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Mechanical Resistance of PC and PMMA Safety Components in Transportation

Michaela Karhankova[a,]*, Jan Turek[a], Milan Adamek[a], Lucie Svacinova[a], Lukas Miskarik[a], Ales Mizera[a]

[a]*Faculty of Applied Informatics, Tomas Bata University in Zlin, Zlin 760 05, Czech Republic*

Abstract

Polycarbonate (PC) and polymethyl methacrylate (PMMA) are widely used thermoplastic polymers in transportation applications due to their exceptional optical clarity, impact resistance, and durability. These materials are integral to safety-critical components such as vehicle light covers, protective shields, and sensors. In this study, PC and PMMA specimens of varying thicknesses were tested using drop-weight impact tests to evaluate their mechanical properties, specifically puncture resistance. The primary objective was to compare the impact resistance and overall performance of these materials under dynamic loading conditions. Statistical analysis revealed that PC outperformed PMMA in mechanical performance, though modifications to PMMA can enhance its impact resistance. This research provides practical insights for optimizing material selection in transportation, ensuring a balance between durability and cost-efficiency.

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Keywords: Transportation; Mechanical resistance; Safety; Polycarbonate; PMMA.

1. Introduction

Polycarbonate (PC) and polymethyl methacrylate (PMMA) are two widely used thermoplastic polymers that are important in transportation applications, particularly in safety-critical components. Their mechanical properties, especially impact resistance, make them valuable materials for various industries, including automotive, aerospace, and engineering.

* Corresponding author. Tel.: +420-576-035-636.
E-mail address: m_karhankova@utb.cz

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Polycarbonate is an amorphous thermoplastic extensively utilized to produce components such as headlamp lenses, bullet-proof glass, displays, and bullet-resistant windows in cars (Kausar, 2018; Wu et al., 2018; Seo et al., 2021). Its exceptional physical properties, including toughness, strength, optical transparency, and resistance to impact and heat, make it ideal for these applications (Čekon and Šikula, 2020; Liu and Lu, 2022; Sohrabi et al., 2022). However, certain limitations, such as sensitivity to notching, weathering, and hydrolysis, can affect its performance (Soekoco et al., 2022). In comparison, PMMA is often used in applications requiring optical clarity and weather resistance, though it generally exhibits lower impact resistance than polycarbonate. Recent advancements in material science, such as incorporating nanofillers, have shown promise in enhancing PMMA's mechanical properties (Anju, 2024; Rehak et al., 2019).

The mechanical resistance of safety elements in transportation, particularly focusing on polycarbonate and PMMA, is an area of significant interest due to the materials' applications in safety-critical components. Recent studies have employed drop-weight impact tests to evaluate the impact resistance of these materials, providing insights into their performance under dynamic loading conditions. Polycarbonate is recognized for its high impact resistance, making it a preferred choice in applications such as safety glasses and protective shields. A study by Ibrahim (2003) highlighted the nature of polycarbonate when combined as a composite with materials like cross-linked polyethylene (XLPE) foam, which enhances its ability to absorb and disperse impact energy effectively (Ibrahim, 2023). This characteristic is crucial for safety applications where energy absorption can prevent catastrophic failure upon impact. Furthermore, the drop-weight impact test has been identified as a reliable method for assessing the impact resistance of polycarbonate composites, as it allows for the adjustment of impact energy through variations in drop height and mass (Liu et al., 2019).

Conversely, PMMA, while generally less impact-resistant than polycarbonate, can exhibit improved mechanical properties when modified or combined with other materials. Recent research has focused on enhancing the impact resistance of PMMA through incorporating nanofillers. For instance, integrating copper oxide nanoparticles into PMMA significantly improves its impact strength by altering the material's microstructure and enhancing its energy absorption capabilities (Anju, 2024). This modification is particularly relevant for applications requiring lightweight yet durable materials, such as automotive and aerospace industries. Studies have shown that the impact resistance of PMMA composites can be effectively evaluated using drop-weight impact tests, which are both simple and cost-effective (Kumar, 2024; Liu et al., 2019).

