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Influence of Strain Rate and Temperature on Compressive Properties and Energy Absorption Efficiency of Expanded Polystyrene and Flexible Polyurethane Foam

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1. Introduction

Polymer foam is a typical cellular structure material with buffering and energy-absorbing ability, which is widely used in impact buffer packaging, protective structure, soft filling of sofa mattresses, transportation construction and military application fields [1-4]. The mechanical properties of polymer foams are similar to cellular structural materials, and the stress-strain curve has a wide stress plateau, which can be expressed in three stages of the linear elastic response under small deformation, the plateau phase where a large amount of energy is absorbed, and the densification phase where the foam cells are compacted.

Most polymer foam properties are sensitive to strain rate, density and temperature, which are one of the most critical parameters affecting the mechanical properties and cushioning energy absorption properties of polymer foams [5-8]. Therefore, much investigation focuses on the mechanical properties of polymer foam materials under different loading conditions. Song [9] investigated the quasi-static and dynamic properties of polystyrene foam using a hydraulic testing machine and SHPB device and analyzed the trends of elastic modulus and yield stress as a function of strain rate. Based on the compression test of polyethylene foam at different loading rates, Tateyama [10] revealed that polyethylene foam has strain rate sensitivity, and the strength strain rate sensitivity is affected by the flow of gas in the foam. Ouellet [11] studied the influence of sample size on the mechanical properties of two polymer foams in high strain rate tests using Hopkinson bar and found that the sample size effect of polystyrene foam is distinct, and the strain rate effect can even be ignored. Karagiozova [12] studied the energy absorption capacity of reinforced foams with different densities and strengths under quasi-static and dynamic conditions. It was found that the strength has a greater effect on material properties during quasi-static compression, whereas density has a greater effect on material properties at high strain rates. Triantafillou [13] investigated the mechanical properties of polyurethane foam (PUF) materials and found that the effect of density under compressive loading condition is greater than that of tensile loading. Linul [14, 15] studied the quasi-static and dynamic fracture behavior of polyurethane foams with different densities at room temperature and low temperature, and analyzed the effects of parameters such as density, loading speed, material orientation and temperature on the dynamic compression behavior of rigid polyurethane foams. It was found that density and temperature were the main parameters affecting fracture toughness. Density, loading speed, material orientation and temperature are all key parameters affecting the compressive properties of polyurethane foams. In general, the elastic modulus and plateau stress of polymer foams increase with density, while the densification strain decreases with density. The strain rate sensitivity of polymer foams is manifested as an increase in plateau stress level and a decrease in densification strain with strain rate increasing. The strain rate sensitivity of polymer foams is mainly attributed to the viscoelastic properties of the matrix material, the extrusion mechanism between adjacent deformed cells, the movement and friction of air within the cells. That is the sensitivity of polymer foams to strain rate is macroscopically affected by material density and temperature [16].

Due to different manufacturing methods and matrix materials, polymer foam materials exhibit two forms of open cells and closed cells in macrostructure and have completely different mechanical properties. Expanded polystyrene foam (EPS) is a typical closed cell material and has the characteristics of light weight, good thermal insulation, strong rigidity, irreversible compression, and recyclability. It is widely used in impact buffer packaging, protective helmets, and traffic construction field. Flexible polyurethane (FPUF) foam is a typical open-cell structural material with the characteristics of compression rebound, low density, good elastic recovery, sound absorption, ventilation, and heat preservation. It is mainly used as furniture pads, seat pads and soft cushioning material. FPUF is often used as impact buffering, shockproof packaging, filtering, sound insulation, and thermal insulation material in industry and civil engineering fields. As typical polymeric foam materials, the mechanical properties of EPS and FPUF foams have been extensively studied in recent years. For mechanical properties of EPS, Di Landro [17] found the EPS density is a key parameter to increase the energy absorption capacity. Chakravarty [18] believed that the change in the properties of foamed plastics at high strain rates was due to the change in the compressive properties of the gas. Vejelis [19] investigated the EPS sample thickness effect on the shear strength and shear elastic modulus. Avalle [20] pointed out that EPS can dissipate kinetic energy and reduce force transmission under impact conditions. For mechanical properties of FPUF, Yang [21] studied the mechanical properties of polyurethane foams by macroscopic experimental tests. Scarfato [3] studied the structure and mechanical properties of mattresses filled with flexible polyurethane foam. Piotr Rojek [22] studied the effect of biopolyols on the mechanical properties, resilience, apparent density, and cellular structure of synthetic foams. Markus [23] provided a method to control the shrinkage properties of closed-cell foams by the degree and duration of overpressure applied during foam synthesis.

In summary, as typical polymer foam materials, EPS and FPUF are widely used in the field of buffer protection. In order to study the mechanical properties and energy absorption properties of EPS and FPUF foams under external load loading, the uniaxial large deformation compression experiments were carried out for the two polymer foams at strain rates ranging from 1 s^{-1} to 100 s^{-1} and at low and room temperature. The effects of strain rate and temperature on the mechanical properties and energy absorption properties of EPS and FPUF were comprehensively studied. Due to the complexity of the microstructure of foam materials, there is still a lack of accurate constitutive relation models under various mechanical conditions. Therefore, according to the experimental results, combined with the Sheerwood-frost constitutive model theory [24], the relationship of the variables such as stress, strain, strain rate, and temperature is established.

2. Experiments methods

Expanded polystyrene foam has high energy absorption efficiency and is widely used as energy absorption or energy management material, but the non-recoverable characteristics after compression deformation limit the applications in many fields. The mechanical properties of Flexible polyurethane foam are different from that of EPS. Its energy absorption efficiency is low, but it has good elasticity, especially after multiple loadings, it can still maintain good recovery, and has good dimensional stability after small permanent deformation. The EPS and FPUF foam samples used for the uniaxial compression large deformation experiment are 50 mm × 50 mm × 50 mm cubes. The density of EPS sample is 44 kg/m^3, and the density of FPUF sample is 78 kg/m^3. Samples of the two materials after compression tests are shown in Fig. 1.

