Effect of fiber length on the mechanical properties and water absorption of bamboo fiber/polystyrene-modified unsaturated polyester composites

S Sugiman¹, P D Setyawan¹, B Anshari²
¹Department of Mechanical Engineering, Faculty of Engineering, University of Mataram, Jl. Majapahit 62 Mataram, 83125 Indonesia
²Department of Civil Engineering, Faculty of Engineering, University of Mataram, Mataram, Jl. Majapahit 62 Mataram, 83125 Indonesia

E-mail: s.sugiman@unram.ac.id

Abstract. The paper presents the effect of fiber length on the mechanical properties and water absorption of bamboo fiber/polystyrene-modified unsaturated polyester composites. The fiber length varied from 2.5 mm to 15 mm at the fiber volume fraction of 0.2, 0.25 and 0.3. For water absorption, the specimens were immersed in distilled water at temperature of 40°C. The results showed that for all volume fractions, the tensile, flexural, and the impact properties tended to increase with the increase of fiber length; however, there was an optimum fiber length for the tensile and flexural properties. The water uptake increased with the increase of both fiber length and volume fraction. In wet condition, for all volume fractions, the flexural properties degraded, whereas, the impact strength did not indicate degradation, even; it significantly increased for all fiber lengths.

1. Introduction
In the recent years, bamboo fiber has been increasingly used for manufacturing green composites as bamboo is abundantly available, and the most importance is that bamboo fiber has high mechanical properties [1]. Among the bamboo species, a Gigantochloa apus strives in Indonesia, and is potential to be used as reinforcement of polymer for biodegradable composites. Unsaturated polyester resin (UPR) is low price and has high mechanical properties [2]. This thermosetting polymer combined with glass fiber has been used for manufacturing boats. Furthermore, UPR has low water absorption [3], which can function as water barrier for natural fiber composites exposed in humid environments.

Expandable polystyrene (EPS) or styrofoam is post-consumer product and can be considered as a plastic waste. This waste is non biodegradable and can stand for 500 years [4]. So this pollutes water, landfill and dangerous for life. In the previous research [5], styrofoam waste had been used for modifying UPR. Adding small amount of polystyrene did not affect the mechanical properties of UPR. This paper investigated the use of polystyrene-modified UPR for manufacturing natural fiber composites with bamboo fiber as the reinforcement. The effect of bamboo fiber length at various fiber contents on the tensile, flexural, and the impact properties as well as the water absorption was investigated.
2. Experimental methods

2.1. Materials
Unsaturated polyester resin was obtained from Eternal (Taiwan). Methyl ethyl ketone was used as hardener. Styrofoam was obtained from electronic packaging waste. Bamboo fibers were mechanically extracted from *Gigantochloa apus* species that strives in Lombok island.

![Figure 1. Graphical flow chart of the experimental procedure.](image)

2.2. Manufacturing of composites specimen
Bamboo fibers were cut to obtain fiber length (FL) of 2.5, 5, 10, and 15 mm. The diameter of bamboo fiber was in the range of 0.2 - 0.46 mm. Bamboo fibers were treated using alkali (NaOH) solution at a concentration of 8% for 2 hours [6]. After treatment, the bamboo fibers were rinsed many times using tap water to remove the alkali. After rinsing, the bamboo fibers were dried under the sun for couple of days and then were transferred into an oven for final drying. The oven drying process was carried out at a temperature of 80°C for 24 hours. The dried bamboo fibers were then kept in a sealed plastic bag.

The styrofoam was ground using a blender to obtain a particle size about 1 mm. The UPR and styrofoam particles were mixed, and then subsequently stirred using hand mixer until all styrofoam particles were dissolved. The styrofoam content was 2% (by weight) [5, 6].

Figure 1 shows the graphical flow chart of the bamboo composites manufacturing and testing. Bamboo fibers were laid up randomly on the steel female mould after having covered with PVC sheet film. The volume fraction (VF) of bamboo fiber was 0.2, 0.25, and 0.3. The modified UPR was mixed with hardener, with resin to hardener ratio of 100:1 (by weight). After mixing, the modified UPR was poured into the mould and waited for several minutes to allow the resin to flow. A PVC sheet film was used to cover the top of lay up before being covered with the male mould. Two spacers with thickness of 3.8 mm were inserted between the female and male moulds to maintain the specimen thickness. The layup was pressed and left under pressure, at least for 6 hours to cure.

