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Characterization of Customized Encapsulant Polyvinyl Butyral Used in the Solar Industry and Its Impact on the Environment

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Abstract: Taking climate and geopolitical issues into account, we must shift our thinking towards “eco” and focus on renewable energy. The accessible solar energy represents 400 times the amount of consumption, while its potential represents 10,000 times the amount of demand. The paper aims to analyze recycled, customized polyvinyl butyral (PVB) with high purity (more than 98%) concerning its physicochemical and mechanical properties and its possible applicability in the photovoltaic industry as an encapsulating material. The detailed investigation on polyvinyl butyral starting from characterizations, homogenization, and moulding process to tensile tests and used exposure testing in laboratory apparatus are performed. Samples of recycled polyvinyl butyral were exposed to ultraviolet (UV) radiation of the value $0.76 \text{ W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}$ at 340 nm, water spray, drying at 50 °C and condensation for 320 h when the radiation was turned off. The results obtained were more controlled in a laboratory environment than those found in external, uncontrolled environments. These conditions subsequently accelerate any degradation of polyvinyl butyral as a material and subsequent degradation of the final product.

Keywords: polyvinyl butyral; solar panels; environment

1. Introduction

Energy consumption grows yearly worldwide by 2.6%. [1]. It is expected by the year 2100 that energy consumption will increase more than 3 times. [1,2]. Europe is committed to significantly reducing CO₂ emissions, with about a 20% share of renewable energy sources. This is supported by extensive research programs and cutting-edge technology and involvement in the solar industry. Nowadays, the installation of solar panels is becoming more efficient and cost-effective [2]. It is assumed that sufficient solar energy is available in densely populated areas.

One of the possibilities is to obtain electricity from sunlight, which is a source of life on our planet as we know it. Solar collectors can meet 60–70% of the annual hot water demand in the household, in summer almost wholly, and in the transition period and winter it will be pre-heated. Energy obtained from the sun is primarily a virtually inexhaustible, safe and renewable energy source accessible for most of the year. The use of the sun’s energy contributes to a sustainable way of life and does not burden future generations [3,4]. The use of solar energy alone does not have any adverse environmental effects during the entire life of the technological equipment, which in our conditions is around 20 to 30 years [5]. The economic goal of the development of a new financial sector of producers

and suppliers of technologies for renewable energy sources is also significant. According to a study by the European Federation for the Thermal Utilization of Solar Energy, the use of solar energy creates incomparably more jobs compared to fossil and nuclear power. For 1000 GWh of primary point supplied, there are 90 jobs created in the coal sector, 72 jobs in the nuclear industry, and up to 3960 jobs in the solar industry [5,6]. It is mainly the production, design, installation and maintenance of solar systems (Figure 1), which, unlike large energy sources, are not centralized in one place.

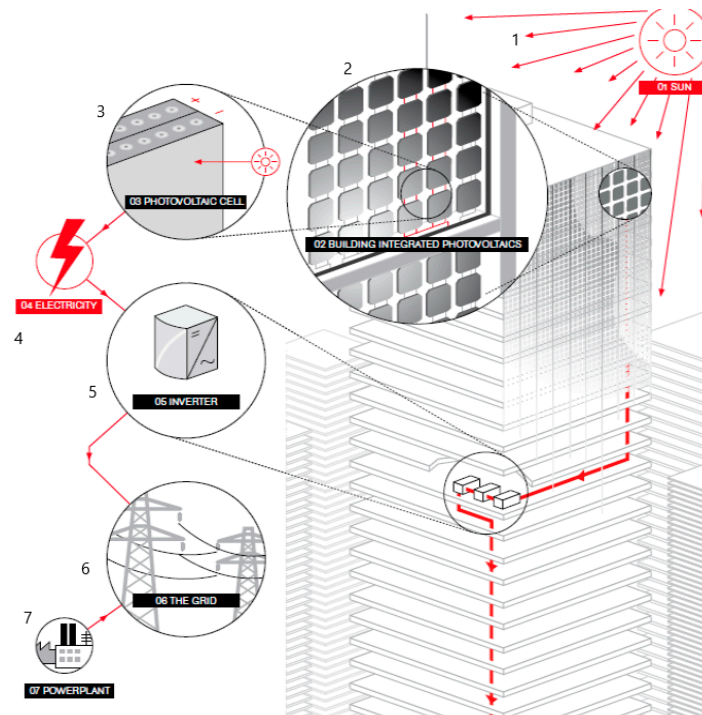


Figure 1. Description of the solar energy process.

