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Quasi-Static Investigations of 240-Bloom Gelatine for Ballistic Tests

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Abstract. The paper presents the results of investigations of ballistic gel properties in quasi-static conditions. Specimens were prepared using the 240 Bloom gelatine, which was determined by product availability. Tests were carried out making use of a material testing machine to estimate the influence of gel share on stress-strain characteristics. Considered values of a gel mass content were equal to 10, 12, and 14%. Assumed parameters were determined on the material calibration stage conducted with steel balls with a diameter of 4.5 mm. The most significant influence of a gel content on mechanical properties of specimens were observed for a share of 10% and 12%. The conducted preliminary tests are a part of investigations aimed at assessment if it is possible to calibrate the ballistic gel making use of mechanical characteristics obtained in quasi-static tests without shooting.

Keywords: mechanical engineering, ballistic gel, natural gelatine, quasi-static investigations, modulus of elasticity

1. INTRODUCTION

Experimental investigations in the area of wound ballistics, i.e., a part of terminal ballistics, dealing with interactions between different projectiles (or elements of projectiles – e.g. debris) with the human body [1, 2], need suitable simulants for body media (e.g. muscles, bones, etc.) [3, 4]. Results of experimental tests allow for desirable modifications of the projectile and ballistic protection design. Investigations of mechanical properties of under-consideration materials additionally allow for theoretical modelling of terminal ballistics phenomena, making use of analytical and numerical models [5, 6].

The most commonly applied simulant of muscles in ballistic tests is gelatine [3]. During tests, two types of materials can be applied – natural gelatine or synthetic ballistic gel, which is very convenient for investigations. A synthetic material is characterised by transparency and resistance to thermal conditions and it is reusable after the required treatment. A natural material is still used due to mainly high availability and low cost of sample preparation.

As it can be found in many reports, the most suitable for ballistic investigations is the 250-Bloom gelatine with a temperature of 4°C [3-5]. Each production batch of material should be verified making use of steel balls with a diameter of 4.5 mm, impacting with a velocity of 180 m/s. The penetration depth of balls should be included in the interval between 81 mm and 89 mm. This interval corresponds to the values characteristic for penetration into pig muscles, which can be comparable with a human body due to similarity to a muscles structure [3, 4].

The results of experimental investigations of ballistic gelatine were presented in many reports [6-8]. The presented paper provides selected data obtained during the investigations conducted as a part of the thesis given in [8]. The tests were carried out for static and dynamic conditions, providing impact of different parameters on the strength properties of gelatine. The main problem in our conditions can be the lack of availability of 250-Bloom material. Much more popular are the materials characterised by 240 degrees of Bloom. Moreover, available results provide limited data on the Kirchhoff modulus of the material, which can be used in the equation of state for numerical simulations. In this paper, we also focused our attention on the relation between penetration depth obtained during calibrations tests with steel balls and mechanical properties obtained in quasi-static experiments.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Gelatine preparation

Gelatine was prepared making use of the following procedure:

i) Adding of water of the temperature of 4-8°C to the appropriate amount of gelatine powder (to get the required content of a final material);
ii) Cooling of the obtained composition at the temperature of 4-8°C for 2 hours;
iii) Melting of the gained gel in a water bath at the temperature of 38-40°C up to get the completely melted liquid (clear and transparent without air bubbles);
iv) Pouring of the obtained liquid into the proper moulds. In the presented investigations, two types of moulds were applied: a cuboid mould (70 × 70 × 150 mm) and a cylindrical mould (30 mm in diameter and height). Cylindrical moulds were prepared using the 3D printing technology (Fig. 1);
v) Cooling of the prepared gel at the temperature of 15°C for 8 hours;
vi) Cooling of the specimens in the refrigerator at the temperature of 3-5°C for 36 hours.

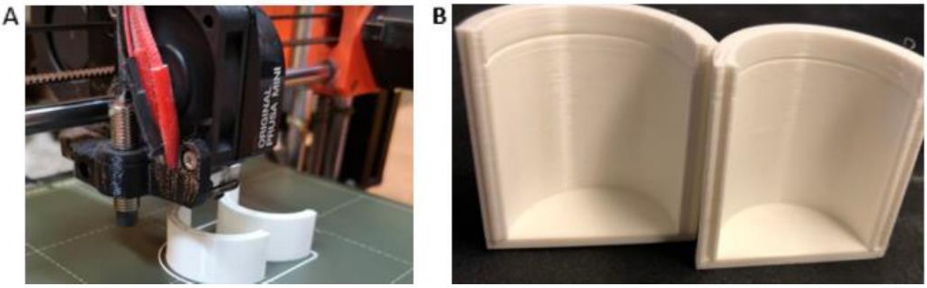

Fig. 1. Moulds used for preparation of gelatin specimens
(A – printing process; B – ready product)

