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Advancements in Bamboo-Based Cushioning Material Manufacturing

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Abstract- **The study focuses on producing cushioning packaging material from bamboo fibres. The effects of varying the surface treatment duration and the proportions of foaming agents, adhesives, plasticisers, cross-linking agents, and other components were analysed in terms of foam density, foaming rate, elasticity, and bubble size. The optimal reagents and the ideal ratios for the different components were identified. The parameters for the foaming process were determined based on a high-efficiency, eco-friendly foaming mechanism. Impact testing was conducted to obtain curves for maximum acceleration versus static stress, dynamic stress versus strain, and dynamic buffering factor versus stress. The study examined the dynamic buffering performance as a function of drop height and compared it to other cushioning materials. The findings indicate that at a height of 450 mm, the bamboo pulp product exhibited a lower peak acceleration value than EPE and EPS in the stress range of 2.8-5.5 kPa, indicating superior cushioning performance under these conditions.**

Keywords— Bamboo fibres, Cushioning packaging, Foaming agents, Dynamic buffering, Impact testing

I. Introduction

To improve product performance, more countries and companies are working on developing cushioning packaging materials from plant fibres. Plant fibre is the most abundant natural polymer material, far surpassing the Earth's existing oil reserves. Fibre-based foam materials are emerging as an ideal option due to their environmental friendliness, simple processing, low cost, and abundant raw material availability [1], [2], [3], [4], [5], [6], [7], [8], [9], [10].

Among the various plant fibres, bamboo fibre holds the greatest potential for exploitation. Indonesian bamboo fibres demonstrate stable performance, low density, good breathability, unique re-elasticity, and excellent water absorption capabilities. Their specific rigidity and strength are higher than those of wood and common steels. Additionally, bamboo fibres possess strong orientation strength in both vertical and horizontal directions [11], [12], [13], [14], [15], [16], [17], [18].

The purpose of this study is to develop and evaluate environmentally friendly foam cushioning materials derived from Indonesian bamboo fibers. The study aims to improve the mechanical properties, durability, and processing efficiency of bamboo fiber-based foams so that they can be a viable alternative to nature-based materials in packaging applications.

Bamboo is easy to cultivate, with a short production cycle, allowing it to be planted once and harvested continuously without harming the environment. Developing foam cushioning materials from bamboo fibre has a dual purpose: reducing "white pollution," improving the ecological environment, and supporting sustainable development. At the same time, it creates new uses for bamboo fibre, enhancing the added value of agricultural products [19], [20], [21], [22], [23], [24], [25].

As an agricultural country with abundant forest resources, Indonesia has significant opportunities, especially in bamboo-rich regions like Java, Sumatra, and Sulawesi. Fully utilising these resources and advancing the development of plant fibre-based packaging materials will bring substantial social and economic benefits [26], [27], [28], [29], [30], [31]. State of the art in the development of plant fibre-based cushion packaging materials focuses on the use of bamboo fibre as a potential and environmentally friendly material.

II. Research Methodology

A. Sample Preparation

Dried bamboo was used as the base material, with the bamboo fibres separated. Approximately 15 grams of

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bamboo required around 20,000 cycles of dissociation. The fibers were soaked in a NaOH solution for a set period and then rinsed until neutral for the experiment. The treated bamboo fibres were thoroughly mixed and stirred with potato starch, which was gelatinised by heating to achieve transparency. Additional components, such as an AC blowing agent, stearic acid, calcium carbonate, and talc, were also incorporated. Finally, a cross-linking agent was added to align and bind the bamboo fibres together. The mixture was placed in a drying oven for foam moulding. The foaming agents decomposed at specific temperatures, releasing gases that caused the plant fibres to expand, thereby reducing the material's density

B. Dynamic Buffer Performance Testing

Involves using the dynamic compression method, which operates as follows: a hammer is released from a specified height, allowing it to fall under the influence of gravity to strike the cushioning packaging material. This simulates loading and unloading impact conditions, enabling the measurement of the dynamic buffering characteristics and the generation of performance curves for the tested packaging materials.

