Suitability of Basalt Fiber Reinforced Polyamide-6 for Crash Relevant Automotive Components

Abstract

The automotive industry faces constantly changing challenges. The increasing demand on security systems and comfort raises the average weight of automobiles. Due to legal requirements regarding climate targets, the scarcity of resources and sustainability, alternative materials are necessary. To reduce the CO_2 emission a reduction in weight is mandatory. Fiber Reinforced Composites (FRCs) offer good mechanical properties at low weight. Thus, FRCs are well suited for lightweight applications in the automotive industry. Thereby, Fiber Reinforced Thermoplastic Composites (FRTCs) offer some great advantages over thermosetting materials. In addition to the possibility of reshaping, recycling and welding, small cycling times are attractive regarding mass production. So far, there is no economic production technology to produce FRTCs in a large scale. Whilst the use of carbon and glass fibers is established in composite manufacturing, another fiber is only barely considered. Basalt fibers offer good mechanical properties at a low price. They are made of volcanic basalt which is almost infinite available. Especially the high energy absorption capacity of the fibers, along with its small weight may enable this material for the use as crash absorbers in automotive applications. To investigate the suitability of Basalt Reinforced Thermoplastic Composites (BRTCs) for the automotive industry, this paper will focus on a comparison of the basic mechanical properties between carbon, glass and basalt reinforced composites. Therefore, different textile structures are manufactured out of all three reinforcement materials. As thermoplastic matrix Polyamide 6 (PA6) is used for all samples. Woven fabrics combined with PA6 foils are united during a film stacking process; hybrid woven fabrics and woven fabrics made of hybrid yarns, as well as hybrid non-woven fabrics are produced at the Institute for Textile Technology of RWTH Aachen University, Aachen (ITA). They are then consolidated to FRTCs in a heat pressing process and tested to determine their mechanical properties. In addition to stress and bend tests, impact tests are made to investigate and compare the energy absorption capacity for the varied materials and textile structures.

1. Introduction

Lightweight construction is one important topic in automotive industry. The average weight of cars is constantly rising dureing the last decades due to increasing requirements in safety and comfort [1]. On the opposite, regulations by the governments force the industry to reduce the carbon emissions which are related to the vehicle's weight. For example, a law by the European Union regulates the average carbon emissions for a company's car fleet to 95 g/km to be reached until 2020 [2]. Fiber Reinforced Composites (FRC) can offer an alternative to common steel production. They combine good mechanical properties with a low weight and are therefore well suited for automotive applications. Moreover, they offer high energy-absorption capacities which predestines them for the use as crash absorbing components in vehicles [3,4]. While FRCs are made of reinforcement fibers combined with a thermosetting matrix material, Fiber Reinforced Thermoplastic Composites (FRTC) work with a thermoplastic matrix material. This offers advantages like shorter cycle times and the possibility to remelt which leads to the virtues of recycling, reforming and weldability [5]. Due to high viscosities of the thermoplastic materials those advantages cannot be harnessed so far and hence they are of great interest for research [6,7]. The most common materials for reinforcement fibers are carbon and glass. Carbon provides high mechanical strength and stiffness by very low weight at high prices. Glass, however, is cheap but the mechanical properties cannot reach the ones of carbon fibers. Volcanic Basalt offers one viable alternative for reinforcement fibers. Basalt provides a good thermal and chemical resistance as well as good mechanical properties at a low weight. [8] Especially their high energy-absorption capacity justifies an investigation of their application as crash absorbers in automotive applications [9]. Moreover, the base material is almost abundantly available because it occurs in the earth’s surface [10]. Nevertheless, there is nearly no experience with Basalt as reinforcement materiel for FRCs and FRTCs. This follows from difficulties in the production of basalt fibers with constant mechanical properties in the past. By now these problems have been solved so that there nothing opposed to basalt as reinforcement fiber for FRCs. [10,11]

In this paper, the mechanical properties of Basalt Fiber Reinforced Plastics (BFRP) are determined for different textile structures and compared with the properties of Glass (GFRP) and Carbon Reinforced Composites (CFRP). Moreover, the energy absorption capacity is determined to receive information about the suitability of the materials for the use as crash absorbing components. Therefore, the reinforcement fibers are combined with a Polyamide 6 (PA6) matrix fiber in various textile structures and consolidated within a heat pressing process. The samples are tested in tensile, bending and impact tests and the results of all materials are opposed to each other to obtain an estimation for the suitability of Basalt as reinforcement fiber for automotive applications.

