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Evaluation of the Durability of Common FDM 3D Printing Materials for Applications in the Restoration of Historical Artefacts and Museum Objects

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Abstract

Fused Deposition Modelling (FDM) three-dimensional printing technology, with its high precision and design flexibility, offers a novel approach for reconstructing missing parts and producing temporary replicas of historical artefacts in museum contexts. This study evaluated the colour and structural stability of four widely available filaments in the Iranian market — polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyamide (PA), and polyethylene terephthalate glycol (PETG) — under accelerated ultraviolet (UV) ageing for 288 hours according to ASTM D4587-11. Prior to ageing, the chemical structure of the polymers was characterised using Fourier-transform infrared spectroscopy (FTIR). Colorimetric analysis (CIE L*a*b*) revealed that PLA exhibited the smallest colour change (ΔE), whereas ABS displayed the largest. Post-ageing FTIR spectra confirmed the formation of carbonyl peaks in PLA, ABS, and PETG, indicating photo-oxidative degradation; no such peak was observed in PA, demonstrating its superior structural stability. PLA is recommended for temporary museum applications owing to its excellent colour stability, while PA is preferred for components requiring high structural durability. ABS was deemed unsuitable due to pronounced colour shifts. Adhering to established conservation ethics, this research highlights the potential of FDM filaments in cultural heritage preservation, provided environmental conditions are rigorously controlled. The results indicate that polyamide (PA), due to its relative structural stability, and PLA, due to its minimal colour change, represent the optimal choices for reconstructing missing fragments or fabricating temporary supports for museum objects.

Keywords: Filament, FDM 3D printing, conservation-restoration, ultraviolet radiation (UV), colorimetry.

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1. Introduction

The conservation and restoration of historical artefacts represent a fundamental pillar of cultural heritage preservation, yet this field faces persistent challenges including technical complexities, material resource limitations, and stringent ethical requirements. Established conservation principles provide a scientific framework that encompasses minimal intervention (reducing impact on the original artefact), reversibility (enabling removal of added materials without damaging the original), distinguishability (ensuring restoration materials remain identifiable from the original), and comprehensive documentation of all processes. These principles, articulated in foundational documents such as the Venice Charter (ICOMOS, 1964), the Nara Document on Authenticity (UNESCO, 1994), and guidelines from ICOM-CC (2014), continue to guide contemporary conservation practice.

Fused Deposition Modelling (FDM) three-dimensional printing technology has emerged as an innovative approach for reconstructing missing fragments and producing temporary replicas of historical artefacts in museum contexts. This technology offers significant advantages, including high precision, design flexibility, reduced direct contact with original artefacts, and cost-effectiveness. Moreover, FDM technology has proven effective in developing protective tools such as balancing mounts for unstable museum objects. Previous research has successfully demonstrated diverse applications of 3D printing in restoration, including the reconstruction of missing sections of ancient pottery and glass objects using ABS filament, and the creation of moulages of ivory artefacts using both SLA and FDM techniques with PLA filament.

Despite these technological advancements, sufficient data regarding the durability of commonly available FDM filaments, including PLA, ABS, PA, and PETG, under ultraviolet (UV) radiation remains limited, particularly for filaments available in the Iranian market. Ultraviolet radiation, a critical environmental factor in museum environments, causes photo-oxidative degradation, colour alteration, and reduction in mechanical properties of polymeric materials, posing serious challenges for their application in cultural heritage conservation. This research gap underscores the necessity for comprehensive investigations to identify filament materials with optimal compatibility for conservation applications while minimizing potential damage to original artefacts.

This study, conducted in adherence to established conservation ethics, represents a step toward integrating modern 3D printing technology with sustainable cultural heritage preservation. The research evaluates the colour and structural stability of four widely available filaments in the Iranian market under accelerated UV ageing for 288 hours according to ASTM D4587-11, aiming to identify the most suitable filament for restoration applications.

2. Research Methodology

This research was designed with an experimental-analytical approach within the framework of conservation-restoration principles, specifically emphasizing minimal intervention and reversibility. The investigation was organized in three phases: (1) baseline identification of restoration materials through chemical characterization of polymers using Fourier-transform infrared spectroscopy (FTIR); (2) application of accelerated ageing to track degradation progression; and (3) comparative-temporal analysis of changes against control samples.

