Hybrid bio-based composites from blends of epoxy and soybean oil resins reinforced with jute woven fabrics

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Abstract

In our world, where environmental factors are taken into consideration more and more, the interest in biomaterials leaves its place to the need and this leads the researchers to search for new materials. The aim of this study is to produce an environmentally friendly, sustainable material with the use of a plant oil-based bio-resin (acrylated epoxidized soybean oil). In this context, bio-composites containing different proportions (from 0 to 100 wt%, in 10% increments) of acrylated epoxidized soybean oil (AESO) and epoxy resin are reinforced with four-ply jute woven fabric and produced by the vacuum infusion method. The bio-composites produced within the scope of the study analyzed physically (fiber weight ratio), mechanically (tensile strength, flexural strength, drop-weight impact resistance, and Charpy impact strength), instrumentally (differential scanning calorimetry and Fourier-transform infrared spectroscopy) and morphologically (scanning electron microscopy). According to the results, the tensile and flexural strength values of the composites containing more than 30 wt% AESO resin increase due to the ductility of the structure; subsequently, composites with AESO content above 50 wt% are found to exhibit superior impact resistance. Composites with pure AESO resin absorb 7 J energy which is almost 3 times higher than pure epoxy composites. The maximum tensile strength (63 MPa) of composites are achieved for 30 wt% AESO content indicating the newly formed hydrogen bonding leading to enhanced fiber-matrix interface. The bio-composites designed and produced in the project have been a promising alternative for various end-use areas, from construction elements to the automotive sector and sports equipment, where human health and environmental elements are considered.

Introduction

The usage of natural materials in the production of composite structures is increasing day by day, with the increasing knowledge about environmental factors. The term of bio-composite is often used for the composites which have partially natural components; either a matrix or reinforcement material. However, it is essential to provide a combination in which both components (matrix and reinforcement material) are natural in order to truly entitle it as a bio-composite [1].

Bio-composites, which have a wide range of usage, are generally composed of petroleum-based thermoset or thermoplastic resins reinforced with natural textile fibers. Although the thermoplastic resins obtained from renewable sources are commercially available, thermoset resins are mostly produced from crude oil [1]. Environmental damage, climate changes, and diminishing fossil sources have led firms and scientists to search for alternative matrix materials and thus bio-based plastics have emerged [2]. The development of bio-based polymers from cheaper and renewable materials instead of petroleum-based materials has significant impacts on the economy and the environment. In addition to its many advantageous properties, the most important feature of bio-based polymers is their overall intrinsic low toxicity [3].

Petroleum-based epoxy resin is the most widely used thermoset polymer in composite materials due to its low cost, ease of use and high mechanical properties. However, the uncertainties about petroleum supplies,
prices and their effects on the environment reveal the fact that the use of epoxy needs to be reduced and substituting biomaterials are required [4].

Considering the automotive sector, which is one of the sectors where composite materials are used most, it is seen that the most important thing to increase the efficiency of automobiles and reduce fuel consumption to diminish its hazardous effects to the environment is to reduce the weight of the vehicle [5]. Studies in the literature and the prototypes produced have shown that a weight gain of 25% can be achieved by using bio-resin based composites instead of steel. In addition to being lightweight, composites offer ease of production and workability compared to metals [6].

Thermoset bio-resins obtained from plant oils (soybean oil, flaxseed oil, linseed oil, palm oil, rapeseed oil, etc) which are unsaturated triglycerides, are promising raw materials for the ‘greening’ of thermosets [7, 8]. Unlike synthetic resins, they are derived from plants and contain carboxylic acid, oil, and isoprene-based hydrocarbons. Bio-resins do not show toxic properties during production and can be used in admixture with all synthetic resins. They are also odorless and have dimensional stability [1].

Among the existing plant oils, soybean oil seems to be the most attractive alternative resource due to its very low price and abundant supply. The building block of soybean oil resin is a triglyceride, the main component of vegetable and animal fats [9]. Epoxidized soybean oil (ESO) is known as a common plasticizer for polyvinyl chloride [10]. AESO is a commercially available soybean oil produced from the epoxidation of soybean oil followed by reaction with acrylic acid. AESO shows non-volatile and non-toxic behaviors [11]. Typical soybean oil is a triglyceride with ~4.5 unconjugated C=C bonds [10]. In addition, AESO is highly viscous at room temperature and has a low crosslinking capacity due to its long aliphatic chains and a low degree of unsaturation [12].