The experiments were carried out at two temperatures of room temperature (20°C) and low temperature (-2°C), and at three different loading rates (0.05 m/s, 0.5 m/s and 5 m/s). Six loading conditions are taken into account and the deformation is to 80% for the compression tests. The characteristic parameters and experimental testing conditions of each sample are shown in Table 1.

a

b

Fig. 1 Test samples of EPS (a) and FPUF (b)

Table 1

Materials and test matrix

Material	Density, kg/m^3	Loading speed, m/s	Experimental temperature, °C
EPS1	43.5	0.05	20
EPS2	43.5	0.5	20
EPS3	43.5	5	20
EPS4	43.5	0.05	-20
EPS5	43.5	0.5	-20
EPS6	43.5	5	-20
FPUF1	77.8	0.05	20
FPUF2	77.8	0.5	20
FPUF3	77.8	5	20
FPUF4	77.8	0.05	-20
FPUF5	43.5	0.5	-20

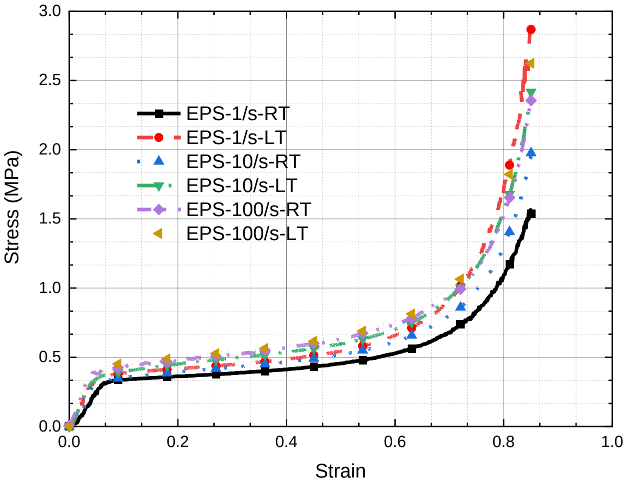
3. Experimental results

The compressive stress-strain curves of EPS at different loading conditions are shown in Fig. 2, a. It behaves the three-stage characteristics of typical closed-cell foam. The linear elastic stage exists in a small strain range, the stress-strain in the small strain range is close to a straight line, and the slope can be regarded as the elastic modulus of EPS. When the strain increases to a certain value, the curve enters the plastic yield plateau stage. In the plateau stage, the stress is almost constant with the increase of strain, which indicates that the EPS material can absorb much compression energy while maintaining a low stress level during the compression process. Hardening occurs during the densification stage when the EPS material stress increases sharply with increasing strain. It is disadvantageous for impact protection. Comparing with the EPS material, the three stages of the stress-strain curve of the FPUF material shown in Fig. 2, b. are not obvious, the trend of the linear elastic stage and the plateau stage are small, and the elastic modulus and the plateau stress are much smaller than those of EPS, which also shows that the performance of FPUF cushioning energy absorption is far less than that of EPS, which is why FPUF is rarely used in the field of impact protection.

Sheerwood [31] established a comprehensive constitutive relation framework for foamed plastics by experimental investigation on the compressive mechanical properties of polyurethane foams, combining strain rate, density, and ambient temperature. In this framework, temperature, density, and strain rate are taken as independent influencing terms to the stress-strain relationship, and the equation:

$$\sigma_s = H(T)G(\rho)M(\varepsilon,\dot{\varepsilon})f(\varepsilon), \tag{1}$$

where: $f(\varepsilon)$ epresents the functional curve of the stress-strain relationship, $M(\varepsilon,\dot{\varepsilon})$, $G(\rho)$, $H(T)$ represent the strain rate, density, and temperature influence terms respectively. In order to compare the mechanical properties and energy-absorbing properties of EPS and FPUF at different temperature and strain rate conditions, the effect of density on the mechanical properties of EPS is not discussed and the $G(\rho)$ term is set to 1.



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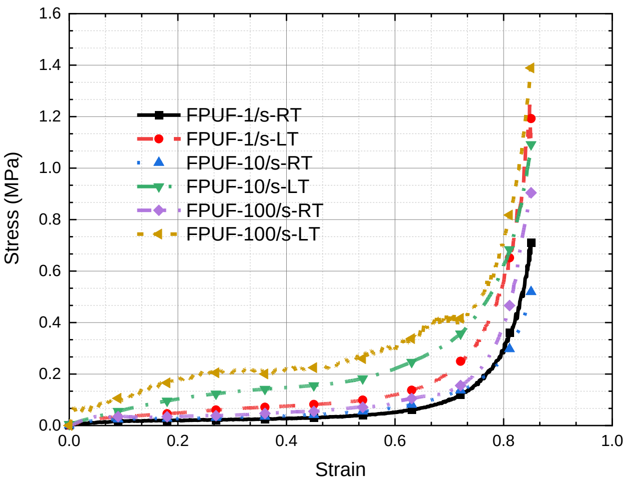

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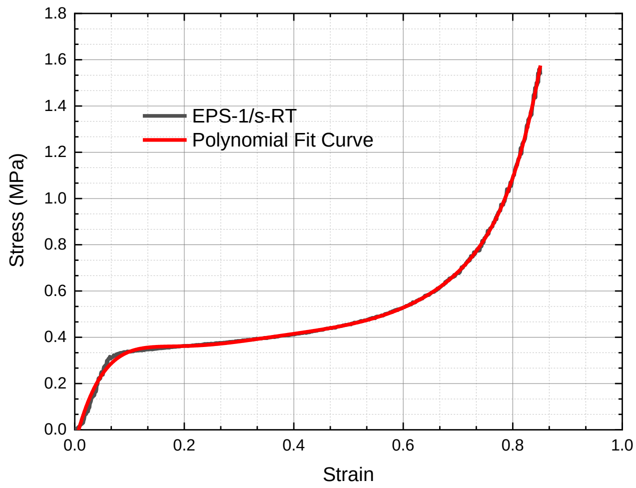
Fig. 2 Stress- strain curve of EPS (a) and FPUF (b)

According to the Sheerwood-frost model, the shape function can reflect the trend of the stress-strain curve of the material. The polynomial function is selected as the shape function of the uniaxial compressive stress-strain curve of the foam material. The accuracy of the shape function increases with the value of n. Take 7 for n in combination with the experimental data, and the specific function form is shown as:

$$f(\varepsilon) = \sum_{i=1}^{n} A_i \varepsilon^i + B. \qquad (2)$$

Taking the stress-strain data at room temperature of 20°C and the loading rate of 0.05 m/s as the reference value, combined with the experimental data, take n as 7 for shape function fitting. The shape function is fitted by the least squares method, the fitting result is shown in Fig. 3, and the relevant parameter values are shown in Table 2 and Table 3.