Legend to Figure 1: 1-Sun; 2-Building Integrated Photovoltaics; 3-Photovoltaic Cell; 4-Electricity; 5-Inverter; 6-The Grid; 7-Powerplant.

A photovoltaic cell [7], otherwise called a solar cell, is a semiconductor device [8,9]. The structure of this semiconductor device is similar to the form of a photodiode. Generally, a photovoltaic cell transforms solar energy into electrical energy, using a photoelectric effect [8]. The term photoelectric effect means the release of electrons from a substance exposed to electromagnetic radiation [9]. The number of emitted electrons depends on the intensity of radiation [9]. Monocrystalline silicon was the first material to be used in practice for the production of photovoltaic cells. In its beginning in 1954, the efficiency of converting solar energy into electrical energy in such a section was around 6%. Later, as science became more concerned with this simple source of electricity, the efficiency value was increased to 17%, which was considered unsurpassed in 1980 [7]. The overall development of photovoltaic cells was hampered by the fact that prices were high and scientists sought to reduce the unit price per panel, thus using less pure silicon, which was not sufficiently efficient [4]. In the year 1992, the maximum efficiency was achieved. The laboratory measurement of the cell showed an efficiency value of up to 35.2%. Monocrystalline cells are composed of monocrystalline silicon crystals, measuring about 10 cm [8]. They are produced from ingots or, in other words, polycrystalline silicon rods by the Czochralski method by the slow drawing of pure molten silicon [10]. These bars are further cut with a particular saw for sheets with a thickness of approximately 0.25 mm to 0.35 mm. Figure 2 shows a chronological overview of the crucial milestones of technologies and materials used in the photovoltaic industry [10]. The year 1958 was essential for the use of the first solar cell made of silicon by Bell Laboratories (New Jersey, USA) [10].

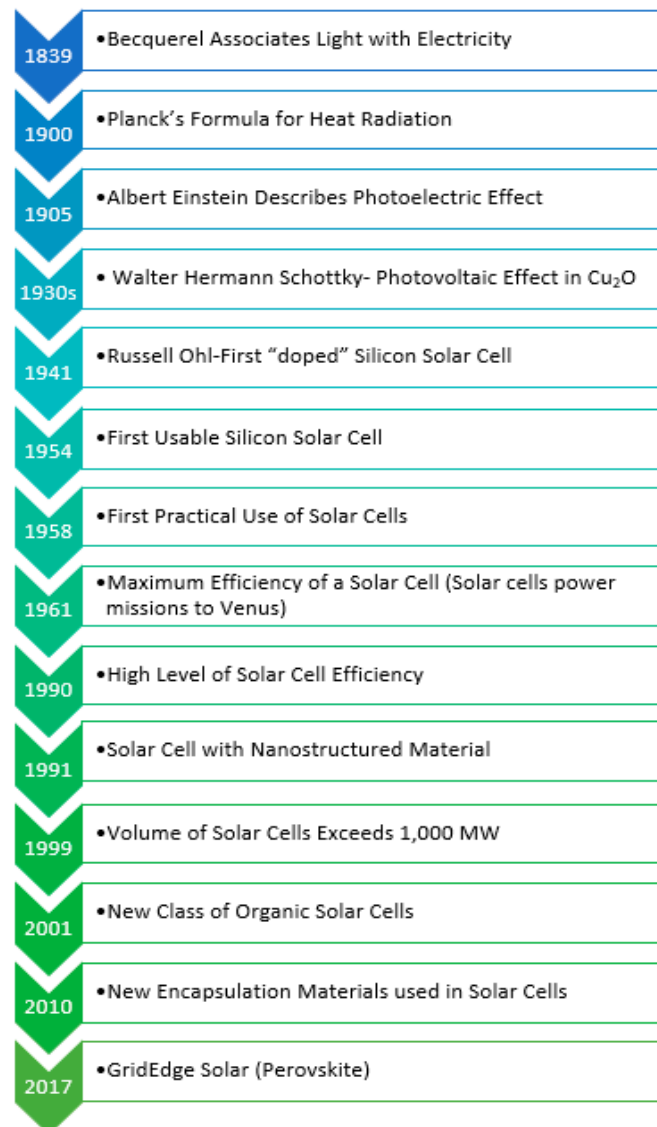


Figure 2. Chronology review of photovoltaics.