On the other hand, the variety of natural reinforcement materials (natural textile fibers, hazelnuts, pine needles, sawdust, etc) is increased day by day, but natural resin is a new study topic for researchers [1]. Natural fiber reinforced composites have many advantages over synthetic fiber reinforced composites. Some of these are less damage to nature, more fiber/less polluting polymer content to achieve the same performance characteristics and their end of life is result in recovered energy and carbon credits [13]. In addition to these advantages, the use of natural fiber-reinforced composites also has positive effects on economic issues [14].

Bast fibers are gathered from certain natural plants’ skin or inner shell of the stem [15]. They have superior mechanical properties (such as high strength and rigidity) than other plant fibers and due to this fact, they are the most used natural fiber reinforcement materials [16, 17]. Among the bast fibers, jute is the most preferred fiber in composite production [18]. It has properties such as; high modulus, low cost, good thermal and electrical insulation abilities, moderate moisture regain, biodegradability, silky luster, high specific strength and commercially availability [19–22].

While the matrix material provides the surface appearance and the resistance to environmental factors in general, the reinforcing material ensures the integrity of the composite material by holding the fibers together in addition to strength and load-bearing properties [2, 23, 24].

In the literature, the studies related to the AESO based composites mostly focus on the use of AESO in a mixture of several matrix types such as styrene [10, 25], polyester [11, 26], vinyl ester [7], epoxy [25–27], etc. There are only a few studies in the literature that works on natural textile fiber reinforced composites consisting of soybean oil resin and epoxy resin in order to improve the toughness of the neat epoxy composites [27–29]. In one of the studies, Bakar et al (2018) mixed epoxidized soybean oil with petroleum-based epoxy resin in different ratios to investigate its effects on mechanical (tensile, impact and flexural strength) and thermal properties. Results indicated that although a slight increase of mechanical properties was observed at 10% epoxidized soybean oil content sample, tensile, flexural and thermal properties of composite structures decreased with ascending epoxidized soybean oil content. When the impact strength results were examined, it was seen that epoxidized soybean oil content enhanced the impact properties of the samples owing to its plasticization effect [4]. Sahoo et al (2017) used sisal fiber as reinforcement material in epoxidized soybean oil/epoxy blend resin to enhance the mechanical and thermo-mechanical properties. With the addition of sisal fibers, tensile strength values were increased. While with increasing soybean oil ratio, tensile strength values were decreased and elongation at break values were increased [30]. In one of the studies, Kocaman and Ahmetli (2016) fabricated banana bark and seashell reinforced epoxy/AESO (50 wt% /50 wt %) based composites to examine the effects of those natural fillers on the tensile strength, elongation at break and hardness values of composites. As for the impact of AESO, AESO improved the plasticity of the epoxy resin [31]. In another study, Temmink et al (2018) reinforced bio-epoxy and AESO resin with post-consumer denim waste with four different manufacturing techniques (compression molding, vacuum infusion, resin transfer molding and hand lay-up). The results showed that bio-epoxy composites have superior properties compared to AESO composites, while both bio-epoxy and AESO-based composite materials are found suitable for structural applications [32]. In a study of Niedermann (2014), the impact of the addition of epoxidized soybean oil on mechanical, storage modulus and glass transition temperature of jute fabric reinforced epoxy composites was investigated. Three types of epoxy
resins (aromatic diglycidylether of bisphenol-A (DGEBA) resin, a glycerol (GER)- and a pentaerythritol (PER)-based aliphatic resins) were utilized as a base resin. From the results, it was revealed that while increasing epoxidized soybean oil content in aliphatic composites increased the Tg value, it decreased Tg in the aromatic system. In all systems, the ascending amount of epoxidized soybean oil content decreased the mechanical properties. However, while the mechanical properties obtained in aromatic systems were higher than those of pure epoxidized soybean oil composites when the epoxidized soybean oil ratio in aliphatic systems exceeded a certain value, the mechanical properties reached a lower level than those of pure epoxidized soybean oil composites [33]. Liu et al (2019) utilized two types of reinforcement materials (bamboo and hemp fibers) and 4 different matrix materials (AESO, AESO with methacrylated isosorbide (MI) as a comonomer (MI-AESO), methacrylated AESO with MI (MI-MAESO) and MI resins) to analyze the synergistic effects of fiber type and resin composition on properties of bio-composites. Results indicated that hemp fiber reinforced composites had higher flexural strength, moduli and water resistance compared to bamboo fiber reinforced composites. Moreover, MI-AESO, MI-MAESO, and MI-based composites had higher mechanical strength, modulus and glass transition temperature compared to AESO based composite because of its flexible structure [34].