2.2. Gelatine calibration

Calibration of gelatine blocks was carried making use of a stand presented in Fig. 3. The elements used were the following:

- investigated gelatine block (A in Fig. 2);
- light screen Kistler type 2521A for velocity measurements (B in Fig. 2);
- pneumatic gun (calibre 4.5 mm) with an adjustable projectile velocity (C in Fig. 2);
- transient recorder Kistler type 2519A;
- personal computer with BAControl transient recorder software.

The calibration procedure required testing to be conducted in 15 minutes to avoid heating of specimens (initially cooled to the temperature of 4-5°C). The tests were based on at least 5 shots with impact velocity close to 180 m/s. The obtained values ensured the possibility of applying linear regression to estimate approximate penetration depth for the required velocity of 180 m/s.

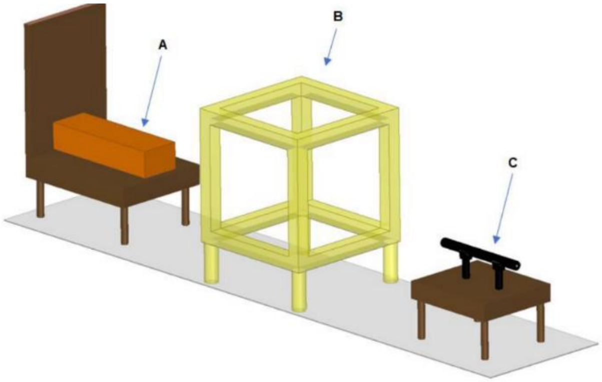

Fig. 2. Experimental stand for calibration of gelatine specimens

Dependencies of a penetration depth on a projectile velocity for three values of a content of gelatine (10%, 12%, and 14%) were presented in Fig. 3.

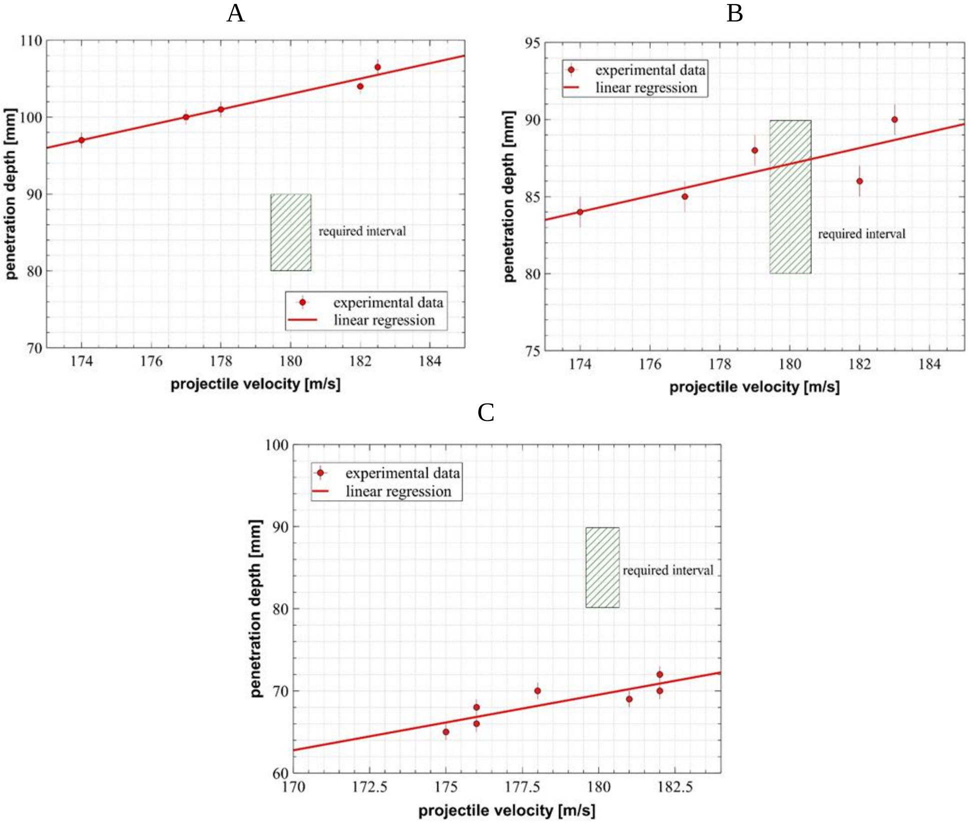

Fig. 3. Penetration depth as a function of impact velocity for different investigated gelatine contents (A – 10%, B – 12%, C – 14%)

As it can be observed, only the second investigated mass share, i.e., 12% has satisfied the formulated requirements (penetration depth equal to approximately 87 mm). For other content values, the difference between the values of a penetration depth and the limiting values were equal to approximately 10 mm.

