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Investigation of Textiles Elastic Properties with a Pendulum Impact Device

Abstract

This investigation concerns the estimation of materials impact behaviour based on the registration of vibration during the pendulum process. In order to find optimal testing conditions, three types of materials: woven fabric, knitted material and polyethylene membrane were chosen and two bobs of different weight and radius ($r_1=13.5$ mm, $r_2=30$ mm) were applied. The initial angles α_0 of the pendulum were: 1; 2; 3; 4 and 5 degrees. To describe the impact behavior of the materials, the impact values and rebound angles of each stroke were used and the elasticity properties of the materials were determined: rebound elasticity ε_r and dynamic elasticity ε_d , on the basis of the initial potential energy V_0 of the pendulum and its energy after one full swing V_1 . A close relationship exists between rebound elasticity ε_r , dynamic elasticity ε_d and initial angles α_0 of the pendulum for all the test materials under different testing conditions. Percentage values of absorbed energy H_1 of the test materials at the first moment of pendulum impact were calculated. It was established that linear regression analysis can be applied to establish dependencies between absorbed energy H_1 of the material at the moment of first impact, as well as the pendulum's potential energy V_1 after a full swing period and the first rebound angle α_1 .

Key words: impact behaviour; vibration process; rebound elasticity; dynamic elasticity.

Introduction

During processing, tailoring or end use, textile fabrics undergo all kinds of external loads and they must retain their shape during all the period of wear, e.g. at the elbow or knee zones. Stability is one of the fundamental requirements for textile fabrics that can be determined by their elastic properties. Thus, investigation of the elastic properties of textile materials is of great importance.

The investigations of textiles properties in uni-axial deformation conditions dominate in most of the scientific works that outline the elastic properties of textile materials. As textile materials are anisotropic, i.e. their mechanical properties differ in different directions, it is advisable to analyse their properties by multi-axial deformation methods. One of the most popular and simple methods of multi-axial deformation is the punch deformation method.

The behaviour of polyethylene membrane in the punch deformation process, in cases where punches of different shape and specimens with defects were used, was investigated in the work of V. Daukantiene and M. Gutasukas. Specimens were loaded with spherical and cylindrical punches until puncture or intermediate deflection of height occurred, and experimental results concerning changes in the super molecular structure of polyethylene membrane during the punch deformation process were presented [1, 2].

Furthermore, during end use, textile materials undergo not only multi-axial deformations, but also short dynamic impact loads. In the work of E. Maklewska et al. comparative analysis of static and dynamic tests indicated that the evaluation of energy absorption abilities carried out in static conditions could be confirmed by dynamic tests [3]. Also [4, 5], a special tester was designed to record time dependencies of the sample deflections and rebound forces during the process of impact.

The impact testing apparatus must simulate the end use applications of textiles, and the magnitude of impact loads has to correspond to real exploitation conditions. Hence, gravity devices, such as a pendulum, can be used to determine textile behaviour during impact loading. Energy losses during impact can be calculated from changes in the pendulum's potential energy, which determine the elastic properties of the materials investigated [6].

There are some works dealing with investigations of elastic properties of polymer membranes based on multi-cycle dynamic impact load conditions using a pendulum impact device [7, 8]. The

elastic properties of polymer membranes were estimated according to parameters obtained by the impact loading method: rebound elasticity and dynamic elasticity. It was found that the impact method is suitable for the characterisation of the elastic properties of polymer membranes with sufficient accuracy. As a continuation of earlier investigations, the purpose of this work was to establish optimal testing conditions for a pendulum impact device, also to determine the potential energy of the pendulum under different testing conditions, and to calculate the parameters that determine the elastic properties of the materials investigated.

Experimental

In order to find optimal testing conditions for the pendulum impact device three types of materials were chosen: woven fabric, polyethylene membrane and knitted material. The characteristics of the materials tested and their composition are presented in Table 1.

The investigations of the behaviour of the materials under repetitive impact loading were based on the recorded decreasing process of the cyclical motions of the pendulum (Figure 1). Investigations

Table 1. Characteristics of materials tested.