The production technologies for polycarbonate and PMMA components, including extrusion, injection molding, and vacuum thermoforming, further expand their applications. For example, thermoforming transforms 2D sheets into 3D structures, while injection molding enables high-quality mass production, making it suitable for industries like automotive and aerospace (Takaffoli et al., 2020; Zulfiqar et al., 2021; Qin et al., 2021).

This article focuses on the mechanical properties of polycarbonate and PMMA, particularly their impact resistance, evaluated through drop-weight impact tests. The main goal of this study is to compare the performance of these materials, considering their durability and cost-effectiveness, thereby providing valuable insights for the design and optimization of safety elements in transportation.

2. Materials and methods

This study is focused on the mechanical impact properties of safety parts from polycarbonate and PMMA. In particular, the drop-weight impact test was used to determine the puncture resistance of the specimens listed in Table 1. These materials are commonly used in the automotive industry for components such as light conductors, front shields of vehicle lights, sensors and other safety-critical elements due to their excellent optical clarity, impact resistance, and durability. The primary aim of this research is to investigate the impact behaviour of these materials under controlled conditions, contributing to the optimization of their performance in real-world applications. The thickness (mm) of materials and price (EUR) is mentioned in the Table 1.

The mentioned materials were cut with a band saw into test specimen plates with dimensions of 80 × 80 mm, ensuring testing uniformity. The impact tests were conducted using the ZWICK HIT 230F drop-weight testing apparatus, following the guidelines specified in ISO 6603-2. This apparatus is designed to simulate dynamic loading conditions, providing a controlled environment for evaluating the puncture resistance of materials. Test specimens were preconditioned according to ISO 10350-1 by storing them for seven days at 23 °C and 50% relative humidity.

This precondition ensured that the material properties were stabilized, reducing the influence of environmental variability on the results. The testing apparatus, equipped with a hemispherical striker tip with a radius of 10 mm, delivered a consistent impact energy of 230 J, controlled via the TestXpert II software.

Table 1. Overview of Tested Materials

Material	Thickness (mm)	Price (EUR/m^2)
Polycarbonate ARLA Plast	3	25
Polycarbonate MAKROCLEAR	4	69
Polycarbonate EXOLON UV	6	60
PMMA GS Plexi	3	27
PMMA GS Plexi XT	4	40
PMMA PLEXI XT	6	60

A total of ten tests were conducted for each specimen group to ensure sufficient statistical reliability. The primary data collected included the maximum impact force and the energy absorbed by the specimen during puncture. This data was analyzed using MS Excel 2019 to calculate key statistical parameters such as the arithmetic mean and standard deviation. After each test, the fracture surfaces of the specimens were carefully examined to assess the failure mechanisms, such as ductile or brittle fracture modes. This qualitative analysis complemented the quantitative data, providing a comprehensive understanding of the materials' behavior under high-speed loading conditions.

3. Experimental part

The main goal of this experimental study was to evaluate the mechanical performance of PC and PMMA under impact loading, focusing on their resistance to puncture. The aim was to simulate real-world applications and determine their suitability for environments requiring high-impact resistance. In addition to assessing mechanical performance, the study considered the cost of each material to identify an optimal balance between durability and economic feasibility. This approach is essential in the automotive sector, where material selection directly influences both safety and cost-effectiveness.

The experimental procedure involved subjecting PC and PMMA specimens to instrumented puncture tests using the ZWICK HIT 230F drop-weight impact tester. Ten specimens were tested for each combination of material and thickness to ensure statistical reliability.

During the tests, key mechanical parameters such as the maximum impact force and total absorbed energy were recorded to provide a detailed understanding of each material's resistance to puncture. The deformation behavior of the specimens was carefully analysed to assess their mechanical performance under dynamic loading. The post-test analysis included a qualitative examination of the fracture surfaces to identify failure modes, such as ductile or brittle behaviour, complementing the quantitative data.

Based on the comparison of all prepared specimens, it was possible to evaluate the suitability of PC and PMMA for safety-critical applications in transportation. The findings of this study provide valuable insights into the impact behaviour of PC and PMMA under dynamic loading conditions. By comparing the performance of these materials across different thicknesses and considering their cost, the research aims to guide material selection for safety-critical applications. This comprehensive evaluation contributes to optimizing component design, reducing material usage, and enhancing production efficiency, ensuring the reliability and cost-effectiveness of final products in real-world applications.

