Positive Environmental and Economic Impact of Polyvinyl Butyral Waste Material after Recycled Windscreen

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The development of the economy and the continual competition for the customer brings new impulses in the area of production, trade, and consumption. Manufacturers are increasingly looking to meet customers, wanting to meet the needs of a wider range of consumers with their manufacturing and sales strategy, with an emphasis on the environmental and economic impact of their products. Therefore, recycling and re-use of raw materials are very important today. The paper is focused on experimental studying and testing of material relaxation of recycled polyvinyl butyral (PVB). Polyvinyl butyral foil is one of the most important parts of the windscreen or safety glass as an interlayer. Polyvinyl butyral carries a large amount of chemically bonded energy. Less harmful vapours are released during combustion of PVB than when combustion of heating oil. However, the price of energy obtained from such a waste product is sometimes lower than the price of energy obtained from oil. Given the global polyvinyl butyral waste production, the price for this attractive commodity is very reasonable. It ranges from 0.25 € to 0.50 € per kilogram of this thermoplastics. After homogenization, the mixture polyvinyl butyral was compressed to the test samples of prescribed shape and size under action of pressure and heat. Recycled polyvinyl butyral was investigated under tensile test and material stress relaxation. Based on the results, it can be stated that the material had the max. values of a tensile stress 0.78 MPa, the strain of the material subject to tensile strain was from 410 % to 520 %.

Keywords: *Polyvinyl butyral (PVB), Safety glass, Cost savings, Sustainability, Mass Customization.*

Introduction

The changes in the economic, socio-cultural, political, competitive and technological environment that have taken place in the world in recent years have forced many companies to acclimatize in the "new economy" environment, bringing new approaches to production strategies and a new philosophy in the marketing´s field (Kotler, 2003). The long-term production focusing of the company, i.e. the production strategy of the company, represents a summary of not only production but also commercial, innovative and other long-term prospective tasks to ensure the strategic goals of the company. (Zhao et al., 2006) The frameworks are created for a very specific production content of the company, whether in terms of product quality, volume, product mix and other requirements (EuroEkonóm.sk, 2015; Mandičák et al., 2018). The implementation of materials from secondary raw materials and their application to possible components reduces the economic and environmental aspects that are very important today (Industrial Property Office of the Czech Republic, 2019; 2. Recycled polyvinyl butyral, Schirmbeck GmbH, 2018). The aim of the work is to find areas of use of recycled polyvinyl butyral (PVB) product, which is the product of windshield recycling (Figure 1), regarding the investigation of material relaxation.

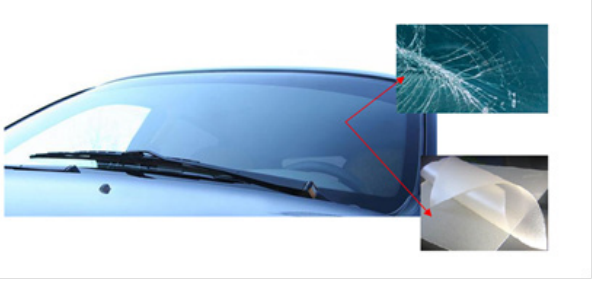

Fig.1. Polyvinyl butyral safety layer in the car windshield Source: own processing

Nowadays, every vehicle and its windscreen are equipped with a polyvinyl butyral film that secures the safety of the glass. The worldwide patent research (Recycled polyvinyl butyral, Schirmbeck GmbH, 2018; Dhaliwal and Hay, 2002) shows the possible use of recycled polyvinyl butyral in practice. PVB film does not contain additives classified as dangerous or harmful. PVB is primarily used as a multilayer foil in the windscreen, all modern vehicles, passenger cars, trucks. (Asik, 2003) PVB film protects the glass from grinding,