Material code	Composition	Area density, g/m ²	Thickness, mm	Density, dm ⁻³	
				warp	weft
WF	100 % cotton	133.18	0.32	220	240
PE	100 % polyethylene	78.29	0.09	-	
KM	92 % PES, 8 % elastane	234.8	0.70	wale	course
				320	160

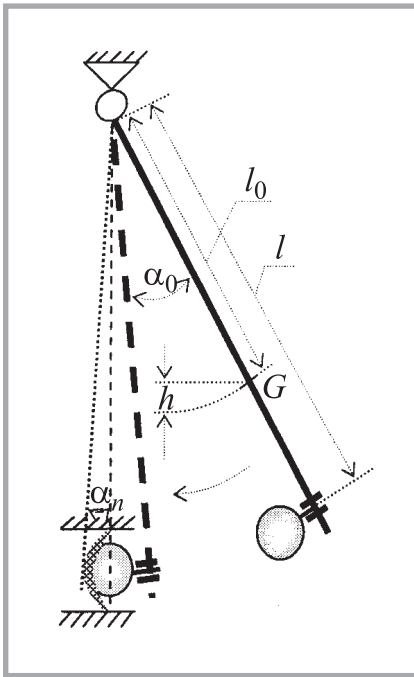


Figure 1. Testing conditions of impact behaviour of the materials.

were performed using a pendulum testing base constructed at Kaunas University of Technology [9].

The pendulum consists of a bar suspended at one end and a bob at the other end where most of the mass of the assemblies is concentrated. The pendulum moves in one plane round a pivot point in up-and-down motions (Figure 1). In operation the bar is displaced at an angle α_0 from its vertical (free hanging) position and clamped. After release, the bar and the bob swings downward. At the lowest point of its path the pendulum applies the impact load. After touching the specimen, the pendulum continues its swing and moves at an angle α_n , which is less than α_0 .

The process of repetitive motion of the pendulum was digitally recorded as a vibration curve (Figure 2) [10]. To describe the impact behavior of the materials, the values of impact (α_n) and rebound (α_0) angles of each stroke were used [11]. Ten samples were used for each test. Total relative errors did not exceed 5 %.

Testing conditions of the impact behaviour of the materials were as follows: the initial angles α_0 of the pendulum: 1; 2; 3; 4; 5 degrees, duration t of one vibration process – 20 seconds, pendulum length l – 1.5 m and radius R of the specimen – 50 mm. Mass m of the bob, mass M of all moving parts, radius r of the bob and dis-

tance l_g from the pivot point to the center of gravity G are given in Table 2.

The energy absorbed by the material at the moment of impact can be calculated using the angular displacement and the parameters of the device. In Figure 1 G is the centre of gravity of the combined mass M of all moving parts of the pendulum, h is the difference between the height of gravity centre G before the release of the pendulum and the position of G at the moment of impact. The energy needed to extend the specimen is the kinetic energy of the pendulum at the moment of impact. This energy can be calculated by the potential energy V_0 of the pendulum in its raised, stationary position, minus energy losses due to friction and minus air resistance during the downward swing of the bar. Frictional losses are generally small and can be eliminated from the calculations [12].

So, V_0 can be expressed by the familiar expression Mgh , where g is the acceleration of gravity. In turn, $h = l_g(1 - \cos \alpha_0)$, so:

$$V_0 = Mg l_g(1 - \cos \alpha_0) \quad (1)$$

Similarly, after the first full swing:

$$V_1 = Mg l_g(1 - \cos \alpha_1) \quad (2)$$

where α_1 is the angle of deflection of the bar after the first full swing. Energy losses due to friction and due to deformation of the material can be calculated as:

$$H_1 = V_0 - V_1 = Mg l_g(\cos \alpha_1 - \cos \alpha_0) \quad (3)$$

where V_0 is constant for a given experiment, while V_{1-n} varies from specimen to specimen. In order to evaluate the elasticity of the material, elasticity we need to know the elasticity value according to the first rebound [13]:

Table 2. Testing conditions.

	m, kg	M, kg	l_g , m
$r_1 = 13.5$ mm	0.107	3.147	0.776
$r_2 = 30.0$ mm	0.912	3.952	0.975

$$\varepsilon_r = \frac{V_1}{V_0} \cdot 100\% = \frac{h_1}{h} \cdot 100\% \quad (4)$$

and dynamic elasticity [13]:

$$\varepsilon_d = \left(\frac{V_1}{V_0}\right)^2 = \left(\frac{h_1}{h}\right)^2 \quad (5)$$

The potential energy of the pendulum V_0 at its stationary position was calculated and is given in Table 3.