4. Results and discussion

The mechanical properties of PC and PMMA were evaluated using drop-weight impact tests to assess their suitability for safety-critical transport applications. These findings highlight the differences in impact resistance, failure modes, and cost-effectiveness between the materials tested.

Fig.1 shows graphically the maximum force values (Fmax) obtained during impact tests for PMMA and PC in thicknesses of 3 mm, 4 mm, and 6 mm. The results show a consistent increase in Fmax with material thickness for both materials. However, polycarbonate shows a significantly higher maximum impact force, with Fmax values ranging from 8555.95 N at 3 mm to 15303.43 N at 6 mm, compared to PMMA, which ranges from 2066.40 N to 4945.65 N at the same thicknesses. In terms of maximum impact force, it is evident that the PC is a more suitable choice for high-impact applications (Karhankova et al. 2023). In contrast, PMMA does not reach the maximum impact force value of PC but exhibits higher optical clarity and weather resistance (Anju, 2024).

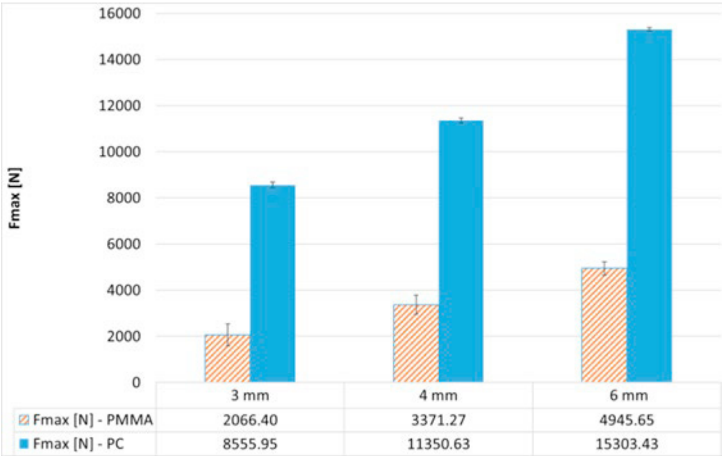

Fig. 1. Evaluation of Maximum impact force (Fmax).

Fig. 2 shows the statistically evaluated values of total absorbed energy (W) during impact tests for PMMA and PC in thicknesses of 3 mm, 4 mm, and 6 mm. The data show a significant difference in the total absorbed energy between the two materials. PMMA specimens with a thickness of 6 mm showed less than 12% of the total absorbed energy value compared to PC specimens of the same thickness. PC specimens with a thickness of 6 mm showed more than 8 times greater value of the total absorbed energy compared to PMMA specimens of the same thickness. Moreover, the 6mm thick PC specimens were the only ones that resisted the puncture in the testing. This major difference highlights the superior ability of PC to effectively dissipate impact energy, making it better suited for applications requiring high energy absorption. However, although the impact resistance of PMMA is significantly lower than that of PC, especially for thinner specimens, it is possible to modify PMMA with e.g. nanofillers to increase the impact resistance of PMMA (Anju, 2024).

Fracture surface analysis revealed different failure mechanisms for the two different materials (Fig. 3). For PC, a predominantly ductile fracture was observed, characterized by energy absorption before failure. In Fig. 3c, it can be observed that at the set energy of 230 J, the PC specimen with a thickness of 6 mm did not break, only a plastic deformation of the material occurred, which led to the impactor stopping and absorbing all the energy by the material. The deformation patterns indicate that PC can retain structural integrity even under high-impact loading. A predominant brittle fracture was observed in PMMA; this behavior may limit the ability of this material to absorb sufficient energy, which may lead to sudden failure of the safety features.