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damage, crash, and the like. In some cases, PVBs are part of the glazing of buildings, especially in areas where hurricanes are frequent, or, of course, in security windows of buildings. (Hidallana-Gamage et al., 2014) At the Michigan Molecular Institute, for years, they have been trying to find applications for the use of PVB waste, these applications are moving further into the automotive industry with efficiency in the US countries (Barry and Orroth, 2000). After the separation itself, the PVB waste still contains glass particles, which, while decreasing its use, but are still widespread in several industries. External storage of PVB material is dissuaded because moisture and ultraviolet radiation generally degrade the properties of PVB (Sekisui chemical.com, 2018). Also, the possibility of primary PVB contamination is increased. Due to the sticky and soft surface of the recycled PVB film, it is assumed that when unsuitable for storage, the number of impurities can be easily adhered to the surface, thereby reducing the quality of the use of the recycled product (Polyvinyl butyral, Kuraray, 2019). PVB storage capacities are limited in many countries (Fischer and Häring, 2009). Accordingly, some countries are already increasing storage costs and are trying to make producers of PVB encourage, that this type of waste to be re-used, they returned it to the production process again. With regard to solar energy, there is a prediction that the fastest growing area of the PVB end-user, with regard to the compound annual growth rate, is projected to increase by more than 6% between years 2015 and 2023 (Mitaľová et al., 2016; Knapčíková et al., 2016). In terms of volume of PVB produced, Asia, in the year 2014, has contributed to more than 35% of PVB use within the global market (Sekisui chemical.com, 2018; Mitaľová et al., 2016). The use of PVB film on the market in Latin America, the Middle East, and Africa is expected to grow significantly over the next eight years, mainly due to the increase in land transport and construction as end-users (Mohammadian-Kohol et al., 2016).

As we can see from the classification of PVB's usability in individual countries of the world, PVB has a wide range, application variability in production conditions with an emphasis on the requirements of the final consumer, the PVB processor to the final products. (Sridhara and Satapathy, 2015) Based on this differentiation of countries, companies and their specific needs, it is possible to apply a targeted customization strategy where pure customization cannot be achieved for the entire product portfolio, but the company can reach it for more than one production area segment. (Iwasaki et al., 2007) The strategy is focused on the demands of consumers, where the company produces its customers based on the specific requirements, but only in certain, targeted markets. Analysing targeted mass customization explains why in some market's companies produce a range of just basic types, while in other markets businesses produce an expanded range of their products to meet customer requirements. This means that a company that offers only a limited number of its products in one country allows its consumers to "tailor to their products" (Cavusoglu et al., 2007).

Materials and methods

Polyvinyl butyral (PVB) (Mitaľová et al., 2016) is a special resin, mainly used as a raw material for laminated safety glass in cars (Figure 1) and in the building construction industry. Application is mainly for skyscrapers. PVB currently produces several companies in Europe and the world, each under its trademark. In addition to the main application and thus the use of PVB films, PVB resins are used for the production of paints, structural adhesives, dry toner paints and as binders for ceramics and composite fibres (Farzana et al., 2016). The PVB foil has many excellent features such as high tensile strength, impact resistance, transparency and flexibility, which is particularly useful in producing safety glass. Due to the alcohol, ester and acetate bond content, PVB foil (Zhang et al., 2016; Valášek et al., 2016) can hold the glass firmly, even if the glass breaks. The glass can adhere to the PVB film interlayer to prevent breakage. Sales of primary end-users of polyvinyl butyral are dependent on the performance of the general economy, especially for safety glass, which is so necessary for the automotive industry and in the construction industry - in architecture (Knapčíková, 2015; Knapčíková et al., 2016). The PVB is exported to the countries with widespread automotive production, which is characterized by a high level of mass customization - customization. According to Lampel and Mintzberg (Lampel and Mintzberg, 1996), the last type of mass customization is customizing customization, in which customers directly interfere with the production process and modify their "products" themselves. The consumer here affects distribution, assembly and production, which has a significant impact on the company's final production. Ultimately, by consuming the recycled PVB in the required condition, quality and characteristics, the consumer obtains the feedstock, which is an essential ingredient for his further transformation process (production). In his publication, D. Anderson (2004) divided mass customization into three primary groups: dimensional, modular and customized. For this process is typically dimensional, this type of MC brings constant changes in mixing ratios, scales, and can have infinitely many options. (Vasiliev and Morozov, 2001) Examples of such customization with an infinite number of possibilities are shearing sheets, mixing chemicals, sewing clothes, etc. Dimensional customization can be applied using CNC (Saad et al., 2006) machines that receive instructions based on orders received.

Recycled polyvinyl butyral

The key material of this study is polyvinyl butyral (Figure 2), which was obtained after windscreens recycling. The flakes have a size from 2 mm to 20 mm, and the thickness is from 0.5 mm to 1.5 mm.

