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Test Method

Dynamic compressive strength and crushing properties of expanded polystyrene foam for different strain rates and different temperatures

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ABSTRACT

In this study, static and dynamic compression and crushing tests were conducted on expanded polystyrene (EPS) foam for material characterisation at high strain rates. This was done to obtain the stress-strain curve for different temperatures and densities. An influence of the strain rate on the experimental data was shown. The resulting curves for modelling were extracted from the experimental data, which were obtained from high speed drop tower tests. The methodology for the processing of the experimental data for use in the finite element (FE) modelling was presented. The foam material model of LS-Dyna was used to simulate the dynamic compression process. This model is dedicated to modelling crushable foam with optional damping, tension cut-off, and strain rate effects. The adjustment of the material parameters for successful modelling has been reported. This FE model of EPS foam was validated with experimental data using impact on a “kerbstone” support. This model can be applied for simulation of dynamic loads on a bicycle helmet. It is useful for designing a reliable bicycle helmet geometry for different types of accidents.

1. Introduction

Foam is used for energy management in a helmet. There are many types, but EPS foam is the choice for most bike helmets, because it has a high energy absorbing efficiency [1,2]. Several remarkable properties have been noted for EPS foam such as: light weight, good thermal insulation, moisture resistance, durability, acoustic absorption and low thermal conductivity, reduction on material costs, excellent energy dissipation properties [3].

The foam in a helmet fulfils two impact-mitigating functions. First, it redistributes a localised external force over a larger area, reducing the local stress on the skull. Second, it sets an upper limit to the magnitude of this distributed force, as determined by the plateau-stress of the foam. The key step in selecting a suitable helmet liner material is to define the acceptable maximum value for this distributed force. Dynamic processes in this type of materials show interesting physical phenomena. An optimal energy-absorbing material needs to dissipate the kinetic energy of the impact while keeping the force on it below a certain limit, thus resulting in a non-dangerous deceleration on the occupants [1]. Of course, also the geometry of the protective structure will affect the load distribution during impact and the capacity to absorb elastic energy, which controls rebound.

EPS foams are well suited for the above mentioned application. They can undergo large compressive deformation and absorb energy. Energy is dissipated through cell bending, buckling or fracture, but the stress is generally limited by the long and flat plateau of the stress-strain curve [4]. This behaviour explains the high energy efficiency that can be obtained with foamed materials. Moreover, for the same amount of dissipated energy, a foam specimen always gives a maximum force lower than a corresponding solid specimen of equal volume made of the same

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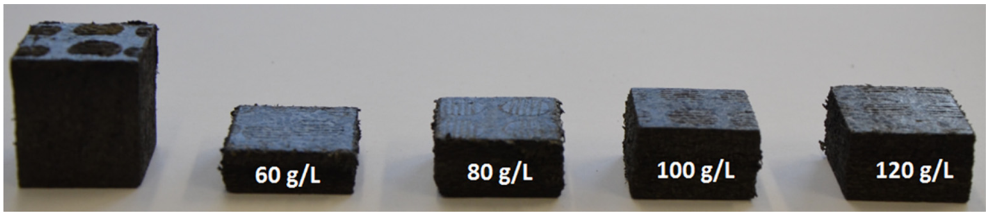

Fig. 1. Results of dynamic compression test of EPS foam at high temperature ≈50 °C.

Table 1
Average foam parameters, obtained from ten specimens.

Nominal density from manufacturing, g/L	60	80	100	120
mass, g	1.15	1.43	1.94	2.12
Volume $\cdot 10^3$, mm^3	16.13	16.25	16.90	16.25
Density $\cdot 10^{-8}$, kg/mm^3	7.16	8.82	11.50	13.10
Relative density $\cdot 10^{-2}$, kg/mm^3	7.16	8.82	11.50	13.10
Young's modulus, MPa	50.50	60.37	70.83	80.12
Poisson's ratio	0.225	0.210	0.200	0.175

material. EPS foam is also relatively insensitive to temperature changes as compared to most other closed cell foams. It keeps its energy absorbing capacities in both cold (−20 °C) and hot conditions (+50 °C), as defined by the European bicycle helmet standard EN1078 [5]. Insight into the dynamic behaviour of the EPS will help creating a FE model of this material, while it may also aid to seek for alternatives.

