Composites Part C: Open Access 7 (2022) 100237

Contents lists available at ScienceDirect

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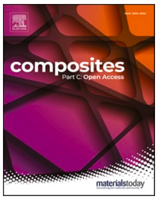

Mechanical properties and energy absorption capacity of chopped fiber reinforced natural rubber

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ARTICLE INFO

Keywords:
Natural rubber
Elastomer
Chopped fiber
Energy absorption
Indentation

ABSTRACT

The present study aims to investigate the effect of incorporating different fibers in an elastomeric media on its mechanical and energy absorption characteristics. To this end, newly developed compounded natural rubber was employed as the matrix and three chopped fibers including glass, carbon and Kevlar were used as the reinforcement at different weight loadings. Dynamic tensile tests revealed that while carbon and glass fibers had similar influence in reducing both strength and failure strain of the composites, Kevlar fibers contributed positively to increasing the ultimate strength. In general, energy absorption capacity of fiber reinforced rubber was observed to be less than that of neat specimens. Based on the dynamic indentation tests, incorporating fibers within the elastomeric matrix could be beneficial in small deformations owing to the more energy absorption capacity of fiber composites at the beginning of the indentation process. The optimum configuration was concluded to be 5 wt.% of carbon fibers in which the deflection-to-failure is improved whilst the energy absorption and ultimate strength remain intact.

1. Introduction

Rubber composites have been increasingly employed in recent decades [1,2]. Rubbers can be combined with other polymers and fillers, leading to numerous unique physical properties in such materials [3]. In general, these composites provide significant properties, such as high flexibility, light weight, high tensile strength, and substantial damping [4–6]. Rubbers are often used to control vibrations and impacts in machinery and electronic devices due to their impact absorption characteristics [7]. Rubbers are widely used in different industries, including oil and gas, automotive, shipping and maritime, railways and aviation, road and bridge construction and impact energy absorption [8,9]. Rubbers are used along with metal or composite layers as a solution to improve impact energy absorption in structures [10]. Taherzadeh et al. [11] studied the effects of an elastomer layer on the ballistic performance improvement of a metal fiber laminate. A rubber layer and a glass/epoxy composite layer were sandwiched between two aluminum layers and subjected to impact loading. It was found that an elastomer layer with the same thickness as the composite would be more efficient in terms of improving energy absorption and reducing the areal density.

Numerous studies investigated high-strength fabric-reinforced elastomer composites to improve the mechanical and impact properties of rubber. Siverman et al. [12] carried out a set of tests to examine the performance of carbon fiber-reinforced rubber layers. They analyzed mechanical properties, including tensile strength, compressive strength, flexural strength, and impact strength. It was found that carbon fiber-reinforced rubber layers outperformed conventional rubber layers in all aspects. Fabric-reinforced composites are also used in seismic isolators to reduce vibration transfer to structures [13,14]. Fabric is employed as an alternative to steel plates in such structures. Since fibers have lower mass and volume than steel plates, a fabric-reinforced seismic isolator would be lighter and smaller than steel plate-reinforced isolators. Moreover, such composites are employed to provide blast load protection. Jia et al. [15] evaluated the protective capabilities of rubber and woven-fabric composite armors by measuring the depth-of-penetration against the shaped charge. The results revealed that Kevlar fabric had the largest contribution to reducing the penetration depth, representing an effective alternative in ballistic and blast

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https://doi.org/10.1016/j.jcomc.2022.100237
Received 13 October 2021; Received in revised form 23 January 2022; Accepted 2 February 2022

Table 1
. Formulation of compounds.

Ingredients	Loading (Phr)
NR	100
Carbon Black (N330)	60
Zink oxide	5
Calcium carbonate	30
Spindle oil	15
Sulfur	2
Coumarone Resin	5
Stearic acid	1
Volcasite D	0.7
Volcasite M	0.7

applications. A number of studies examined the performance of fabric-reinforced elastomer composites under impact loads [16–19]. Khodadadi et al. [20,21] experimentally and numerically studied the impact performance of Kevlar-reinforced elastomer composites and compared them to Kevlar/epoxy composites. In light of the higher flexibility and energy absorption of rubber, the Kevlar/rubber composites showed much higher energy absorption performance than Kevlar/epoxy composts.

Short fiber-reinforced rubbers have been of great interest to researchers since they enjoy improved physical and mechanical properties and high economic advantages while maintaining flexibility [22–24]. These composites are more workable than long fiber-reinforced ones since short fibers could be easily added to rubber mixtures and be processed by conventional rubber processing methods, such as extrusion, rolling, and molding. The efficiency and properties of short fiber-reinforced composites are dependent on a number of factors, such as the material, fiber length, orientation, and rubber matrix attachment [25,26]. Researchers have experimentally and numerically predicted the mechanical properties of short fiber-reinforced rubber composites. Gao et al. [27,28] conducted a numerical study on the mechanical properties of aramid fiber-reinforced rubber composites. They developed a finite element (FE) model for the prediction of mechanical properties through experimental data. The representative volume element (RVE) technique was adopted to investigate heterogeneous materials in terms of mechanical behavior. Mahdavi et al. [29] numerically simulated carbon fiber-reinforced natural rubber at three fiber concentrations under different loads. They sought to explore the influences of different loads on nanocomposites in terms of thermo-mechanical behavior. The mechanical loads were found to be capable of enhancing the modulus of elasticity and thermal conductivity. Ghoreyshi et al. [30] measured the effect of new and waste nylon 66 short fibers on the physical and mechanical properties of natural rubber-based

Fig. 1. Chopped glass, carbon and Kevlar fibers with an average grain size of 6 mm.

Fig. 2. Dynamic indentation tests using a 10 mm hemispherical indenter and 100*100 mm^2 clamp opening.

Fig. 3. Tensile testing machine.

composites. The composites were fabricated by a single-stage mixing method, and the curing characteristics were determined by a rheometer. It was found that a rise in the fiber fraction shortened the curing of the mixtures and increased the maximum mixing momentum. Furthermore, the mechanical properties of the mixtures significantly enhanced as the fraction of short fibers increased. Likewise, Andideh et al. [31] studied the curing, physical and mechanical properties, structures, and morphology of Nylon 66-reinforced NR/SBR nanocomposites. It was found that the fibers enhanced tensile strength, tear resistance, and stiffness. Pittayavinai et al. [32] studied the contributions of polarity in the matrix on the mechanical behavior of short aramid fiber-reinforced rubber composites. They exploited natural rubber as a non-polar rubber, whereas acrylonitrile rubber represented the polar one. It was found that the aramid fibers had high reinforcing effects on not only polar but also non-polar rubbers. However, the polar rubber enjoyed significantly higher reinforcement than the non-polar one.

The reinforcement of natural rubber through chopped fibers has rarely been studied using dynamic penetration tests. Thus, the present work explores the contributions of different fibers within an elastomeric medium to the energy absorption and mechanical behavior of the composite. Hence, a recently-introduced compound natural rubber was used to serve as the matrix. Also, Kevlar, carbon, and glass fibers (6 mm of particle size) were exploited at various mass fractions. The developed composites were subjected to dynamic penetration and dynamic tensile testing.