C. Statistical Calculation

Stress statistics are calculated using the formula:

$$\sigma_s = \frac{W}{A} \quad (1)$$

σs: the static stress experienced by the sample, 104 Pa, W: the hammer's weight, N, A: the impact sample areas, cm2. The maximum acceleration, denoted as Gm, is determined by conducting five consecutive impacts during the test. The average of the last four acceleration values is calculated to establish the maximum acceleration for each test group. Maximum stress is calculated using the formula:

$$\sigma_m = G_m \times \sigma_m \quad (2)$$

σm the maximum stress endured by the sample, 104 Pa. the residual strain from dynamic compression:

$$\varepsilon = \frac{T - T_d}{T} \times 100\% \quad (3)$$

ε: the residual strain from dynamic compression, %, T: the initial thickness of the sample, cm, Td: the thickness after dynamic compression, cm. In the dynamic compression test, the buffering coefficient is defined by the following formulation:

$$C = G_m \times \frac{T}{H} \quad (4)$$

III. Results and Discussion

Characterisation: Structural characterisation of foam refers to examining the foam's structure at both the macro and micro levels.

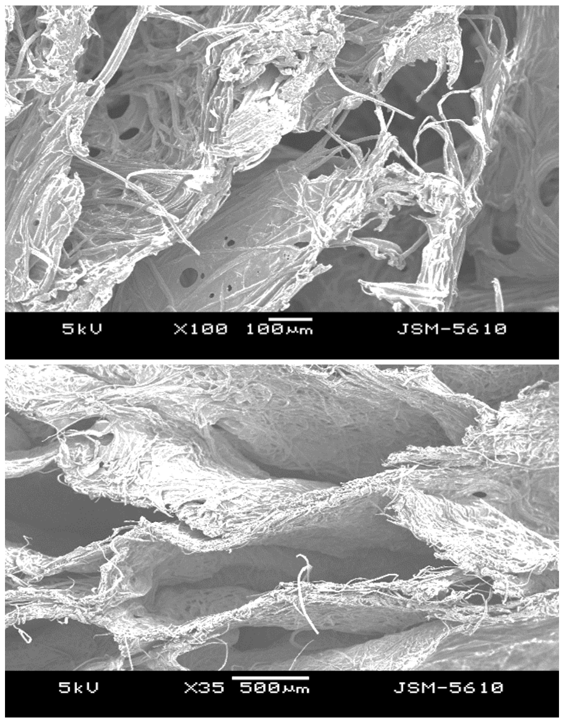

Figure 1. The microscopic structure of the foam (SEM)

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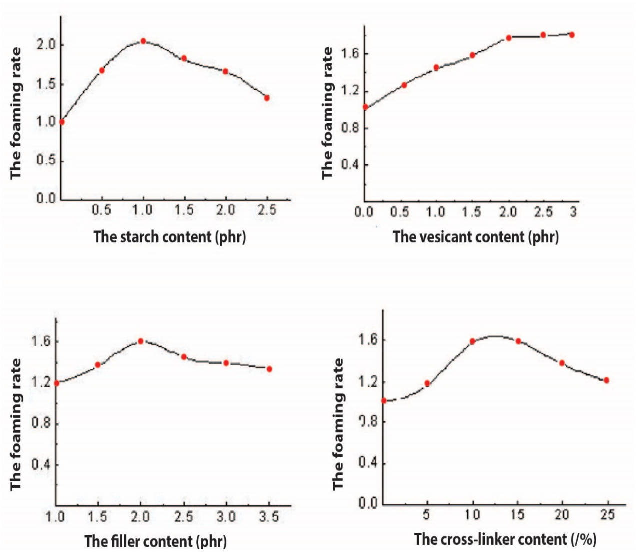

Figure 2. The influence of component composition on the foaming rate of the products.

Figure 1 shows cross-sectional images. The foam products exhibit a consistent rate, with uniform cell sizes arranged in orderly rows. A three-dimensional network structure is visible, with good bonding observed between the fibres. The cell walls are smooth and possess a certain thickness.

Figure 2 illustrates that at a starch content of 1.0 [phr], the maximum foaming rate of the system is achieved. Starch plays a role in enhancing adhesion between fibres, but as the starch content increases, the degree of foaming decreases due to excessive viscosity. Initially, the foaming rate of the products increases more rapidly with the addition of the blowing agent, reaching its peak at a blowing agent content of 2.0 [phr]. After that, the rate of increase slows down as a higher content of the blowing agent causes degradation of the starch and fibre macromolecules, leading to lower molecular weight, reduced viscosity, and incomplete gas encapsulation in the system. Although the foaming rate continues to rise, it does so at a slower pace.

