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The Effect of Surface Bump Towards EPDM Rubber Brake Hose Performance

A. N. Rosli, **A. A. Rashid*** and A. H. Abdullah

School of Mechanical Eng., College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia

*Corresponding author: amirul2550@uitm.edu.my

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ABSTRACT – *The function of the brake hose is to distribute relatively high-pressure brake fluid to the complete fixed line leading to the brake calipers on the wheel. The flexible Ethylene- polypropylene-dine- monomer (EPDM) rubber used to manufacture the hose allows it to move with the car's suspension system. During the manufacturing process of this hose, the presence of a surface bump on the outer surface results in significant scrap rates. The objective of this research was to investigate the physical condition as well as mechanical properties of the defective samples in comparison with the normal ones. Scanning Electron Microscopy (SEM) results did not reveal any morphology or elemental composition differences between the two groups of samples. Tensile strength and volumetric expansion T-test probability value (p-value) obtained were higher than 0.005 suggesting that both samples have similar mechanical property performance. The outcome of this study can be used as the preliminary data to perform a further rigorous and stressful test of the bump samples to determine if the defect is just cosmetic and has no reliability issue and hence should be accepted in production.*

KEYWORDS: Surface bump, product defect, EPDM brake hose, vulcanized rubber, quality assurance

1. INTRODUCTION

The auto industry is a major economic and industrial force all over the world. It makes about 60 million cars and trucks a year, and they use almost half of the world's oil. There are four million direct jobs in the industry, and many more indirect jobs (Sturgeon & Florida, 2000; Papatheodorou & Harris, 2007; Williams & Blyth, 2023). The automotive industry is one of the large economic sectors contributing to an overall 4.3% of Malaysia's GDP (Gross Domestic Product) in 2019 (Borneo Post Online, 2020). Due to the criticalness of this sector to the Malaysian economy, on the 21st of February 2020, the Ministry of International Trade and Industry (MITI) launched the National Automotive Policy (NAP) 2020 (Kassim et al., 2020). The automotive industry plays a critical role in driving economic growth and supporting the growth of other industries. Its influence is felt across various sectors, from manufacturing and energy to technology and services (Orsato & Wells, 2007).

Rubber is one of the key materials used in this sector (Abidin et al., 2019; Borneo Post Online, 2020). The continuous evolution of the automotive industry drives the advancement of rubber-based components. This in turn significantly contributes to the safety, comfort, efficiency, and quietness of the modern automobile (Olthuis, 2020). The many uses for rubber depend in nearly every case on its unusual physical properties, and on the combinations of physical properties that can be obtained by modifying the rubber and by combining it with fabrics and metals in various mechanical structures (Rodgers & Waddell, 2005; Shit & Shah, 2013; Lin et al., 2019; Abidin et al., 2019; Fazli & Rodrigue, 2020).

Vulcanization is the most significant process innovation which made rubber material usable in the automotive industry. This is the chemical process to insert a network of cross-links made up of sulfur between polymer chains under an optimum temperature which increases the elasticity of the rubber and reduces its plasticity hence producing good elastic properties, good mechanical strength, and sustainability towards high heat. This made the vulcanized rubber very high endurance (Guise-Richardson, 2010).

The rubber brake hose was designed to sustain a pressure of 17 MPa and above. The good durability of the brake hose comes from the design itself. The rubber hose for an automotive hydraulic brake hose is composed of three layers (inner Ethylene-propylene Diene Monomer – EPDM, yarn fabrics reinforcement layer, and outer EPDM layers) as illustrated in Figure 1.

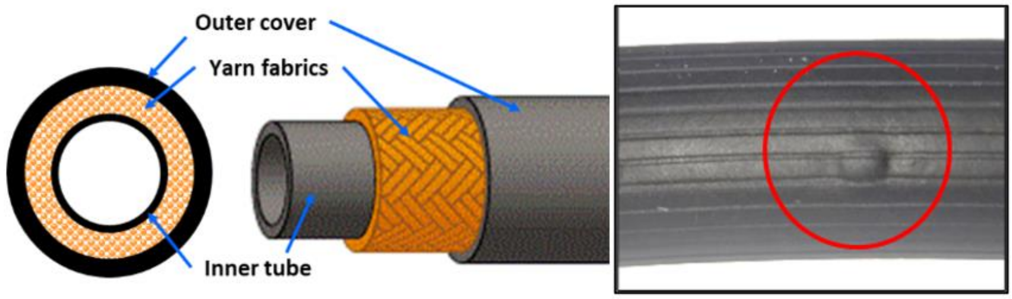

FIGURE 1: Structure of (a) EPDM brake hose layers and (b) Typical bump spotted on the outer surface of the hose

