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Characterisation of Polyurethane-urea as Leading-Edge Erosion Resistant Materials of Wind Turbine Blades

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Abstract. Surrounded by oceans, building offshore wind turbines is a great strategy for archipelago countries, like Indonesia, to harvest renewable energy from wind. However, because of high rainfall rate, water droplet erosion on wind turbine blades is inevitably to be one of the most challenging problems. It causes decreasing produced energy and increasing cost of maintenance and repairment. A novel coating material which has better mechanical properties is therefore required. As a preliminary step, this work aims to characterise thermal and mechanical properties of soft and hard polyurethane-urea (PUU). In this work, the materials are soft PUU30 which has a hardness of 30 shore A, and hard PUU95 which has a hardness of 95 shore A. Thermal properties are characterised by Differential Scanning Calorimetry (DSC), while mechanical properties are investigated by tensile test at various strain rates. The results show that PUU95 has a higher strain rate dependence on modulus, tensile strength, and strain at break, which need to be considered for application regarding the range of wind speeds.

1. Introduction

Because of global warming, a negative consequence of using fossil fuels, using a green energy resource such as wind is a great strategy. For archipelago countries, like Indonesia, harvesting wind energy from offshore wind turbines will be beneficial. Table 1 shows five regions Indonesia which have the highest wind power technical potential at 50 m and 100 m hub height [1].

Table 1. Top five regions in Indonesia with highest wind energy [1].

No.	Region	Technical potential at 50 m hub height / MW	Technical potential at 100 m hub height / MW
1	South Sulawesi	8,732.7	6,525
2	East Nusa Tenggara	4,933.0	5,943.8
3	Maluku	6,391.7	4,857.6
4	Aceh	1,104.5	1,211.1
5	Papua	1,085.2	161.4

Reflecting from cases in European countries where the wind speed is higher than Indonesia's [1], Leading Edge Erosion (LEE) of wind turbine blades is a challenge in developing wind field. In 2019, UK spent £76.5 million to overcome LEE [2]. LEE also leads to decreasing annual energy production by 1-5% [2]. The main cause of LEE is water droplet erosion comes from rain [3].

To prevent LEE, the quality of coating of wind turbine blades should be improved. Currently, the coating for large wind turbine consists of several layers with different properties such as hardness [4]. Material for Leading Edge Protection (LEP) is usually polyurethane [5]. However, polyurethane-urea (PUU) is reported to have more potential as it has higher energy dissipation than polyurethane [6].

PUU is a polymer formed by the reaction of polyol, diisocyanate, and amine compounds [7]. PUU is usually fabricated through two steps polymerisation. In the first step, a polyol and excess amount of diisocyanate are reacted to form polyurethane (PU) chain with isocyanate groups at both edges [7]. In the second step, the PU chains are linked to each other by a reaction between the isocyanate groups and amine groups [7]. In each reaction, plasticiser is usually used to ease the process [7]. After curing, hydrocarbon from polyol and plasticiser form soft segment, while urea and urethane groups are attached by hydrogen bond to form hard segment [7].

As a polymer, a lightweight material, PUU is suitable for Indonesia's low wind speed, 3 – 6 m/s [1]This range is important to be considered for developing new materials for coating wind turbine blades. Therefore, the purpose of this work is to investigate the thermal and mechanical properties of PUU, including the effect of strain rate on tensile properties. To accommodate the need for different hardness for coating, soft and hard PUU were investigated in this work.

2. Experimental

Materials used in this research were Duroflex30 as soft PUU (PUU30) and Duroflex95 as hard PUU (PUU95). They are commercially available. They were made of part A and part B. Part A contained 2(or 4)-methyl-4,6(or 2,6)-bis(methylthio)- or DMTDA and polyol plasticiser, while part B contained isomers of diisopropylnaphthalene (DIPN), diphenylmethane-2,4'-diisocyanate, diphenylmethane-4,4'-diisocyanate, and prepolymer. The procedure of synthesis was illustrated in figure 1 of which part A is mixed with part B, followed with moulding into a film and curing.