2. Experimental procedure

2.1. Materials and fabrication of specimens

Natural rubber (SMR 20) was employed as the elastomer layer (produced by Rubber Research Institute of Malaysia) in light of its high damping, flexibility, and tear resistance. Apart from the curing agents (such as sulfur), carbon black and $CaCO_3$ (produced by Pars Carbon Black Company and Yazd Tire Company) were added to the elastomer compound to improve the mechanical properties of the rubber. Table 1

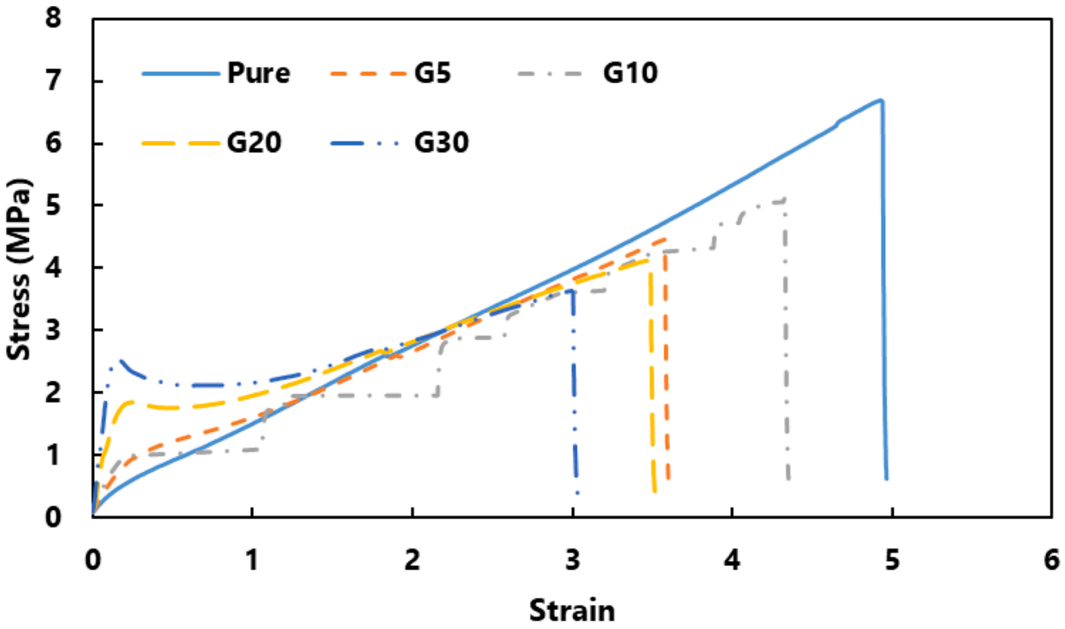

Fig. 4. Stress-strain curve of glass fibers reinforced NR in tensile tests.

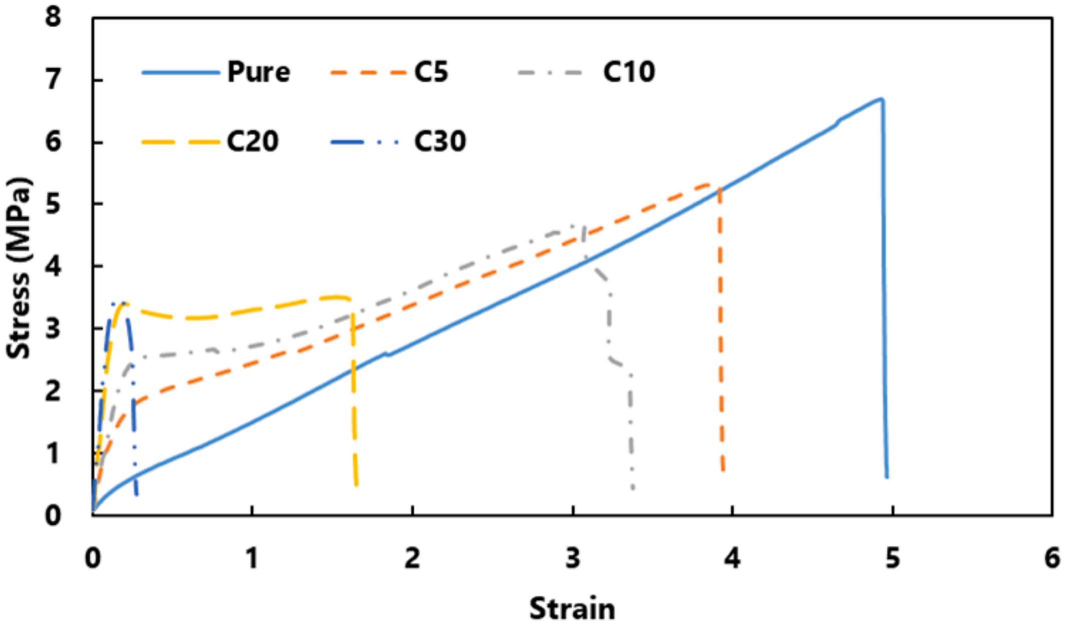

Fig. 5. Stress-strain curve of Carbon fibers reinforced NR in tensile tests.

provides the formulation of the rubber. Also, ZnO, stearic acid, accelerator, and sulfur were obtained from LG Korea Company to use in the vulcanization of rubber.

The rubber components were synthesized in the Iran Polymer and Petrochemical Institute. The components were precisely weighed. Then, the components, except for sulfur, Volcasite M, and Volcasite D, were blended in a Banbury mixer for 6 min. Then, the curing agents were added to the compound, and the compound was subjected to a laboratory roller for 4–5 min.

Continuous fibers are not recommended as they would diminish the collision energy absorption performance of the elastomer phase. Chopped fibers not only enhance ballistic performance but also are expected not to be an elastomer inhibitor. Thus, chopped glass, carbon, and Kevlar fibers with a grain length of 6 mm were purchased, as shown in Fig. 1.

To fabricate specimens, pure elastomer components, except for curing agents and fillers, were blended by a Banbury mixer. Then, based on the prior calculations, the curing agents and reinforcement components were added to the mixture using a laboratory roller. This step is important in the sense that it uniformly distributes the fillers within the substrate phase. Raw elastomers were cured within a hot press apparatus, extracting not only square specimens but also standard tensile test specimens. It should be noted that the curing process is performed at 160 °C for 4 min through the rheological test.