The latest research is from 2017 and continues to the present day. The Massachusetts Institute of Technology (MIT) is working on research and development to reduce the technological and market risks of lightweight and flexible photovoltaic modules through proof of testing analyses by which we can significantly reduce these impacts on the environment.

Nowadays, it is also possible to produce cells with a thickness of 0.1 mm, with the lowest possible waste that is generated when cutting sections. Polycrystalline silicon cells are today one of the most common types of solar cell [4,11]. Their production consists of the extraction of monocrystalline silicon, or by casting pure silicon into moulds, where they are subsequently cut to the required thickness [8]. This method of casting silicon is a much simpler way than drawing the single silicon crystal itself because the manufacturer can cast the shape he needs [9]. The disadvantage of casting is more low efficiency, but their advantage is a better use of this material, lower production cost and the possibility of larger size [7]. The manufacturing of amorphous solar cells is much simpler than monocrystalline and polycrystalline cells. Generally consumes much less material. This material saving, of course, means that when buying an amorphous cell, we save significantly compared to buying a single crystal and polycrystalline cell [12]. A 1.0 mm thickness of the amorphous cell absorbs 90% of the sun's radiation, making it possible to produce much thinner modules that can be used to cover the roofs of

buildings [13]. According to research, the polymer ethylene-vinyl acetate (EVA) belongs to key material for solar cells as encapsulation. EVA with its excellent processing properties offers a wide range of applications possibilities. The company Kuraray Co., Ltd. (Tokyo, Japan) [7], through cooperation with the National Institute of Advanced Industrial Science and Technology (AIST)), has developed high-strength encapsulating polyvinyl butyral (PVB) films [12,14] (Figure 3). PVB films produce photovoltaic (PV) modules easier and cheaper, and the project has started to take them into the test markets.

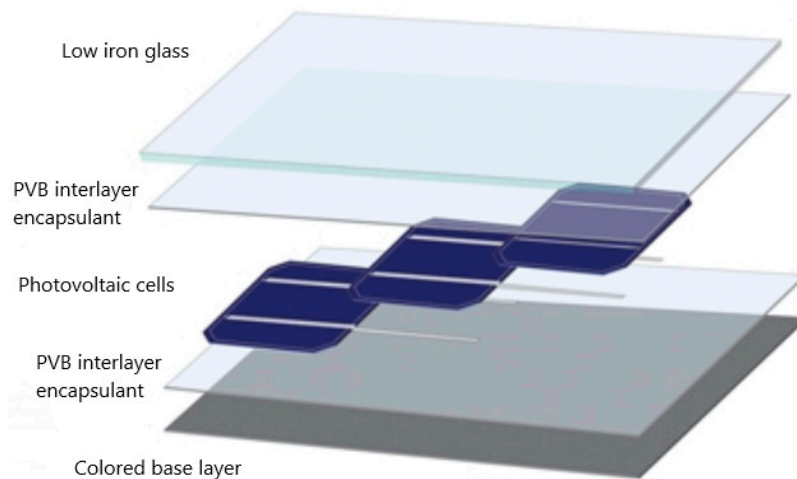


Figure 3. Solar panel composition used polyvinyl butyral (PVB) interlayer encapsulate.

For durability of the module and the long-term production of energy, the cell encapsulation materials must have specific essential properties, e.g.,

- Mechanical cell protection;
- Weather protection;
- Electrical insulation;
- Resistance to external impact;
- Protection against oxygen and water vapor;
- Minimization of cell corrosion;
- High adhesion to other components of the module (glass, chamber, base foil, contacts, etc.);
- Maximum guarantee of transparency and high protection against ultraviolet (UV) radiation.