In a typical brake hose manufacturing facility, high rejection has been detected which is associated with the appearance of a "bump" on the surface of the rubber hose as illustrated in Figure 1. The average rejection rate for this type of defect can be as high as 3% per production lot. Initial data analysis shows that there is no correlation between defect rate and hose type by car model produced by the company instead the reject rate is highly correlated to the production rate of the hose by the model itself. Figure 2 illustrates the bump rejection rate for all brake hose car models within a twelve-month period. As an example, the spike in bump defects observed in the month of November was traced back to the high production rate of the Axia car model brake hose during that production time.

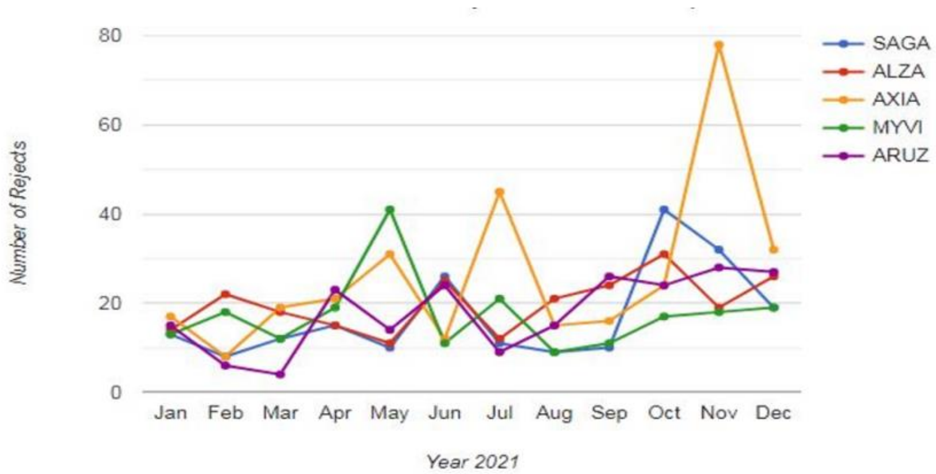

FIGURE 2: Brake hose bump defects by different model

The main objective of this research is to study the difference in the material at the affected area of the bumps hose in terms of density difference, morphology, cross-link strains, tensile strength, and functional performance compared to the normal hose. This study examines how the presence of a bump in a vulcanized synthetic rubber brake hose affects the crosslinking density and demonstrates how to calculate/estimate the various parameters associated with swelling, crosslinking density, tensile strength, and determining the morphologies obtained.

It is assumed that the appearance of the bump is mainly contributed by crosslinking densities. Lower crosslink density has a higher tendency to cause swelling or in this case, the bump condition when exposed to the environment including moisture level (Valentín et al., 2008). In contrast, increased crosslink density restricts the polymer chain's stretchability, which minimizes the spaces between the chains and restricts the solvent molecule absorption into the networks (El Shafee & Naguib, 2003).

2. METHODOLOGY

In this research, the main approach used is to compare the testing and experiments between the control group and the defect group. All the specimens were obtained from the manufacturing facility without any modification to the parameters or the product ingredients. The quantity of the samples was prepared according to the different settings of the analysis and experiments conducted which includes SEM analysis, tensile testing, volumetric expansion, and swelling equilibrium test.

2.1 Scanning Electron Microscopy (SEM)

For defect specimen preparation, the exact location of the bump was identified before the surface is coated with platinum using an EmitechK575X sputter coater for one minute. The coated specimens are scanned using a ZEISS SUPRA 35 VP (Oberkochen, Germany) SEM with 1000x magnification. The voltage acceleration is set at 15 kV.

To analyze the elemental composition of the hose, EDX analysis, also known as Energy Dispersive X-ray Spectroscopy, was used as part of SEM analysis. The energy of the X-rays emitted by each element is unique, so by analyzing the energy spectrum of the emitted X-rays, the elemental composition of the sample can be determined.

2.2 Tensile Strength

The tensile test for this study was conducted according to FMVSS 106 test standards (Einsiedel, 2020; Chillakuru, 2022). The test will determine the tensile stress required to break the connection between the hose and fitting on normal hose conditions and the hose with bumps. By using Autograph Tensile Machine, the hose brake was pulled in two directions up and down, creating tension at the crimping area of the hose.