2.2. *Characterization tests*

To investigate the behavior of the specimens, the dynamic indentation test was performed on the specimens using a universal compression-tensile test machine [33]. A spherical penetrator tip with a diameter of

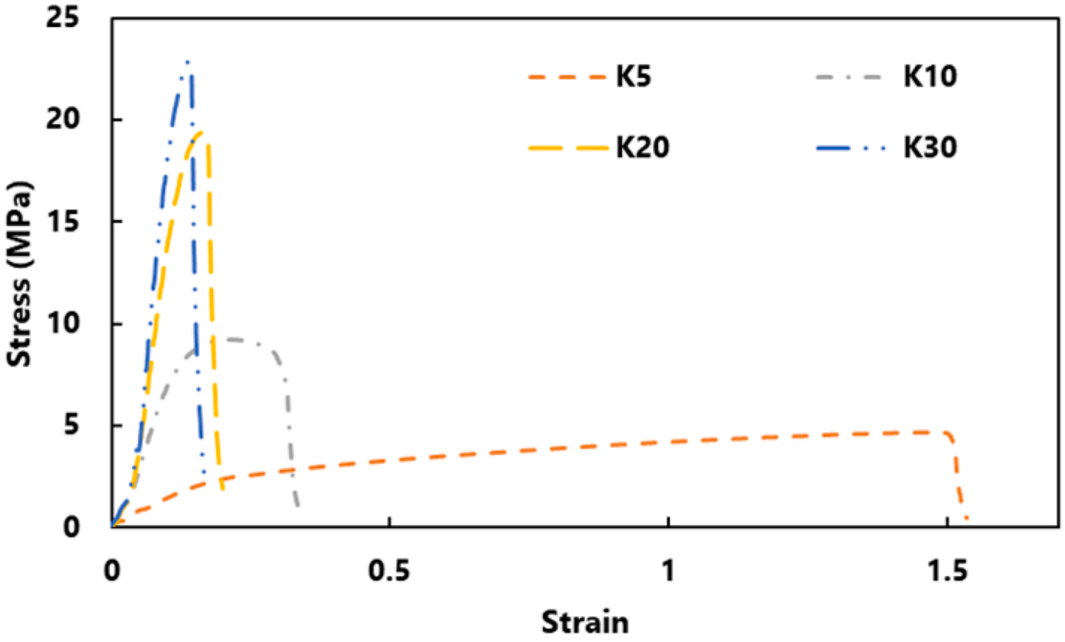

Fig. 6. Stress-strain curve of Kevlar fibers reinforced NR in tensile tests.

10 mm was applied at a feeding rate of 500 mm/min. Each test was carried out three times, recording the average values as the final output. Fig. 2 depicts a specimen within the fixture of the machine during the test.

Additionally, a number of tensile specimens were fabricated according to ASTM standard D412 and subjected to a tensile rate of 500 mm/min through a Santam test machine at the Rubber Laboratory of the Tarbiat Modares University. The measurement device is very accurate and allows for more accurately comparing different specimens. Each specimen was tested at least two times to ensure the accuracy of the results. Fig. 3 depicts the testing machine during the tensile tests.

3. Results and discussion

3.1. *Tensile test*

Tensile tests of standard rubber specimens were performed and the results are presented in this section for each type of fiber and their weight loadings. In order to facilitate comparing the performance of different configurations, the stress-strain results are depicted within Figs. 4–6.

According to Figs. 4 and 5, the addition of glass and carbon fibers has similar effects on the bulk performance of the resulted composites. Indeed, fibers significantly change the behavior of the specimens at the beginning and end of the loading range. The addition of glass and Carbon fibers to rubber not only reduces the ultimate strength but also diminishes the fracture strain. This suggests that these fibers have a negative effect on the energy absorption performance of the specimens since it would decrease the area under the load–displacement curve (representing energy absorption to the failure point). In order to have a deep insight of the underlying reasons, SEM images of the fractured surface of Glass and Carbon fiber-reinforced rubber are presented in Figs. 7 and 8.

One important phenomenon is observed especially in the glass/rubber composites in Fig. 7, which is regarded to the dispersion of holes within the fractured surface. Indeed, the adhesion between fiber and matrix is not appropriate enough to transmit the load within the constituents. As a result, the fiber pulling-off is occurred which not only prevents the full exploitation of fiber properties but also creates some defects as the holes observed in the fractured area. Therefore, the ultimate strain and strength are reduced compared with the neat sample. In Carbon/rubber composites, however, the fiber-induced defects in the matrix is not observed but the high amount of fiber to matrix volume ratio and the random orientation of fibers could be major problems. In other words, the density of Carbon is smaller than the glass fiber and in the same weight ratio, there will be higher volume of carbon fibers. This could weaken the effect of rubber matrix and diminish the hyper elastic behavior of the whole composite. Besides, although the Carbon fibers have quite been less fragmented than the glass fibers, their random orientation has prevented them to establish a robust network to carry out the exerted load. The result is the reduction of strength as depicted in Fig. 9.

The situation in Kevlar/rubber samples is quite different. Kevlar fibers substantially changed the beginning and end of the stress–strain curves. A rise in the weight loading of fibers not only reduces the fracture strain but also increases the ultimate strength of the elastomeric specimens. To have an in-depth investigation, SEM images of the fractured surface in Kevlar/rubber samples are presented in Fig. 10.

The most notable observation could be regarding the morphology of the Kevlar fibers. Indeed, high capacity of Kevlar fibers against fragmentation during the manufacturing process has resulted in an interwoven network throughout the section. This phenomenon could magnify the effect of fibers within the matrix by simultaneously increasing the strength and reducing the failure strain as it is also observed in Figs. 6 and 10.

The overall interaction between ultimate strength and the fracture strain could be identified through the energy absorption capacity, which is the area under the load-deformation diagram and is depicted in Fig. 11 for different samples.

It is quite expected that the energy absorption capacity reduces in glass and Carbon composites since the both engaged parameters, i.e. ultimate strength and fracture strain reduce. On the other hand, however, it can be said that Kevlar fibers have a larger contribution to fracture strain reduction than to ultimate strength enhancement. As a