In this study, AESO modified epoxy resin reinforced with four-ply jute woven fabrics and are produced by the vacuum infusion method. When literature is examined, it is seen that mostly four, six, eight and ten plied fabric reinforced composite plates were produced [35–45]. Since the main aim of this study is to investigate the effect of bio-resin ratio on the properties of composite material, the minimum number of fabric layers (4) is chosen. The optimizing the resin content in the composite structure is one of the most important parameters in composite production. The reinforcement material should be saturated with matrix material with as little excess as possible. The technique of ‘squeezing out’ the excess resin to maximize fiber-to-resin content is the main theory of the vacuum infusion system [46]. The fiber/matrix ratio, tensile strength, flexural strength, drop-weight impact resistance and Charpy impact strength together with differential scanning calorimetric analysis, Fourier-transform infrared spectroscopic analysis and scanning electron microscopy analysis of the hybrid bio-composites are examined in order to determine the effect of AESO blends in physical, mechanical, instrumental and morphological properties of the composites.

Materials and method

Materials

Jute woven fabric (300 g m⁻²) is used as a reinforcement material in bio-composite production, while epoxy resin (F-1564, Fibermak), hardener (F-3486, Fibermak) and acrylated epoxidized soybean oil (AESO, Sigma Aldrich) are used as matrix material. The density and viscosity values of matrix system elements are given in table 1.

Methods

Composite fabrication

The composite structures within the scope of this study are produced by the vacuum-infusion method under 1 bar pressure at room temperature (20 °C ± 2 °C). The applied vacuum helps to distribute the homogeneous resin flow from the jute fabrics, while vacuuming the excess amount of resin in the composites, thereby achieving constant composite thickness. The vacuum infusion set-up is shown in figure 1(a). For the performance analysis, samples are cut by CNC milling machine at 0° and 90° directions of composite plates (figure 1(b)).

For each composite sample, four-ply jute woven fabric is used as reinforcement material. The proportions of the AESO polymer in the resin system range from 0 to 100 wt% by weight in the increment of 10%. When preparing resin systems, 25 wt% of hardener is used in the whole resin system. The remaining 75% is used for predetermined proportions of AESO resin, epoxy resin or mixtures thereof. As an example of the sample code,
0BIO indicates 0 wt% AESO, 75 wt% epoxy and 25 wt% hardener, while 10BIO indicates 7.5 wt% AESO, 67.5 wt% epoxy and 25 wt% hardener. Hardener ratio is kept constant for all resin systems. In this encoding type, samples are encoded in the range 0BIO to 100BIO. The codes of the samples according to the resin system ratios are given in table 2 in detail.

Physical analysis

Fiber weight ratio
The fiber weight ratios of the composites are calculated according to their measured volumes and weights. At least five samples for each composite are performed and results are given with standard deviation (SD) values.

Water absorption test
The water absorption tests of the composites are carried out in distilled water at room temperature (20 °C ± 2 °C) according to ASTM D570-10 standard. The samples are placed in an oven at 50 °C for 24 h and then cooled to room temperature in sealed plastic bags. The samples are weighed on the balance and their dry weight (wd) is noted. The samples are then immersed in distilled water at room temperature for 24 h. Excess water is removed by tissue and wet weights (ww) are recorded. The water absorption rates of the samples are calculated as (ww–wd)/wd × 100%. At least five samples for each composite are performed and results are given with standard deviation (SD) values.

