由含硫与二硫化苯并噻唑促进剂比率为 2.15 的天然橡胶硫化胶获得的。该比率还产生了机械性能（撕裂和拉伸强度）、弹性性能（压缩永久变形、卢普克回弹性和弹性模量）和最高有效剪切模量值的最佳值。撕裂强度、拉伸强度、压缩永久变形、卢普克 E 回弹性、弹性模量和有效剪切模量的值为 28.5 牛/毫米；25.2 兆帕；3.65%；79; 3.89 兆帕和 0.169 兆帕。在含硫天然橡胶硫化橡胶与二硫化苯并噻唑促进剂之比为 0.14 的等效阻尼比为 1.39% 时，获得了最佳减振值。

关键词：天然橡胶、硫与促进剂的比例、交联密度、机械性能, 动态性能。

1. Introduction

Most elastomeric engineering materials for vibration isolators need mechanic, elastic, and damping properties to fulfill the product requirements. Rubber is generally good for vibration damping material. The vibration damping capacity of rubber materials varies widely, and it is usually influenced by its viscoelastic properties [1, 2, 8]. In general, butyl rubber is a synthetic rubber that has the best vibration damping capacity, while the natural one is classified as having a lower vibration damping capacity [3]. The tangent delta value (loss factor) indicates that the vibration damping capacity of natural rubber is lower than that of synthetic one [3]. Some studies on increasing the vibration damping capacity of natural rubber have been carried out by increasing the stiffness or changing the viscoelastic properties [4-11]. The research was carried out to obtain a vibration-damping capacity that meets the requirements for applications in machinery, automotive, or earthquake-resistant buildings.

The chemicals used in manufacturing rubber compounds improve elasticity and strength, especially for crosslinking materials or vulcanizing agents [12-21]. Nabeel Alshabatat and Ahmad Abouel-Kasem [14] stated that sulfur is the most widely used crosslinking material for unsaturated elastomer, with a carbon-carbon double bond in its molecular structure, such as natural rubber. The crosslinks formed in the sulfur vulcanization system are sulfide crosslinks greatly influenced by the sulfur ratio to the accelerator [12-15, 19-21]. In the sulfur vulcanization system, the formation of sulfide crosslink depends on the sulfur ratio to the accelerator, temperature, and vulcanization time [19, 20]. The sulfur ratio to accelerator added to rubber compounds can set the amount and type of sulfide crosslinking in the rubber molecules [13, 19]. The types of sulfide crosslink formed include monosulfide crosslink, disulfide crosslink, or polysulfide crosslink [13, 14, 17, 19, 21].

The number and types of monosulfide, disulfide, and polysulfide crosslinks can influence the mechanical properties of rubber products [13, 14, 17, 19, 21]. The crosslink density shows the number of crosslinks formed on rubber macromolecules during the vulcanization process. The density of sulfide crosslink significantly influences the mechanical properties of the resulting vulcanizate [12-15, 17, 19, 20]. The formation of crosslinks in this vulcanization process can increase material elasticity and strength [19, 22-24]. The emergence of hysteresis indicated by the ratio between the viscous and elastic components of the material deformation resistance is also affected by the crosslinks number. Generally, the higher the crosslinks formed, the lower the hysteresis value [25]. Therefore, this research will study the relationship of variations in the sulfur ratio to the accelerators on the crosslink density, mechanical, elastic, viscoelastic, and vibration damping properties of NR vulcanizate for rubber compound formulation vibration isolator.

2. Material and Methods

2.1. Research Materials

The rubber compound production requires natural rubber type SIR 20 as a base elastomer, an activating agent in the form of zinc oxide (ZnO) UN 3077 from Lanxess Germany, stearic acid Aflux®52 from Lanxess Germany, an accelerator in the form of 2-2'-dithiobenzothiazole (MBTS) of Kemai brand from China, and vulcanizing material in the form of sulfur (Midas SP 325 produced by Miwon Co Japan). The rubber compound chemicals used are entirely at the technical quality level. The rubber compound formula applied in this experiment is designed at various doses of sulfur for the MBTS accelerator, as shown in Table 1.

Table 1 Natural rubber compound formula

Sample Code	NR (% Wt)	ZnO (phr)	Stearic Acid (phr)	Sulfur (phr)	MBTS (phr)	Ratio (Sulfur/MBTS)
A1	100	5	2	0.20	1.45	0.14
A2	100	5	2	0.24	1.41	0.17

Continuation of Table 1						
A3	100	5	2	0.30	1.35	0.22
A4	100	5	2	1.50	1.35	1.11
A5	100	5	2	2.90	1.35	2.15

Note: The amount of these additives to be added is expressed in parts per hundred rubber (phr).

2.2. Rubber Compound Production

The rubber compound is made by mixing rubber with some chemicals in a laboratory-scale open mill with a capacity of 1000 g/batch with the German brand, Bernstorff. The rubber compound production refers to the ASTM 3182 standard with the mixing stages shown in Table 2. First, natural rubber is masticated until its viscosity level drops significantly so that it is easier to mix it with the chemicals. Then, masticated natural rubber becomes softer, characterized by its plasticity level. Next, the rubber compound chemicals are added to natural rubber in the order of ZnO, stearic acid, MBTS, and the last is sulfur. After all the rubber compound chemicals have been added, the rubber is continuously grounded and homogenized.

