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Mechanical Characterization of Polyurethane Elastomers: For Retrofitting Application against Blast Effects

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ABSTRACT: In recent years, structural and materials engineers have focused their attention to develop feasible, constructible and cost effective retrofitting techniques to enhance the structural capacity and to minimize the damage due to impulsive loadings such as blast and impact. In this aspect, elastomeric polymers offer a unique proposition as retrofitting material for civil infrastructures, due to their attractive characteristics and morphology such as high elongation and energy absorption capacity. However, comprehensive understanding and proper evaluation of their characteristics and behavior are vital prior to developing a feasible retrofitting technique based on these materials. This paper discusses on the findings of experimental investigations undertaken to evaluate the mechanical properties under uniaxial tensile loading of selected types of palm-oil based polyurethane which were prepared by varying the chain extender (Polyethylene glycol, PEG), for it to be utilized as a retrofitting coating material on reinforced concrete structures, to enhance their resistance to blast effects. It was found that the properties of polyurethane elastomer are within the desired range and there is a higher possibility to apply the material as a sustainable and feasible retrofitting application for reinforced concrete structures under impulsive loadings.

1 INTRODUCTION

Presently, consideration of utilizing polyurethane (PU) polymers for structural and infrastructural applications becomes a competitive area due to its captivating morphology and characteristics as a material: highly elastic, flexible and resistant to impact, abrasion and aggressive weather condition (Chattopadhyay & Raju, 2007). PU covers an extremely wide range of applications, such as in bedding materials, adhesives, thermal insulation, the manufacture of tires, as well as in structural elements. PU capitalizes on its wide range of mechanical properties due to the ability to alter its microstructure. PU is formed by the rapid chemical reaction of diisocayante [a monomer with at least two isocyanate (–NCO) functional groups] with diol [another monomer containing at least two alcohol (hydroxyl, or –OH) groups], in the presence of a catalyst (Chattopadhyay & Raju, 2007; Badri, 2012). Generally, PU is a linear segmented blocked copolymer comprising of “soft” and “hard” segments, and an increase in content of hard segment results in increased ultimate strength, and tensile flexural modulus

while decreasing the strain capacity (Russo & Thomas, 1983). Micro separation of those domains due to the dissimilarity of properties is responsible for the wide range of properties of the PU and broad class of polymer (O'Sickey et al., 2002).

Most elastomers exhibit a high degree of strain rate dependency, stress–strain non-linearity, and a high level of pressure dependency when compared with other construction materials mainly due to the complexity of their microstructures (Bahei-El-Din & Dvorak., 2007; Raman et al., 2012). In addition, PU demonstrates a higher energy absorption density compared to other elastomeric materials. In past few decades, polymer spray-in-place application technique has been introduced, and were used in numerous industrial application as strengthening surface coating to improve the durability and as secondary coating on several types of structural elements, including in roofs, bridges, and parking decks, coating for insulation, and protective coating for tank liners, tunnel and manhole. These polymers have also indicated the capacity as a strengthening coating application to resist extreme loadings of blast and ballistic in concrete structures. The findings of previous studies have indicated that in addition to enhancing the structural capacity against blast effects, the application of elastomeric polymer coatings (including PU) was also effective in minimizing the fragmentation, controlling the deformation and displacement, and collapse potential of the several types of structural elements such as unreinforced masonry walls, metallic structures, composite structural systems, and concrete structures (Davidson et al., 2004; Bahei-El-Din & Dvorak., 2007; Tekalur et al., 2008; Amini et al., 2010; Grujicic et al., 2012; Raman et al., 2012; Ackland et al., 2013).

