SECM/15/024

Analysis of Strain Rate Dependent Tensile Behaviour of Polyurethanes

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Abstract: The stress-strain behaviour of elastomeric polymers, such as polyurethane (PU), exhibit high rate dependency, stress–strain non-linearity, and high pressure dependency when compared to other construction materials. Since these polymers exhibit the potential to be applied as retrofitting and protective material for various types of structural materials, in enhancing their load-carrying capacity, ductility and structural survivability under different loading regimes, it is essential to comprehensively investigate their mechanical behaviour at varying strain rates. This study was undertaken to investigate the tensile stress-strain characteristics of elastomeric PU at varying strain rates, ranging from 0.001 s^{-1} to 0.1 s^{-1} (low to intermediate). The primary emphasis of this study was on the strain rate sensitivity of the tensile properties, including the Young's modulus, tangent modulus, ultimate tensile stress, fracture strain, and strain energy modulus. The findings indicated that stress-strain behaviour of the PU exhibited high dependence to variations in strain rates and stress–strain non-linearity. The behaviour of PU also provided good concurrence with recent studies, which explored the strain rate dependency of other elastomeric polymers.

Keywords: Dynamic loading, Polyurethane, Strain rate, Stress-strain behaviour, Tensile behaviour.

1. Introduction

Elastomeric polymers, such as polyurethane (PU), are currently considered amongst promising materials for several types of structural applications, where these polymers provide extra structural capacity, and resistance against severe environmental conditions. Typical examples for applications of elastomeric polymers in numerous industries vary from building structural elements (masonry, concrete, steel and composite elements), vehicles, infrastructures including underground structures (such as pipelines), marine constructions, etc. [1-3]. The conventional technique of enhancing the capacity of a structural element is by increasing the mass and the stiffness of the element. Though it is used commonly, it forms obstacles such as; high initial cost, high materials and resources consumption, and inappropriateness for the existing structures [3]. Consequently, structural and material engineers have been investigating to find more appropriate solutions as alternative for those techniques.

Based on the prior investigations, it can be observed that increasing the energy absorption capacity of the element is an efficient technique to reduce the level of destruction and fragmentation effect of failures under impulsive loading conditions [2,3]. To achieve high energy absorption in structural elements, it is essential to use materials which possess high stiffness and strain capacity. Although cementitious materials are known to have high stiffness values, they fail via tensile cracking when overloaded, since cementitious materials have low tensile strain capacity (with tensile strain of about 0.0001, nearly one-tenth that of compressive strain), and with low fracture toughness approximately 0.01 kJ/m^2, compared with other construction materials such as mild steel (100 kJ/m^2), they are extremely brittle [4]. Elastomeric polymers including PU have been of great interest among the structural and material engineers, and are also considered for the blast protection of several structural elements. Since PU exhibits characteristics such as high toughness-to-density ratio under high strain rate conditions, and

leads to enhancement in the dynamic performance and failure resistance under impulsive conditions. [2,3]. PU readily adheres to numerous types of surfaces including concrete, masonry, metal, and wood, and has a fast curing time with straight forward techniques of preparation and application. Therefore this technique shows a better concurrence to be used as a strengthening material for existing structures to enhance the blast and ballistic resistance of structures [2,3].

The properties of most types of elastomers are highly variable. They depend on many factors including chemical combination which were used to synthesise, temperature, loading rate which is applied during testing, etc. Therefore, a major challenge is, however, to select the best material since the characteristics of the elastomers are rate dependent, and are considerably non-linear. Prior to investigating the dynamic response and the resistance mechanisms of elastomeric PU as a retrofitting material, it is important to study the behaviour of the PU elastomer at a wide range of strain rates to simulate the behaviour of the material under static and dynamic loading regimes. Considering that structures experience different loading conditions during their service life, and impact loading being one of the critical. In addition, PU elastomers exhibit wide range of mechanical properties, generally from soft (or lower stiffness) to hard (or higher stiffness), depending on the chemical composition and their characteristics. At room temperature, elastomeric PU is highly flexible, elastic, and resistant to impact, abrasion, and weather [1]. Therefore, the evaluation of structural behaviour of elastomeric PUs, and their response under wide range of temperatures, strain-rates and pressures conditions should be clearly understood.

