Malaysian Journal of Chemistry, 2024, Vol. 26(3), 339-346
(Special Issue: *3rd Virtual International Symposium on Sciences 2023*)

Exploring the Role of Bamboo Charcoal Powder as Filler in Rubber Vulcanisates

Falah Abu, Mohd Iqbal Misnon, Mona Rita Othman, Hairani Tahir and Norazura Ibrahim*
School of Industrial Technology, Faculty of Applied Sciences, Universiti Teknologi MARA,
40450 Shah Alam, Selangor, Malaysia
*Corresponding author (e-mail: noraz371@uitm.edu.my)

Bamboo charcoal (BC) derived from bamboo plants is a widely known material with many uses and benefits. It has been utilised in various applications, including medical, cosmetic, food processing, and health-related products. In this paper, vulcanisates of natural rubber (NR) filled with bamboo charcoal powder (BCP) were mixed using a laboratory-sized two-roll mill. The effects of BCP loading ranging from 10 to 50 parts per hundred rubber (phr) on curing characteristics and mechanical properties were investigated. Unfilled NR was processed under the same conditions for comparison. The results indicated that the addition of BCP resulted in a longer scorch time and higher Mooney viscosity in NR. Furthermore, the mechanical properties of the vulcanisates were studied, revealing that the tensile strength, modulus at 100% elongation, and abrasion resistance increased by 32%, 86%, and 13%, respectively, compared to unfilled rubber. Overall, the results suggest that BCP-reinforced NR vulcanisates have the potential to be environmentally friendly materials and are also cost-effective, owing to their sustainable and abundant sources.

Keywords: Bamboo charcoal; curing characteristics; mechanical properties; natural rubber; filler loading

Received: October 2023; Accepted: February 2024

Carbon black is undoubtedly the most commonly used rubber reinforcement filler due to its physical, chemical, and mechanical characteristics, enhancing the performance of original rubber. The majority of carbon black is utilised as reinforcement in vulcanised rubber products, with over 60% involved in the tyre industry alone. However, its dependence on petroleum feedstock for synthesis, coupled with the price instability of petroleum and the high cost and energy consumption associated with its production, has sparked increased interest in alternative reinforcing fillers.

In recent years, there has been a surge in demand for natural products in industrial applications, which is driven not only by the depletion of non-renewable resources but also by environmental concerns and waste disposal issues. Renewable resources offer a sustainable platform for potentially substituting petroleum-based materials, leveraging the advantages of cost-effectiveness and high eco-friendliness values [1, 2]. Both non-renewable (petroleum-based) and renewable resources have been utilised for the production of green composites, combining natural fillers, as highlighted by numerous studies over the last decade [3].

Bamboo stands out as an abundant, low-cost natural resource, readily accessible worldwide, with 64% of bamboo plantations are located in Southeast Asia, 33% in South America, and the remainder in Africa and Oceania [4]. Beyond its traditional uses in construction materials and paper sheet production, bamboo offers environmental benefits, such as erosion control and embellishments [5]. Due to its high strength, environmentally friendly characteristics, and availability, bamboo also has considerable potential in composite production. Thus, bamboo is widely used in the production of biocomposites, as well as in advanced polymer biocomposites [6-10].

In the absence of oxygen, bamboo can be carbonised in a furnace at high temperatures to make bamboo charcoal (BC). Bamboo charcoal emerges as a sustainable, low-cost, renewable, and non-toxic material, characterised by high porosity, antibacterial and antifungal properties, thermal regulation, and odour control [11-14]. With its high carbon content [15], BC presents an alternative option to partially replace conventional fillers in the rubber industry, deserving greater attention as a renewable and low-cost filler [16].

Many researchers have attempted to use certain natural fillers to reinforce vulcanisates in order to enhance their properties [17-18]. A lot of fillers from renewable resources were reportedly used to substitute the commonly used carbon black filler. These include rice husk [19-20], starch [21-22], chitosan [18-23], kenaf [24-25], and cuttlebones [26-27]. None of them has, however, focused on the properties of natural

†Paper presented at the 3rd Virtual International Symposium on Sciences (3rd VISoS 2023)

rubber (NR) vulcanisates reinforced with bamboo charcoal powder (BCP) [28]. The incorporation of BCP into styrene-butadiene rubber (SBR) has been reported [16]. The experimental results indicate that most of the mechanical properties improved.

