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Composites Part B 183 (2020) 107722

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Investigating the effects of liquid-plasma treatment on tensile strength of coir fibers and interfacial fiber-matrix adhesion of composites

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ARTICLE INFO

Keywords:
Coir fiber
Liquid-plasma treatment
Interfacial shear strength
Sodium bicarbonate

ABSTRACT

The liquid-plasma treatment based on microwave plasma in the liquid was used to treat coir fiber in this study. The effects of such treatment on tensile properties of coir fiber and its compatibility with the epoxy matrix were investigated. Water and sodium bicarbonate ($NaHCO_3$) solution was used as a medium in this treatment. Tensile properties and interfacial shear strength (IFSS) between coir fiber and epoxy resin were determined with single fiber tensile and pull-out tests respectively. Fourier transform infrared spectroscopy, scanning electron microscope and X-ray diffraction were used to characterize the alteration of treated coir fibers. The results show that tensile strength of coir fibers slightly reduce after liquid-plasma treatment with both water and sodium bicarbonate medium except on 12 wt% sodium bicarbonate solution medium for 5 min exposure time. Meanwhile, the interfacial shear strength of coir fiber/epoxy matrix is obtained improvement after water and sodium bicarbonate medium treatment due to good interfacial adhesion between fiber and matrix which could be influenced by micropores on fiber surfaces leading to interlocking adhesion.

1. Introduction

Composites made from natural fibers have obtained more attention in various industrial applications [1]. They have more benefits for application in comparison with synthetic fiber composites such as inexpensive, safe to the environment, biodegradability, and low density [2–5]. Some natural fibers are used as reinforcement of composite such as ramie, jute, flax, coir fiber, etc. Coir fiber is extracted from husk of coconut. The tensile and modulus strengths of this fiber are relatively lower than other natural fibres, but has high strain to failure [6]. It has been developed for reinforcement of composite for more applications like automobil parts, packaging, insulation and construction [7]. However, natural fibers like coir fiber has a problem of weak interfacial bonding with synthetic polymers in the composite due to their hydrophilic behavior nature leading to incompatible with such polymers. The interfacial bonding between fiber and matrix have a significant role in the performance of the composites [8,9]. A number of effort have been performed to repair compatibility of natural fibers with a synthetic polymer including chemical and physical treatments [10].

Chemical treatments such as alkali and silane treatments have been used for surface treatments of natural fibers. These treatments can change the tensile properties of fibers and improve fiber-matrix adhesion in composite [9,11,12]. Although these treatments were effective to improve interfacial bonding between fiber and matrix, they have limitation due to ecological interest considering chemical disposal after treatment [13,14].

Plasma treatment is one of physical treatments which can used to replace chemical treatments. In composite material, such treatment is performed to modify chemical and physical structure of surface layer of natural fibers for improvement of fiber-matrix adhesion strength, without altering their bulk mechanical properties [15]. The tensile strength of single fibers after plasma treatment has positive, negative or unchanging effects depending on treatment condition [15,16]. Low and atmospheric pressure plasma treatments have been studied to evaluate their effects on tensile strength of fibers and interfacial bonding of fiber-matrix in composite. Low-pressure plasma treatment with argon and air [16] and oxygen [17] improved the interfacial adhesion of fiber-matrix due to improved surface roughness and new oxygen functional groups on the fiber surface occur [17]. Meanwhile, tensile strength of treated fibers did not change significantly in comparison with untreated fiber. For plasma treatment with atmospheric pressure plasma treatment with helium gas, the effect of this treatment on the

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https://doi.org/10.1016/j.compositesb.2019.107722
Received 12 July 2019; Received in revised form 9 December 2019; Accepted 16 December 2019
Available online 17 December 2019
1359-8368/

tensile strength of ramie fibers is not noticeable. However, the interfacial shear strength of ramie-polypropylene (PP) matrix raised compared to untreated fiber due to the enhancement of surface hydrophobicity on ramie fibers and mechanical adhesion occurs by plasma etching [18]. This result is similar to that reported by Li et al. [19] with atmospheric pressure DBD plasma. The tensile strength of flax fabric declines after atmospheric pressure plasma (argon and air) because of the cracks and grooves on the flax fiber surface, but this surface condition has benefits for enhancing interaction bonding between fiber and matrix (HDPE and polyester) due to mechanical interlocking [20]. All plasma treatments on natural fibers aforementioned are dry-plasma system.

In this paper, liquid-plasma system is introduced as an alternative technique for surface treatment of coir fibers for reinforcement composite. The advantages of liquid-plasma system are no need polymerizing and non-polymerizing gas to generate plasma and also has the potential for combine of plasma-chemical activity with selectivity of process in liquid [21]. This liquid-plasma treatment was stimulated by several types of research for modifying of cotton yarn [21] and bast fibers [22]. The liquid-plasma treatment with NaOH and water solutions of the bast fibers can reduce the content of lignin in the fibers. The combination of alkaline and plasma treatments get effective results to decline lignin in the fibers [22]. Underwater plasma has been used for polymer surface functionalization [23,24]. In liquid-plasma system, the discharge in aqueous solution can produce active species like electron (e^-_{aq}), radicals (H•, O•, •OH), ions (H^+, $•OH^-$) and molecules (H_2O_2, O_3 and H_2) [21,24,25]. These species may achieve the surface of substrate in the solution when the generation of bubble intensively take place. Besides that, UV radiation emitted from the plasma inside any liquid may support the polymer surface modification which may improve wetting behavior, adhesion and bondability [21,24].