In the process of preparing foam materials, fillers help fill the gaps between fibres, not only reinforcing the connections between them and improving dimensional stability but also acting as nucleating agents [32], [33], [34], [35], [36], [37]. The maximum foaming rate is achieved at a filler content of 2.0 [phr], with minimal changes in the foaming rate as the filler content is increased further.

The system's foaming rate initially increases with the addition of the cross-linker and then decreases. The optimal range for cross-linker content is 11%-16% of the total starch. This is because the cross-linker forms a polynuclear complex network structure with the starch adhesive, increasing adhesive tack, enhancing water resistance, and improving natural drying capability [38], [39], [40], [41], [42]. However, if the cross-linker content is too high, it results in a brittle layer, reducing the bonding effectiveness [43], [44], [45].

According to the national standard GB8168-87, which outlines the testing methods for the dynamic compression cushioning performance of package buffer materials, a hammer is dropped from a specified height and allowed to fall freely under the influence of gravity to strike the buffer packaging materials. This simulates the loading and unloading impact conditions, allowing for the evaluation of the dynamic buffering performance and the generation of performance curves for the tested package buffer materials.

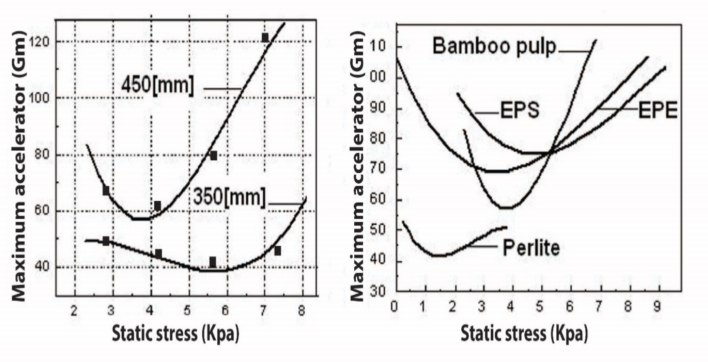

Figure 2. G_m - σ_m curves of the cushioning materials.

IV. Conclusion

The comparison between products made from bamboo powder and bamboo pulp revealed that those utilising bamboo pulp exhibited superior performance. Treatment with a NaOH solution significantly enhanced the system's phase capacitance, with optimal soaking conditions identified as 5% NaOH for a duration of two to four hours.

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An orthogonal test was conducted to vary the content of each constituent and analyse their effects on the product. This analysis focused on the impact of each foam component on various factors, including foaming rate, density, diameter, and mechanical properties of the cells, leading to the identification of more suitable conditions for combining bamboo foam. The resulting material demonstrated a certain level of buffer performance, making it effective for packaging products that are sensitive to minor shocks.

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References

[1] C. Huang, X. Zhang, and Z. Liu, “Effects of Porosity on the Static Compression of Foam Buffer Materials of Plant Fiber and Their Numerical Model,” *Shock Vib.*, vol. 2021, 2021, doi: 10.1155/2021/5568653.

[2] Y. Luo, S. Xiao, and S. Li, “Effect of initial water content on foaming quality and mechanical properties of plant fiber porous cushioning materials,” *BioResources*, vol. 12, no. 2, pp. 4259 – 4269, 2017, doi: 10.15376/biores.12.2.4259-4269.

[3] J. Zheng, C. Li, and S. Gao, “Pore structure and cushioning properties of wastepaper-pulp-reinforced starch-based foams,” *Green Mater.*, vol. 12, no. 3, pp. 209 – 222, 2023, doi: 10.1680/jgrma.22.00110.

