AN INTEGRATED APPROACH TO THE DEVELOPMENT OF AUTOMOTIVE PLASTIC COMPONENTS: POLYMER SELECTION, DESIGN OPTIMIZATION, AND COATING COMPATIBILITY

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Аннотация

В статье рассмотрен комплексный подход к разработке автомобильных пластиковых компонентов, объединяющий выбор полимерного материала, оптимизацию конструкции изделия и обеспечение его совместимости с лакокрасочными покрытиями. Цель исследования заключалась в сравнительной оценке физико-механических и теплофизических свойств полипропилена PP J350, а также композитов на его основе, содержащих 30 % стекловолокна и 30 % базальтового волокна. Сравнение проводили по плотности, показателю текучести расплава, прочности и удлинению при растяжении, модулю упругости, ударной вязкости по Изоду, устойчивости к деформации и температуре тепловой деформации. Установлено, что введение 30 % базальтового волокна повышает прочность при растяжении с 25 до 84 МПа, модуль упругости — с 1280 до 6300 МПа, ударную вязкость — с 6,5 до 41 кДж/м², а температуру тепловой деформации — с 45 до 150 °C. При этом удлинение при разрыве уменьшается до 3,2 %, что необходимо учитывать при проектировании рёбер жёсткости, бобышек, радиусов и зон соединения. Показано, что свойства базальтоволокнистого композита незначительно превосходят показатели стеклонаполненного полипропилена. Для обеспечения качества окрашивания полипропиленовых деталей обоснована необходимость подготовки низкоэнергетической поверхности, применения соответствующего праймера и выбора режима отверждения покрытия с учётом

теплостойкости субстрата. Предложенный подход позволяет согласовать свойства материала, параметры конструкции, условия переработки и требования лакокрасочной системы при разработке прочных и термостойких автомобильных компонентов.

Abstract

This article presents an integrated approach to the development of automotive plastic components by combining polymer material selection, structural design optimization, and compatibility with automotive coating systems. The study aimed to compare the physical, mechanical, and thermal properties of PP J350 polypropylene with those of polypropylene composites containing 30 % glass fiber and 30 % basalt fiber. The materials were evaluated in terms of density, melt flow rate, tensile strength, elongation at break, elastic modulus, Izod impact strength, resistance to deformation, and heat deflection temperature. The results demonstrated that the incorporation of 30 % basalt fiber increased tensile strength from 25 to 84 MPa, elastic modulus from 1,280 to 6,300 MPa, Izod impact strength from 6.5 to 41 kJ/m², and heat deflection temperature from 45 to 150°C. However, elongation at break decreased to 3.2 %, which must be considered when designing ribs, bosses, radii, wall transitions, and joining zones. The basalt-fiber-reinforced polypropylene exhibited slightly higher strength and thermal resistance than the corresponding glass-fiber-reinforced composite. For reliable coating performance on polypropylene components, the study substantiates the need for appropriate surface preparation, adhesion-promoting primers, and curing conditions compatible with the thermal characteristics of the polymer substrate. The proposed approach integrates material properties, component geometry, processing conditions, and coating requirements, thereby supporting the development of durable, dimensionally stable, and heat-resistant automotive plastic components.

Ключевые слова: полипропилен; базальтовое волокно; стекловолокно; оптимизация конструкции; механические свойства; термостойкость; лакокрасочные покрытия; адгезия.

Keywords: polypropylene; basalt fiber; glass fiber; design optimization; mechanical properties; thermal resistance; automotive coatings; adhesion.

Introduction

The automotive industry increasingly uses polymeric materials to reduce vehicle weight, simplify production, and improve component design. Plastics and polymer composites are widely applied in bumpers, instrument panels, door trims, mirror housings, and other interior and exterior parts. Their main advantages include low density, corrosion resistance, good processability, and suitability for manufacturing components with complex geometries by injection molding [1,2].

However, the reliability of automotive plastic components depends not only on the selected polymer but also on component geometry, processing conditions, reinforcing fillers, and compatibility with coating materials. An inappropriate combination of these factors may cause shrinkage, warpage, cracking, insufficient rigidity, poor coating adhesion, and premature delamination. Therefore, polymer selection, structural design, processing parameters, and surface preparation should be considered as interrelated stages in the development of automotive plastic components [3,4].

