

## PRESERVATION OF PLASTIC CULTURAL HERITAGE. A REVIEW

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### Abstract

*This article deals with the broad topic of the conservation of plastics, which, as objects of historical or artistic value an essential part of collections all around the world. This review focuses on the risks associated with plastic art, its degradation pathways, methods of identification and characterization, and currently used methods of preservation. Besides the literature review, an online survey of European museums and galleries was conducted, which allowed us to gain an overview of the current state of plastic conservation. Twelve institutions participated in the survey and there is a marked difference in the level of information regarding plastics in their collections. The results underline the relevance and urgency of this issue if we want to prevent the irreversible losses of cultural heritage, as many institutions do not have the means to ensure the effective protection of plastic artifacts. The study of available resources shows us that great progress has been made in recent years, but further research and improvement are still needed.*

**Keywords:** Conservation of cultural heritage; Polymers; Plastic degradation; Material survey

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### Introduction

Today, plastic artefacts form a significant part of museum collections, whether as works of art or objects of historical, scientific, or cultural importance. Despite the general belief that plastics are indestructible, plastic artefacts in collections institutions are beginning to degrade at an alarming rate, which can lead to irreversible losses of the cultural heritage of incalculable value. As the degradation of plastics became evident, experts in the field of cultural heritage began to pay more attention to these modern materials. Detailed surveys of collections have been carried out in institutions around the world, since material surveys aimed at the identification and quantification of plastics, together with the subsequent evaluation of the degradation state of the artefacts, are the first key steps on the way to saving plastic cultural heritage.

Preserving plastics is not an easy task, many challenges stem from the lack of knowledge about these types of materials and their degradation mechanisms, as well as the lack of experience in conservation science. Compared to traditional art materials, synthetic polymers are still considered new materials, and little can be done to stabilize and degrade them in the long term. Conservators face a major challenge to understand a very heterogeneous and ever-growing group of materials (plastics) and find ways to preserve them before it is too late. Degradation studies cannot be focused only on the degradation of the polymer matrix itself; one must also consider the influence of additives on the stability and degradation rate of plastic. These additives have a

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significant effect on the overall stability of the material; therefore, it is very important to know the exact components of the studied material and the way these components interact with each other. A detailed study of the mechanism of plastic degradation is a basic requirement for the development of successful conservation strategies to preserve and extend the life of plastic objects.

In practice, the terms polymer and plastic are often confused and taken as synonyms, which is incorrect from a chemical point of view and are not always the same thing. A polymer is defined as a substance composed of macromolecules, where a macromolecule is defined as a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molecular mass [1]. According to their origin, polymers can be divided into natural, such as natural rubber, cellulose, starch, cotton, semi-synthetic, based on chemical modification of natural polymers and synthetic, which are synthesized from monomers. Based on their behaviour under applied heat polymers can be divided into two groups – elastomers and plastics. Therefore, all plastics are polymers but not all polymers are plastics. Elastomers are easily deformed by the action of a small force, while this deformation is reversible. A typical example of elastomers is rubber. Plastics, on the other hand, are polymers that can be heated into a plastic shape and then shaped. Applying a large force to plastics leads to their irreversible/permanent deformation. There are two types of plastics – thermoplastics and thermosetting plastics. Thermoplastics are formed by linear or branched individual chains of polymers (macromolecules) which are connected only by intermolecular bonds. These bonds can be broken by the action of heat or solvent, which allows the recycling of thermoplastics (for example acrylics, polypropylene, polystyrene, and polyamides). Unlike thermoplastics, thermosetting plastics cannot be thermally processed again. Thermosets (such as epoxy resins, polyurethanes, phenolic resins) are obtained through a curing process, which results in the creation of an extensively cross-linked polymer network. For this work, the term plastics refers to semi-synthetic and synthetic man-made materials, whose main component is a polymer and contains additives that modify their properties.

This article aims to provide the reader with a comprehensive overview of the current situation in the field of plastic conservation, as it summarizes general knowledge from this field and informs about new studies focusing on this issue. The article also presents the results of our online survey conducted in European museums and galleries, which emphasize the importance of further research aimed at finding efficient ways to protect plastic cultural heritage. Due to the urgency of this issue and the still relatively low level of experience in this area, it is crucial to spread awareness and share gained knowledge with experts in the field. Since this is an interdisciplinary field, the information presented in this review that may be trivial for some experts may prove to be important for others, especially those active in conservation science.

## Historical development of plastics

Knowledge of the historical development of plastics is important for understanding the historical context of plastic artifacts and it may also prove helpful in identification, or in determining the age of plastic artifacts. One of the milestones on the way to fully synthetic polymer materials is the creation of Ebonite, the first material produced by chemical modification of natural polymer, by Nelson Goodyear in 1851. Production of Ebonite consists of the vulcanization of natural rubber, while the resulting material can contain up to 40% of sulphur. Ebonite was mainly used as a substitute for expensive and less accessible natural materials, such as ebony wood, from which its name is derived [2, 3]. In the second half of the 19th century, the production of so-called semi-synthetic plastics started to develop. The greatest commercial success and application were recorded by cellulose esters. In 1862, Alexander Parkes introduced the first man-made plastic, a semi-synthetic plastic prepared from cellulose, which he called Parkesine. It was cellulose nitrate (CN) plasticized with camphor [2–4]. Several years later, John

Hyatt came up with virtually the same material under the name Celluloid, which achieved great success as a cheap substitute for expensive natural materials. Its ability to faithfully imitate materials such as ivory, horn, tortoiseshell or mother-of-pearl made it perfect for the manufacture of imitations. At the end of the 19<sup>th</sup> century, celluloid found application in the film industry as a material to produce photographic films [3]. Along with the commercial success of celluloid, its negative properties, mainly high flammability, combustibility, and explosiveness, were fully manifested. Nitrate cellulose films used in movie theatres in particular, posed a great threat. Despite the obvious risk associated with this material, celluloid films were widely used until the 1920s [2, 3, 5]. From the 1920s, CN was gradually replaced by a more stable ester - cellulose acetate (CA), while celluloid films stopped being used completely after 1940 [5, 6]. CA was first prepared in the 1860s, however, its production did not start until 1894, when a production process suitable for industrial manufacture was developed. In the beginning, it was mainly used for films as a replacement for flammable CN and the preparation of waterproof materials used mainly in the production of aircraft parts during WWI. Its later use was very similar to that of CN [2, 3]. Another natural polymer used for the creation of synthetic material at the end of the 19<sup>th</sup> century is casein. Casein formaldehyde (CSF) first appeared under the commercial name Galalith in 1900 at an exhibition in Paris. Galalith was available in a wide variety of colours and patterns and for several decades it was used to make buttons, buckles, and clasps [2, 3, 7].

The first man-made fully synthetic plastic was Bakelite which is a trade name for phenol-formaldehyde (PF), a thermoset prepared and patented in 1907 by Leo Baekeland [4]. Bakelite has properties suitable for a wide range of applications, in the first half of the 20<sup>th</sup> century, it has been used to produce bowling balls, music records, radios and telephones. Thanks to its excellent electric and thermal insulation properties, it was also used as a material to produce electrical insulation and kitchen utensils. The main disadvantage of Bakelite and other phenol-formaldehyde resins in general, is their dark colour, for this reason, Bakelite products were only available in black or dark shades of red and brown [3]. The demand for colourless materials with properties similar to phenolic resins led to the development of aminoplastics - formaldehyde resins prepared by polycondensation of formaldehyde and an amino compound (urea, melamine). Urea-formaldehyde (UF) and thiourea-formaldehyde resins began to be produced, which quickly found use as kitchenware, telephones, lampshades and in the field of electro-installation. The production of melamine-formaldehyde (MF) started later, in the 1930s. Despite the higher price, this material slowly replaced UF, mainly thanks to its higher resistance to heat, water, and various chemicals [2, 3, 7].

Poly(vinyl chloride) (PVC) was first synthesized at the end of the 19<sup>th</sup> century and the first patent was obtained in 1912. However, industrial production did not fully take off until the 1930s, when plasticizers, specifically phthalates, were added to the mixture to modify the chemical and physical properties of the material as needed. During World War II, there was a rapid growth in the number of possible applications for PVC, both flexible and rigid. Thanks to its excellent properties, resistance to water and acids, non-flammability, and simple production, PVC gradually replaced rubber [3, 7]. An equally long delay between initial synthesis and commercial success/application accompanied the development of polystyrene (PS). It was first synthesized in the first half of the 19<sup>th</sup> century, but production began in the 1930s. In approximately the same period styrene also began to be used for the preparation of various copolymers, for example, acrylonitrile butadiene styrene copolymer [2, 3, 7].

Great credit for the development of new plastic in the first half of the 20<sup>th</sup> century goes to the British chemical company Imperial Chemical Industries (ICI). Research in the ICI laboratories led to the development of poly(methyl methacrylate) (PMMA) and polyethylene (PE) in the 1930s. PMMA is characterized by properties such as high strength, durability and resistance to atmospheric influences and transparency, which made this acrylic a perfect substitute for glass, known under the names Perspex or Plexiglass. The manufacture of PMMA saw a sharp increase during WWII when it was used for military aircraft glazing [2, 3]. The

production of PE started in the 1930s when the polymerization was performed under extreme conditions (very high pressure and temperature) and the product of this process was a low-density polyethylene [2, 3]. It was not until 1956 that scientists managed to prepare high-density polyethylene (HDPE), whose properties differ from LDPE, which enabled a wider range of applications [7]. PE is a thermoplastic with good mechanical properties, great chemical resistance, and electrical insulation properties. The production of PE currently constitutes the largest part of global polymer production [2, 3, 7].

During the war in the 1940s, the production of polymeric materials started in full swing. The extensive research by DuPont Chemicals led to the development of new polymeric materials, among them polyamide-6,6 (PA-6,6) and polytetrafluoroethylene (PTFE). PA-6,6, known as Nylon, prepared in 1935, was the first polymer that could be processed into fibres by melting, this enabled the creation of the first synthetic fibre. During the war, these polyamide fibres were used as a substitute for silk in the production of parachutes, later nylon stockings appeared on the market and immediately became a huge hit [3, 7]. Polytetrafluoroethylene, the first fluoroplastic, was accidentally synthesized in 1938 during an experiment involving tetrafluoroethylene gas. The manufacture of this material began in the 1940s, most famously under the trade name Teflon. PTFE is a thermoplastic that is characterized by good resistance to heat and cold, good isolation properties and resistance to various chemicals. The most famous application of PTFE is non-stick Teflon cookware. In approximately the same period, 1935-1945, the first silicones and epoxides with exceptional adhesive properties were also developed [2, 3].

Another significant group of polymers is polyesters. An important representative of this group is poly(ethylene terephthalate) (PET), a linear polyester. The first patent for PET fabrication was issued in 1941 in the United Kingdom. PET is a thermoplastic prepared by the polycondensation reaction of polyethylene glycol with terephthalic acid and at the time of its creation, it was mainly prepared in the form of fibres and films [2, 7]. A bit earlier, in 1933, unsaturated polyester resins were discovered, and they began to be produced industrially in 1941. Polyester resins reinforced with glass fabrics, so-called fiberglass, were used during the war, for example, in the construction of boats, and were later used in the production of designer furniture [2, 3].

## Plastics and cultural heritage

Both 3D and 2D plastics artifacts (including synthetic paints and coatings) are found in the collections. The 3D artifacts comprise of artworks created solely for the artistic purpose, utility and design objects appearing in specific collections and various plastic objects collected for their significance. They can be found in collections of toys, furniture, cinematographic films or collections of science museums and archives [8-12]. Artworks can be created “from scratch” using a specific type of polymer to achieve the desired properties or by using prefabricated plastic objects, the so called readymade [13]. Synthetic paints are mentioned but will not be discussed in further as they are a separate category and are usually omitted from surveys focusing on plastics in collections.

The plastic artifacts in the collections are evidence of the evolution of science, and technology as well as witnesses to major historical events [14]. Plastics found their way into art at the beginning of the 20th century. The implementation of these new modern materials in the field of art is mainly due to the representatives of constructivism, cubism, futurism, and suprematism. Artists of the Russian avant-garde, Naum Gabo and Antoine Pevsner, are generally considered to be the first artists who brought plastics into art around 1915. Initially, the most used materials were semi-synthetics such as celluloid and cellulose acetate, which were gradually replaced by more suitable PMMA in the 1930s. The success of plastics in sculpture was slow and limited only to certain artistic movements. On the other hand, synthetic acrylic paints succeeded almost immediately after their market launch in the 1940s and gradually replaced traditional oil

paints. Acrylic paints were extensively used by prominent artists such as Andy Warhol, Rory Lichtenstein, David Hockney, and Mark Rothko. Other types of synthetic paints were used by Pablo Picasso, Jackson Pollock, Wilhelm de Kooning, and more [14, 15]. After WWII, the demand for plastics as well as the possibilities of their applications increased rapidly, which naturally reflected on the art scene. Therefore, the number of plastics appearing in art exhibitions only increased in the 1960s, when artists became fascinated by the inexhaustible possibilities offered by these new materials.