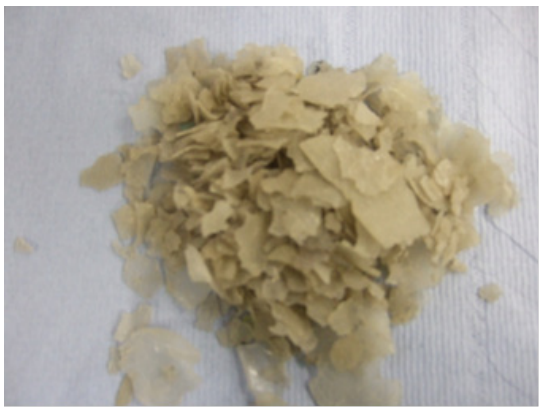

Fig.2. Recycled polyvinyl butyral Source: own processing

This recycled polyvinyl butyral is contaminated with dust, glass fragments, so it is important to thoroughly wash the material and dry it before starting laboratory work. Polyvinyl butyral as the thermoplastic material is soluble in ethanol, butanol, ethyl acetate, butyl acetate, in a mixture of chlorinated hydrocarbons and insoluble in aliphatic hydrocarbons (in gasoline) (Knapčíková et al., 2016). The polyvinyl butyral density used by the research was 1.07 g.cm^{-3}, and the sales price of recycled polyvinyl butyral is from 0.25 € to 0.50 € per kilogram. The economic potential of this "waste" material is very high.

Tab. 1. Material Advantages of recycled polyvinyl butyral for manufacturing

Recycled polyvinyl butyral	
• Form	flakes
• Size	20-30 mm
• Purity	more than 97%
• Fire point	None
• Glass temperature transition	130°C -170°C
• Viscosity (dynamic)	100 – 175 m Pa*s According to DIN 53015
• MVR (Melt Volume Rate)	6 -7 cm³. 10 min^{-1}
• MFR (Melt Flow Rate)	5 – 6 g.10 min^{-1}

Source: own processing

Material preparation

Before to compression moulding process technology, the thermoplastic material was homogenized used double screw machine (Del Linz et al., 2016; Botko et al., 2018; Kulikov et al., 2018). Continuous mixing was used to prepare the homogenized mixture (Knapčíková et al., 2016; Valášek et al., 2016). Homogenization of the material (Figure 3) was carried out on a Brabender Plasti-Corder W 350 E (Valášek et al., 2016). Laboratory investigations were performed at room temperature 22 ° C and 60% humidity. The homogenization process lasted 15 min. The material was thoroughly mixed, and the formation of air bubbles that were undesirable during the moulding process (occurring during compression, incomplete mixing, or incomplete filling of the thermoplastic mould cavity) was avoided. (Sheng and Zhang, 2016) After homogenization of the recycled polyvinyl butyral on a Brabender Plasti-Corder W 350 E, the material was carefully selected and prepared for moulding. In compression moulding, thermoplastic or thermoset material (in the form of granules or flakes) is melted in the mould cavity under heat and pressure, followed by cooling and part removal after it is cured (Knapčíková et al., 2010). Table 2 shows the moulding characteristics used Brabender W 350 mould equipment.

Tab. 2. Moulding specifications

Equipment	Brabender W350
• Molding temperature	190 °C
• Pre-heating time	20 min
• Molding time	20 min
• Cooling time	20 min
• Molding pressure	10 MPa

Source: own processing

Stress relaxation of recycled polyvinyl butyral

Stress relaxation means the degradation of the material by cyclic (repetitive) stress and mechanical load (Figure 3) (Knapčíková et al., 2016; Telišková et al., 2018). If the amplitude of the stress is greater than the fatigue limit of the material, it ultimately leads to crack initiation. If a crack is predicted or spread, then the test specimen can break (Knapčíková, 2015).

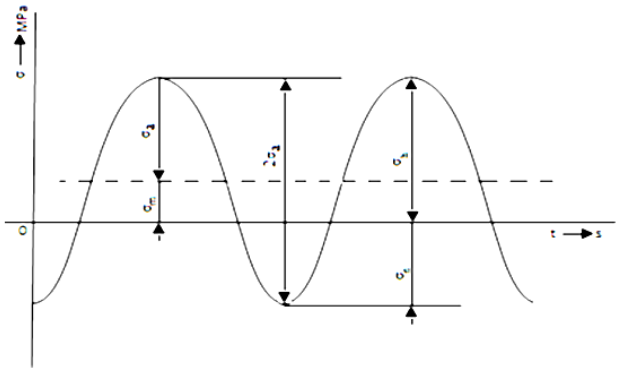

Fig.3. Repeated cyclic relaxation of recycled polyvinyl butyral material. Source: Mitaľova et al.,2016

The following characteristics are known from the above mentioned Figure 3(Mitaľova et al., 2016):

σ_h - maximum stress [MPa]
σ_n - minimum stress [MPa]
σ_m - medium stress [MPa]
σ_a - stress amplitude [MPa]
R - cycle asymmetry parameter [MPa]

Material relaxation was performed on the Zwick Z020 Universalpruefungsmaschine (Figure 4) (Valášek et al., 2016), using a climate chamber where test conditions were set. The temperature ranges from -80 °C to + 250 °C was used for the climate chamber tests. (Cormie et al., 2009) The choice of temperature is given by the internal and external factors of the investigation, whether the tests are at controlled temperature or the ambient temperature test (Knapčíková et al., 2016).