2. Methods

In this chapter, the different methods used in the study to produce FRTCs are presented. As thermoplastic matrix material Polyamide 6 (PA6) is utilized for all samples. In order to compare the properties of basalt with the properties of carbon and glass, diverse textile structures are produced and consolidated within a heat pressing process. The textile structures investigated are hybrid woven fabrics (HWF), hybrid yarn woven fabrics (HYWF) and woven fabrics out of reinforcement fibers combined with PA6 films. The hybrid yarns used in the HYWFs are produced within the commingling process. The process is shown in figure 1. The PA6 and the reinforcement fiber are delivered into an air jet. Inside the air jet an asymmetrical and turbulent air flow is created which opens the yarns and commingles them into one hybrid yarn. The process aims to provide a high mixing of the fibers by minimized fiber damage.

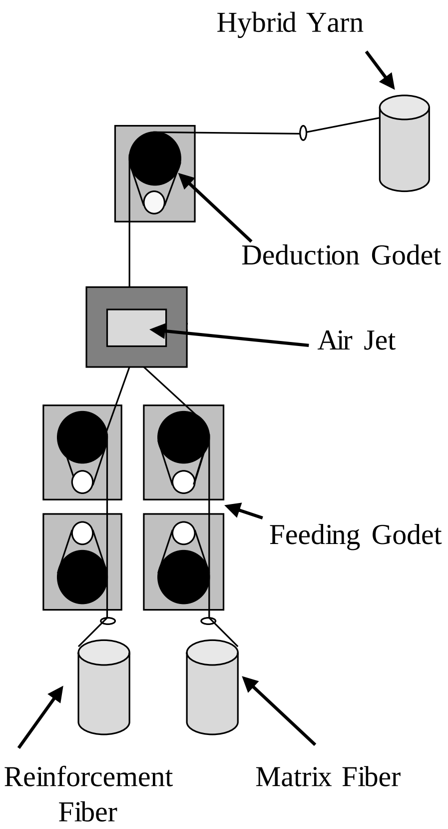

Figure 1: Principle of the commingling Process

The fabrics are woven on a narrow fabric weaving system of the Jakob Müller AG, Frick, Swiss [12] using the plain weave binding. The hybrid yarn woven fabrics are produced from the commingled hybrid yarns as weft and warp yarns. For the hybrid fabric, the reinforcement fibers are used as warp and the PA6 yarn as weft yarn. The weaving parameters are shown in table 1.

Table 1: Parameters of the weaving process

RF material	**Basalt**		**Carbon**		**Glass**	
Parameters	HYWF	HWF	HYWF	HWF	HYWF	HWF
Warp yarn count [1/6 cm]	26	27	23	24	23	24
Warp yarn density [1/cm]	4,33	4,5	3,83	4	3,83	4
Weft yarn density [1/cm]	4,2	9,4	4,2	7,8	6,6	9,8
Warp yarn material	HY	Basalt	HY	Carbon	HY	Glass
Weft yarn material	HY	PA 6	HY	PA 6	HY	PA 6
Process speed [weft insertions/ minute]	200	200	200	200	200	200

Plain woven carbon, glass and basalt fabrics are combined with the PA6 matrix using the film-stacking process. In this process, a PA6 film is inserted between each layer of reinforcement fabric. Due to the film's impermeability, entrapped air is a frequent problem for the FRTCs produced with this process.

All hybrid textile structures are consolidated to FRTCs within a heat-pressing process. The heat press used consists of a heat control unit, a pressing tool with mold cavity and a pneumatic cylinder. The process is shown in figure 2. At first, the cavity is heated up to 250°C. The textile structures are brought into the cavity and the process pressure set. After two minutes the temperature is decreased to 180°C and the sample demolded when reaching this temperature.