Results and discussion

In our earlier investigations the impact behavior of cotton fabrics treated with stiffener (PVA dispersion) was analysed, and it was determined that the first impact of the pendulum on the specimen, and the first deflection of the pendulum clearly distinguishes the impact behaviour of the fabrics tested [11].

In order to determine optimal testing conditions for the pendulum impact device, three types of materials were investigated: woven fabric (WF), knitted material (KM) and polyethylene membrane (PE). Tests were performed at different initial deflection angles of the pendulum using two types of bobs (Table 2).

Curves of the decaying vibration process in time at different initial angles of the pendulum for all the materials investigated, where a bob of $r_1 = 13.5$ mm was applied are given in Figure 3 (see page 54).

Test results show that rebound and impact angles differ with respect to the initial deflection angle of the pendulum. Also, it

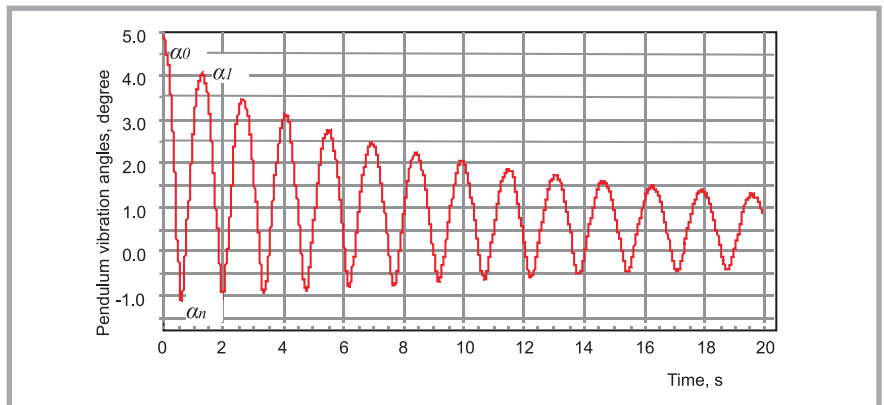


Figure 2. Registration of the pendulum vibration process for knitted material.