Despite mounting evidence of their instability, the number of plastics in art is still increasing. Nowadays plastics have a stable position among traditional art materials and represent an important part of our cultural heritage. When objects become part of a collection or acquire the status of cultural heritage, the owning institution is responsible for their long-term preservation. The problem is the expected lifespan of plastic objects. The lifetime of plastics, especially those from the beginning of the 20<sup>th</sup> century, is counted only in tens of years, which is significantly less than that of traditional materials (stone, metals, oil painting), which can be preserved for centuries or even millennia [5, 16, 17]. Despite the extensive research in this area in recent years, plastics still degrade in ways that are difficult to characterize and thus prevent. To a certain extent, the responsibility for the accelerated degradation of plastic art lies with the artists themselves, who often use undocumented techniques and materials in ways that may negatively impact the lifespan of the artwork.

Plastics in collections were neglected for quite a long time, which was probably connected to their reputation as cheap and inferior materials and the association of plastics with only the modern era. In 1996 Keneghan, a specialist from the London Victoria & Albert Museum defined the term “plastic denial syndrome” – curators refused to admit the possibility of plastic infiltrating their collections and denied their presence [18]. However, the rapid degradation of plastic artifacts led to attention being drawn to these materials. A typical example of a shocking deterioration of plastic art is the degradation of *Construction in Space: Two Cones* by Naum Gabo. The work was first created in 1936 and already in 1960, it was visibly deteriorated. In 1968 Gabo created a replica of his work, which was met with the same fate. It became obvious that the problem lies within the material used, in this the unstable cellulose acetate [19]. Attention was drawn to this issue by the conference „Saving the 20<sup>th</sup> century” held in 1991 [20]. Based on new information regarding plastics and the rate of their degradation, material surveys focusing on plastics began to be carried out, which brought information about the representation of plastics, and the degree and type of degradation, which complete the picture of the seriousness of this issue. Some of the first surveys were conducted in London, namely at the Victoria & Albert Museum, the Science Museum, and the British Museum. A study of plastics present in the collection of the Victoria & Albert Museum carried out in 1992 led to the identification and analysis of more than 4500 plastic artifacts [21]. The survey continued in 2001 when 7938 artifacts containing plastic were discovered, most of which were found in the collection of toys [9]. In 1995 a total of 3032 plastic artifacts were discovered in the collections of the British Museum through surveying the electronic documentation system [3]. The collections of the Science Museum in London contained around 1500 plastic artifacts according to a survey done in 1990 [22]. A survey of plastics conducted under the auspices of the Plastic Historical Society and the Museums and Galleries Commission uncovered several shortcomings regarding the general care of plastic objects [23]. The most detailed and extensive research on plastics in art so far was carried out within the European project POPART, which took place from 2008 – 2012 [24]. Besides identification, the project also focused on the stability and degradation of different types of plastics [25-27]. There are not enough published surveys to accurately evaluate the representation of plastics in the collections. Moreover, the survey showed, that the representation of individual types of plastics reflects the nature of the collection and its dating. For example, the collections of fashion accessories of the Paris gallery Musée Galliera contain a large share of semi-synthetic plastics, such as CA, CN, and CSF, frequently used as an imitation of luxury materials. On the

other hand, collections of modern and contemporary art and design collections are mostly made up of acrylates (such as PMMA), polyesters, polyurethanes (PURs), and PVC [28]. A significant portion of plastics remains unidentified as the identification of plastics is a complex process and not all institutions have the means to execute it. Overall, material surveys published so far, lead to the conclusion that the most common plastics in collections are PVC, polyesters, PE and PMMA, well represented are also PS, PURs, MF, and PF (Table 1). Besides surveys listed in Table 1 several others have been published recently. During the survey at the Harvard Art Museum more than 400 artifacts have been examined, identified and their condition evaluated [29]. Two Belgian Museums, Design Museum Gent and S.M.A.K., whose collections contain together almost 4000 plastic objects jointly initiated a project called ‘Know, name, and assess your plastics’ that emphasizes the need for identification and proper characterization of plastics in collections [30]. Bell published a study containing a detailed review of material surveys of plastics with the goal of creating a collection survey methodology which could facilitate cross-institutional comparison of survey results [31].

**Table 1.** Different types of plastics present in the surveyed collections of museums and galleries around Europe: (✓ - is present; x - is not present; BM – British Museum; VAM – Victoria & Albert Museum; MAMAC - Musée d'Art Moderne et d'Art Contemporain de Nice; MAM - Musée d'Art moderne; MG - Musée Galliera; SM - Stedelijk Museum), source: [3, 15, 28]

Material	Institution					
	BM	VAM	MAMAC	MAM	MG	SM
Phenol -formaldehyde	✓	✓	x	x	✓	x
Urea-formaldehyde	✓	✓	x	x	✓	x
Melamine-formaldehyde	x	x	✓	✓	✓	✓
Casein-formaldehyde	x	x	x	x	✓	x
Cellulose nitrate	✓	✓	x	x	✓	x
Cellulose acetate	✓	✓	x	x	✓	✓
Polyamides	✓	x	✓	x	✓	✓
Poly(vinyl chloride)	✓	✓	✓	✓	✓	✓
Polyesters	✓	✓	✓	✓	✓	✓
Polyethylene	✓	✓	✓	✓	✓	✓
Poly(methyl methacrylate)	✓	✓	✓	✓	✓	✓
Polystyrene	✓	✓	✓	✓	x	✓
Polyurethanes	✓	✓	✓	✓	✓	✓
Poly(vinyl alcohol)	x	x	x	x	x	✓
Polycarbonate	x	x	x	x	✓	x
Epoxide resins	✓	✓	x	x	x	x
Rubber	x	✓	✓	✓	✓	x
Acrylates	x	x	x	x	x	✓
Polyacrylonitrile	x	x	x	x	x	✓
Poly(ethylene terephthalate)	x	x	x	x	x	✓
Silicone	x	x	x	x	x	✓
Other	x	x	x	✓	✓	✓

When examining the collections of Slovak institutions, we discovered that there is a relatively large number of plastic-containing artifacts, however, most of them are not identified. Information regarding plastics in the collection was obtained from the electronic cataloguing system of museums and galleries. In the collection funds of Slovak National Museums and

associated museums, there are 22641 records of collection items containing some type of synthetic material [32]. The representation of different types of plastics is presented in figure 1.

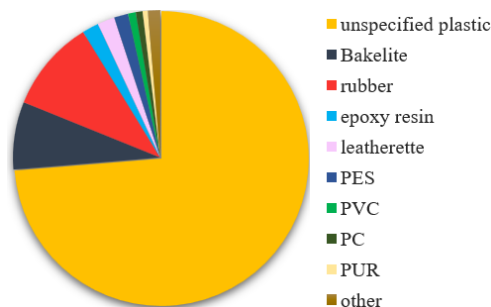


Fig. 1. Material representation of plastics in the collection of Slovak National Museum, information was obtained from the electronic database ESEZ 4G (Central record of museum collections in Slovakia)

In the funds of the Slovak National Gallery and associated galleries, the number of plastics is more than 9000 which represents around 5% of the total number of collection artifacts [33, 34]. Unfortunately, most artifacts are classified simply as plastic or synthetic material, so we cannot draw relevant conclusions about the material representation of collections.

### Ageing and degradation of plastics

When creating, artists usually choose materials (plastics) based on their aesthetic and processing qualities and do not pay much attention to the long-term stability of the materials and their mutual compatibility. Moreover, they often incorporate recycled, old, and partially degraded materials and objects, which means that already upon creation the final artwork contains plastics in various condition grades. Condition of plastics in museums has been widely characterized using a four-grade system shown in Table 2 [3, 9, 28, 31, 35].

Table 2. Condition grades employed to describe the condition of plastic artifacts

Condition grade	Overall condition	Description
1	<i>Good</i>	Limited visible degradation, stable, minor physical damage (e.g., staining, dirt), no chemical damage, no need for intervention
2	<i>fair</i>	Moderate visible degradation, reasonable condition, physical damage such as slight yellowing or discoloration
3	<i>poor</i>	Considerable visible degradation, chemical damage manifesting as brittleness, blooming or sweating, unstable, intervention (conservation) is necessary
4	<i>unacceptable</i>	Unstable, combination of physical and chemical damage, actively deteriorating, not suitable for handling and exhibiting

The state of some plastics can change dramatically over a short period since their degradation is characterized by a short induction period followed by a period of accelerated degradation. For this reason, regular monitoring and evaluation of conditions play a vital role in preserving plastic cultural heritage [28, 36]. Accurate documentation and degradation assessment are crucial steps preceding any kind of conservation treatment; however, condition assessment is often subjective, and the relevance and reliability of the results are questionable. Therefore, unequivocal definitions of different types of damages can be a great help. Several authors focused on defining different types of damage inherent to plastics and on compiling glossaries often

containing photos and detailed descriptions to help better characterize the deterioration of studied artifacts. One of the outputs of the POPART Project was a list containing definitions for the most common terms describing the deterioration of plastics [37], as well as a damage atlas presenting typical damage of the 6 most common types of plastics supplemented with visual documentation of several case studies [38]. Most recently, Krieg focused on creating a damage atlas with a detailed description of the unique degradation phenomena of plastics, providing the reader with a visual to help facilitate collection surveys [39].

In recent years the need for detailed research on plastics and their ageing mechanisms has become more intense, which is a key prerequisite for the development of effective conservation strategies for these materials [40-43]. The degradation of synthetic and semi-synthetic polymers is mainly caused by their chemical structure and reactivity, as well as the influence of external factors. The most important environmental factors causing the degradation of polymers include humidity, heat, UV light (radiation), chemicals and pollutants and biological agents of degradation [44-46].

The study of degradation processes in plastic objects is very challenging due to the extreme variability of materials and due to the possible synergistic or antagonistic effects of external factors. While the effect of increased temperature and light intensity on ageing is well-studied (it accelerates ageing), the effect of humidity and pollutants on (historical) polymers is less researched [47, 48]. The severity of individual degradation factors is relative as it depends on the type of polymer, present additives, and processing conditions. The degradation process is also affected by improper handling and inappropriate conservation treatments. It is important to keep in mind that degradation pathways as well as the rate of degradation for plastics in the controlled conditions of museum depositaries would differ from the degradation of plastics exposed to uncontrolled natural environment. However, this is a complex issue that would require separate research.

The degradation of plastics can be generally divided into three categories: physical degradation, chemical degradation, and biodegradation [46]. Physical degradation results from the disruption of polymer morphology, rather than reactions at the molecular level [49]. Physical degradation can occur as a result of mechanical wear and improper manipulation of the artifact. It also includes volume expansion and contraction due to temperature fluctuations, swelling because of moisture absorption and migration of additives, which will be discussed in more detail in the next chapter [50]. There are several mechanisms that lead to chemical changes in polymer chains, namely thermal degradation, photodegradation, thermo-oxidation and photo-oxidation [46]. The role of additives in chemical degradation cannot be ignored since many additives are unstable during ageing and can provide enough energy and a suitable environment to break selected chemical bonds [3]. Besides physical and chemical degradation, biodegradation of plastics in museum environment must also be considered [51, 52]. The issue of biodegradation of plastics in cultural heritage has been mainly connected with the biodegradation of synthetic paints and coatings and polymers used in conservation practice (e.g., adhesives, consolidants) [53, 54], however several cases of biodegradation of plastic artifacts has been reported [55-59].

### ***Polymer degradation***

Polymer degradation is a change in the properties of the polymer – such as tensile strength, colour, shape, molecular weight – or of a polymer-based product under the influence of one or more environmental factors, such as heat, light, chemicals, or any other applied force [60]. Degradation factors cause changes in the chemical and physical structure of polymer chains and initiate chain reactions leading to a decrease in the molecular weight of the polymer. The structure of a polymer strongly influences its susceptibility to degradation. While epoxies and aromatic chains are mainly prone to degradation by exposure to ultraviolet radiation, hydrocarbon chains are more susceptible to thermal degradation [60, 61].



There are several types of structural changes caused by chemical degradation – chain scission, cross linking, and development of new functional groups. During chain scission monomers are formed as the scission of bonds along the polymer backbone occurs, which ultimately results in a decrease in the molecular weight of the polymer. Since the properties of the polymer strongly depend on its molar mass, its decrease can be manifested by a significant loss of strength and hardness [49, 62, 63]. Chain cleavage can occur either randomly (statistical chain fragmentation) or at precisely specified locations, for example, chain-end scission. An example of random scission is the degradation of polyolefins characterized by the formation of a mixture of chains with different lengths and a rapid decrease in molecular weight [64, 65]. A typical example of chain scission induced by chemical ageing and subsequent loss of mechanical strength is the crumbling of PUR foams [66, 67]. Chain-end scission is involved in a process called depolymerization, in which monomers are clipped from the end of the polymer chain [68]. Chemical cross-linking represents the creation of covalent bonds between two individual polymer chains. Linear polymers such as polystyrene and PVC are more susceptible to cross-linking which causes an increase in molecular weight, leading to an increase in glass transition temperature ( $T_g$ ), stiffness, brittleness, and a decrease in solubility [3, 60]. The development of new functional groups due to oxidation or hydrolysis involves the formation of chromophores or the formation of polar groups. Formed chromophoric species such as carbonyls or quinones and unsaturated carbon bonds absorb light at specific wavelengths causing colour change (yellowing) [3, 62].