This study utilises BCP as a novel filler in NR, aiming to illustrate the impact of varying BCP loading in NR vulcanisates. Thus, the curing characteristics and mechanical properties of the vulcanisates with different BCP contents were investigated.

EXPERIMENTAL

Materials

The raw elastomer used in this study was the Standard Malaysian NR (grade SMR20). The BCP, with an average particle size of 29.67 µm, was purchased from Lanchang Edible Garden in Pahang and utilised in rubber compounding without further treatment aside from drying. Alongside the raw elastomer and BCP, the additives employed included sulphur, zinc oxide, stearic acid, n-cyclohexyl benzothiazole sulfenamide (CBS), and either Flectol H or poly(1,2-dihydro-2,2,4-trimethylquinoline).

Mixing

The BCP underwent drying in an oven at 70 °C for 24 h to eliminate moisture. Compounds were mixed using a conventional laboratory-sized two-roll mill. In total, five compounds were prepared in this study (Table 1). Nip gap, roll mill speed ratio, mixing time, and sequence of ingredient addition remained consistent across all compounds. Following mixing, the sheeted rubber compound was stored at an ambient temperature of 23 °C for at least 24 h before vulcanisation. The respective scorch time (t_2), cure time (t_{90}), and cure rate index (CRI) of the vulcanisates were determined using a rotorless rheometer at 160 °C.

Characterisation

Compression moulding was performed on the compounds at 160 °C, based on their respective t_{90} values, utilising a laboratory hydraulic press. The Mooney viscosity (ML_{1+4}) at 100 °C was determined using a Mooney viscometer.

Scanning electron microscopy (SEM) analysis of the BCP was conducted using a Hitachi TM3030Plus tabletop scanning electron microscope. The tensile test was carried out using a universal testing machine (5569, Instron, Canton, MA) according to ASTM D412, at a crosshead speed of 500 mm/min. Tensile strength, tensile modulus, and elongation at break were obtained from these tests. Five dumbbell-shaped samples were tested for reproducibility of the results. The hardness test was conducted according to ISO 48, using a dead load hardness tester (H14, Wallace Instrument Ltd., Surrey, England) with the results being read directly in International Rubber Hardness Degrees (IRHD). Measurements of rebound resilience were carried out according to ISO 4462:2009, while the abrasion resistance index (ARI) was measured according to ISO 4649:2010, using the Akron abrasion tester.

Table 1. Formulations for the BCP-filled NR vulcanisates.

Composition	Mixture				
(phr)	1	2	3	4	5
NR	100	100	100	100	100
Zinc oxide	5	5	5	5	5
Stearic acid	2	2	2	2	2
CBS	0.5	0.5	0.5	0.5	0.5
Sulphur	2.5	2.5	2.5	2.5	2.5
Flectol H	1	1	1	1	1
BCP	-	10	20	30	50

RESULTS AND DISCUSSION

Curing Characteristics

Table 2 shows the effects of BCP loading on the t_{S2}, t_{90}, and CRI, as determined using the rheometer. The t_{S2} values of the vulcanisates increased slightly with higher BCP content. These results align with findings from Meng et al. [16], indicating that BCP hinders the vulcanisation process. However, the t_{90} and CRI values did not exhibit significant differences with increasing BCP content. A gradual increase in both minimum torque (M_L) and maximum torque (M_H) values was observed as BCP loading increased. The rise in M_L values indicated that the mobility and flexibility of the unvulcanised vulcanisates decreased in the presence of the BCP. The increase in the M_H values indicated that the mobility and flexibility of the macromolecular chains of the NR decreased as the stiffness of the vulcanisates increased [18].

Furthermore, Table 2 and Figure 1 present the Mooney viscosity trend, which increased with higher BCP content. This suggests that the filler in the NR matrix has diminished the mobility of NR macromolecular chains. A similar observation was also reported by Meng et al. [16] for the BCP-reinforced SBR vulcanisates.

Table 2. Curing characteristics of the BCP-filled NR vulcanisates.