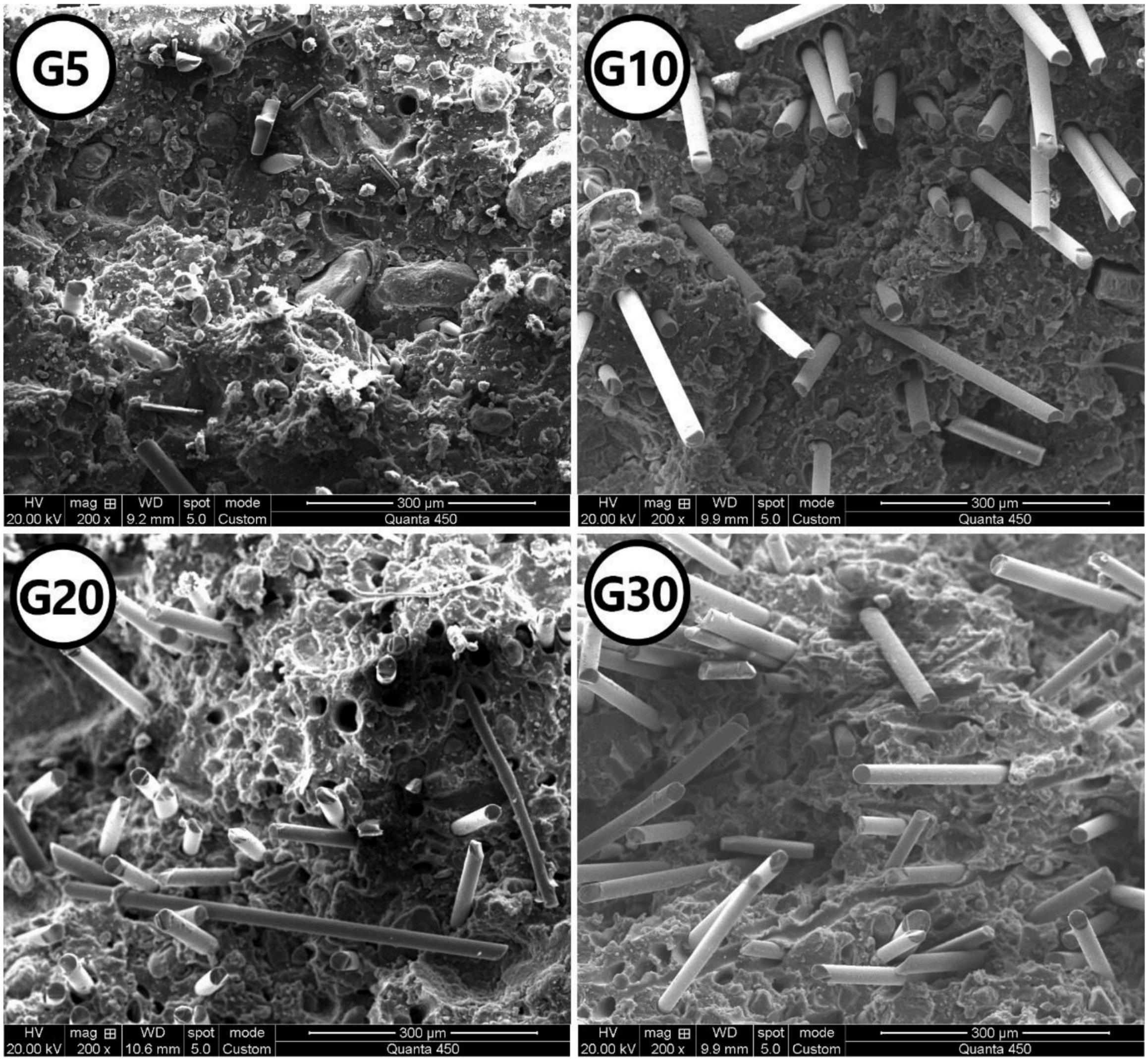

Fig. 7. SEM images of the fractured surface in glass fiber reinforced rubber samples within the tensile test.

result, energy absorption dramatically declines as the weight loading of Kevlar fibers increases.

3.2. Dynamic penetration testing of elastomer/fiber composites

The elastomers with the chopped fiber contents of 0, 5, 20 and 30% were subjected to the dynamic penetration test, as reported in Figs. 12–14.

According to Fig. 12, an increase in the glass fiber fraction in the compound dramatically diminished both ultimate strength and fracture strain. This finding is in good agreement with the tensile test results, suggesting the sufficient accuracy of specimen fabrication and tests. The diminished performance of the composites can be attributed to the change in the microstructure. The addition of glass fibers to rubber increased defects in the matrix phase, as it is observed in Fig. 7, and the negative effect of the defects dominated the positive direct effect of the fibers.

Similarly, Carbon fibers reduced the fracture strain; however, they enhanced the ultimate strength. This is important in protective structures since a structure with the ability to induce a negative acceleration would decrease damage to equipment. According to Fig. 13, the carbon fiber-reinforced specimens resisted larger loads than neat specimens at penetration depths below 45 mm. This can add to the popularity of carbon/elastomer composites as structural components to resist loads.

On the other hand, Kevlar fibers dramatically reduced the fracture strain (to one-third of the neat specimen) while increased the ultimate strength significantly. For example, the ultimate strength of the specimen with 30wt% Kevlar fibers was three times as large as that of the neat specimen. The underlying reason would be the interwoven network formed by these fibers as a result of maintaining their original length within the fabrication process, as it is observed in the SEM images of Fig. 10.

It would be also beneficial to assess the interaction between ultimate strength and failure strain by calculating the area under the load-deformation diagrams, which is a representation of the absorbed energy (Figs. 15–17).

According to Fig. 15, reduced ultimate strength and fracture strain were reflected in the decreased energy absorption of the glass fiber-reinforced specimens. It should be noted that the fiber-reinforced specimens, particularly at a fraction of 30%, had higher energy absorption than the neat specimen in the beginning of the process. This implies that glass fibers are efficient at small deformations.

Turning to the Carbon fibers, the response of the specimen with a weight loading of 5% is significant. This specimen not only underwent less deflection but also had almost the same energy absorption and ultimate strength as that of the neat specimen. It can be said that the fracture strain reduced only slightly, and this specimen has the potential to be used in protective structures. A comparison of the other carbon-