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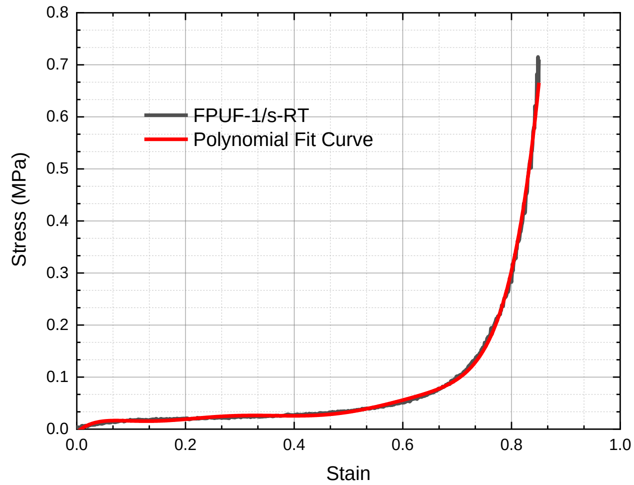

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Fig. 3 EPS (a) and FPUF (b) shape function fitting curve

Table 2

EPS material property parameters

Parameter	A1	A2	A3	A4	A5	A6	A7	B
Value	9.3794	-84.116	391.12	-1015.4	1496.1	-1171.5	381.39	-0.062

Table 3

FPUF material property parameters

Parameter	A1	A2	A3	A4	A5	A6	A7	B
Value	0.9254	-13.967	98.507	-354.21	674.44	-647.42	247.35	-0.0062

4. The effect of strain rate on the mechanical properties

According to the EPS and FPUF stress-strain curves shown in Fig. 2, It indicates the mechanical properties of two materials have strong strain rate sensitivity. When the room temperature is constant, the mechanical properties parameters (such as the elastic modulus, yield stress, plateau stress) of EPS and FPUF increase with strain rate increasing. While the densification strain and yield strain decrease with strain rate increasing, and the mechanical properties of the two materials show a strain rate strengthening effect.

Important properties of foam materials include high specific energy absorption and transmit stress, and the absorbing energy per unit volume of the foam material during compressive loading is approximately below the stress-strain curve [25]. The compression energy absorption performance of foam can be expressed by the strain energy W absorbed per unit volume during the deformation process.

$$W = \int_0^{\varepsilon_m} \sigma d\varepsilon, \tag{3}$$

where: σ represents the flow stress, which is a function of the strain ε and W is equivalent to the area under the compression curve when the strain is ε_m. Therefore, the shape and position of the compression curve can reflect the level of energy absorption of foam material.

Miltz [26] proposed to use the energy absorption efficiency E (Efficiency) and the ideal energy absorption efficiency I (Ideality) to evaluate the energy absorption characteristics of foam materials.

$$E = \frac{\int_0^{\varepsilon_m} \sigma d\varepsilon}{\sigma_m}, \tag{4}$$

$$I = \frac{\int_0^{\varepsilon_m} \sigma d\varepsilon}{\sigma_m \varepsilon_m}, \tag{5}$$

where: ε_m and σ_m are the arbitrary strain and its corresponding stress respectively. This formula expresses that the energy absorption efficiency E is the ratio of the energy absorbed by the foam to the corresponding stress, and the ideal energy absorption efficiency I is the ratio of the energy absorbed by the foam to the corresponding stress and strain. Efficiency can often be used to determine the optimal energy-absorbing working state of a foam material for a given working condition. Ideality is often used to evaluate the energy absorption of different foam materials.

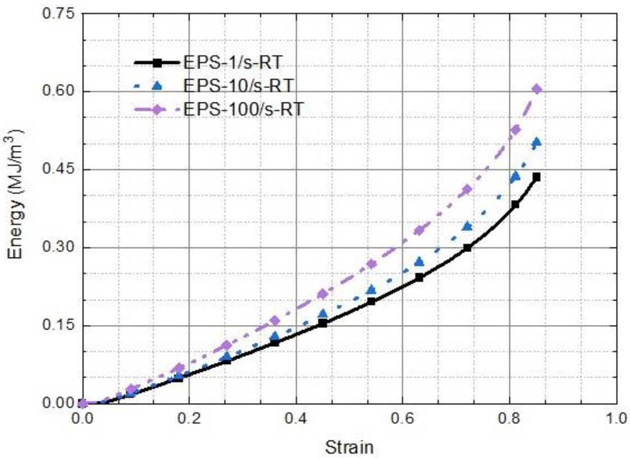
Based on the formulas (3) - (5) and the stress-strain curves of EPS and FPUF, the strain energy absorption and energy absorption efficiency and ideal energy absorption efficiency curves of EPS and FPUF under various working conditions are shown in Figs. 4 and 5. It means the foam absorbs very little energy in the linear elastic stage and assumes most of the energy absorption in the plateau stage. As FPUF is with low plateau stress, the strain energy absorbs far less energy than EPS.

The energy absorption efficiency and ideal energy absorption efficiency of FPUF materials and EPS materials are basically not affected by strain rate changes in Figs. 4 and 5. The EPS strain is around 0.33 to achieve the maximum ideal energy absorption efficiency of 0.82 and maintains it around 0.62 to achieve the maximum energy absorption efficiency of 0.45. FPUF reaches the maximum ideal energy absorption efficiency of 0.78 when the strain is around 0.28 and reaches the maximum energy absorption efficiency of 0.31 when it remains at around 0.51. It also shows that the buffer energy absorption performance of FPUF is far inferior to EPS materials. According to the energy absorption efficiency and ideal energy absorption efficiency in the strain range of the two materials, the obtained strain energy absorption of EPS changed from 0.10-0.24 MJ/m^3 to 0.24-0.34 MJ/m^3, and FPUF changed from 4.67 -12.20 MJ/m^3 to 8.90-22.77 MJ/m^3. It indicates that EPS and FPUF have higher energy absorption capacity at high strain rate, but the strain rate does not affect the optimal energy absorption state of the material itself.