### *Effects of additives*

According to the European Chemical Agency, an additive is defined as a substance which is intentionally added to plastics to achieve a physical or chemical effect during the processing of the plastic or in the final material or article; it is intended to be present in the final material or article [69]. Additives are essential components of plastics; without them, the development of the plastic industry would not be possible. They modify properties without altering the chemical structure of the polymer, facilitate processing, and significantly extend the lifespan of otherwise unstable polymers. Additives comprise a wide range of substances, such as complex organic molecules, inorganic and organometallic compounds. The main requirements for additives are stability during both processing and use, low toxicity, inertness, low price, and the ability to remain in the formulation of the polymer material throughout the intended useful lifetime [3, 70]. Polymer additives are usually divided into groups according to their function rather than their chemical composition. One of the possible classifications is:

- additives extending the useful life of plastic products: antioxidants, light stabilizers, heat stabilizers, acid scavengers, biocides
- additives facilitating processing: plasticizers, lubricants
- additives affecting the application properties and appearance of plastics: flame retardants, fillers, pigments, optical brighteners, plasticizers.

Due to the great number of additives, it is not possible to generally evaluate their effect on the stability of plastics. Some additives are specifically tailored to extend the lifetime of plastics, however, during the production of plastics and the addition of additives, the required lifetime of the product is considered. The required lifetime of plastics usually ranges from 1 to 50 years and after this time additives are exhausted, they degrade, lose their function, or migrate out of the polymer matrix, which leads to accelerated degradation of the material [3, 71]. Plasticizers, the most widely used additives, are characterized by relatively low molecular weight, which might be associated with a higher migration rate. The most common types of plasticizers are phthalates, the migration of which is well researched, especially in the food industry in connection to the migration of toxic phthalates from food packaging into food [72-74]. Plasticizer loss is a well-observed degradation mechanism for several types of plastics, for example, plasticized PVC (pPVC), CA and CN drawing a lot of attention from experts in the field [75,76].

### ***Malignant plastics***

Based on stability and degradation rate we distinguish two types of plastics – malignant and benign. Malignant plastics, which include CN, CA, pPVC, PUR foam, and highly vulcanized rubber (e.g., Ebonite) represent the most acute problem for curators and conservators since they degrade much faster than the more durable benign plastics. Moreover, the biggest threat posed by these materials lies in the production of noxious compounds which cause autocatalytic degradation of the object itself as well as accelerate the degradation of other objects stored in their vicinity [77]. Damage can occur by transfer of corrosive substances by direct contact with the malignant plastic), or by dispersion of noxious gases emitted by the malignant plastic to remote artifacts in the collection. A typical example of a negative effect of malignant plastics on surrounding objects is the corrosion of metals caused by degradation products of CN and CA, specifically nitric acid, and acetic acid [38, 78]. Even if we do not consider the production of plastics, cellulose esters degrade at an alarming rate, often leaving often conservators with no other choice but to create copies of degraded works. A great example of this phenomenon is the degradation of Antione Pevsner's Portrait of Marcel Duchamp (cellulose nitrate with copper on iron) [79]. Degrading cellulose acetate movie films emit beside the most common acetic acid several other volatile organic compounds, namely dimethylformamide, butanol, formic acid and more as detected using Proton Transfer Reaction "Time-of-Flight" Mass Spectrometer [80]. Degradation of pPVC is closely associated with the migration and degradation of additives, mainly plasticizers, which may comprise up to 50% of the material. Migration of additives generally manifests by the formation of a surface deposit, either of crystalline (bloom) or oily nature (sweating). Under conditions enabling thermal degradation, dehydrochlorination of the polymer chain occurs, which leads to the evolution of hydrochloric acid [78, 81]. The increased degradation rate of PUR foam is a result of its open structure and high porosity which ensures better penetration of degradation factors into the material. Due to the action of the degradation factors, complete disintegration of the material can occur in a relatively short time. The precise mechanisms depend on the chemical composition of the foam – polyether PUR foams degrade mainly through oxidation, while polyester PUR foams are more susceptible to hydrolysis at high relative humidity [77, 82]. Malignant plastics, together with some other types of plastics, are closely associated with the phenomenon of cross-infection [83]. Malignant plastics pose a threat especially to metals and organic materials, such as paper and other plastics [84]. The cross-infection was observed also on PP, when the thermo-oxidation of several polymers proved to be accelerated in the presence on unstabilized PP, in return, the effect these polymers had on unstabilized PP could also be observed [85]. Based on the above-mentioned information, we advise as one of the first steps for the preservation of plastics to identify malignant plastics in collections. Because of their malignancy, conservation strategies must deal with these plastics as a priority.

### **Identification and analysis of plastics**

One of the ways institutions can identify plastics is using cross-referencing kits of samples of different polymers or using a proposed sets of questions as guidelines, for example the ResinKit™ by The Plastics Group [86], the reference collection SamCo developed for the project POPART [87] or the Plastic Identification Tool, the PIT kit, developed as a part of the Project Plastics [88, 89]. Since plastics are complex materials, identification based on visual assessment, possibly in combination with odour assessment, can lead to incorrect conclusions, thus the use of instrumental analysis is necessary. For example, cellulose derivatives can be easily confused with natural materials they are meant to imitate, such as tortoiseshell [90]. The analysis of heritage artifacts requires a special approach due to the specific nature of the objects; special care must be taken to preserve the integrity of the artifact. Non-invasive analytical techniques must be used in

cases where sampling is not possible, the instrumentation should be portable and easy handling and low cost are a great advantage.

In the field of cultural heritage, infrared spectroscopy is the most widely used analytical method, mainly due to the great number of applications, the possibility of non-invasive analysis, and relatively simple operation [91-95]. Most institutions rely on infrared spectroscopy with Fourier transformation (FTIR) for the identification of plastics. This is also evident from the online survey we conducted, the results of which are summarized in chapter 8. FTIR spectroscopy was one of the main analytical methods used with the project POPART, where taken samples were analysed using transmission FTIR, while in-situ analyses were carried out using a portable ATR FTIR device [96]. In addition to identification, ATR-FTIR can be used to characterize artifacts containing plastics more closely [97]. The condition of non-invasive analysis is best met by portable FTIR devices operating in reflection mode. For the proper characterization of plastics using external reflection FTIR (ER-FTIR), it is necessary to know the limitations of this method and possible ways of adjusting and evaluating obtained spectra, which differ greatly from the transmission and ATR ones. The use of Kramers-Krönig transformation significantly facilitates the comparison of reflection spectrum with available databases and reference spectra and spectrum identification [98, 99]. In addition to ER-FTIR, diffuse reflection infrared Fourier transform spectroscopy (DRIFTS), which proved to be more suitable for rough and matte surfaces than ER-FTIR, has been used for the identification of plastics and degradation assessment [100]. Identification of plastics in a museum environment is in many cases hampered by the lack of reference spectra. This problem can be solved by compiling databases of infrared spectra recorded in different modes, which include the spectra of historical plastics such as CN, CA, and CSF [101, 102]. FTIR spectroscopy combined with chemometrics, partial least squares-discriminant analysis (PLS DA) and principal component analysis coupled with linear discriminant analysis (PCA-LDA), provides good results in the monitoring and assessment of plastics degradation and the creation of degradation models [103].

Another popular analytical method with a wide range of applications in the field of cultural heritage is Raman spectroscopy. Advancements in portable Raman instrumentation and techniques such as surface-enhanced Raman spectroscopy (SERS) contributed to the expansion of the method into the conservation practice [104, 105]. A SERS based strategy has been used to detect degradation markers, oligomeric fragments, released from the surfaces of aged polymer samples and museum artifacts [106]. Portable or handheld Raman spectrometers significantly broadened the possibilities of in situ analysis of artifacts [107-109]. One of the main applications of Raman spectroscopy is the analysis and identification of pigments and characterization of paint layers on various substrates [110-117]. Both benchtop and portable Raman instruments equipped with various types of lasers are suitable for the analysis of plastic objects. Raman spectrometers use various kinds of laser, the most common ones are lasers with emission at 785 and 1064nm, which can be used in both benchtop and portable instruments and are suitable for identification of the polymer component of plastics and some additives, such as phthalates or camphor [96, 104, 118, 119].

Detailed characterization of artifacts made of plastic frequently requires a multi-analytical approach, often combining non-invasive analytical methods with micro-invasive to get complete information. For example, ATR-FTIR can be used for preliminary analysis to obtain information about the main components of the object. Then pyrolytic techniques – a combination of Py-GC/MS and EGA-MS - are used to obtain more specific information on the composition of the individual materials. Moreover, the combination of these methods can reveal signs of degradation [120, 121]. This kind of multi-analytical approach has been successfully used to determine the composition of design objects in the collections of the Triennale Design Museum of Milan [122].

The analysis of degradation products also plays a vital role in the conservation of plastic artifacts. As was mentioned before, the cross-infection effect of plastics, for which volatile

compounds emitted from degrading plastics are responsible, poses a threat to the entire collection. Identification of emitting compounds, especially volatile organic compounds (VOCs), and identification of plastics based on their emission can be achieved through solid-phase microextraction-gas chromatography coupled with mass spectrometry (SPME-GC/MS) [123, 124]. Research conducted at the sculpture Construction in Space ‘Two Cones’ by Naum Gabo, which is too degraded for display but still good for research, suggests that SPME-GC/MS is a suitable method for in-situ monitoring of VOC emission [125]. A study suggests the application of non-invasive thermal desorption-gas chromatography coupled with mass spectrometry for the analysis of vapours emitted from plastic objects, since the detected VOCs can be used to identify CA, CN, PURs, rubber, PE, PP, and styrene-based polymers [126]. In the case of pPVC identification of plasticizers is crucial, as some plasticizers may promote degradation of the material while others may inhibit it [127]. For this reason, Rijavec focused on creating a model capable of identification and of several different types of plasticizers commonly used in pPVC based on non-destructive analysis by IR spectroscopy combined with machine learning [128]. A research study used mathematical modelling to predict plasticizer loss over time on samples of cellulose acetate plasticized with diethyl phthalate in enclosed environment. The results could be applied into museum practice to adjust the dimensions of storage systems to inhibit plasticizer loss [129].

### **Conservation of plastics**

Plastics are still considered new materials and we have minimum experience with them compared to other materials found in collections. Conservators have been gaining experience and knowledge regarding the conservation of traditional materials like wood, stone, or oil paintings for several centuries, while the conservation of plastic artifacts has been a topic of recent decades. The development of contemporary art conservation started at the end of the 20th century and much of the attention was focused on the conservation of modern materials including plastics. So far, attention has been paid to the most endangered plastics, mainly malignant plastics such as cellulose nitrate [130, 131], cellulose acetate [132, 133], pPVC [134], and PUR foam [135-137].

According to the International Council of Museums – Committee for Conservation (ICOM-CC) conservation is defined as “all measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations. Conservation embraces preventive conservation, remedial conservation, and restoration. All measures and actions should respect the significance and the physical properties of the cultural heritage item” [138]. Shashoua distinguishes two types of approaches to conservation – active (interventive) and preventive (inhibitive). Active conservation includes direct treatment according to the specific needs of an artifact aimed at mitigating the consequences of degradation and limiting its further spread. It encompasses both remedial conservation and restoration [3]. This term encompasses both remedial conservation and restoration defined by ICOM-CC.

#### ***Inhibitive conservation***

Preventive conservation is defined by ICOM-CC as “all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item, but more often a group of items, whatever their age and condition. These measures and actions are indirect – they do not interfere with the materials and structures of the items. They do not modify their appearance” [138]. Preventive conservation can be more accurately called inhibitive, since the degradation of plastics, once started, cannot be stopped, or reversed, only slowed down (inhibited).

An effective conservation strategy for plastics is usually aimed at slowing the degradation by modulating the conditions in which the artifacts are stored and minimizing exposure to degradation factors. Many artifacts spend most of their time in storage rather than exhibition,

therefore providing stable environmental conditions is crucial for their preservation [139]. Regular monitoring plays a vital role, as the condition of plastics can change radically within a few months. In the case of malignant plastics, early detection of degradation manifestations is crucial not only for the degrading objects themselves but also for the objects in their vicinity. Canadian Conservation Institute offers a Preventive conservation guideline for collections, online resource. This guideline presents a control strategy for mixed collections containing malignant plastics consisting of five stages: removing harmful plastics; checking the undeteriorated plastics for acidic emissions, identifying potentially malignant plastics; coping with corrosive plastics; clean [50].

There are no internationally accepted guidelines regarding the environmental conditions. Most institutions apply general conditions suitable for inhibiting degradation rates, such as low temperature, low level of relative humidity, low oxygen levels and elimination of UV light. In most institutions, the following storage conditions are applied: stable relative humidity at around 50%, temperature of 18 - 20 °C, low light level with a maximum of 50-100 lux, and elimination of UV light [139]. A review by Liébana combined with an online survey points out the deficiency of emission control and the lack of protocols regarding plastics emitting gaseous pollutants [84]. Here it would be appropriate to mention that not only plastics artifacts pose a threat but also plastics used for storage and display may emit hazardous compounds endangering collection items [140-142].