Polypropylene is commonly used in the automotive industry because of its low density, chemical resistance, good processability, and relatively low cost. Nevertheless, neat polypropylene has limited mechanical strength, stiffness, and thermal stability. Reinforcement with short glass or basalt fibers can improve tensile and flexural strength, elastic modulus, impact resistance, dimensional stability, and heat resistance. At the same time, the resulting properties depend on the fiber type, fiber–matrix interfacial adhesion, processing conditions, and structural configuration of the component [5,6].

Coating compatibility is another important factor because polypropylene has low surface energy and insufficient adhesion to conventional paints. Consequently, appropriate surface preparation, adhesion-promoting primers, plasma or other activation treatments, and suitable curing conditions are required. The selected curing temperature must be compatible with the thermal properties of the polymer substrate to prevent deformation, residual stresses, and deterioration of the finished component [7,8].

Accordingly, the present study compares neat PP J350 polypropylene with composites containing 30% glass fiber and 30% basalt fiber. The study evaluates their physical, mechanical, and thermophysical characteristics and develops an integrated

approach combining material selection, structural optimization, processing requirements, and coating compatibility. Particular attention is paid to the suitability of fiber-reinforced polypropylene for automotive components and to the surface-treatment requirements affecting the adhesion and durability of protective and decorative coatings [9,10].

Materials and Methods

The study compared neat polypropylene and two fiber-reinforced polypropylene composites intended for automotive plastic components. Commercial PP J350 was used as the polymer matrix. Short glass fiber and basalt fiber were incorporated separately at a concentration of 30 wt.%. The selected fiber content corresponds to the reinforcement level commonly used in injection-molded automotive components requiring increased stiffness, dimensional stability, and heat resistance.

The study was designed as a comparative engineering assessment at a fixed filler content. Therefore, it evaluated the influence of fiber type rather than the effect of different fiber concentrations. This limitation was considered when interpreting the results. Further optimization should include glass- and basalt-fiber concentrations of 10, 20, and 30 wt.% under identical processing conditions.(Table 1)

Table 1. Composition of the investigated polymer materials

Sample designation	Polymer matrix	Reinforcing filler	Filler content, wt.%
PP	PP J350	—	0
PP/GF30	PP J350	Short glass fiber	30
PP/BF30	PP J350	Short basalt fiber	30

Before compounding, PP J350 and reinforcing fibers were dried to minimize the influence of residual moisture. The components were weighed using a calibrated electronic balance with a resolution of 0.001 g. The composites were prepared by melt compounding, followed by injection molding of standard test specimens. Identical barrel-temperature profiles, injection pressure, holding time, mold temperature, and cooling duration were maintained for PP/GF30 and PP/BF30 to ensure an objective comparison.

Density was measured using a calibrated density determination device in accordance with ISO 1183-1. Melt flow rate was measured at 23 ± 2 °C using a melt-flow index tester conforming to ISO 1133-1. Tensile properties were determined with a calibrated universal

testing machine equipped with an extensometer and an appropriate load cell. Izod impact strength was measured using a pendulum impact tester, while heat-deflection temperature was determined using a thermomechanical testing unit.

At least five independent specimens (n=5n=5) from each material group were used for tensile, impact, and thermal tests. Density and melt flow rate were determined in at least three independent replicates (n=3n=3). Instrument calibration was checked before testing. Measurement uncertainty was evaluated from instrument resolution, calibration information, and the dispersion of repeated measurements.

Test methods

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Table 2. Evaluated properties and test methods

Property	Unit	Test method	Number of replicates
Density	g/cm³	ISO 1183-1	n=3
Melt flow rate at 230°C	g/10 min	ISO 1133-1	n=3
Tensile strength	MPa	ISO 527-2	n=5
Elongation at break	%	ISO 527-2	n=5
Tensile modulus	MPa	ISO 527-2	n=5
Izod impact strength	kJ/m²	ISO 180	n=5
Heat deflection temperature at 1.8 MPa	°C	ISO 75-2	n=3
Coating adhesion	Classification 0–5	ISO 2409	n=3

Density was determined to assess the influence of reinforcement on component mass. Melt flow rate was used to characterize the processability of the materials during

injection molding. Tensile strength, tensile modulus, and elongation at break were determined to evaluate strength, stiffness, and deformability. Izod impact testing characterized resistance to short-term impact loading. Heat-deflection temperature was used to assess dimensional stability under simultaneous thermal and mechanical loading.