In the present work, liquid-plasma treatment used was based on the microwave discharge in liquid where the discharge breakdown takes place in the bubble (gas phase) but does not in the water (liquid phase) [26,27]. Liquid-plasma treatment using water and sodium bicarbonate solution as a medium was used by exposing coir fibers in the reactor. The use of liquid-plasma treatment method has never been done before for the application of natural fiber treatment for composite reinforcement. Sodium bicarbonate solution is used as medium for liquid-plasma treatment because this solution is non-toxic [5,28,29] and also easy to generate plasma in the liquid.The effect of liquid-plasma treatment on the tensile strength of coir fibers and the interfacial shear strength of fiber-epoxy matrix was investigated by fiber tensile test and pull-out test respectively. The functional group, crystallinity index and surface morphology of coir fibers were characterized by FTIR, XRD and SEM respectively.

2. Materials and methods

2.1. Materials

The coir fibers used in this study were collected from Tawaeli – Palu area, Central Sulawesi, Indonesia. Such fibers were extracted from the husk of coconut by mechanical extraction and cleaned with water for removing the surface impurities. Sodium bicarbonate ($NaHCO_3$) (M = 84.01 g/mol) was supplied by Merck KGaA, 64271 Darmstadt Germany. Epoxy matrix used was Eposchon A (EPR174) resin and Eposchon B (Versamid 140) hardener.

2.2. Liquid-plasma treatment

A microwave oven (model Electrolux EMM2007X/EMM2006W/1250 W input power) was modified to generate plasma. The scheme of experimental set up of liquid plasma can be seen in Fig. 1. Modified microwave oven was set up with 600 W of magnetron output. The pressure in the reactor was set up ~ 20 kPa and maintained to the end process. In this study, liquid-plasma system was used to treat the coir fibers using water and sodium bicarbonate ($NaHCO_3$) solution medium. Raw coir fibers were exposed in the liquid-plasma with water medium for 3, 4, 5, and 6 min, and in the liquid-plasma with the difference of sodium bicarbonate densities by 8 wt%, 10 wt% and 12 wt% for 3 and 5 min. Parameters of liquid-plasma treatment can be seen in Table 1. After liquid-plasma treatment with water medium, fibers were dried directly for 24 h in room temperature. Meanwhile liquid-plasma treatment with sodium bicarbonate solution medium, fibers were washed with distillated water and dried in room temperature for 24 h. Both treated fibers were followed by drying in an oven at 110 °C for 1 h.

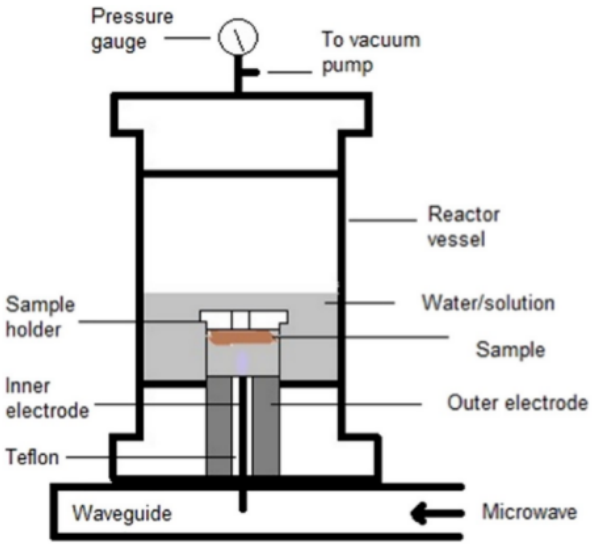

Fig. 1. Scheme of experimental set up.

2.3. Tensile test

The tensile test of single coir fibers was performed according to ASTM 3379 using Universal Testing Machine – Llyod LR10K Plus with load capacity of 10 kN. The twenty specimens were tensile tested and then the mean values and standar deviations were calculated. All the tensile test was conducted with 30 mm gauge length of sample and 2.5 mm/min strain rate. The coir fiber diameter was measured by an optical microscope at five different locations along the fiber for determining the cross-sectional area of each fiber. The cross sectional area was assumed as a circular cross section. The formula for calculating of the tensile strength of coir fibers is as follow [30,31].

$$T = \frac{F}{A} \quad (2)$$

where T is tensile strength (MPa), F is a maximum force of tensile (N)

Table 1
Parameters of liquid-plasma treatment.