After the composite was cured, the mould was opened and the bamboo fiber/modified UPR was released from the mould. The composite then was cut to obtain the tensile, flexural and the impact
specimens according to ASTM D3039 [7], ASTM D790 [8] and ASTM D256 [9], respectively. The tensile and flexural testing were conducted using a Tensilon universal testing machine with displacement rate of 2 mm/min for both. For the impact test, an Izod testing machine was used. The specimen dimensions are shown in figure 2.

![Specimen dimensions for tensile, flexural, and Izod impact tests.](image)

**Figure 2.** The specimen dimension of (a) tensile, (b) flexural, (c) Izod impact tests.

### 2.3. Water absorption studies

Water absorption study used specimens with dimension of $(60 \times 30 \times 3.8)$ mm$^3$, in triplicate. The specimens were immersed in distilled water at temperature of 40°C. The specimens were periodically taken from the immersion and weighed using a Kenko microbalance. Before weighing, the specimens were wiped out using a tissue to remove water on the surface of the specimens. The absorbed water ($M_t$) was calculated using equation (1),

$$ M_t = \frac{(W_t - W_o)}{W_o} \times 100\% $$

where $W_t$ and $W_o$ are respectively the weight at time $t$ and at the initial. The water uptake data were plotted against square root of time. Fickian diffusion model (equation (2)) was fitted into the experimental water uptake data. The diffusion rate ($D$) was determined experimentally using the slope of the linear part of water uptake vs. square root of time, according to equation (3) [10].

$$ \frac{M_t}{M_\infty} = 1 - 8 \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2 \pi^2} \exp \left[ \frac{-(2n+1)^2 \pi^2}{d^2} Dt \right] $$

$$ \frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[ -\frac{(2n+1)^2 \pi^2}{d^2} Dt \right] $$. 

$$ \frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[ -\frac{(2n+1)^2 \pi^2}{d^2} Dt \right] $$

$\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[ \frac{-(2n+1)^2 \pi^2}{d^2} Dt \right] $
where \( t \) is the immersion time, \( d \) is the specimen thickness, \( m \) is the slope of the linear part of water uptake vs. square root of time curve, \( M_\infty \) is the water uptake at equilibrium.

After the saturation was reached and after the specimen was weighed, the specimens were cut to obtain the flexural and impact specimens. The flexural and impact testing were conducted immediately after cutting to avoid water desorbed from the specimen. This was intended to obtain the flexural and impact properties in wet condition. Three replications were used in this study.

3. Results and discussion

3.1. Tensile properties

Figure 3 shows the typical tensile stress-strain curves, the tensile strength and the elastic modulus of bamboo fiber/modified UPR composites with fiber length at various fiber volume fractions. It is seen in figure 3(a, b) that the initial stress-strain curves were dominated by the linear curve (elastic portion) and close to the peak load the curves deviated to be nonlinear, which was caused by the damage process. It is observed in figure 3(c, d) that for all volume fractions, the tensile strength and the flexural modulus increased with the increase of fiber length up to 10 mm and then tended to decrease afterward. For example, compared to the fiber length of 2.5 mm, the tensile strength at the fiber length of 10 mm and at the volume fraction of 0.25 increased by 37%. For all the volume fractions, the highest tensile strength was obtained at the volume fraction of 0.25 (except at the fiber length of 2.5 mm), whereas the lowest tensile strength was obtained at the volume fraction of 0.3. At the fiber length of 10 mm, the tensile strength at the volume fraction of 0.25 was about 12% and 6.5% higher than those at the volume fractions of 0.3 and 0.2, respectively.

![Figure 3](image-url)

**Figure 3.** (a, b) Typical tensile stress-strain curve at various fiber lengths and volume fractions, (c) Tensile strength and (d) Elastic modulus of bamboo fiber/modified UPR composites.
Generally, a long fiber length enables to transfer load easily, so that the tensile strength is high. However, for randomly oriented fibers, the fiber could transfer the load effectively when the fiber direction is parallel to the applied load [11]. Furthermore, for randomly oriented fiber, the longer fiber contributed to more voids. This is expected as the density of the composite tended to decrease with the increase of fiber length. For example, at the volume fraction of 0.2, the density of bamboo fiber/modified UPR composites at the fiber lengths of 2.5 and 15 mm was 1.224 g/cm³ and 1.168 g/cm³, respectively. Meanwhile, the low tensile properties for higher volume fraction (i.e. volume fraction of 0.3) could be caused by the lack of matrix for bonding the bamboo fibers and more voids content. Figure 4 show the images of fibers in the composite at the different volume fraction. It is seen that qualitatively, the increase of volume fraction (the same fiber length) tended to increase the spaces between fibers, so it tended creating more voids.