Evaluation of coating compatibility

Coating compatibility was evaluated theoretically by considering the surface characteristics of polypropylene, the thermal properties of the investigated materials, and the technological requirements of automotive coating systems. Experimental adhesion testing was beyond the scope of the present study. Therefore, the proposed surface preparation and coating sequence should be regarded as an engineering recommendation requiring further validation through standardized adhesion tests, including the cross-cut test according to ISO 2409.

Data analysis

The experimental data were expressed as the arithmetic mean and standard deviation:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

The normality of the data distribution was evaluated using the Shapiro–Wilk test. Differences among PP, PP/GF30, and PP/BF30 were assessed by one-way analysis of variance, followed by Tukey's post-hoc test. Differences were considered statistically significant at $p<0.05p<0.05$. Where the assumptions of parametric analysis were not satisfied, the Kruskal–Wallis test was used.

The relative change in each property compared with neat PP J350 was calculated as follows:

$$\Delta X = \frac{X_c - X_{\mathrm{PP}}}{X_{\mathrm{PP}}} \times 100\%$$

Where

ΔX — relative change in the property, %;

X_c — property value of the composite material;

X_{PP}— corresponding property value of neat PP J350 polypropylene.

The results were used to determine the influence of fiber type on strength, stiffness, impact resistance, processability, and thermal stability and to formulate recommendations for automotive component design and coating application.

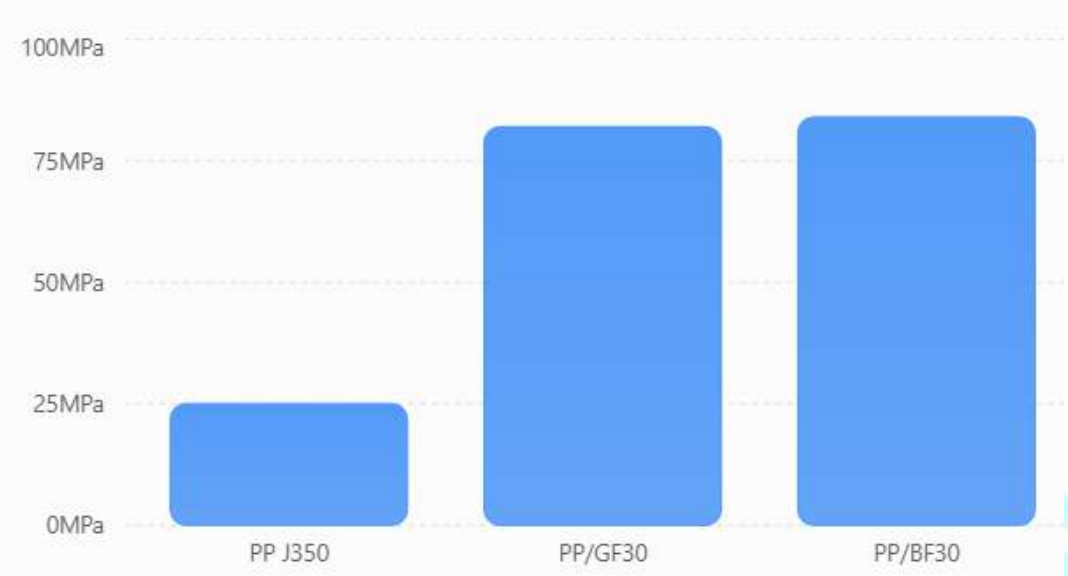


Figure 1. Tensile strength of the investigated materials

The industrial relevance of the investigated materials was evaluated with reference to Uzbekistan's automotive sector. According to the Statistics Agency, **424,808 passenger cars of different types were produced in Uzbekistan in 2024**. This production scale demonstrates that even a relatively small reduction in the mass of one serial automotive component may result in a substantial annual saving of polymer raw materials [11].

For a component manufactured in Uzbekistan, the material mass was calculated using its volume and experimentally determined density:

$$m=\rho V$$

where m is the component mass, ρ is the material density, and V is the component volume.

Annual material consumption was estimated as:

$$M_{annual}=mN$$

where N is the annual number of manufactured vehicles or components.

