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Original article

Accelerated ageing test (Oddy test) of additive manufacturing materials for cultural heritage use

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ABSTRACT

Restoring missing parts of cultural heritage (CH) objects, such as sculptures, archaeological artefacts, or decorative arts, typically marks the final phase in the conservation process. During this treatment, conservators rely on materials known for their ageing properties and lack of adverse effects on the historical item. As technology progresses, new methods and techniques emerge, including additive manufacturing (AM), which has been employed in CH restoration since the early 2010s. However, questions within the CH conservation community have arisen about the suitability of AM materials for this purpose.

This paper outlines the process and presents the outcomes of an accelerated ageing test on collected ceramic, ceramic-like, glass-like, paper-based and polymer AM materials. The Oddy test results suggest that some commercially available AM materials are suitable for conservation use. However, inconsistent results across different labs highlight concerns about the reliability and consistency of Oddy testing. This procedure is an integral part of a doctoral research project focused on the use of additive manufacturing method to restore ceramic and glass archaeological artefacts. This research could benefit conservators of antiquities and works of art, museum curators and material scientists who would like to use the additive manufacturing method as a complementary restoration method for their conservation process or museum curation.

1. Introduction

Restoration is often the final phase in the conservation process for an object. When an object is incomplete or damaged, restoration aims to enhance its visual integrity while maintaining its authenticity and historical significance. Traditional restoration methods for archaeological artefacts involve reconstructing missing parts using materials such as epoxy and acrylic resins, calcium compounds (e.g., Plaster of Paris), and synthetic resins, as well as techniques like moulding, balloon supports, and modelling [1–4]. These methods adhere to strict professional ethical guidelines [5,6]. The reconstruction should be easily reversible and identifiable, and the materials chosen should have known ageing properties and pose no harm to the historical object [7]. The outcome of a restoration is somewhat subjective and heavily reliant on the conservator's expertise in recreating the missing portions of the artefact. Today, methods like additive manufacturing (AM) can be used to offer more objective and precise results. By using 3D scanning and digital restoration methods, restorers can recreate the missing parts based on accurate data minimizing human bias [8].

The first AM technology was created in 1983–84 by Charles "Chuck" W. Hull using a polymer liquid as a material. Since then, >20 technologies have been developed (Table 1), using a variety of materials (Table 2), such as ceramic, metal, wax and paper, which have been used in applications related to engineering, medicine, architecture, fashion, art, the food industry and CH [9–11].

In the conservation of CH artefacts, examples of application of the AM method can be found since the beginning of the 2010s, mostly on ceramic objects [12–16], but also marble [17], wood [18] and glass [19]. As the interest in using this method has increased, the conservation community has raised questions, frequently through forums like the Global Conservation Forum, regarding the suitability of the AM materials for restoration purposes. A 2023 survey by the Image Permanence Institute (NY, USA) revealed that over 80 % of CH institutions using AM for exhibition

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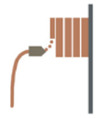
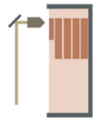
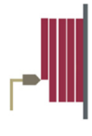
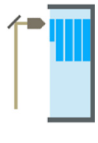
Table 1
Different technologies of additive manufacturing that have been developed through the years.

Additive Manufacturing Method							
Techniques	Binder Jetting	Powder Bed Fusion	Directed Energy Deposition	Material Extrusion	Material Jetting	Sheet Lamination	Vat Photopolymerization
Technique Schematic							
Technologies	Three-dimensional printing (3DP)	Selective Laser Sintering (SLS) Selective Laser Melting (SLM) Multi-Jet Fusion (MJF)	Laser Metal Deposition (LMD) Laser Engineered Net Shaping (LENS) Directed Light Fabrication (DLF)	Fused Deposition Modelling (FDM) Fused Filament Fabrication (FFF) Paper Pulp Printer (PPP)	Inkjet Printing (IJP) Multi-Jet Modelling (MJM) Thermojet	Ultrasonic Additive Manufacturing (UAM) Laminated Object Manufacturing (LOM) Selective Deposition Lamination (SDL)	Stereolithography Apparatus (SLA) Digital Light Processing (DLP) Continuous Digital Light Processing (CDLP)
Manufacturing accuracy Level of thickness:	0035–0,4 mm	0,1–0,15 mm (SLS) 0,02–0,05 mm (SLM)	0,01–0,05 mm	0,05–0,4 mm	0016–0032 mm	Depends on the sheet thickness	0001–0,1 mm
Dimensional accuracy:	0,05 mm	0,3 mm (SLS) 0,1 mm (SLM)	0,1mm	0,2 mm	0,05 mm		0,01 mm

and display had not assessed the materials before implementation [20].