Curing Characteristics	Mixture				
	1	2	3	4	5
Scorch time (t_{s2}) [min]	1.1	1.3	1.3	1.3	1.2
Cure time (t_{90}) [min]	5.2	5.1	5.2	5.2	5.3
Minimum torque (M_L) [dN·m]	0.21	0.26	0.27	0.37	0.42
Maximum torque (M_H) [dN·m]	2.43	2.49	2.64	2.92	3.64
Cure rate index (CRI) [min^{-1}]	24.3	26.5	25.6	25.6	24.4
Mooney viscosity [$ML_{1+4\ at\ 100\ °C}$]	26	33	35	49	57

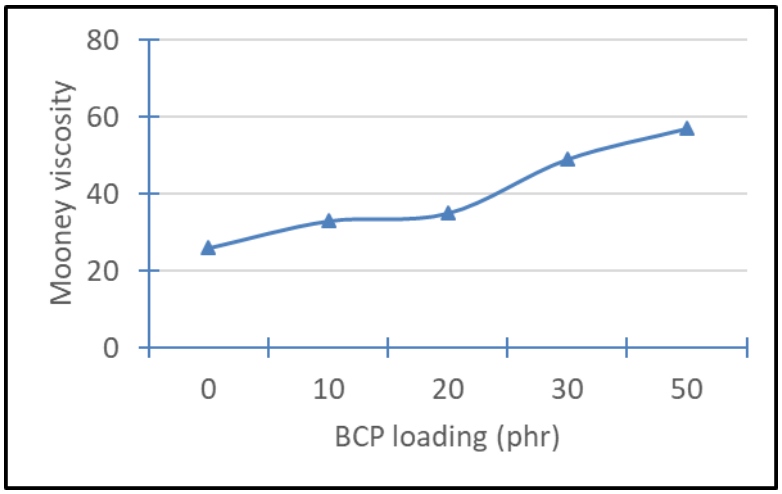

Figure 1. Effects of BCP loading on the Mooney viscosity of the NR vulcanisates.

Effects of BCP Loading on The Mechanical Properties

Table 3 shows the effects of BCP loading on the mechanical properties. The incorporation of natural fillers into a polymer matrix can generally either increase or decrease the strength of vulcanisates. Tensile strength increased by 32% as filler loading increased to 20 phr, compared to unfilled rubber strength (Figure 2). Further increases in BCP loading led to a gradual decrease in these properties, indicating anticipated poor compatibility between BCP and NR, resulting in the formation of a conventional composite at the microscale. As filler loading increased from 20 phr to 50 phr, tensile strength decreased from 10 MPa to 6 MPa due to filler-filler interactions being more significant than filler-rubber interactions [29]. High filler loading also caused increased filler particle agglomeration, forming stress concentration points. According to Bigg [30], composite strength decreases with irregularly shaped fillers due to their inability to support stress transferred from the polymer matrix. Figure 3 displays the SEM micrograph of the BCP used in this study, comprising particles of various shapes, sizes, and lengths. The irregular shapes of BCP, coupled with its hydrophilic nature resulting in poor adhesion to the hydrophobic NR matrix, are the main factors contributing to the deterioration of tensile strength with increasing filler loading. Ideally, filler particles should possess a more regular shape, while strong adhesion between filler and NR is necessary for effective reinforcement.

Table 3. Properties of the NR vulcanisates containing different loadings of BCP.

	Mixture				
Properties	1	2	3	4	5
Tensile strength [MPa]	7.8	9.3	10.3	8.7	5.6
Elongation at break [%]	608	608	617	568	453
M100 [MPa]	0.7	0.9	1.0	1.1	1.3
M300 [MPa]	1.5	1.8	2.0	2.2	2.7
M500 [MPa]	3.5	4.5	5.0	6.0	-
Hardness [IRHD]	38	43	47	69	70
Resilience [%]	67	68	66	69	65
Abrasion resistance index [%]	118	124	128	131	133