[4] Y. Liu, S. Qin, and Z. Shi, “The research of bamboo pulp buffer packaging material,” in *17th IAPRI World Conference on Packaging 2010*, 2010, pp. 392 – 395. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-79960889011&partnerID=40&md5=dca82dcebd8ef71f92e52963dd0c5bb7

[5] H. Xiu, X. Yang, J. Li, Y. Cui, H. Dong, and X. Zhao, “Effect of amylopectin dosage on the structure and properties of plant fibers based foam material; [淀粉用量对植物纤维基泡沫材料结构与性能的影响],” *Chung-kuo Tsao Chih/China Pulp Pap.*, vol. 38, no. 8, pp. 34 – 39, 2019, doi: 10.11980/j.issn.0254-508X.2019.08.006.

[6] P. Nechita and S. M. Năstac, “Overview on Foam Forming Cellulose Materials for Cushioning Packaging Applications,” *Polymers (Basel).*, vol. 14, no. 10, 2022, doi: 10.3390/polym14101963.

[7] S. Liu, Y. Gao, L. Ma, R. Wu, and P. Lu, “Plant fiber foam reinforced with distiller’s grains and its static cushioning properties,” *Ind. Crops Prod.*, vol. 206, 2023, doi: 10.1016/j.indcrop.2023.117658.

[8] X. Lu, T. Jiang, and X. Ma, “Progress in the Preparation Process of Plant Fiber Foam and Its Bubble Forming Theory; [植物纤维发泡材料的制备工艺及气泡成形理论研究进展],” *Gaofenzi Cailiao Kexue Yu Gongcheng/Polymeric Mater. Sci. Eng.*, vol. 39, no. 6, pp. 182 – 190, 2023, doi: 10.16865/j.cnki.1000-7555.2023.0126.

[9] M. Fan and Z. Dai, “Influences of composite adhesive components on the performance of bagasse cushion pads,” *J. Chem. Pharm. Res.*, vol. 6, no. 5, pp. 739 – 744, 2014, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84907095524&partnerID=40&md5=781fb11413bef02812e45cc689c8065b

[10] L. Deng, H. He, Z. Chen, S. Liu, and V. S. Chevali, “Effects of wood fiber size on the performance of biodegradable foam,” *J. Biobased Mater. Bioenergy*, vol. 11, no. 3, pp. 206 – 209, 2017, doi: 10.1166/jbmb.2017.1662.

[11] L. Osorio, E. Trujillo, F. Lens, J. Ivens, I. Verpoest, and A. W. Van Vuure, “In-depth study of the microstructure of bamboo fibres and their relation to the mechanical properties,” *J. Reinf. Plast. Compos.*, vol. 37, no. 17, pp. 1099 – 1113, 2018, doi: 10.1177/0731684418783055.

[12] A. I. Amjad, “Bamboo fibre: A sustainable solution for textile manufacturing,” *Adv. Bamboo Sci.*, vol. 7, 2024, doi: 10.1016/j.bamboo.2024.100088.

[13] D. R. Trisatya, D. A. Indrawan, F. A. Syamani, E. N. Aini, and I. M. Sulastiningsih, “Effect of strand dimension and specific pressure on the performance of strandboards made from Tali bamboo (Gigantochloa apus (JA & JH Schultes) Kurz),” in *AIP Conference Proceedings*, L. M.A.R., L. S.H., A. P., and K. L., Eds., American Institute of Physics, 2024. doi: 10.1063/5.0184785.

[14] N. Mishra, V. M. Rane, and A. Sabale, “Newer varieties of biodegradable fibres - Bamboo fibre,” *Int. Dye.*, vol. 193, no. 1, pp. 13–14+16–18, 2008, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-38049161390&partnerID=40&md5=52fa63709b1257c3bc936be26a1124c5

[15] H. Li, G. Y. Zhou, and H. Y. Zhang, “Research and utilization status of natural bamboo fiber,” *Adv. Mater. Res.*, vol. 159, pp. 236 – 241, 2011, doi: 10.4028/www.scientific.net/AMR.159.236.

[16] A. Javadian, I. F. C. Smith, N. Saeidi, and D. E. Hebel, “Mechanical properties of bamboo through measurement of culm physical properties for composite fabrication of structural concrete reinforcement,” *Front. Mater.*, vol. 6, 2019, doi: 10.3389/fmats.2019.00015.