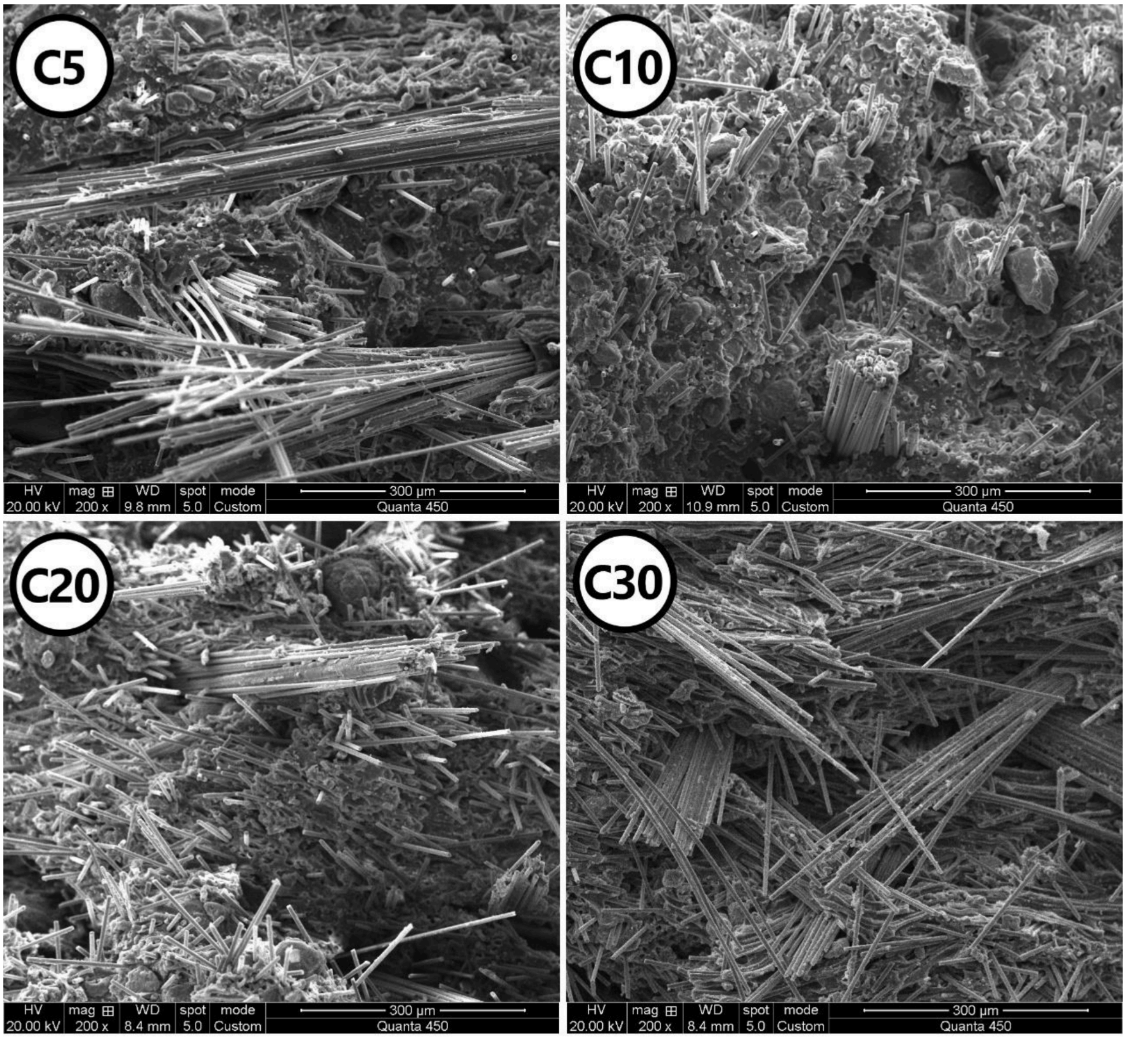

Fig. 8. SEM images of the fractured surface in Carbon fiber reinforced rubber samples within the tensile test.

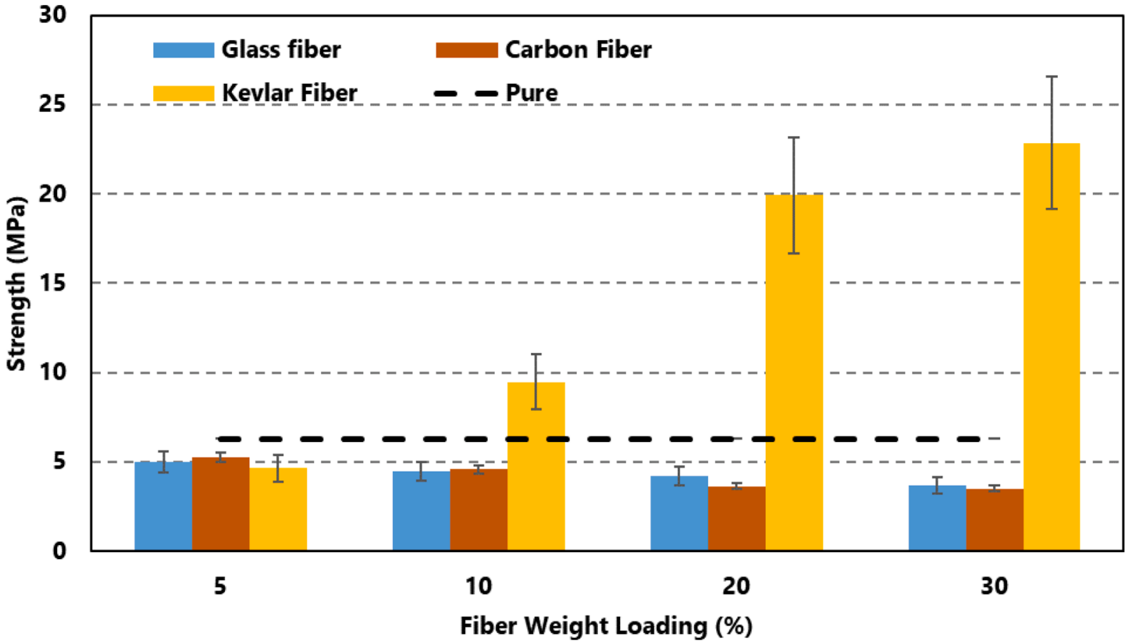

Fig. 9. Ultimate strength of glass, Carbon and Kevlar fiber reinforced natural rubber.

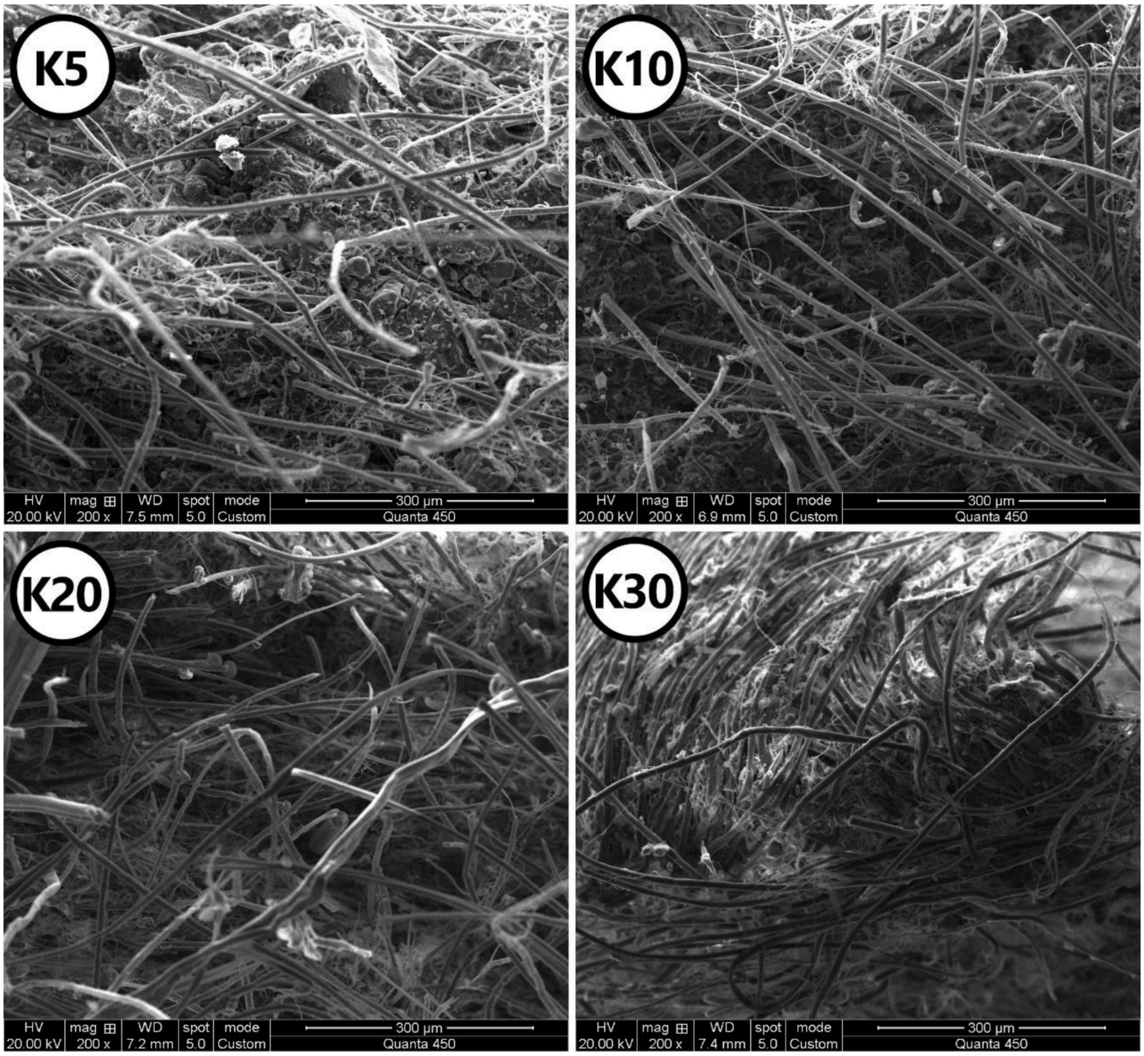

Fig. 10. SEM images of the fractured surface in Kevlar fiber reinforced rubber samples within the tensile test.