The comprehensive understanding on the behavior of these polymeric materials is necessary prior to recommending them as an effective and feasible alternative to existing structural retrofitting materials. The mechanical behavior of elastomeric polymers such as PU and polyurea has been studied by several researchers in recent times. Generally, impulsive loadings are associated with high loading rates, therefore synthesis of the characteristics and behavior of the material under a wide range of strain rates (quasi-static and high strain rates) is essential for such applications. One of the earlier studies on the high strain rate characteristics of elastomeric polymers was by Yi et al. (2006), where they investigated the compressive stress–strain behavior of three types of PU and one polyurea samples using the split Hopkinson pressure bar system. Their findings highlighted that the polymeric materials show a highly non-linear behavior in stress–strain relationships, and indicated strong hysteresis and rate dependency. Sarva et al. (2007) reported on the uniaxial compression stress-strain behavior of one of the PU sample and the polyurea sample studied by Yi et al. (2006), over a wide range in strain rates (from 0.001 s^{-1} to 10,000 s^{-1}). Shim and Mohr (2009) performed relaxation experiments, continuous and multi-step compression experiments within strain rate ranges of 10^{-3} to 10^{1} s^{-1}, and compressive strains up to 1. Roland et al. (2007) reported on the behavior of polyurea in tension over the strain rate region of 0.06 to 573 s^{-1}, while Raman et al. (2013) reported the findings of a series of uniaxial tensile test that were conducted on polyurea for strain rates ranging from 0.006 to 388 s^{-1}. This paper presents the findings of an experimental investigation program undertaken to analyze the tensile stress-strain behavior of three types of palm-based PU samples produced by varying the plasticizer (chain extender) content in the quasi-static regime.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

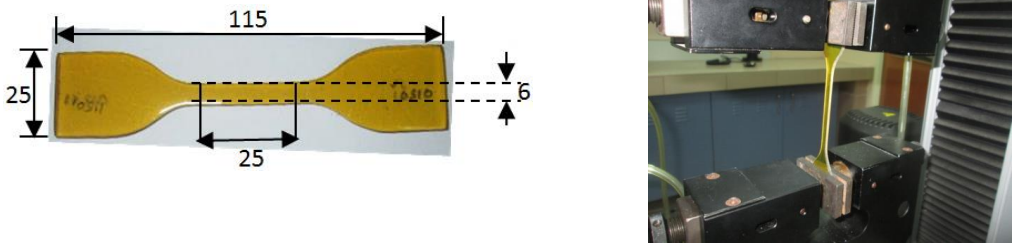
Palm-based polyol (PKO-p), 2,4-diphenylmethane diisocyanate (MDI), Acetone and polyethylene glycol (PEG) were synthesized at the Polymer Research Centre (PORCE), of Universiti Kebangsaan Malaysia (The National University of Malaysia), Bangi, Malaysia.

2.2 Preparations of the Palm oil-based polyurethane elastomer

The palm-based PU elastomer was synthesized from the rapid reaction between PKO-p and MDI with PEG as the plasticizer via pre-polymerization. Three types of PU were casted with three different PEG contents (0, 6, and 12 (wt. %)) with respect to the weight of the PKO-p, while keeping the mix percentage of PKO-p, MDI and Acetone ratio constant at 1: 0.8: 0.35 throughout the experiment. The three types of PU were synthesized by solution casting process and were referred to as PU0, PU6 and PU12, (PU6 indicate that the PU contained 6% PEG). Clear yellowish and bubbleless PU samples were prepared, and cured at ambient temperature.

2.3 Tensile test

The tensile specimens were tested uniaxially on a Instron Universal Testing Machine in accordance to the ASTM D 412: Method A specification. Dumbbell shaped test specimens with average thickness of 3 mm were cut from the pre-casted PU sheets [Figure 1(a)], in the same direction of the sheets, in order to minimize the effect of anisotropy or grain directionality due to the direction of the flow during the preparation and the processing of the PU sheets. All dumbbell shaped test specimens were cut using a die C in accordance with the dimension selection procedure described in the specification. The median of three measurements were used for the dimensions (width and thickness) of each samples. During the testing, all test specimens were clamped in to the grip automatically with a clamping distance of 65 mm, were tested with a uniform rate of 50 mm/min [Figure 1(b)], at ambient temperature.