[17] V. Sharma and A. Goel, “Bamboo plant to fibre: An approach to various implications,” *Man-Made Text. India*, vol. 38, no. 8, pp. 291 – 295, 2010, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-81255203573&partnerID=40&md5=dd7209d13fec15f62d244a4efbcca6e2

[18] A. H. D. Abdullah, N. Karlina, W. Rahmatiya, S. Mudaim, Patimah, and A. R. Fajrin, “Physical and mechanical properties of five Indonesian bamboos,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 60, no. 1, p. 012014, Mar. 2017, doi: 10.1088/1755-1315/60/1/012014.

[19] S. Chaiwong *et al.*, “Natural rubber latex cushioning packaging to reduce vibration damage in guava during simulated transportation,” *Postharvest Biol. Technol.*, vol. 199, 2023, doi: 10.1016/j.postharvbio.2023.112273.

[20] R. Saengwong-ngam *et al.*, “Cushion performance of eco-friendly natural rubber latex foam composite with bamboo leaf fiber for impact protection of guava,” *Postharvest Biol.*

Technol., vol. 208, 2024, doi: 10.1016/j.postharvbio.2023.112663.

[21] K. Jitkokkruad, K. Jarukumjorn, C. Raksakulpiwat, S. Chaiwong, J. Rattanakaran, and T. Trongsatitkul, "Effects of Bamboo Leaf Fiber Content on Cushion Performance and Biodegradability of Natural Rubber Latex Foam Composites," *Polymers (Basel).*, vol. 15, no. 3, 2023, doi: 10.3390/polym15030654.

[22] Y. Liu and S. Wang, "The research of the green buffer packaging materials for the small pieces of express items," *Appl. Mech. Mater.*, vol. 275–277, pp. 2346 – 2349, 2013, doi: 10.4028/www.scientific.net/AMM.275-277.2346.

[23] C. Qiu *et al.*, "The preparation and properties of polyurethane foams reinforced with bamboo fiber sources in China," *Mater. Res. Express*, vol. 8, no. 4, 2021, doi: 10.1088/2053-1591/abf1cd.

[24] Y. Liu, S. Y. Qi, and Z. Y. Shi, "The key problems in the manufacturing of the bamboo buffer packaging material," *Adv. Mater. Res.*, vol. 306–307, pp. 1585 – 1588, 2011, doi: 10.4028/www.scientific.net/AMR.306-307.1585.

[25] Y. Liu and S. Wang, "Experimental study of bamboo fiber cushion packaging materials for the express packaging," *Appl. Mech. Mater.*, vol. 300–301, pp. 1348 – 1351, 2013, doi: 10.4028/www.scientific.net/AMM.300-301.1348.

[26] Y. Munde, A. Panigrahi, A. Shinde, and I. Siva, *Bamboo fibers, their composites and applications*. Elsevier, 2022. doi: 10.1016/B978-0-12-824528-6.00001-1.

[27] C.-S. Wu, D.-Y. Wu, and S.-S. Wang, "Preparation and Characterization of Polylactic Acid/Bamboo Fiber Composites," *ACS Appl. Bio Mater.*, vol. 5, no. 3, pp. 1038 – 1046, 2022, doi: 10.1021/acsabm.1c01082.

[28] Y. Liu, S.-Y. Qi, and Z.-Y. Shi, "Discussion on the forming technologies and properties of bamboo fiber buffer packaging material," in *ICMREE2011 - Proceedings 2011 International Conference on Materials for Renewable Energy and Environment*, 2011, pp. 1300 – 1303. doi: 10.1109/ICMREE.2011.5930574.

[29] S. Yusuf, F. A. Syamani, W. Fatriasari, and Subyakto, "Review on Bamboo Utilization as Biocomposites, Pulp and Bioenergy," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, 2018. doi: 10.1088/1755-1315/141/1/012039.

[30] K. M. K. Iwasaki, P. A. Reis, and R. De Medeiros, "Characterization of long bamboo Guadua Angustifolia fibre composite extracted via rotary–peeling method," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 44, no. 4, 2022, doi: 10.1007/s40430-022-03433-x.

[31] A. Sulaeman *et al.*, "Review on quality enhancement of bamboo utilization: Preservation, modification and applications," *Asian J. Plant Sci.*, vol. 17, no. 1, pp. 1 – 18, 2018, doi: 10.3923/ajps.2018.1.18.