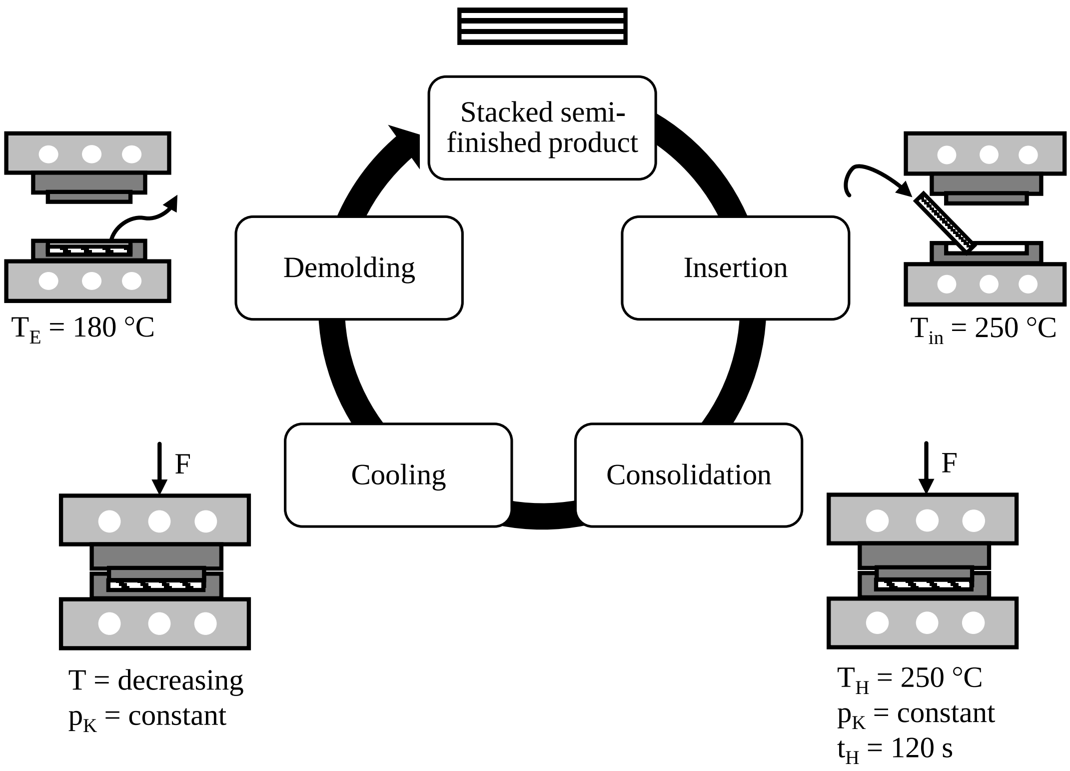

Figure 2: Heat pressing process

In addition to the general comparison of the different reinforcement materials, samples are produced with varying cavity pressures. The used pressure parameters are shown in table 2.

Table 2: Pressure parameters

Adjustment Number	Holding temperature T_H [°C]	Demolding temperature T_E [°C]	Holding time t_H [s]	Cavity pressure p_K [bar]
1	250	180	120	6
2	250	180	120	9
3	250	180	120	12
4	250	180	120	15
5	250	180	120	18

The mechanical properties of the samples are determined in stress and bending tests according to the DIN standards DIN EN ISO 527-4 and DIN EN ISO 14125. Moreover, the energy absorption capacity is determined according to DIN EN ISO 6603-1. Here, weights are dropped onto the consolidated samples from a specific height and the failure pattern is analyzed.

3. Results

In the following the results of the mechanical tests are presented for the different textile structures and materials. For all tests the specific properties are considered. Therefore, the absolute properties are related to the sample weight.

Impact of cavity pressure on mechanical properties

To show the impact of the cavity pressure on the mechanical properties figure 3 shows the specific tensile strength of HYWFs exemplary for the three tested materials. Due to the minor differences in tensile strength for the different cavity pressures, it can be assumed that there is no major influence on the mechanical properties. Therefore, in the remainder of this study only the samples produced with a cavity pressure of 12 bar are investigated.