The solar industry is one of the fastest growing areas of polyvinyl butyral end-use on the market. In terms of offer and demand for PVB interlayers in the photovoltaic industry, we can say that this material is a leader. Studies clearly show a shift to renewable energy sources, which is why the consumption of PVB interlayers is expected to increase [8]. The current state is that the intermediate layers of PVB film are mainly used in 70% of laminated glass applications. The basic function is to increase safety and improve the acoustic and UV protection of glass [11,12]. In terms of construction, these interlayers are used in traditional quadrilateral supported glass and 1–3 side and minimally supported glass in windows, façade systems, ceilings, floors and railings [12]. These interlayers also have limitations, like a low strength and higher weight with comparison to functional glass.

The most important representatives of PVB manufacturers are Eastman Chemical Company (US), Kuraray (Germany), Sekisui Chemicals (Japan), Everlam (Belgium), Genau Manufacturing Company (India), KB PVB (China), Chang Chun Group (China), DuLite (China), Huakai Plastic (China), Willing Lamiglass Materials (China), Jiangsu Darui Hengte Technology (China), and Tiantai Kanglai Industrial (China) [13].

PVB is a polymeric material with excellent mechanical properties and is mainly used as an interlayer for laminated glass [11–13]. PVB is used in the solar industry, in the production of PV panels,

as well as in the automotive and construction industries. Recently, the demand for the use of PVB as an intermediate layer in sandwich laminated glass has increased significantly due to its use for safety and security purposes [14]. Acoustic insulation and protection against UV radiation are the main properties of PVB, which increase their use for the above applications. PVB interlayers also absorb more than 99% of UV light rays [11]. In buildings, PVB interlayers are used in facades, windows, ceiling glazing, partitions, and floors.

Demand for polyvinyl butyral (PVB) is increasing due to its increased use in the production of films and foils, which are further used in the automotive and construction industries for the production of laminated glass [14]. With the growing solar industry, the demand for excellent optical clarity, strong binding ability and exceptional adhesion properties increases. It is estimated that the photovoltaic end-use sector recorded the highest value between 2016 and 2021 in terms of the market share of use. The growing use of PVB films and films in the manufacturing of solar components is driving the market for the photovoltaic industry forward. The transparent polyvinyl butyral (PVB) film is placed on the front and back of the photovoltaic cells. When the melting point is reached, the polyvinyl butyral film melts and subsequently fills all gaps and removes air between the layers. [15].

The photovoltaic market is very dynamic and has developed rapidly in recent years. Due to the growing interest in renewable energy sources, production processes have recently improved considerably. The main goal of all manufacturers is to increase the efficiency of cells while reducing production costs. Price per unit of output is still a significant factor in this area. Therefore, in order to obtain that objective, it is necessary to lower the price of the input material, simplify and reduce the production technology, and increase the conversion efficiency of PV cells. Other no less important factors are, of course, the lifespan of the cells and the decline in performance over time.

It is known that the European Union (EU) as a whole is more than 50% dependent on imports of primary energy sources. In most cases, this is from politically or economically unstable regions [8]. Another impact on the EU's energy strategy is the commitments made in the field of air protection. Therefore, the EU's energy efforts focus mainly on energy efficiency and the use of renewable energy sources, the potential of which is not negligible in the individual member states [7,9].

2. Material and Methods

2.1. Material Characterization

PVB is produced from polyvinyl acetate (PVA) by reaction with butyraldehyde ($\text{CH}_3\text{CH}_2\text{CH}_2\text{CHO}$) and formaldehyde (CH_2O) [12]. PVB is a transparent, strong and flexible thermoplastic with high optical purity and good adhesion to a large number of substrates. Polyvinyl butyral belongs to the group of amorphous polymers with a very high VA (vinyl acetate) content higher than 63.3% by weight [16,17]. The melting point (T_m) is between 171 °C and 218 °C [18]. DSC 204 equipment from NETZSCH company was used to determine the T_g and T_m temperatures. The obtained data were evaluated by the NETZSCH Proteus program, which is a part of the equipment. Small weights of the test sample, in our case 9 mg, are used for analysis. The device was set in the temperature mode from -50 °C to 300 °C.