Though the mechanical performance of elastomeric polymers under essentially static loads can be evaluated using a variety of specifications and techniques, standard test methods available for determining the dynamic response of those materials are scarce. Over the last few decades, various instrumentations and testing procedures have been developed to investigate the dynamic response of elastomeric materials. Among the various techniques used for this purpose are: Universal test machine, the Hopkinson bar testing system, the high speed impact or drop hammer testing system, the Zwick screw drive mechanical tester, various servo-hydraulic testing systems, as well as other types of customized high speed test configurations [5-16]. According to the findings of the above studies on the behaviour and the strain rate sensitivity of the elastomeric polymers, the researchers have highlighted, that the stress-strain response of most elastomeric polymer materials exhibits significant non-liner rate sensitivity under low, intermediate and high strain rate conditions [5-13].

In the present study, the authors have focussed to investigate on the tensile behaviour of two types of elastomeric Pus, from low to intermediate strain rate ranges (0.001 to 0.1 s^{-1}), using a hydraulic universal testing machine (Instron 5566 universal testing machine).

2. Experimental Programme

2.1 Materials

Palm-based polyol (PKO-p) was supplied by the Polymer Research Centre (PORCE) of Universiti Kebangsaan Malaysia. 4,4-diphenylmethane diisocyanate (MDI) was obtained from Cosmopolyurethane Sdn. Bhd., Malaysia. Acetone (industrial grade) and polyethylene glycol (PEG: Mw 200 Da) were purchased from Sigma Aldrich (M) Sdn. Bhd., Malaysia.

2.2 Preparations of the polyurethane elastomer

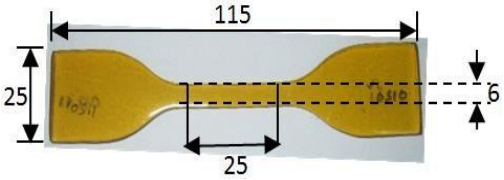
Two types of polyurethane (PU) resins were prepared by solution casting technique, from the rapid reaction between PKO-p and MDI in the presence of PEG as the plasticizer via pre-polymerisation technique. They were labelled as PU-A and PU-B comprising of 6 and 8 % w/w of PEG, respectively. The PKO-p, MDI and acetone were formulated at the ratio of 100: 80: 35. Clear yellowish and bubble-free PU films were obtained, and let to condition at ambient temperature for further characterization.

2.3 Tensile test

The uniaxial tensile tests were carried out in an Instron model 5566 testing machine under displacement controlled conditions (different crosshead speed were used to obtain different strain rates) [Figure 1(a)]. The cured pre-cast PU sheets of 3 mm thickness were cut to dumbbell shaped specimens (Die C) for tension tests as per ASTM D 412: Method-A specification [Figure 1(b)], in the same direction of the sheets, in order to minimise the effect of anisotropy or grain directionality due to the direction of the flow during the preparation and the processing of the PU sheets. The median of three measurements were used for the dimensions (width and thickness) of each samples. All test specimens were clamped

to the grip automatically with a clamping distance of 65 mm, and tested at ambient temperature with uniform rates of 1.5, 15 and 150 mm/min to attain strain rates of 0.001, 0.01, and 0.1 s^{-1} respectively. The time, load, and deflection data were recorded until the rupture of specimens.

(a)



(b)

Figure 1: The: (a) Uniaxial tensile test; and (b) Dimensions of specimens (in mm).

3. Results and Discussion

The tensile characteristics of PUs were analysed based on the experimental data and the values was obtained as an average of five sets of tests for each category

3.1 Tensile Characteristics

The tensile responses (engineering stress-strain relationship) of PU-A and PU-B are shown in Figures 2 and 3 respectively at lower to intermediate strain rates (0.001 to 0.1 s^{-1}). All stress-strain curves follow the behaviour of typical elastic-plastic material. Figures 2 and 3 indicated that the all PUs exhibited significant hysteresis behaviour during loading. The is further supported by the findings in Figure 4(a-e), which depict the variation of the Young's modulus, stress at elastic limit, tangent modulus, ultimate tensile stress, and failure strain as a function of strain rate at various increasing strain rates. In addition, the tensile strain energy response and characteristics, which are the cumulative strain energy density, resilience and toughness modulus and their ratios at increasing strain rates are illustrated in Figures 5 and 6.