In the field of CH conservation, conservators must have a thorough understanding of the material properties of any potential restoration materials before embarking on a conservation or restoration treatment. Essential information regarding these material properties includes their ageing characteristics [7]. A widely accepted and standardised method for assessing the suitability of conservation materials before their application is the accelerated ageing test [21–23]. While the visible changes in materials may take years to become apparent, the accelerated ageing test offers valuable insights into the chemical stability of these materials. This aspect is crucial for material selection because chemical reactions can produce by-products that could harm the objects being conserved [7].

So far, this test has been applied to some polymer AM materials by Bharti and Durant [24], Aure-Calvet [25] and Andrés et al., [26]. This paper presents the application of the accelerated ageing test - Oddy test on collected ceramic, ceramic-like, glass-like, paper and polymer AM materials, comparing the results with conventional restoration materials. This research is part of a PhD research regarding the use of the AM method for the restoration of ceramic and glass archaeological artefacts.

2. Research aim

This research aims to assess the stability and suitability of AM materials for cultural heritage conservation by applying the Oddy test to evaluate their potential risks to heritage collections. Given the increasing use of AM materials for conservation treatments-often without prior testing [20]-this research seeks to provide conservators with critical insights into material behaviour, challenging assumptions of inertness, and advocating for the standardisation of material assessment protocols before implementation in conservation practice.

3. Method used and selection of AM materials

3.1. Accelerated ageing test - Oddy test

The Oddy test is an accelerated corrosion test which was introduced in 1973 by W.A. Oddy. The purpose of the test is to help the conservators access material that can be used in conservation practises and exclude corrosive materials from museum displays and storage usage. It is based on the optical assessment of the corrosion of three metal coupons (silver, lead, copper) after they have been exposed for one month at 60 °C with sample of material inside a sealed flask [22]. Since then, many variations of the test have been introduced [21]. For this research, the variation of the "3-in-1″ method, introduced by Robinet and Thickett in 2003, was used for the assessment of collected AM materials. In this variation the three metal coupons (Ag, Cu, Pb) are enclosed with 2 g of the sample materials inside a glass tube of 50 ml, which also includes a smaller glass tube of 0.8 ml with distilled water covered with cotton and sealed with inert silicone stoppers. The tubes are then exposed for 28 days at 60 °C [23]. Although recent studies [27,28] have shown that variations in evaluation criteria and differences in test methodologies significantly impact discrepancies in the results regarding the deterioration of metal coupons and can lead to inconsistencies in the results, making it difficult to compare and share test results between institutions, the Oddy test is still considered reliable for identifying materials that emit harmful emissions detrimental to the conservation of cultural assets [27,28].

Table 2
The additive manufacturing materials used in each technique.

Additive Manufacturing Materials								
Techniques		Binder Jetting	Powder Bed Fusion	Directed Energy Deposition	Material Extrusion	Material Jetting	Sheet Lamination	Vat Photopolymerization
Technique Schematic								
Materials	***Ceramic***	√	√	√	√	√	√	√
	Metal	√	√	√		√	√	
	Polymer	√	√	√	√	√	√	√
	Paper				√		√	
Type of material		**Powder**	**Powder**	**Powder**	**Solid**	**Liquid**	**Solid**	**Liquid**

Table 3
The number of organisations contacted, replied and agreed to contribute with AM materials and the number of AM materials collected.

Organisations	Contacted	Replied	Agreed to contribute	Number of materials
Ceramic/ceramic-like suppliers	9	4	1	6
Glass/glass-like suppliers	35	2	1	2
Paper suppliers	1	1	1	4
Institutes and universities	8	8	3	18
Total numbers	**53**	**15**	**7**	**30**

3.2. Selection of AM materials

For the selection of the AM materials, the online database Senvol.com was used. This database allows companies to access, generate and analyse AM data. By the time this research was written (May 2023), the online database included >3646 AM materials, which were available on the market from 237 suppliers [29]. These materials were categorised as ceramic, composite, metal, polymer, sand and wax.