PVB is an essential example of the light, highly transparent, elastic and durable films. The polyvinyl butyral used in our research (Figure 4) came from the recycling of safety glasses with a purity of more than 98%.



Figure 4. Polyvinyl butyral used in this research.

With its properties such as toughness, good adhesion to other components, light fastness and excellent transparency, polyvinyl butyral is one of the key materials used in the solar industry [13,19]. PVB foil fulfils a safety function. Recycled polyvinyl butyral, which was used, has the following values (Table 1).

Table 1. Characterization of selected polyvinyl butyral.

Material	
Type	flakes form neutral
Coloring-matter	20–30 mm
Flakes parameter	>98%
Purity	<%
Impurity content	ca. 2%
Residual amount of humidity	Less as 2%
Ratio of glass particle content	
Fire point	none
Glasstransition temperature	130–170 °C
Viscosity (dynamic)	100–175 m Pa*s
MVR (Melt VolumeRate)	(DIN 53015)
MFR (Melt Flow Rate)	6–7 cm ³ /10 min 5–6 g/10 min

2.2. Homogenization and Moulding Process

Thorough homogenization of the material was ensured by continuous mixing of polyvinyl butyral [18,19]. The material was mixed on a Brabender Plasti-Corder W 350 E, under laboratory conditions at 22 °C and 60% humidity. The kneading process took 15 min.

During this process, the removal of air bubbles, which are undesirable during the pressing process, was achieved.

After homogenization of the recycled polyvinyl butyral, the material was extruded and prepared for the tensile test. Moulding technology took place on a laboratory press Brabender W 350 with the following parameters (Table 2).

Table 2. Moulding process characteristics.

Moulding Parameters	Brabender W 350
Moulding Temperature	190 °C
Heating	20 min (±2 min)
Moulding Time	20 min (±2 min)
Cooling	20 min (±2 min)
Pressure	10 MPa (±0.1 MPa)

The moulding cycle consisted of the following operations [18]:

- opening the mould,
- material filling,
- moulding process,
- moulding process,
- opening the mould,
- removing process,
- cooling and cleaning process.

2.3. Polyvinyl Butyral Testing Used Methods of Exposure to Laboratory Light Sources

The application possibilities of polyvinyl butyral are undoubtedly an advantage in the solar industry. It is always crucial assign the intensity of sunlight, heat, humidity and other climatic influences on the behavior of the material [13,15]. Exposures in laboratory apparatus (Figure 5) is performed under more monitored aspects than those found in natural environments and aimed to accelerate any polymer degradation and product failure. In preparing the material for laboratory testing, we followed the standard EN ISO 4892 (Plastics—Methods of exposure to laboratory light sources) [15].



Figure 5. The ThermoTec Laboratory equipment.

According to EN ISO 4892 [15], the test conditions were determined, which are listed in Table 3. The test specimens were subjected to water, a temperature in the range from -50 °C to $+120\text{ °C}$, UV radiation with a value of $0.76\text{ W}\cdot\text{m}^{-2}\cdot\text{Nm}^{-1}$, and relative humidity. The whole cycle lasted 10 h,

and in our case, the samples were tested first for seven cycles i.e., 70 h and the total duration of action in the climate chamber was 32 cycles, i.e., 320 h. After taking samples from the climate chamber, we subjected the material to mechanical and physical-mechanical tests.

Table 3. Measurement characteristics.

No. Cycle	Load Cycle	The Lamp Type	Radiation Intensity	Prescribed Temperature	Relative Humidity
2	8 h Drying		0.76 W.m ⁻² .Nm ⁻¹ By 340 nm	(50 ± 3) °C	Unregulated
	0.15 h Water spray	Type 1 A	-	Unregulated	Unregulated
	0.15 h Water spray	(Ultraviolet	-	Unregulated	Unregulated
	0.15 h Water spray	(UV-A-340))	-	Unregulated	Unregulated
	0.15 h Water spray		-	Unregulated	Unregulated
	2 h Condensation		Radiation off	(50 ± 3) °C	Unregulated

UV stability is very important for long-term exposure of the material, such as the exposure required for the encapsulation of a photovoltaic module [19,20]. High transparency is required to achieve an effective wavelength for PVB components. By using benzotriazole (0.2–0.35% by weight) we achieve the mitigation of the effects of UV radiation. [13].