Since the main degradation factors of different types of plastics are not the same, it is important to identify the specific causes of degradation before determining the best storage conditions for a specific artwork. For example, polyester resins are prone to hydrolytic degradation, therefore it would benefit from a lower relative humidity. Microclimates specifically proposed for the given type of plastics can be achieved through the employment of adsorbents, which regulate the conditions near the artifact [78]. The most used adsorbents are active charcoal, silica gels, zeolites, and oxygen scavengers. Active charcoal can remove nitrogen dioxide from the environment, which is produced during the degradation of CN. Zeolites can serve the same function and can also adsorb water and acetic acid, which might for inhibiting the degradation of CA. Silica gels, such as Art-Sorb, are generally used to reduce the relative humidity in the storage area or display cases. Oxygen scavengers, such as the commercial products Ageless or Atco, contain iron particles and bind oxygen by forming iron oxides. They are an alternative to sealing objects in an inert atmosphere, for example, a nitrogen atmosphere, they are suitable when storing objects made of PURs, pPVC, rubber, and other plastics susceptible to oxidation and photodegradation [78, 139]. Ageless has been successfully used to inhibit the rate of deterioration of rubber since the end of the 20th century [143]. Oxygen scavengers should be used together with bags with a low gas permeability, in which the objects would be stored [144].

Even though the use of adsorbents is quite a common practice, their use must be properly considered, since they can adsorb plasticizers and other additives instead of emitted degradation products, which is highly undesirable as it can lead to accelerated degradation. This might be the case with employing zeolites for the preservation of CA artifacts as they can adsorb more plasticizers than acetic acids leading to shrinkage and increased degradation rate [145]. Similar phenomena occurred while assessing the degradation of animation cells. Art-Sorb (silica gels) adsorbed primarily plasticizers, not acetic acid [8]. Studies show that CA artifacts benefit from enclosure and lower temperature, which inhibit plasticizer loss. Thickness of material and volume of enclosure affect the degradation rate of CA and can be useful when predicting plasticizer loss [146]. Experts in Deutsches Museum focused on the malignant cellulose nitrate artifacts and transferred them into a separate area with improved ventilation and lower temperature to extend their lifetime, however the physical stress and condensation phenomena connected with cold storage need to be considered [147].

The role of the storage environment and surface cleaning on the degradation of pPVC is quite significant and can greatly affect its useful lifetime. Both plasticizer loss and yellowing of

naturally aged pPVC occur at a slower rate when enclosure and cleaning are involved [148]. Storing PVC on an open shelf or enclosed in adsorbent materials promotes plasticizer loss and accelerates degradation, enclosing the objects in a glass container or storing them in a freezer therefore significantly slows the deterioration [149]. Wrapping pPVC in adsorbent materials such as LDPE or PET (polyester) can accelerate plasticizers loss, suitable alternative is wrapping pPVC objects in silk. Another alternative is wrapping pPVC objects in silk [150, 151] or enclosing them in chemically inert silicone coated PTFE commercially available as Mylar or silicone-release Mylar [152].

### ***Interventive conservation***

Interventive conservation represents interventions such as cleaning, disinfection, consolidation, reassembling objects, filling in the missing parts or retouching. Although many artifacts would benefit from treatments such as surface cleaning, these treatments are not as common as preventive ones. The great range of plastics found in collections also makes it difficult for conservators to share conservation techniques because of the specificity of each treatment and the need to assess each case individually. One of the main principles of cultural heritage conservation is the reversibility of any modification made, but some experts state that reversibility is not a priority when the chosen intervention is the only option to save the artwork [153].

Cleaning of plastics artifacts carries many risks. Many plastics are susceptible to organic solvents, aqueous solutions, and water itself and inappropriate intervention can do more harm than good. In the case of mechanical surface cleaning, the friction can generate heat which can lead to softening of plastics with lower glass transition temperatures such as pPVC or polyethylene [81]. Project POPART focused also on testing the effect of various cleaning methods on several types of plastics, namely CA, HDPE, high-impact polystyrene, expanded polystyrene and PMMA. The results show that mechanical cleaning carries a significant risk of surface damage. Amongst the methods of chemical cleaning, aqueous solutions are the safest choice, whereas acetone was proven unsuitable [154]. A study of dry-cleaning methods for pPVC has been undertaken using three commercial cloths recommended for plastics artifacts, as an alternative to cotton swabs traditionally used in art conservation [155]. In addition, a study focused on testing cleaning methods of pPVC objects indicates that it is possible to carry out safe cleaning of pPVC, both aged and unaged, using several types of solutions or commercial products [156].

Researchers and conservators at the Smithsonian American Art Museum recently focused their work on plastics and published several case studies concerning the conservation of artworks. Amongst the treated artworks was a sculpture made of cellulose acetate butyrate scratched and covered in a white haze, an assemblage of polymer coated license plate vandalized with a blue marker and black cast polyester resin sculpture with scratched surface and chipped edges. In the case of the last-mentioned artwork, the possibility of communication and consultation with the author of the artwork was a great benefit [157].

Lots of information regarding the conservation of PUR foam can be found in the book “PUR Facts” together with some case studies presenting specific methods of treatment [137]. Research in RCE continued with the aim of finding a consolidation method that would both inhibit the photooxidation and prolong the lifespan of PUR foam and it resulted in the conservation of artwork by Piero Gilardi [153]. The degradation of Gilardi’s work has been further studied, considering the interaction between polyurethane foam and the paint layer, which can negatively impact the stability of the object [158].

Artifacts made of unsaturated polyester resins or acrylic resins such as PMMA represent a big challenge for the conservators. These objects are often transparent and have a smooth and seamless surface which makes them more susceptible to surface damage (scratches, abrasion, chips, and cracks) [159]. Instead of invasive treatments of unsaturated polyester resins leading to the loss of original materials, new additive methods for the reduction of the visual impact of

surface damage have been successfully tested [160]. According to recent studies, there are also reliable methods for repairing damaged objects made of PMMA (filling the cracks, treating scratches and abrasion) using various types of synthetic resins and treating damage caused by heat (inappropriate storage conditions [161, 162]. More examples of case studies and information on the conservation of specific types of plastics can be found in a recently published book by Thea van Oosten which can be a great asset for conservators as it contains information regarding the properties of plastics which are crucial for their preservation [163].

Not all degrading artifacts can be saved, for example early works of Naum Gabo in the collection of Tate show signs of advanced stage of deterioration are expected to reach the end of their display lives in near future. In this case Tate is working on creating replicas to ensure the preservation of these artifacts in addition to research into long-term preservation of cellulose acetate and cellulose nitrate artifacts [164].

### The online survey in museum and galleries in Europe

In addition to the literature survey, we conducted an online survey in several memory institutions across Europe with aim to get a comprehensive picture of the situation regarding the current state of plastic conservation because even though more and more surveys are conducted, the results are often not available or are only partially published. We focused not only on the numbers and types of plastics present in collections but also on their degradation, used identification procedures and employed conservation treatments. A questionnaire was drawn up and sent out to museum, galleries, and archives around Europe. We received 12 answers, most of them from institutions focused on modern and contemporary art and design, which makes them ideal for this type of survey.

75% of respondents stated that they keep records of plastics in their collections, and they have an overview of the number of plastic artifacts. The number ranges from 1.5% (Slovak National Museum) to 25% (Deutsches Museum) of the overall number of collection items. All the surveys aimed at plastics conducted in the institutions were carried out relatively recently, at the earliest in 2019, which confirms our assumptions, that the interest of conservators in plastics is growing and the question of plastic conservation is a serious issue that more and more institutions have been dealing with.

When researching plastics, most institutions focus solely on 3D objects and do not consider synthetic polymer paints and coatings. The most widespread types of plastics include polyesters, PVC and then PUR foam, CA, and PE. Results regarding the presence of different types of plastics in the collections can be seen in figure 2.

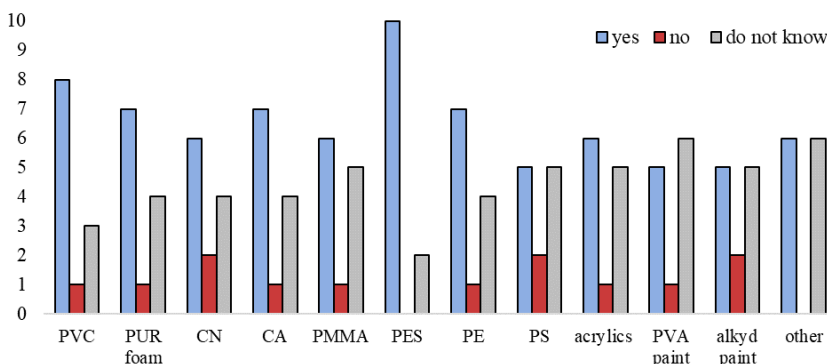


Fig. 2. The occurrence of different types of plastics in the collections of institutions involved in the survey

As for the percentage representation of plastics, in most collections the individual types are represented equally, PMMA and polyesters slightly predominate. Only 42% of respondents were able to comment on this issue, thus the relevance of these results is therefore questionable. Moreover, these are usually estimated numbers and not real results-based analytical identification of materials.

When identifying plastics, institutions rely mainly on visual assessment (92% of respondents) and obtaining information directly from the artist (75% of respondents). However, identification based on visual assessment is difficult and can lead to faulty conclusions, as there are many types of plastics, which are characterized by a wide range of optical properties, depending on the additives they contain. We also encountered several cases of incorrect material classification during the material survey carried out in Slovak institutions. Apart from the visual assessment, 58% of institutions use instrumental analytical techniques for the identification of plastics in their collections, namely FTIR spectroscopy and Py-GC/MS. Some institutions, for example, Slovak National Archive, use simple procedures that do not require the use of analytical instruments to identify materials. To distinguish between nitrocellulose, cellulose acetate, and polyester photographic mats, they use polarization tests, spot tests, flame tests, and reactions with diphenylamine. Several institutions are currently investigating the possibilities of non-destructive analysis and are looking for suitable methods for fast and reliable identification of plastics *in situ*. The survey results tell us, that institutions that employ instrumental analytical techniques have a better overview of different materials in their collections and can address the materials representation of plastics in more detail.

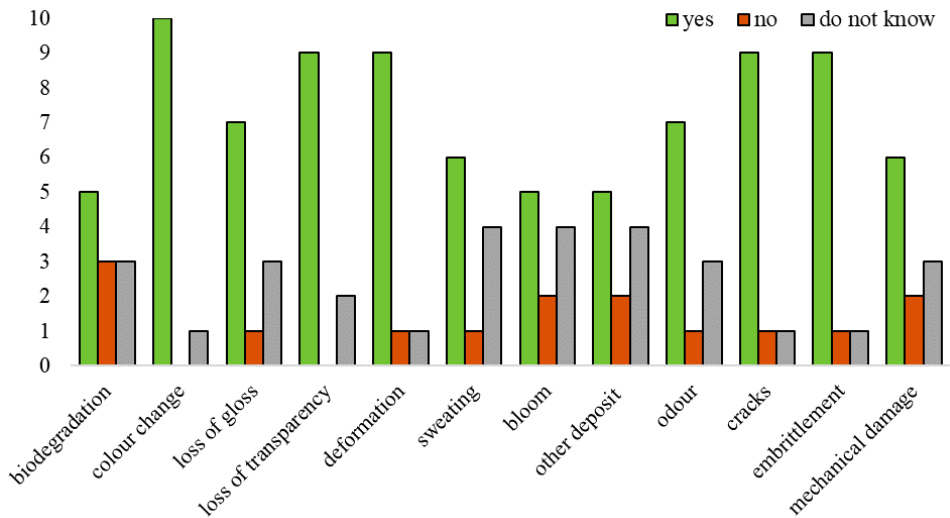
The results of the survey tell us that the degradation of plastic artifacts is a problem that institutions all over the world must face every day. More than 90% of participating institutions have experienced the degradation of plastics first-hand. Despite this high number, only 75% of them regularly monitor the state of their artifacts, therefore the degradation of plastics can often go unnoticed until the moment when irreversible losses of cultural heritage occur. In three museums – Design Museum Gent, Deutsches Museum and S.M.A.K Museum, the conservators have encountered all 12 types of plastic degradation mentioned in the questionnaire. The answers show that the most common manifestations of degradation are the easily observable and identifiable changes in optical properties change of colour, loss of transparency, and loss of gloss. Very common are also visible manifestations of changes in mechanical properties, such as breaks, deformation, embrittlement, and mechanical damage due to manipulation. More details are presented in figure 3.

Symptoms of degradation typical for synthetic polymers, like bloom and sweating, are not that common according to the answers. This may be related to the lack of experience with these phenomena and thus the inability of the responsible workers to correctly identify these symptoms.