Plasma	Liquid medium	Sample	Exposure time (min.)
Microwave plasma	Water	P-3	3
		P-4	4
		P-5	5
		P-6	6
	8% $NaHCO_3$	P8	3
			5
	10% $NaHCO_3$	P10	3
			5
	12% $NaHCO_3$	P12	3
			5

and A is cross-sectional area (mm^2).

2.4. Fourier transform infrared spectroscopy (FTIR)

FTIR measurement of raw and treated coir fibers was carried out with using IRPrestige-21 FTIR-8400S SHIMADZU. Coir fiber powder and KBR reagent (KBr: coir fiber powder = 10:1) were pressed into a disc using hand press machine. The formed sample was fixed on the sample holder. All spectra of samples were recorded with the resolution in 2 cm^{-1} and in the range 4000 cm^{-1} to 500 cm^{-1} regions.

2.5. X-ray diffraction (XRD)

An XRD 6000 X-Ray Diffraction SHIMADZU type X-ray powder diffraction was used to analyse the crystallinity index of raw and treated of coir fibers. The X-ray tube is the copper (Cu) type and generates at a voltage of 40 kV and a current of 30 mA. The samples were scanned in the range from 10° to 40° of 2θ (Bragg angle) with a step rate 0.02° and a scanning speed of 2°/min. The formulation of crystallinity index based on the Segal method is as the following equation [32].

$$CI\ (\%) = \ (I_{002} - I_{am}) / I_{002} \quad (1)$$

where I_{002} is the maximum intensity of diffraction peak at a 2θ about 22° related to crystalline material and I_{am} is the minimum intensity of diffraction peak at a 2θ about 18° related to amorphous material in cellulose fibers.

2.6. Fiber pull-out test

Interfacial shear strength (IFSS) of coir fiber – matrix was determined by using pull-out test. The resin/hardener ratio used is 2:1. Samples of pull-out test were moulded by using a metal mould with the end coir fiber bonded on the ruler. After mould was poured resin/hardener, it was then the curing process in room temperature (about 29 °C) during 24 h. Samples then were released from mould and drilled through the coir fiber and matrix at distance from the entrance point of the fiber (Fig. 2). The embedded length of coir fibers in the matrix was used in this paper is 1.0 mm (l_e = 1.0 mm). A single coir fiber pull-out test was carried out by Universal Testing Machine – Llyod L10K Plus with speed rate 2.5 mm/min. The gauge length of fiber samples was 15 mm.

Interfacial shear strength (IFSS) was calculated as the following equation [33].

$$\tau = \frac{F_{max}}{\pi d l_e} \quad (3)$$

Where F_{max} is the maximum of force, d is the coir fiber diameter and l_e is the embedded length of fiber in the epoxy matrix.

2.7. Scanning electron microscope (SEM)

Scanning electron microscope (SEM) was carried out to analyse the change in surface morphology upon liquid-plasma treatment of coir fibers. SEM – JEOL JSM 6510 LA was used to characterize the surface morphology of coir fibers. The samples were secured to a carbon tab on an aluminium stub and gold coated to make them conductive before SEM characterization.

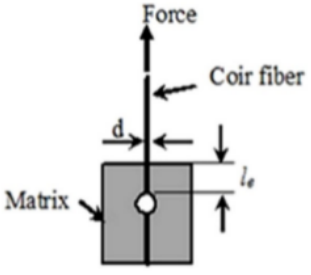

Fig. 2. Sample of single fiber pull out.

3. Results and discussion

3.1. Tensile strength of single coir fibers

The average tensile strengths of single coir fibers after liquid-plasma treatment with water and sodium bicarbonate solution medium can be seen in Fig. 3. The tensile strength of raw coir fiber has been published by authors previously [34]. The value of its strength is 142.39 ± 6.94 MPa. In Fig. 3a, the tensile strength of single fiber is obtained a slightly decrease after liquid-plasma treatment with water medium for different exposure time (3, 4, 5, and 6 min). The decrease in the tensile strength is approximately ranged 1% to 18%. Among the highest tensile strength of coir fiber after liquid-plasma treatment with water medium is P-3 sample (141.70 ± 11,20 MPa) for 3 min exposure time followed by P-5 (126.29 ± 8.96 MPa), P-6 (121.22 ± 7.59 MPa) and P-4 samples (116.07 ± 4.91 MPa).

For liquid-plasma treatment with sodium bicarbonate solution medium, the densities of sodium bicarbonate and exposure time parameters are used to describe the relationship with the tensile strength of coir fiber. In Fig. 3b, the tensile strengths of coir fiber decrease after liquid-plasma treatment with the densities of 8 wt% (P8) and 10 wt% (P10) for 3 and 5 min periods and also 12 wt% (P12) for 3 min. The decrease in the tensile strength is approximately ranged 3% to 18%. P8 sample with exposure time of 3 min (117.08 ± 6.24 MPa) has lower tensile strength than other treated coir fibers. This decrease take place due to removal of lignin which might weakens chemical bond and may be also reorientation of cellulose did not completely occur in the fiber [35]. Meanwhile, the tensile strength of P12 sample (148.05 ± 10.54 MPa) for 5 min exposure time increases moderately when compared to raw coir fiber. This increase occurs due to microfibril cellulose in secondary wall of fiber may begin regularly formed which is unidirectional with fiber axis when applied load [36].