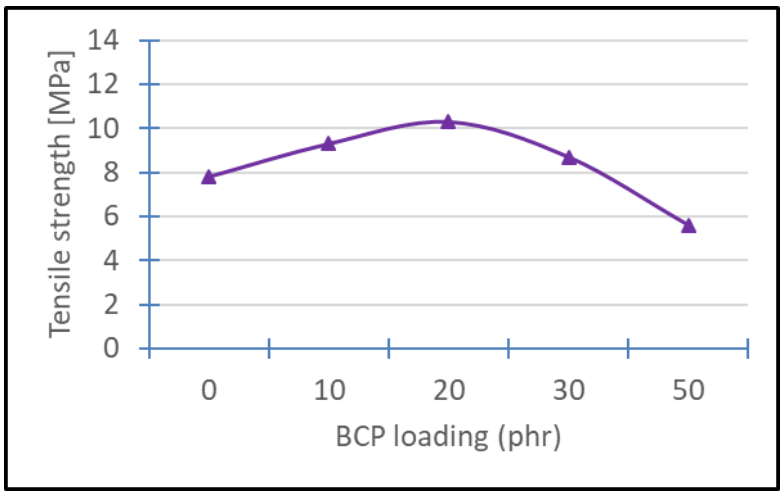

Figure 2. Effects of BCP loading on the tensile strength of the NR vulcanisates.

Figure 3. SEM of the BCP at 100× magnification.

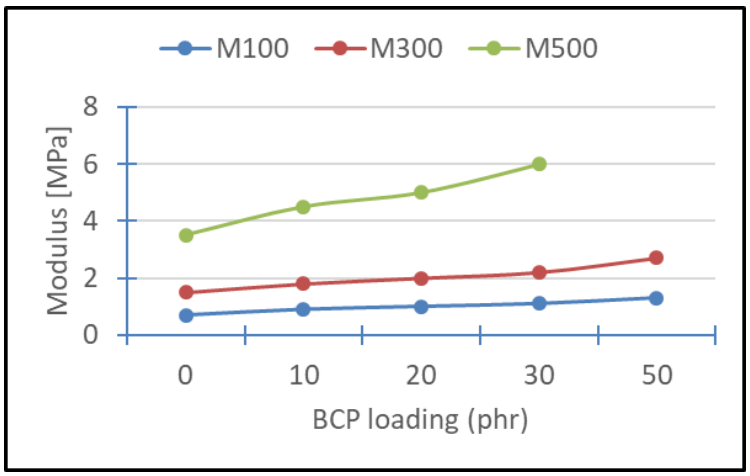

Figure 4. Effects of BCP loading on the modulus of the NR vulcanisates.

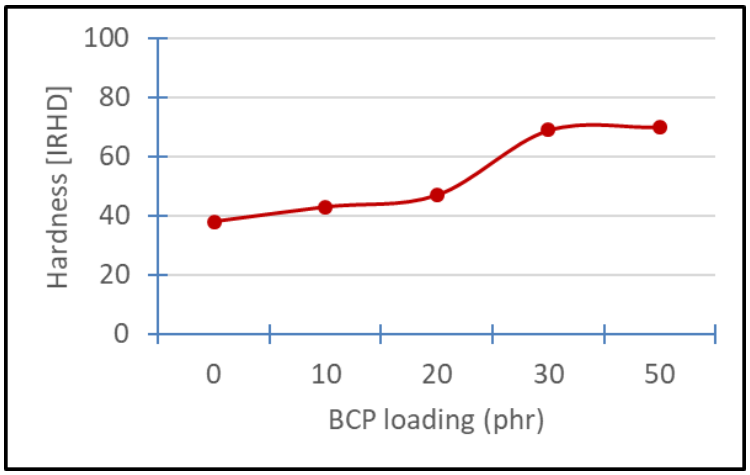

Figure 5. Effects of BCP loading on the hardness of the NR vulcanisates.

It is evident from Figure 4 that the tensile modulus and hardness (Figure 5) of the vulcanisates increased, while the elongation at break (Figure 6) decreased with increasing BCP loading. The absence of M500 results for the sample at 50 phr indicates that the sample broke before reaching a modulus at 500% elongation. These findings indicate that the inclusion of BCP in the rubber matrix enhanced the stiffness of the vulcanisates. Despite the presence of BCP, the elastic characteristics of NR were maintained, as evidenced by the rebound resilience (Figure 7).