Mechanical analyses
The mechanical properties of composite samples are evaluated by v-notched Charpy impact, drop-weight impact, tensile strength, and three-point bending tests. At least five samples for each composite are tested for each direction (0° and 90°) and results are given with standard deviation (SD) values.

| Sample code | Epoxy ratio (%) | AESO ratio (%) | Hardener ratio (%) |
|-------------|----------------|---------------|-------------------|
| 0BIO        | 75             | —             | 25                |
| 10BIO       | 67.5           | 7.5           | 25                |
| 20BIO       | 60             | 15            | 25                |
| 30BIO       | 52.5           | 22.5          | 25                |
| 40BIO       | 45             | 30            | 25                |
| 50BIO       | 37.5           | 37.5          | 25                |
| 60BIO       | 30             | 45            | 25                |
| 70BIO       | 22.5           | 52.5          | 25                |
| 80BIO       | 15             | 60            | 25                |
| 90BIO       | 7.5            | 67.5          | 25                |
| 100BIO      | —              | 75            | 25                |

Figure 1. (a) The vacuum infusion set-up, (b) Cutting test samples by CNC milling machine.
Charpy impact test
Zwick 5113 pendulum-type impact test machine is used to evaluate Charpy impact resistance of the composite samples according to BS EN ISO 179:1997 standard. The energy applied to the sample is 5 Joule.

Drop-weight impact test
Drop-weight impact tests for composites are conducted using a BESMAK impact testing machine according to ASTM D7136 standard. Samples are tested with 12 Joule impact energy with a standard hemispherical head with a 16 mm diameter striker. The inner diameter of the circular specimen holder is 100 mm. Results are evaluated both visually as a damage pattern and numerically including maximum load, maximum displacement absorbed energy and damage degree data with their SD values.

Tensile strength test
Tensile testing is done using a Shimadzu AG-IS test machine according to ASTM D638-10 standard with a cross-head speed of 3 mm min$^{-1}$.

Three-point bending test
Three-point bending test is carried out with a Shimadzu AG-IS testing machine with a cross-head speed of 6 mm min$^{-1}$ according to ASTM D790-10 standard.

Instrumental analyses
Differential scanning calorimetry (DSC), Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) are used for the instrumental analyses of the samples.

DSC analysis
The thermal behaviors of composites are analyzed by differential scanning calorimeter (Mettler Toledo). The measurement is conducted by heating the samples from 25 °C to 300 °C with a rate of 10 °C min$^{-1}$ in the nitrogen atmosphere.

FTIR analysis
FTIR analysis is performed using Perkin Elmer Spectrum Two model FTIR machine to observe the characteristic peaks of composite components.

SEM analysis
Tescan Vega3 scanning electron microscopy is used to analyze the microstructure of fiber/matrix interaction of composites.

Statistical analysis
Analysis of variance (ANOVA) is performed in order to figure out the statistical significance among various production groups while the comparisons between two selected production groups are analyzed with Student’s t-test at Minitab 16. Differences are considered significant, when $p < 0.05$.

Results and discussion

Physical analysis
Fiber weight ratio
The fiber weight ratios of samples are listed in table 3.
Since the viscosity of the epoxy resin is much lower than AESO resin (table 1), it is more easily vacuumed by the pump, while AESO resin remains on the fabric more intensely and leads to a lower fiber weight ratio. According to the statistical analysis, there is no significant difference ($p = 0.896$) among the fiber weight ratios of the samples from 0BIO to 40 BIO however, above 40 wt% AESO content, the decrement is found statistically significant ($p = 0.000$). AESO resin, which has a very viscous structure, presents difficulties in production, and studies to reduce its viscosity by using together with other synthetic polymeric resins/components (styrene, methacyralted isosorbide, etc) as a solution to this situation are included in the literature [32, 34]. The slight decrement of the fiber weight ratio of the 50BIO sample can result from the excess resin on the fabric.

Water absorption test
The water absorption rates of composites and the images of the selected samples after testing are listed in table 4.
According to the results, it is clearly noticed that the increment of AESO content from 50 wt% to 100 wt% results in higher water absorption levels. 100BIO samples have almost 10 times higher water absorption rates (95%) than the samples including 50 wt% or lower bio-content ($p = 0.003$). Supporting this, the visual results also show the degree of deformation of the samples with increasing bio-content.