3.2. Tensile modulus of single coir fibers

The average tensile modulus of single coir fibers after liquid-plasma treatment with water and sodium bicarbonate solution medium can be seen in Fig. 4. Tensile modulus of raw coir fibers is 2.18 ± 0.18 GPa. This modulus value is similar to previously study [37], but it is lower than the value obtained from the more studies [6,9,38]. In Fig. 4a, the tensile modulus of coir fibers increases slightly in liquid-plasma treatment with water medium for 3 and 5 min exposure time (P-3 and P-5 samples) i.e. 2.30 ± 0.30 GPa (5.5%) and 2.23 ± 0.30 GPa (2.3%) respectively with compared to raw coir fiber. Both P-4 (2.05 ± 0.26 GPa) and P-6 (2.03 ± 0.22 GPa) samples have lower tensile modulus than raw coir fiber. Then, the effect of liquid-plasma treatment with sodium bicarbonate medium of coir fibers on tensile modulus is shown in Fig. 4b. The tensile modulus of P8 for 3 min (2.14 ± 0.25 GPa) and for 5 min (2.08 ± 0.18 GPa) declines moderately compared to raw fiber sample. Meanwhile, the tensile modulus of P10 and P12 for 3 and 5 min showed an increase when compared to raw fiber. The highest tensile modulus of coir fibers takes place at P12 (2.80 ± 0.26 GPa) for 5 min exposure time. The increase in tensile modulus P12 for 5 min is approximately 28% in comparison with raw coir fibers. These improvements may occur due to the removal of a part lignin, hemicellulose, and impurities in coir fiber [9, 30].

3.3. FTIR analysis

The effect of liquid-plasma treatment with water and sodium

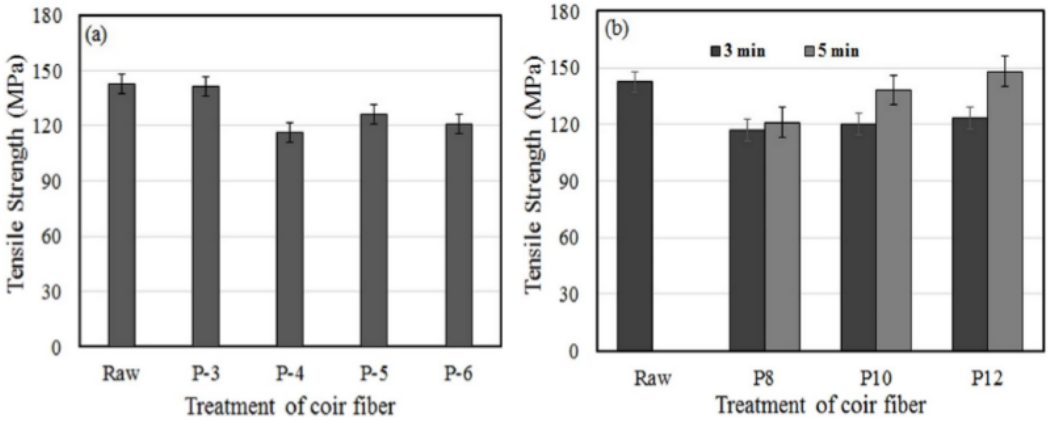

Fig. 3. Tensile strength of coir fibre with liquid plasma treatment with (a) water and (b) sodium bicarbonate solution medium.

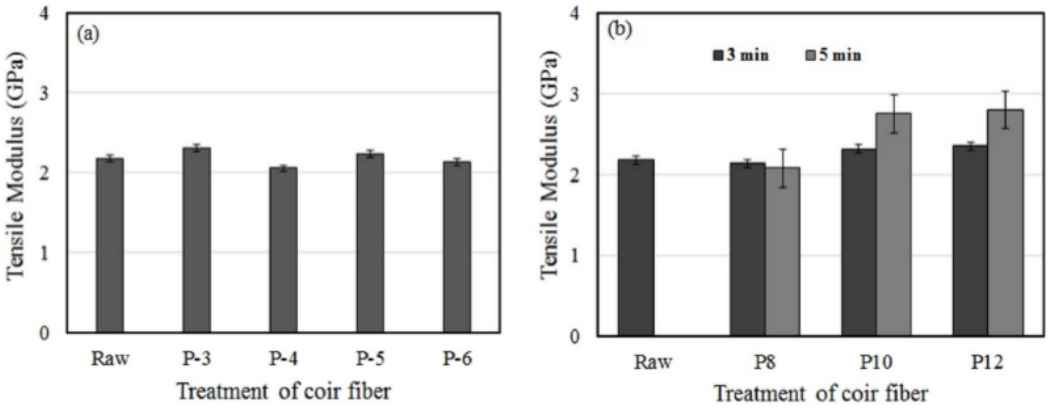

Fig. 4. Tensile modulus of coir fiber with liquid plasma treatment with water and sodium bicarbonate solution medium.

bicarbonate solution medium could lead to change in functional group and deteriorate of the surface of coir fibers. This may caused by the reaction of generated active species like electron (e^-_{aq}), radicals (H•, O•, •OH), ions (H^+, $•OH^-$) and molecules (H_2O_2, O_3 and H_2) in the solution [21,24,25]. These active species and radicals may penetrate to the surface of coir fibers. These effects can be characterized by Fourier transform infrared spectroscopy (FTIR).