(a) (b)

Figure 3. The: (a) Dimensions of specimens (in mm) prepared for the uniaxial tensile test; and (b) Performance of the uniaxial tensile test.

3 RESULTS AND DISCUSSION

3.1 Tensile Characteristics

In this study, the tensile test at quasi-static loading condition was performed at a rate of 0.033 s^{-1}. This rate of straining was within the quasi-static strain rates adopted by Roland et al. (2007) and Raman et al. (2013) in their studies. Figure 2(a-c) show the quasi-static engineering stress-strain curves for the three types of PU composition that were analyzed in this study. All tensile characteristics reported in this paper were computed based on the engineering stress-strain parameters of the samples.

3.1.1 PU0

Sample PU0 (which contained 0 % PEG) exhibited an initial linear region in the engineering stress-strain curves with an average Young's modulus of 146 MPa [Figure 2(a)]. Subsequently after the linear region, the material started yielding after reaching an elongation of 8.5 % with a yielding stress of 12 MPa, and which resulted in permanent or inelastic deformation. The material underwent a brief period of yielding until achieving an elongation of 18 % while the stress increased until it reached a value of 15.5 MPa, and subsequently continued until it achieved 35 % elongation while reducing the stress to 14.8 MPa. At this stage, the PU samples would have gone through a structural breakdown in its molecules, and following in permanent deformations (yielding) and undergoing large elongations while having marginal decrement in the applied stress. After this stage, the PU exhibited an almost linear curve, before the subsequent failure after an (average) elongation of 68%, while having an average stress of 14.2 MPa at rupture.

3.1.2 PU6

PU6 samples recorded a Young's modulus (average) of 61 MPa, where it reached an elongation of 10% with a yielding stress of 5.2 MPa, and started yielding after that respective point [Figure 2(b)]. The PUs underwent a period of yielding until achieving an elongation of 28% at a stress of 7.0 MPa. Further application of load after this point resulted in a marginal increase in the stress, showing a strain hardening mechanism. Subsequently the PUs exhibited a linear relationship of stress and strain over significant range of strain (28 to 177%), prior to failing after an (average) elongation of 177%, with a (average) fracture stress of 9.3 MPa.

3.1.3 PU12

The average Young's modulus of PU12 samples was 12 MPa, with an average yield stress of 2 MPa after reaching an elongation of 12%. Subsequently PU samples underwent a brief period of yielding until reaching an elongation of 34% at a stress of 2.8 MPa [Figure 2(c)]. Since the samples will have gone through a breakdown in its molecular structure after this point, it resulted in permanent deformations with large elongations while showing only a minor increment in the resulting stress. Further application of load resulted in PU12 samples undergoing strain hardening mechanism as PU6. Failure occurred at an average elongation of close to 200%, with an average fracture stress of 4.5 MPa.