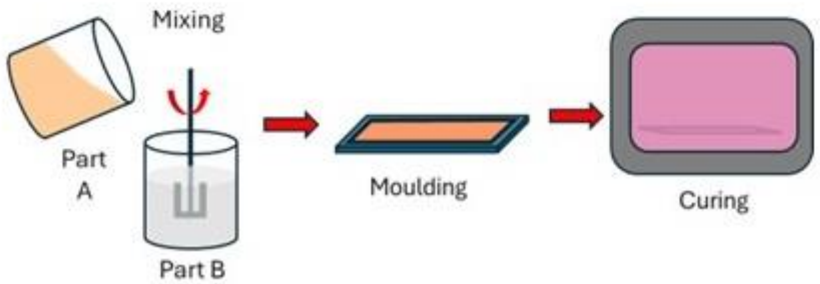

Figure 1. Synthesis procedure of PUU30 and PUU95.

Investigation of physical, mechanical, and thermal properties of PUU was repeated three times in this research. Thermal property was investigated by using TA Instruments DSC25 (Differential Scanning Calorimetry). A 5 mg of PUU was placed in Tzero Aluminium Hermetic pan. The method included 2 steps. First step was fast cooling to -90 ℃ with a cooling rate of 20 ℃/min to prevent the change of structure because of temperature. The second step was heating to 90 ℃ with rate of 5 ℃/minute. DSC curve is normalised heat flow *vs* temperature. Curve from the second step was used to determine glass transition temperature (T_g) based on ASTM E1356-Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry of which Tg was characterised using the half height midpoint of the step in the normalised heat flow.

Physical and mechanical tests were performed at 21 °C ± 1 °C, 55% relative humidity, and atmospheric pressure conditions. Shore A hardness measurements were performed according to ASTM D2240. The tool used for hardness test is Shore A Durometer. INSTRON Mode 5697 was used for tensile test. The samples were cut into dumbbell shapes, as shown in figure 2, by using ISO-37 type 4 die cutter and a hydraulic die press. Strain rate variation was 0.001, 0.01, 0.1 and 1 /s.

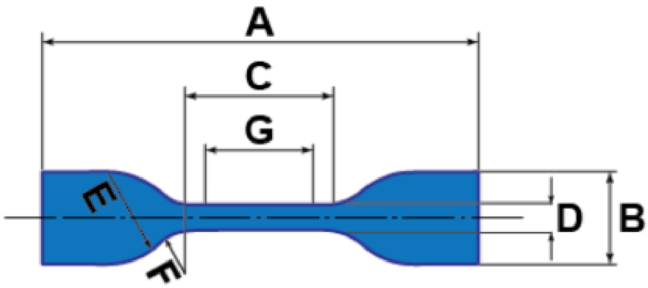

Figure 2. Dumbbell shape for samples of tensile and cyclic test. A = 35 mm, B = 6 mm, C =12 mm, D = 2 mm, E = 3mm, F = 3 mm, G = 10 mm.

3. Results and Discussion

Based on the hardness test, the hardness of PUU30 is 30 shore A, while hardness of PUU95 is 95 shore A. It indicates that PUU95 has larger hard segment than PUU30 as hardness has a positive correlation with hard segment content [8]. Hardness can be a criterion in choosing coating materials for wind turbine blades. Although soft polymer has higher erosion resistance, hardness of polymer should be matched with the hard inner part of the blades such as graphene fiber reinforced plastic (GFRP) to avoid delamination [3].

