

Evaluation of novel temperature-stable viscoelastic polyurea foams as helmet liner materials



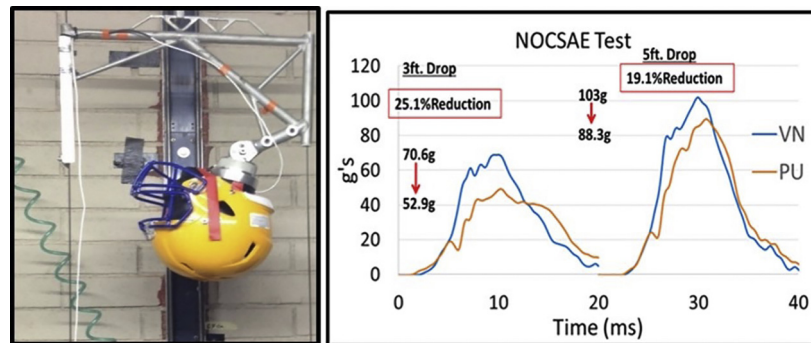
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HIGHLIGHTS

- Viscoelastic polyurea foams were manufactured that exhibit excellent temperature stability from -15°C to 50°C .
- Polyurea foams were tested using the NOCSAE and FMVSS 218 standards for the football and motorcycle helmets, respectively.
- Polyurea foam resulted in a reduction of 22% in peak g's and 25% in the Severity Index and Head Injury Criteria.
- Polyurea foam reduced the headform's peak g's by 26% at -15°C and 20% at 50°C .

GRAPHICAL ABSTRACT



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ABSTRACT

Viscoelastic polyurea foams with densities of 98, 170, and 230 kg/m^3 were manufactured and integrated into helmet shells and tested using the NOCSAE and FMVSS 218 standards for football and motorcycle helmets, respectively. For football helmet testing, a Riddell Revolution helmet shell was used. The helmets with a foam liner thickness of 28 mm were dropped using a NOCSAE medium headform (4.9 kg) from heights ranging from 0.305 to 1.524 m. All impact tests were done on the crown of the helmet and dropped on a 12.7 mm modular elastomer programmer pad. Use of PU98 foam resulted in a reduction of 22% in peak g's and 25% in Severity Index and Head Injury Criteria values when compared to helmets with the original VN600 foams under ambient conditions. These tests were repeated under varying temperatures along with a reduced liner thickness of 22.2 mm. In these tests, PU98 foam reduced the peak g's by 18% at 23°C , 26% at -15°C , and 20% at 50°C when compared to VN600 helmets. The FMVSS motorcycle helmet tests demonstrated the success of using an additional layer of polyurea foam liner on top of the existing expanded polystyrene liner in reducing the peak g's by 17%.

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1. Introduction

Use of elastomeric and plastic foams is ubiquitous in mechanical, civil, and aerospace structures and all protective head and body gears [1–4]. Most sports applications use viscoelastic elastomeric foams because of the need to take multiple impacts within the same sporting

event whereas motorcycle and bicycle helmets use plastic crushable foams to protect the wearer from occasional impacts and requires replacement of helmets after an accident [5–12]. These foams dissipate impact energy through local viscoelastic or plastic crushing processes that involve bending, twisting, and buckling of the struts that form the skeleton of their structure [13–18]. The compressive stress-strain behavior of a typical viscoelastic or a plastic foam exhibits three distinct regions: (i) a linear elastic region associated with cell wall bending, (ii) a stress plateau region that results from continuous collapse of the foam's

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cell structure on itself through non-linear fully recoverable (viscoelastic foams) or irrecoverable (plastic foams) buckling of its struts, and (iii) a densification region where the already-collapsed cells begin to compress against each other to near full density, resulting in a steeply rising stress. The amount of energy absorbed or dissipated by the foam is roughly equal to the area under its stress-strain curve [13–18].

For a given foam thickness, which is typically constrained by the specific application, the design process reduces to determining the lowest density of the foam per unit volume that maximizes impact energy absorption while keeping the peak load below the injury threshold level. For head health applications, the peak transmitted stress must be kept below 1.5 MPa [1,2]. The manufacturing technology has advanced significantly over the past two decades that any polymer can be foamed into the desired density by controlling the process variables and by use of various surfactants, foaming and gelling agents. The industrial processes are also well developed to produce foams with *uniform* microstructures in large quantities at fairly low cost. Today foams are used in practically every industry. Despite their ubiquity and maturity, there are still areas where improvements in the foam technology can be made, especially those that pertain to impact applications. These are discussed next.

Almost every current application utilizes foams with a *uniform* microstructure. Even with the choice of the lowest density, these foams are not truly optimized. This is because the initial linear response and the plateau stress which determine the impact attenuation and momentum trapping properties of the foam depend strongly on the loading rate [1–2,15–18]. The loading rate, however, changes within the same impact event. The material strain rate is lower at the start of the loading as the foam cells start to collapse, and then builds up quickly during the densification process, and finally, reduces significantly when the velocity of the impactor has slowed down considerably. One way to *further* optimize the foam's performance is to create a section with modulated stiffness or density to account for this varying material strain rate within the same loading event. Such a foam structure cannot be manufactured in a single low-cost manufacturing step. It would require lamination where foam layers of different density, stiffness, and thickness are stacked up in a specific order. In addition to being expensive, the lamination process is not easily scalable as required for production of high volume commodity products.