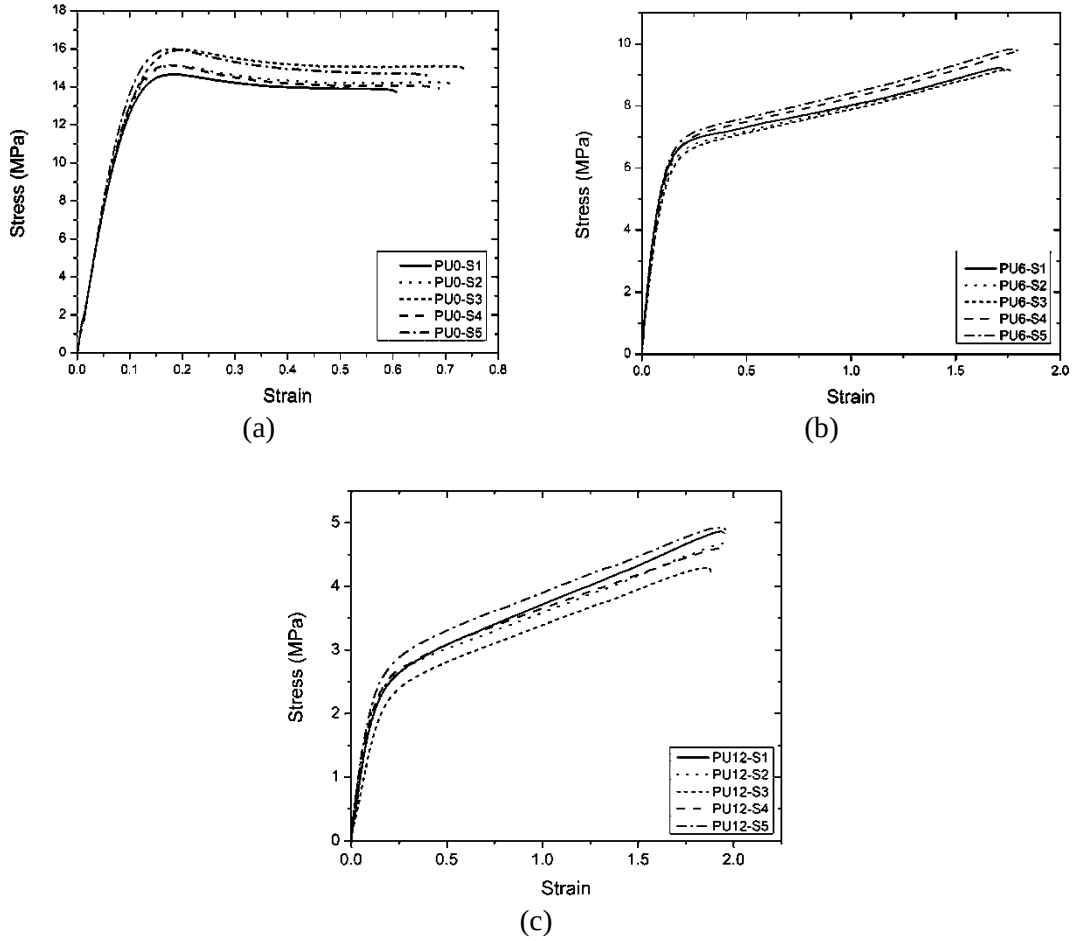


Figure 2. The engineering stress-strain curves of: (a) PU0 samples; (b) PU6 samples; and (c) PU12 samples.

3.2 Comparison of tensile properties

The obtained results were analyzed and the variation of the properties are illustrated in Figure 3. Stress-strain relationship of selected specimens of the three types of PU is shown in Figure 3(a), and it generally followed the shape of typical elastic-plastic material behavior for PU6 and PU12. Both PU6 and PU12 also exhibited strain hardening mechanism. Meanwhile, PU0 exhibited the highest Young's modulus (146 MPa), while the lowest value (12.0 MPa) was recorded by PU12. From PU0 to PU12 (i.e. when the plasticizer content was increased), the Young's modulus decreased significantly. Even though the same amount of plasticizer was increased in each stage (from PU0 to PU6 and from PU6 to PU12), the reduction of Young's modulus from PU0 to PU6 was nearly 1.8 times compared with the decrement from PU6 to PU12. The addition of plasticizer (i.e. the chain extender) increases the length of pre-polymer chain, and leads to the polyurethane sample to posses a higher mobility in their molecular structure, thus resulting in reduced stiffness in the material.

In addition, the failure stress gradually decreased from PU0 to PU12, and the decrement shows approximately similar value. The failure strain increased during this period and the strain increment from PU0 to PU6 is significant compared to the increment from PU6 to PU12.

Therefore it can be concluded that, the content of plasticizer has significantly affected to the tensile properties of PUs.