The FTIR spectra of raw and plasma treatment in liquid (for water and sodium bicarbonate medium) coir fibers are shown in Fig. 5 and Fig. 6. The peak range from 3200 to 3600 cm^{-1} suggests a strong band from cellulose, hemicellulose and lignin of coir fibers [39]. Raw and treated coir fibers show a strong band at ~3442 cm^{-1} corresponds to OH-stretching vibration of cellulosic structure [33,38,39]. In liquid-plasma treatment with water medium, the change in ~3442 cm^{-1} peak takes place indicating participation of active species like OH radical which may interact to coir fiber surfaces. This peak is also changed after liquid-plasma treatment with sodium bicarbonate medium. For 2912 cm^{-1} peak of raw coir fiber as described by authors previously, it relates to C–H stretching vibration from $–CH_2$ group of cellulose and hemicellulose [9,34,40]. The peak at about 2350 cm^{-1} appears after treatment. This peak could not be recognized with any molecule origin [41] and also was not explained by Mir et al. [39]. But, according to Mandu et al. [42] this peak related to existing of wax which exhibits C═C stretching. The peak at 1743 cm^{-1} corresponds to carbonyl (C═O) stretching in coir fiber which is a characteristic group of hemicellulose [40,43].

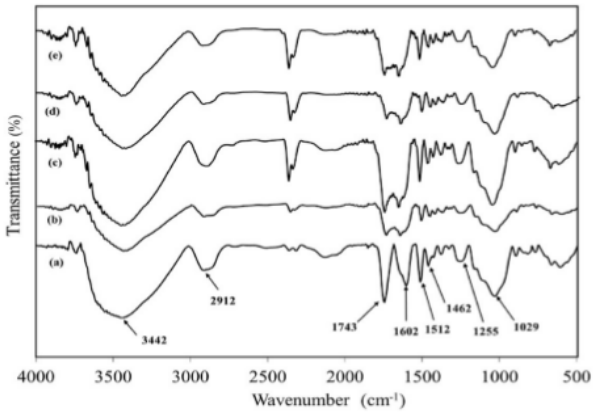

Fig. 5. FTIR spectra of coir fibres (a) Raw, plasma treatment in liquid with water medium (b) P-3, (c) P- 4, (d) P-5 and (e) P-6.

The 1602 cm^{-1} and 1512 cm^{-1} peaks of raw coir fiber are associated with C═C aromatic stretching vibration due to lignin [34,39,40,44]. After liquid-plasma treatment with water and sodium bicarbonate medium, these peaks tend to shift which indicate the removal of lignin in the fiber surfaces. This is supported by Titova et al. [22] that the

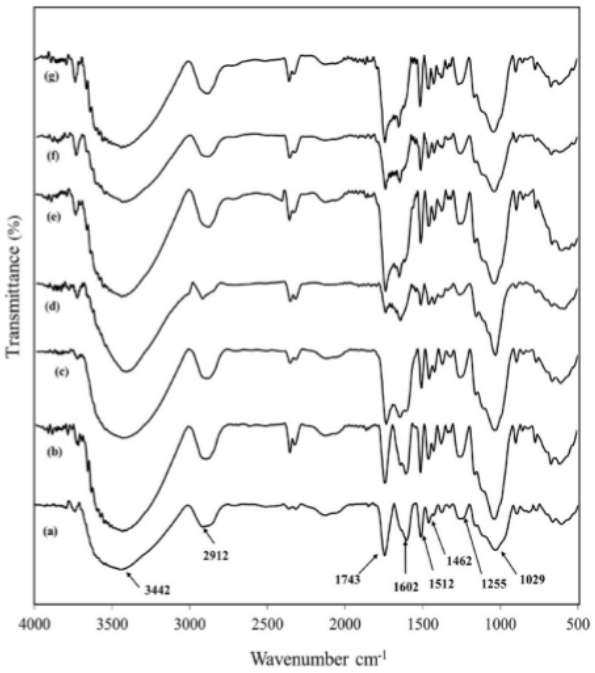

Fig. 6. FTIR spectra of coir fibres (a) Raw, plasma treatment in liquid with sodium bicarbonate medium (b) P8, (c) P10, (d) P12 for 3 min and e) P8, (f) P10, (g) P12 for 5 min.

reduction of lignin content in the bast fibers took place after plasma-solution treatment with water and NaOH solution medium.