![Image of fibers in composite](image1.png)

**Figure 4.** The image of fibers in the bamboo fiber/modified UPR composites at the fiber lengths of 10 mm, at the volume fractions of (a) 0.2, (b) 0.25, and (c) 0.3.

![Image of tensile fracture](image2.png)

**Figure 5.** The photograph of tensile fracture of the composite at fiber length of 10 mm, at the volume fractions of (a) 0.25 and (b) 0.3.

Figure 5 shows the images of tensile fracture specimens at the fiber length of 10 mm and at different volume fraction. It is observed that at low volume fraction (0.25), the fiber tended to break, indicating high interfacial strength between the fiber and the matrix. Meanwhile at the volume fraction of 0.3, some fibers tended to be pulled out and some fibers were broken. The former indicated that some fibers could not bond well with the matrix due to lack of matrix, while the latter have good bonding. As the tensile strength and the elastic modulus tended to decrease at the volume fraction of 0.3 and at the fiber length beyond 10 mm, more voids and lack of matrix were considered to be the main cause of the low strength at the longer fiber length and high volume fraction for randomly oriented fibers.
3.2. Flexural properties

Figure 6 shows the typical of load-displacement curves, the flexural strength and the flexural modulus of bamboo fiber/modified UPR composites with fiber length at various volume fractions, in dry and wet conditions. As seen in figure 6(a), the initial load-displacement curves showed linearity and close to the peak load they deviated from the linearity due to damage process. After the peak load, at dry condition, the loads progressively dropped, indicating the brittle failure of the composite. In general, as seen in figure 6(b, c), the trend of flexural strength and flexural modulus with the fiber length was about similar to that of the tensile strength, as expected. The optimum flexural strength and flexural modulus were obtained at the fiber length of 10 mm. The flexural strength of composites having the volume fraction of 0.2 was the highest at the fiber length of 10 mm; however, as the variation at this volume fraction was high so that it might not be the case. The best performance of flexural properties was obtained at the volume fraction of 0.25.

Figure 6. (a) Typical load-displacement curve at the volume fraction of 0.25, (b) Flexural strength and (c) Flexural modulus of bamboo fiber/modified UPR composites.

Figure 7 shows the failed flexural specimens at the volume fraction of 0.25 and at various fiber lengths in dry and wet conditions. It is seen that the failure occurred at the bottom of the specimens, but the crack did not always occur straight under the load applied, where the stress was the highest. The crack initiated at the weakest part of the bottom, where it could not sustain the stress.
Figure 7. The photograph of the failed flexural specimens at the volume fraction of 0.25 at the fiber lengths of (a) 2.5 mm (dry), (b) 5 mm (dry), (c) 10 mm (dry), (d) 15 mm (dry), (e) 2.5 mm (wet), and (f) 15 mm (wet).

3.3. Impact properties
Figure 8 shows the impact strength of bamboo fiber/modified UPR composites with fiber length at various volume fractions. Different to the tensile and flexural strength, the impact strength tended to linearly increase with the increase of fiber length up to 15 mm. Furthermore, the impact strength also tended to increase with the increase of volume fraction for all fiber lengths. A composite material that has capability to absorb more energy is expected to have high impact strength. The energy absorption for composite was contributed by debonding of the fiber, the pulling out of the fiber, and matrix and fiber fractures. Debonding and fiber pulled out more contributed to the impact strength than the matrix and fiber fractures [12]. Therefore, it is expected that longer fiber length contributed to the high-energy absorption, as it needs high energy for debonding and pulling out of the fiber rather than the shorter fiber. Similarly, high fiber volume fraction also needs more energy for debonding and fiber pulling out. It is observed that the fiber length seems having significant effect in increasing the impact strength. As seen in figure 9, in dry condition the longer fibers pulled out was observed for fiber length of 15 mm (figure 9b) than the fiber length of 2.5 mm (figure 9a).
Figure 8. Impact strength of bamboo fiber/modified UPR composites.