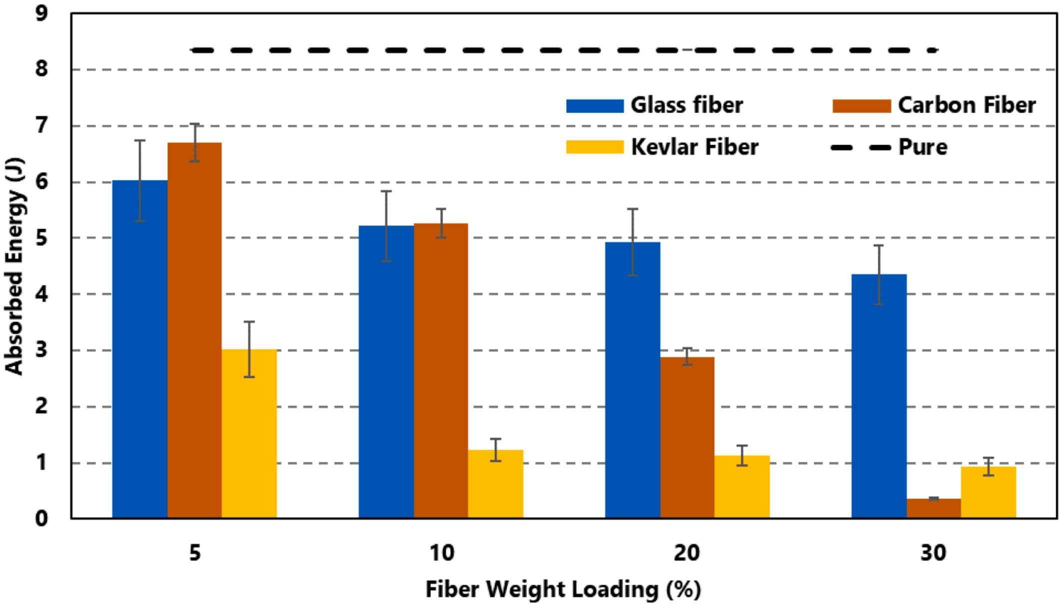

Fig. 11. Energy absorption capacity of different fiber/rubber configurations within the tensile test.

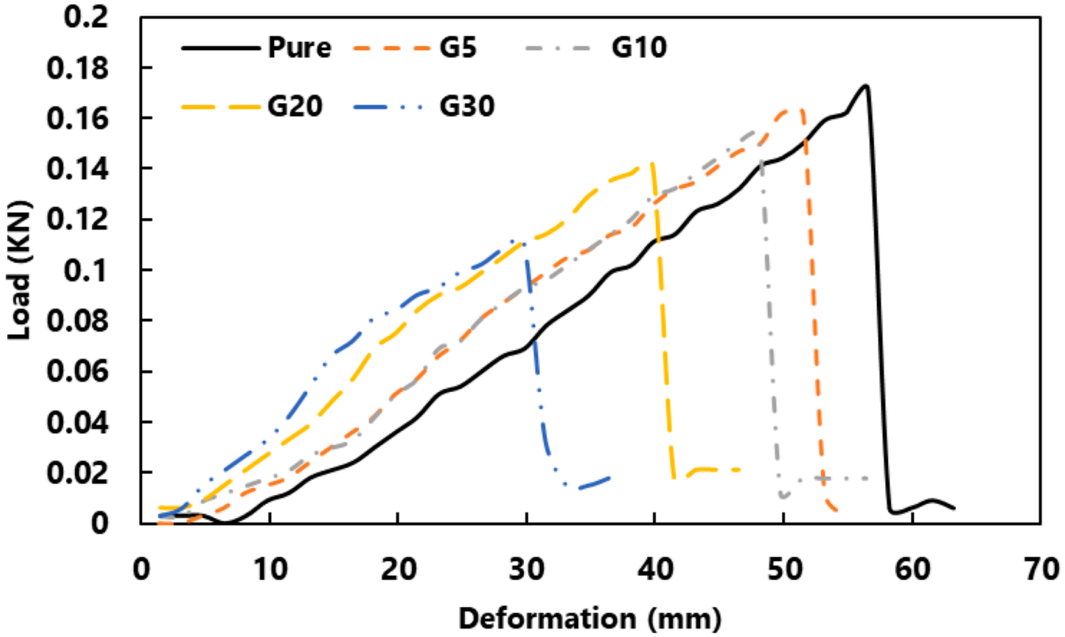

Fig. 12. Load-deformation response of glass/rubber composites within the indentation test.

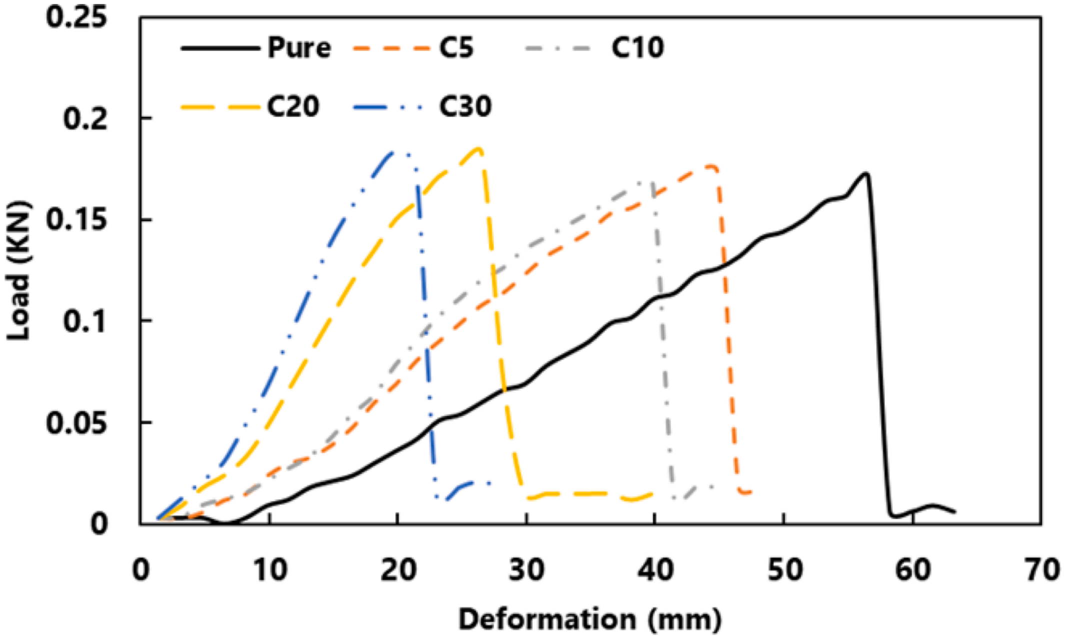

Fig. 13. Load-deformation response of Carbon/rubber composites within the indentation test.

reinforced specimens indicates that energy absorption reduced, even though the ultimate strength improved. For example, the specimen with a carbon mass fraction of 30% experienced an energy absorption decline to nearly 2J, which is almost half the energy absorption of the neat specimen. A comparison of the energy absorption capacity of different samples is depicted in Fig. 18.

