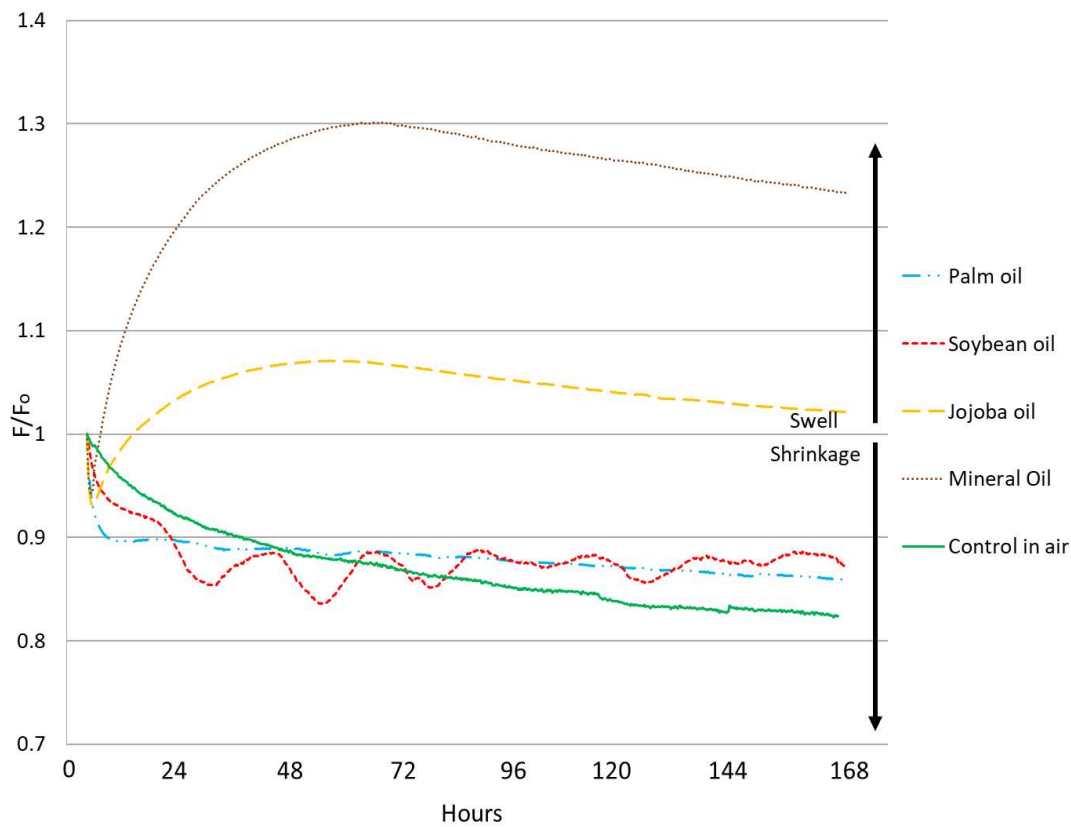

Figure 3, Results from Stress Relaxation Tests with EPDM O-rings

3.3   Performance of FKM seals

Figure 4 shows the average stress relaxation data for FKM showing little difference between the results for all the bio-base stocks tested, as well as mineral oil. The control test showed a gradual and small reduction in the force required to maintain the distance between plates, with results for normalised force going to 0.95 and seeming to reach an equilibrium state. The majority of the other results fall in the range of 0.81-0.9 for normalised force data. This shows only slightly more degradation of the elastomer in the base stocks than air.
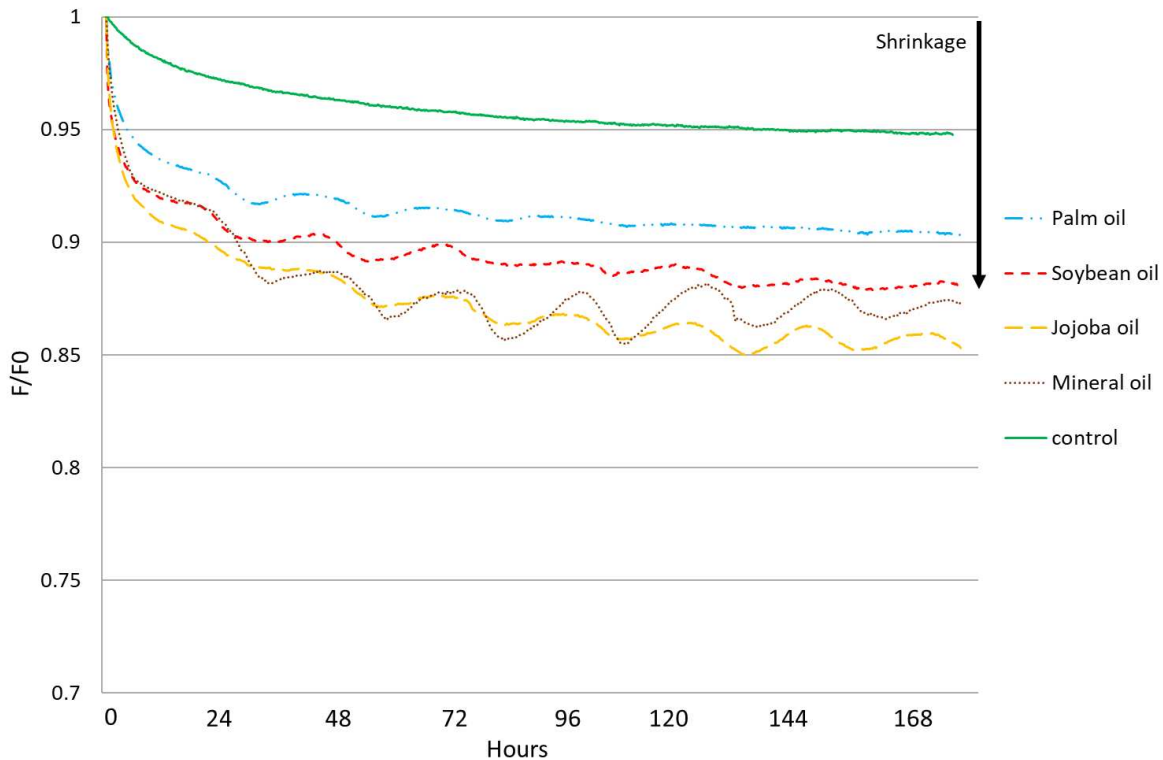
Figure 4, Results from Stress Relaxation Tests with FKM O-rings

3.4 Performance of NBR Seals

Similarly to FKM, there is little variation in stress relaxation results between the base stocks and NBR, as seen in Figure 5Figure 4. This shows that the bio-base stocks are consistent with mineral base stock in terms of compatibility performance. All tests showed a considerable drop off in the force required to maintain the distance between plates in the first 48 hours of testing, demonstrating shrinkage in the seal. This is attributed mainly to the leaching of plasticisers (25), as discussed in 4.1.1.

As with the tests carried out with EPDM, results do not agree with those provided in industrial chemical resistance data; there is no specific data on jojoba and palm oil, but 'vegetable', soybean and mineral oil are all rated '1' for minor degradation. This is clearly not the case when considering stress relaxation data. This is attributed to the discrepancies in test method, specifically in test temperatures. Industry standard chemical resistance data is obtained from tests carried out at room temperature, and the extraction of plasticisers, which is the most likely cause of the considerable shrinkage in the seal, is temperature driven, therefore results would differ at room temperature and 80˚C. NBR has more plasticisers than other common elastomer materials (25), which also accounts for the fact that there is considerable shrinkage in NBR and not FKM and EPDM. Heitzig et al. (26) also attributed the degradation of NBR elastomers tested to the extraction of plasticisers.