On the other hand, the use of AESO up to 20 wt% proves the elimination of air gaps in the composite structure by enhancing the fiber-matrix interaction which results in the reduction of water absorption rates. It is known that the formation of voids is one of the most common production defects observed in composites. These voids let the composites absorb more moisture and become more sensitive to environmental conditions while reducing their mechanical strengths [32]. Mechanical strength test results also support the change in performance around 30BIO samples.

**Mechanical analyses**

**Charpy impact test**

Charpy impact resistance values of specimens are given in figure 2.

The impact resistance of AESO modified epoxy composites are higher than that of neat epoxy composite (0BIO) and gradually increased with the increment in bio-resin content from 10 wt% to 80 wt% due to the improvement in ductility. 80BIO composite has over 52 kJ m$^{-2}$ impact resistance which is almost ten times higher than 0BIO composite (5.5 kJ m$^{-2}$) ($p = 0.005$). On the other hand, by adding 10 wt% AESO to four plies jute fabric results in enhanced impact resistance in comparison to pure epoxy resins (5.67 kJ m$^{-2}$ [49]). This enhancement in ductility of the neat epoxy with the additional plant oil-based bio-resins is also stated in the literature [27, 29, 50].

For samples with a bio-resin ratio of more than 80 wt% show extremely ductile behavior related to over plasticization and impact test machine is not able to break them properly. Thus, these samples (90BIO and 100BIO) are not taken into consideration since the unpredictable friction effect between the pendulum and specimen changes the measured energy amount severely.

**Drop-weight impact test**

Visual inspection of damage patterns of the composite samples as a result of the drop-weight impact test is given in figure 3.

According to the results of the drop-weight impact test at 12 J; while there is a whole opening formed at 0BIO, 10BIO, 20BIO and 30BIO coded composite samples; partial opening is observed with the increased AESO content (40BIO and 50BIO). When the soybean oil ratio is 60 wt% or more, the damage behavior changes with the improving thermoplastic behavior which results in small and cross-shaped cracks without an opening occurred. Moreover, it is seen that these samples are recovered with their elastic structures after testing. It can be explained by the ductile structure of the AESO resin and the brittle structure of epoxy resin. The addition of a soft segment of AESO into the DGEBA epoxy resin reduces the bulky benzene group of the epoxy resin and improves the flexibility of the structure. Since AESO acts as a plasticizer in the epoxy blends, the ductility of the composites is improved which leads to enhancement of the ability of the composites absorbing impact [27]. In addition, the diameter of the resulting damage area tends to decrease as a result of improved toughness values.

The drop-weight impact strength test results of bio-composite materials are listed in table 5.

| Sample code | Fiber weight ratio (%) ± SD |
|-------------|-----------------------------|
| 0BIO        | 45.0 ± 0.5                  |
| 10BIO       | 43.6 ± 0.9                  |
| 20BIO       | 43.0 ± 0.7                  |
| 30BIO       | 43.7 ± 1.8                  |
| 40BIO       | 43.2 ± 0.6                  |
| 50BIO       | 38.0 ± 0.7                  |
| 60BIO       | 40.6 ± 2.4                  |
| 70BIO       | 40.0 ± 0.7                  |
| 80BIO       | 38.4 ± 1.2                  |
| 90BIO       | 37.4 ± 1.0                  |
| 100BIO      | 37.0 ± 0.7                  |

According to the results, it is clearly noticed that the increment of AESO content from 50 wt% to 100 wt% results in higher water absorption levels. 100BIO samples have almost 10 times higher water absorption rates (95%) than the samples including 50 wt% or lower bio-content ($p = 0.003$). Supporting this, the visual results also show the degree of deformation of the samples with increasing bio-content.

On the other hand, the use of AESO up to 20 wt% proves the elimination of air gaps in the composite structure by enhancing the fiber-matrix interaction which results in the reduction of water absorption rates. It is known that the formation of voids is one of the most common production defects observed in composites. These voids let the composites absorb more moisture and become more sensitive to environmental conditions while reducing their mechanical strengths [32]. Mechanical strength test results also support the change in performance around 30BIO samples.