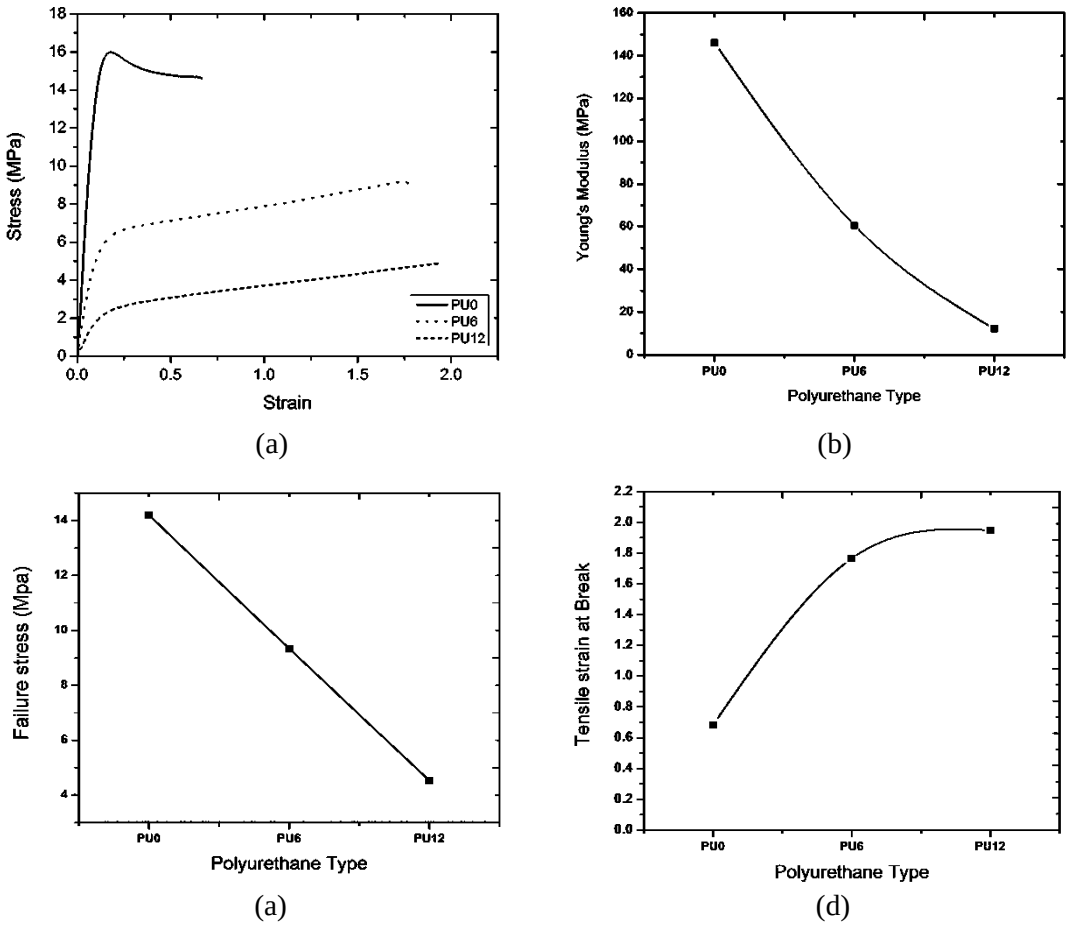


Figure 4. The tensile mechanical characteristics of the three PU samples: (a) Stress-strain curve; (b) Young's modulus; (c) Tensile stress at rupture; and (d) Strain at rupture.

