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# An experimental-finite element analysis on the kinetic energy absorption capacity of polyvinyl alcohol sponge

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A B S T R A C T

Polyvinyl alcohol (PVA) sponge is in widespread use for biomedical and tissue engineering applications owing to its biocompatibility, availability, relative cheapness, and excellent mechanical properties. This study reports a novel concept of design in energy absorbing materials which consist in the use of PVA sponge as an alternative reinforcement material to enhance the energy loss of impact loads. An experimental study is carried out to measure the mechanical properties of the PVA sponge under uniaxial loading. The kinetic energy absorption capacity of the PVA sponge is computed by a hexahedral finite element (FE) model of the steel ball and bullet through the LS-DYNA code under impact load at three different thicknesses (5, 10, 15 mm). The results show that a higher sponge thickness invokes a higher energy loss of the steel ball and bullet. The highest energy loss of the steel ball and bullet is observed for the thickest sponge with 160 and 35 J, respectively. The most common type of traumatic brain injury in which the head subject to impact load causes the brain to move within the skull and consequently brain hemorrhaging. These results suggest the application of the PVA sponge as a great kinetic energy absorber material compared to commonly used expanded polystyrene foams (EPS) to absorb most of the impact energy and reduces the transmitted load. The results might have implications not only for understanding of the mechanical properties of PVA sponge but also for use as an alternative reinforcement material in helmet and packaging material design.



## 1. Introduction

Polyvinyl alcohol (PVA) sponges are currently in widespread use for the removal and management of diffuse fluids/blood at surgical site [1]. They are also contemplated as the most attractive biomedical polymers owing to a combination of qualities, such as biocompatibility [2–5], highly hydrophilicity [6–8], excellent mechanical strength and flexibility [4–7,9,10], thermal stability and absence of toxicity [11], availability, and relative cheapness [12]. However, the application of these versatile biomaterials has been limited to ophthalmic, plastic, and hand surgeries as a biocompatible biodegradable material.

Recently, Karimi et al. [13] characterized the mechanical properties of a fabricated PVA sponge for tissue engineering applications. Their results showed the Young's modulus and maximum stress of 40 and 9.79 MPa for PVA sponge, respectively. Further tests were also carried out to measure the Young's modulus of the PVA sponge at higher strain rates. The results revealed the Young's modulus of 4.28, 208.33, and 187.51 MPa at the strain rates of 1, 20, and 100 mm/min, respectively [14]. The Young's modulus of the PVA sponges was also measured under longitudinal (38.91 MPa) and circumferential (33.34 MPa) loads. The maximum stress, in addition, in the longitudinal direction was 17.90% greater than that of the circumferential direction [15]. The mechanical behavior of PVA sponge has shown to be similar to rubber-like materials, such as time-dependent viscoelastic behavior which can be formulated by the visco-hyperelastic approach under low strain uniaxial loading [16–19]. Considering both the advantage of biocompatibility and suitable mechanical properties of the PVA sponges, they can be used as an alternative reinforcement material to enhance the mechanical properties of the materials for biomedical or industrial applications. The suitable mechanical properties of the PVA sponges especially under fast strain rates would also enable them to be used as an energy absorber material for helmet design. However, a critical barrier to the use of the PVA sponge as an energy absorber material is a lack of knowledge on its kinetic energy absorption capacity. Among the energy absorbing materials available in the market, expanded polystyrene foams (EPS) are often used for the design of the helmet liners [20,21], due to their capability of providing multidirectional resistance to impacts, combined with light weight and relatively low costs of production and excellent kinetic energy absorption capacity [22]. A way to improve the energy absorption properties of current helmets could be the use of non-conventional materials capable of higher energy absorption, while keeping the accelerations transmitted to the head at a safe level.

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This study is aimed to introduce a novel concept of design in helmet materials which consists in the use of PVA sponge as an alternative reinforcement material to enhance the kinetic energy absorption capacity of commonly used expanded polystyrene foams. Finite element (FE) analysis of the sponge and steel ball or bullet is executed through the LS-DYNA code under impact load to compute the kinetic energy absorption capacity of the PVA sponge at three different thicknesses (5, 10, 15 mm). The kinetic energy of the steel ball and bullet is also computed after penetration in the PVA sponge.

## 2. Materials and methods

### 2.1. Materials and specimen preparation

The preparation of the polyvinyl alcohol sponge has been thoroughly described in our previous studies [15,16]. Briefly, to prepare the PVA aqueous solution, 2 g of PVA (molecular weight = 40,000, Sigma-Aldrich) was dissolved in 100 ml of distilled water at 50 °C under stirring at 400 rpm for 6 h. The polymer solution was then cast into cylindrical molds and freeze dried in order to obtain PVA spongy matrix. To improve its stability in water, the above sponge was cross-linked by exposure to the vapors of a glutaraldehyde aqueous solution (25%) at 37 °C for 24 h. After rinsed with distilled water, the sponge was freeze dried again. The final solution was poured into Petri dishes and allowed to stand at room temperature (25–30 °C) until crosslinking was completed (48 h).