According to Fig. 17, energy absorption was observed to be higher in the Kevlar-reinforced specimens than in the neat ones at the beginning of penetration. However, the small fracture strain deteriorated the performance of the Kevlar/elastomer specimens. As a result, the energy absorption of the Kevlar-reinforced specimens was lower than the neat specimens as shown in Fig. 18. The reason of such a behavior could be attributed to the domination of fiber properties according to which the energy absorption has an increasing trend for Kevlar weight fraction greater than 20%.

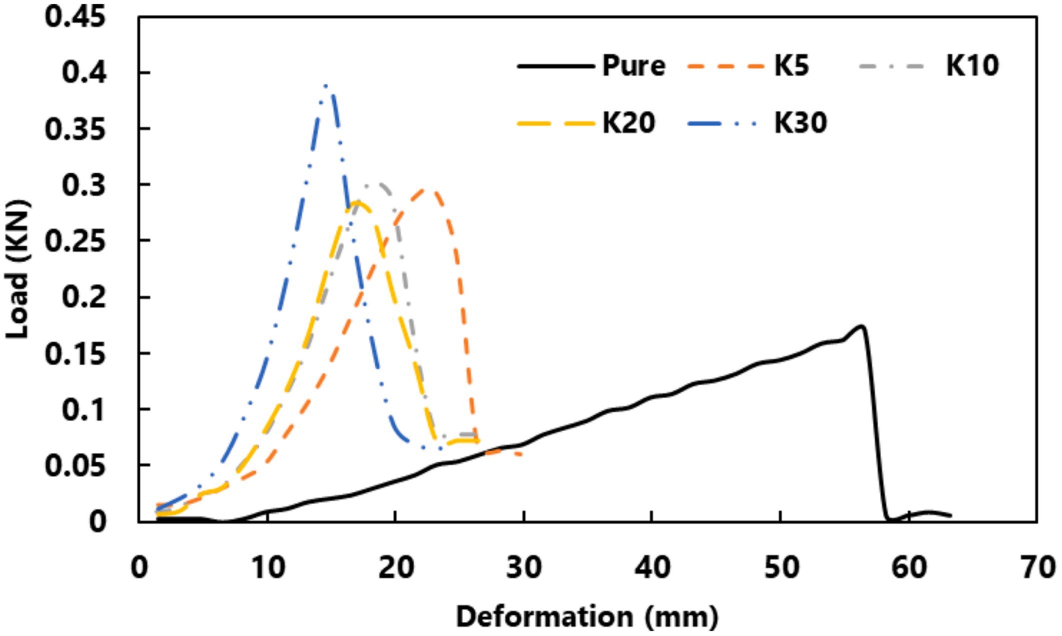

Fig. 14. Load-deformation response of Kevlar/rubber composites within the indentation test.

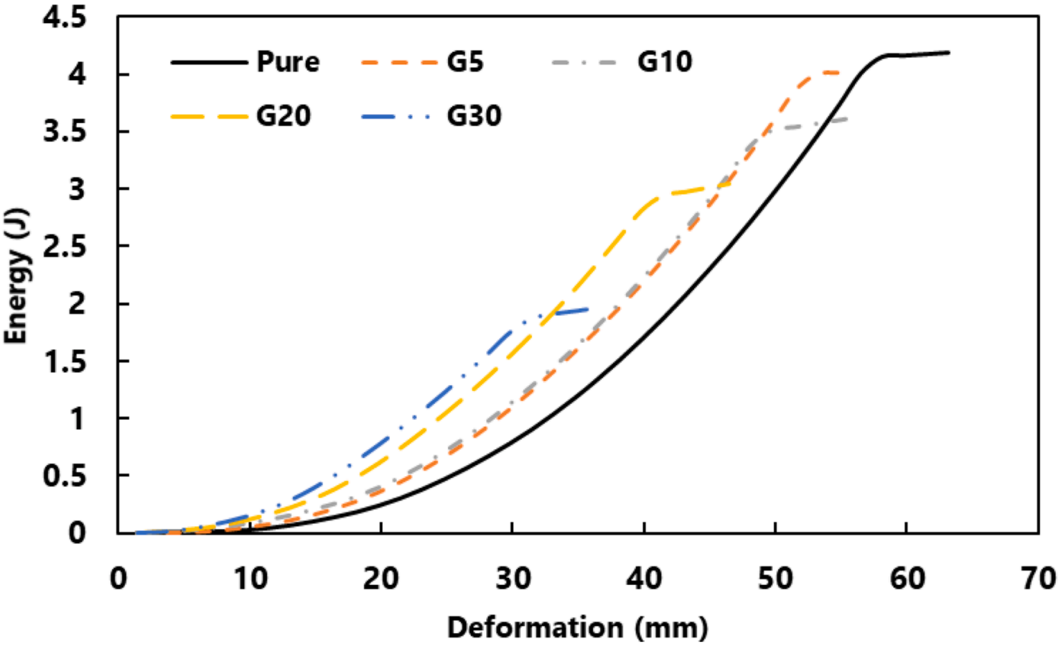

Fig. 15. Energy absorption of glass/rubber compounds in the indentation test.

4. Conclusion

The present study evaluates the effects of chopped fibers in an elastomer matrix on the mechanical performance of composites. Glass, carbon, and Kevlar leaves with a particle size of 6 mm were added to natural rubber at certain weight loadings. Then, dynamic tensile and penetration tests were performed on the specimens.

The results showed that the energy absorption performance in elastomer/fiber composites declined due to the decline in the fracture strain. More specifically, the composites with glass and carbon fibers in the elastomer matrix showed similar behavior. The dynamic tensile tests revealed that glass and carbon fibers dramatically diminished the fracture strain and ultimate strength. As a result, energy absorption declined, leading to composites with the insufficient resisting capability. This can be attributed to the rise in the number of defects within the elastomer phase due to the chopped fibers. In contrast, Kevlar fibers were found to have a different effect on the composites; Kevlar fibers enhanced the ultimate strength and decreased the fracture strain. Finally, the fracture strain reduction was larger than ultimate strength enhancement, leading to a decline in energy absorption.