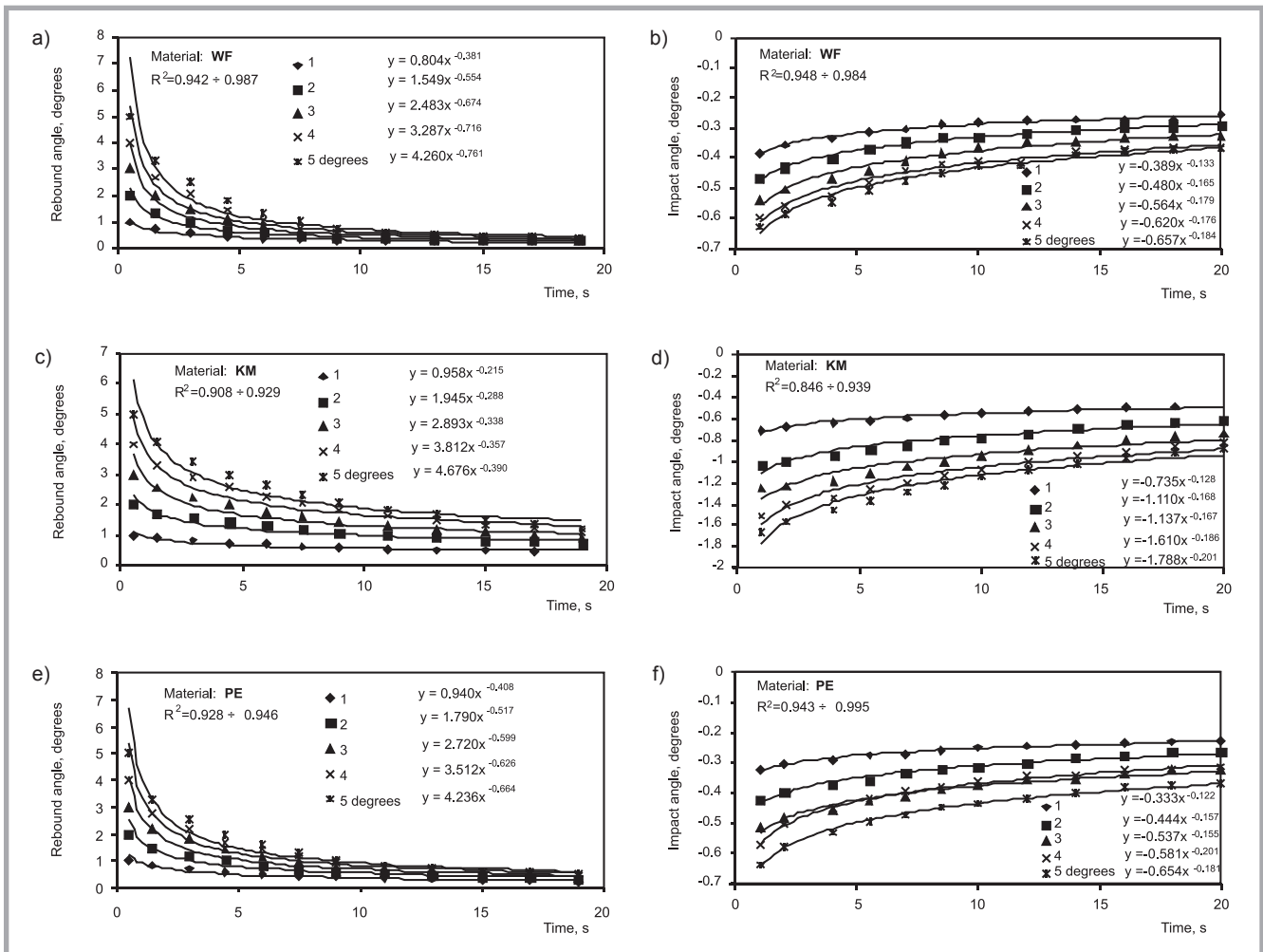


Figure 3. Rebound (a, c, e) and impact (b, d, f) angles of pendulum at different initial angles: \blacklozenge 1 \blacksquare 2 \blacktriangle 3 \times 4 \times 5 degrees ($r_1=13.5$ mm). WF – woven fabric, KM – knitted material, PE – polyethylene membrane.

must be noted that knitted material (KM) gives a 21% higher value of rebound angles of the pendulum compared with the other materials investigated. The stored compressive energy of this material is released back to the pendulum, giving it kinetic energy which causes the pendulum to move back at a certain angle. This angle is about 18% less than the initial angle because of energy losses in the cyclical motion. Also, values of the first rebound angle increase with an increase in the initial angle of the pendulum (for knitted material $\alpha_1 = 0.896 \div 4.063$ degrees). Analysing woven fabric (WF), and polyethylene membrane (PE), the pendulum vibration process decreases faster, and after four strokes the differences between the rebound angles of the pendulum at different initial angles becomes negligible with a decrease in the vibration process. Hence, energy losses due to material deformation are higher.

The values of impact angles at an absolute value decrease with an increase of

the initial angle of the pendulum. As far as impact angles are concerned, knitted material (KM) showed a considerable difference compared to other materials tested, because in this case the angles of first impact at different initial angles increased from 0.709 to 1.677 degrees, while for the other materials investigated they were from 0.325 to 0.638 degrees. The energy lost in the deformation of knitted materials is negligible; and such fabrics are called elastic fabrics. Results showed the rebound angle was the highest for knitted material, which was deformed the most.

The vibration process with respect to the changes in the rebound angles of the pendulum for all initial angles and for all the materials tested can be described by power equation $y = ax^c$ with the coefficient of determination $R^2 = 0.908 \div 0.987$. With respect to the impact angles of the pendulum's vibrations, the coefficient of determination $R^2 = 0.846 \div 0.995$.

Comparative analysis of the pendulum vibration process was performed using two bobs of different radius, i.e. $r_1 = 13.5$ mm and $r_2 = 30$ mm. The results showed that for $r_2 = 30$ mm, compared to $r_1 = 13.5$ mm, the deflection of the pendulum after the first full swing decreased by about 5%, where all 5 initial angles of the pendulum were applied for all the materials tested, whereas the impact angle for all the materials tested decreased by about 3%. In this instance, the potential energy of the pendulum available was higher (Table 3), but the area of contact interface between the bob and material was larger. Thus, the process of energy dissipation was more intense, and the quantity of absorbed energy was larger; therefore the impact and rebound angles were lower. In this case, the pendulum lost more energy due to internal friction and air resistance. It must also be noted that the accuracy of the test results was higher when higher initial angles of the pendulum were applied, i.e. between 4 - 5 degrees. The vibration process and

Table 3. Potential energy V_0 of pendulum.