The degradation in the NBR seal sample during the control test was considerably less than when the seal is tested in the base stocks. The rate of diffusion of plasticisers into air was slower, as they are not as chemically compatible. The main driver of degradation in the control test was the application of heat, giving the plasticiser molecules increased kinetic energy.
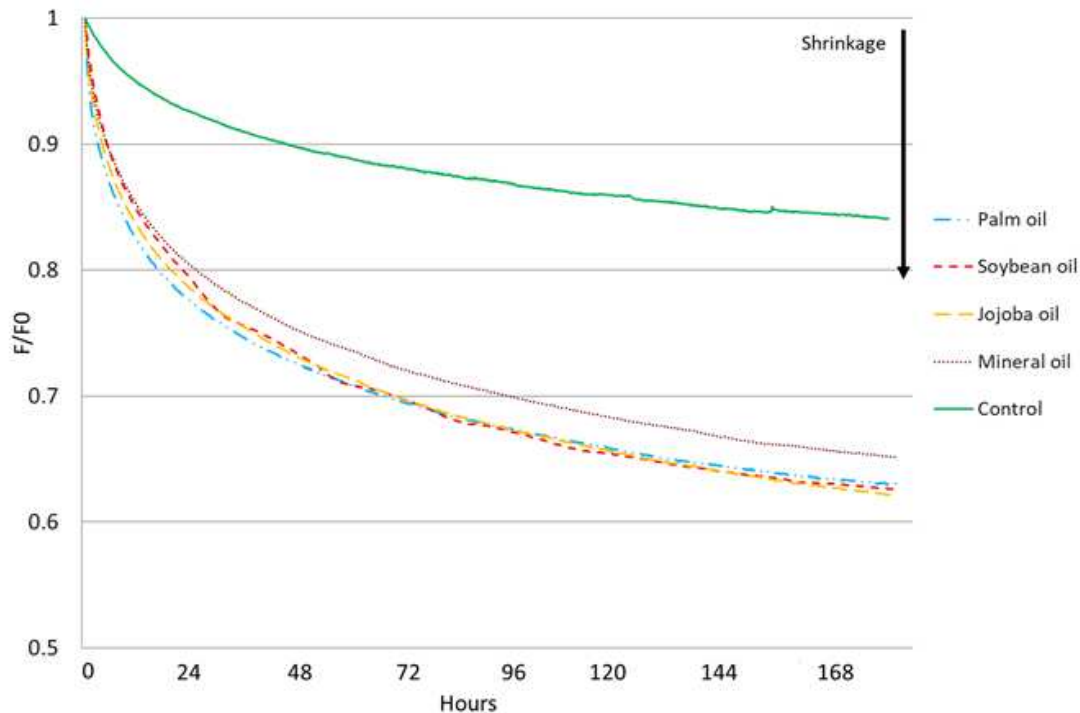

Figure 5, Results from Stress Relaxation Tests with NBR O-rings

4   Assessment of HSP method

4.1 Comparison of experimental data with HSPiP data

Figure 6 shows the average percentage mass change of the three elastomer o-rings when tested in the base oil candidates, compared with the Relative Energy Difference (RED) values derived from the HSPiP software. The average values for change in mass are from a minimum of three repeats.

The results show that it is possible to relate the experimental data with the theoretical data to some extent for EPDM. The closer the RED is to 1, the less interaction should be observed between the fluid and elastomer. The RED data demonstrates that the mineral base oil interacts with EPDM, resulting in a RED of 0.24, the lowest RED of the oils tested. The largest variation in mass and applied force occurred with EPDM O-rings and mineral oil. Palm oil and EPDM have a RED of 0.61, the highest of the oils tested with EPDM, showed the least variation in mass change and applied force.

For both FKM and NBR a trend is less apparent, little shrinkage or swell was seen, this may explain the tight cluster of results when comparing RED values in Figure 6. The lack of correlation, a trend also noted by Nielson & Hansen (14) and Heitzig et al. (15), may also be due to the fact that FKM based elastomers are co-polymers, each polymer has its own HSP values that could vary considerably. The co-polymer theory may also explain the lack of trend for NBR as well. There have however been reports in literature of correlations with RED and the amount of swell in NBR. Liu (20) showed clear correlation with these values, they had significantly more data and used a variety of fluids with different HSP values. The data for NBR in Figure 6 maybe comparing HSP values for NBR with experimental results of the interaction between the plasticisers, rather than the interaction of the base oils and NBR. It is thought the mass change that occurred with NBR is mainly due to the extraction of plasticisers.
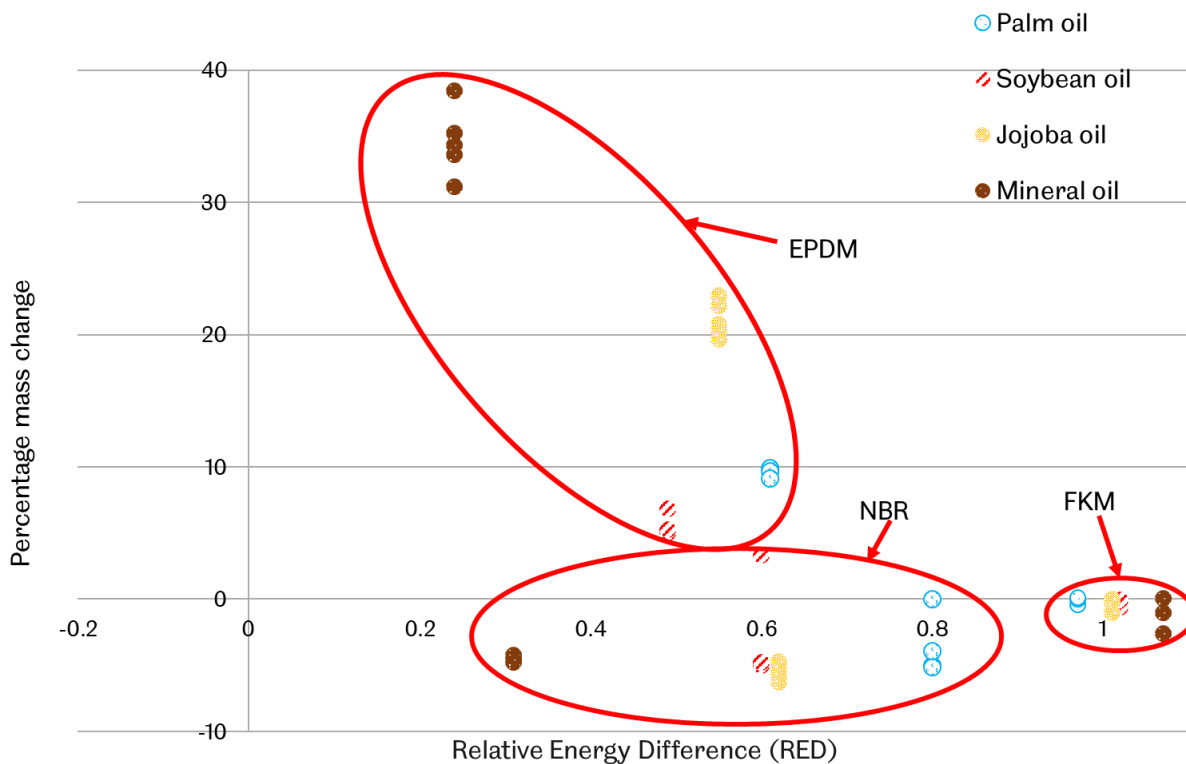
Figure 6, Percentage mass loss during stress relaxation tests correlated with relative energy difference.