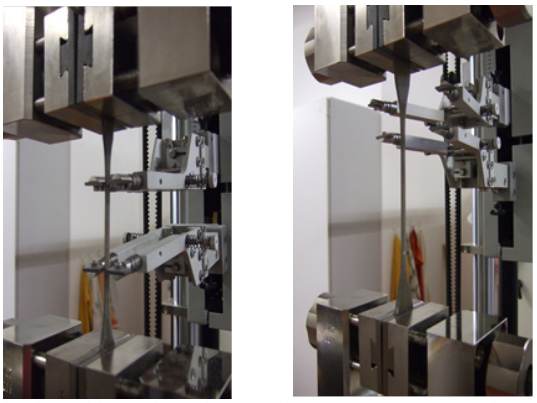

Fig.4. Fixturing a sample of recycled polyvinyl butyral at relaxation during 5 min, 15 min and 25 min period. Source: Knapčíková et al., 2016

Results and discussion

The investigation of material relaxation was carried out according to the standard EN ISO 4892. In the case of testing of samples from recycled polyvinyl butyral, a constant temperature of 23 °C was set in the climate chamber (Farzana et al., 2016; Liu et al., 2012; Botko et al., 2018). The duration of the maximum stress at the material relaxation is always 10 minutes (5 min, 15 min and 25 min for all tested period). All experiments were repeated 10 times with triplicate samples for each group. Significant differences between two groups were evaluated using a one-way analysis of variance (ANOVA) with a 95 % confidence interval. Underneath, graphical representations presented the result of a tensile test carried out on a Zwick Z020 Universalpruefungsmaschine equipment.

Tab. 3. Measured material characteristics of recycled polyvinyl butyral during the relaxation test

No.	Period	Tensile stress [MPa]	Strain [%]	Stress at break [N]	Strain at break [%]
1.	0	0	0	0	0
	5	0.451	400	234.597	281.358
	15	0.255	260	68.381	330.848
	25	0.301	400	214.633	289.634
2.	0	0	0	0	0
	5	0.350	550	196.74	394.727
	15	0.350	480	168.185	179.929
	25	0.300	500	240.024	343.954

Source: own processing

Tab. 4. Measured force characteristics of recycled polyvinyl butyral material during the relaxation test

No.	Period	Max. force after relaxation F´εges [N]	Max. force before relaxation F εges [N]	Strain after relaxation ε´ges [mm]	Strain before relaxation ε ges [mm]
1.	0	0	0	0	0
	5	4.708	9.775	21.120	21.121
	15	4.628	9.175	21.031	21.020
	25	3.754	8.173	21.080	21.070
2.	0	0	0	0	0
	5	5.643	10.614	21.032	21.031
	15	4.278	11.332	20.980	20.980
	25	4.350	11.740	21.111	21.100

Source: own processing

By introducing the above measurement conditions (Telišková et al., 2018; Botko et al., 2018), the material manufactured by compression moulding from recycled polyvinyl butyral was tested for its ability to withstand a continuous load of 10 cycles. The relaxation time (Farzana et al., 2016) was 10 minutes in all cases. It can be seen from the graph that with a period of 5 minutes, the relaxation time of 10 minutes and a total number of cycles at this stress, the sample was ruptured by strain results between 410% and 570%, tensile stress from 11.2 MPa to 11.5 MPa. By 15 min period testing, the relative strain values were from 260% to 460% and the tensile stress from 9.3 MPa to 9.5 MPa. The testing cycle, which lasted 25 min, had a relative strain value from 435% to 520% and tensile stress from 10.1MPa to 11.9MPa (Figure 5).