75% of respondents commented on the condition of their plastics and 71% of them stated that more than 50% of their artifacts are in good condition without visible changes and need for conservation. Plastics in the fourth condition category, unacceptable condition, represent the smallest share of all the artifacts. In three institutions they do not occur at all and in the remaining three they make up 10% or less of all the artifacts. These numbers are lower than the numbers in the results of the POPART project, which raises the question of whether they reflect reality or are just the result of insufficient monitoring. The largest number of plastics in bad or unacceptable condition is in the Deutsches museum, which, based on our survey, has the largest number of plastics in its collections, as well as an excellent overview of their types and condition.

Application of passive or inhibitive treatments, mainly setting suitable storage conditions and display conditions, can significantly extend the induction period of degradation and thus lengthen the lifespan of the artifact. However, in the survey, only 42% of respondents stated that they have established special storage conditions for plastics. These conditions mostly include regulation of relative humidity, oxygen concentration, temperature or separate storage areas for plastics, packaging in special boxes or storage in inert atmospheres.





**Fig. 3.** The frequency of occurrence of different types of plastic degradation in collections institutions participating in the survey

The set conditions match those described in the literature. On the other hand, 58% of participating institutions use active conservation treatments when necessary. These include mostly mechanical cleaning and removal of dirt before exhibition. In addition to mechanical cleaning, some institutions also use solvent cleaning, but only to a small extent, since these procedures have not yet been sufficiently researched for the needs of conservation science. The smaller percentage of institutions employing inhibitive conservation may be related to the lack of space in depositories and the overall difficulty of implementing and executing these measures.

## Conclusions

The issue of conservation of plastic cultural heritage has been a topic since the end of the 20<sup>th</sup> century, however awareness of this issue is still not as widespread as it would be appropriate given its importance and urgency, which is evident both from our literature survey and online survey. Nowadays, plastics are probably present in collections of almost all museums and galleries around the world and their importance cannot be understated. In many cases, the information regarding the degradation and conservation of plastics is still insufficient to ensure their proper protection and conservation. The online survey helped us gain an overview of the situation regarding the conservation of plastics in European galleries and museums. Some institutions, namely Design Museum Gent, Guggenheim Bilbao Museum, Deutsches Museum, S.M.A.K. (Municipal Museum of Contemporary Art) and Museum of Modern Art in Warsaw are more devoted to this issue and have an excellent overview of plastics in their collections. These institutions are equipped with analytical devices designed for reliable identification of different types of plastics, which also enables the quantification of different plastics, and their personnel is qualified enough to identify specific degradation symptoms, such as bloom and sweating. However, we can see from the results, that many institutions still do not have the resources necessary to ensure the adequate protection of plastic artifacts, either because of a lack of qualified personnel or because of a general lack of information on this issue. In many cases, the information on the material composition of collections and the representation of individual types of plastics is missing, which makes it impossible to perform effective conservation. On the bright side, in recent years more and more attention has been paid to these endangered materials, which

is indicated by the increased number of material surveys carried out. The results, such as those regarding the prevailing types of plastics and implemented inhibitive conservation treatments, match our expectations, and confirm information from literature sources.

The research in the field of plastic conservation is progressing, but there are still many areas to explore. A great challenge is presented by mixed media (artifacts containing several different materials), where mutual interactions between the materials must be considered. Each artifact requires an individual approach, and each intervention should be backed up and preceded by detailed research. However, this is not possible in all institutions, so it is necessary to share their experience and relevant results with other experts in the field. Identification and characterization of plastics are crucial, as both the literature sources and our survey tell us a large part of plastics in collections are unidentified, which presents a problem when it comes to risk assessment, collection management and proposing conservation treatments. The focus should be put on correct classification and record keeping, which enables early identification of risks and detection of degradation signs. This is connected to the study of possibilities of non-invasive identification of materials and the creation of a standard analysis methodology that can be used in conservation practice. FTIR spectroscopy appears to be the most promising method for routine analysis, which is supported by the results of our survey. Moreover, it is crucial to disseminate gained knowledge and spread awareness and information regarding this issue. As a follow-up to the research, it is recommended to implement the education of museum and gallery experts (restorers, conservators, curators) to gain an overview of the possible risk associated with plastics in collections and can approach the preservation of plastics more effectively.

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### Abbreviations

CN	Cellulose nitrate	PMMA	Poly(methyl methacrylate)
CA	Cellulose acetate	PE	Polyethylene
CSF	Casein-formaldehyde	LDPE	Low density polyethylene
PF	Phenol formaldehyde	HDPE	High density polyethylene
MF	Melamine formaldehyde	PTFE	Polytetrafluoroethylene
UF	Urea-formaldehyde	PET	Poly(ethylene terephthalate)
PVC	Poly(vinyl chloride)	PA	Polyamide
pPVC	Plasticized poly(vinyl chloride)	PUR	Polyurethane
PS	Polystyrene	K-K	Kramers-Krönig

### References

- [1] A.D. Jenkins, R.F.T. Stepto, P. Kratochvíl, U.W. Suter, *Glossary of basic terms in polymer science (IUPAC Recommendations 1996)*, **Pure and Applied Chemistry**, **68**, 1996, pp. 2287-2311. <https://doi.org/10.1351/PAC199668122287>.
- [2] \* \* \*, **The Plastics Historical Society** – Celebrating all things plastic, (n.d.). <http://plasticquarian.com/>.
- [3] Y. Shashoua, **Conservation of Plastics**, 1<sup>st</sup> Edition, 2008.

- [4] S.C. Rasmussen, *Revisiting the early history of synthetic polymers: Critiques and new insights*, **Ambix**, **65**, 2018, pp. 356-372. <https://doi.org/10.1080/00026980.2018.1512775>.
- [5] O. Madden, *Balancing Ingenuity and Responsibility in the Age of Plastic*, in: **The Age of Plastic: Ingenuity and Responsibility** (Editors: O. Madden, A.E. Charola, K.C. Cobb, P.T. DePriest, R.J. Koestler), Smithsonian Institution Scholarly Press, Washington D.C., 2017. <https://doi.org/doi:10.5479/si.19492367.7>.
- [6] K. McCormick, M. Schilling, *Animation Cells, Preserving a Portion of Cinematic History, Conservation Perspectives*, **The GCI Newsletter**, **29**, 2014.
- [7] D. Feldman, *Polymer history*, **Des Monomers Polym.**, **11**, 2008, pp. 1-15. <https://doi.org/10.1163/156855508X292383>.
- [8] K. McCormick, M.R. Schilling, M.T. Giachet, J. Mazurek, H. Khanjian, T. Learner, *Animation Cells: Conservation and Storage Issues*, **Source: Objects Specialty Group Postprints**, **21**, 2014, pp. 251-261.
- [9] B. Keneghan, *A survey of synthetic plastic and rubber objects in the collections of the Victoria and Albert museum*, **Museum Management and Curatorship**, **19**, 2001, pp. 321-331. [https://doi.org/10.1016/S0260-4779\(01\)00054-1](https://doi.org/10.1016/S0260-4779(01)00054-1).
- [10] S. Mossman, *Science Museum in London features plastics*, **MRS Bulletin**, **36**(8), 2011, pp. 586-588. <https://doi.org/10.1557/MRS.2011.201>.
- [11] C. Chu, P. Nel, **Plastics in Australian Archives: An Industry Survey Regarding Prevalence, Condition, and Preservation Strategies**, **68**(2), 2023, pp. 136-150. <https://doi.org/10.1080/00393630.2021.1996093>.
- [12] B. Habalová, Z. Maděričová, A. Maková, **Spracovanie a ochrana negatívnych fotografických materiálov**, **Slovenský národný archív**, Bratislava, 2016.
- [13] \* \* \*, **Readymade | MoMA**, (n.d.). <https://www.moma.org/collection/terms/readymade> [accessed February 20, 2023].
- [14] M. Lazzari, D. Reggio, *What fate for plastics in artworks? An overview of their identification and degradative behaviour*, **Polymers**, **13**(6), 2021, Article Number: 886. <https://doi.org/10.3390/polym13060883>.
- [15] R. Mustalish, **Modern Materials: Plastics**, Heilbrunn Timeline of Art History, 2004. [https://www.metmuseum.org/toah/hd/mome/hd\\_mome.htm](https://www.metmuseum.org/toah/hd/mome/hd_mome.htm) [accessed December 7, 2021].
- [16] M. Strlič, K. Curran, *Special issue "polymers in Art and History" - Editorial*, **Polymer Degradation and Stability**, **107**, 2014, pp. 189-190. <https://doi.org/10.1016/j.polymdegradstab.2014.07.001>.
- [17] F. Waentig, **Plastics in Art: A Study from the Conservation Point of View**, Michael Imhof Verlag, Petersbrg, 2008.
- [18] B. Keneghan, *Plastics? Not in My Collection*, **Conservation Journal**, **21**, 1996. <http://www.vam.ac.uk/content/journals/conservation-journal/issue-21/plastics-not-in-my-collection/>
- [19] J. Mundy, **Lost Art: Naum Gabo – Essay**, Tate, 2020. <https://www.tate.org.uk/art/artists/naum-gabo-1137/lost-art-naum-gabo> [accessed February 8, 2021].
- [20] D.W. Grattan (editor), *Saving the Twentieth Century: The Conservation of Modern Materials*, **Symposium '91: Saving the Twentieth Century**, Canadian Conservation Institute, Ottawa, 1991.
- [21] E. Then, V. Oakley, *A survey of plastic objects at The Victoria & Albert Museum*, **Conservation Journal**, **6**, 1993. <http://www.vam.ac.uk/content/journals/conservation-journal/issue-06/a-survey-of-plastic-objects-at-the-victoria-and-albert-museum/>.

- [22] S. Mossman, *Plastics in the Science Museum, London: A curator's view*, **Postprints of Saving the Twentieth Century: The Conservation of Modern Materials Ottawa** (Editor: D. Grattan), Canadian Conservation Institute, 1993, pp. 25-35.
- [23] J. Morgan, *Survey of Plastics in Historical Collections*, 1994. <http://web.archive.org/web/20061015204042/http://www.plastiquarian.com/survey/survey.htm>.
- [24] \* \* \*, **Preservation Of Plastic ARTEfacts in Museum Collections**, Popart, (n.d.). <http://popart-highlights.mnhn.fr/index.html>.
- [25] M. Bacci, C. Cucci, T. van Oosten, Y. Shashoua, J. Rychlý, *Surveying plastic artefacts collections in museums*, **POPART - Preservation of Plastic ARTEfacts in Museum Collections**. 2012. <https://popart-highlights.mnhn.fr/>.
- [26] N. Balcar, A. Lattuati-Derieux, A. Vila, *Analysis of degradation products found during surveys of three French collections*, **POPART - Preservation of Plastic ARTEfacts in Museum Collections**, 2012, pp. 302-308. <https://popart-highlights.mnhn.fr/>.
- [27] G. Barabant, *Degradation associated with some plastics found during surveys of three French collections*, **POPART - Preservation of Plastic ARTEfacts in Museum Collections**, 2012. <https://popart-highlights.mnhn.fr/>.
- [28] B. Keneghan, T. van Oosten, A. Laganà, M. Wagenaar, G. Barabant, N. Balcar, H. Bluzat, C. Bollard, J. Fayein, S. Kuperholc, S. Ramel, A. Lattuati-Derieux, *In what condition are my artefacts? Case studies*, **POPART - Preservation of Plastic ARTEfacts in Museum Collections**, 2012, pp. 109-137. <https://popart-highlights.mnhn.fr/>.
- [29] G. Rayner, S. D. Costello, A. Chang, E. la Duc, *Understanding Plastics In Our Collection: A Survey At The Harvard Art Museums*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, Virtual conference, November 16<sup>th</sup>–19<sup>th</sup> 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 14, 2023].
- [30] H. Hendrickx, E. van der Velde, G. Kockelkoren, W. Fremout, *SAVE THE PLASTICS! Identification and Condition Survey in Belgian Museums*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, Virtual conference, November 16<sup>th</sup>–19<sup>th</sup> 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 14, 2023].
- [31] J. Bell, K.M. Thompson, K. Palmer, G. McCarthy, M. Barrett, E. Burrows, P. Nel, *Collaborative Development of Polymer-Based Collection Survey Methodology and Relational Data Model*, **Studies in Conservation**, **67**, 2022, pp. 10-22. <https://doi.org/10.1080/00393630.2022.2049034>.
- [32] P. Urbanová, K. Vizárová, S. Klempová, K. Čížová, R. Tiňo, **Syntetické Polymérne Materiály V Zbierkach Kultúrneho Dedičstva**, 2022. [https://educell.sk/wp-content/uploads/2022/03/Resers\\_SYNETICKE-POLYMERNE-MATERIALY-V-ZBIERKACH-KULTURNEHO-DEDICSTVA-.pdf](https://educell.sk/wp-content/uploads/2022/03/Resers_SYNETICKE-POLYMERNE-MATERIALY-V-ZBIERKACH-KULTURNEHO-DEDICSTVA-.pdf).
- [33] \* \* \*. **Centrálny katalóg diel/SNG**, (n.d.). <https://www.sng.sk/sk/zbierky/centralny-katalog-diel#> [accessed May 4, 2021].
- [34] P. Urbanová, **Materiálový prieskum novodobých zbierok výtvarného umenia zameraný na syntetické polymérne materiály**, 2021.
- [35] S. Babo, J.L. Ferreira, *A survey of acrylic sheet in Portuguese art collections*, **Conservar Património**, **39**, 2022, pp. 61-70. <https://doi.org/10.14568/ep2020075>.