Table 4

Mechanical property parameters

Materials	Parameters	1 s^{-1}	10 s^{-1}	100 s^{-1}
EPS	Yield stress, MPa	0.304	0.319	0.434
	Yield strain	0.058	0.048	0.037
	Plateau stress, MPa	0.041	0.462	0.577
	Compact strain	0.489	0.476	0.452
FPUF	Yield stress, MPa	0.016	0.022	0.031
	Yield strain	0.051	0.057	0.034
	Plateau stress, MPa	0.026	0.039	0.051
	Compact strain	0.464	0.440	0.395



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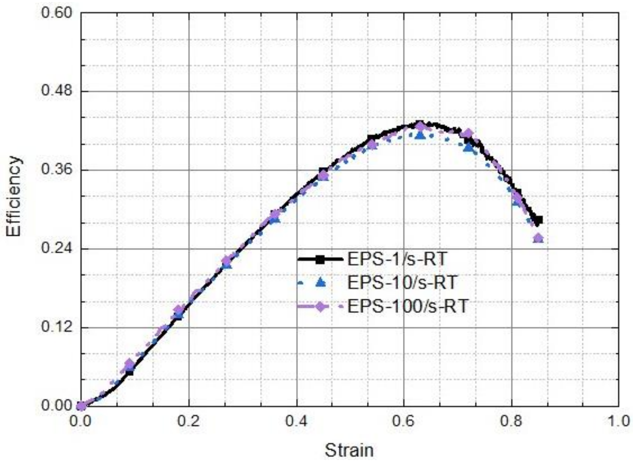

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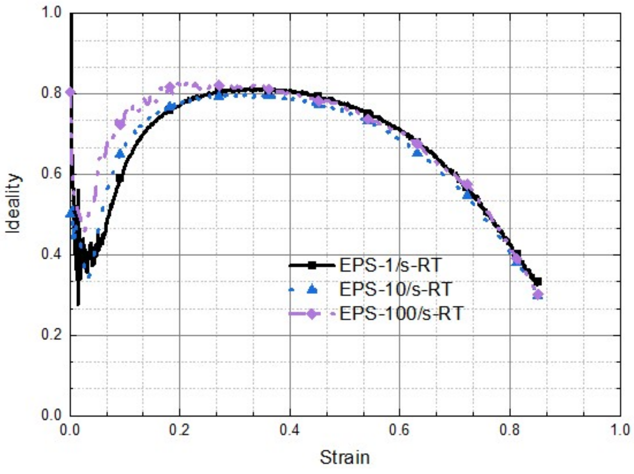
Fig. 4 EPS energy effectiveness curve at 20℃: strain energy-strain curve (a); efficiency-strain curve (b); ideality-strain curve (c)



c

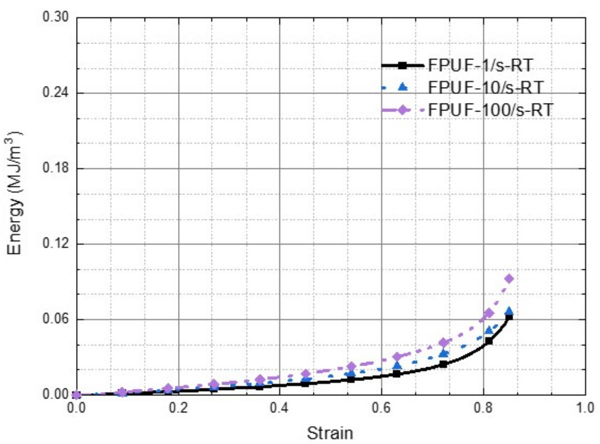
Fig. 4 Continuation

Based on the theory of the sheerwood-frost constitutive model, the parameters of the strain rate term $M(\varepsilon, \dot{\varepsilon})$ were fitted. To quantify the effect of strain rate on the mechanical properties of the foam, the stress-strain data at 1/s is taken as the reference curve. Take the stress ratios of 10/s and 100/s to 1/s at room temperature, the stress ratios of 10/s and 100/s to 1/s at low temperature as the ordinate and take the strain as the abscissa. The effect of strain rate on stress ratio curve of EPS and FPUF is shown in Fig. 6. Ignoring the linear elastic stage, the stress ratio curve is roughly a linear function when the strain is between 0.05 and 0.6 in Fig. 6a. It means that the effect of strain rate on the mechanical properties of EPS increases linearly with strain increase in the plateau stage. Therefore, the influence term of the strain rate in the EPS constitutive model is:

$$M_E(\varepsilon, \dot{\varepsilon}) = \left[a_1 ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) + a_2 \right] + a_3 ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) + a_4.$$

According to the fitting curve, the parameter values are as: $a_1 = -0.0061$, $a_2 = 0.203$, $a_3 = 0.107$, $a_4 = 0.804$.

The effect of strain rate on the mechanical properties of FPUF is shown in Fig. 6, b. It indicates that strain rate effect increases with the strain, reaches a peak at the strain 0.2 and then decreases with the strain increasing.



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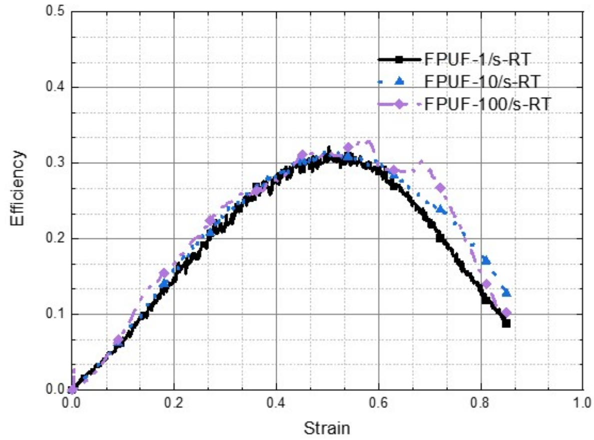

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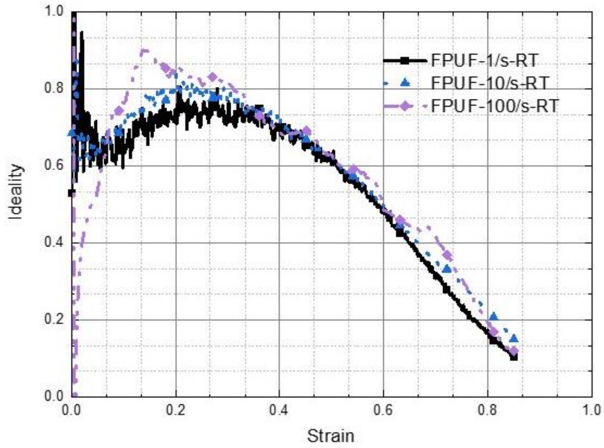

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Fig. 5 FPUF energy absorption curve at 20°C: strain energy-strain curve (a); efficiency-strain curve (b); ideality-strain curve (c)

Therefore, the strain rate effect term of FPUF is taken as a power function:

$$M_F(\varepsilon, \dot{\varepsilon}) = b_1 \ ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\varepsilon^{0.5} + b_2 ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right).$$

Finally, according to the fitting curve, the parameters are obtained as $b_1 = 0.2073$, $b_2 = 1.250$.