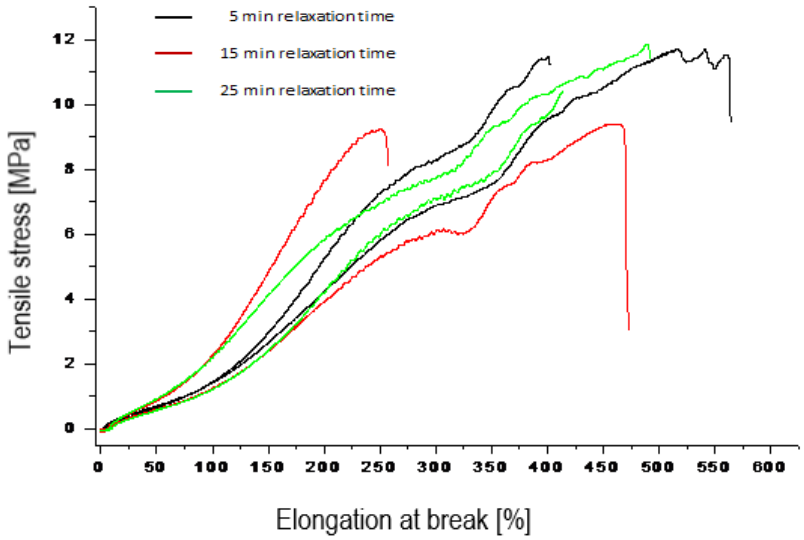

Fig. 5. Graphical representation of recycled polyvinyl butyral stress relaxation (by 5-, 15- and 25-min relaxation time)
Source: own processing

In Figure 6, the view of relaxation by 5-min and the number of cycles 10 can be seen. The tensile stress has the max. value of 0.65 MPa by 5-min relaxation time. All presented curves; i.e. dependencies of individual variables were evaluated by Origin Ver.6.

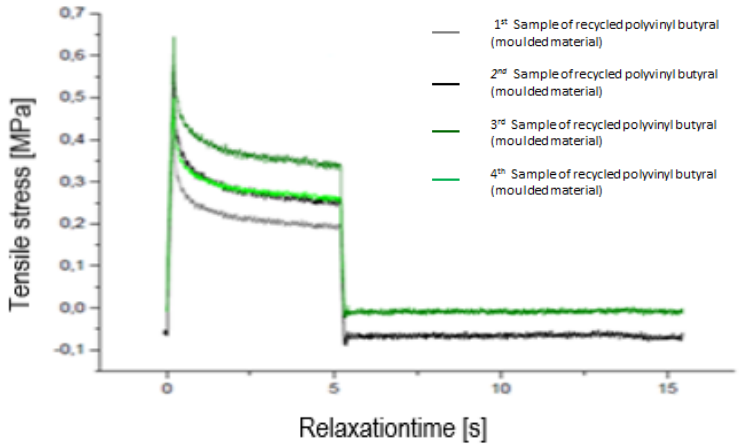

Fig.6. Graphical representation of recycled polyvinyl butyral stress relaxation (by 5 min relaxation time)
Source: own processing

The cyclic relaxation of the material was by the regular relaxation of the material at a constant speed, and a force of 5.01 N. Orange colour presented correction of curves (optimal condition) in dependence on the strain and tensile stress. Neon green colour by 25-min relaxation is presented an optimal condition. Figures 7 and 8 show the material relaxation for 10 cycles and for all tested samples together.

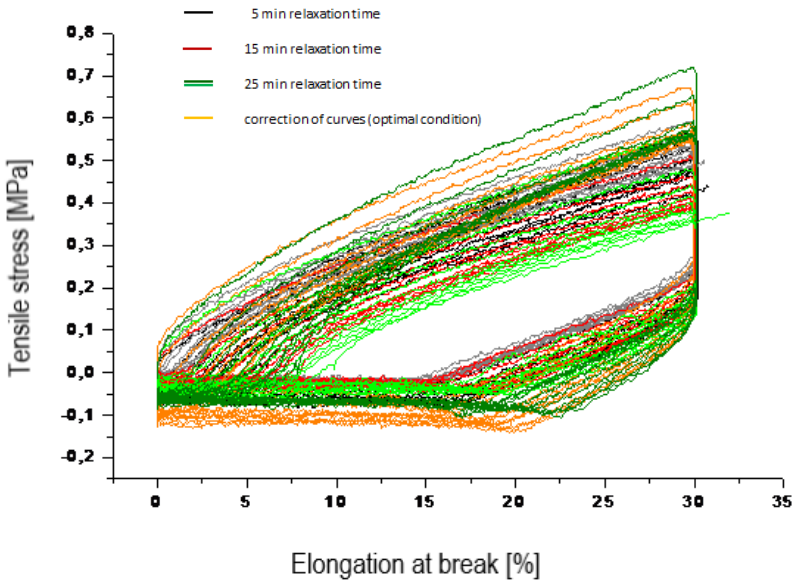

Fig.7. Graphical representation of material relaxation by the 5-min, 15-min and 25-min testing period (10 cycles)
Source: own processing