- [36] B. Keneghan, *Plastics preservation at the V&A*, **Conservation Journal**, **50**, 2005. <http://www.vam.ac.uk/content/journals/conservation-journal/issue-50/plastics-preservation-at-the-v-and-a/>.
- [37] \* \* \*, **List of Degradation Terms**, (n.d.). [https://popart-highlights.mnhn.fr/wp-content/uploads/3\\_Collection\\_survey/1\\_What\\_is\\_the\\_condition\\_of\\_the\\_collection/List\\_of\\_terms.pdf](https://popart-highlights.mnhn.fr/wp-content/uploads/3_Collection_survey/1_What_is_the_condition_of_the_collection/List_of_terms.pdf) [accessed September 27, 2022].
- [38] G. Martin, B. Lavédrine, A. Fournier, *Atlas of case studies presenting typical damages*, **POPART - Preservation of Plastic ARTefacts in Museum Collections**, 2012, pp. 1-22.
- [39] T. Krieg, C. Mazzon, E. Gómez-Sánchez, *Material analysis and a visual guide of degradation phenomena in historical synthetic polymers as tools to follow ageing processes in industrial heritage collections*, **Polymers**, **14**(1), Article Number: 121, 2022. <https://doi.org/10.3390/polym14010121>.
- [40] D. Atek, N. Belhaneche-Bensemra, *FTIR investigation of the specific migration of additives from rigid poly(vinyl chloride)*, **European Polymer Journal**, **41**(4), 2005, pp. 707-714. <https://doi.org/10.1016/J.EURPOLYMJ.2004.10.043>.
- [41] T.R. Newman, **Plastics as an Art Form**, Chilton Book, Radnor, 1969.
- [42] A. Werner, *Synthetic materials in art conservation*, **Journal of Chemical Education**, **58**(4), 1981, pp. 321-324. <https://doi.org/10.1021/ED058P321>.
- [43] C.V. Horie, **Materials for Conservation: Organic Consolidants, AdhesiveC and coatings**, 1987, p. 281.
- [44] S.H. Hamid, **Handbook of Polymer Degradation**, CRC Press, 2000. <https://doi.org/10.1201/9781482270181/HANDBOOK-POLYMER-DEGRADATION-HALIM-HAMID>.
- [45] M. Hazlinger, R. Moravčík, E. Čaplovič, **Degradačné procesy a predikcia životnosti materiálov**, Slovenská Technická Univerzita, 2010.
- [46] E. Martuscelli, **The Chemistry of Degradation and Conservation of Plastic Artefacts of Pre-Synthetic “Era” Based on Natural or Artificial Polymers**, Edizioni Paideia Firenze, Firenze, 2010.
- [47] N.S. Allen, M. Edge, **Fundamentals of Polymer Degradation and Stabilisation**, Elsevier, 1992.
- [48] G. Pastorelli, C. Cucci, O. Garcia, G. Piantanida, A. Elnaggar, M. Cassar, M. Strlič, *Environmentally induced colour change during natural degradation of selected polymers*, **Polymer Degradation and Stability**, **107**, 2014, pp. 198-209. <https://doi.org/10.1016/j.polymdegradstab.2013.11.007>.
- [49] W.L. Hawkins, *Polymer Degradation*, **Polymers Proprieties and Applications**, **8**, 1984, Springer, pp. 3-34. [https://doi.org/10.1007/978-3-642-69376-2\\_2](https://doi.org/10.1007/978-3-642-69376-2_2).
- [50] J. Fenn, R.S. Williams, *Caring for plastics and rubbers*, **Preventive Conservation Guidelines for Collections** (n.d.). <https://www.canada.ca/en/conservation-institute/services/preventive-conservation/guidelines-collections/caring-plastics-rubbers.html#a1> [accessed March 12, 2021].
- [51] F. Cappitelli, F. Villa, P. Sanmartín, *Interactions of microorganisms and synthetic polymers in cultural heritage conservation*, **International Biodeterioration & Biodegradation**, **163**, 2021, Article Number: 105282. <https://doi.org/10.1016/j.ibiod.2021.105282>.
- [52] C.N. Zmeu, P. Bosch-Roig, *Risk analysis of biodeterioration in contemporary art collections: the poly-material challenge*, **Journal of Cultural Heritage**, **58**, 2022, pp. 33-48. <https://doi.org/10.1016/J.CULHER.2022.09.014>.

- [53] F. Cappitelli, E. Zanardini, C. Sorlini, *The biodeterioration of synthetic resins used in conservation*, **Macromolecular Bioscience**, **4**(4), 2004, pp. 399-406, <https://doi.org/10.1002/mabi.200300055>.
- [54] I. Gomoiu, R. Cojoc, R. Ruginescu, S. Neagu, M. Enache, M. Dumbrăvician, I. Olteanu, R. Rădvan, L. Ghervase, *The Susceptibility to Biodegradation of Some Consolidants Used in the Restoration of Mural Paintings*, **Applied Sciences**, **12**(14), 2022, Article Number: 7229. <https://doi.org/10.3390/app12147229>.
- [55] D. Danko, G. Babu, M. Mohan, M. Rucker, N. Singh, A. Regberg, M.S. Bell, K. Venkateswaran, *Characterization of Spacesuit Associated Microbial Communities and Their Implications for NASA Missions*, 2020, preprint: <https://doi.org/10.21203/RS.3.RS-70768/V1>.
- [56] M. Breuker, C. Mcnamara, L. Young, T. Perry, A. Young, R. Mitchell, *Fungal growth on synthetic cloth from Apollo spacesuits*, **Annals of Microbiology**, **53**(1), 2003, pp. 47-54.
- [57] D. Pangallo, M. Bučková, L. Kraková, A. Puškárová, N. Šáková, T. Grivalský, K. Chovanová, M. Zemánková, *Biodeterioration of epoxy resin: A microbial survey through culture-independent and culture-dependent approaches*, **Environmental Microbiology**, **17**(2), 2015, pp. 462-479. <https://doi.org/10.1111/1462-2920.12523>.
- [58] F. Cappitelli, P. Principi, C. Sorlini, *Biodeterioration of modern materials in contemporary collections: can biotechnology help?*, **Trends Biotechnology**, **24**(8), 2006, pp. 350-354. <https://doi.org/10.1016/j.tibtech.2006.06.001>.
- [59] J. Szostak-Kotowa, *Biodeterioration of textiles*, **International Biodeterioration & Biodegradation**, **53**(3), 2004, pp. 165-170. [https://doi.org/10.1016/S0964-8305\(03\)00090-8](https://doi.org/10.1016/S0964-8305(03)00090-8).
- [60] J.G. Speight, *Monomers, polymers, and plastics*, **Handbook of Industrial Hydrocarbon Processes** (Editor: J.G. Speight), Second Edition, 2020, pp. 597-649. <https://doi.org/10.1016/B978-0-12-809923-0.00014-X>.
- [61] T. Liptáková, P. Alexy, E. Gondár, V. Khunová, I. Hudec, I. Ivan, **Polymérne konštrukčné materiály**, 2012, p. 189.
- [62] X. Colin, G. Teyssedre, M. Fois, *Ageing and Degradation of Multiphase Polymer Systems*, **Handbook of Multiphase Polymer Systems** (Editors: A. Boudenne, L. Ibos, Y. Candau, S. Thomas), 2011, pp. 797-841. <https://doi.org/10.1002/9781119972020.ch21>.
- [63] A. Göpferich, *Mechanisms of polymer degradation and erosion*, **Biomaterials**, **17**(2), 1996, pp. 103-114. [https://doi.org/10.1016/0142-9612\(96\)85755-3](https://doi.org/10.1016/0142-9612(96)85755-3).
- [64] B. Fayolle, X. Colin, L. Audouin, J. Verdu, *Mechanism of degradation induced embrittlement in polyethylene*, **Polymer Degradation and Stability**, **92**(2), 2007, pp. 231-238. <https://doi.org/10.1016/J.POLYMDEGRADSTAB.2006.11.012>.
- [65] H. Bhuvaneshwari, G. *Degradability of Polymers*, **Recycling of Polyurethane Foams** (Editors: S. Thomas, A.V. Rane, K. Kanny, V.K. Abitha, M.G. Thomas), 2018, pp. 29-44. <https://doi.org/10.1016/B978-0-323-51133-9.00003-6>.
- [66] F. Xie, T. Zhang, P. Bryant, V. Kurusingal, J.M. Colwell, B. Laycock, *Degradation and stabilization of polyurethane elastomers*, **Progress in Polymer Science**, **90**, 2019, pp. 211-268. <https://doi.org/10.1016/j.progpolymsci.2018.12.003>.
- [67] S. França de Sá, J.L. Ferreira, I. Pombo Cardoso, R. Macedo, A.M. Ramos, *Shedding new light on polyurethane degradation: Assessing foams condition in design objects*, **Polymer Degradation and Stability**, **144**, 2017, pp. 354-365. <https://doi.org/10.1016/j.polymdegradstab.2017.08.028>.

- [68] K. Pielichowski, J. Njuguna, **Thermal Degradation of Polymeric Materials**, iSmithers Rapra Publishing, 2005.
- [69] \* \* \*. **Plastic Additives Initiative** - ECHA, (n.d.). <https://echa.europa.eu/plastic-additives-initiative> [accessed October 10, 2022].
- [70] J.C.J. Bart, **Additives in Polymers: Industrial Analysis and Applications**, John Wiley & Sons, Ltd, 2005, <https://doi.org/10.1002/0470012064>.
- [71] J.N. Hahladakis, C.A. Velis, R. Weber, E. Iacovidou, P. Purnell, *An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling*, **Journal of Hazardous Materials**, **344**, 2018, pp. 179-199. <https://doi.org/10.1016/j.jhazmat.2017.10.014>.
- [72] J. Bošnjir, D. Puntarić, A. Galić, I. Škes, T. Dijanić, M. Klarić, M. Grgić, M. Čurković, Z. Šmit, *Migration of Phthalates from Plastic Containers into Soft Drinks and Mineral Water*, **Food Technol Biotechnology**, **45**(1), 2007, pp. 91-95.
- [73] J. Yang, W. Song, X. Wang, Y. Li, J. Sun, W. Gong, C. Sun, *Migration of phthalates from plastic packages to convenience foods and its cumulative health risk assessments*, **Food Additives & Contaminants: Part B**, **12**(3), 2019, pp. 151-158. <https://doi.org/10.1080/19393210.2019.1574909>.
- [74] E. Fasano, F. Bono-Blay, T. Cirillo, P. Montuori, S. Lacorte, *Migration of phthalates, alkylphenols, bisphenol A and di(2-ethylhexyl)adipate from food packaging*, **Food Control**, **27**(1), 2012, pp. 132-138. <https://doi.org/10.1016/J.FOODCONT.2012.03.005>.
- [75] R. King, J. Grau-Bové, K. Curran, *Plasticiser loss in heritage collections: its prevalence, cause, effect, and methods for analysis*, **Heritage Science**, **8**, 2020, Article Number: 123. <https://doi.org/10.1186/s40494-020-00466-0>.
- [76] H.G.M. Edwards, A.F. Johnson, I.R. Lewis, P. Turner, *Raman spectroscopic studies of "Pedigree Doll disease"*, **Polymer Degradation and Stability**, **41**(3), 1993, pp. 257-264. [https://doi.org/10.1016/0141-3910\(93\)90072-Q](https://doi.org/10.1016/0141-3910(93)90072-Q).
- [77] R.S. Williams, **Care of Plastics: Malignant plastics**, 2002.
- [78] Y. Shashoua, *Inhibiting the inevitable; current approaches to slowing the deterioration of plastics*, **Macromolecular Symposia**, **238**(1), 2006, pp. 67-77. <https://doi.org/10.1002/masy.200650610>.
- [79] E. Rankin, *A Betrayal of Material: Problems of Conservation in the Constructivist Sculpture of Naum Gabo and Antoine Pevsner*, **Leonardo**, **21**(3), 1988, pp. 285-290. <https://doi.org/10.2307/1578657>.
- [80] J. Kammer, F. Truong, C. Boissard, A.L. Soulié, A.L. Dupont, L. Simon, V. Gros, B. Lavédrine, *Quantitative and qualitative assessment of VOCs emitted from cellulose acetate movie films by PTR-ToF-MS*, **Journal of Cultural Heritage**, **47**, 2021, pp. 50-58. <https://doi.org/10.1016/J.CULHER.2020.09.004>.
- [81] Y. Shashoua, **Inhibiting the deterioration of plasticized poly(vinyl chloride)**, 2001.
- [82] N. v. Gama, A. Ferreira, A. Barros-Timmons, *Polyurethane Foams: Past, Present, and Future*, **Materials**, **11**(10), 2018, Article Number: 1841. <https://doi.org/10.3390/MA11101841>.
- [83] K. Curran, A. Možir, M. Underhill, L.T. Gibson, T. Fearn, M. Strlič, *Cross-infection effect of polymers of historic and heritage significance on the degradation of a cellulose reference test material*, **Polymer Degradation and Stability**, **107**, 2014, pp. 294-306. <https://doi.org/10.1016/j.polymdegradstab.2013.12.019>.