The dynamic penetration test yielded consistent results with the tensile test findings. It was observed that the use of fibers in the

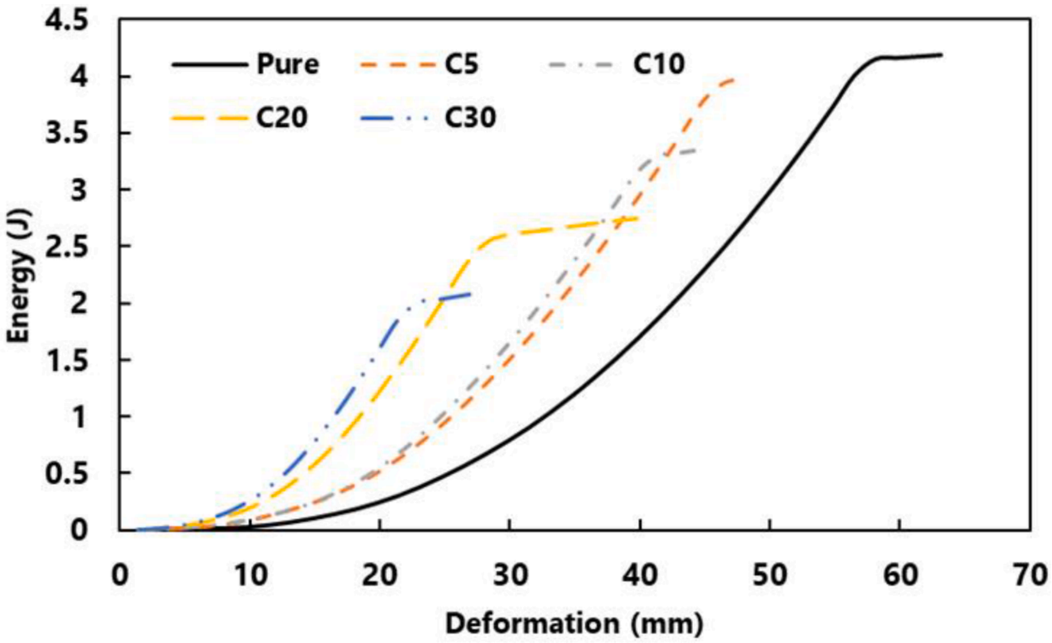

Fig. 16. Energy absorption of Carbon/rubber compounds in the indentation test.

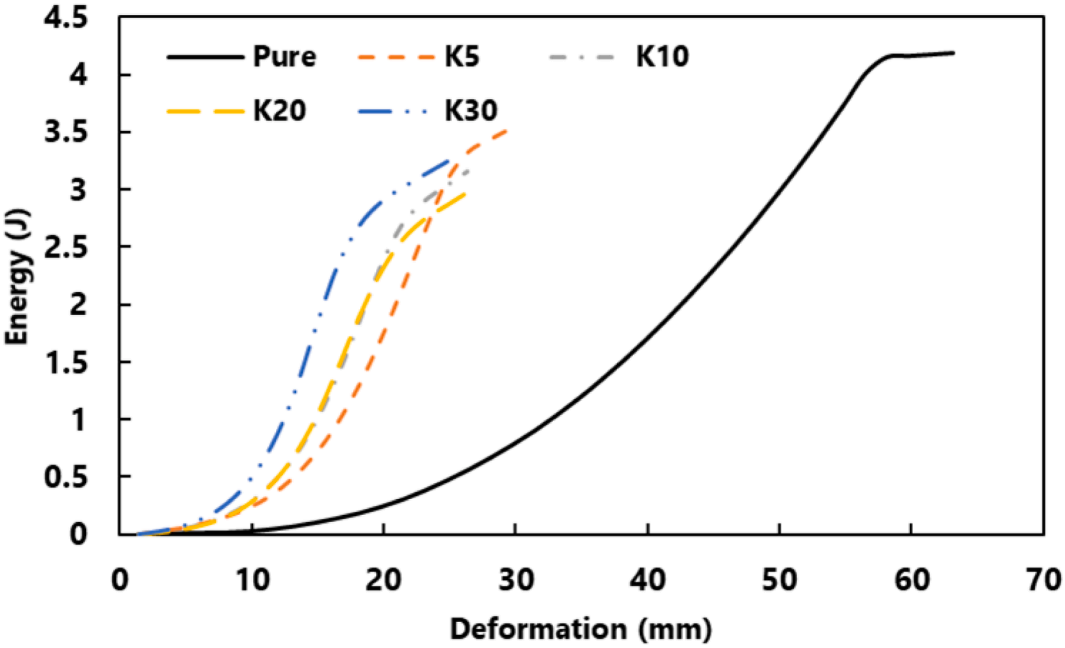

Fig. 17. Energy absorption of Kevlar/rubber compounds in the indentation test.

elastomer matrix could be reasonable at low deformation since the fiber/elastomer composites showed higher energy absorption than the neat specimens at the beginning of loading. Among the specimens, the composite with a carbon mass fraction of 5% was found to have unique behavior. It showed almost the same energy absorption and ultimate strength as that of the neat specimen while having far less deflection.

Ethical statement

The authors declare that have considered ethical standards, and the paper is compliance with ethical standards.

Funding body

The authors declare that they have no funding Body.

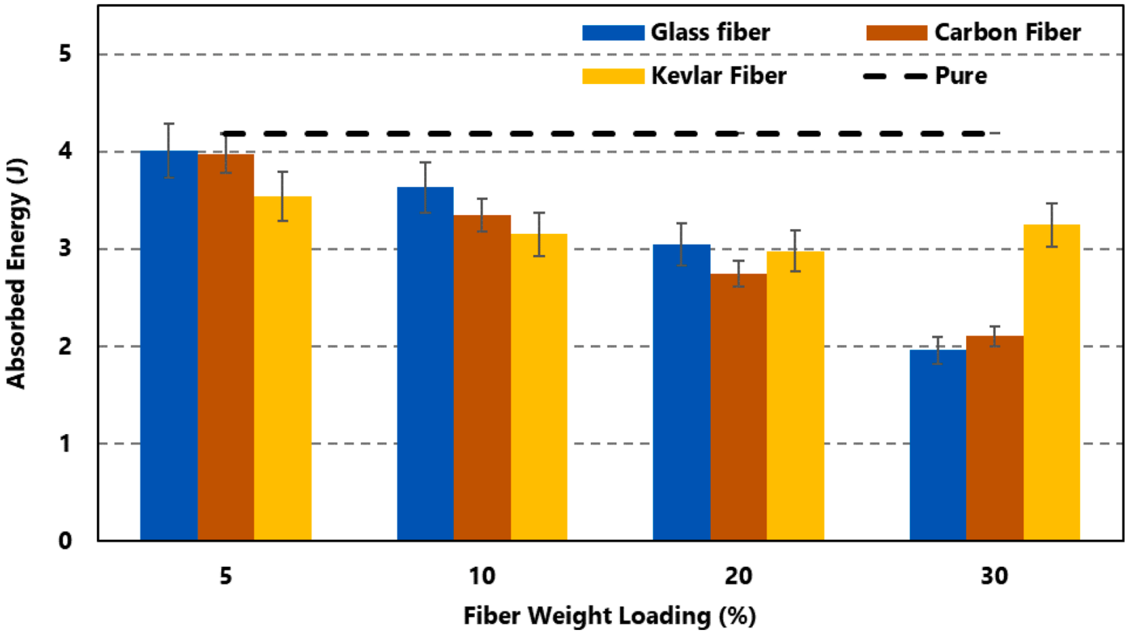

Fig. 18. Energy absorption capacity of different fiber/rubber configurations within the indentation test.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgments

The authors declare that they have no acknowledgements.

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