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For samples with a bio-resin ratio of more than 80 wt% show extremely ductile behavior related to over plasticization and impact test machine is not able to break them properly. Thus, these samples (90BIO and 100BIO) are not taken into consideration since the unpredictable friction effect between the pendulum and specimen changes the measured energy amount severely.

**Drop-weight impact test**

Visual inspection of damage patterns of the composite samples as a result of the drop-weight impact test is given in figure 3.

According to the results of the drop-weight impact test at 12 J; while there is a whole opening formed at 0BIO, 10BIO, 20BIO and 30BIO coded composite samples; partial opening is observed with the increased AESO content (40BIO and 50BIO). When the soybean oil ratio is 60 wt% or more, the damage behavior changes with the improving thermoplastic behavior which results in small and cross-shaped cracks without an opening occurred. Moreover, it is seen that these samples are recovered with their elastic structures after testing. It can be explained by the ductile structure of the AESO resin and the brittle structure of epoxy resin. The addition of a soft segment of AESO into the DGEBA epoxy resin reduces the bulky benzene group of the epoxy resin and improves the flexibility of the structure. Since AESO acts as a plasticizer in the epoxy blends, the ductility of the composites is improved which leads to enhancement of the ability of the composites absorbing impact [27]. In addition, the diameter of the resulting damage area tends to decrease as a result of improved toughness values.

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Table 4. Water absorption rates for the composites and the images of samples after testing.

| Sample code | Water absorption rates (%) ± SD | Images of selected samples after water absorption test |
|-------------|---------------------------------|-------------------------------------------------------|
| 0BIO        | 12.01 ± 1.62                    |                                                       |
| 10BIO       | 9.43 ± 0.17                     |                                                       |
| 20BIO       | 6.19 ± 0.52                     |                                                       |
| 30BIO       | 10.25 ± 0.76                    |                                                       |
| 40BIO       | 16.97 ± 1.03                    |                                                       |
| 50BIO       | 10.81 ± 0.15                    |                                                       |
| 60BIO       | 27.39 ± 1.27                    |                                                       |
| 70BIO       | 31.60 ± 0.69                    |                                                       |
| 80BIO       | 38.28 ± 0.56                    |                                                       |
| 90BIO       | 91.72 ± 1.73                    |                                                       |
| 100BIO      | 94.93 ± 0.54                    |                                                       |
to a significant increase in absorbed energy (5.13 J; \( p = 0.002 \)) and results in a damage degree of nearly twice (0.43). Composites with a higher epoxy resin content exhibit lower displacement, while a higher AESO content absorbs more energy, thereby increasing the AESO resin within the epoxy resin, increasing the toughness of the composite material. It is possible to say that 100BIO has almost three times higher absorbed energy, damage degree, and maximum displacement values (7 J; 0.58 and 15.90 mm, respectively) than those of 0BIO samples (2.47 J; 0.21 and 5.87 mm, respectively).

**Tensile strength test**

Tensile test results are given in figures 4 and 5.
The results show that the addition of AESO to pure epoxy resin increases the tensile strength of composite to some extent (up to 30 wt% AESO content) (figure 4). In AESO modified epoxy composites, the –OH groups of lignocellulosic jute fibers observed around 3300 cm\(^{-1}\) absorbance band [50] forms hydrogen bonding with the –OH and –COO groups of the crosslinked bio-resins which improves the fiber-resin interface resulting in almost 40% increment \((p = 0.008)\) in tensile strength of 30BIO composites compared to 0BIO composites. Therefore, the reason for the maximum tensile strength (63 MPa) achieved at 30BIO composites can be explained with good packing and strong interfacial adhesion without debonding or delamination [27]. On the other hand, the addition of AESO content up to 50 wt% to the four plies jute fabric reinforced epoxy composite results in higher tensile strength values in comparison to pure epoxy [49].

The rapid tensile strength decrement of the 50BIO sample at both testing directions may result from the excess resin content as mentioned in the physical analysis (table 3). The tensile strength of composite materials which have above 50 wt% AESO content in the aliphatic epoxy matrix is decreased to the half because of the over plasticization caused by the higher content of flexible aliphatic long chains of AESO resin [27, 28].