All crimping parameters were made sure to be within specifications in accordance with JIS D2601 (JSA, 1998), crimping diameter within 10.05 ± 0.05 mm while the crimping position is within 4 ± 0.3 mm. The sample is tested under a 500 kgf test load, and a pull speed of 30 mm/min, as shown in Figure 3.

FIGURE 3: Sample being tested in tensile strength test using Autograph Tensile Machine

2.3 Volumetric Expansion

Volumetric expansion is an important assessment to determine the functionality of rubber hoses used in high-pressure applications, such as hydraulic systems. The ability of the hose to maintain its shape and volume under pressure is critical to its effectiveness and longevity. The volumetric expansion test is used to ensure that the hoses meet the necessary standards for performance and safety.

The rubber hose samples with a free length of 305 mm were prepared and were crimped with fittings at the end of the samples. The samples were fixed with the volumetric tester. The bubbles' presence was removed completely from the glass tube to prevent reading errors. Using water as a medium, the hydraulic pressure is applied in the rubber brake hose samples to 6.9 MPa and 10.3 MPa at the rate of 171.6 ± 68.6 MPa/min. The volumetric expansion was measured by the rise of the liquid level in the burette.

2.4 Swelling Equilibrium Test

The swelling equilibrium test is carried out on the bump subject to investigate the difference in crosslinking density between the bump surface and the normal surface. In this experiment, the equipment used was a heating oven, 30 sets of beakers, and a 20 ml measuring cylinder. The idea is that a higher level of cross-linking will lead to a lower level of swelling at equilibrium. The amount of crosslinking makes the number of links grow. When there are more crosslinks, the chain between where two networks meet is shorter.

There will be less swelling all around. Two swell ratios are used to figure out how much something is swelling. The rate of vulcanizate swelling in a suitable solvent is used to measure the crosslink density of unfilled vulcanizates (v) and, eventually, the molecular weight of rubber segments between two cross-links (Mc). The specimens of normal hose surface weighted 0.28 ± 0.005 g and the specimens of bump surface hose weighted 0.28 ± 0.005 g were prepared.

The sample was immersed into the beaker filled with Toluene and inserted into the oven under 50 ºC for 24 hours (Norhazariah et al., 2016). The mass of the swollen sample was checked after 24 hours of soaking from time to time until consistent mass was achieved. The swollen sample is considered under an equilibrium state when there is no room for Toluene absorption anymore and the weight is constant. The average weight obtained from 15 specimens was used to calculate the swell ratio using Eq. (1). The swell ratio is defined as;

$$\text{swell ratio } (v_r) = \frac{weight\ of\ the\ swollen\ rubber}{weight\ of\ the\ dry\ rubber} \quad (1)$$

Using the Flory-Rehner equation (Darko, 2022), the cross-link density (ρ_c) is calculated in reference with swell ratio;

$$\rho_c = \frac{\mathrm{In}(1 - \text{Ø}_2) + \text{Ø}_2 + \chi\,\text{Ø}_2{}^2}{\mathrm{V_s}(\sqrt[3]{\text{Ø}_2} - 0.5\text{Ø}_2)} \quad (2)$$

where V_s is molar volume of used solvent. Ø_2 is the ratio of the volume of an unswollen network to the volume of the swollen network at equilibrium (Bruck, 1961).

$$\text{Ø}_2 = \frac{1}{V_r} \quad (3)$$

χ is Huggins´ interaction parameter between rubber and solvent) is rubber volume fraction of the swollen sample at equilibrium swelling (the total volume of the sample does not include filler volume) (Kuei & Gomez, 2017).

$$\chi \cong 0.34 + \frac{V_s\,(\delta_s - \delta_r)^2}{\mathrm{RT}} \quad (4)$$

where δ_s, is the solubility parameter of solvent, δ_r solubility parameter of the polymer, R is the gas constant (i.e., 8.3144598 J/mol) and T is the environmental temperature which is 323.15 K ≅ 50 ºC. In this experiment, V_s is 106.5 cm^3 and δ_s is 18.2 $(\mathrm{MPa})^{1/2}$ (Darko, 2022). δ_s for EPDM is 16.3 $(\mathrm{MPa})^{1/2}$ (Hrnjak-Murgić et al., 1996). X is calculated using Eq. (4).

$$\chi \cong 0.34 + \frac{106.5\ (18.2 - 16.3)^2}{8.3144598 \text{ x } 323.15} = 0.483 \qquad (5)$$

3. RESULTS AND DISCUSSION

3.1 Scanning Electron Microscopy (SEM)

SEM micrograph images was used to verify the morphology of both normal and defect brake hose is shown in Figure 4 and 5. At 200X magnification, the pattern for bump samples having curvy shape as compared to normal samples which have no specific pattern.