3.1.1 Young's modulus

The engineering stress-strain curves indicated that the initial response in each case depicted a linear elastic region, with the average Young's modulus approaching 25.0, 44.1, and 85.8 MPa for PU-A, and 22.6, 34.5, and 70. 5 MPa for PU-B at strain rates of 0.001, 0.01, and 0.1 s^{-1} respectively. The variation of the Young's modulus of PUs with varying strain is shown in the Figure 4(a).

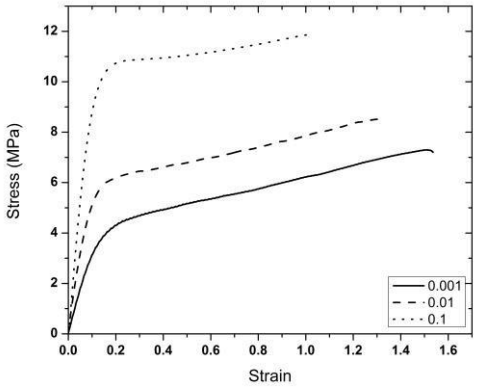


Figure 2: The engineering stress-strain curves of PU-A at varying strain rates.

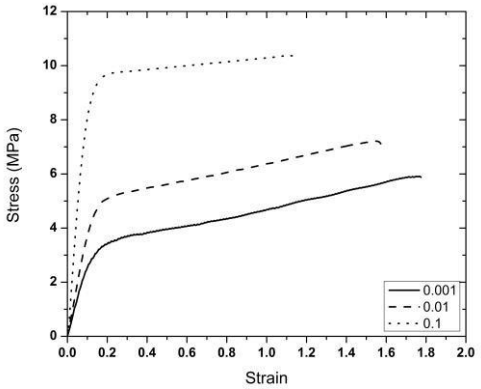


Figure 3: The engineering stress-strain curves of PU-B at varying strain rates.

As illustrated in Figures 2 and 3, both PU-A and PU-B show similar behaviour, and the Young's modulus was increased significantly with the increasing strain rate. Findings indicate the 1.8, and 3.4 increment of PU-A, and 1.5, and 3.1 increment of PU-B for strain rates of 0.01 and 0.1 s^{-1}, when compared with the Young's modulus at 0.001 s^{-1}, and they exhibited strain hardening mechanism.

3.1.2 Stress at elastic limit

Subsequently after the linear region, the PUs started yielding after reaching considerable stress and elongation for all cases [Figure 4(b)]. Within this region, it can be concluded that, the stress at

elastic limit increases significantly with increasing strain rates. In this case, the variation of the stress at elastic limit is similar for both PUs, and with the increasing trend of Young's modulus at varying strain rates. The stress at elastic limit for 0.01 and 0.1 s^{-1} strain rates, of PU-A was 1.4, and 2.6 times higher, and for PU-B was 1.6, and 2.9 times higher, than the value at 0.001 s^{-1} strain rate, though the yield strains were almost similar for all cases .

3.1.3 Tangent modulus

All PUs underwent a brief period of yielding which resulted in permanent or inelastic deformation under all strain rate conditions. Further increase in the stress above the elastic limit caused molecular breakdown of the material and result in permanent deformation. The tangent modulus defines the behaviour of the material at stress beyond its elastic limit. The variation of tangent modulus with strain rates was obtained using the findings obtained above; the respective results are presented in Figure 4(c). The tangent modulus was influenced significantly by the strain rate effects, and it decreased with increasing strain rates for both PU-A, and PU-B. In addition, PU-A showed a rapid reduction between the strain rates of 0.01 and 0.1 s^{-1} in comparison to PU-B. PU-B is more ductile due to its higher content of plasticizer. Moreover, all PUs yielded over wide range of strains. Although each PU system underwent permanent deformations, it was still able to withstand more load prior to ultimate failure.