3.3 Strain energy

In the initial elastic region of the stress-strain curve, the deformation resulting from the applied axial load was not accompanied by dissipation of energy. The applied load was stored as strain energy in the material throughout its volume which resulted in elastic deformation, due to the "work" (product of applied load and deformation) done by the material (Hibbeler, 2011). The energy absorption capacity of the material is another key property which should be considered for a retrofitting material. The resilience modulus and the toughness modulus characterize the density of embedded strain energy for a given volume of the material. The resilience modulus of the material depicts the ability of the material to absorb the energy imparted without experiencing permanent deformation or damage. The resilience modulus for PU0, PU6 and PU12 were 0.56, 0.30 and 0.14 x 10^6 J/m^3, respectively, and the toughness modulus were 9.44, 13.28 and 6.97 x 10^6 J/m^3, respectively. Even though the resilience modulus showed a decreasing trend from PU0 to PU12, PU6 recorded the highest toughness modulus, since strain capacity was increasing from PU0 to PU12. The toughness modulus represents the strain energy

density in the material just before undergoing failure (Hibbeler, 2011). The PUs evaluated in this study have exhibited toughness modulus that were almost 17, 44 and 50 times higher their resilience modulus. These findings have provided a good agreement to the main objective of the current study to investigate the PU as a retrofitting material for structures subjected to high impulsive loadings. It indicates that PU would be able to absorb considerable amounts of energy even after yielding of the material. This characteristic is preferred in a retrofitting material, distinct to most brittle materials that are used in construction such as concrete and ceramics, which would fail suddenly after their yielding.

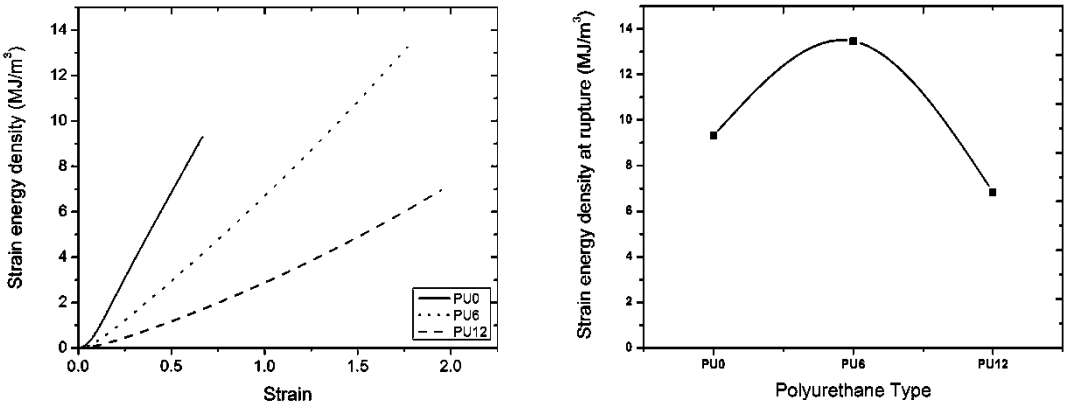


Figure 4. The tensile mechanical characteristics of the three PU samples: (a) Strain energy density vs. strain; (b) Strain energy at failure.

4 CONCLUSIONS

This paper presented the findings from the experimental investigation undertaken to analyze the behavior of three types of palm-based PU samples with varying plasticizer content, under uniaxial tension. The following conclusions have been drawn based on the findings this study.

1. Stress-strain relationship indicated that all types of PU samples deform significantly after reaching its yield point and it will not fracture suddenly without a warning prior to failure, and PU12 exhibits the higher performance while PU0 showing the lower performance under this behavior.

2. Addition of plasticizer significantly influenced the tensile characteristics of the PU samples, i.e. by decreasing the Young's modulus and fracture stress, while enhancing the elongation capacity from PU0 to PU12.

3. Even though the resilience modulus was decreased from PU0 to PU12, PU6 shows best energy absorption capacity among all, since it exhibited the highest toughness modulus.

4. PU0 shows a behavior of a material which is high in stiffness but lower in terms of toughness, while the behavior of PU12 was like a material which is high in toughness but lower in stiffness. PU6 exhibited a behavior of a material which has desirable stiffness and toughness qualities.

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