Table 2 Procedure for mixing natural rubber compounds

Stage	**Process or Ingredients**	**Time (minutes)**
1.	Mastication of NR	5
2.	ZnO	1
3.	Stearic Acid	1
4.	MBTS	1
5.	Sulfur	1
6.	Mixing for homogenization	2

2.3. Vulcanization Characteristics Testing

The vulcanization characteristics of the rubber compounds are identified based on the standard ASTM D5289-12 method at 150 °C using an Alfa 2000 moving die rheometer (Alfa Technologies, Akron, USA). In this test, the data on the curing characteristics of the rubber compounds are obtained, including the maximum and minimum torque, the difference between the maximum and minimum torque, optimum cure time (t_{90}), and scorch time (ts_2). The optimum cure time value is then used for molding the rubber compounds to be the test sample vulcanizate. The molding process is carried out on a KMC brand hydraulic press made in Japan.

2.4. Crosslink Density Test

The degree of an unfilled natural rubber vulcanizate is determined using the Mooney-Rivlin method [22, 23], which is based on the stress-strain behavior of the rubber with the following equation:

$$F = 2A_o\,(\lambda - \lambda^{-2})(C_1 + C_2/\lambda) \quad (1)$$

$$F / [2A_o\,(\lambda - \lambda^{-2})] = C_1 + C_2/\lambda \quad (2)$$

$$n_{phys} = C_1/RT \quad (3)$$

The intercept value of C_1 can be obtained by plotting the relationship curve of $F/[2A_o(\lambda - \lambda^{-2})]$ vs. $1/\lambda$. Furthermore, the value of C_1 can be used to determine the crosslink density of rubber vulcanizate according to equation (3).

2.5. Mechanical and Elastic Properties Test

The rubber vulcanizate is tested for its mechanical properties, such as Shore A hardness test according to ISO 48 standard, tensile strength, elongation at break test according to ISO 37 standard method, and tear resistance test based on ISO 34 standard. Then, rubber vulcanizate's elastic properties are examined through the LUPKE rebound resilience test according to the ASTM D1054 standard. A fixed compression test is also based on the ISO 815 type A standard.

2.6. Dynamic Shear Properties Testing

The rubber's dynamic shear properties are examined based on the ISO 4664-1 standard method using a four-block lap shear-type shown in Fig. 1a at 10 Hz, 100% strain for four test cycles.

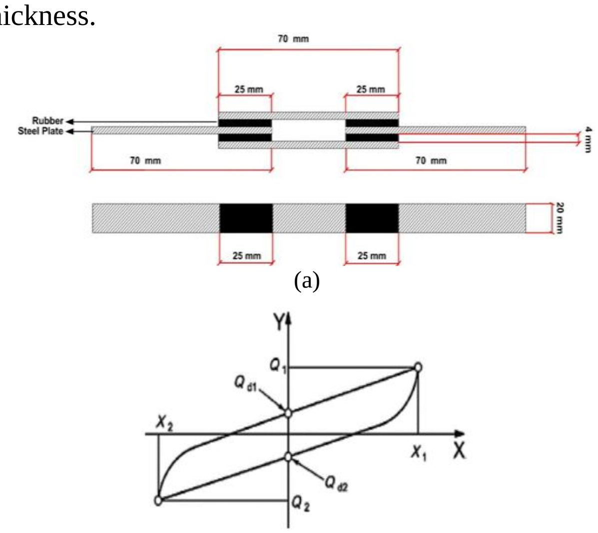
The results show a displacement (mm) vs. shear force (N) relationship curve in the form of a loop. The data are then analyzed using equations (4), (5), and (6) to obtain shear stiffness (K_H), damping ratio (h_{eq}), and effective shear modulus (G_{eff}) [4].

$$K_H = \frac{Q_1 - Q_2}{X_1 - X_2} \quad (4)$$

$$h_{eq} = \frac{2\,\Delta W}{\pi K_h\,(X_1 - X_2)^2} \quad (5)$$

$$G = \frac{K_H\ t_r}{A_r} \quad (6)$$

where K_H is the shear stiffness, h_{eq} is the equivalent damping ratio, Q_1 is the maximum shear force, Q_2 is the minimum shear force, X_1 is the maximum extension, X_2 is the minimum extension in the third cycle, ΔW is the area enclosed by the third hysteresis loop, and A_r and t_r are the one-layer rubber area and thickness.



(a)

(b)

Fig. 1 Dynamic shear test, (a) four-block lap shear-type specimen, (b) typical shear hysteresis loop

3. Results and Discussion

3.1. Curing Characteristics of Rubber Compounds

The determined curing characteristics of unfilled natural rubber compounds are the maximum torque (M_H), the minimum torque (M_L), the difference between the maximum and minimum torque, optimum cure time (t_{90}), and scorch time (ts_2). Based on the test results in Table 3, the curing characteristics of the rubber compound are strongly influenced by the sulfur ratio to the MBTS accelerator. The value of the sulfur ratio to the accelerator is closely connected to the types of sulfur vulcanization systems. Based on the sulfur ratio to the accelerator, unfilled natural rubber compounds with sample codes of A1, A2, and A3 are classified as efficient sulfur vulcanization systems. At the same time, A4 and A5 are respectively included as semi-efficient and conventional sulfur vulcanization systems. Increasing the sulfur ratio to the MBTS causes increasing maximum torque (M_H) and the difference between the maximum and minimum torque (M_H-M_L). It also triggers faster optimum cure time (tc_{90}) and scorches time (ts_2). The maximum torque (M_H) represents the maximum crosslinks established during the vulcanization [15]. The minimum torque (M_L) shows the compound's viscosity and also provides information regarding the compounds' processability [23]. Table 3 shows that the minimum torque values of all unfilled natural rubber compounds are relatively the same. The difference between maximum and minimum torsion (M_H-M_L) or torque delta is not directly connected to the total crosslink density of a rubber compound [15]. Table 3 shows that the torque delta increases when the sulfur ratio to the MBTS also increases. Therefore, the torque delta of unfilled natural rubber compounds using a conventional sulfur vulcanization system will be higher than NR compounds with semi-efficient and efficient sulfur vulcanization systems.