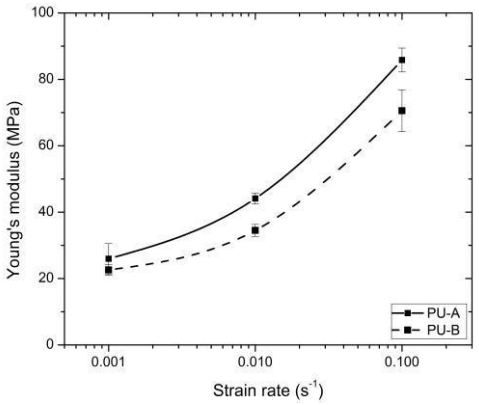
3.1.4 Ultimate Tensile Stress

The variation of ultimate tensile stress, against strain rates is presented in Figure 4(d). Higher strain rates resulted in an increase in ultimate tensile stress, up to more than 17% and 82% for PU-A and 24% and 88% for PU-B at strain rates of 0.01 s^{-1} and 0.1 s^{-1}, when compared to ultimate tensile stress at 0.001 s^{-1}. PU-A which contains lower content of plasticizer, shows higher ultimate tensile stress at all strain rates.

3.1.5 Failure Strain

The failure strain of a material is one of the key characteristic to evaluate its behaviour under different loading conditions and indicates its capability to undergo the required deformation prior to fracture. Engineers often select more ductile materials for retrofitting applications under dynamic loading events, since those materials are capable of absorbing energy or shock imparted. In addition, if the material is overloaded, it will usually provide "signs" through its deformation before failure.

The plot of failure strain versus strain rate is shown in Figure 4(e). The failure strain of PUs decreased with increasing strain rates. The materials exhibited viscoelastic characteristics, which were inclined to fail at a higher stress, but at a lower strain.



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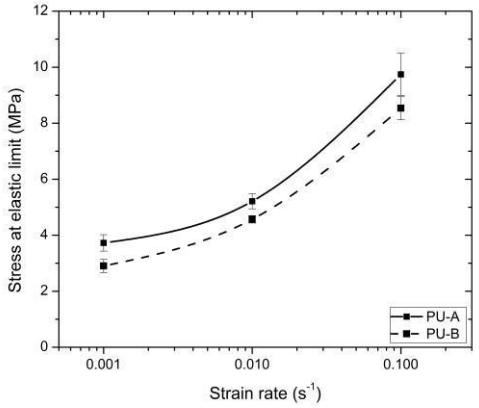

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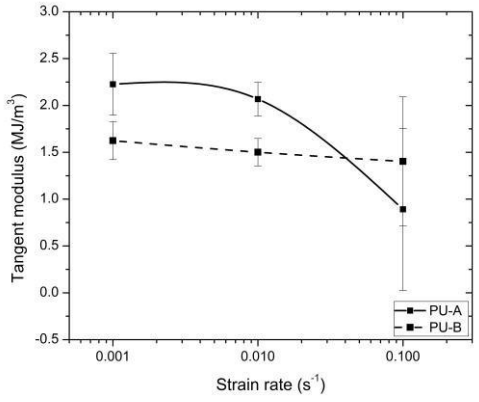

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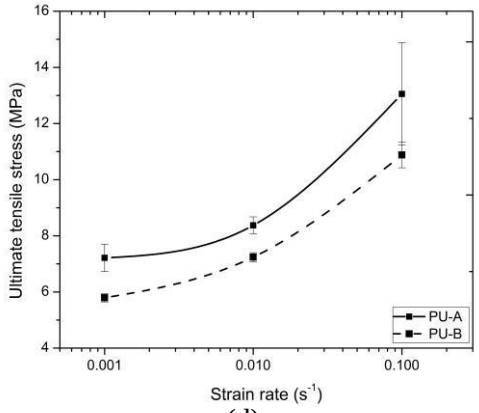