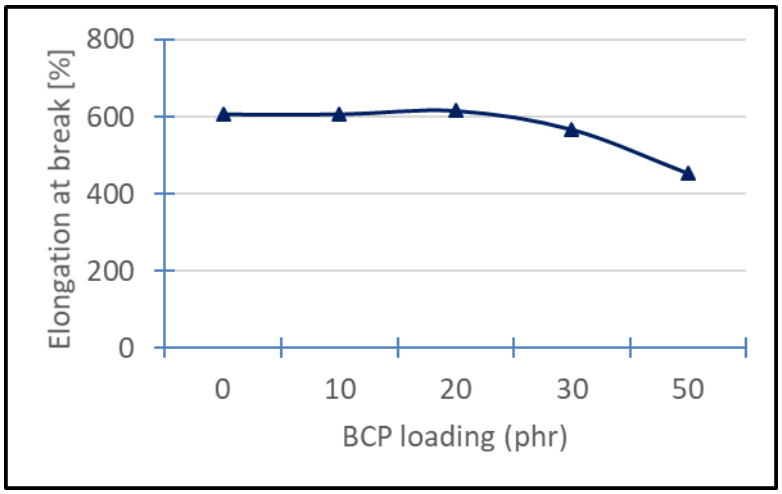

Figure 6. Effects of BCP loading on the elongation at break of the NR vulcanisates.

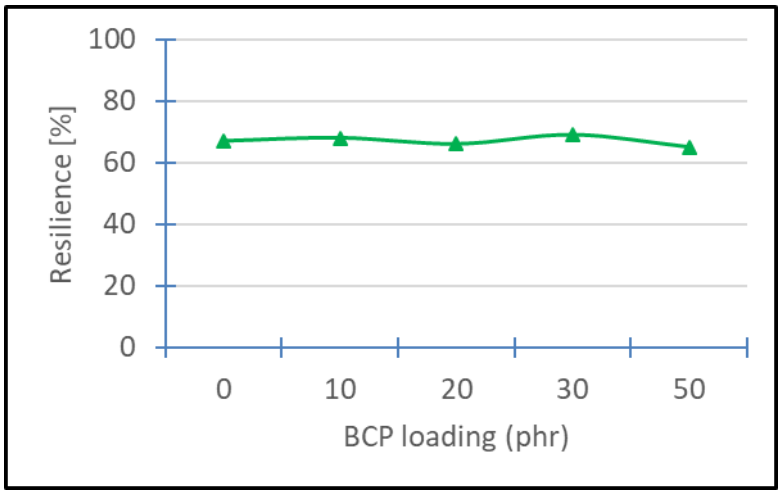

Figure 7. Effects of BCP loading on the rebound resilience of the NR vulcanisates.

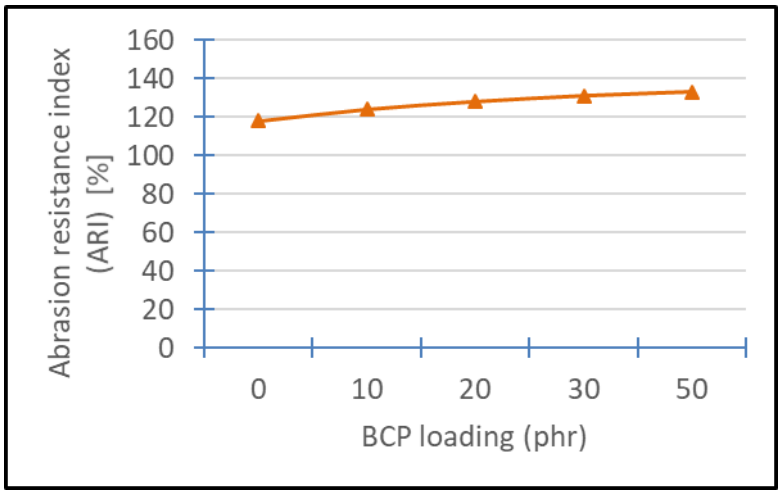

Figure 8. Effects of BCP loading on the abrasion resistance of the NR vulcanisates.

Moreover, the abrasion resistance of the vulcanisates exhibited a steady increase with rising BCP content (Figure 8), reaching up to a 13% improvement for the 50 phr sample. This enhancement could be attributed to the excellent thermal stability and low heat conduction coefficient of BCP [16].