Table 3 Curing characteristics of unfilled NR compound

Curing Characteristics	Sulfur Ratio to Accelerator (S/MBTS)				
	(0.14)	(0.17)	(0.22)	(1.11)	(2.15)
M_H, dNm	2.93	3.19	3.55	5.75	7.01
M_L, dNm	0.36	0.39	0.49	0.75	0.41
$M_H – M_L$, dNm	2.57	2.8	3.06	5.00	6.60
ts_2, min:sec	25:38	26:11	23:56	14:46	9:56
tc_{90}, min:sec	30:42	20:15	17:33	9:36	5:07

3.2. Crosslink Density

In this research, the crosslink density of unfilled natural rubber vulcanizate was set using the Mooney-Rivlin method, and the crosslink density values are shown in Table 4. The crosslink density values were related to the sulfur amount that reacts with the molecular rubber chains through the crosslink. A higher amount of sulfur triggers improved formation of crosslinks. Sansanee Srichan and Sarawut Prasertsri [20] stated that the types of sulfide crosslinks formed in the vulcanization process include monosulfide, disulfide, or polysulfide crosslinks which are influenced by the sulfur vulcanization system, vulcanization time, and temperature. Table 4 shows that the increasing sulfur ratio to MBTS will also increase the crosslink density values of a rubber vulcanizate. Therefore, the sulfur ratio to the accelerator can determine whether the sulfur vulcanization system is conventional, semi-efficient, or efficient. The unfilled rubber vulcanizate using a conventional sulfur vulcanization system produces higher crosslink density values than the NR vulcanization using semi-efficient and efficient systems. These crosslink density values can affect a natural rubber vulcanizate's mechanical, viscoelastic, and vibration damping properties.

Table 4 Crosslink density values on unfilled NR vulcanizate

Sample Code	Sulfur/MBTS	Crosslink Density by Mooney-Rivlin Method (mol/cm^3)
A1	0.14	7.45×10^{-6}
A2	0.17	2.38×10^{-5}
A3	0.22	2.85×10^{-5}
A4	1.11	5.20×10^{-5}
A5	2.15	7.16×10^{-5}

3.3. Mechanical and Elastic Properties

The mechanical properties of natural rubber vulcanizate were strongly influenced by the density and type of crosslinks [13, 14, 17, 19, 21]. The mechanical properties of natural rubber vulcanizate obtained from varying sulfur ratios to the MBTS accelerator are presented in Fig. 2. This research examined mechanical properties, including hardness, tear strength, tensile strength, and elongation at break.

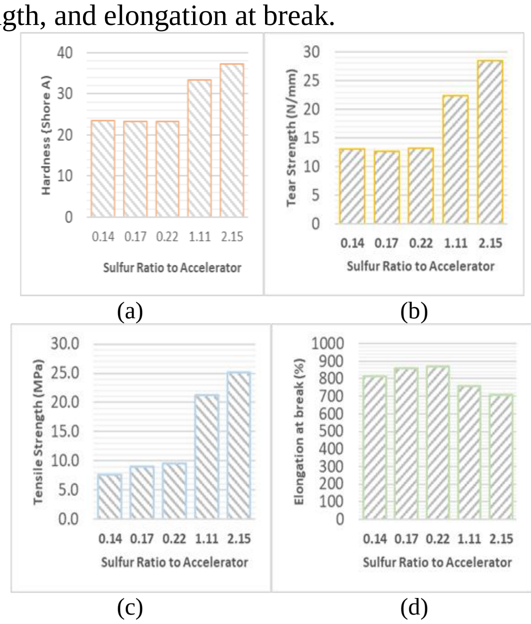


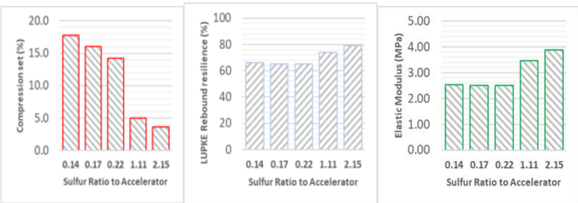
Fig. 2 The relationship of variations in the sulfur ratio to accelerator to the mechanical properties of unfilled NR vulcanizate: (a) hardness, (b) tear strength, (c) tensile strength; (d) break elongation

Fig. 2 shows that increasing sulfur ratio of sulfur to the accelerator (MBTS) caused an increase in the hardness, tear strength, and tensile strength level and also caused decreasing elongation at break properties of an unfilled rubber vulcanizate. In addition, the increasing sulfur ratio to accelerator caused higher crosslink density values and further increased the strength and elastic properties [19]. Based on the results shown in Fig. 2, the increase in the sulfur ratio to the accelerator also increases the material strength, indicated by the increasing tear and tensile strength. Furthermore, this event is associated with increased crystallinity upon stretching [26, 27]. Furthermore, from Fig. 3, it can be seen that an increase in the sulfur ratio to the accelerator caused an increase in the elastic properties, as indicated by a lower compression set (Fig. 3a), higher LUPKE rebound resilience value (Fig. 3b), and higher elastic modulus values (Fig. 3c).