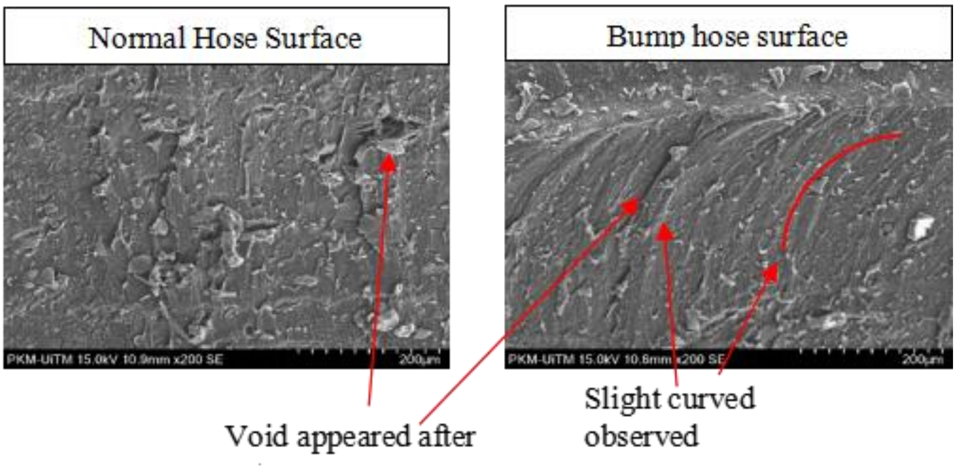

FIGURE 4: SEM micrograph of brake hose samples at 200 X

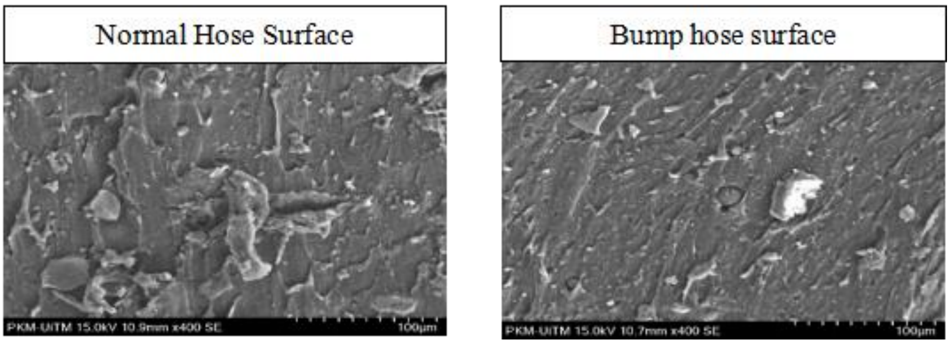

FIGURE 5: SEM micrograph of brake hose samples at 400 X

Observation on the same samples at 400 X confirms that the curvy appearance is not caused by any hairline crack or any other mechanical defect appearance. Figure 6 is the EDX analysis of element composition for both bump samples and normal sample. Further analysis of main elements form both group samples discover some percentage contents different listed exhibit in Figure 7.