2.3 Quasi-static tests

Quasi-static tests were carried out making use of the universal material testing machine Z3-X500. In order to ensure the possibility of specimen compression tests, additional grips were made (Fig. 4).

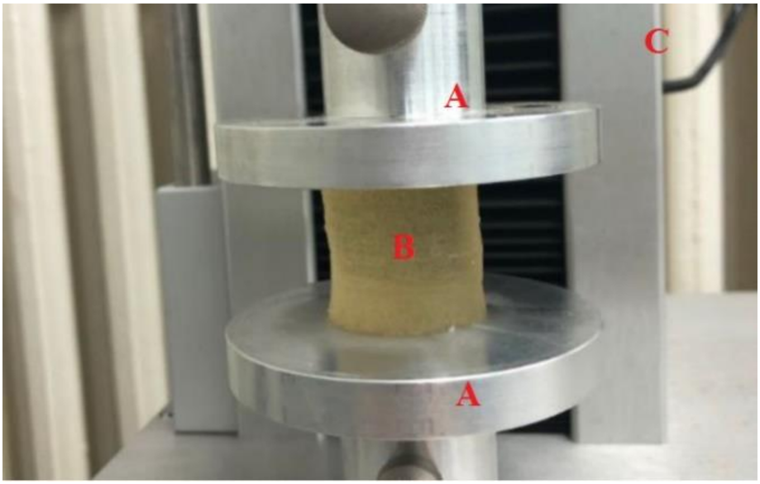

Fig. 4. Compression test configuration (A – grips made of aluminium alloy; B – exemplary specimen for preliminary control of a measurement chain; C – material testing machine)

In order to conduct tests with the reduced Poisson effect, the piston–cylinder system made of steel, presented in Fig. 5, was applied. During the tests, additional lubricant was used to reduce friction between gelatine and steel/aluminium alloy. Seven tests for each mass content and investigated configuration were carried out. The tests were conducted in the conditions of a strain rate of 0.01 1/s.

Fig. 5. Piston–cylinder system for the Poisson's effect reduction

In order to include the influence of specimen deformations on stress and strain, the true values were estimated making use of the following relations in case of compression tests:

$$\varepsilon_T = \ln\left(1-\varepsilon\right) \tag{1}$$

$$\sigma_T = \sigma\left(1-\varepsilon\right) \tag{2}$$

where σ and ε denote the absolute values of engineering stress and strains, σ_T and ε_T are the absolute true values.

The engineering absolute values were estimated making use of the following relations, based on measurement data:

$$\varepsilon = \frac{\left|\Delta l\right|}{l_0} \tag{3}$$

$$\sigma = \frac{\left|F\right|}{S_0} \tag{4}$$

where l is the specimen length, l_0 denotes its initial length, F is the compressive force, and S_0 is the initial specimen cross-section area.

The obtained stress-strains curves allowed for assessment of elasticity moduli, i.e., longitudinal and volumetric elasticity moduli. It was estimated making use of the linear regression of the first part of the curve.

The achieved engineering and true stress-strain curves for the case of free lateral specimen surface were presented in Figs. 6 and 7. On the other hand, pressure-volumetric strain curves for one dimensional (axial) strain case were shown in Fig. 8.