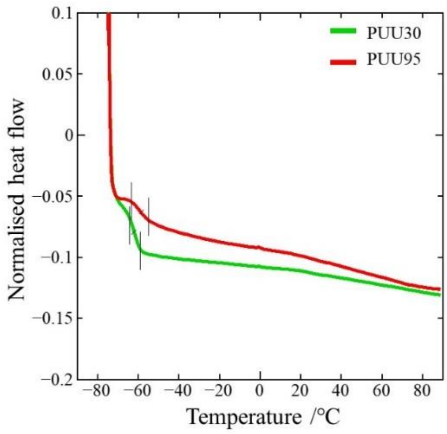

Figure 3. PUU30 shows sharper slope in DSC curve indicating lower T_g.

For thermal property, as shown in figure 3, the results of DSC, PUU30 has lower T_g (-61.43 ± 0.81 °C) than PUU95 (-58.74 ± 1.81 °C). It indicates that the soft segment in PUU30 has more ability to move than that in PUU95 because PUU30 contains more plasticiser than PUU95. This phenomenon has been reported previously on PUU with di-2(ethylhexyl) phthalate (DEHP) [9] and water as plasticiser [10]. The portion of soft/hard segment is important to fabricate PUU with high quality erosion resistance. It is because hard segment transmits impact energy generated from raindrops to soft segment which use the energy to be more mobile [3]. The T_g of both PUUs which is below 20 °C provide advantage for this function. Because the structure of hard and soft segment can change because of applied force, the mechanical properties are investigated in this work through tensile test.

Stress-strain curves, as results of tensile tests at various strain rates, for PUU30 and PUU95 are shown in figure 4. Notably, the shape of the curve of PUU30 shows independence towards strain rates, while for PUU95, a strong strain rate dependence is clearly shown. Moreover, yielding phenomena is clearly observed in stress-strain curve in PUU95 at strain around 0.15 – 0.25. Those characteristics of PUU95 indicates the existence of a significant amount or size of the hard segment as also found in oligomers diols-based PUU [11]. Further analysis about the modulus at 10% and 25% elongation are shown in figures 5 and 6.

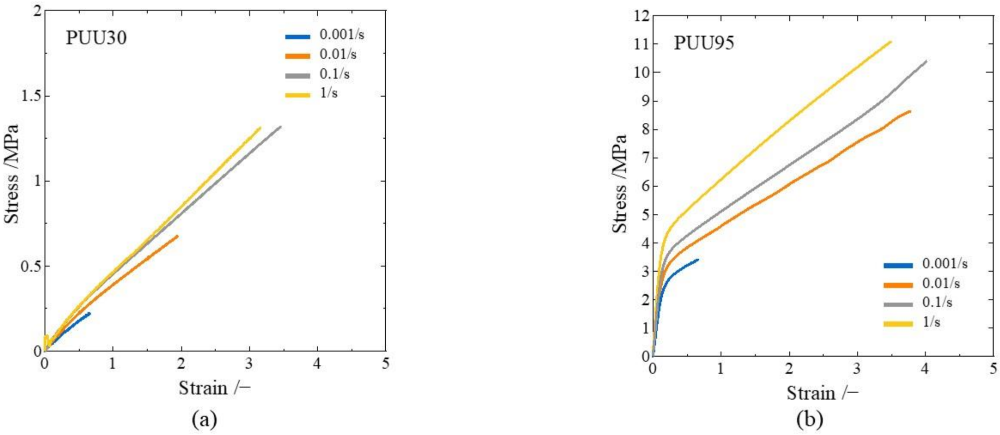

Figure 4. Stress – strain curve of PUU30 (a) is obviously different from that of PUU95 (b).