CONCLUSIONS

The curing characteristics and mechanical properties of the BCP-reinforced NR vulcanisates were examined as a function of BCP loading. Both the t_{S2} and Mooney viscosity increased with increasing filler loading. The experimental results of the mechanical properties of the vulcanisates indicated notable enhancements: the tensile strength, modulus at 100% elongation (M100), and abrasion resistance increased by 32%, 86%, and 13%, respectively, compared to the unfilled rubber. As for the tensile strength, an increase in BCP loading up to 20 phr led to improvement, but further introduction of the filler resulted in a decrease of tensile strength. Overall, the results suggest that BCP-reinforced NR vulcanisates have the potential to be environmentally friendly materials and offer cost-effectiveness due to sustainable and abundant sources. The adhesion between BCP and NR using bonding agents is currently under investigation, and will be reported in a forth-coming article.

ACKNOWLEDGEMENTS

The authors acknowledge the Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam, for their support of this work.

REFERENCES

1. Lou, C. W., Lin, C. W., Lei, C. H., Su, K. H., Hsu, C. H., Liu, Z. H. and Lin, J. H. (2007) PET/PP blend with bamboo charcoal to produce functional composites. *Journal of Materials Processing Technology*, **192-193**, 428–433.

2. You, Z. and Li, D. (2014) Highly filled bamboo charcoal powder reinforced ultra-high molecular weight polyethylene. *Materials Letters*, **122**, 121–124.

3. Jawaid, M., Abdul Khalil, H. P. S. and Abu Bakar, A. (2010) Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. *Materials Science and Engineering: A*, **527(29)**,7944–7949.

4. Bonilla, S. H., Guarnetti, R. L., Almeida, C. M. V. B. and Giannetti, B. F. (2010) Sustainability assessment of a giant bamboo plantation in Brazil: exploring the influence of labour, time and space. *Journal of Cleaner Production*, **18(1)**, 83–91.

5. Suhaily, S. S., Khalil, H. P. S. A., Nadirah, W. O. W. and Jawaid, M. (2013) Bamboo Based Biocomposites Material, Design and Applications. *IntechOpen: Rijeka*.

6. Abdul Khalil, H. P. S., Bhat, I. U. H., Jawaid, M., Zaidon, A., Hermawan, D. and Hadi, Y. S. (2012) Bamboo fibre reinforced biocomposites: A review. *Materials & Design*, **42**, 353–368.

7. Srisuk, R., Techawinyutham, L., Mavinkere Rangappa, S., Siengchin, S. and Dangtungee, R. (2020) Development of masterbatch for composites using bamboo charcoal powders in poly(lactic) acid. *Polymer Composites*, **41(12)**, 5082–5095.

8. Wang, S., Zhang, L., Semple, K., Zhang, M., Zhang, W. and Dai, C. (2020) Development of biodegradable flame-retardant bamboo charcoal composites, Part I: Thermal and elemental analyses. *Polymers*, **12(10)**, 1–18.

9. Yusof, A. A. M. Y., Mustapa, M. S., Ariffin, A. H., Ibrahim, M. R., Masirin, M. I. M., Siswanto, W. A. and Yoshiharu, M. (2022) The effect of bamboo charcoal powder on the tensile strength of wood plastic composite. *Materials Science Forum*, **1075**, 79–85.

10. Zhao, M., Hu, L., Dai, L., Wang, Z., He, J., Wang, Z., Chen, J., Hrynsphan, D. and Tatsiana, S. (2021) Bamboo charcoal powder-based polyurethane as packing material in biotrickling filter for simultaneous removal of n-hexane and dichloromethane. *SSRN Electronic Journal*, 1–8.

11. Shenxue, J. (2004) Training manual of bamboo charcoal for producers and consumers. *Bamboo Engineering Research Center Nanjing Forestry University*, 1–54.

12. Nitayaphat, W., Jiratumnukul, N., Charuchinda, S. and Kittinaovarat, S. (2009) Mechanical properties of chitosan/bamboo charcoal composite films made with normal and surface oxidized charcoal. *Carbohydrate Polymers*, **78(3)**, 444–448.