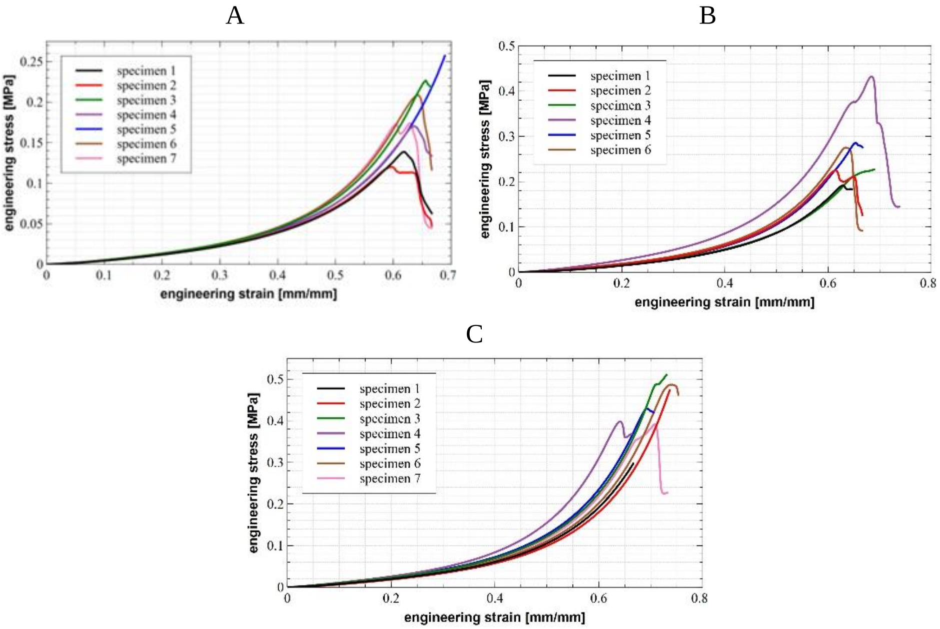

Fig. 6. Engineering stress-strain curves for different gelatine mass shares
(A – 10%, B – 12%, C – 14%)

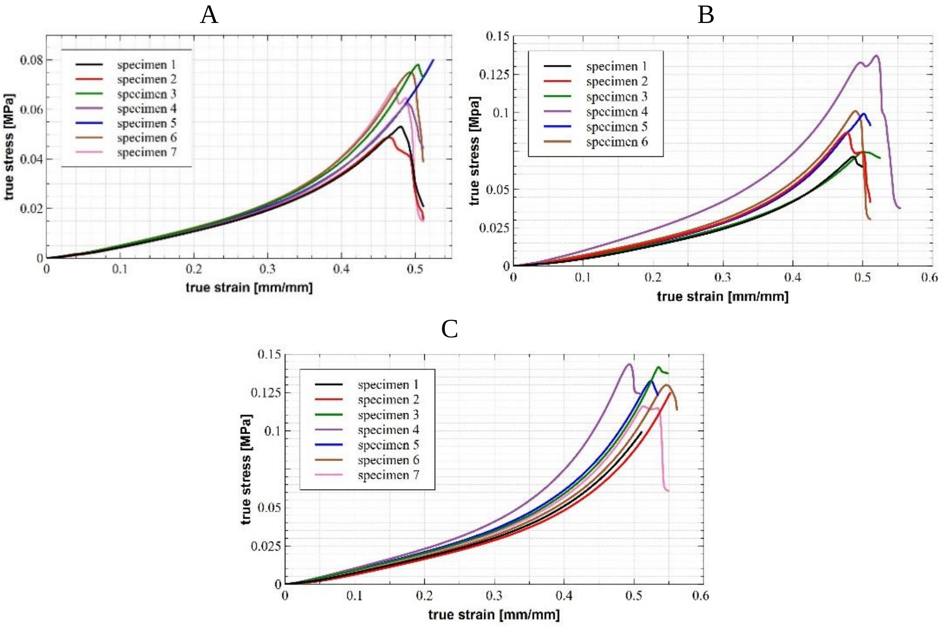

Fig. 7. True stress-strain curves for different gelatine mass shares
(A – 10%, B – 12%, C – 14%)