Figure 9. The photographs of the failed impact specimens at volume fraction of 0.3, at the fiber lengths of (a) 2.5 mm (dry), (b) 15 mm (dry), (c) 2.5 mm (wet), (d) 15 mm (wet).
3.4. Water absorption

Figure 10 shows the water uptake vs. square root of time curves of bamboo fiber/modified UPR composites at two fiber lengths and various volume fractions. The water uptake parameters (the equilibrium water uptake and the diffusion rate) are shown in Table 1. The Fickian fits corresponding to the studied volume fraction and fiber length are also shown in Figure 10. At the beginning, the water uptake increased linearly and then the water absorption slowed down and reached the equilibrium. It is observed that for all volume fractions, the longer fiber (15 mm) absorbed more water than the shorter fiber (2.5 mm). Water absorption also increased with the increase of volume fraction for all fiber lengths. Similarly, the diffusion rate also increased with the increase of fiber length and volume fraction. It is also observed that regardless the volume fraction, at the fiber length of 2.5 mm, the water uptake followed the Fickian diffusion law, but at the fiber length of 15 mm, most water uptake curves deviated from the Fickian diffusion law.

At the same volume fraction, the longer fiber was able to absorb water along the fiber and the interface of fiber/matrix, without interruption. Whereas, for the shorter fiber, the capability of fiber to absorb water was hindered by the matrix, as matrix absorbed less water than the fiber. Sugiman et al. [13] showed that at the volume fraction of 0.2, the 8% alkali treated bamboo fiber/modified UPR composites absorbed water five times higher than the modified UPR matrix. Similar to the effect of fiber length on the absorbed water, the absorbed water also increased with the increase of volume fraction, and this effect was getting higher with the increase of fiber length. The increase of water uptake with the increase of fiber length at the volume fraction of 0.2, 0.25, and 0.3 was 30%, 34%, and 44% respectively. Meanwhile, the increase of water uptake with the volume fraction for the fiber length of 2.5 mm was 35% and 44% for the volume fractions of 0.25 and 0.3, respectively, relative to the volume fraction of 0.2. For the fiber length of 15 mm, the increase of water uptake was 39% and 59% for the volume fractions of 0.25 and 0.3, respectively relative to the volume fraction of 0.2.

![Figure 10. Water uptake vs. square root of time of bamboo fiber/modified UPR composites.](image-url)
Table 1. Water uptake parameters of bamboo fiber/modified UPR composites.

| Volume fraction (VF) and fiber length (FL) | \( M_\infty \) (wt%) | \( D \) (mm\(^2\)/day) |
|------------------------------------------|----------------------|------------------|
| VF0.2, FL2.5 mm                          | 4.83 ± 0.10          | 0.14 ± 0.03      |
| VF0.25, FL2.5 mm                         | 6.50 ± 0.95          | 0.33 ± 0.13      |
| VF0.3, FL2.5 mm                          | 6.92 ± 0.52          | 0.55 ± 0.06      |
| VF0.2, FL15 mm                           | 6.37 ± 0.20          | 0.52 ± 0.02      |
| VF0.25, FL15 mm                          | 8.72 ± 0.71          | 0.94 ± 0.38      |
| VF0.3, FL15 mm                           | 9.52 ± 1.03          | 0.71 ± 0.17      |

3.5. Effect of water on the flexural and impact properties

The flexural strength and the flexural modulus of bamboo fiber/modified UPR composites after being immersed in distilled water at a temperature of 40°C for approximately 1055 hours can be seen in figure 6. In this condition, the composites had been saturated with water. It is seen that the flexural strength and the flexural modulus significantly reduced, and the reduction is higher for the longer fiber. It is also seen that although the reduction increased with the increase of volume fraction; however, the effect of volume fraction on the reduction seemed not significant. The reduction of flexural strength in wet condition was in the range of 30-38% for the fiber length of 2.5 mm and 39-45% for the fiber length of 15 mm. While the reduction of flexural modulus in wet condition was in the range of 39-52% for the fiber length of 2.5 mm and 52% for the fiber length of 15 mm, regardless the volume fraction.

Most of the absorbed water resided in the bamboo fiber and interface fiber-matrix. The water attacked the interface fiber/matrix and then weakened the interface strength. Water also caused the reduction of fiber and matrix strength. For matrix, water caused plasticization, leading to the tensile strength degradation. The longer fiber has longer interfacial region and able to absorb more water. As a result, the flexural strength and flexural modulus degradation of the longer fiber was higher than the shorter fiber.