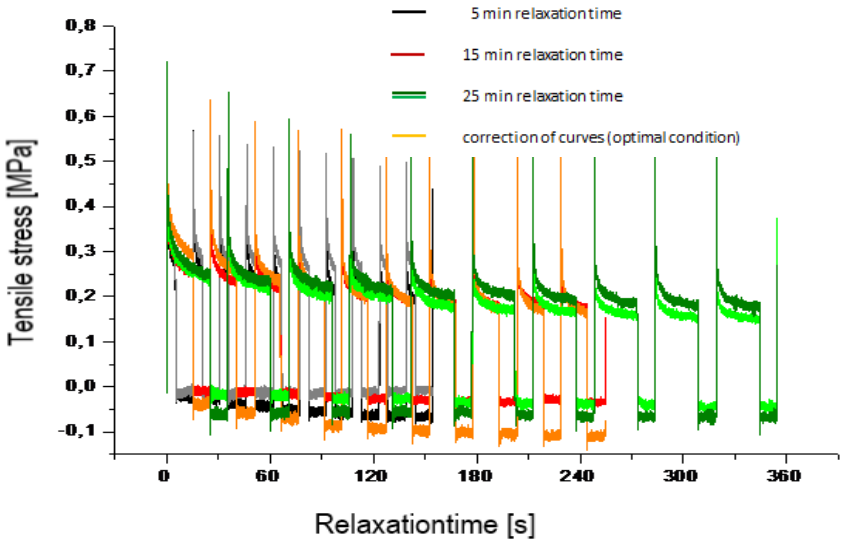

Fig.8. Graphical representation of material relaxation under 10 cycles
Source: own processing

According to ISO 3384-1:2011 performed laboratory testing of recycled polyvinyl butyral show less manual work and measurement can continue throughout the test after it is started. Advantages of this measurement are no physical movement of the rigs after the test is started. With a comparison of our obtained results and already published results, we have to observe the completion of regular cycles of 5-min, 15-min, and 25-min, the material was brought to a state where it reached the tensile stress of the test material at failure. This is mainly because the tensile stress amplitude was greater than the fatigue limit of the material. Ultimately, this led to crack initiation. This phenomenon arises especially when there is a certain presumption of crack formation or its potential, and there is a presumption of its assumption. After that, a test sample of moulded recycled polyvinyl butyral was broken. We see the novelty of the presented paper in the testing of material manufactured with recycled polyvinyl butyral.

Conclusions

Recycled polyvinyl butyral, as one of the most important parts of safety (for example, automotive) glass, was investigated under material stress relaxation. Based on the results, it can be stated that:

1. The material had the max. values for tensile stress of 0.78 MPa, the strain of the material for the tensile strain was up 410% to 520%.
2. Upon completion of regular cycles of 5-min, 15-min, 25-min, the material was brought to a state where it reached tensile stress at break σ_B which is also characterised as the tension of the test material in the tensile stroke of the test sample.
3. The amplitude of the tensile stress was greater than the material fatigue limit. In the end, it has led to crack initiation.

Recycled PVB is an important part of the production of new materials, and we can say that the variation in the use of this type of material is high. It is characterized by very well:

- elasticity,
- adhesion to various surfaces,
- good water resistance,
- economic investment,
- environmental friendly material.

According to the presented results, the advantage of this material is high compatibility with other polymers, as well as very good processing and subsequent production of composite materials. Last but not least, the economic potential of this new material is very important. Given the cost of this alternative commodity, which is in the range of 0.25-0.50 € per kilogram of this thermoplastic and its physical, chemical and ecological properties make it a very desirable raw material for the end-user.
Obtained results of our research:

- minimise deficiencies or problems with the raw material of car windscreens.
- Can be reused in the production process.
- New material can be implemented in selected engineering production, for example, indoor and outdoor.
  material´s cap, and not only there. According to its own of properties and processing is an open application to the construction industry,
  garden construction, road construction, for example, insulation material, facing panel,
- Manufactured materials based on recycled polyvinyl butyral save the company's initial investment

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As part of the mass customization strategy, the manufacturer has the opportunity to apply this recycled raw material to a wide portfolio of its products in order to maximise customer satisfaction, minimize production costs while paying attention to the environmental ecology.

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