The foam density has an influence on the foam microstructure and accordingly on the properties of the foam [6,7]. The performance of foams has thus to be studied as a function of several parameters such as density, microstructure and also the strain rate imposed during dynamic loading. These studies have been summarised in several publications [4,8,9]. The compressive stress—-strain behaviour of these foams has been investigated over a wide range of engineering strain rates from 0.01 to 1500 s^{-1} in order to demonstrate the effects of foam density and strain rate on the initial collapse stress and the hardening modulus in the post-yield plateau region. Unfortunately, none of these studies were done on EPS foam. The data in these papers can help to construct and validate predictive models, however, because this material is multiscale (constitutive beads at the mesoscopic scale, that are made of microscopic closed cells) [10–12].

The results of an extensive experimental investigation into the static and dynamic mechanical properties of EPS foam were presented in a paper by Wensu Chen et al. [13]. This paper presents

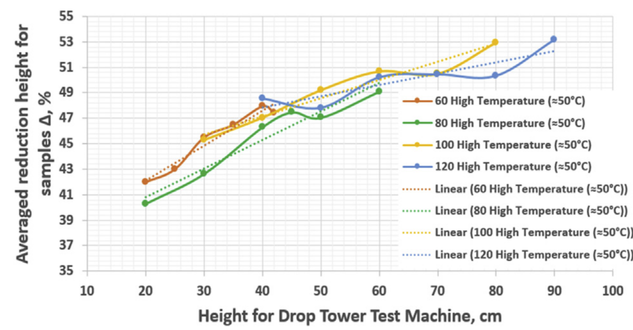

Fig. 3. The thickness reduction in the foams for high temperature (≈50 °C).

static and dynamic compressive and tensile test data of EPS with densities of 13.5 kg/m^3 and 28 kg/m^3 at different strain rates. The dynamic strength, Young's modulus and energy absorption capacities of the two EPS foams at different strain rates were obtained and presented in the paper. Based on the testing data, some empirical relations were derived. However, they did not explain how to apply the data from the experimental results. It is very important, because the strain rate in the test is not a constant. The observed maximum compressive strain rate in their experiment was approximately 280 1/s, not 533 1/s as expected. Some testing results of the EPS foam under dynamic and static compressive loading have also been reported in the literature [14,15]. This data has been used to investigate a common foam constitutive model, and shows that strain rate effects become more pronounced at rates above approximately 1000/s. This work did not present a numerical model which can be used to predict EPS properties in simulations of dynamic responses to impact loads.

There are only a few articles about modelling EPS foam, especially with high dynamic strain rate. Quasistatic compression tests were conducted on the EPS crushable foam for material

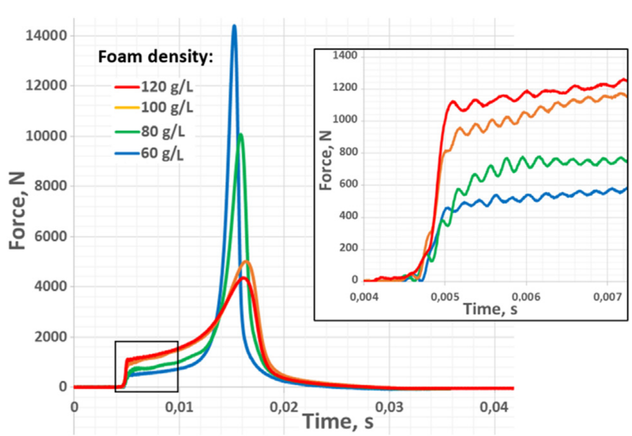

Fig. 2. Dynamic compression test results (room temperature (≈18 °C)).

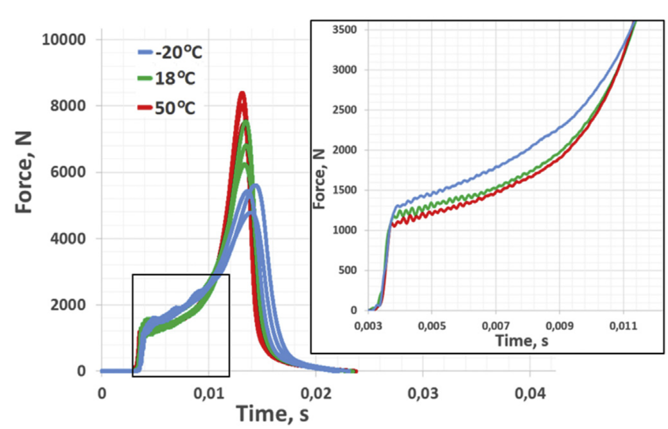

Fig. 4. Temperature effect during dynamic compression test (Foam density = 120 g/L).