When testing the effect of radiation, heat and humidity on the physical, chemical and optical properties of polyvinyl butyral using artificially accelerated irradiation of specific laboratory light sources, we achieved simulation of real climatic conditions in the laboratory [21]. These controlled conditions are used to determine the rate of degradation of the material in the exposed environment.

3. Results and Discussion

Obtaining results from a real environment where the material is exposed to extreme conditions for a short time is difficult. Therefore, it is important to simulate real conditions in the laboratory and look for bottlenecks that would ultimately lead to material failure of the respectively finished product. Therefore, our primary goal in the presented paper was to test polyvinyl butyral and its physicochemical and mechanical properties, which were subsequently compared with the values of tests from the climate equipment ThermoTec.

3.1. Differential Scanning Calorimetry Testing

Differential scanning calorimetry (DSC) gives an overview of the glass transition temperatures (T_g) and melting points (T_m) for recycled polyvinyl butyral [22]. We obtained important information that helped us decide the right manufacturing process for the material. [18,23]. We can see from Figure 6 that the measurement of the recycled polyvinyl butyral seal took place as a function of mW/mg at a temperature of °C. If the measurement is set to mW/mg, it means that the calorimeter was calibrated before starting the measurement. The actual measured value (T_g) is the temperature deviation with respect to the reference sample. The first and most important information of the analyzed sample is the temperature at which we find the glass transition temperature T_g, with respect to melting point T_m. Peak is associated with the temperature at which the maximum reaction rate occurs (exothermic reaction). The glass transition (T_g) in materials is important information regarding the phase transition of materials. It is also used to quantify enthalpy characteristics that are associated with both physical and chemical transformations of substances in test systems. This method can be used to measure heat capacity, determine the purity of substances and for other particular purposes. The samples were analyzed under laboratory conditions, at a interior temperature of 22 °C and an interior humidity of 60%, following DIN ISO 113 57.

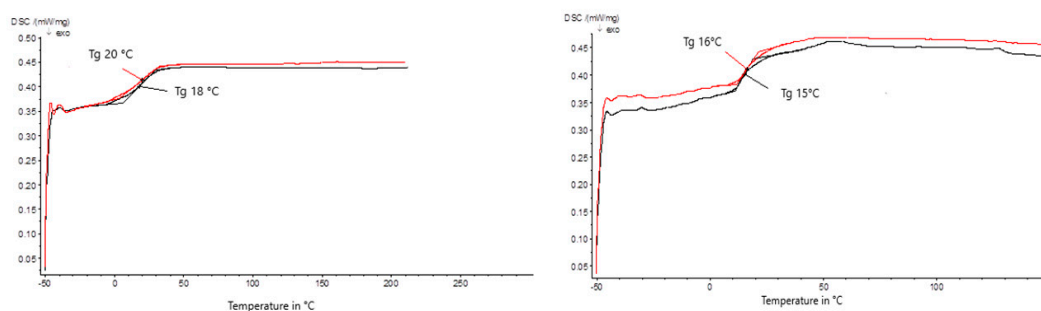


Figure 6. Differential scanning calorimetry (DSC) results for recycled polyvinyl butyral before (**left side**) and after (**right side**) exposure to laboratory light sources.

Legend to the Figure 6: Black line- 1st heating of recycled polyvinyl butyral before and after exposure to laboratory light sources; Red line-2nd heating of recycled polyvinyl butyral before and after exposure to laboratory light sources

By differential scanning calorimetry, the temperature of recycled polyvinyl butyral was maintained isothermally with the reference value. Such an amount of energy is needed to maintain isothermal conditions. The course is plotted as a function of time or temperature. The material is placed on metal pads, which reduce the thermal gradient to a minimum [24,25]. The condition was to achieve high heating values (in tens of $\text{K}\cdot\text{min}^{-1}$, $^{\circ}\text{C}\cdot\text{min}^{-1}$) in the analysis, thus ensuring a high resolution of heating and, therefore, the obtained temperature scale [26].