The annual material saving achieved by replacing the reference material was calculated as:

$$\Delta M = (m_{reference} - m_{composite}) \times N$$

The material-cost difference was determined by:

$$\Delta C = (m_{reference} C_{reference} - m_{composite} C_{composite}) \times N$$

where $C_{reference}$ and $C_{composite}$ are the purchase prices per kilogram of the corresponding materials.

The assessment also considered processing costs, rejected-component rate, surface-preparation and painting costs, tooling requirements, and the potential service-life extension associated with improved stiffness, impact resistance, and thermal stability. Because commercial prices vary by supplier and procurement period, the economic calculations should use documented prices obtained from Uzbek manufacturers or suppliers for the same reporting period.

Results and Discussion

The physical, rheological, mechanical, and thermal properties of neat PP J350 and the fiber-reinforced composites are presented in Table 3. The results characterize the effect of fiber type at a fixed reinforcement content of 30 wt.% (Table 3)

Table 3. Physical, mechanical, and thermal properties of the investigated materials

Property	**Unit**	**PP J350**	**PP/GF30**	**PP/BF30**
Density	g/cm³	0.90	1.12	1.13
Melt flow rate at 230°C	g/10 min	10	5	5
Tensile strength	MPa	25	82	84
Elongation at break	%	100	3.0	3.2
Tensile modulus	MPa	1,280	5,600	6,300
Izod impact strength	kJ/m²	6.5	35	41
Heat deflection temperature at 1.8 MPa	°C	45	146	150

Fiber reinforcement increased density from 0.90 g/cm³ to 1.12–1.13 g/cm³ and reduced the melt flow rate from 10 to 5 g/10 min. Thus, the reinforced composites require

appropriate adjustment of injection pressure, melt temperature, gate dimensions, and mold-filling conditions.

Tensile strength increased from 25 MPa for PP J350 to 82 MPa for PP/GF30 and 84 MPa for PP/BF30, corresponding to increases of 228% and 236%, respectively. The tensile modulus increased by approximately 338% for PP/GF30 and 392% for PP/BF30. PP/BF30 exhibited a 12.5% higher modulus than PP/GF30, indicating greater rigidity and dimensional stability.

The improvement in strength and stiffness was accompanied by a reduction in elongation at break from 100% to 3.0–3.2%. Therefore, sharp corners, abrupt wall-thickness transitions, insufficient radii, and local stress-concentration zones should be avoided in components produced from these composites.

Izod impact strength increased from 6.5 kJ/m² to 35 kJ/m² for PP/GF30 and 41 kJ/m² for PP/BF30. Heat-deflection temperature increased from 45 °C to 146 and 150 °C, respectively. Overall, PP/BF30 provided the most favorable combination of strength, stiffness, impact resistance, and thermal stability, whereas PP/GF30 demonstrated slightly lower but comparable performance.

The industrial relevance of these results is particularly important for Uzbekistan, where 424,808 passenger cars of different types were produced in 2024. Consequently, introducing fiber-reinforced polypropylene into serial automotive components may have a substantial cumulative effect on material consumption and component durability. However, an exact economic effect can be calculated only after determining the redesigned component mass, raw-material prices, processing costs, reject rate, and annual production volume.

Coating compatibility was assessed theoretically by considering the low surface energy of polypropylene, the need for surface activation and an adhesion-promoting primer, and the thermal compatibility of the curing process. Since standardized adhesion testing was not conducted, conclusions regarding coating performance should be regarded as engineering recommendations rather than experimentally confirmed results.

Conclusion

The comparative evaluation showed that reinforcement of PP J350 with 30 wt.% glass or basalt fiber substantially improved its mechanical and thermal properties. PP/BF30 demonstrated the best overall performance: tensile strength increased from 25 to 84 MPa, tensile modulus from 1,280 to 6,300 MPa, Izod impact strength from 6.5 to 41 kJ/m², and heat-deflection temperature from 45 to 150 °C. However, its reduced melt flow rate and elongation at break require appropriate optimization of injection-molding parameters and component geometry.

PP/BF30 may be considered a promising material for rigid, impact-resistant, and heat-resistant automotive components. This finding is relevant to Uzbekistan's expanding automotive industry and may support the localization of polymer-composite components. However, the study was limited to a fixed fiber content of 30 wt.%; therefore, further research should compare different reinforcement levels and include statistical validation, standardized coating-adhesion testing, and a component-specific economic assessment.

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