As the number of AM materials was too large to all be tested for suitability in the conservation of CH, it was necessary to use selection criteria and eliminate the number of materials for testing in this research. Bharti and Durant [24], Aure-Calvet [25] and Andrés *et al*. [26] have tested polymer materials for their suitability in CH, therefore, this research focused mainly on (i) the ceramic category, (ii) materials containing ceramic and glass from the composite category, and (iii) paper material. The suppliers of the selected materials, as well as institutes and university departments involved in the use of AM technologies (either by having their own patent of AM material or having used commercial materials) were contacted and requested to contribute to this research by sending samples of their materials for the Oddy test. Table 3 presents the number of organisations contacted and the number of AM materials collected.

The contributors of the AM material were Lithoz, the Centre for Print Research from the University of West of England (UWE), Clear Green 3D[1] (CG3D), Stratasys, the Engineering Department from the University of Southampton, and the UCL Department of Medical Physics and Biomedical Engineering (which contributed with a polymer material).

In addition to the AM materials, materials traditionally used for restoration purposes in CH were also sourced. The selection of these materials was informed by a literature review of conservation publications and insights from conservators at the British Museum. The chosen traditional materials included: (i) the acrylic resin adhesive Paraloid B72, (ii) the epoxy adhesive Araldite 2020, (iii) the gypsum-based Plaster of Paris, and (iv) the epoxy adhesive HXTAL NYL-1. Although these traditional materials have undergone previous testing, the results from our current tests will be directly compared with those of the AM materials. This comparison is facilitated by ensuring that the testing conditions remain consistent.

The samples of the traditional restoration materials raised the number of samples to 34. Table 4 presents the trade name and material type of the collected samples.

3.3. Oddy test of AM materials

Due to COVID-19 restrictions [30], access to available equipment posed challenges between March 2020 and February 2021. Consequently, (i) Oddy tests were conducted in two different Conservation Labs, at the Natural History Museum (NHM) in London and at the Institute of Archaeology at UCL, and each accessed by different conservators, and (ii) not all materials were tested in both sessions due to variations in the times they were received.

The conservators from both labs followed the "3-in-1″ method by Robinet and Thickett [23], with the only difference being the cleaning preparation of the tubes. At the NHM, the cleaning process involved warm water and Decon 90, whereas at UCL, the preparation included IPA and deionised water.

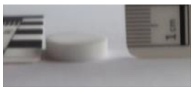
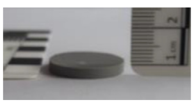
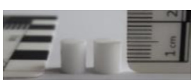
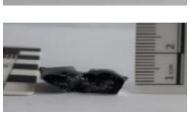
The results from the Oddy test were categorised into three groups:

(i) Pass/Suitable for long-term use (P): Materials that showed no visible signs of corrosion or adverse reactions on any of the three metal coupons. This typically includes a shiny or uniformly tarnished silver surface, a reddish or evenly brown copper patina, and either no change or a faint white haze on the lead coupon.
(ii) Temporary/Suitable for short-term use (T): Materials that exhibited minor corrosion, such as slight black tarnish or iridescence on silver, light green spotting on copper, or thin white patina or limited crystalline efflorescence on lead.
(iii) Failed/Not suitable (F): Materials that caused significant corrosion, including black, flaking, or iridescent corrosion on silver; bright green or powdery corrosion on copper; or thick, crusty white corrosion on lead.

According to Feller's [31] materials classification, those who pass the test can be associated with classes A – can be used for >100 years, B – Can be used 20–100 years, and C – can be used

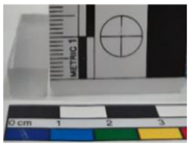
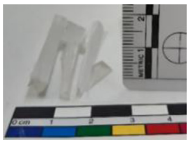
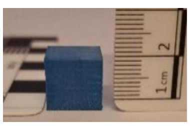
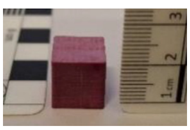
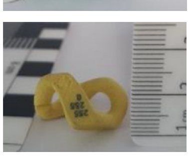
[1] In April 2022, CleanGreen3D Limited closed. The CEO of the company suggested using Fab Lab MH, a commercial company that uses the same printer and material that CleanGreen3D Limited used to for additive manufacturing.

Table 4
Material type and trade name of collected material samples.