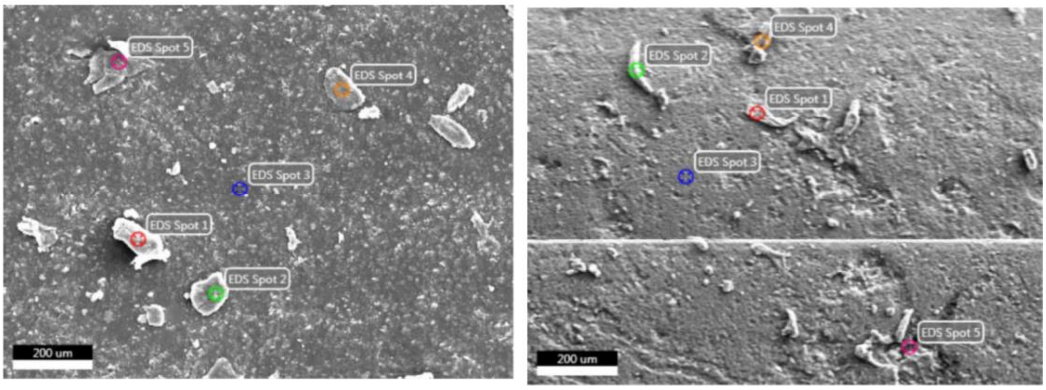

FIGURE 6: (a) Normal sample; and (b) Surface bump sample

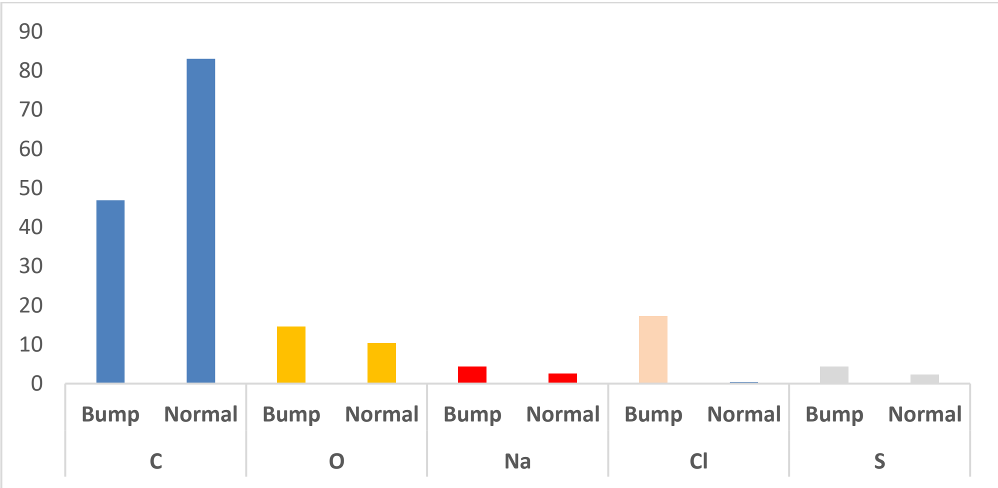

FIGURE 7: Elements weightage (%) distribution

Based on five (5) spot analyses of each group in Figure 6, it was found that the average Carbon % for the normal group is relatively higher compared to the bump group while the Oxygen for the bump group is slightly higher. This is also true for Chlorine and Sulphur elements where bump data shows a higher concentration of these two elements compare to the normal group.

3.2 Tensile Strength

15 samples were used to perform tensile strength for each group of samples. The result from both groups shows a higher value than the 150 kgf/mm min specification limit requirement in FMVSS 106 (NHTSA, 2004). Table 3 represents the computation of the two-tailed T-test of tensile strength obtained from the experiment.

TABLE 1: Statistical data for two-tailed T-test tensile strength analysis

Sample Type	Normal Hose	Bump Hose
Mean (kgf/mm)	342.38	345.34
Standard Deviation	20.67	27.45
Coefficient of Variance (%)	6.04	7.95
Two-tailed (p<=0.05)	0.7595	

From Table 1, there is no significant difference between the value of tensile strength of the normal hose and the bump surface hose based on a P-value of 0.7595 which is higher than the P-value (P = 0.05). It is expected that the bump surface hose has similar tensile strength as the normal hose which suggests can endure peak burst pressures of more than 100 MPa in practical situations before rupturing.

3.3 Volumetric Expansion

Table 2 exhibits the Volumetric Expansion (VE) result when both groups of hose were subjected to an incrementally elevated range of pressure from 7 MPa, 10 MPa, 14 MPa, 17 MPa, and 20 MPa. Two-tailed T-test also confirmed that for all the pressure setup value, none of the VE P-value is lower than 0.05 which give the indication that the bump appearance will not affect the expansion capability of the hose within the tested pressure limits hence no leakage is expected due to this defect type.

The expansion standard value (VE) does not exceed 0.25 mm to provide low cubical expansion and superior durability (Mizutani et al., 2004). This is because when the thickness of the rubber layer was decreased below the 0.3 mm or greater thickness, the amount of expansion of the yarn layer due to the rubber elasticity of the EPDM outer layer also decreased, thereby reducing the amount of displacement of the yarn layer (Mizutani et al., 2004). Figure 8 illustrates the linear correlation for both samples of the group which suggests there is no significant difference in terms of VE between the bump surface as well as normal hose.