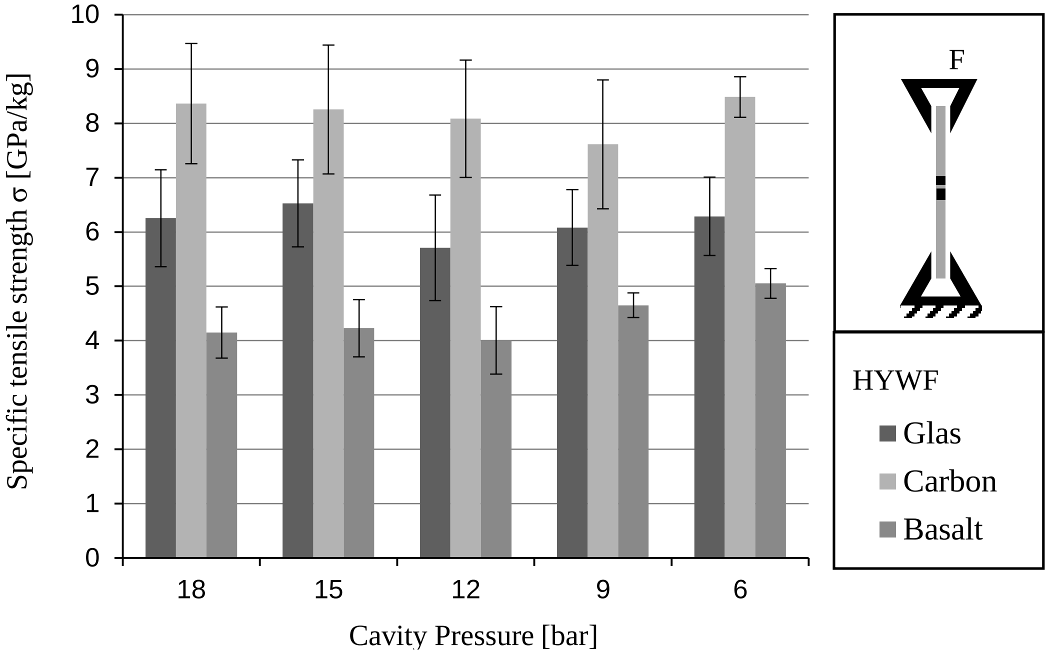

Figure 3: The influence of Cavity Pressure on the tensile strength of HYWFs

Stress test

The results of the stress test are shown in figure 4. For all textile structures carbon fibers show the highest tensile strength. The highest tensile strength of 37 GPa/kg is achieved for the carbon HWF. The lowest tensile strength is measured for the HYWFs. The tensile Modulus of basalt in HWF is the highest, reaching a value of 540 GPa/kg. Just as for the tensile strength, the HYWFs reach the lowest value in tensile Modulus. Despite the samples of Film Stacking achieving average values for glass and basalt, the carbon samples reach the absolute lowest Modulus with only 80 GPa/kg.

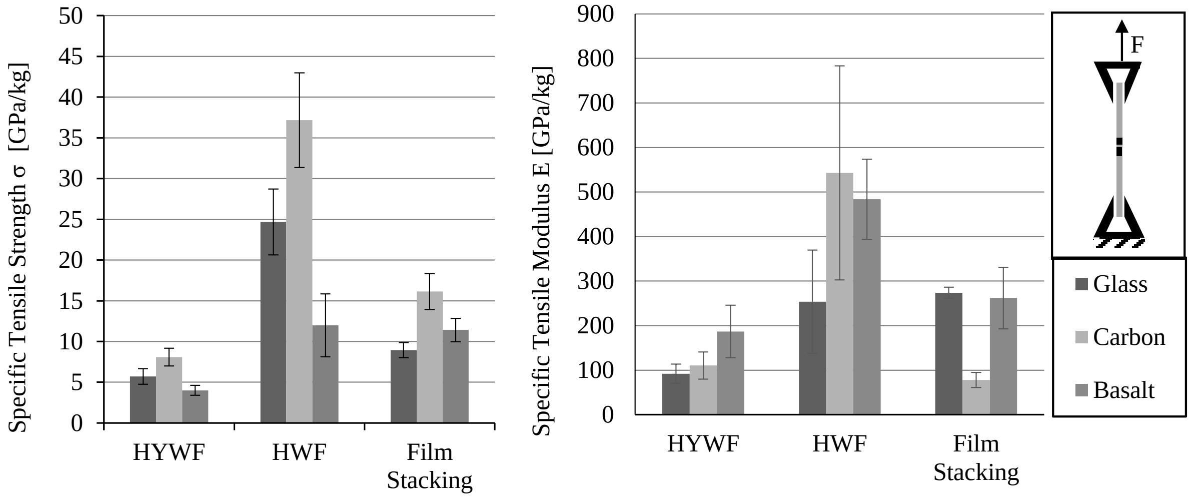

Figure 4: Results of Stress Test

Bending Test

The results for the bending tests are shown in figure 5. The highest bending strength of 82 GPa/kg is achieved by the glass HWF. The carbon fibers show the lowest bending strength and modulus in all three textile structures. The lowest values for both properties are reached for the film stacking samples. Basalt fibers show average results for all textile structures. The bending modulus shows high variations and thus high standard deviations. Especially the standard deviations for the HWFs are particularly high due to diverse results for the individual samples.