The elastic modulus value in Fig. 3c is obtained based on the indentation technique through the relationship of the Shore A hardness value to the elastic modulus according to the following equation proposed by Kunz and Studer [28]:

$$E_H = \left(\frac{1-v^2}{2r_d}\right) x \left(\frac{0.549 + (0.07516\, x\, Sh_A)}{0.025\, x\, (100 - Sh_A)}\right) x \left(2.6 - (0.02\, x\, Sh_A)\right) \tag{7}$$

Sh_A means the Shore-A hardness value, r_d is the tip radius of the durometer (0.395 mm), and v is the assumed value of the Poisson ratio of 0.475.



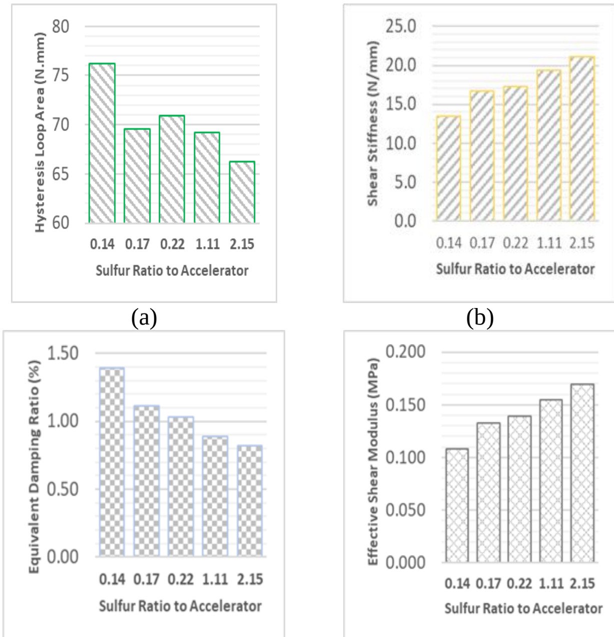
(a) (b) (c)

Fig. 3 The relationship of variations in the sulfur ratio to accelerator on the elastic properties of unfilled natural rubber vulcanizate: (a) compression set, (b) LUPKE rebound resilience, (c) elastic modulus

3.4. Viscoelastic Properties and Vibration Damping

Rubber belongs to viscoelastic materials with specific viscous and elastic properties. The viscoelastic behavior of natural rubber vulcanizate can be identified by testing its dynamic properties but depends on the strain frequency, strain amplitude, and temperature [5]. Hysteresis values can demonstrate viscoelastic properties by measuring dynamic properties [4, 8]. The hysteresis event shows the energy lost per cycle during rubber deformation related to the vibration damping capacity [8].

In the rubber compounds vulcanizate, the hysteresis value is greatly affected by the types of raw rubber and its chemicals [8]. The influential chemicals include the types and amount of the filler [8], type and number of vulcanizing materials [15], softener [8], and resin materials [9]. Based on the dynamic shear properties test results shown in Fig. 4, it can be seen that the values of the hysteresis loop area, shear stiffness, equivalent damping ratio, and effective shear modulus are affected by the sulfur ratio to the accelerator in natural rubber vulcanizate. Fig. 4a shows that the dynamic shear properties test resulted in various hysteresis loop areas, significantly influenced by the sulfur ratio to MBTS accelerator. The hysteresis loop area value means that natural rubber vulcanizate is viscoelastic. The highest hysteresis loop area value and equivalent damping ratio occur in natural rubber vulcanizate, with sulfur to accelerator ratio of 0.14. Increasing the sulfur ratio to the accelerator in the unfilled rubber vulcanizate caused an increase in the shear stiffness (Fig. 4b) and effective shear modulus (Fig. 4d) values. However, the equivalent damping ratio will decrease (Fig. 4c). The sulfur ratio to MBTS accelerator can affect the crosslink density so that this ratio increase can cause the vulcanizate to become stiffer, indicated by higher hardness values (Fig. 2a). It means that the shear stiffness values may increase due to increasing values of the NR vulcanizate hardness. The shear stiffness values greatly influence the equivalent damping ratio and the effective shear modulus. The higher shear stiffness values result in a decrease in the equivalent damping ratio and an increase in the effective shear modulus values.



(c) (d)

Fig. 4 The relationship of the sulfur ratio to accelerator to the dynamic shear properties of unfilled natural rubber vulcanizate: (a) hysteresis loop area, (b) shear stiffness, (c) damping ratio, and (d) effective shear modulus

4. Conclusion

4.1. Scope of the Results

The compounds curing characteristics, crosslink density, and mechanical, elastic, viscoelastic, and vibration dampening properties of unfilled natural rubber vulcanizate are strongly influenced by the sulfur ratio to accelerator used. Testing results showed that the increment of sulfur to MBTS accelerator ratio increased crosslink density value. The highest crosslink density was measured at a 7.16 x 10^{-5} mol/cm^3 obtained by NR vulcanizates containing sulfur to MBTS accelerator ratio at 2.15. This ratio also produced optimum value for mechanical properties (tear and tensile strength), elastic properties (compression set, LUPKE rebound resilience, and elastic modulus), and the highest effective shear modulus value. The value of tear strength, tensile strength, compression set, LUPKE rebound resilience, elastic modulus, and an effective shear modulus were 28.5 N/mm; 25.2 MPa; 3.65%; 79; 3.89 MPa, dan 0.169 MPa. In addition, the optimum value of vibration dumping was obtained at 1.39% of an equivalent damping ratio produced by NR vulcanizates containing sulfur to MBTS accelerator ratio at 0.14.