Another area of opportunity is improving the performance of foams at low and high temperatures. Present viscoelastic foam pad systems (e.g., vinyl nitrile, VN and thermoplastic polyurethane, TPU) become hard at cold temperatures and soft at high temperatures [19]. In both situations, the peak transmitted stress greatly exceeds the injury threshold limit. Ideal foam should have a T_g well below 0 °C so that it can maintain its viscoelastic properties over a wide range of temperatures.

Motivated by these goals, in a previous communication [3], we presented polyurea-based strain rate sensitive viscoelastic foams that

became increasingly more efficient in dissipating the impact energy as the loading rate was increased. Tests done using the Split-Hopkinson Bar setup showed that they dissipated more impact energy than the plastic expanded polystyrene (EPS) foam at strain rates $>2000\text{ s}^{-1}$ while maintaining the peak stress below 1.5 MPa. Because of the very low glass transition temperature of polyurea ($T_g = -50\text{ °C}$) they were able to maintain their ambient impact properties at low and high temperatures [20–22]. Furthermore, even with their uniform microstructure, they performed similar to foams with modulated stiffness and density. Finally, being viscoelastic, they recovered fully after each impact and were able to reproduce their energy absorbing characteristics impact after impact that were spaced 30s apart. This unique behavior was tied to their microstructure that comprised of large polyhedral cells (300 μm –500 μm) covered with perforated membranes with small apertures (20 μm –70 μm) as shown in Fig. 1. This makes the polyurea (PU) foam strain rate sensitive as the rate at which the air escapes the cells through perforations depends upon the loading rate. At lower strain rate, typically at the start of the loading event, big cells simply collapse with air escaping freely through tiny perforations. This limits excess buildup of stress like any other viscoelastic foam. As the loading proceeds, both strain rate and level of material stress increases. During this phase, the rate at which the air escapes the cells cannot catch up with the rate of loading. Consequently, the air that remains inside each cell acts to stiffen the cell while the air that escapes adds to viscoelastic damping. Finally, when the impactor velocity has substantially reduced and the strain rate has dropped, the remaining undeformed cells collapse slowly, giving plenty of time for the air to escape freely through tiny perforations. Each cell thus acts like a time-dependent viscoelastic damper on the microstructural scale. Therefore, the PU foams are able to manage the varying material strain rate that occurs within the same loading event without the need to modulate the material density or stiffness. In addition to the microstructure, energy is also dissipated by dynamic bending, twisting and rotation of the cell walls during impact like any other foam. In PU foams, cell walls are made using the polyurea elastomer which itself is capable of absorbing the impact energy through sliding and stretching of its flexible molecular chains. The micro-phase segregation of hard and soft domains along with extensive hydrogen bonding present within the polyurea structure also grants it the ability to chemically tailor its mechanical toughness, resiliency, and hardness [23–28]. The polyurea chemistry chosen for the foams presented in this paper was already optimized for maximum energy dissipation, as coating liners [29,30] and adhesives [31–33], while exhibiting exceptional strain rate sensitivity [34–36] and strength [37,38].

In this paper, the combined benefits of temperature stability and rate sensitivity of low density ($\leq 200\text{ kg/m}^3$) viscoelastic PU foams are demonstrated by integrating them as liners into football and motorcycle helmets, and evaluating their performance using the NOCSAE (National Operating Committee for Standards in Athletic Equipment) and

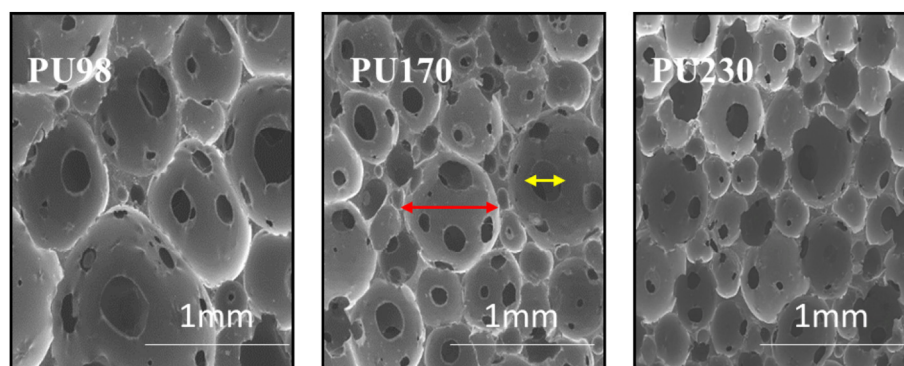


Fig. 1. Scanning electron micrographs of the microstructure of the PU foams. The red arrow shows the cell diameter (“cell size”) while the yellow arrow shows the cell aperture (“cell windows”). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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