Initial deflection angles of the pendulum in degrees	Potential energy V_0 of pendulum ($\cdot 10^{-2}$ J)	
	r_1	r_2
1°	0.36	0.57
2°	1.46	2.30
3°	3.28	5.17
4°	5.84	9.21
5°	9.12	14.39

the changes in the pendulum's rebound and impact angles for all initial angles and for all the materials tested can be described by the same power equation $y = ax^c$ with the coefficient of determination $R^2 = 0.907 \div 0.992$.

Figure 4 (see page 56) shows the relationships between pendulum potential energy V_1 at the moment of first deflection and initial angles α_0 of the pendulum for all the materials tested, where a bob of $r_1 = 13.5$ mm was applied. The accumulated energy V_1 of the pendulum during the first rebound at a certain deflection angle of the pendulum gives the best characterisation of the behaviour of the material tested during the impact loading. The forces of positive value (rebound moment) decrease the vibration process of the pendulum, and the forces of negative value (moment of impact) maintain the pendulum vibration, transmitting impulses of the force to the pendulum, induced by the material. The highest impulses of the force to the pendulum were transmitted by knitted material (KM) at a pendulum deflection angle α_0 of 5 degrees ($V_1 = 4.87 \cdot 10^{-2}$ J), and the highest resistance was produced by woven fabric (WF), at the same deflection angle ($V_1 = 3.07 \cdot 10^{-2}$ J). The relationships between pendulum energy V_1 at the first moment of deflection (first rebound angle) and initial angles α_0 of the pendulum can be described by linear equation ($y = a + bx$; the coefficient of determination – $R^2 = 0.97 \div 0.99$), i.e. pendulum energy V_1 increased with an increase in the initial angle of the pendulum.

Analysing the impulses transmitted by the materials to the pendulum and their stored kinetic energy showed slightly different results, which were obtained when a bob of bigger radius ($r_2 = 30$ mm) was applied. Hence, in this case the highest resistance was produced by polyethylene membrane (PE).

Percentage values of absorbed energy H_1 of the test materials at the first mo-

ment of pendulum impact are given in Table 4. Knitted material (KM) absorbed a smaller quantity of the pendulum's energy, i.e. about 25% less compared to the other materials investigated. The quantity of absorbed energy increased with an increase in the initial deflection angle α_0 and potential energy V_0 of the pendulum. According to the rebound angle of the pendulum and the quantity of the energy absorbed by the materials, during the impact loading, the behaviour of woven fabric (WF) and polyethylene membrane (PE) was similar.

To establish the elastic properties of the materials, two parameters characterising elasticity were determined: rebound elasticity ε_r and dynamic elasticity ε_d [13]. These parameters characterise the elasticity of materials according to the initial energy of the pendulum V_0 , and according to stored pendulum energy after the first full swing V_1 . Relationships between dynamic elasticity ε_d , rebound elasticity ε_r and initial angles of the pendulum for all the materials tested are given in Figures 5 and 6 (see page 56). Figure 5 shows that rebound elasticity ε_r for all the materials tested decreases at different intensities with an increase in the initial angle of the pendulum. For example, rebound elasticity decreased by 12% for knitted material (KM), 9% for woven fabric (WF) and 21% for polyethylene membrane (PE). It is evident that the values of rebound elasticity depend on the initial angle α_0 of the pendulum, the difference between the height h of gravity centre G before the release of the pendulum and the position G at the moment of impact [13]. The behaviour of materials during an increase in the impact energy of the pendulum, caused by the increase in the initial angle, can be characterised by the decreasing intensity of the rebound elasticity. The curves show that knitted material (KM) is characterised by the highest rebound elasticity, woven fabric (WF) by the lowest, when the pendulum bob $r_1 = 13.5$ mm was applied.

Table 4. Percentage values of absorbed energy H_1 at the first moment of pendulum impact.

Initial angles of the pendulum	Tested materials					
	WF		KM		PE	
	r_1	r_2	r_1	r_2	r_1	r_2
1°	58.06	58.65	34.17	35.56	44.44	61.09
2°	62.60	62.97	37.47	38.05	55.14	60.75
3°	63.12	64.14	41.16	42.60	56.77	63.42
4°	65.51	65.55	43.89	46.16	61.83	75.85
5°	66.88	66.88	46.60	49.31	65.13	75.69

During impact loading, the behaviour of polyethylene membrane (PE) and woven fabric (WF) becomes similar when the initial angle of the pendulum increases.