The impact strength of bamboo fiber/modified UPR composites in wet condition can be seen in figure 8. Similar to the flexural specimen, the impact specimens had reached the saturation before being tested. The impact strength in wet condition increased significantly compared to those in dry condition both for the volume fraction and the fiber length. Compared to dry condition, the significant increase was seen for the volume fractions of 0.25 and 0.3, which was about 38% and 71% for the fiber length of 2.5 mm, respectively, and 45% and 66% for the fiber length of 15 mm, respectively. In wet condition, the increase of impact strength with the fiber length from 2.5 mm to 15 mm was 100%, 75%, and 60% for the volume fractions of 0.2, 0.25, and 0.3, respectively.

Again, the absorbed water attacked the fiber, matrix, and the interface fiber/matrix. The most important factors contributing the impact strength is the interface strength, as the interface provides high-energy absorption by debonding and fiber pulling out. As seen in figure 9(c-d), water that attacked the interface degraded the interface strength and promoted the failure by debonding and fiber pulled out rather that the fiber fracture. This leaded to high impact strength. The effect of fiber length (at the same volume fraction) seemed higher than the effect of volume fraction (at the same fiber length). This is expected, as the longer fiber needed high energy to debond and then to pull it out.

4. Conclusions

Investigation on the effect of fiber length on the mechanical properties and water absorption of bamboo fiber/polystyrene-modified unsaturated polyester composites had been undertaken. It was found that the tensile properties had the similar trend to the flexural properties, in which the tensile and flexural properties tended to increase with the increase of fiber length, and reached the optimum at
the fiber length of 10 mm, for all fiber volume fractions. Meanwhile, the impact strength tended to increase with the fiber length up to 15 mm. The water absorption tended to increase with the fiber length and fiber volume fraction. In wet condition, the flexural properties degraded and the degradation was higher for the longer fiber. In contrast to the flexural properties, in wet condition, the impact strength significantly increased, compared to dry condition for all fiber lengths and volume fractions. The effect of fiber length was more dominant than the volume fraction in increasing the impact strength.

Acknowledgements
This work was supported by the Ministry of Research, Technology, and Higher Education, the Republic of Indonesia with grant number [808/UN18.L1/PP/2018]. Authors would like thank Mr. B. Ulum for preparing the specimens.

References
[1] Amada S, Ichikawa Y, Munekata T, Nagase Y and Shimizu K 1997 Fiber texture and mechanical graded structure of bamboo Composites Part B 28 13–20
[2] Gay D, Hoa S V, Tsai S W 2003 Composite materials design and applications (Florida: CRC Press)
[3] Sugiman S, Gozali M H and Setyawan P D 2017 Hygrothermal effects of glass fiber reinforced unsaturated polyester resin composites aged in steady and fluctuating conditions Advanced Composite Materials In Press DOI: 10.1080/09243046.2017.1405597
[4] Gaggino R 2012 Water-resistant panels made from recycled plastics and resin Construction and Building Materials 35 468–82
[5] Setyawan P D and Sugiman 2012 Pengaruh penambahan styrofoam dan partikel karet terhadap sifat mekanik resin polyester tak jenuh Proceeding Seminar Nasional Tahunan Teknik Mesin XI (SNTTM XI) & Thermofluid IV (Yogyakarta: Universitas Gadjah Mada)
[6] Sugiman S, Setyawan P D and Anshari B 2018 Effect of alkali treatment on the flexural strength of bamboo fibers reinforced styrofoam-modified polyester resin AIP Conference Proceedings 1983 050005 doi: 10.1063/1.5046278
[7] ASTM D3039 2002 Standard test method for tensile properties of polymer matrix composite materials (PA: ASTM International)
[8] ASTM D790 2003 Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials (PA: ASTM International)
[9] ASTM D256 2002 Standard test methods for determining the izod pendulum impact resistance of plastics (PA: ASTM International)
[10] Sugiman S, Putra I K P and Setyawan P D 2016 Effects of the media and ageing condition on the tensile properties and fracture toughness of epoxy resin Polymer Degradation and Stability 134 311–21
[11] Manalo A C, Wani E, Zukarnain N A, Karunasena W and Lau K T 2015 Effects of alkali treatment and elevated temperature on the mechanical properties of bamboo fibre-polyester composites Composites Part B 80 73–83
[12] Öztürk S 2005 The effect of fibre content on the mechanical properties of hemp and basalt fibre reinforced phenol formaldehyde composites Journal of Materials Science 40(17) 4585–92
[13] Sugiman S, Setyawan P D and Anshari B 2018 Water absorption and impact strength of bamboo fiber/polystyrene-modified unsaturated polyester composites: Effects of alkali treatment IJASEIT, Submitted for publication