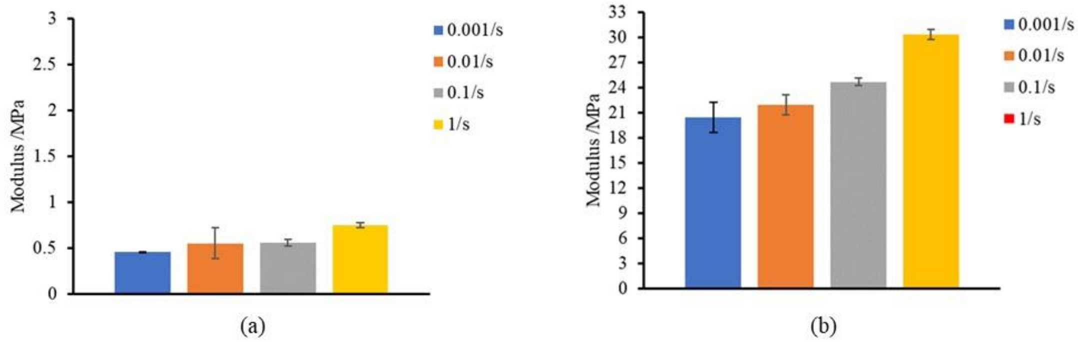

Figure 5. Modulus at 10% elongation of PUU95 (b) is around 20x higher than that of PUU30 (a).

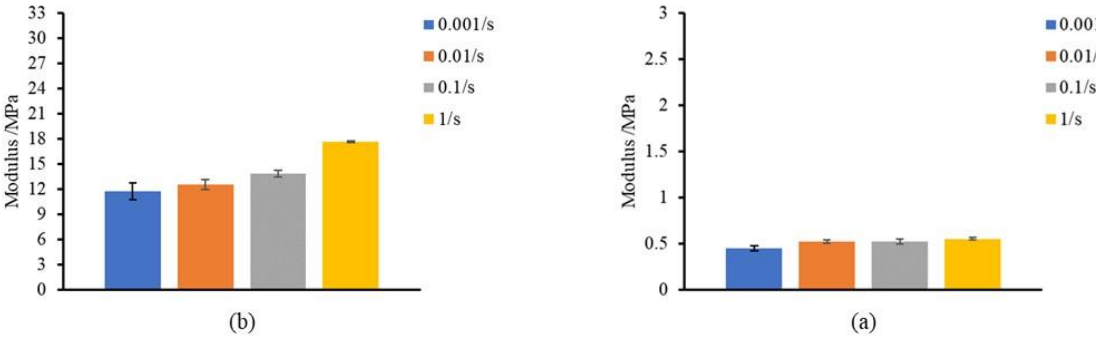

Figure 6. Modulus at 25% elongation of PUU95 (b) is around 15x higher than that of PUU30 (a).

Figure 5 shows modulus at 10% elongation or strain of 0.1 for PUU30 and PUU95. Modulus at 25% elongation or strain of 0.25 for both PUUs are shown in figure 6. A positive correlation between modulus and strain rate is clearly shown for PUU95. The correlation is because a higher strain rate provides less time for PUU chain to undergo stress relaxation [11]. It is also shown that modulus of PUU95 is higher than that of PUU30. It can be the effect of a hard segment. Strains at 0.1 and at 0.25 are in elastic region for both PUUs. In this region, hard segments experience higher stress [7]. However, for PUU95, the modulus at strain of 0.25 in figure 6 is lower than that at strain of 0.1 in figure 5. It can be affected by the yielding of hard segments. In the yielding region, the plastic deformation of the hard segment dominates the mechanical behaviour [7] It may occur through the disruption of hydrogen bonds, rotation, and rearrangement of the hard segment [7].