Image of the material	Material type	Trade name	Manufacturer	AM Technology used
	AM ceramic/ceramic-like	ZP 151 Powder	3D Systems	Binder Jetting
	AM ceramic/ceramic-like	LithaLox HP 500 (HP500 Alumina, high grade purity)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	LithaLox 350 (350D alumina grade I, standard grade)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	LithaNit 770 (silicon nitrade)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	LithaBone HA 400 (HA/Hydroxy Apatite)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	LithaBone TCP 300 (TCP/Tricalcium Phosphate)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	LithaCon (Zirconia)	Lithoz	Vat Photopolymerization
	AM ceramic/ceramic-like	UWE white glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE blue glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE yellow glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE red glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE light yellow glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE dark teal glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE black glazed painted cover	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	UWE plain (not paint or glazed)	UWE	Powder Bed Fusion
	AM ceramic/ceramic-like	new UWE ceramic plain (not paint or glazed)	UWE	Powder Bed Fusion

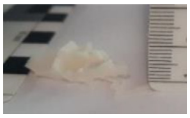
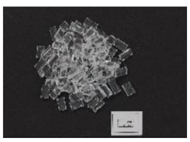
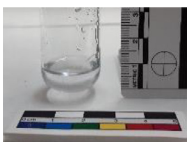
(*continued on next page*)

Table 4 (*continued*)

Image of the material	Material type	Trade name	Manufacturer	AM Technology used
	AM glass/ glass-like	Vero Clear	Stratasys	Material Jetting
	AM glass/ glass-like	Ultra Clear	Stratasys	Material Jetting
	Paper	CG3D-WHITE	CG3D/ Fab Lab MH	Sheet Lamination
	Paper	CG3D-CYAN	CG3D/ Fab Lab MH	Sheet Lamination
	Paper	CG3D-MAGENTA	CG3D/ Fab Lab MH	Sheet Lamination
	Paper	CG3D-YELLOW	CG3D/ Fab Lab MH	Sheet Lamination
	AM polymer/resin	HP 3D CB PA 12- WHITE	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- BLACK	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- DARK BLUE	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- LIGHT BLUE	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- GREEN	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- YELLOW	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	HP 3D CB PA 12- HOT PINK	HP 3D printing	Powder Bed Fusion

(*continued on next page*)

Table 4 (*continued*)

Image of the material	Material type	Trade name	Manufacturer	AM Technology used
	AM polymer/resin	HP 3D CB PA 12- SALMON PINK	HP 3D printing	Powder Bed Fusion
	AM polymer/resin	Formlabs (white resin)	Formlabs	Vat Photopolymerization
	Acrylic resin adhesive	Paraloid B72	HMG paints Ltd	
	Epoxy adhesive	Araldite 20/20	Huntsman	
	Epoxy Adhesive	HXTAL NYL-1	Sylmasta.com	
	Gypsum Plaster	Plaster of Paris	Potterycraft	

<20 years, while materials deemed suitable for temporary use correspond to class T – can be used <6 months.

4. Results

4.1. Results of the Oddy test from the Natural History Museum (NHM)

The first Oddy test, conducted at the NHM in London, UK, was completed on March 3, 2021. A total of 16 materials underwent assessment. The evaluation involved comparing three coupons of each material with the corresponding three coupons of the control sample. The results, summarised in Table 5, indicate that only two materials—LithaBone HA 400 and UWE yellow glazed painted cover —were deemed suitable for long-term use. Conversely, ZP 151 Powder and Vero Clear were considered unsuitable for any use, while the remaining materials were considered suitable for short-term applications. (Fig. 1)

4.2. Results of the Oddy test from the Institute of Archaeology, UCL

The Oddy tests at the UCL Institute of Archaeology, UK, were conducted on various dates between February and May 2022, corresponding to the time of collection of the AM materials. A total of 25 materials underwent assessment. The evaluation involved comparing three coupons of the control sample with three coupons of each material. A summary of the results is presented in Table 6.

According to these findings, 19 materials, including LithaNit 770, LithaBone HA 400, LithaBone TCP 300, LithaCon, CG3D-CYAN, CG3D-MAGENTA, the two patent materials from UWE, all HP 3D CB PA 12 variants (regardless of colour), Araldite 2020, Plaster of Paris, and HXTAL NYL-1, were deemed suitable for long-term use. On the other hand, ZP 151 Powder and LithaLox 350 were considered unsuitable for use, while the remaining materials were classified as suitable for temporary use.