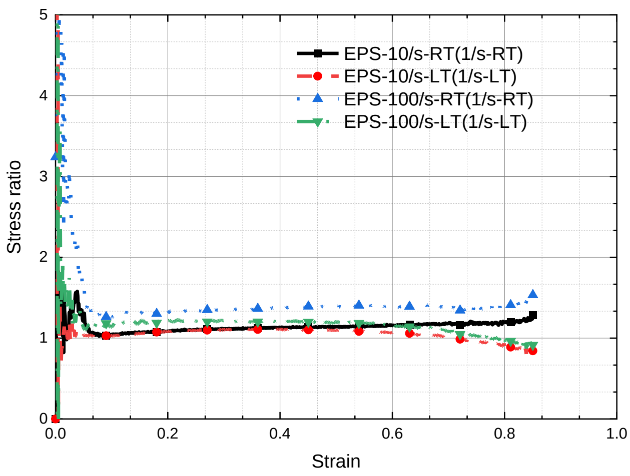

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Fig. 6 Effect of strain rate on stress ratio curve of EPS (a) and FPUF(b)

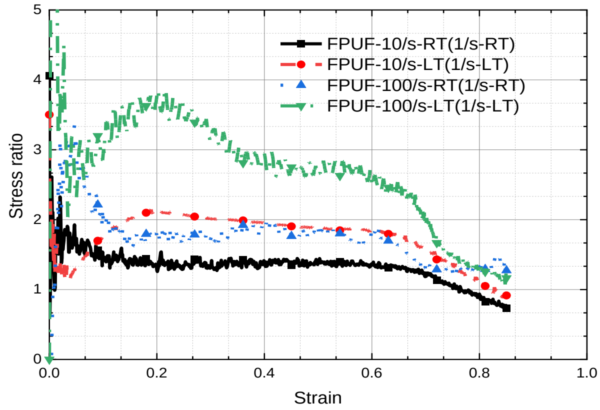

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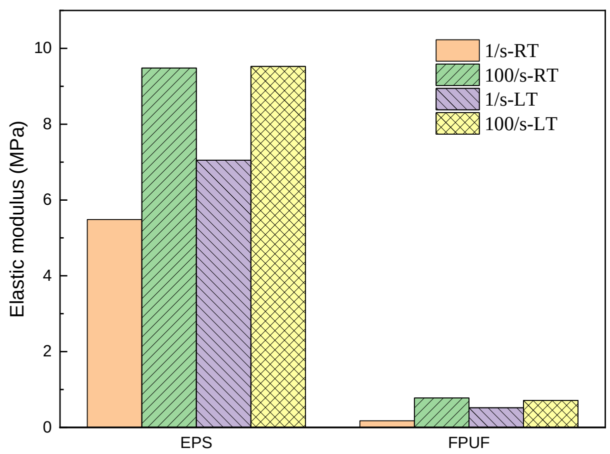
Fig. 6 Continuation

5. The effect of low temperature on the mechanical properties

As shown in the stress-strain curve of EPS in Fig. 7. The elastic modulus and plateau stress of EPS material in low temperature environment are significantly stronger than those in room temperature environment. The elastic modulus of EPS material increases with temperature decreasing. However, the effect of low temperature on the mechanical properties of EPS materials (including parameters such as elastic modulus, yield stress, plateau stress, densification strain, etc.) decreases significantly with the strain rate increasing. when the strain rate reaches 100/s, the yield stress and plateau stress at room temperature are basically the same as those at low temperature. It can be concluded that the effect of low temperature on the mechanical properties of EPS at high strain rate is negligible compared to the effect of strain rate. Although high strain rate and low temperature can enhance the mechanical properties of FPUF, unlike EPS, the effect of low temperature on the mechanical properties of FPUF does not weaken with the strain rate increasing. The cause may be that air in the cells of the open-cell structural foam is more severely affected by temperature. The energy absorption performance of EPS and FPUF foam plastics at low temperature is significantly enhanced compared with that at room temperature, and the low temperature strengthening effect has a greater influence on FPUF.

The energy absorption capacity of EPS material increases from 236.3 kJ/m^3 to 281.7 kJ/m^3 at 1/s strain rate in Fig. 8, and the energy absorption capacity of FPUF material increases from 14.8 kJ/m^3 to 37.6 kJ/m^3 at 1/s strain rate in Fig. 9. The Magnitude of low temperature effects on the energy absorption of EPS and FPUF is about 19.2% and 154%. Based on the energy absorption efficiency and ideal energy absorption efficiency curves of EPS and FPUF, it means low temperature does not affect the optimal energy absorption level of EPS and FPUF.



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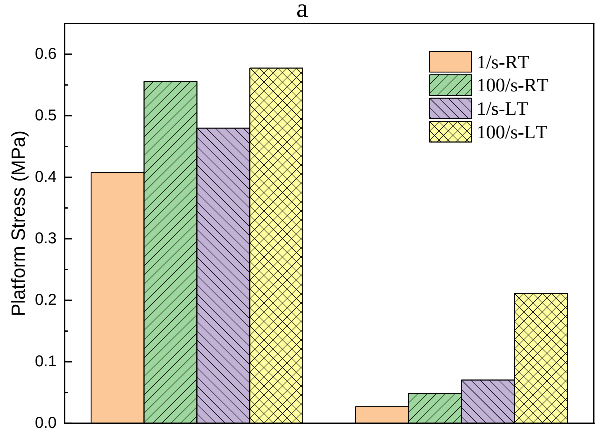

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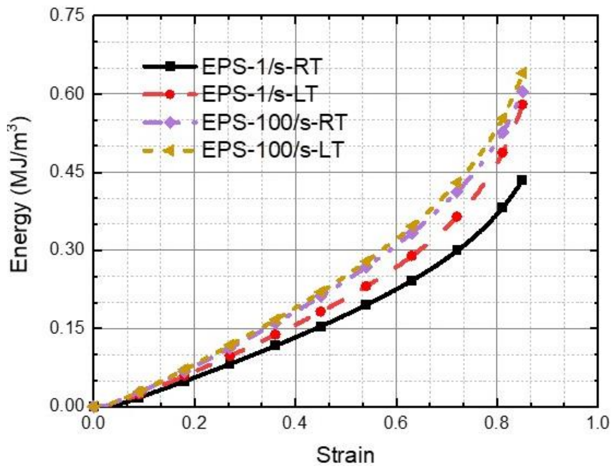
Fig. 7 EPS and FPUF elastic modulus (a) and strain platform stress contrast (b)