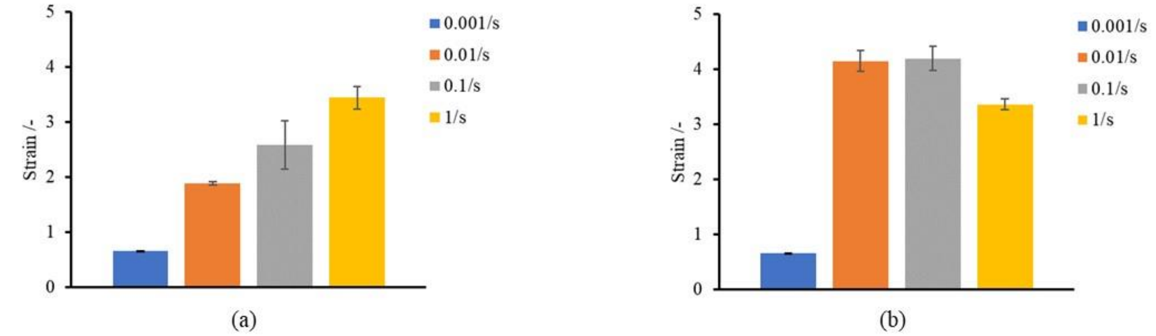

Figure 7. For PUU30 (a), strain at break increases with increasing strain rate, while for PUU95 (b), it fluctuates.

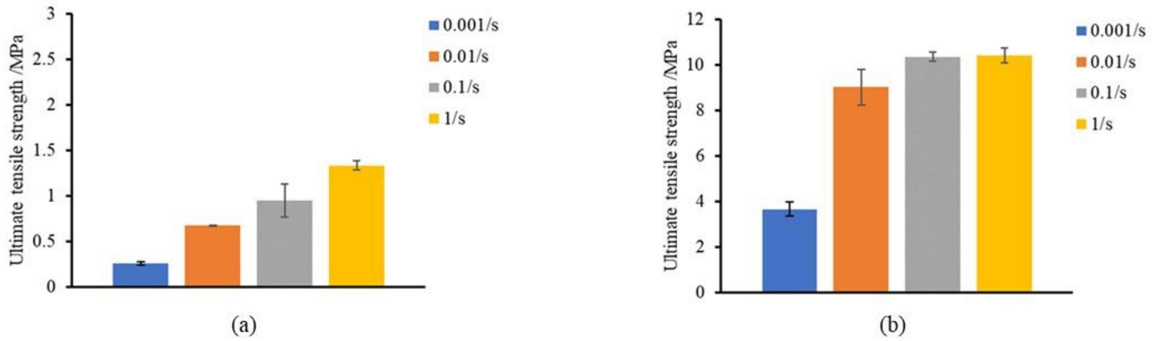

Figure 8. For both PUU30 (a) and PUU95 (b), ultimate tensile strength increases with increasing strain rate.

Elongation at break and ultimate tensile strength for both PUUs are shown at figures 7 and 8, respectively. At exceptionally low strain rate, 0.001/s, PUU30 and PUU95 have similar elongation at break, yet PUU95 has higher ultimate tensile strength. It indicates that PUU95 builds higher strain energy density than PUU30. Interestingly, positive correlations between strain rate and elongation at break as well as strain rate and ultimate tensile strength are more pronounced on PUU30 than that on PUU95. It indicates that PUU30 gains more strain energy density when the strain rate increases. It is suspected that this ability is caused by reaction among the chemical functional groups in PUU30. Isocyanate end group of PU, a product of the first step of polymerisation, which may be still exist in PUU can react with amide, urethane, and hydroxyl groups at 25 °C without any catalyst [6]. The reaction between isocyanate and primary hydroxyl is one thousand times faster than reaction between isocyanate and amide [6].

4. Conclusion

In this work, hardness, glass transition temperature and strain rate dependence of tensile properties are investigated on PUU as a potential coating material for wind turbine blades. To accommodate the need of different hardness for coating, soft PUU (PUU30) and hard PUU (PUU95) were used as objects in this work. According to the investigation findings, PUU95 exhibits a higher glass transition temperature, hardness, modulus, and ultimate tensile strength compared to PUU30. Moreover, the strain rate dependence of tensile property of PUU95 is more pronounced than in PUU30. All those properties can be caused by the characteristics of the hard segments and the structural changing in PUU95 during tensile test. Further investigation on the structural changing is our further work. For application as a coating material for wind turbine blades, the significant strain rate dependence of PUU95 need to be considered as well as chemical functional groups in PUU because chemical reaction is suspected to occur during tensile test in this work.

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Acknowledgments

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