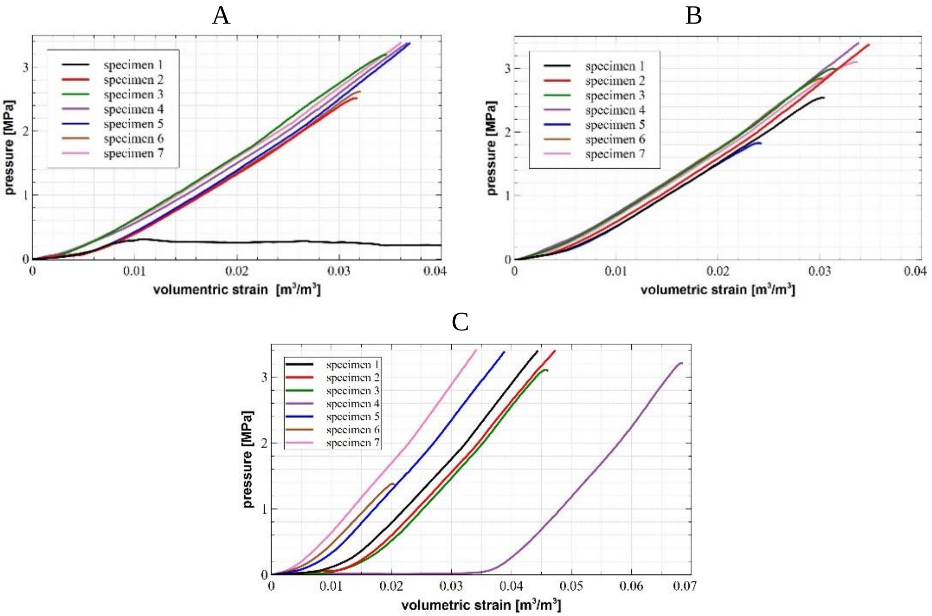

Fig. 8. Volumetric strain – pressure curves obtained for different gelatine contents (A – 10%, B – 12%, C – 14%)

3. DISCUSSION

The obtained stress-strain curves allowed for estimation of longitudinal elasticity modulus, which can be defined as:

$$E = \frac{d\sigma_T}{d\varepsilon_T} \tag{5}$$

The above mentioned slope coefficient of stress-strain curves was estimated making use of the linear regression.

A similar approach was applied in the case of estimation of the volumetric elasticity modulus (Helmholtz modulus):

$$K = \frac{dp}{d\varepsilon_V} \tag{6}$$

The results of approximation were summarised in Tables 1 and 2, as well as, in Figs. 9 and 10. As it can be noticed, the most significant differences are between mass shares of 10 and 12 percent. Moreover, the most content-sensitive seems to be the longitudinal elastic modulus and further investigations should be focused on this parameter, especially in order to improve the quality of the specimens to obtain lower dispersion of results (which is noticeable in Fig. 10).

Table 1. Results of longitudinal elasticity modulus estimation for the investigated specimens

Specimen No.	**Mass share (%)**	**Longitudinal elasticity modulus (MPa)**	**Mean value of modulus (MPa)**	**Standard deviation (MPa)**
1	10	0.016	0.020	0.006
2		0.013		
3		0.023		
4		0.010		
5		0.024		
6		0.024		
7		0.027		
8	12	0.025	0.038	0.010
9		0.031		
10		0.057		
11		0.035		
12		0.037		
13		0.034		
14		0.049		
15	14	0.044	0.048	0.010
16		0.034		
17		0.061		
18		0.061		
19		0.049		
20		0.037		
21		0.048		

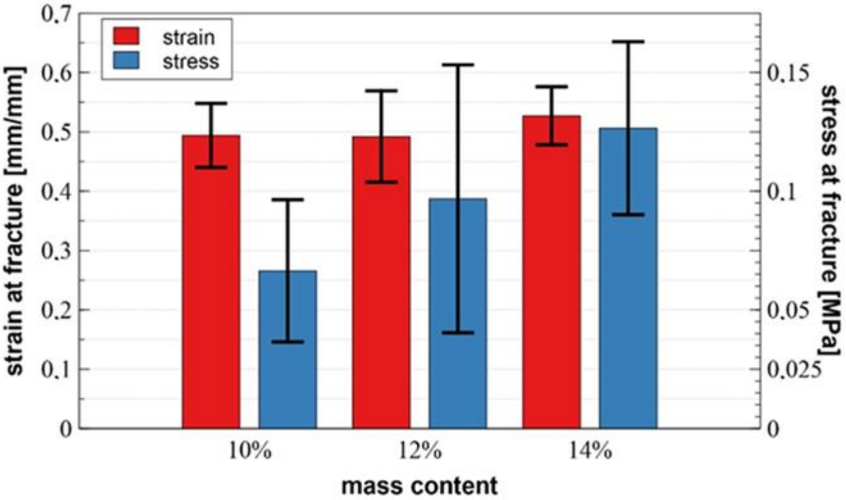

Fig. 9. Influence of a gelatine mass share on engineering stress and strains at fracture

Table 2. The results of volumetric elasticity modulus estimation for the investigated specimens

Specimen No.	Mass share (%)	Volumetric elasticity modulus (MPa)	Mean value of modulus (MPa)	Standard deviation (MPa)
1	10	86.27	88.87	3.39
2		95.49		
3		85.50		
4		89.55		
5		86.54		
6		89.87		
7		88.64		
8	12	93.23	98.09	2.62
9		95.40		
10		101.34		
11		98.20		
12		98.97		
13		100.14		
14		99.34		
15	14	95.16	98.06	3.92
16		94.91		
17		98.34		
18		95.82		
19		99.16		
20		96.05		
21		106.95		