- [84] S. Liébana Molina, *Current guidelines review for the preservation of plastics emitters of gaseous pollutants in Contemporary Art museums*, **Ge-Conservacion**, **11**, 2017. <https://doi.org/10.37558/gec.v11i0.507>.
- [85] X. Liu, R. Yang, *Cross-infection in thermo-oxidation of polymers*, **Polymer Degradation and Stability**, **161**, 2019, pp. 7-12. <https://doi.org/10.1016/j.polyimdegradstab.2019.01.009>.
- [86] \* \* \*, **The Complete Guide for Identifying and Testing Plastic Resins**, (n.d.). <https://www.plasticsgroup.com/wp-content/themes/deeplevel/assets/docs/resinkit.pdf> [accessed February 7, 2023].
- [87] A. Laganà, B. Keneghan, *Which plastics are in my collection? The need for a plastic reference sample collection (SamCo)*, **POPART - Preservation of Plastic ARTefacts in Museum Collections**, 2012. <https://popart-highlights.mnhn.fr/>.
- [88] \* \* \*, **Plastic Identificatie Tool** | Rijksdienst Cultureel Erfgoed, (n.d.). <https://plastic-en.tool.cultureelerfgoed.nl/> [accessed February 7, 2023].
- [89] C. van Aubel, O. van Rooijen, S. de Groot, H. van Keulen, L. Beerkens, *Plastification: The Plastic Identification Tool and workshop that helps to identify plastics in your collection*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 15, 2023].
- [90] A. Pereira, A.T. Caldeira, B. Maduro, P. Vandenabeele, A. Candeias, *Tortoiseshell or polymer? Spectroscopic analysis to redefine a purported tortoiseshell box with gold decorations as a plastic box with brass*, **Applied Spectroscopy**, **70**(1), 2016, pp. 68-75. <https://doi.org/10.1177/0003702815615344>.
- [91] M.R. Derrick, D. Stulik, J.M. Landry, **Infrared Spectroscopy in Conservation Science, Scientific Tools for Conservation**, 1999.
- [92] S. Prati, G. Sciutto, I. Bonacini, R. Mazzeo, *New Frontiers in Application of FTIR Microscopy for Characterization of Cultural Heritage Materials*, **Analytical Chemistry for Cultural Heritage** (Editor: R. Mazzeo), Springer International Publishing, 2016. <https://doi.org/10.1007/978-3-319-52804-5>.
- [93] S. Prati, E. Joseph, G. Sciutto, R. Mazzeo, *New Advances in the Application of FTIR Microscopy and Spectroscopy for the Characterization of Artistic Materials*, **Account Chemical Research**, **43**(6), 2010, pp. 792-801. <https://doi.org/10.1021/ar900274f>.
- [94] F. Rosi, L. Cartechini, D. Sali, C. Miliani, *Recent trends in the application of fourier transform infrared (FT-IR) spectroscopy in Heritage Science: From micro: From non-invasive FT-IR*, **Physical Sciences Reviews**, **4**(11), 2019, Article Number: 20180006. <https://doi.org/10.1515/psr-2018-0006>.
- [95] G.L. Liu, S.G. Kazarian, *Recent advances and applications to cultural heritage using ATR-FTIR spectroscopy and ATR-FTIR spectroscopic imaging*, **Analyst**, **147**, 2022, Article Number: 1777. <https://doi.org/10.1039/d2an00005a>.
- [96] C. Cucci, M. Bacci, J. Kolar, D. Koleša, *Chemical composition/structural characterisation using spectroscopic techniques*, **POPART - Preservation of Plastic ARTefacts in Museum Collections**, n.d. <https://popart-highlights.mnhn.fr/>.
- [97] G. Mitchell, F. France, A. Nordon, P.L. Tang, L.T. Gibson, *Assessment of historical polymers using attenuated total reflectance-Fourier transform infra-red spectroscopy with principal component analysis*, **Heritage Science**, **1**, 2013, Article Number: 28. <https://doi.org/10.1186/2050-7445-1-28>.



- [98] J. Bell, P. Nel, B. Stuart, *Non-invasive identification of polymers in cultural heritage collections: evaluation, optimisation and application of portable FTIR (ATR and external reflectance) spectroscopy to three-dimensional polymer-based objects*, **Heritage Science**, **7**, 2019, Article Number: 95. <https://doi.org/10.1186/S40494-019-0336-0/TABLES/7>.
- [99] M. Picollo, G. Bartolozzi, C. Cucci, M. Galeotti, V. Marchiafava, B. Pizzo, *Comparative study of fourier transform infrared spectroscopy in transmission, attenuated total reflection, and total reflection modes for the analysis of plastics in the cultural heritage field*, **Applied Spectroscopy**, **68**(4), 2014, pp. 389-397. <https://doi.org/10.1366/13-07199>.
- [100] E.M. Angelin, S.F. de Sá, I. Soares, M.E. Callapez, J.L. Ferreira, M.J. Melo, M. Bacci, M. Picollo, *Application of Infrared Reflectance Spectroscopy on Plastics in Cultural Heritage Collections: A Comparative Assessment of Two Portable Mid-Fourier Transform Infrared Reflection Devices*, **Applied Spectroscopy**, **75**(7), 2021, pp. 818-833. <https://doi.org/10.1177/0003702821998777>.
- [101] C. Cucci, G. Bartolozzi, V. Marchiafava, M. Picollo, E. Richardson, *Study of semi-synthetic plastic objects of historic interest using non-invasive total reflectance FT-IR*, **Microchemical Journal**, **124**, 2016, pp. 889-897. <https://doi.org/10.1016/j.microc.2015.06.010>.
- [102] D. Saviello, L. Toniolo, S. Goidanich, F. Casadio, *Non-invasive identification of plastic materials in museum collections with portable FTIR reflectance spectroscopy: Reference database and practical applications*, **Microchemical Journal**, **124**, 2016, pp. 868-877. <https://doi.org/10.1016/j.microc.2015.07.016>.
- [103] M. Manfredi, E. Barberis, E. Marengo, *Prediction and classification of the degradation state of plastic materials used in modern and contemporary art*, **Applied Physics A**, **123**, 2017, Article Number: 35. <https://doi.org/10.1007/s00339-016-0663-x>.
- [104] F. Casadio, C. Daher, L. Bellot-Gurlet, *Raman Spectroscopy of cultural heritage Materials: Overview of Applications and New Frontiers in Instrumentation, Sampling Modalities, and Data Processing*, **Topics in Current Chemistry**, **374**, 2016, Article Number: 62. <https://doi.org/10.1007/s41061-016-0061-z>.
- [105] D. Bersani, C. Conti, P. Matousek, F. Pozzi, P. Vandenabeele, *Methodological evolutions of Raman spectroscopy in art and archaeology*, **Analytical Methods**, **48**, 2016, pp. 8395-8409. <https://doi.org/10.1039/c6ay02327d>.
- [106] M. Gómez, D. Reggio, M. Lazzari, *Detection of degradation markers from polymer surfaces by a novel SERS-based strategy*, **Talanta**, **191**, 2019, pp. 156-161. <https://doi.org/10.1016/J.TALANTA.2018.08.046>.
- [107] F. Pozzi, E. Basso, A. Rizzo, A. Cesaratto, T.J. Tague, *Evaluation and optimization of the potential of a handheld Raman spectrometer: in situ, noninvasive materials characterization in artworks*, **Journal of Raman Spectroscopy**, **50**(6), 2019, pp. 861-872. <https://doi.org/10.1002/jrs.5585>.
- [108] P. Colomban, *On-site Raman study of artwork: Procedure and illustrative examples*, **Journal of Raman Spectroscopy**, **49**(6), 2018, pp. 921-934. <https://doi.org/10.1002/JRS.5311>.
- [109] D. Mancini, A. Percot, L. Bellot-Gurlet, P. Colomban, P. Carnazza, *On-site contactless surface analysis of modern paintings from Galleria Nazionale (Rome) by reflectance FTIR and Raman spectroscopies*, **Talanta**, **227**, 2021, Article Number: 122159. <https://doi.org/10.1016/j.talanta.2021.122159>.
- [110] P. Arjonilla, M.J. Ayora-Cañada, R. Rubio Domene, E. Correa Gómez, M.J. de la Torre-López, A. Domínguez-Vidal, *Romantic restorations in the Alhambra monument:*

- Spectroscopic characterization of decorative plasterwork in the Royal Baths of Comares*, **Journal of Raman Spectroscopy**, **50**(2), 2019, pp. 184-192. <https://doi.org/10.1002/jrs.5422>.
- [111] E.M. Angelin, S. Babo, J.L. Ferreira, M.J. Melo, *Raman microscopy for the identification of pearlescent pigments in acrylic works of art*, **Journal of Raman Spectroscopy**, **50**(2), 2019, pp. 232-241. <https://doi.org/10.1002/jrs.5431>.
- [112] A.R. David, H.G.M. Edwards, D.W. Farwell, D.L.A. de Faria, *Raman spectroscopic analysis of ancient Egyptian pigments*, **Archaeometry**, **43**(4), 2001, pp. 461-473. <https://doi.org/10.1111/1475-4754.00029>.
- [113] L. Burgio, R.J.H. Clark, *Library of FT-Raman spectra of pigments, minerals, pigment media and varnishes, and supplement to existing library of Raman spectra of pigments with visible excitation*, **Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy**, **57**(7), 2001, pp. 1491-1521. [https://doi.org/10.1016/S1386-1425\(00\)00495-9](https://doi.org/10.1016/S1386-1425(00)00495-9).
- [114] V. Košarová, Z. Čermáková, **Přenosné Přístroje Pro Infračervenou a Ramanovu spektroskopii: metodika pro jejich použití v neinvazivním průzkumu malířských děl in situ**, Akademie Výtvarných Umění v Praze Laboratoř ALMA, 2015.
- [115] V. Kohútová, **Studium malířských výtvarných děl infračervenou a Ramanovou spektroskopií, dizertačná práce**, Přírodovědecká fakulta, Masarykova univerzita, 2016.
- [116] D. Bersani, P.P. Lottici, *Raman spectroscopy of minerals and mineral pigments in archaeometry*, **Journal of Raman Spectroscopy**, **47**(5), 2016, pp. 499-530. <https://doi.org/10.1002/JRS.4914>.
- [117] G. Marucci, A. Beeby, A.W. Parker, C.E. Nicholson, *Raman spectroscopic library of medieval pigments collected with five different wavelengths for investigation of illuminated manuscripts*, **Analytical Methods**, **10**, 2018, pp. 1219-1236. <https://doi.org/10.1039/c8ay00016f>.
- [118] A. Klisińska-Kopacz, B. Łydźba-Kopczyńska, M. Czarnecka, T. Koźlecki, J. del Hoyo Mélendez, A. Mendys, A. Kłosowska-Klechowska, M. Obarzanowski, P. Frączek, *Raman spectroscopy as a powerful technique for the identification of polymers used in cast sculptures from museum collections*, **Journal of Raman Spectroscopy**, **50**(2), 2019, pp. 213-221. <https://doi.org/10.1002/jrs.5407>.
- [119] A. Neves, E.M. Angelin, É. Roldão, M.J. Melo, *New insights into the degradation mechanism of cellulose nitrate in cinematographic films by Raman microscopy*, **Journal of Raman Spectroscopy**, **50**(2), 2019, pp. 202-212. <https://doi.org/10.1002/jrs.5464>.
- [120] J. la Nasa, G. Biale, F. Sabatini, I. Degano, M.P. Colombini, F. Modugno, *Synthetic materials in art: a new comprehensive approach for the characterization of multi-material artworks by analytical pyrolysis*, **Heritage Science**, **7**, 2019, Article Number: 8. <https://doi.org/10.1186/s40494-019-0251-4>.
- [121] J. la Nasa, G. Biale, B. Ferriani, M.P. Colombini, F. Modugno, *A pyrolysis approach for characterizing and assessing degradation of polyurethane foam in cultural heritage objects*, **Journal of Analytical and Applied Pyrolysis**, **134**, 2018, pp. 562-572. <https://doi.org/10.1016/j.jaap.2018.08.004>.
- [122] J. la Nasa, G. Biale, B. Ferriani, R. Trevisan, M.P. Colombini, F. Modugno, *Plastics in heritage science: Analytical pyrolysis techniques applied to objects of design*, **Molecules**, **25**(7), 2020, Article Number: 1705. <https://doi.org/10.3390/molecules25071705>.
- [123] A. Lattuati-Derieux, C. Egasse, S. Thao-Heu, N. Balcar, G. Barabant, B. Lavédrine, *What do plastics emit? HS-SPME-GC/MS analyses of new standard plastics and plastic objects*