3.4. X-ray diffraction analysis

X-ray diffraction (XRD) is utilized to analyse the crystallinity index (CI) of natural cellulose fibers. CI parameter is used to explain the crystalline material content in cellulose. The value of CI of coir fiber has been evaluated by several researchers which have different results ranging from 25.7% to 62.4% [45–49]. The CI of raw coir fiber in this study was published by authors previously [34]. The CI of raw and treated coir fibers are displayed in Fig. 7a and b. The CIs of coir fiber before and after liquid-plasma treatment with water medium from the highest are raw (35.02%) > P-3 (34.91%) > P-5 (34.65%) > P-6 (34.30%) > P-4 (33.77%). Then, after liquid-plasma treatment with sodium bicarbonate medium from the highest are raw (35.02%) > P12 (34.60%) > P10 (34.45%) > P8 (33.67%) for 3 min and P12 (37.43%) > raw (35.02%) > P10 (34.96%) > P8 (28.78%) for 5 min. The increase of CI occurs only in P12 for 5 min compared to raw coir fiber owing to the removal of a part lignin and other impurities in fiber so that microfibril cellulose crystalline may be formed with better packing of cellulose chain. However, the CIs of fibers after plasma treatment both water and sodium bicarbonate medium slightly reduce except P12 for 5 min compared to raw coir fiber. This case could be caused by damage occur in fiber cell wall which influences crystalline structure due to penetration of OH radical and other active species in the fiber. Some reasons of CI in natural fibers after treatment decreased are due to degradation of cellulose chain occurred [45], a part of crystalline cellulose dissolved when treatment process [50] and due to the increase of amorphous portion in the cellulose [51,52].

From the CI results of coir fiber after liquid-plasma treatment showed the existing corresponds to tensile strength of fiber. The CI enhances, the tensile strength of fiber also enhances or vice versa. Meanwhile the CI decreases, the tensile strength of fiber decreases.

3.5. Interfacial shear strength of coir fiber-epoxy matrix

The interfacial bonding of fiber-matrix can be determined with interfacial shear strength (IFSS) through pull-out test. The interfacial shear strength (IFSS) of coir fiber and epoxy resin is analysed to understand the effect of liquid-plasma treatment of both water and sodium bicarbonate solution medium. IFSS of raw and liquid-plasma treatment of coir fibers are shown in Fig. 8a and b. The IFSS of raw coir fiber is 2.82 ± 0.23 MPa. Liquid-plasma treatment with water medium of coir fiber by different exposure time in the reactor is used to describe its relation to the interfacial shear strength of coir fiber and epoxy resin. The IFSS increases significantly for all samples of liquid-plasma treatment with water medium over the raw coir fiber. Sample of P-3 (4.74 ± 0.28 MPa) for 3 min exposure time has a higher interfacial shear strength than other treated samples (P-5 (4.50 ± 0.36 MPa), P-6 (4.03 ± 0.19 MPa) and P-4 (4.01 ± 0.29 MPa)). The IFSS of P-3, P-5, P-6 and P-4 samples show an increase about 68%, 60%, 43% and 42% respectively of in comparison with raw coir fiber. The highest interfacial shear strength of P-3 sample take place due to mechanical interlocking formation between fiber and matrix which might be caused by the removal of lignin and other impurities so that better adhesion between fiber and matrix. Then, liquid-plasma treatment with sodium bicarbonate medium also significantly influences the interfacial shear strength between coir fiber and epoxy. Both densities of sodium bicarbonate (8 wt%, 10 wt % and 12 wt %) and exposure time (3 and 5 min) parameters give an

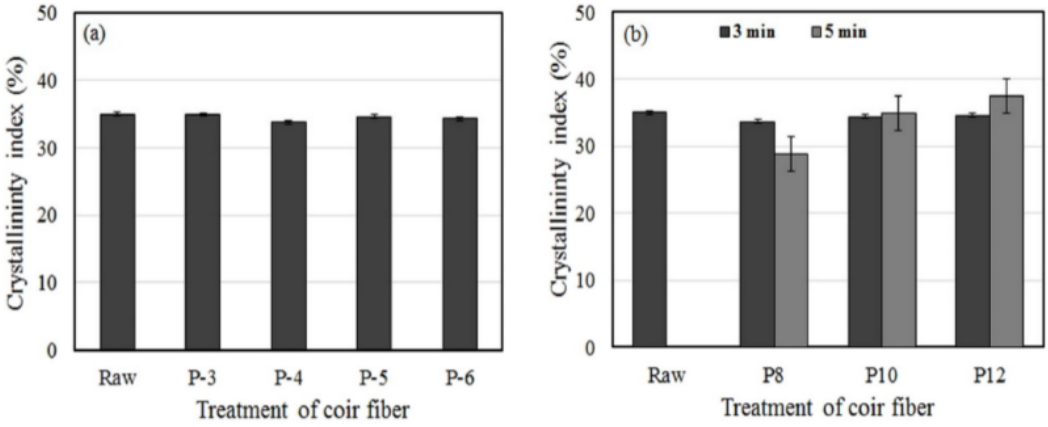

Fig. 7. Crystallinity index of coir fibre with liquid-plasma treatment with (a) water and (b) sodium bicarbonate solution medium.