The values of rebound elasticity ε_r were higher for woven fabric (WF) compared with polyethylene membrane (PE) when the bob was changed to a bigger weight ($m = 0.912$ kg), and when the potential energy increased (Figure 6). In this regard rebound elasticity ε_r for polyethylene membrane decreased by only 14%. Relationships between the rebound elasticity and initial angles of the pendulum can be described by the linear equation $y = a + bx$, with the coefficient of determination $R^2 = 0.81 \div 0.99$.

The values of dynamic elasticity ε_d also depend on the initial angles α_0 of the pendulum and on the height h : the character of the curves obtained was very similar to the character of the curves, which determined rebound elasticity ε_r . These curves can also be described by the same linear equation $y = a + bx$, with the coefficient of determination $R^2 = 0.81 \div 0.99$. It was determined that for each material analysed the dynamic elasticity ε_d decreased with an increase in the initial angle of the pendulum, i.e. the dynamic elasticity with the highest intensity decreased for polyethylene membrane (PE) – 19% when the bob $r_1 = 13.5$ mm was applied (Figure 5). When the bob $r_2 = 30$ mm was applied, the dynamic elasticity with the highest intensity decreased for knitted material (KM) – 16% (Figure 6).

Relationships between lost pendulum energy H_1 , its accumulated energy after one full swing V_1 and the first rebound angle α_1 are given in Figure 7. The smaller the losses of pendulum energy H_1 in material deformation, the higher the first rebound angles α_1 and the stored potential energy of the pendulum V_1 are after the first full swing.

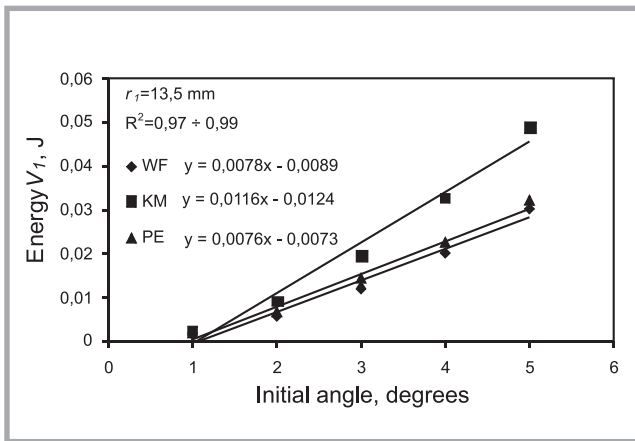


Figure 4. Relationships between potential energy V_1 of the pendulum and initial angles α_0 of the pendulum.

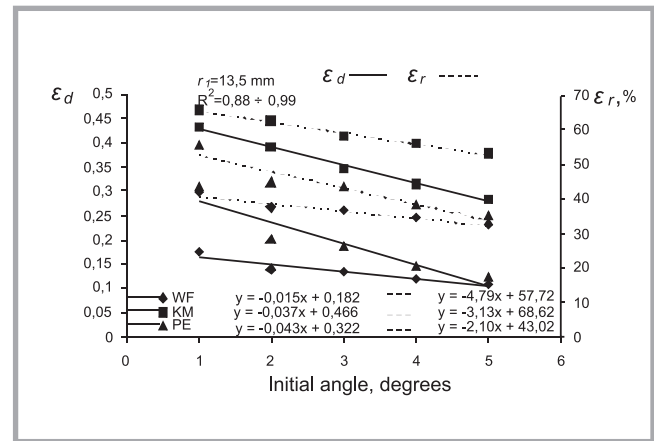


Figure 5. Relationships between dynamic elasticity ϵ_d , rebound elasticity ϵ_r , and initial angles α_0 of the pendulum.