3.2. Mechanical Testing (Tensile Test)

The tensile test was used to evaluate all requirement tensile strength characteristics of recycled polyvinyl material. The aim of testing was to stress the test specimen until the moment when the sample ruptured. The test specimen was clamped in the jaws of a tensile machine [27–29]. Regarding constant tensile speed, the material reached the maximum tensile strain. Along with the increasing deformation, the force required to maintain a constant speed of movement of the jaws of the tearing machine also increased. The tensile test of the tested samples from recycled polyvinyl butyral (Table 4) was performed at an interior temperature of $23\text{ }^{\circ}\text{C}$ and humidity of 60%, according to standard DIN EN ISO 527.

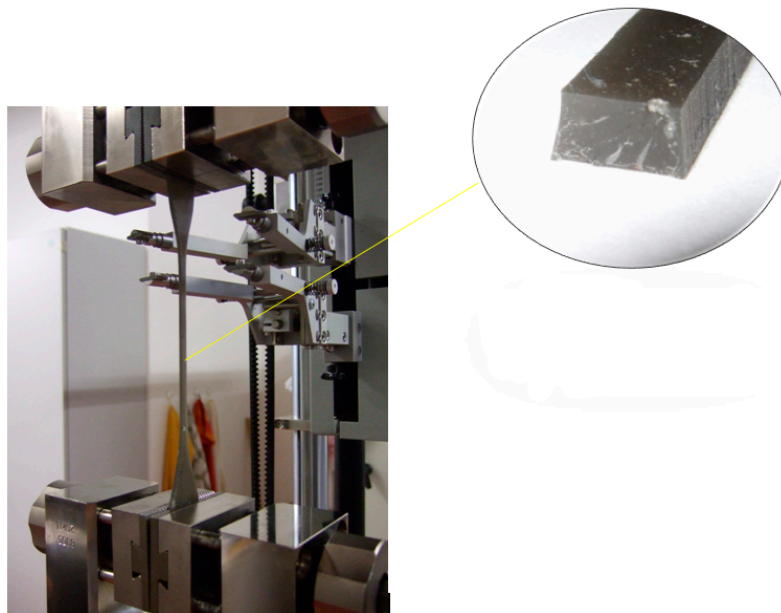
Table 4. Tensile test characteristics.

Equipment	Zwick Z020 Universalpruefungsmaschine
Max. Force	20 kN
Testing Speed	100 mm/min
Standard	DIN EN ISO 527

The measured values of the tensile test were evaluated by statistical data processing evaluated by the software [30] Test Xpert (Table 5). We work with statistical constants with mean value, variance and deviation. The tested sample of material is clamped in the jaws of the tearing machine (Figure 7) and gradual stretching is performed at a constant speed [31,32], where max. the tensile strain value gives us a value of 145.9610%. The aim of our measurement was to get as close as possible to the correct value of the measured quantity for the required degree of reliability. However, using statistics, we can determine these values with limited accuracy from a set consisting of a finite number of measurements.

Table 5. Tensile test results according to DIN EN ISO 527 before exposure to laboratory light sources.

The Statistic Variables	The Thickness of the Test Sample [mm]	Width of the Test Sample [mm]	E-Module [MPa]	Tensile Stress at Break [MPa]	Tensile Strain at Break [%]	Max. Tensile Stress [MPa]	Max. Tensile Strain [%]
x	2.9701	6.0250	5.0000	17.2360	146.140	17.5182	145.9610
s	0.0294	0.0129	2.0000	1.4731	11.5940	1.6361	11.6471
v	0.9900	0.2100	52.450	8.3401	7.9300	9.3400	7.9800

**Figure 7.** Tensile test of recycled polyvinyl butyral (left side—sample held, right side—PVB zoomed 50×).

With increasing deformation, the force increases. The force is required to maintain a constant feed speed of the jaw the tensile machine. The tensile test works on the principle of stressing the test specimen until the time [32], when the sample ruptures, which indicates the value of tensile stress at break σ_B (17.2360 MPa).