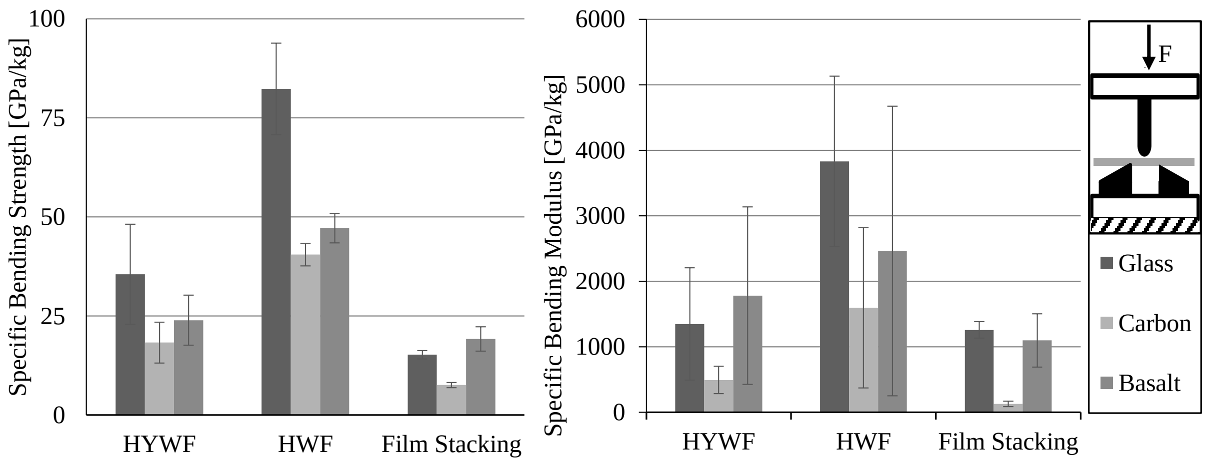

Figure 5: Results of Bending Test

Impact Test / Energy Absorption

The results for the impact tests are shown in figure 6. The graph shows the energy absorption referred to the sample weight. The highest energy absorption capacity shows the film stacked carbon material with a value of 4246 J/kg. Glass and Basalt show lower results in film stacking. They reach energy absorption capacities of about 1700 J/kg and 1900 J/kg. In HYWF all materials show high capacities whilst basalt performs best with a value of 4220

J/kg and glass worst with 3085 J/kg. As HWF all three materials show low energy absorption capacities of approximately 500 J/kg.