13. Ren, Q., Zeng, Z., Jiang, Z. and Li, H. (2020) Functionalization of renewable bamboo charcoal to improve indoor environment quality in a sustainable way. *Journal of Cleaner Production*, **246**, 1–11.

14. Ho, M. P., Lau, K. T., Wang, H. and Hui, D. (2015) Improvement on the properties of poly-lactic acid (PLA) using bamboo charcoal particles. *Composites Part B: Engineering*, **81**, 14–25.

15. Mui, E. L., Cheung, W., Lee, V. K. and McKay, G. (2008) Kinetic study on bamboo pyrolysis. *Industrial & Engineering Chemistry Research*, **47(15)**, 5710–5722.

16. Meng, X., Zhang, Y., Lu, J., Zhang, Z., Liu, L. and Chu, P. K. (2013) Effect of bamboo charcoal powder on the curing characteristics, mechanical properties, and thermal properties of styrene–butadiene rubber with bamboo charcoal powder. *Journal of Applied Polymer Science*, **130(6)**, 4534–4541.

17. Ismail, H., Edyham, M. and Wirjosentono, B. (2002) Bamboo fibre filled natural rubber composites: the effects of filler loading and bonding agent. *Polymer Testing*, **21(2)**, 139–144.

18. Ismail, H., Shaari, S. and Othman, N. (2011) The effect of chitosan loading on the curing characteristics, mechanical and morphological properties of chitosan-filled natural rubber (NR), epoxidised natural rubber (ENR) and styrene-butadiene rubber (SBR) compounds. *Polymer Testing*, **30(7)**, 784–790.

19. Sae-Oui, P., Rakdee, C. and Thanmathorn, P. (2002) Use of rice husk ash as filler in natural rubber vulcanizates: In comparison with other commercial fillers. *Journal of Applied Polymer Science*, **83(11)**, 2485–2493.

20. Ibrahim, N., Shokri, A. H. M., Kamarun, D. and Mohd, A. F. (2018) Cure characteristic and mechanical properties of natural rubber vulcanizates with digested rice husk ash (RHA). *AIP Conference Proceedings*, **1985(1)**, 1–6.

21. Liu, C., Shao, Y. and Jia, D. (2008) Chemically modified starch reinforced natural rubber composites. *Polymer*, **49(8)**, 2176–2181.

22. Rouilly, A., Rigal, L. and Gilbert, R. G. (2004) Synthesis and properties of composites of starch and chemically modified natural rubber. *Polymer*, **45(23)**, 7813–7820.

23. Johns, J. and Rao, V. (2009) Mechanical properties and swelling behavior of cross-linked natural rubber/chitosan blends. *International Journal of Polymer Analysis and Characterization*, **14(6)**, 508–526.

24. Ismail, H., Norjulia, A. and Ahmad, Z. (2010) The effects of untreated and treated kenaf loading on the properties of kenaf fibre-filled natural rubber compounds. *Polymer-Plastics Technology and Engineering*, **49(5)**, 519–524.

25. Anuar, H. and Zuraida, A. (2011) Improvement in mechanical properties of reinforced thermoplastic elastomer composite with kenaf bast fibre. *Composites Part B: Engineering*, **42(3)**, 462–465.

26. Poompradub, S., Ikeda, Y., Kokubo, Y. and Shiono, T. (2008) Cuttlebone as reinforcing filler for natural rubber. *European Polymer Journal*, **44(12)**, 4157–4164.

27. Klungsuwan, P., Jarerat, A. and Poompradub, S. (2013) Mechanical properties and biodegradability of cuttlebone/NR composites. *Journal of Polymers and the Environment*, **21**, 766–779.

28. Ibrahim, N., Dalgiri, N., Roslan, N. A. F., Bahtiar, S. F. and Mazlam, M. S. M. (2018) Bamboo charcoal filled natural rubber vulcanizates: The effect of filler loading and bonding agent. *AIP Conference Proceedings*, **1985(1)**, 1-8.

29. Daud, S., Lik, O. Y. H. and Azura, A. R. (2020) The effects of nano-cellulose filler on tensile and thermal properties of natural rubber latex films. *AIP Conference Proceedings*, **2267(1)**, 1–8.

30. Bigg, D. (1987) Mechanical properties of particulate filled polymers. *Polymer Composites*, **8(2)**, 115–122.