Four commonly available filaments in the Iranian market were selected for evaluation: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyamide (PA), and polyethylene terephthalate glycol (PETG), all with white colour and 1.75 mm diameter, sourced from the current Tabriz market (Y.S company, China). Samples measuring 2×2×0.5 cm were fabricated using an Anet ET5 Pro 2020 3D printer. The accelerated ageing process was conducted according to ASTM D4587-11 standards using UV-A radiation at 18-27°C, with samples positioned 15 cm from the lamp, at 50% relative humidity for 288 hours, with sampling conducted every 72 hours. Colorimetric analysis was performed using the CIE L*a*b* colour system with a Precision Computer Colorimeter 3nh model 555, and FTIR spectroscopy (FT-IR-680Plus, Jasco, Japan) in the 400-4000 cm^{-1} range at 4 cm^{-1} resolution was employed for structural analysis before and after ageing.

Data analysis was conducted using a comparative-descriptive approach, and results were categorized based on two criteria: colour stability and structural stability, ensuring that research outcomes directly translate to practical prioritization for conservators.

3. Discussion

3.1. Baseline Chemical Characterization of Filaments

FTIR spectroscopy analysis confirmed the chemical structure of all four filaments before ageing, establishing a reference baseline for post-ageing comparison. For PLA, characteristic peaks were observed at 3434 cm^{-1} (O-H stretching vibration), 2921 and 2853 cm^{-1} (C-H alkane stretching), 1757 cm^{-1} (C=O

lactone carbonyl stretching), 1384 and 1467 cm^{-1} (methyl bond deformation), 1088 and 1186 cm^{-1} (C-O stretching), and 871 cm^{-1} (C-COO stretching). For ABS, the spectrum revealed peaks at 3431 cm^{-1} (N-H stretching), 2922 and 2852 cm^{-1} (C-H alkane stretching), 2237 cm^{-1} (C≡N nitrile stretching), 1638 and 1602 cm^{-1} (C=C conjugated bonds in aromatic rings), 1462 cm^{-1} (C-H alkane bending), and 760 and 700 cm^{-1} (aromatic substituted C-H out-of-plane bending).
The PA spectrum showed peaks at 3434 cm^{-1} (N-H stretching), 2921 and 2853 cm^{-1} (C-H alkane stretching), 1631 cm^{-1} (C=O carbonyl stretching, Amide I band), and 1465 cm^{-1} (C-H alkane bending). For PETG, characteristic peaks were identified at 3434 cm^{-1} (O-H stretching), 2922 and 2852 cm^{-1} (C-H alkane stretching), 1634 cm^{-1} (C=C stretching), 1465 cm^{-1} (C-H alkane bending), 1114 cm^{-1} (C-O stretching in ester structure), and 831 and 723 cm^{-1} (aromatic C-H out-of-plane vibrations). These spectral features confirmed the chemical identity of all filaments and aligned with previously reported data in the literature.

3.2. Colorimetric Analysis of Filament Degradation

Colorimetric analysis revealed significant differences in colour stability among the four filaments. PLA exhibited the most favourable colour stability with minimal changes across all colour parameters, demonstrating $\Delta L^* = 1.9$ (shift toward whiteness), $\Delta a^* = 0.4$ (slight reddening), and $\Delta b^* = 0.9$ (slight yellowing), resulting in a total colour difference (ΔE) of 2.12 after 288 hours of UV exposure. This minimal colour change indicates excellent colour stability and makes PLA particularly suitable for temporary museum applications where visual aesthetics are critical.
In stark contrast, ABS showed the most pronounced colour changes, with $\Delta b^* = 21.5$ after 288 hours, indicating strong yellowing, along with $\Delta L^* = -3.2$ (darkening) and $\Delta a^* = 1.6$ (slight reddening), resulting in a total ΔE of approximately 22. The rapid yellowing observed from the initial 72-hour measurement ($\Delta b^* = 17.6$) demonstrates the extreme photosensitivity of ABS, rendering it unsuitable for visible restoration applications. PA displayed moderate colour changes with $\Delta b^* = 3.5$ (yellowing), $\Delta L^* = 2.9$ (whitening), and $\Delta a^* = -1.0$ (slight greening), yielding $\Delta E = 4.68$. While PA demonstrated acceptable colour stability relative to ABS, its total colour difference was more than double that of PLA.
PETG exhibited relatively favourable colour stability with $\Delta b^* = 2.4$ (yellowing), $\Delta L^* = -2.0$ (darkening), and $\Delta a^* = 0.75$ (slight reddening), resulting in $\Delta E = 3.2$. Notably, PETG showed minimal colour changes during the initial 72 hours, with yellowing becoming apparent only after extended exposure, suggesting a delayed degradation onset. The overall ranking of colour stability from most to least stable was PLA > PETG > PA > ABS.