Elongation at break values also support the tensile strength test results (figure 5). Elongation at break values decrease till the bio-resin content by up to 30 wt% (while tensile strength values increase), and then it begins to increase until it completely reaches the 100 wt% AESO resin content. This enhanced ductility results in a decrement in the tensile strength of the composites. A study conducted by Temmink et al. (2018) also proves this fact. In that study, AESO with 30 wt% styrene content composites manufactured by vacuum infusion technique has the lower tensile strength with higher elongation values than pure epoxy composites. The reason for this was
explained by higher flexibility of the AESO resin and incomplete curing of the AESO resin that results in free movement of polymer chains and thus higher elongation \[32\].

For all samples, the strength values at the warp direction are higher than the strength values of weft direction samples. The changing material characteristic with an increasing amount of bio-resin can be seen from the stress-strain curve of the selected samples (figure 6). Supporting the results of this study, the outcomes of the work of Temmink et al (2018) presents that, AESO has higher impact resistance than the epoxy samples, indicating that the bio-epoxy resin is more brittle. This data is also supported by the stress-strain curves of composites (figure 6). The pure epoxy content (0BIO) has the characteristic peaks of a brittle material while the 90BIO with its high AESO content has a specific ductile material curve \[32\].

Three-point bending test

Flexural strength test results are given in figure 7.

When the obtained results are examined, it is seen that the flexural strength of the samples taken from the 0° direction is quite higher compared to the samples taken from the 90° direction. In addition, it is evident that the flexural strengths of composite materials decrease at an increasing rate with the ascending bio-resin amount, especially above 30 wt% AESO content. The decrement in flexural strength from 30BIO to 40BIO (\(p = 0.015\)) and 40BIO to 50BIO (\(p = 0.015\)) is found statistically significant. This shows the increment in the ductility of the composite material with the increasing rate of bio-resin, in other words, over plasticization or the surplus.
ductility of the matrices that also cause a decrease in tensile strength of the composites [27]. In a study of Liu et al. (2019), the lowest flexural strength was achieved for pure AESO resin with the highest flexural strain, which was resulted from its low crosslinking density and long molecular chains of AESO [34]. Similar results were obtained within the scope of the study conducted by Wu and Li (2018). The data presented showed that the AESO additive ratio exceeding 50 wt% leads to a significant decrease in bending properties for composites as well as other mechanical properties [51]. The flexural strength of the composites including 0–40 wt% AESO content shows 200–540 MPa which is higher than the flexural strength of pure epoxy resin (118 MPa [49]) stated in the literature indicating the positive effect of introducing jute fabric as reinforcement material and the AESO resin up to a limit (40 wt%).

Instrumental analyses

**DSC analysis**

Differential scanning calorimetry analysis is performed to the 0BIO, 50BIO and 100BIO samples. The DSC plots of the samples are given in figure 8.

Endothermic reactions at about 50 °C are obtained from DSC curves of all samples, which are thought to be due to the moving away of impurities and moisture that included in jute fabric, at this temperature. The peak at 51.5 °C of 0BIO sample belongs to the T_g of epoxy resin system since the T_g of the epoxy resin used in this study is stated between 48–52 °C in the datasheet [47]. Although 50BIO sample has a 50% epoxy content, the T_g peak is not observed in the DSC curve. While the DSC curves of the 0BIO and 50BIO samples go stable up to 300 °C heating, it can be said that an exothermic reaction, i.e. degradation, starts at about 250 °C in the 100BIO sample. The degradation temperature of AESO is stated between 250 to 300 °C in the literature [52, 53].

**FTIR analysis**

The FTIR results applied to the resins (AESO and epoxy) and reinforcement material used in the project are given in figures 9–11.

Characteristic peaks of AESO resin are detected at around 2922, 2853, 1463, and 1455 cm⁻¹ corresponding to -CH₃ and -CH₂ stretching vibrations (figure 8). Moreover, −C=C−, −COOC, and −C−O−C− groups can also be observed from the peaks at about 1651, 1743, and 1098 cm⁻¹ indicating the unsaturated double bonds in the AESO resin [54].