4.2. Novelty, Limitation, and the Research Perspectives

The natural rubber has good elasticity properties and low vibration damping capacity. Therefore, modification of the properties through crosslink in natural rubber vulcanizates molecular chains is required to produce a better vibration isolator. In addition, the sulfur ratio of the accelerator added to natural rubber compounds can control the crosslink density in the rubber molecules and influence the rubber vulcanizate's mechanical properties, especially viscoelasticity properties and strength. These variables are essential to developing NR vulcanizates properties appropriate to the vibration isolator product requirement.

Dynamic Mechanical Analysis (DMA) is usually utilized to investigate the vibration damping capacity of a rubber vulcanizate. The dynamic shear properties testing determined the vibration damping capacity in this research. A study on the correlation between crosslink density and dynamic shear properties of NR vulcanizates has not been conducted. The correlation between crosslink density and dynamic shear properties of NR vulcanizates, including hysteresis loop area, shear stiffness, equivalent damping ratio, and effective shear modulus, is revealed in this report. Crosslink density is determined by the Mooney-Rivlin method based on the stress-strain behavior of the rubber and correlated to the dynamic shear properties. The compound formulation technique could set the crosslink density of the natural rubber compounds to achieve the optimum value of the viscoelasticity and damping properties of NR vulcanizates.

The crosslink density of NR vulcanizates represents as total crosslink density. This research was to study the effects of total crosslink density on the NR vulcanizates' properties. In contrast, the composition of types of crosslink density such as monosulfide, disulfide, and polysulfide crosslink density was ignored. For further study, the correlation between types of crosslink density and dynamic shear properties will be reported separately. Based on the influence of sulfur ratio to accelerator on the crosslink density of NR vulcanizates, the research focused on increasing the vibration damping capacity of rubber vulcanizates and designing a rubber compound formulation for the preparation of a specific rubber isolator or rubber product.

References

[1] LEI T., ZHANG Y.-W., KUANG D.-L., and YANG Y.-R. Preparation and Properties of Rubber Blends for High-Damping-Isolation Bearings. *Polymers*, 2019, 11: 1374. https://doi.org/10.3390/polym11081374

[2] VAŠINA M., PÖSCHL M., and ZÁDRAPA P. A study of Significant Factors Affecting Viscoelastic Damping Properties of Polymer Materials. *Manufacturing Technology*, 2018, 18(3): 523-529. https://doi.org/10.21062/ujep/132.2018/a/1213-2489/mt/18/3/523

[3] HALLADAY J. R., & JAGLOWSKI K. T. Sources of Hysteresis in Rubber Compound. *Rubber and Plastic News*, 2017, 7: 13-17. https://s3-prod.rubbernews.com/s3fs-public/RN11142784.PDF

[4] MURNIATI R., RAHMAYANTI H. D., UTAMI F. D., CIFRIADI A., ISKANDAR F., and ABDULLAH M. Effect of Magnetically modified natural zeolite addition on the crosslink density, mechanical, morphological, and damping properties of SIR 20 natural rubber reinforced with nano-silica compounds. *Journal of Polymer Research*, 2020, 27: 37. https://doi.org/10.1007/s10965-020-2013-0

[5] KOUPAI S. A., BAKHSHI A., and TABRIZI V. V. Experimental investigation on effect of elastomer component on dynamic and mechanical properties in seismic isolator compounds. *Construction and Building Materials*, 2017, 135: 267-278. http://dx.doi.org/10.1016/j.conbuildmat.2016 .12.184

[6] HENTSCHKE R. The Payne Effect Revisited. *eXPRESS Polymer Letters*, 2017, 11(4): 278–292. https://doi.org/10.3144/expresspolymlett.2017.28

[7] WANG Y., LIAO L., LIN H., ZHANG F., ZHONG J., XU K., and PENG Z. Damping Properties of Natural Rubber/ Epoxidized Natural Rubber Composite with Different Filler. *Advances in Engineering Research*, 2017, 120: 772-775. http://dx.doi.org/10.2991/ifeesm-17.2018.145

[8] MOHAMAD N., YAAKUB J., AB MAULOD H. E., JEEFFERIE A. R., YUHAZRI M. Y., LAU K. T., AHSAN Q., SHUEB M. I., and OTHMAN R. Vibrational damping behaviors of graphene nanoplatelets reinforced NR/EPDM nanocomposite. *Journal Mechanical Engineering and Sciences*, 2017, 11(4): 3274-3287. https://doi.org/10.15282/jmes.11.4.2017.28.0294

[9] MA R., ZHANG X., LIU C., and WU W. Hindered Phenol-Mediated Damping of Polyacrylate Rubber: Effect of Hydrogen Bonding Strength on the Damping Properties. *Journal of Polymer Engineering*, 2019, 39(7): 642-652. https://doi.org/10.1515/polyeng-2018-0378