3.3. Structural Changes Analysis Through FTIR Spectroscopy

Post-ageing FTIR analysis provided crucial insights into the structural degradation mechanisms of each filament. PLA exhibited the formation of a strong carbonyl peak at 1766 cm^{-1} after UV exposure, indicating significant photo-oxidative degradation through chain scission and oxidation reactions. This structural degradation, despite PLA's excellent colour stability, raises concerns about its long-term mechanical integrity and dimensional stability in applications requiring extended durability.
ABS demonstrated the appearance of a carbonyl peak at 1716 cm^{-1} with moderate intensity, confirming substantial oxidation within its polymer backbone. The formation of carbonyl groups in ABS is particularly concerning given its simultaneous severe colour degradation, indicating that both aesthetic and structural integrity are compromised under UV exposure. The combined effect of structural and colour degradation makes ABS completely unsuitable for conservation applications where long-term stability and visual consistency are paramount.
PETG exhibited a carbonyl peak at 1723 cm^{-1} with moderate intensity, confirming notable oxidation in its ester-based structure. The relative intensity increase of the 1723 cm^{-1} peak compared to the reference peak at 1465 cm^{-1} indicates significant structural degradation. This oxidation compromises the mechanical properties of PETG, though its moderate colour stability may still permit short-term applications in controlled environments.
Remarkably, PA demonstrated no carbonyl peak formation in the 1700 cm^{-1} region, confirming the absence of photo-oxidative degradation. While PA exhibited some spectral shifts toward higher wavenumbers, indicating stress development in the pseudo-crystalline structure, the absence of carbonyl formation demonstrates superior structural stability among all tested filaments. This stability is attributed to PA's

amide-based structure, which exhibits greater resistance to UV-induced oxidation compared to ester-based polymers.

3.4. Comparative Assessment and Practical Recommendations

Based on the comprehensive analysis of colour and structural stability, a clear hierarchy of filament suitability for conservation applications emerges. PLA, with its exceptional colour stability ($\Delta E = 2.12$) and bio-based origin (derived from corn starch and sugarcane), is recommended for temporary museum applications such as rapid prototyping, temporary replicas for exhibition, and short-term structural supports. The biodegradability of PLA (under industrial composting conditions) is particularly advantageous for reversible interventions. However, PLA's structural degradation under UV exposure, evidenced by the strong carbonyl peak formation, limits its use to temporary applications of 9-12 months duration in environments with relative humidity below 50%.

PA, despite its moderate colour change ($\Delta E = 4.68$), is preferred for components requiring high structural durability. The absence of carbonyl formation confirms PA's resistance to UV-induced oxidation, making it suitable for long-term structural applications such as permanent support structures, functional components, and load-bearing elements. The water absorption tendency of PA necessitates controlled environmental conditions (relative humidity < 50%) to prevent dimensional changes and hydrolysis.

PETG, with acceptable colour stability ($\Delta E = 3.2$) and moderate structural degradation, may be considered for conditional applications in dry environments. Its delayed degradation onset suggests suitability for short-to-medium term applications where UV exposure can be rigorously controlled. ABS, due to pronounced colour shifts ($\Delta E \approx 22$) and significant structural degradation, is deemed unsuitable for any conservation applications where aesthetics and long-term stability are required.

4. Conclusion

This study evaluated the colour and structural stability of four common FDM 3D printing filaments (PLA, ABS, PA, and PETG) under accelerated UV ageing for 288 hours. The investigation established that PLA exhibits the smallest colour change ($\Delta E = 2.12$), making it optimal for temporary museum applications requiring visual consistency, while PA demonstrates superior structural stability (no carbonyl peak formation) and is preferred for components where long-term durability is paramount. PETG presents a moderate alternative with acceptable colour stability ($\Delta E = 3.2$) but notable structural degradation, suitable only in controlled dry environments (relative humidity < 50%). ABS was deemed entirely unsuitable due to severe colour alterations ($\Delta E \approx 22$) and significant structural degradation.

The research underscores the importance of material selection in 3D printing applications for cultural heritage preservation. While PLA and PA emerge as the optimal choices for different application types, their use must be subject to rigorous environmental control. PLA is recommended for temporary applications of 9-12 months duration, while PA is suitable for permanent applications in controlled museum environments with UV radiation below 75 μW/lm. The findings emphasize that the integration of FDM technology in conservation requires a balanced consideration of ethical principles, material compatibility, and environmental management.

Future research should investigate mechanical properties, including tensile strength (ASTM D638), adhesion characteristics of polymeric materials to historical substrates using compatible adhesives, evaluation of alternative 3D printing technologies (SLA and PolyJet) offering higher resolution and surface quality, and the impact of post-processing treatments such as UV-protective coatings. Additionally, long-term ageing studies extending to the full 1000 hours specified in ASTM D4587-11 would provide more comprehensive degradation profiles. By adhering to conservation principles including minimal intervention, comprehensive documentation, and material compatibility, this study contributes to the responsible application of modern technologies in sustainable cultural heritage preservation.