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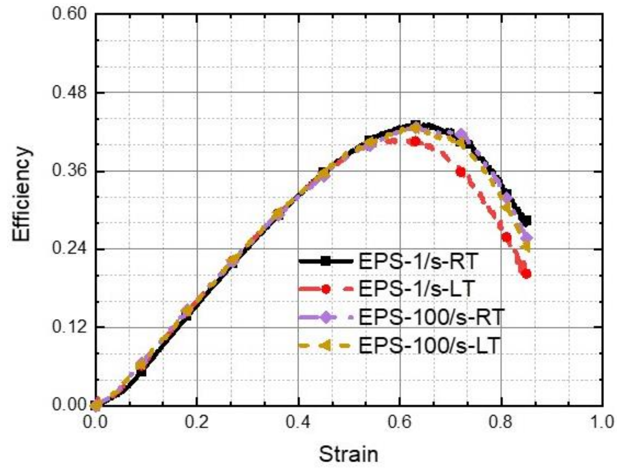

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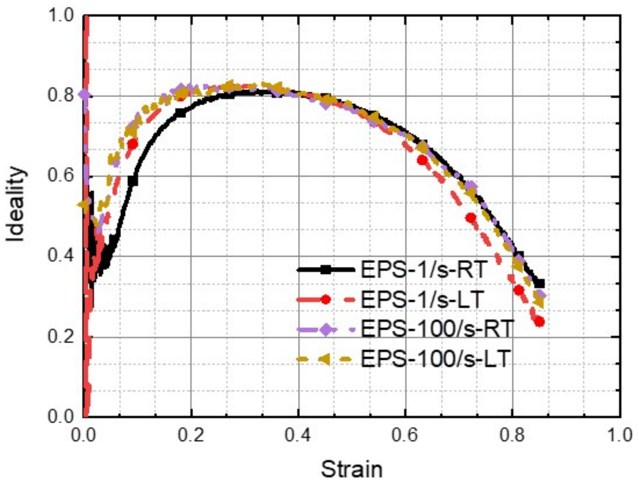
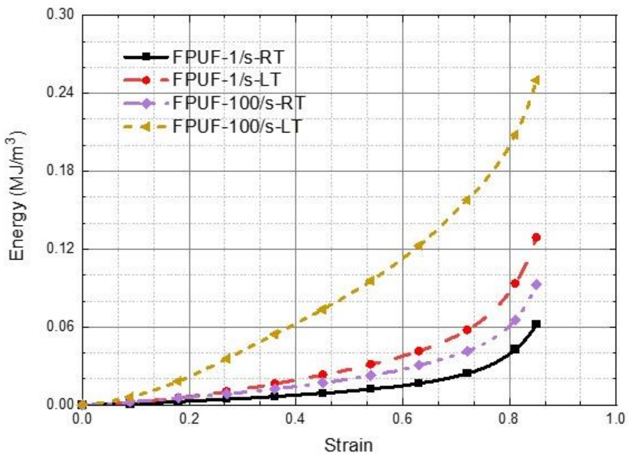
Fig. 8 EPS energy effectiveness curve at 1/s and 100/s: strain energy-strain curve (a); efficiency-strain curve (b); ideality-strain curve(c)



c

Fig. 8 Continuation

Based on the effect of temperature on the mechanical properties of EPS and FPUF, combined with the theory of the sheerwood-frost constitutive model, the temperature term $H(\varepsilon,T)$ parameters were fitted. The ratio of the stress of 1/s, 10/s, and 100/s to 1/s at low temperature and the stress ratio of the same strain rate at room temperature are taken as the ordinate, and the strain is plotted as the abscissa in Fig. 10.



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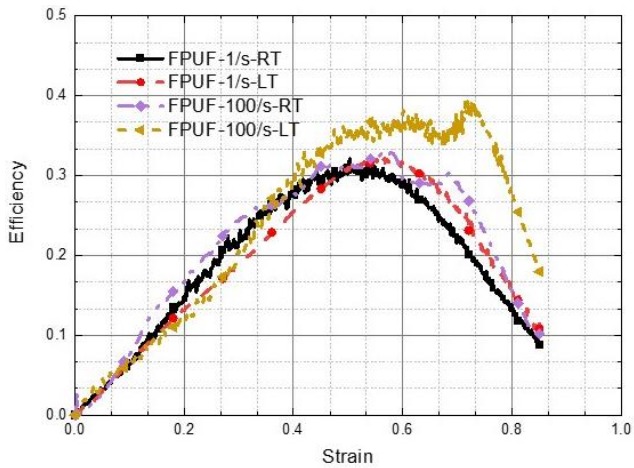

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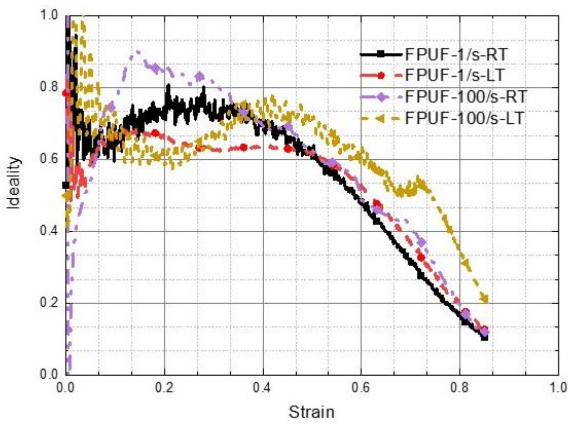

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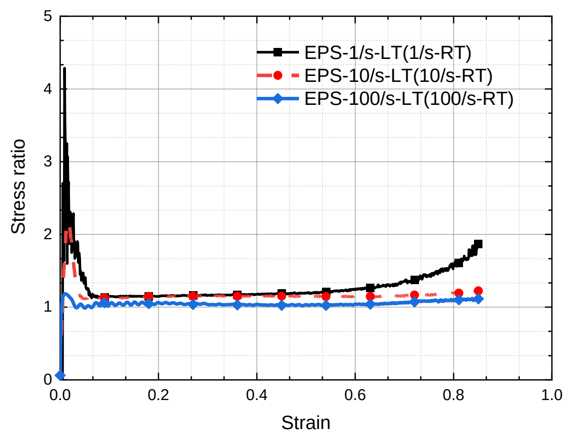
Fig. 9 FPUF energy effectiveness curve at 1/s and 100/s: strain energy-strain curve (a); efficiency-strain curve (b); ideality-strain curve (c)

The stress versus strain curve at low temperature and room temperature is roughly parallel to the strain axis. It means that the effect of temperature on the mechanical properties of EPS does not change with strain in the plateau stage. the effect of EPS temperature is expressed $H_E(\varepsilon, T)=c\Delta t$, and the parameter value c = 0.028 is obtained according to the fitting curve.