[32] J. Hao, X. Wang, H. Xie, Q. Chen, X. Chen, and Y. Chen, "Development of high-performance EGMA/EVA-bamboo powder composite foams with enhanced stability, strengthening and toughening for sustainable applications," *Polym. Eng. Sci.*, 2024, doi: 10.1002/pen.26963.

[33] A. H. Shaik *et al.*, "Foam stability and thermo-mechanical properties of micro/nano filler loaded castor oil based flexible polyurethane foam," *Mater. Res. Express*, vol. 11, no. 1, 2024, doi: 10.1088/2053-1591/ad19b1.

[34] S. M. Husainie, S. U. Khattak, J. Robinson, and H. E. Naguib, "A Comparative Study on the Mechanical Properties of Different Natural Fiber Reinforced Free-Rise Polyurethane Foam Composites," *Ind. Eng. Chem. Res.*, vol. 59, no. 50, pp. 21745 – 21755, 2020, doi: 10.1021/acs.iecr.0c04006.

[35] S. Członka, A. Strąkowska, and A. Kairytė, "Coir fibers treated with henna as a potential reinforcing filler in the synthesis of polyurethane composites," *Materials (Basel).*, vol. 14, no. 5, pp. 1 – 16, 2021, doi: 10.3390/ma14051128.

[36] E. S. Ali and S. A. Zubir, "The mechanical properties of medium density rigid polyurethane biofoam," in *MATEC Web of Conferences*, Q. N., D. J., and K. S.-K., Eds., EDP Sciences, 2016. doi: 10.1051/matecconf/20163901009.

[37] A. Lagzdin¸š, A. Zilaucs, I. Beverte, and J. Andersons, "Estimation of the elastic constants of highly porous cellular plastics reinforced with fibres embedded in foam struts," *J. Compos. Mater.*, vol. 50, no. 9, pp. 1169 – 1180, 2016, doi: 10.1177/0021998315589771.

[38] S. K. Vineeth, R. V Gadhave, and P. T. Gadekar, "Investigation of crosslinking ability of sodium metabisulphite with polyvinyl alcohol–corn starch blend and its applicability as wood adhesive," *Indian Chem. Eng.*, vol. 64, no. 2, pp. 197 – 207, 2022, doi: 10.1080/00194506.2021.1887769.

[39] S. Wang, F. Zhang, F. Chen, and Z. Pang, "Preparation of a crosslinking cassava starch adhesive and its application in coating paper," *BioResources*, vol. 8, no. 3, pp. 3574 – 3589, 2013, doi: 10.15376/biores.8.3.3574-3589.

[40] T. Jin *et al.*, "Development of boiling water resistance starch-based wood adhesive via Schiff base crosslinking and air oxidation strategy," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 698, 2024, doi: 10.1016/j.colsurfa.2024.134592.

[41] H. Yu *et al.*, "Preparation of self-assembled modified reed fiber reinforced starch-based adhesive and the study of cross-linking mechanism," *Ind. Crops Prod.*, vol. 211, 2024, doi: 10.1016/j.indcrop.2024.118204.

[42] R. V Gadhave, P. A. Mahanwar, and P. T. Gadekar, "Cross-linking of polyvinyl Alcohol/Starch blends by Epoxy Silane for improvement in thermal and mechanical properties," *BioResources*, vol. 14, no. 2, pp. 3833 – 3843, 2019, doi: 10.15376/biores.14.2.3833-3843.

[43] K. C. Ofokansi, *Biopolymer cross-links: Strategies for improving drug release and delivery*. Bentham Science Publishers Ltd., 2009. doi: 10.2174/97816080507891090101 0095.

[44] M. Tsige and M. J. Stevens, "Effect of cross-linker functionality on the adhesion of highly cross-linked polymer networks: A molecular dynamics study of epoxies," *Macromolecules*, vol. 37, no. 2, pp. 630 – 637, 2004, doi: 10.1021/ma034970t.

[45] H. Atashi and M. Shiva, "Study of governing mechanisms on failure properties of filled rubber compound in different sulfur crosslink densities and types," *Asian J. Chem.*, vol. 22, no. 9, pp. 6778 – 6790, 2010, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-80051739234&partnerID=40&md5=af9b51bb6fbbddcd83a76d521cf39fa2