[10] LI J.-C., ZHANG H.-S., ZHAO X.-Y., JIANG J.-G., WU Y.-X., LU Y.-L., ZHANG L.-Q., and NISHI T. Development of high damping natural rubber/butyl rubber

composites compatibilized by isobutylene-isoprene block copolymer for isolation bearing. *eXPRESS Polymer Letters*, 2019, 13(8): 686-696. https://doi.org/10.3144/expresspolymlett.2019.58

[11] WANG J., ZHAO X., WANG W., GENG X., ZHANG L., GUO B., NISHI T., and HU G.-H. Significantly improving strength and damping performance of nitrile rubber via incorporating sliding graft copolymer. *Industrial and Engineering Chemistry Research*, 2018, 57(49): 16692-16700. https://doi.org/10.1021/acs.iecr.8b03871

[12] HAN S., GU B., KIM S., KIM S., MUN D., MORITA K., KIM D., and KIM W. Effect of Sulfur Variation on the Vulcanizate Structure of Silica-Filled Styrene-Butadiene Rubber Compounds with a Sulfide-Silane Coupling Agent. *Polymers*, 2020, 12(12): 2815. https://doi.org/10.3390/polym12122815

[13] KIM D. Y., PARK J. W., LEE D. Y., and SEO K. H. Correlation between the Crosslink Characteristics and Mechanical Properties of Natural Rubber Compound via Accelerators and Reinforcement. *Polymers*, 2020, 12(9): 2020-2033. https://doi.org/10.3390/polym12092020

[14] ALSHABATAT N., & ABOUEL-KASEM A. The Effects of Sulfur Content on the Mechanical Properties of Nitrile Butadiene Rubber with Different Aging Conditions. *Jordan Journal of Mechanical and Industrial Engineering*, 2021, 15(4): 387-393. https://www.researchgate.net/publication/355360526_The_Effects_of_Sulfur_Content_on_the_Mechanical_Properties_of_Nitrile_Butadiene_Rubber_with_Different_Aging_Conditions

[15] G. SHI, W. WANG, H. LU, G. WANG, F. YANG, and RUI X. Study of Crosslink Structure and Dynamic Mechanical Properties of Magnetorheological Elastomer: Effect of Vulcanization System. *Journal of Intelligent Material Systems and Structures*, 2019, 30(8): 1189-1199. https://doi.org/10.1177/1045389x19835940

[16] HAIT S., VALENTÍN J. L., JIMÉNEZ A. G., ORTEGA P. B., GHOST A. K., STÖCKELHUBER K. W., WIEßNER S., HEINRICH G., and DAS A. Poly(acrylonitrile-co-butadiene) as Polymeric Crosslinking Accelerator for Sulfur Network Formation. *Journal of Heliyon*, 2020, 6(8): e04659. https://doi.org/10.1016/j.heliyon.2020.e04659

[17] LARPKASEMSUK A., RAKSAKSRI L., CHUAYJULJIT S., CHAIWUTTHINAN P., and BOONMAHITTHISUD A. Effect of Sulfur Vulcanization System on Cure Characteristics, Physical Properties and Thermal Aging of Epoxidized Natural Rubber. *Journal of Metals, Materials, and Minerals*, 2019, 29(1): 49-57. https://doi.org/10.14456/jmmm.2019.8

[18] ZAREI A., & JALALI-ARANI A. The relationship of Vulcanization and Structural Characteristic-dispersion of Organoclay-Mechanical Properties in (Butadiene Rubber/Natural Rubber) Based Nanocomposite. *Advances in Polymer Technology*, 2018, 37: 1469-1477. https://doi.org/10.1002/adv.21805

[19] BOONKERD K., DEEPRASERTKUL C., and BOONSOMWONG K. Effect of Sulfur to Accelerator Ratio on Crosslink Structure, Reversion, and Strength in Natural Rubber. *Rubber Chemistry and Technology*, 2016, 89(3): 450-464. https://doi.org/10.5254/rct.16.85963

[20] SRICHAN S., & PRASERTSRI S. Influence of Accelerator/Sulfur Ratio on Mechanical Properties and Thermal Resistance of Natural Rubber Containing Hybrid Fillers. *Key Engineering Materials*, 2017, 744: 300-304. https://doi.org/10.4028/www.scientific.net/kem.744.300

[21] TAMÁSI K., & KOLLÁR M. S. Effect of Different Sulfur Content in Natural Rubber Mixture on Their Thermo-mechanical and Surface Properties. *International Journal of Engineering Research & Science*, 2018, 4(2): 28-37. https://ijoer.com/assets/articles_menuscripts/file/IJOER-FEB-2018-6.pdf

[22] MOK K. L., & ENG A. H. Characterisation of Crosslinks in Vulcanised Rubbers: from Simple to Advanced Techniques. *Malaysian Journal of Chemistry*, 2018, 20(1): 118-127. https://doi.org/10.55373/mjchem.v20i1.11

[23] HIRANOBE C. T., RIBEIRO G. D., TORRES G. B., PRADO DOS REIS E. A., CABRERA F. C., ELOIZO JOB A., PAIM L. L., and JOSE DOS SANTOS R. Cross-linked Density Determination of Natural Rubber Compounds by Different Analytical Techniques. *Material Research*, 2021; 24(1): e20210041. https://doi.org/10.1590/1980-5373-MR-2021-0041