5. Conclusions from the Oddy test results

Completing the Oddy test at two different conservation labs may compromise the absolute consistency of testing conditions - in this case, due to the different cleaning procedures used for preparing the tubes. However, it provides the advantage of comparing how different professional conservators interpret the results. Nevertheless, the purpose of the Oddy test is to identify materials that potentially could be corrosive and exclude them from conservation use and materials that can be used temporarily and for long-term exhibition and storage. Even though not all the materials were tested twice, the above results show how different labs can vary in their assessment of the results. Of the six AM samples of materials that were tested from both labs, only two samples gave the same results; the LithaBone HA 400 was considered suitable for long-term use and the ZP 151 powder was considered not suitable, twice. Three materials that were considered suitable for temporary use from NHM, were considered suitable for long-term use from UCL, and one material that was considered suitable for temporary use from NHM, was considered not suitable from UCL. Table 7 presents the results from the double-tested AM materials.

Table 5
The results of the Oddy test of the AM and the replica materials, by the NHM. P= Pass/suitable for long-term use, T= Temporary/suitable for short-term use, F= Failed/not suitable.

Trade Name	Ag	Cu	Pb	APPROVED/FAILED
ZP 151 Powder	T	T	F	F
LithaLox HP 500 (HP500 Alumina, grade high purity)	P	T	T	T
LithaLox 350 (350D alumina grade I, standard grade)	P	T	T	T
LithaNit 770 (silicon nitrade)	P	T	T	T
LithaBone HA 400 (HA/Hydroxy Apatite)	P	P	P	P
LithaBone TCP 300 (TCP/Tricalcium Phosphate)	P	T	T	T
LithaCon (Zirconia)	P	T	T	T
UWE white glazed painted cover	P	T	T	T
UWE blue glazed painted cover	P	T	T	T
UWE yellow glazed painted cover	P	P	P	P
UWE red glazed painted cover	P	T	T	T
UWE light yellow glazed painted cover	P	T	T	T
UWE dark teal glazed painted cover	P	T	T	T
UWE black glazed painted cover	P	T	T	T
Vero Clear	P	F	T	F
Ultra Clear	P	T	P	T

Fig. 1. The control coupons (left) in comparison with the coupons of the LithaBone HA 400 (middle) and the UWE yellow glazed painted cover (right).

Hence, it can be argued that LithaBone HA 400 is suitable for long-term use in the conservation of CH. LithaNit 770, LithaBone TCP, and LithaCone may also be potential candidates, given that they were deemed suitable for long-term use in the UCL test and temporary use in the NHM test. Nevertheless, conservators should exercise caution and carefully consider the potential damage an AM material may inflict on the original substance, especially when it exhibits mild corrosion on copper and lead.

However, as the LithaLox 350 was considered suitable for temporary use on NHM test and not suitable on the UCL test, it might not be the most secure choice of AM material. Finally, ZP 151 powder should not be used in the conservation of CH, as in both tests it was considered not suitable for use.

At this point, it is noteworthy that, according to the website Digit [32],[2] ZP 151 replaced ZP 150 in 2013. ZP 150 was used by Antlej *et al.* [13] and might have also been used by Arbace et al. [14], as they used the same technology as Antlej *et al.* However, a common material safety data sheet for both materials, written by the supplier (with no known date), indicates that both materials consist of Plaster (<90 %) and vinyl polymer (<20 %). A revised safety data sheet from 2016, specifically for ZP 151, states that it is composed of 90 % calcium sulphate hemihydrate (Plaster of Paris). Additionally, following the Oddy test at UCL, the sample created from ZP 151 powder, was partially dissolved (Fig. 2).

Fig. 2. The ZP 151 after the Oddy test at UCL.

Another noteworthy observation from both laboratories involves the UWE and CleanGreen3D sample materials. In both instances,

[2] The authors cannot guarantee that this information is accurate, as it was found only on one website, and it was not confirmed by the supplier.

Table 6
The results of the Oddy test of AM materials and traditional conservation materials by UCL. P= Pass/suitable for long-term use, T= Temporary/suitable for short-term use, F= Failed/not suitable.