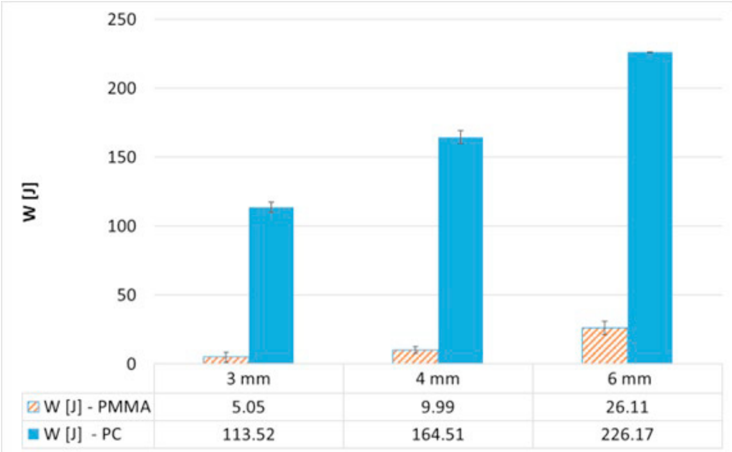

Fig. 2. Evaluation of Total absorbed energy (W).

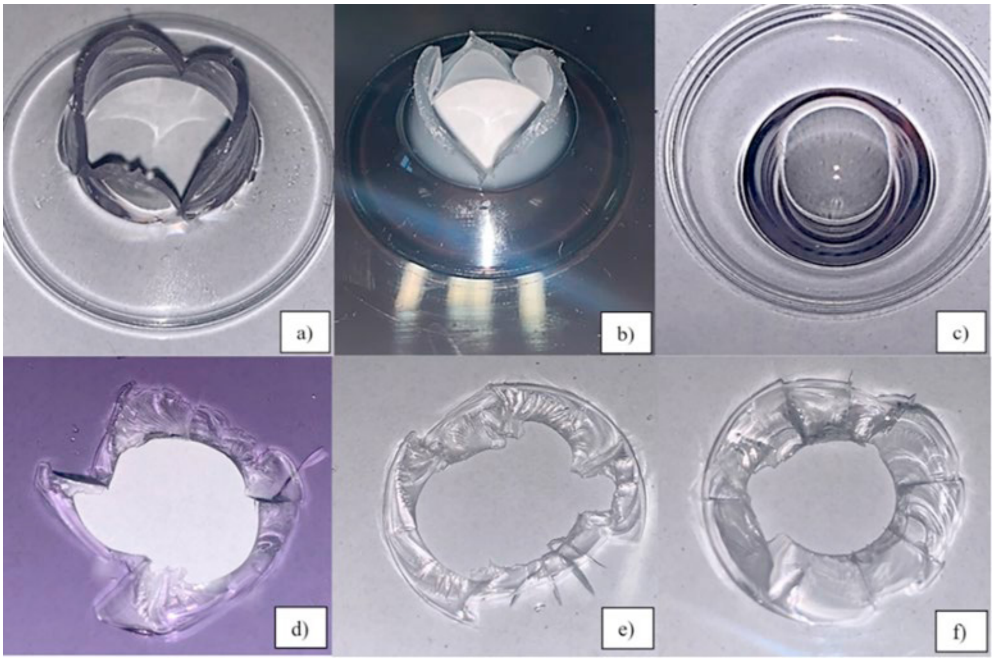

Fig. 3. Fracture surface: a) PC 3 mm; b) PC 4 mm; c) PC 6 mm; d) PMMA 3 mm; e) PMMA 4 mm; f) PMMA 6 mm.

5. Conslusions

Polycarbonate (PC) and polymethyl methacrylate (PMMA) were evaluated for mechanical properties and impact resistance. PC exhibits significantly higher impact resistance compared to PMMA, absorbing much more energy in the tests (e.g. 226.17 J for 6 mm thick PC compared to 26.11 J for PMMA of the same thickness). PC exhibits ductile behavior in impact, which means that it does not fail immediately under high loads. In contrast, PMMA has brittle fracture behavior, which limits its ability to absorb energy and can lead to sudden failure on impact. Although PMMA is slightly cheaper for thinner specimens, PC offers a better price/performance ratio, especially in applications requiring high-impact resistance.

Due to its durability and ability to absorb impact energy, PC is proving to be an optimal choice for transport safety features such as headlight covers and protective shields. PMMA, despite its lower resistance, finds application in areas where optical clarity and weather resistance are a priority, for example in decorative or low-load protective elements.

In addition, research suggests that the addition of nanofillers can improve the mechanical properties of PMMA, which could make it a more competitive material even for more demanding applications. The results contribute to the optimization of material design and selection, helping to improve manufacturing efficiency and safety in transportation.

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