[24] SETIYANA B., ISMAIL R., JAMARI J., SUGIYANTO., and HARYANTO I. Mechanical Properties Identification of Vulcanized Rubber by Using Mooney-Rivlin Method. Proceedings of the 2nd Borobudur International Symposium on Science and Technology, Magelang, 2021, pp. 99-103. https://doi.org/10.2991/aer.k.210810.016

[25] LE CAM J.-B. Energy storage due to strain-induced crystallization in natural rubber: The physical origin of the mechanical hysteresis. *Polymer*, 2017, 127: 166-173. https://doi.org/10.1016/j.polymer.2017.08.059

[26] CANDAU N., OGUZ O., FEDERICO C. E., STOCLET G., TAHON J-F., and MASPOCH M. L. Strain induced crystallization in vulcanized natural rubber containing ground tire rubber particles with reinforcement and nucleation abilities. *Polymer Testing*, 2021, 101: 107313. https://doi.org/10.1016/j.polymertesting.2021.107313

[27] MASA A., HAYEEMASAE N., SOONTARANON S., MOHD PISAL M. H., and MOHAMAD RASIDI M. S. Effect of Stretching Rate on Tensile Response and Crystallization Behavior of Crosslinked Natural Rubber. *Malaysian Journal of Fundamental and Applied Sciences*, 2021, 17: 217-225. https://doi.org/10.11113/mjfas.v17n3.2039

[28] SCHIAVI A., & PRATO A. Elastic and Viscoelastic Properties of Synthetic Rubber (Polychloroprene): Dynamic and Static Characterization. Proceedings of the 24th International Congress on Sound and Vibration, London, 2017, pp. 1-8. https://www.researchgate.net/publication/318816684

参考文:

[1] LEI T., ZHANG Y.-W., KUANG D.-L., 和 YANG Y.-R. 高阻尼隔震轴承用橡胶混合物的制备和性能。聚合物, 2019, 11: 1374. https://doi.org/10.3390/polym11081374

[2] VAŠINA M., PÖSCHL M., 和 ZÁDRAPA P. 影响高分子材料粘弹性阻尼性能的重要因素研究。制造技术, 2018, 18(3): 523-529. https://doi.org/10.21062/ujep/132.2018/a/1213-2489/mt/18/3/523