The FTIR analysis illustrated in figure 10 demonstrates the characteristic peaks of the neat epoxy resin. The –OH stretching band is observed at 3445 cm⁻¹ while 2972 and 1383 cm⁻¹ peaks reveal –CH₃, 2870 and 1457 cm⁻¹ peaks indicate –CH₂ asymmetric and symmetric stretching bands.

The characteristic absorption peaks of epoxide groups and the ether bonds in the structure are shown at 915 and 1245 cm⁻¹ bands, respectively. Moreover, the aromatic rings in neat epoxy resin are assigned at 1607, 1511 and 829 cm⁻¹ [55].

A wide absorption band around 3300 cm⁻¹ belongs to −OH bond stretching is shown in figure 11. This bond enhances the fiber resin interface which results in improved strength as mentioned above. The characteristic peak of jute at 2900 cm⁻¹ indicates C–H stretching in methyl and methylene groups in the cellulose and hemicellulose. The C–O stretching in the glycosidic linkage of the cellulose is observed at 1042 cm⁻¹ band [56]. Moreover, some of the cellulose absorbance bands at 662, 895, 1423, and 2883 cm⁻¹ can be detected in figure 10 [50].
Figure 9. FTIR analysis of AESO resin.

Figure 10. FTIR analysis of epoxy resin.

Figure 11. FTIR analysis of jute fabric.
SEM analysis
The SEM images of 0BIO and 100BIO samples are represented in figure 12.

The difference in mechanical and physical properties of AESO-based and epoxy-based composites is also supported by SEM images. The noticeable difference in the mechanical and physical test results of AESO-based and epoxy-based composites is also supported by SEM images. When the images are examined, it is understood that the AESO resin has a gripping structure around the fiber in the composite material, while the epoxy resin has a sharper-lined interface with the fiber. The fluid structure of the AESO resin material observed in figure 12(c) coincides with the higher elongation and lower strength values of 100BIO sample, while the sharp/brittle epoxy matrix structure of figure 12(d) supports the lower elongation and higher strength values of the 0BIO compared to 100BIO sample (figures 4–6). Furthermore, the whole opening formed in 0BIO-30BIO samples; the partial opening observed at 40BIO and 50BIO samples and the small and cross-shaped cracks without an opening formed in samples with 60 wt% and over AESO ratio observed in the drop-weight impact test (figure 3) can also be supported by this phenomenon.

Conclusion
Considering the life cycles of environmentally friendly bio-composites, it is obvious that they will contribute to the national economy in the sense of solid waste management in the long term.
In this study, different amounts of AESO resin are blended to neat epoxy resin and reinforced with four-ply jute woven fabric to analyze the effect of bio-content on the physical (fiber/weight ratio), mechanical (tensile strength, flexural strength, drop-weight impact resistance and Charpy impact strength), instrumental (differential scanning calorimetry and Fourier-transform infrared spectroscopy) and morphological (scanning electron microscopy) properties of composites.

Results show that:

- The ascending amount of AESO content in the resin system leads to a lower fiber weight ratio regarding its high viscous structure.
- With the ascending AESO resin amount above 30 wt%, the tensile and flexural strength values decrease (whereas the elongation at break values increase) due to the enhanced ductility of the composites and over plasticization.
- Above 50 wt% AESO content, the bio-composites show superior impact properties. Besides the change in damage pattern of drop impact test samples, the diameter of the damaged area also tends to lessen owing to the improved toughness.
- The Tg value (51.5 °C) of epoxy resin and the degradation temperature (~250 °C) of AESO resin are observed from the DSC curves of composite samples.
- The characteristic peaks of –OH groups of jute fibers that form hydrogen bonding with the –OH and –COO groups of the bio-resins, which enhance the fiber-resin interface, are observed in FTIR analysis.
- The physical and mechanical test results showing the different characteristics of bio-resin and epoxy resin are also examined and supported morphologically with SEM analysis.

Considering both the reinforcing element and the matrix material, bio-composites are promising materials for a sustainable and eco-efficient product portfolio that can compete with markets dominated only by products based on petroleum raw materials. The automotive industry, the construction industry and sports equipment (snowboard, longboard, skateboard bodies, etc) can be the major potential usage areas of bio-composites.

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