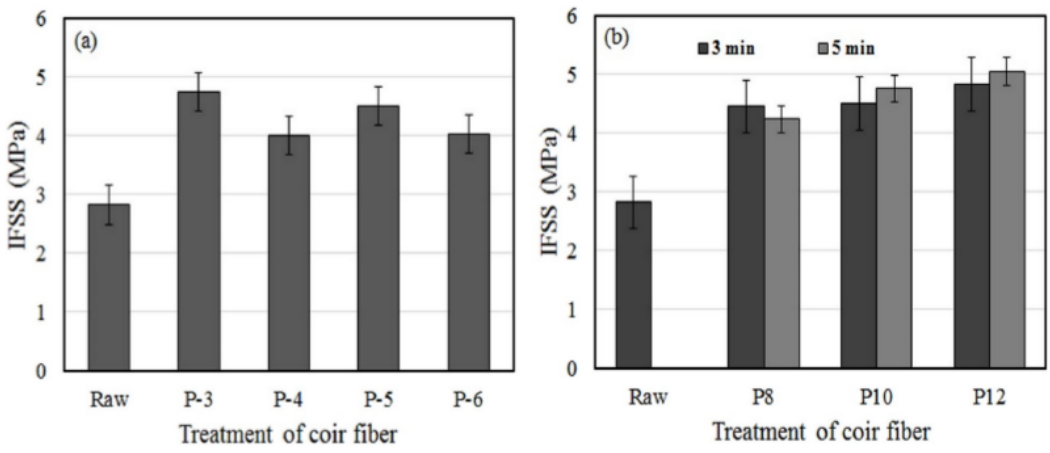

Fig. 8. Interfacial shear strength of coir fibre-epoxy matrix with liquid plasma treatment with (a) water and (b) sodium bicarbonate solution medium.

alteration in interfacial adhesion of coir fiber-epoxy matrix. After plasma treatment with sodium bicarbonate medium, the IFSS increases with increasing the sodium bicarbonate densities. For 3 min exposure time, the IFSS of P8, P10 and P12 samples are 4.58 ± 0.32 MPa, 4.65 ± 0.28 MPa and 4.84 ± 0.28 MPa respectively. The increase in IFSS of P8, P10 and P12 for 3 min exposure time compared to raw coir fiber reaches 62%, 65% and 72% respectively. Meanwhile, for 5 min exposure time, the IFSS of P8, P10 and P12 samples are 4.23 ± 0.29 MPa, 4.75 ± 0.34 MPa and 5.04 ± 0.35 MPa respectively. If compared to raw coir fiber, the IFSS of P8, P10 and P12 samples for 5 min increases 50%, 68% and 79% respectively. The IFSS of P12 sample for 5 min is higher than other treated coir fibers and raw coir fiber. The improvement of interfacial adhesion is possibly due to a cleaner surface and a formation of micropores on the surface of coir fibers as shown in the SEM analysis because of partial removal of lignin and other impurities leading to better adhesion between fiber and matrix, resulting in more mechanical interlocking and may also occur chemical adhesion on the coir fiber surface. According to Bozaci et al. [20], the increasing of IFSS between fiber and matrix after plasma treatment occurred due to the surface roughness of fiber leading to better mechanical interlocking and improvement oxygen ratio to carbon in fiber surface which may facilitate bonding formation between fiber and matrix.

As can been seen that existing of sodium bicarbonate solution as a medium liquid-plasma treatment has an important role for improvement of interfacial bonding of coir fibers and epoxy matrix because it can enhance the interfacial shear strength about 79% from raw coir fiber. Also, water medium is also potentially used in liquid-plasma treatment because it can improve interfacial shear strength approximately 68% even if it is lower than 12 wt% sodium bicarbonate solution medium. These results indicate that plasma-liquid treatment for coir fibers can improve interface adhesion between the fiber and the matrix and only requires a relatively short time compared to the chemical treatment [5,9,28] as well as without use the polymerizing and non-polymerizing gas to generate plasma [20].

3.6. SEM analysis

One of ways to determine the influence of liquid-plasma treatment of coir fiber is to analyse the morphology of fiber surface before and after treatment utilizing scanning electron microscope (SEM). In Fig. 9 and Fig. 10, SEM images display that the morphological coir fibers change after liquid-plasma treatment both water and sodium bicarbonate medium. The morphology of raw coir fiber has more impurities on the surface of fiber (Fig. 9a). The raw coir fiber image of SEM has been published by authors [34]. After liquid-plasma treatment with water