- in museum collections*, **Journal of Cultural Heritage**, 14(3), 2013, pp. 238-247. <https://doi.org/10.1016/j.culher.2012.06.005>.
- [124] K. Curran, M. Underhill, J. Grau-Bové, T. Fearn, L.T. Gibson, M. Strlič, *Classifying Degraded Modern Polymeric Museum Artefacts by Their Smell*, **Angewandte Chemie International Edition**, 57(25), 2018, pp. 7336-7340. <https://doi.org/10.1002/anie.201712278>.
- [125] M. Kearney, I. Parkin, J.H. Townsend, M. Hidalgo, K. Curran, *Characterisation of VOCs Surrounding Naum Gabo's Construction in Space 'Two Cones', (Tate) by in situ SPME GC-MS Monitoring*, **Studies in Conservation**, 63, 2018, pp. 369-371. <https://doi.org/10.1080/00393630.2018.1486530>.
- [126] G. Mitchell, C. Higgitt, L.T. Gibson, *Emissions from polymeric materials: Characterised by thermal desorption-gas chromatography*, **Polymer Degradation and Stability**, 107, 2014, pp. 328-340. <https://doi.org/10.1016/j.polymdegradstab.2013.12.003>.
- [127] G. Wypych, ed., *Effect of Plasticizers on Properties of Plasticized Materials*, **Handbook of Plasticizers** (Editor: G. Wypych), William Andrew Publishing, 2012, pp. 209-306. <https://doi.org/10.1016/B978-1-895198-50-8.50012-6>.
- [128] T. Rijavec, D. Ribar, J. Markelj, M. Strlič, I. Kralj Cigić, *Machine learning-assisted non-destructive plasticizer identification and quantification in historical PVC objects based on IR spectroscopy*, **Scientific Reports**, 12, 2022, Article Number: 5017. <https://doi.org/10.1038/S41598-022-08862-1>.
- [129] A. Gili, I. del Gaudio, R. King, L. Mazzei, K. Curran, *Modelling plasticiser loss inside closed environments*, **Polymer Degradation and Stability**, 206, 2022, Article Number: 110204. <https://doi.org/10.1016/j.polymdegradstab.2022.110204>.
- [130] A. Quye, D. Littlejohn, R.A. Pethrick, R.A. Stewart, *Investigation of inherent degradation in cellulose nitrate museum artefacts*, **Polymer Degradation and Stability**, 96(7), 2011, pp. 1369-1376. <https://doi.org/10.1016/j.polymdegradstab.2011.03.009>.
- [131] M. Silva, *Investigating cellulose nitrate degradation caused by fungal attack*, **Postprints of The Future of the Twentieth Century—Collecting, Interpreting and Conserving Modern Materials** (Editors: C. Rogerson, P. Garside), Archetype Publications, London, 2005, pp. 72-76.
- [132] D. Littlejohn, R.A. Pethrick, A. Quye, J.M. Ballany, *Investigation of the degradation of cellulose acetate museum artefacts*, **Polymer Degradation and Stability**, 98(1), 2013, pp. 416-424. <https://doi.org/10.1016/j.polymdegradstab.2012.08.023>.
- [133] K. Sutherland, M. Kokkori, *Investigating formulations of cellulose acetate plastics in the collections of the Art Institute of Chicago using pyrolysis gas chromatography mass spectrometry*, **Journal of Analytical and Applied Pyrolysis**, 163, 2022, Article Number: 105484. <https://doi.org/10.1016/j.jaap.2022.105484>.
- [134] T. Rijavec, M. Strlič, I.K. Cigić, *Plastics in Heritage Collections: Poly(vinyl chloride) Degradation and Characterization*, **Acta Chimica Slovenica**, 67(4), 2020, pp. 993-1013. <https://doi.org/10.17344/acsi.2020.6479>.
- [135] D. Lovett, D. Eastop, *The degradation of polyester polyurethane: Preliminary study of 1960s foam-laminated dresses*, **Studies in Conservation**, 49(sup2), 2004, pp. 100-104. <https://doi.org/10.1179/sic.2004.49.s2.022>.
- [136] E. Pellizzi, A. Lattuati-Derieux, B. Lavédrine, H. Cheradame, *Degradation of polyurethane ester foam artifacts: Chemical properties, mechanical properties and comparison between accelerated and natural degradation*, **Polymer Degradation and Stability**, 107, 2014, pp. 255-261. <https://doi.org/10.1016/j.polymdegradstab.2013.12.018>.

- [137] T. van Oosten, A. Lorne, O. Béringuer, **PUR Facts**, Amsterdam University Press, 2011. <https://doi.org/10.2307/J.CTT6WP6JJ>.
- [138] \* \* \*, **ICOM-CC | Terminology for conservation**, (n.d.). <https://www.icom-cc.org/en/terminology-for-conservation> [accessed October 13, 2022].
- [139] Y. Shashoua, *A Safe Place, Storage Strategies for Plastics*, **Conservation Perspectives, The GCI Newsletter**, **29**(1), 2014, pp. 13-15.
- [140] K. Curran, A. Aslam, H. Ganiaris, R. Hodgkins, J. Moon, A. Moore, L. Ramsay, *Volatile organic compound (VOC) emissions from plastic materials used for storing and displaying heritage objects*, **ICOM Committee for Conservation 18<sup>th</sup> Triennial Meeting Copenhagen, Denmark 4-8 September 2017**, Pulido & Nunes; ICOM Committee for Conservation, Copenhagen, 2017.
- [141] E. Canosa, S. Norrehed, M. Hacke, A. Wiman, **Characterization of Emissions from Display Case Materials**, 2019. <https://doi.org/10.13140/RG.2.2.22913.71524>.
- [142] O. Chiantore, T. Poli, *Indoor Air Quality in Museum Display Cases: Volatile Emissions, Materials Contributions, Impacts, Atmosphere*, **12**(3), 2021, Article Number: 364. <https://doi.org/10.3390/ATMOS12030364>.
- [143] Y. Shashoua, *Ageless® oxygen absorber: From theory to practice*, **ICOM Committee for Conservation 12<sup>th</sup> Triennial Meeting Lyon**, James & James (Science Publishers) Ltd, 1999.
- [144] I. Godfrey, **Conservation and Care of Collections**, revised edition, (2017). <https://manual.museum.wa.gov.au/conservation-and-care-collections-2017/foreword> [accessed February 2, 2023].
- [145] Y. Shashoua, M. Schilling, *The effectiveness of conservation adsorbents at inhibiting degradation of cellulose acetate*, **ICOM Committee for Conservation 17<sup>th</sup> Triennial Meeting Melbourne Australia**, Pulido & Nunes; ICOM Committee for Conservation, Melbourne, 2014.
- [146] A. Gili, R. King, L. Mazzei, S. da Ros, J. Grau-Bové, R. Koestler, M. Petr, O. Madde, K. Curran, *Decision making in conservation based on modelling and measuring diethyl phthalate plasticiser loss from cellulose acetate in varied ventilation conditions*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 15, 2023].
- [147] C. Elsässer, M. Pamplona, T. Donner, V. Mayr, A. Micheluz, S. Griebbach, *How to deal with a self-destructive plastic in museum collections? Storing cellulose nitrate 3D objects at the Deutsches Museum*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 15, 2023].
- [148] A. Royaux, I. Fabre-Francke, N. Balcar, G. Barabant, C. Bollard, B. Lavédrine, S. Cantin, *Aging of plasticized polyvinyl chloride in heritage collections: The impact of conditioning and cleaning treatments*, **Polymer Degradation and Stability**, **137**, 2017, pp. 109-121. <https://doi.org/10.1016/J.POLYMDEGRADSTAB.2017.01.011>.
- [149] Y.R. Shashoua, *Effect of indoor climate on the rate and degradation mechanism of plasticized poly (vinyl chloride)*, **Polymer Degradation and Stability**, **81**, 2003, pp. 29-36. [https://doi.org/10.1016/S0141-3910\(03\)00059-4](https://doi.org/10.1016/S0141-3910(03)00059-4).

- [150] A. Royaux, E. Apchain, I. Fabre-Francke, N. Balcar, G. Barabant, C. Bollard, B. Lavédrine, O. Fichet, S. Cantin, *Conservation of plasticized PVC artifacts in museums: Influence of wrapping materials*, **Journal of Cultural Heritage**, **46**, 2020, pp. 131-139. <https://doi.org/10.1016/J.CULHER.2020.07.002>.
- [151] A. Royaux, I. Fabre-Francke, N. Balcar, G. Barabant, C. Bollard, B. Lavédrine, S. Cantin, Long-term effect of silk paper used for wrapping of plasticized PVC objects: Comparison between ancient and model PVC, **Polymer Degradation and Stability**, **155**, 2018, pp. 183-193. <https://doi.org/10.1016/J.POLYMDEGRADSTAB.2018.07.016>.
- [152] C. Stein, J. Pace, L. McCann, *Identification and storage of plastics in libraries and archives*, **IFLA Journal**, **48(2)**, 2022, pp. 275-281. <https://doi.org/10.1177/03400352211023082>.
- [153] T. van Oosten, *Preserving Plastic: Challenges in the Conservation of Modern Art Objects*, **The Age of Plastic: Ingenuity and Responsibility** (Editor: O. Madden), Smithsonian Institution Scholarly Press, Washington D.C., 2017. <https://doi.org/doi:10.5479/si.19492367.7>.
- [154] N. Balcar, G. Barabant, C. Bollard, S. Kuperholc, B. Keneghan, A. Laganà, T. van Oosten, K. Segel, Y. Shashoua, *Studies in cleaning plastics*, **POPART - Preservation of Plastic ARTeifacts in Museum Collections**, 2012. <https://popart-highlights.mnhn.fr/>.
- [155] C. Morales Muñoz, *Surface modification of plasticized PVC by dry cleaning methods: Consequences for artworks*, **Applied Surface Science**, **256(11)**, 2010, pp. 3567-3572. <https://doi.org/10.1016/J.APSUSC.2009.12.156>.
- [156] C. Morales Muñoz, H. Eggsgaard, J. Sanz Landaluze, C. Dietz, *A model approach for finding cleaning solutions for plasticized poly(vinyl chloride) surfaces of collections objects*, **Journal of the American Institute for Conservation**, **53(4)**, 2014, pp. 236-251. <https://doi.org/10.1179/0197136014Z.00000000040>.
- [157] O. Madde, K.C. Cobb, M. Brooks, R. Friedel, **The Age of Plastic: Ingenuity and Responsibility**, Smithsonian Institution Scholarly Press, Washington D.C., 2017. <https://doi.org/10.5479/si.19492367.7>.
- [158] N. Macro, M. Ioele, M. Brevi, G. Scicolone, M. Lazzari, *New insight on the oxidative degradation in materials used by Piero Gilardi in two second generation Nature Carpets: A micro-invasive spectroscopic approach*, **Journal of Cultural Heritage**, **46**, 2020, pp. 278-282. <https://doi.org/10.1016/J.CULHER.2020.07.003>.
- [159] A. Laganà, R. Rivenc, *LESS IS MORE, Exploring Minimally Invasive Methods to Repair Plastic Works of Art*, **Conservation Perspectives, The GCI Newsletter**, **29(1)**, 2014, pp. 16-17.
- [160] A. Laganà, J. Langenbacher, J. Griswold, *Looking through Plastics: Investigating Options for the Treatment of Scratches, Abrasions, and Losses in Cast Unsaturated Polyester Works of Art*, **N ICOM-CC 17<sup>th</sup> Triennial Conference Preprints**, Melbourne, 2014.
- [161] A. Laganà, R. Rivenc, V. Dion, T. Learner, *The Future of Looking Younger: A New face for PMMA. Research into fill materials to repair poly (methyl methacrylate) in contemporary objects and photographs*, **ICOM-CC 18<sup>th</sup> Triennial Conference Preprints**, Copenhagen, 2017.
- [162] M.C. Lanza, M.E. Prunas, G. Sidoti, P. Iazurlo, *The decay of PMMA and its conservation treatment: The case study of a kinetic work*, **iTranscending Boundaries: Integrated Approaches to Conservation. ICOM-CC 19<sup>th</sup> Triennial Conference Preprints**, ICOM-CC, Beijing, 2021.

- [163] T. van Oosten, L. Beerkens, A. Cudell, A. Laganà, R. Veiga, **Getty Conservation Institute, Properties of Plastics: A Guide for Conservators**, Getty Conservation Institute, 2022. <https://yalebooks.co.uk/page/detail/properties-of-plastics/?k=9781606066935> [accessed October 14, 2022].
- [164] G. Sofer, D. Cane, J.H. Townsend, *THE CASE OF THE VANISHING GABOS: The Gabo Collection at Tate*, **Plastics in Peril: Focus on Conservation of Polymeric Materials in Cultural Heritage**, 2020. [https://www.leibniz-forschungsmuseen.de/fileadmin/user\\_upload/Forschungsmuseen/Pamplona\\_Plastics\\_in\\_Peril\\_final.pdf](https://www.leibniz-forschungsmuseen.de/fileadmin/user_upload/Forschungsmuseen/Pamplona_Plastics_in_Peril_final.pdf) [accessed February 15, 2023].

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