It can be seen from Fig. 10, b. The effect of strain rate on the mechanical properties of FPUF increases firstly with the strain, reaches a peak after reaching a certain strain, and then decreases with the strain increasing. The tempera-



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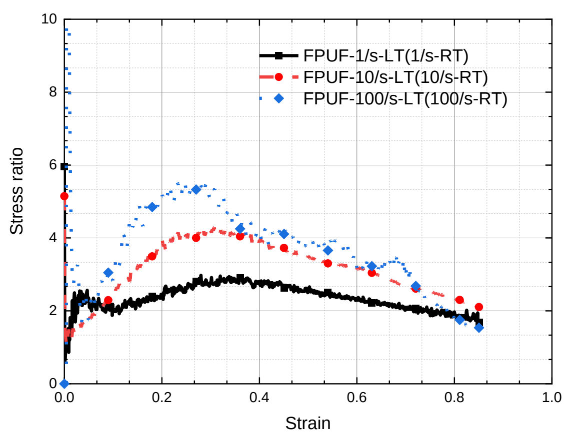

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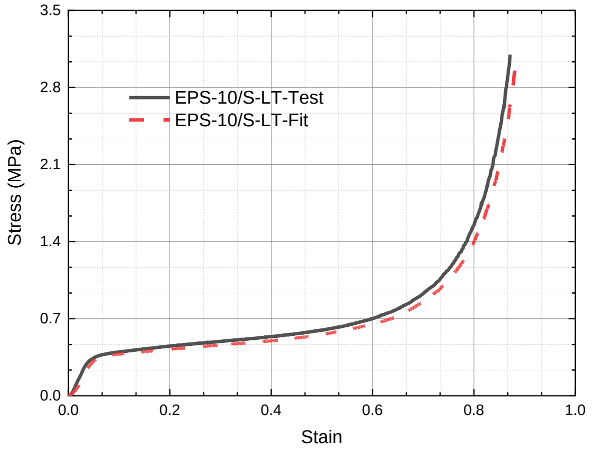
Fig. 10 Effect of temperature on stress ratio curve of EPS (a) and FPUF(b) ture effect term of FPUF can be set as the quadratic function $H_F(\varepsilon,T) = d_1\Delta t\varepsilon^2 + d_2\Delta t\varepsilon + d_3\Delta t$. According to the fitting curve, $d_1 = -0.136$, $d_2 = 0.107$, $d_3 = 0.046$.

6. Validation of the constitutive model

The verification of the constitutive model is shown in Fig. 11. The fitting results are in good agreement with the experimental data, which indicates that the obtained constitutive model has good reliability.



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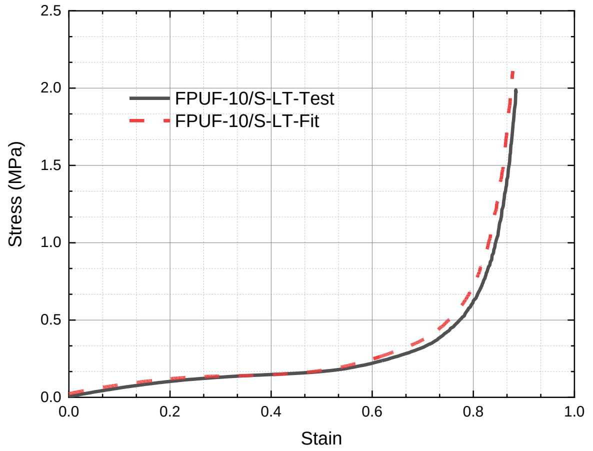

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Fig. 11 EPS (a) and FPUF (b) comparison of fitting data and test results at 10/s and at -20℃

7. Conclusion

1. Temperature and strain rate have a great influence on the mechanical properties and energy absorption properties of EPS and FPUF materials, and the optimal energy absorption state of EPS and FPUF will not be affected by strain rate and temperature. The mechanical parameters and energy absorption of EPS and FPUF are significantly enhanced at low temperature and high strain rate. When faced with high strain rate and low temperature conditions at the same time, the mechanical properties of FPUF will be enhanced more significantly. However, under the high strain rate of EPS, the low temperature will no longer have a significant impact on its mechanical properties.

2. Based on the experimental results of uniaxial compression and large deformation of EPS and FPUF, this paper combines the framework of the sheerwood-frost constitutive model to comprehensively analyze the effects of strain rate and temperature on the mechanical properties of EPS and FPUF. Establish material parameters between stress, strain, strain rate, and temperature. It can provide a reference for research and analysis in the field of EPS and FPUF impact protection.

References

1. **Chen, W.;** et al. 2015. Static and dynamic mechanical properties of expanded polystyrene, Materials & Design 69: 170-180.
https://doi.org/10.1016/j.matdes.2014.12.024.
2. **Liu, K.;** et al. 2019. The study on compressive mechanical properties of rigid polyurethane grout materials with different densities, Construction and Building Materials 206: 270-278.
https://doi.org/10.1016/j.conbuildmat.2019.02.012.
3. **Scarfato, P.; Maio, L. D.; Incarnato, L.** 2017. Structure and physical-mechanical properties related to comfort of flexible polyurethane foams for mattress and effects of artificial weathering, Composites Part B Engineering 109.jan:45-52.
https://doi.org/10.1016/j.compositesb.2016.10.041.
4. **Ouellet, S.; Cronin, D.; Worswick, M.** 2006. Compressive response of polymeric foams under quasi-static, medium and high strain rate conditions, Polymer Testing 25(6): 731-743.
https://doi.org/10.1016/j.polymertesting.2006.05.005.
5. **Zhao, H.; Gary, G.** 2001. Behaviour characterisation of polymeric foams over a large range of strain rates, International Journal of Vehicle Design 30(1-2): 135-145.
https://doi.org/10.1504/IJVD.2002.002028.
6. **Thirumal, M.;** et al. 2008. Effect of foam density on the properties of water blown rigid polyurethane foam, Journal of Applied Polymer Science 108(3): 1810-1817.
https://doi.org/10.1002/app.27712.
7. **Hwang, B. K.;** et al. 2020. Dynamic compressive behavior of rigid polyurethane foam with various densities under different temperatures, International Journal of Mechanical Sciences 180: 105657.
https://doi.org/10.1016/j.ijmecsci.2020.105657.
8. **Bouix, R.; Viot, P.; Lataillade, J. L.** 2009. Polypropylene foam behaviour under dynamic loadings: Strain rate, density and microstructure effects, International Journal of Impact Engineering 36(2): 329-342.
https://doi.org/10.1016/j.ijimpeng.2007.11.007.
9. **Song, B.;** et al. 2005. Strain-rate effects on elastic and early cell-collapse responses of a polystyrene foam, International Journal of Impact Engineering 31(5): 509-521.
https://doi.org/10.1016/j.ijimpeng.2004.02.003.
10. **Tateyama, K.; Yamada, H.; Ogasawara, N.** 2016. Effect of strain rate on compressive properties of foamed polyethylene film, Polymer Testing 52: 54-62.
https://doi.org/10.1016/j.polymertesting.2016.04.002.
11. **Quellet, S.;** et al. 2013. High rate characterization of polymeric closed-cell foams: challenges related to size effects, Dynamic Behavior of Materials, Volume 1: Proceedings of the 2012 Annual Conference on Experimental and Applied Mechanics. Springer New York:21-28.
https://doi.org/10.1007/978-1-4614-4238-7_4.
12. **Karagiozova, D.;** et al. 2016. On the energy absorption of tube reinforced foam materials under quasi-static and