TABLE 2: Mean value of VE experiment

Pressure (MPa)	VE, µ (Normal, cc/ft)	VE, µ (Bump, cc/ft)	Two-tail (p)
6.9	0.1308	0.1312	0.5667
10.3	0.1803	0.2009	0.0555
13.7	0.2355	0.2389	0.0691
17.1	0.2935	0.2877	0.0598
20.5	0.3309	0.3317	0.0718

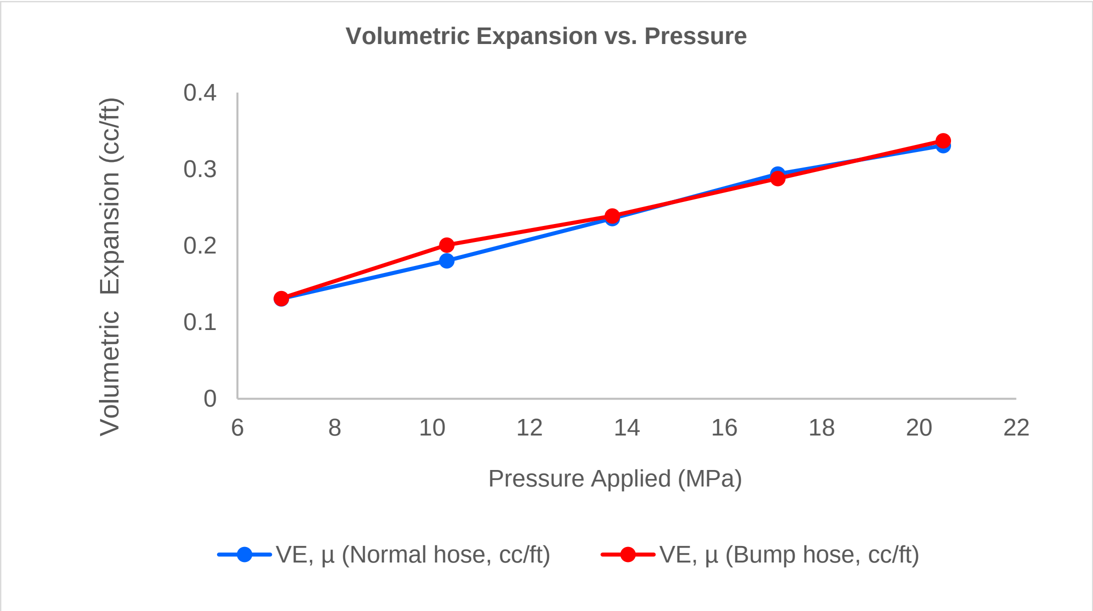

FIGURE 8: Pressure vs. VE correlation for bump and normal samples

3.4 Swelling Equilibrium Test

The swelling data is used to determine the cross-link density of the EPDM rubber hose samples. Swelling data include mass swelling ratio and volume swelling ratio. The cross-link density was calculated using the Flory-Rehner equation. Table 3 shows the cross-link density results of the normal hose and bump surface sample.

In Table 3, a hose sample with a bumped surface has a slightly higher cross-link density than a standard hose. The crosslink density of EPDM rubber is highly dependent on the number of crosslinks in the rubber network. The smaller the equilibrium degree of swelling, the higher the degree of cross-linking. The bump surface hose has a lower swelling index than the normal hose, which indicates that the bump surface hose was less absorbent than the normal hose.

Charles's investigation (Darko, 2022) on the cross-link density of EPDM rubber compound supports the result that suggests typical EPDM rubber compound has a cross-link density of 2.00 Mc x 10^{-3}. In Charles's study, a concentration of 15% paraffin oil is used to manufacture EPDM compound, which is slightly higher compared to 10% paraffin oil used in this research. The results of this investigation differed marginally from Charles' cross-link density findings due to variations in the plasticizer mixture employed and the percentage of paraffin oil used.

TABLE 3: The cross-link density of the normal hose vs. hose with bump surface

Testing	Normal Hose	Bump Surface Hose
$Ø_2$	0.598	0.598
V_r	1.674	1.673
Cross-link density (ρ_cx 10^{-3})	2.075	2.046

4. CONCLUSION

All the analysis in terms of physical and mechanical properties was successfully conducted and the result reveals that there is no significant difference observed between the surface bump hose as compared to the normal hose. This result is supported by statistical analysis where the two-tailed T-test value is smaller than the p-value of 0.05 for all experiments. This outcome strongly suggests that the classification of this bump surface as a defect may require a deeper review to consider it as a cosmetic issue and therefore should not be rejected from the production line. Nevertheless, a more rigorous reliability and stress test should be performed before any acceptance decision been made to confirm this initial finding.

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