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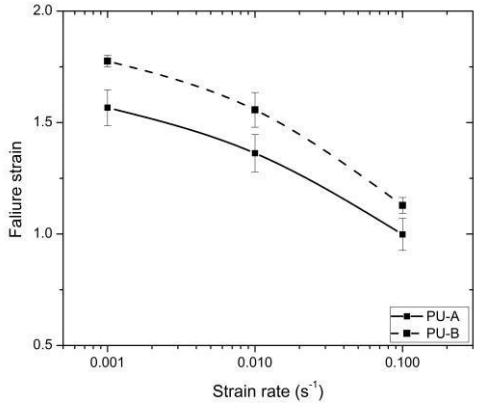


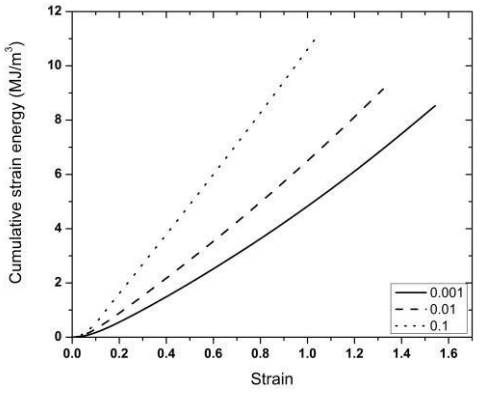
(e)

Figure 4: The tensile characteristics of the PUs at varying strain rates: (a) Young's modulus; (b) Stress at elastic limit; (c) Tangent modulus; (d) Ultimate tensile stress; and (d) Failure strain.

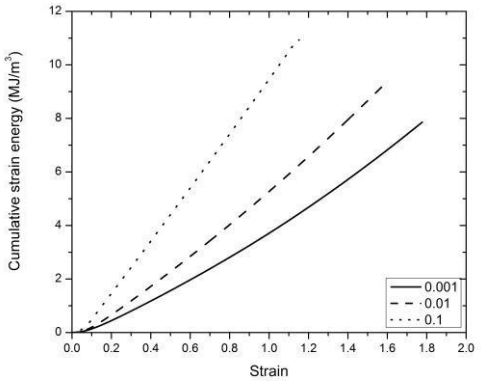
Similar observations were reported by Roland et al. [11] based on their experimental findings of uniaxial tensile behaviour of elastomeric polyurea in over a range of strain rates from 0.06 to 573 s^{-1}. Moreover, PU-B showed higher failure strain at all strain rates. The addition of plasticizer increases the chain length of the polymer, and leads to the PU sample to have a higher mobility in its molecular structure, thus reducing the stiffness of the sample.

3.2 Strain energy

The energy stored internally in a material due to change of its original shape is known as the strain energy. The strain energy per unit volume is referred to as the strain energy density, and is computed by integrating the area underneath the specific stress-strain curve up to the reference point of deformation. The energy absorption and dissipation ability of a material are a key properties that should be considered in the retrofitting application for a structural element subjected to dynamic loadings. The applied load on a material is stored as strain energy throughout its volume. The comparison of cumulative strain energy density against strain for PU-A and PU-B, is shown in Figure 5, for the three different strain rates.



(a)



(b)

Figure 5: Cumulative strain energy versus strain at varying strain rates, for: (a) PU-A; and (b) PU-B.

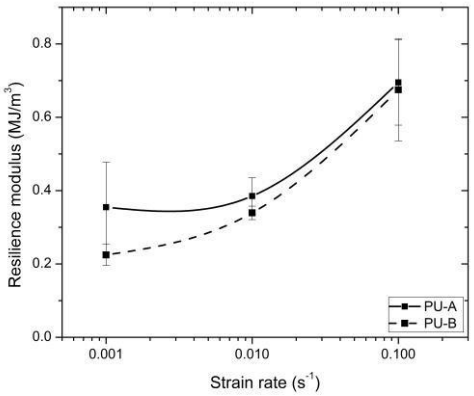
3.2.1 Resilience Modulus

In particular, due to the application of loads, the resulting deformation up to the elastic limit of the stress-strain curve, was only accompanied by the absorption of energy. The resilience modulus (U_r) is defined as the strain energy density when the stress reaches the proportional limit, and is computed by taking the area under the stress-strain curve from zero to the proportionality limit [17]. The variation of the U_r of PUs with enhancing strain rates is exhibited in Figure 6(a). Based on the results, it was deduced that the U_r tends to be increased with increasing strain rates. In addition, the difference of the U_r values of PU-A and PU-B decreased with the increasing strain rate.