### 2.2. Axial measurements

The initial dimensions of all specimens were measured precisely. The tensile test was performed using a uniaxial tensile test apparatus adapted for testing biological specimens used in our previous studies [23–29]. All tests were performed at 25 °C and each sample was tested only once. A low strain rate of 5 mm/min which is typical for surgical procedures and gives more insight into tissue behavior was employed by the action of an axial servo motor [30–32]. In order to make sure about a firm fixation of samples between the jaws of the machine a small tensile pre-load of 0.05 N was applied to each specimen. Moreover, rough sandpaper was used between the jaw and sample to assure no slip boundary. Preconditioning of spongy tissues has become a common procedure in tensile testing to assess the history dependence of spongy tissues. Therefore, ten cyclic preconditioning with a suitable pre-load based on experimental results was applied to each PVA sponge sample before any measurement begin. The sample's length was measured after the application of the pre-load. This also helped minimize the bending effect caused by the weight of each specimen.

### 2.3. Finite element model

A 3D FE model of the PVA sponge was established using the explicit dynamics finite element code LS-DYNA 970 (LSTC, Livermore, CA, United States). The kinetic energy absorption capacity of the PVA sponges at different thicknesses, including 5, 10, and 15 mm, was computed by FE analyses. The mechanical properties of the PVA sponge [13] and the steel ball or bullet [33] were assigned to the FE models. To obtain greater computational precision, the hexahedral element was used for the sponge, steel ball, and bullet. To achieve a dynamic separation and spatter effect, the elements in the PVA sponge and angle region were selected for node release. The properties of boundary element of the surface mesh for the sponge were used to determine the boundary between the sponge and fixed area. The final model of the PVA sponge along a steel ball was meshed with 4842, 9684, and 14,526 8-noded hexagonal elements besides 6377, 11,591, and 16,805 nodes for 5, 10, and 15 mm thickness, respectively. An FE model of a 6.3 mm steel ball (1.03 g) was meshed with 6984 8-noded hexagonal elements and 7939 nodes. The final model of the PVA sponge along a bullet was meshed with 27,018, 54,036, and 81,054 8-noded hexagonal elements plus 31,017, 59,241, and 87,465 nodes for 5, 10, and 15 mm thickness, respectively. An FE model of a 7.62 mm pointed-nose bullet (7.92 g) was meshed with 5440 8-noded hexagonal elements and 6490 nodes. Since the bullet consisted of a carbon steel core and a copper jacket, the bullet and the steel ball were both classified as low-carbon steel materials in this analysis. The material model for the sponge, steel ball, and bullet was *MAT_PIECEWISE_LINEAR_PLASTICITY, which was *MAT type 24 in LS-DYNA version 970. The material properties of the PVA sponge, steel ball, and bullet are listed in Table 1.

### 2.4. Numerical simulation

The numerical simulations were performed using the nonlinear explicit FE code LS-DYNA version 970. In the current simulation, the elements of the sponge surfaces region of the FE model were fixed in the **X**, **Y**, and **Z** directions. An entire simulation lasted 80 μs, with time increments of 1 μs. The post-processing software (LS-PREPOST of LS-DYNA) simulated and measured the stress distribution in each region when the model was hit by the steel ball or bullet.

During the simulation, three different thicknesses for the sponge were used. The steel ball and bullet also were shot with the same angle. An impact velocity of 734 m/s was used for the steel ball and bullet. The kinetic energy of the steel ball and bullet when they penetrated the sponge at three different thicknesses (5, 10, and 15 mm) was calculated using FE modeling results. The energy loss from the projectile was determined using the formula $\Delta\mathbf{E} = \mathbf{m}(\mathbf{v}_1^2 - \mathbf{v}_2^2)/2$, where $\Delta\mathbf{E}$ is the energy loss, $\mathbf{v}_1$ is the impact velocity, and $\mathbf{v}_2$ is the residual velocity, to study the degree of damage that was produced when the steel ball or bullet penetrated the sponge. Therefore, the energy loss was calculated to investigate the damage efficiency of the sponge.

### 2.5. Statistical analysis

Data were first analyzed by analysis of variance (ANOVA); when statistical differences were detected, Student's **t**-test for comparisons between groups was performed using SPSS software version 16.0 (SPSS Inc., Chicago, IL, USA). Data are reported as mean ± std at a significance level of $\mathbf{p} < 0.05$.

## 3. Results and discussion

PVA sponges possess many attractive features, such as biocompatibility, thermal stability, availability, and relative cheapness. However, the application of these versatile biomaterials is limited to biomedical and tissue engineering [34]. The excellent mechanical strength of PVA sponges enables them to be used as an energy absorber material for biomedical and industrial applications. Computing the kinetic energy of PVA sponges is, therefore, an important part of a comprehensive evaluation of their kinetic energy absorption capacity. With that in mind, the purpose of this study was to quantify the kinetic energy of a PVA sponge intended for use as an energy absorber in helmet and packaging material design. The kinetic energy absorption capacity of PVA sponge was computed through gunshot finite element modeling by the steel ball and bullet.

**Table 1**
Material properties of the finite element models.

| Material properties | Bullet and steel ball (low-carbon steel) | Polyvinyl alcohol sponge |
|---|---|---|
| Young's modulus (MPa) | 210,000 | 40 |
| Poisson's ratio | 0.284 | 0.499 |
| Yield stress (MPa) | 260 | 9.790 |
| Failure strain (%) | 0.330 | 0.660 |