[3] HALLADAY J. R., 和 JAGLOWSKI K. T. 橡胶化合物中滞后的来源。橡塑新闻, 2017, 7: 13-17. https://s3-prod.rubbernews.com/s3fs-public/RN11142784.PDF
[4] MURNIATI R., RAHMAYANTI H. D., UTAMI F. D., CIFRIADI A., ISKANDAR F., 和 ABDULLAH M. 添加磁性改性天然沸石对用纳米二氧化硅化合物增强的标准印度尼西亚橡胶 20 天然橡胶的交联密度、机械、形态和阻尼性能的影响。高分子研究杂志, 2020, 27: 37. https://doi.org/10.1007/s10965-020-2013-0
[5] KOUPAI S. A., BAKHSHI A., 和 TABRIZI V. V. 弹性体组分对隔震器化合物动态和力学性能影响的实验研究。建筑和建筑材料, 2017, 135: 267-278. http://dx.doi.org/10.1016/j.conbuildmat.2016 .12.184
[6] HENTSCHKE R. 重新审视佩恩效应。快递聚合物字母, 2017, 11(4): 278–292. https://doi.org/10.3144/expresspolymlett.2017.28
[7] WANG Y., LIAO L., LIN H., ZHANG F., ZHONG J., XU K., 和 PENG Z. 不同填料的天然橡胶/环氧化天然橡胶复合材料的阻尼性能。工程研究进展, 2017, 120: 772-775. http://dx.doi.org/10.2991/ifeesm-17.2018.145
[8] MOHAMAD N., YAAKUB J., AB MAULOD H. E., JEEFFERIE A. R., YUHAZRI M. Y., LAU K. T., AHSAN Q., SHUEB M. I., 和 OTHMAN R. 石墨烯纳米片增强天然橡胶/乙烯丙烯二烯单体纳米复合材料的减振行为。机械工程与科学杂志, 2017, 11(4): 3274-3287. https://doi.org/10.15282/jmes.11.4.2017.28.0294
[9] MA R., ZHANG X., LIU C., 和 WU W. 受阻酚介导的聚丙烯酸酯橡胶阻尼：氢键强度对阻尼性能的影响。高分子工程学报, 2019, 39(7): 642-652. https://doi.org/10.1515/polyeng-2018-0378
[10] LI J.-C., ZHANG H.-S., ZHAO X.-Y., JIANG J.-G., WU Y.-X., LU Y.-L., ZHANG L.-Q., 和 NISHI T. 隔离轴承用异丁烯-异戊二烯嵌段共聚物增容的高阻尼天然橡胶/丁基橡胶复合材料的研制。快递聚合物字母, 2019, 13(8): 686-696. https://doi.org/10.3144/expresspolymlett.2019.58
[11] WANG J., ZHAO X., WANG W., GENG X., ZHANG L., GUO B., NISHI T., 和 HU G.-H. 通过加入滑动接枝共聚物显着提高丁腈橡胶的强度和阻尼性能。工业与工程化学研究, 2018, 57(49): 16692-16700. https://doi.org/10.1021/acs.iecr.8b03871
[12] HAN S., GU B., KIM S., KIM S., MUN D., MORITA K., KIM D., 和 KIM W. 硫含量变化对具有硫化物-硅烷偶联剂的二氧化硅填充苯乙烯-丁二烯橡胶胶料的硫化胶结构的影响。聚合物, 2020, 12(12): 2815. https://doi.org/10.3390/polym12122815
[13] KIM D. Y., PARK J. W., LEE D. Y., 和 SEO K. H. 天然橡胶胶料通过促进剂和增强剂的交联特性与力学性能的相关性。聚合物, 2020, 12(9): 2020-2033. https://doi.org/10.3390/polym12092020
[14] ALSHABATAT N., 和 ABOUEL-KASEM A. 不同老化条件下硫含量对丁腈橡胶力学性能的影响。约旦机械与工业工程杂志, 2021, 15(4): 387-393. https://www.researchgate.net/publication/355360526_The_Effects_of_Sulfur_Content_on_the_Mechanical_Properties_of_Nitrile_Butadiene_Rubber_with_Different_Aging_Conditions
[15] G. SHI, W. WANG, H. LU, G. WANG, F. YANG, 和 RUI X. 磁流变弹性体的交联结构和动态力学性能研究：硫化体系的影响。智能材料系统与结构杂志, 2019, 30(8): 1189-1199. https://doi.org/10.1177/1045389x19835940
[16] HAIT S., VALENTÍN J. L., JIMÉNEZ A. G., ORTEGA P. B., GHOST A. K., STÖCKELHUBER K. W., WIEßNER S., HEINRICH G., 和 DAS A. 聚（丙烯腈-共-丁二烯）作为聚合物交联促进剂用于硫网络的形成。日光杂志, 2020, 6(8): e04659. https://doi.org/10.1016/j.heliyon.2020.e04659
[17] LARPKASEMSUK A., RAKSAKSRI L., CHUAYJULJIT S., CHAIWUTTHINAN P., 和 BOONMAHITTHISUD A. 硫磺硫化体系对环氧化天然橡胶硫化特性、物理性能和热老化的影响。金属、材料和矿物杂志, 2019, 29(1): 49-57. https://doi.org/10.14456/jmmm.2019.8
[18] ZAREI A., 和 JALALI-ARANI A. （丁二烯橡胶/天然橡胶）基纳米复合材料的硫化与结构特性-有机粘土分散-力学性能的关系。聚合物技术的进步, 2018, 37: 1469-1477. https://doi.org/10.1002/adv.21805
[19] BOONKERD K., DEEPRASERTKUL C., 和 BOONSOMWONG K. 硫与促进剂比对天然橡胶交联结构、回复性和强度的影响。橡胶化学与技术, 2016, 89(3): 450-464. https://doi.org/10.5254/rct.16.85963
[20] SRICHAN S., 和 PRASERTSRI S. 促进剂/硫比对含有混合填料的天然橡胶的机械性能和耐热性的影响。关键工程材料, 2017, 744: 300-304. https://doi.org/10.4028/www.scientific.net/kem.744.300
[21] TAMÁSI K., 和 KOLLÁR M. S. 天然橡胶混合物中不同硫含量对其热机械和表面性能的影响。国际工程研究与科学杂志, 2018, 4(2): 28-37. https://ijoer.com/assets/articles_menuscripts/file/IJOER-FEB-2018-6.pdf
[22] MOK K. L., 和 ENG A. H. 硫化橡胶中交联键的表征：从简单技术到高级技术。马来西亚化学杂志, 2018, 20(1): 118-127. https://doi.org/10.55373/mjchem.v20i1.11
[23] HIRANOBE C. T., RIBEIRO G. D., TORRES G. B., PRADO DOS REIS E. A., CABRERA F. C., ELOIZO JOB A., PAIM L. L., 和 JOSE DOS SANTOS R. 用不同的分析技术测定天然橡胶化合物的交联密度。材料研究, 2021; 24(1): e20210041. https://doi.org/10.1590/1980-5373-MR-2021-0041
[24] SETIYANA B., ISMAIL R., JAMARI J.,

SUGIYANTO., **和** HARYANTO I. **用穆尼-里夫林方法**鉴定硫化橡胶的力学性能。第二届婆罗浮屠国际科学技术研讨会论文集，马格朗，2021, **第** 99-103 页. https://doi.org/10.2991/aer.k.210810.016

[25] LE CAM J.-B. **天然橡胶中**应变诱导结晶引起的能量储存：机械滞后的物理起源。聚合物, 2017, 127: 166-173. https://doi.org/10.1016/j.polymer.2017.08.059

[26] CANDAU N., OGUZ O., FEDERICO C. E., STOCLET G., TAHON J-F., **和** MASPOCH M. L. **含有具有增**强和成核能力的轮胎橡胶颗粒的硫化天然橡胶中的应变诱导结晶。**聚合物**测试, 2021, 101: 107313. https://doi.org/10.1016/j.polymertesting.2021.107313

[27] MASA A., HAYEEMASAE N., SOONTARANON S., MOHD PISAL M. H., **和** MOHAMAD RASIDI M. S. **拉伸速率**对交联天然橡胶的拉伸响应和结晶行为的影响。马来西亚基础与应用科学杂志, 2021, 17: 217-225. https://doi.org/10.11113/mjfas.v17n3.2039

[28] SCHIAVI A., **和** PRATO A. **合成橡胶**（聚氯丁二烯）的弹性和粘弹性：动态和静态表征。第 24 **届国**际声音与振动大会论文集，伦敦，2017, **第** 1-8 页. https://www.researchgate.net/publication/318816684