4.2 Uses and limitations of HSP and HSPiP

The use of HSP and HSPiP software to predict material compatibility has potential for assessing the compatibility of certain types of elastomer with lubricant base stock candidates. The software translates some complex molecular interaction theory into simple to understand visual representations. The HSPiP software is simple to use and gives quick results for estimates of compatibility, provided information on solubility parameters for the elastomers and fluids is available. HSPiP could be a useful filtering tool for large engineering organisations, such as automotive and aviation manufacturers. The aviation industry, for example, has rigorous and lengthy approval processes for elastomers, fuels and lubricants, and similarly the automotive and industrial fluids industries, albeit to a lesser extent. Within HSPiP's current limitations it has the potential to filter out materials that are clearly compatible or not compatible. Its limitation lies in predicting compatibility of materials where the interactions are more subtle. The software is currently orientated to the chemical industry, rather than the lubricant or fuel industry and cannot accurately model co-polymers or complex fluids. This could be improved by experimentally determining solubility parameters for some of the more common co-polymer elastomers.

Seals are made of elastomers predominantly, but also contain plasticisers, curing agents and stabilisers, which could contribute to the interaction of elastomers and solvents. Krauskopf (21) calculated HSP values for several plasticizers, using additive factors of molecular group functionality rather than experimental methods. Using this method could be useful if the plasticizers in the given elastomer are known. The issue is that often, elastomer manufacturers will not reveal which plasticizers and additives are used in their elastomer 'recipes', therefore only speculative conclusions can be formed.

5   Conclusions

The following main conclusions can be drawn from this work;

1) Biolubricant base stock candidates soybean and palm oil showed good compatibility with EPDM. Jojoba oil is likely not compatible with EPDM and could result in seal failure, but the small increase in stress observed during testing could be advantageous in aiding seal performance, however it is unclear whether the increase in mass would have a detrimental impact on the material performance long term.

2) All base stock candidates were found to be compatible with FKM seals, and it is likely that none would cause failure of this seal material. Very little mass loss was observed, most mass change was seen with FKM samples tested with mineral oil. No significant stress relaxation occurred during the length of testing.

3) The use of the base oil candidates with NBR is not advised; the extraction of the plasticisers used with this particular seal material caused significant stress relaxation due to shrinkage in the seal and this would cause seal failure if used in application.

4) The results for compatibility tests with EPDM and NBR contradict industry defined chemical resistance data. Due to low test temperatures employed for these standards, they may not provide an accurate view for higher temperature applications such as automotive lubricants. It is suggested therefore that stress relaxation tests may provide relevant data that provides more realistic predictions for compatibility and performance.

5) Further work is required to improve the accuracy of modelling elastomer compatibility using the HSPiP software. The expansion of the database for both lubricants and elastomers, particularly improving the accuracy of co-polymer elastomers, is required. It is, however, proposed that the software could act as a useful tool in filtering out materials that are not compatible.

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