The test specimens were subject to a change of water, a temperature ranging from $-50\text{ }^{\circ}\text{C}$ to $+120\text{ }^{\circ}\text{C}$, to UV radiation with a value of $0.76\text{ W}\cdot\text{m}^{-2}\cdot\text{Nm}^{-1}$, and relative humidity of 60%. One cycle lasted 10 h; the total time of action in the climate chamber was 32 cycles, i.e., 320 h. The value of the E-module after exposure to the set conditions was 4.9850 MPa, as can be seen from the previous measurement, and the decrease was minimal (5.000 MPa before exposure to laboratory light sources). At the values when the maximum effect of tensile characteristics σ_{\max} and ε_{\max} (maximum tensile stress and maximum tensile strain) occurs, the values after the action of climatic conditions were with minimal differences (Table 6). It was confirmed that polyvinyl butyral is UV stable and its mechanical properties do not change significantly under laboratory conditions.

Table 6. Tensile test results according to DIN EN ISO 527 after exposure to laboratory light sources.

The Statistic Variables	The Thickness of the Test Sample [mm]	Width of the Test Sample [mm]	E-Module [MPa]	Tensile Stress at Break [MPa]	Tensile Strain at Break [%]	Max. Tensile Stress [MPa]	Max. Tensile Strain [%]
x	2.8901	6.0050	4.9850	17.1890	145.940	17.4981	144.8700
s	0.0199	0.0021	2.0030	1.3931	10.6840	1.5931	11.2561
v	0.8900	0.1990	51.650	7.9501	7.8700	9.2910	7.8500

The recycled polyvinyl butyral is exposed to many internal and external influences over time. Internal influences include thermodynamic imbalance, external include heat, solar radiation, atmospheric oxygen, ozone, humidity, rain, oxides of sulfur and nitrogen, dust gradient, aggressive media (gases, vapors, liquids), ionizing radiation, mechanical force (often variable) and microorganisms. These effects affect the structure, change it and thus also change the useful properties of the polymer. Each acts by a different mechanism and affects a different structural level of the polymer. Exposure to excessively high temperatures for some time severely disrupts the macromolecular chains of the polymers. Our priority was to present the possibility of using the polyvinyl butyral with our obtained results as an excellent alternative for encapsulation in the solar industry.

4. Conclusions

In the solar industry, in the production of photovoltaic modules, there has been an effort since 2005 to replace existing encapsulations with PVB films in order to increase substantially the safety of laminated glass in the solar industry [33]. Using solar energy saves the natural resources of our planet. The use of fossil fuels such as oil, coal or natural gas brings with it several severe problems with our environment. Nowadays, global warming and climate change have become a reality, so it is essential to strive for a wider use of “clean” technologies, which undoubtedly include the use of solar energy. Unlike the combustion of conventional fuels, the use of solar energy does not release pollutants or greenhouse gases released into the atmosphere, causing the atmosphere to warm up [34] gradually.

The presented research aimed to evaluate the physicochemical and mechanical properties of recycled polyvinyl butyral, which came from the recycling of car windows. The tests took place in a climatic chamber, under the prescribed conditions. The UV radiation had a value of $0.76 \text{ W}\cdot\text{m}^{-2}\cdot\text{Nm}^{-1}$ at 340 nm. Samples of extruded polyvinyl butyral were exposed to UV radiation, water spray, drying at $50 \text{ }^\circ\text{C}$, and condensation for 320 h when the radiation was turned off. It is known from the results that the values of recycled material after the tests differ only exceptionally. The value of the E-module after exposure to the set conditions was 4.9850 MPa, as can be seen from the previous measurement, and the decrease was minimal (5000 MPa before exposure to exposure to laboratory light sources). At the values when the maximum effect of tensile characteristics σ_{max} 17.4981 MPa and ϵ_{max} 144.8700% (maximum tensile stress and maximum tensile strain) occurs, the values after the action of climatic conditions were minimal.

The applicability and application of polyvinyl butyral varies with respect to location, mainly due to differences in UV radiation, atmospheric humidity, temperature changes, etc.

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