3.2.2 Toughness Modulus

The toughness modulus (U_t) at varying strain rates is shown in Figure 6(b). Physically, the U_t

represents the strain energy density just before the rupture of the material, and quantify the entire area underneath the stress–strain diagram [17]. With increasing strain rate, the PUs exhibited increments in their toughness moduli.



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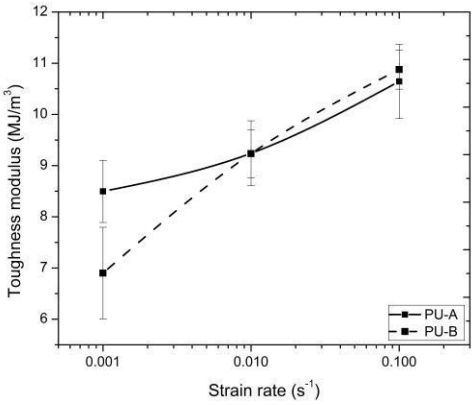

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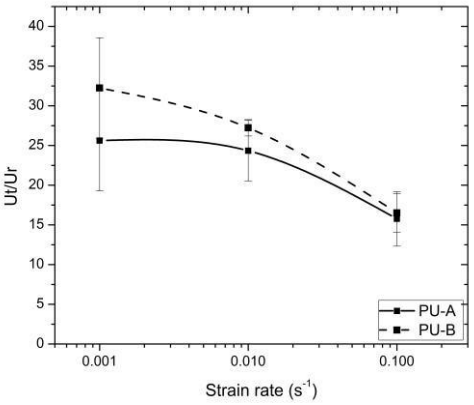

(c)

Figure 6: Strain energy characteristics of the PUs at varying strain rates: (a) Resilience modulus; (b) Toughness modulus; and (c) Ratio between toughness and resilience modulus.

While at low strain rates, PU-A exhibited lower U_t compared to PU-B, both PUs recorded almost similar values at 0.01 s^{-1}. Subsequently, at 0.1 s^{-1}, PU-B showed higher U_t value compared to PU-A. This may be due to the higher content of plasticizer in PU-B resulting in it exhibiting higher ductility. Though the U_r and U_t were enhanced with increasing strain rates, the ratio between the toughness and resilience modulus decreased for both PU-A and PU-B with increasing strain rates [Figure6(c)]. Moreover, PU-B showed higher ratio at all strain rates. While at lower strain rates, PU-B exhibited ratio which was almost 1.3 times compared to PU-A, the ratio were much closer at higher strain rates.

These outcomes suited with the objectives of the present study, to deliver PU as a retrofitting material for structures subjected to dynamic loadings. The findings implied that PU would be able to absorb considerable amount of energy throughout elastic-plastic deformations (even after yielding of the material), before undergoing total failure.

4. Conclusions

The analysis of the tensile behaviour of two types of PUs under varying strain rates which were undertaken in this research indicated the following salient points:

- Both PU-A and PU-B exhibited significant rate dependency in terms of tensile properties, namely the Young's modulus, stress at elastic limit, ultimate tensile stress, tangent modulus, failure strain and strain energy modulus.
- The stress–strain behaviour of both PU-A and PU-B at varying strain rates was considerably non-linear.
- For both types of PU, the Young's modulus, stress at elastic limit, and ultimate tensile stress were enhanced, while the tangent modulus, and failure strain was reduced, with increasing strain rates.
- Even though the U_r and U_t increased with increasing strain rates, the ratio between U_t and U_r decreased. The increment of strain energy with increasing strain rate gives a good agreement as a characteristic of strengthening or retrofitting material to resist dynamic loadings.

Acknowledgement

The authors would like to express their gratitude to the Ministry of Higher Education, Malaysia in providing the necessary funding for this research through the ERGS Grant Scheme (ERGS/1/2013/ TK03/UKM/02/6), and to the Polymer Research Centre of UKM for the generous supply of palm-based polyol through the grant ETP-2013-026.

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