dynamic compression, International Journal of Mechanical Sciences 105: 102-116.
https://doi.org/10.1016/j.ijmecsci.2015.11.013.

13. **Triantafillou, T. C. ;** et al. 1989. Failure surfaces for cellular materials under multiaxial loads – II. Comparison of models with experiment, International Journal of Mechanical Sciences 31(9): 665-678.
https://doi.org/10.1016/S0020-7403(89)80002-5.
14. **Linul, E. ;** et al. 2013. Study of factors influencing the mechanical properties of polyurethane foams under dynamic compression, Journal of Physics: Conference Series, IOP Publishing 451(1): 012002.
https://10.1088/1742-6596/451/1/012002.
15. **Linul, E.;** et al. 2020. Static and dynamic mode I fracture toughness of rigid PUR foams under room and cryogenic temperatures, Engineering Fracture Mechanics 225: 106274.
https://doi.org/10.1016/j.engfracmech.2018.12.007.
16. **Cronin, D. S.; Ouellet, S.** 2016. Low density polyethylene, expanded polystyrene and expanded polypropylene: Strain rate and size effects on mechanical properties, Polymer Testing 53: 40-50.
https://doi.org/10.1016/j.polymertesting.2016.04.018.
17. **Landro, L. D.; Sala, G.; Olivieri, D.** 2002. Deformation mechanisms and energy absorption of polystyrene foams for protective helmets, Polymer testing 21(2): 217-228.
https://doi.org/10.1016/S0142-9418(01)00073-3.
18. **Chakravarty, U.;** et al. 2003. Strain rate effects on sandwich core materials: An experimental and analytical investigation, Acta Materialia 51(5): 1469-1479.
https://doi.org/10.1016/S1359-6454(02)00541-4.
19. **Vejelis, S. ;** et al. 2008. Shear strength and modulus of elasticity of expanded polystyrene (EPS), Materials Science 14(3): 230-233.
https://doi.org/10.1016/j.msec.2006.12.001.
20. **Avalle, M.; Belingardi, G.; Montanini R.** 2001. Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram, International Journal of Impact Engineering 25(5): 455-472.
https://doi.org/10.1016/S0734-743X(00)00060-9.
21. **Yang, Z.;** et al. 2017. Flexible and stretchable polyurethane/waterglass grouting material – science direct, Construction and Building Materials 138: 240-246.
https://doi.org/10.1016/j.conbuildmat.2017.01.113.
22. **Rojek, P.; Prociak, A.** 2012. Effect of different rapeseed-oil-based polyols on mechanical properties of flexible polyurethane foams, Journal of Applied Polymer Science 125(4): 2936-2945.
https://doi.org/10.1002/app.36500.
23. **Rampf, M.;** et al. 2012. Structural and mechanical properties of flexible polyurethane foams cured under pressure, Journal of cellular plastics 48(1): 53-69.
https://doi.org/10.1177/0021955X11429171.
24. **Sherwood, J.A.; Frost, C. C.** 1992. Constitutive modeling and simulation of energy absorbing polyurethane foam under impact loading, Polymer Engineering & Science 32(16): 1138-1146.
https://doi.org/10.1002/pen.760321611.
25. **Miltz, J.; Gruenbaum, G.** 1982. Evaluation of cushioning properties of plastic foams from compressive measurements, Polymer Engineering & Science 21(15): 1010-1014.
https://doi.org/10.1002/pen.760211505.
26. **Schulze, C.;** et al. 2019. Calibration of crushable foam plasticity models for synthetic bone material for use in finite element analysis of acetabular cup deformation and primary stability, Computer Methods in Biomechanics and Biomedical Engineering 22(1): 25-37.
https://doi.org/10.1080/10255842.2018.1524884.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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INFLUENCE OF STRAIN RATE AND TEMPERATURE ON COMPRESSIVE PROPERTIES AND ENERGY ABSORPTION EFFICIENCY OF EXPANDED POLYSTYRENE AND FLEXIBLE POLYURETHANE FOAM

S u m m a r y

In this work, large deformation compressive experiments of expanded polystyrene foam (EPS) and flexible polyurethane foam (FPUF) at low temperature (-20°C) and room temperature (20°C) with strain rates ranging from 1 s-1 to 100 s-1 were performed using high speed material test machine. According to the experimental results, both EPS materials and FPUF materials show the stress features of the wide platform, and the mechanical properties and the cushioning energy performance of EPS are far better than the FPUF. The testing results indicate the yield strength, plateau stress and energy absorption efficiency of EPS and FPUF increase with strain rate, and the properties at low temperature are higher slightly than that of room temperature. However, the efficiency of the two-material buffer absorption is only related to the material itself. The strain rate and external temperature do not affect the best energy absorption efficiency of the material. Finally, on the basis of the experimental results, combine the Sheerwood-Frost model framework, establish the relationship between EPS materials and FPUF materials stress and strain, strain rate, temperature and other variables. This can provide accurate material attributes for simulation analysis.

Keywords: expanded polystyrene foam, flexible polyurethane foam, energy absorption, strain rate, low temperature.

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