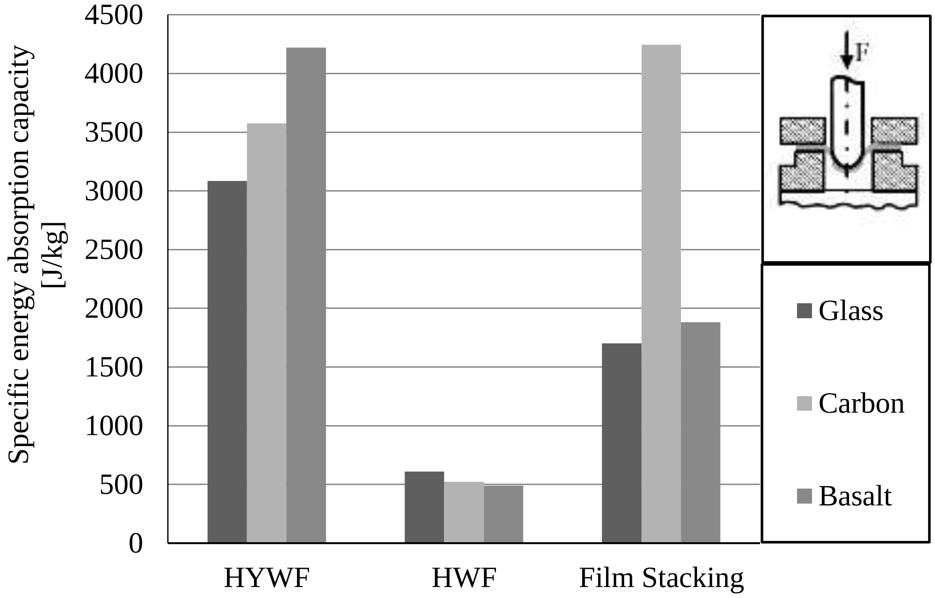

Figure 6: Results Impact Test

4. Discussion

Due to its structure, the HWF show the best results for tensile and bending strength and modulus. During the pressing process, the matrix yarn melts around the reinforcement fibers which are pressed into a plain form. Thus, the fibers are oriented fully unidirectional in stress direction and can absorb high forces. Especially carbon fibers can withstand big tensile forces in grain direction. The commingling process damages the reinforcement fibers. Hence the tensile and bending strength for the HYWFs is lower than for the HWFs. However, due to their structure, HYWFs can absorb forces not only in one but in two directions. To improve the properties of HYWFs an enhancement of the commingling process is necessary. The aim is a fiber damage as low as possible in conjunction with a high blending of the fibers.

In bending tests, the carbon material is outperformed by glass and basalt. One possible explanation can be found in the sizing of the fibers. While basalt and glass are sized with silane-based sizing, the carbon fibers have an epoxy-based sizing. The other sizing material may lead to a lower fiber/matrix-adhesion which influences the bending behavior negatively. Most clearly this influence can be seen for the carbon film-stacking samples.

The low energy absorption capacity of the HYFs follows from to the unidirectional structure of the samples. Because the matrix fibers melt around the reinforcement fibers, this structure is obtained. The impact of the weights lead to a failure of the matrix material along the fibers. Because the impact cannot be absorbed into the reinforcement fibers, the sample fails at a low amount of energy. The mode of failure is shown in figure 7 and compared with the mode of failure for HYWFs.

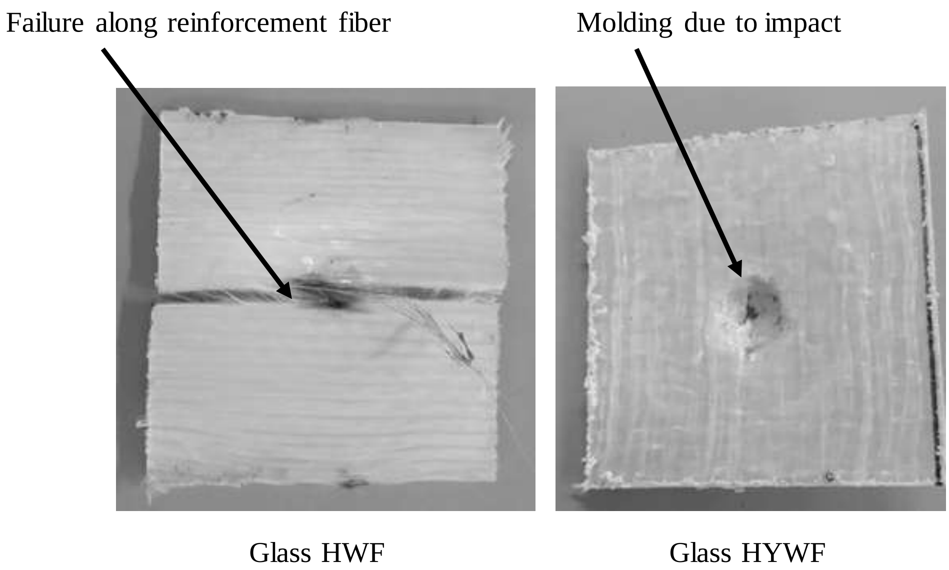

Figure 7: Mode of failure for HWFs and HYWFs

Although Carbon shows the best results for engery-absorption in film stacking samples, Basalt and Glass only show average values. This can possibly be explained by entrapped air. The air inside the sample cannot escape during heat pressing process and remains inside the sample. This leads to a poor adhesion between fibers and matrix material and hence a bad force transmission during impact tests.

5. Conclusion

Different textile structures have been manufactured and tested and the results have been presented for the various fiber materials. Although carbon shows the best results for stress test and glass for bending tests, the properties of basalt fibers seem promising for the use in composite materials. Especially the high energy-absorption capacity of the basalt composites predestines the material for the use in crash absorbing components. Concerning the different textile structure the HWFs show the best results for stress and bending test but come off badly in impact tests. This is due to their structure. The energy of the impact cannot be transferred on the fibers which leads to a failure of the samples at low weights. Apparently, HYWFs are best suited for crash absorbing applications, nonetheless film-stacking samples should be investigated more precisely to analyze the influence of possibly entrapped air inside the sample. Overall, regarding the results of the mechanical tests, basalt fibers have some promising properties which is why they should be considered for composite structures in automotive applications.

6. Bibliography

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