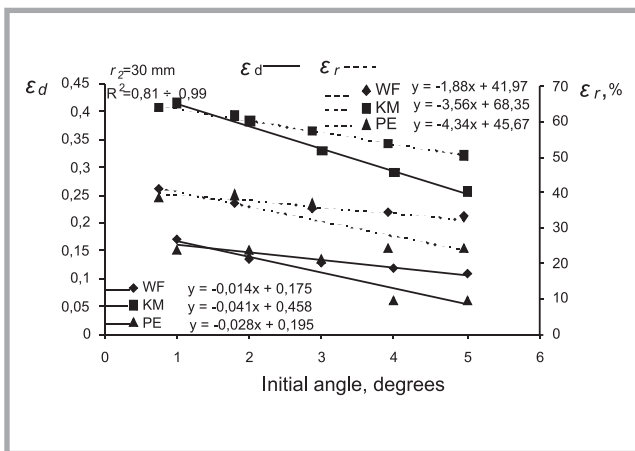


Figure 6. Relationships between dynamic elasticity ϵ_d , rebound elasticity ϵ_r , and initial angles α_0 of the pendulum.

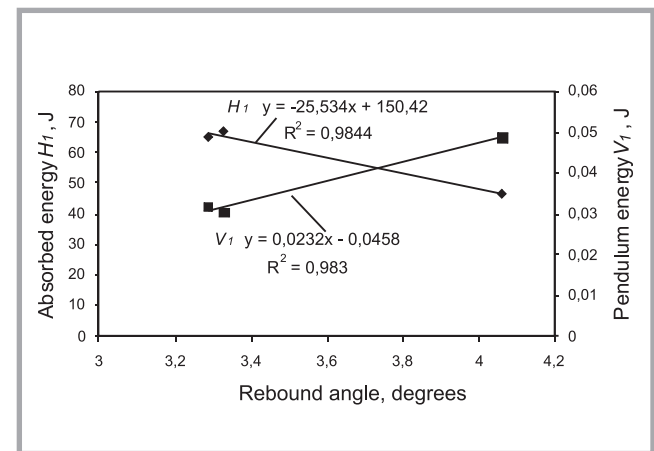


Figure 7. Relationships between absorbed energy H_1 of the pendulum, its energy after one full swing V_1 and the first rebound angle α_1 ($r_1=13.5$ mm; initial deflection angle of the pendulum – 5 degrees).

Summary

Optimal testing conditions of the pendulum impact device were established.

The decaying vibration process in time at different initial angles α_0 showed that rebound and impact angles differ with respect to the initial deflection angle of the pendulum. The vibration process with respect to the changes in the rebound and impact angles of the pendulum for all the initial angles, and all the materials tested, can be described by power equation $y = ax^c$, with the coefficient of determination $R^2 = 0.846 \div 0.995$. Values of the first rebound angle increase with an increase in the initial angle of the pendulum, and values of the impact angle decrease with an increase in the initial angle of the pendulum.

The accumulated energy V_1 of the pendulum during the first rebound at a certain deflection angle of the pendulum gives the best characterisation of the behaviour

of material tested under impact loading. Pendulum energy V_1 increases with an increase in the initial angle of the pendulum. Relationships between the pendulum energy at the first α_0 moment of deflection V_1 and initial angle of the pendulum for all the materials tested can be described by linear equation $y = a + bx$ with the coefficient of determination $R^2 = 0.97 \div 0.99$.

The relationships between dynamic elasticity ϵ_d , rebound elasticity ϵ_r and initial angles α_0 of the pendulum for all tested materials were determined. Rebound elasticity ϵ_r and dynamic elasticity ϵ_d for all tested materials decrease at different intensity with the increase of initial angle of pendulum and depends on the initial angle of the pendulum and on the weight m of the bob. They can be described by the linear equation $y = a + bx$, with the coefficient of determination $R^2=0.81 \div 0.99$. The increase in pendulum energy with respect to an increase in initial angle α_0 and

to the weight M of all moving pendulum parts was determined.

It can be concluded that all the testing conditions applied are suitable to characterise the elastic properties of woven fabric and knitted material. Yet in the cases when the initial potential energy V_0 of the pendulum was within the range of $9.21 \cdot 10^{-2} \div 14.39 \cdot 10^{-2}$ J ($r_2 = 30$ mm and the initial angles were 4 and 5 degrees), reliability of the test results was higher. Lower initial potential energies of the pendulum i.e. from $0.36 \cdot 10^{-2}$ J to $9.12 \cdot 10^{-2}$ J are advisable for characterisation of the elastic properties of polyethylene membranes.

It was determined that the quantity of energy loss of the pendulum during impact loading depends on the composition of the material investigated. Knitted material absorbs the least quantity of pendulum energy H_1 , i.e. about 25% less compared to other materials investigated.

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