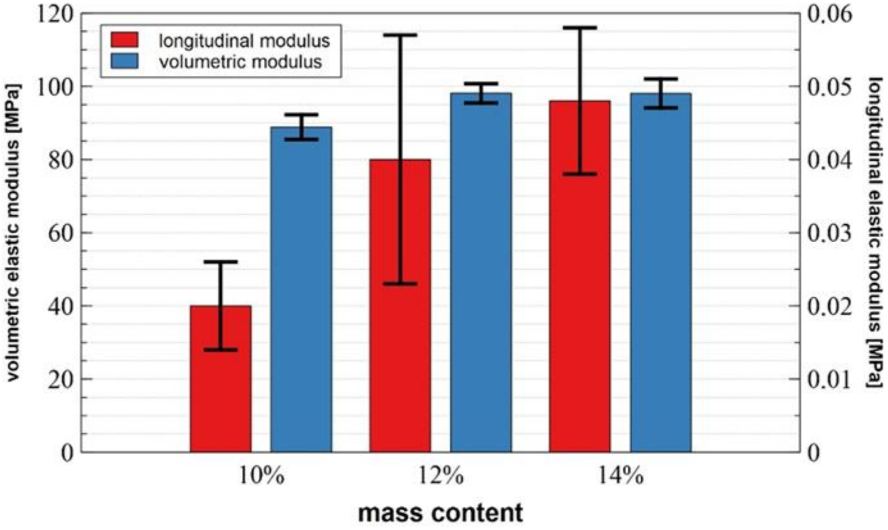

Fig. 10. Influence of a gelatine mass share on elastic moduli

4. CONCLUSIONS

The results of preliminary investigations of characteristics of the 240-Bloom gelatine lead to the following conclusions:

- the applied methodology allowed for preliminary investigations of ballistic gelatine mechanical properties in quasi-static conditions;
- in the case of investigated gelatine, the specimens characterised by mass content of 12% fulfilled the main requirements for ballistic tests. Taking into account the comparable density of gelatine and water, this modification should not impact seriously on the final specimen density;
- the longitudinal elastic modulus seems to be the most sensitive on the gelatine mass content. Taking into account the obtained scatter of values, further investigations should also be focused on specimen preparation precision.

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Badania quasi-statyczne żelatyny 240 Bloom dla testów balistycznych

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Streszczenie. Niniejsza praca stanowi opis oraz wyniki prac realizowanych w ramach badań quasi-statycznych żelatyny (o sile żelowania 240 Bloom) przeznaczonej do testów balistycznych, która jest najczęściej stosowanym substytutem tkanek miękkich w badaniach balistyki końcowej. W ramach prac przeprowadzono proces przygotowania materiału do badań, jego kondycjonowania, kalibracji oraz badań w warunkach quasi-statycznych w celu określenia modułu sprężystości wzdłużnej oraz modułu sprężystości objętościowej. Na podstawie wstępnych badań kalibracyjnych podjęto decyzję o przebadaniu próbek o zawartości żelatyny równej 10 %, 12 % oraz 14 %. Rezultaty badań (krzywe siła-przemieszczenie) pozwoliły na ocenę odkształceń oraz naprężeń (inżynierskich oraz rzeczywistych) występujących w badanym materiale. To z kolei pozwoliło na ocenę wartości wyżej wspomnianych modułów sprężystości. Należy zwrócić uwagę na relatywnie duży rozrzut uzyskanych wyników, co może sugerować konieczność dalszych prac nad precyzją wykonania próbek. Uzyskane wyniki wykazały łatwość oraz efektywność zastosowanej metodyki przygotowania próbek, jak również znaczący wpływ zawartości żelatyny na moduł sprężystości wzdłużnej (szczególnie w przypadku dwóch niższych wartości zawartości żelatyny). Zdecydowania mniejszą rozbieżność zauważono w przypadku modułu sprężystości objętościowej. Ponadto, okazało się, że przygotowanie próbek o udziale masowym 20 % jest nieuzasadnione ze względu na dużą czasochłonność całości procesu.

Słowa kluczowe: inżynieria mechaniczna, moduł sprężystości, żelatyna balistyczna, żelatyna naturalna, badania quasi-statyczne