Trade Name	Ag	Cu	Pb	APPROVED/ FAILED
ZP 151 Powder	P	P	F	F
LithaLox 350 (350D alumina grade I, standard grade)	P	P	F	F
LithaNit 770 (silicon nitrade)	P	P	P	P
LithaBone HA 400 (HA /Hydroxy Apatite)	P	P	P	P
LithaBone TCP 300 (TCP/Tricalcium Phosphate)	P	P	P	P
LithaCon (Zirconia)	P	P	P	P
CG3D-PLAIN WHITE	P	P	T	T
CG3D-CYAN	P	P	P	P
CG3D-MAGNETA	P	P	P	P
CG3D-YELLOW	P	P	T	T
UWE plain (not paint or glase)	P	P	P	P
new UWE ceramic plain (not paint or glase)	P	P	P	P
HP 3D CB PA 12 White	P	P	P	P
HP 3D CB PA 12 Black	P	P	P	P
HP 3D CB PA 12 Dark Blue	P	P	P	P
HP 3D CB PA 12 Light Blue	P	P	P	P
HP 3D CB PA 12 Green	P	P	P	P
HP 3D CB PA 12 Yellow	P	P	P	P
HP 3D CB PA 12 Hot Pink	P	P	P	P
HP 3D CB PA 12 Salmon	P	P	P	P
Formlab white resin	P	P	T	T
Paraloid B72	P	P	T	T
Araldite 20/20	P	P	P	P
Plaster of Paris	P	P	P	P
HXTAL NYL-1	P	P	P	P

Table 7
The results of AM materials that were tested from NHM and UCL. P= Pass/suitable for long-term use, T= Temporary/suitable for short-term use, F= Failed/not suitable.

Trade Name	Ag		Cu		Pb		Approved/ Failed	
	NHM	UCL	NHM	UCL	NHM	UCL	NHM	UCL
LithaLox 350	P	P	T	P	T	F	T	F
LithaNit 770	P	P	T	P	T	P	T	P
LithaBone TCP	P	P	T	P	T	P	T	P
LithaCone	P	P	T	P	T	P	T	P
LithaBone HA 400	P	P	P	P	P	P	P	P
ZP 151 powder	T	P	T	P	F	F	F	F

the samples comprised the same AM material—powder for UWE and paper for CleanGreen3D. These samples were assessed in their plain form (without any additional colour) and in combination with various colours, where UWE utilized paint, and CleanGreen3D incorporated pigment. From the results of the UWE samples, only the samples of the new material, the UWE plain (not paint or glazed), and the one with the yellow glazed colour were deemed suitable for long-term use. Conversely, the remaining UWE samples, featuring different glazed colours, were considered suitable only for temporary use. Similar outcomes were observed in the CleanGreen3D samples, with the cyan and magenta-coloured samples considered suitable for long-term use, while the yellow and plain variants were deemed suitable for temporary use.

Since only one test occurred for each of these materials, it is difficult to have a comprehensive opinion, and further Oddy tests would be considered useful in both cases. However, since none of the samples were considered unsuitable for use, both materials could be used in the conservation of CH, if the original material is not affected by the corrosion factors that damaged the metallic

Fig. 3. The magenta cube after the Oddy test at UCL.

coupons in each case (copper and lead in UWE and lead in CleanGreen3D). A potential concern with CleanGreen3D materials arises from the appearance of the samples after the Oddy test. All four paper cubes disintegrated into their layers (see Fig. 3), losing their original shape.

In the case of the two materials from the supplier Stratasys, both underwent testing only once at the NHM. Vero Clear failed the test, rendering it unsuitable for use in conservation. As for the Ultra Clear sample, despite causing minimal corrosion on lead and being categorized as a temporary material, it could potentially be considered suitable. The conservator, however, would need to identify the specific factor corroding the lead (whether organic acids, aldehydes, or acidic gases) and assess the potential impact on the original material's glass.

As for the two polymer materials, all HP 3D CB PA 12 samples, regardless of colour, were deemed suitable for long-term use, while the white resin from Formlabs was considered suitable for short-term use.

The UCL Oddy test outcomes for traditional conservation materials indicate that Araldite 2020, Plaster of Paris, and HXTAL NYL-1 were deemed suitable for long-term use. Conversely, Paraloid B72, a widely used resin in conservation, was considered suitable only for short-term use. This aligns with recent research on the long-term use of Paraloid B72, highlighting how its stability can be affected by factors such as high temperatures, light exposure, and the choice of solvents [33–35].

6. Discussion

The Oddy test results indicate that there are currently commercially available AM materials suitable for use in conservation. However, it is essential to note a potential discrepancy in the accuracy of the results. Among the two Oddy tests employing the same six AM materials, only two materials yielded consistent results in both tests. This raises questions about the reliability and precision of Oddy test outcomes.