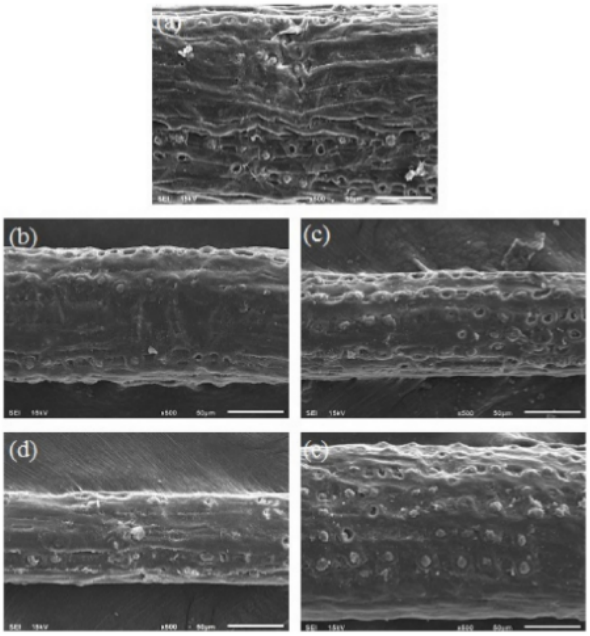

Fig. 9. SEM image coir fibers (a) Raw [32], plasma treatment in liquid with water medium (b) P-3, (c) P- 4, (d) P-5 and (e) P-6.

medium of coir fiber in Fig. 9b–e, the fiber surfaces seem relatively cleaner with micropores appear. More micropores appear in Fig. 9c and e. This case is similar to images which were displayed in Fig.s. 10b–f after liquid-plasma treatment with sodium bicarbonate solution of coir fiber where fiber surfaces display also more micropores and relative clear except in Fig. 10a still seems no clean. Micropores or holes on the surface of fiber after treatment may reduce tensile strength of coir fibers. However, these would possibly improve the interfacial bonding between fiber and matrix in the composite as a result of mechanical interlocking occur [9,33]. This prediction is suitable results of interfacial shear strength of coir fiber-matrix after liquid-plasma treatment with both water and sodium bicarbonate solution medium.

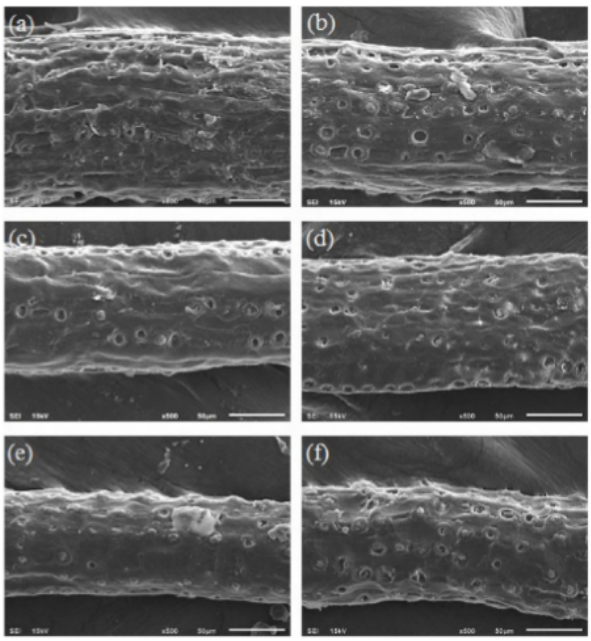

Fig. 10. SEM images of coir fibers with liquid-plasma treatment with sodium bicarbonate medium (a) P8, (b) P10, (c) P12 for 3 min and d) P8, (e) P10, (f) P12 for 5 min.

4. Conclusions

Liquid-plasma treatment with both water and sodium bicarbonate solution medium of coir fibers has an influence in improvement on interfacial adhesion of coir fiber and matrix in comparison with raw coir fiber. The change of coir fiber surface after liquid-plasma treatment takes place with shifting functional groups by FTIR identification and reducing or enhancing of crystallinity index by XRD analysis. These changes are also supported by SEM images which display a cleaner and micropores on the coir fiber surfaces which may affect the tensile strength and the interfacial shear strength of coir fiber and epoxy matrix. Tensile strength of coir fibers is a slightly decrease after liquid-plasma treatment for both water and sodium bicarbonate medium except on 12 wt% sodium bicarbonate solution medium for 5 min exposure time. This could be induced by delignification which leads to the weakening of fibers, while it is expected to have role for improvement in performance of adhesion compatibility between fiber and matrix. In practice, the interfacial shear strength of coir fiber-epoxy matrix increased after liquid-plasma treatment with both water and sodium bicarbonate solution medium due to mechanical interlocking and may take place chemical adhesion in this adhesion. Based on this result, the liquid-plasma treatment can be an alternative treatment for surface modification of natural fibers as reinforcement in composite.

Acknowledgments

The authors would like to thank the Ministry of Research, Technology and Higher Education for financial support on this research work. We also acknowledge to the SEM Laboratory, Faculty of Mathematics and Sciences The Bandung Institute of Technology, Research and Science Development Laboratory, Faculty of Mathematics and Sciences Hasanuddin University, and Material Laboratory, Academy of Industrial Engineering Makassar.

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