It is important to consider that many AM materials are composites, meaning their behaviour under test conditions may differ from that of their individual components. Since these materials will be used in their composite form in conservation practice, comparing test outcomes to the performance of individual constituents is often neither feasible nor relevant. Instead, the Oddy test results should be interpreted based on the composite material as a whole. However, understanding the composition and potential interactions between components can still offer valuable insight into the material's behaviour and help inform responsible decision-making in conservation workflows.

The outcomes from both laboratories indicate that a material (ZP 151), previously used in the aesthetic restoration of ceramic artefacts, was deemed unsuitable. This underscores the crucial importance of thorough research on AM materials before incorporating the AM method into conservation practices. Additionally, the results highlighting Paraloid B72 as a temporary/short-term material underscore the need for a re-evaluation of materials that have been long-standing in conservation use.

7. Further work

In light of the findings from this research, further investigations could explore the mechanical properties of identified suitable AM materials, encompassing factors such as tensile, compression, and flexural strength. While mechanical properties for some collected AM materials are publicly available on senvol.com or supplier websites, those not available could benefit from dedicated mechanical tests. This is especially pertinent since certain materials, deemed suitable for long-term use in CH based on the Oddy test, might fail due to inappropriate mechanical properties.

Moreover, it is recommended to continue testing other AM materials available on the market. To offer a more comprehensive evaluation, assessing materials for additional properties such as colour, surface reflection, refractive index, transparency/translucency, density, weight, porosity, and friability should also be considered.

Furthermore, given the ongoing nature of this research, establishing an online database through common-based peer production is advised. This database would serve as a collaborative platform for conservators, researchers, and labs to contribute their findings on the suitability of AM materials and the aesthetic results achievable with various AM technologies. While databases such as the AIC Wiki Materials Testing Results already compile Oddy test data (AIC [36]), they focus solely on these results and do not include aesthetic outcomes or mechanical properties. Expanding such existing resources or developing a new database that encompasses a broader range of material characteristics would be invaluable for those working with AM method, fostering a collective understanding of the technology's capabilities and limitations. A proposed implementation could involve using an open-source content management system, hosted by a university lab, museum consortium, or professional organisation (e.g., ICOM-CC or IIC). Contributors would submit results through structured forms, ensuring consistency in data entry, while an editorial committee or peer moderation system would oversee content quality. To ensure sustainability, the platform could be supported through institutional partnerships, research funding, or integration into established conservation networks.

Thus, the findings of this study raise several research questions that warrant further investigation:

- What mechanical properties (e.g. brittleness, flexibility, dimensional stability) of AM materials are most critical for conservation applications?
- What role do aesthetic outcomes (e.g. surface texture, gloss, colour) play in determining the suitability of AM materials for visible restoration in heritage objects?
- Which AM materials show consistent performance across both aesthetic and chemical stability criteria when used in conservation contexts?
- How can collaborative platforms support the systematic collection and comparison of AM material performance data, including Oddy results, visual outcomes, and mechanical testing?
- How can inter-laboratory discrepancies in Oddy test results be reduced through standardised preparation, cleaning, and evaluation protocols?

8. Consideration before choosing an AM material for cultural heritage use

Selecting AM materials for cultural heritage use requires balancing material properties, conservation ethics, and long-term stability. Conservators should first define the requirements, considering functionality, longevity, environmental exposure, and reversibility. The choice of AM material can be intertwined with the AM technology and vice versa, as not all technologies can use all the materials. Furthermore, not all technologies can give the same aesthetic and mechanical result, thus this is another aspect that conservators need to consider. Materials must be assessed for aging behaviour, chemical stability, mechanical strength and aesthetic suitability. Suitability testing, such as the Oddy test for emissions, mechanical testing for durability, and visual evaluations for aesthetic compatibility, helps determine whether a material is appropriate for each use. Furthermore, conservators should think the ethical perspectives, including reversibility, potential risks to artifacts, and sustainability. Findings should be documented for future reference and shared through conservation databases. For example, in recreating a missing porcelain fragment, a conservator may choose SLA for its smooth finish and translucency, test a photopolymer resin, conduct an Oddy test, and choose reversible adhesives, ensuring both functionality and adherence to conservation principles.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Open AI Chat GPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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