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Put the Lime in the Coconut; An Investigation of the Mechanical and Aging Properties of Coconut Shell and Recommendations for Compatible Conservation Materials

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Put the Lime in the Coconut; An Investigation of the Mechanical and Aging Properties of Coconut Shell and Recommendations for Compatible Conservation Materials

A thesis submitted in partial satisfaction of the requirements for the degree Master of Arts in Conservation of Archaeological and Ethnographic Materials

by

Elena Veronica Bowen

2020

ABSTRACT OF THE THESIS

Put the Lime in the Coconut; An Investigation of the Mechanical and Aging Properties of Coconut Shell and Recommendations for Compatible Conservation Materials

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Elena Veronica Bowen

Master of Arts in Conservation of Archaeological and Ethnographic Materials

University of California, Los Angeles, 2020

Professor Ellen J. Pearlstein, Chair

Coconut shell is a material that has been used in cultural heritage across the continents and has been linked with human migration and colonization for thousands of years. Though ubiquitous, as a material coconut shell lacks the extensive conservation research done on similar cellulosic materials such as wood. Coconut shell objects are housed and displayed in museums across the globe, without knowledge of the effects of humidity, temperature, or lighting and no information about coconut shell morphology for identification and responsiveness to conservation treatment.

This study attempts to address all of these gaps by surveying museum professionals regarding the care, treatment, and state of coconut shell materials, and connect these findings to results of aging, humidity, and adhesive tests. The ultimate goal of this work is to provide suggestions for best practices for coconut shell objects in museum collections and inspire future research into coconut shell as a material. Coconut shell bowl samples were subjected to fluctuating humidity conditions, light aging, and Oddy testing. These results were then compared to morphology of coconut shell using cross-sections taken of the bowls following the procedures used for wood sampling.

The thesis of Elena Veronica Bowen is approved.

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Glenn Wharton

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2020

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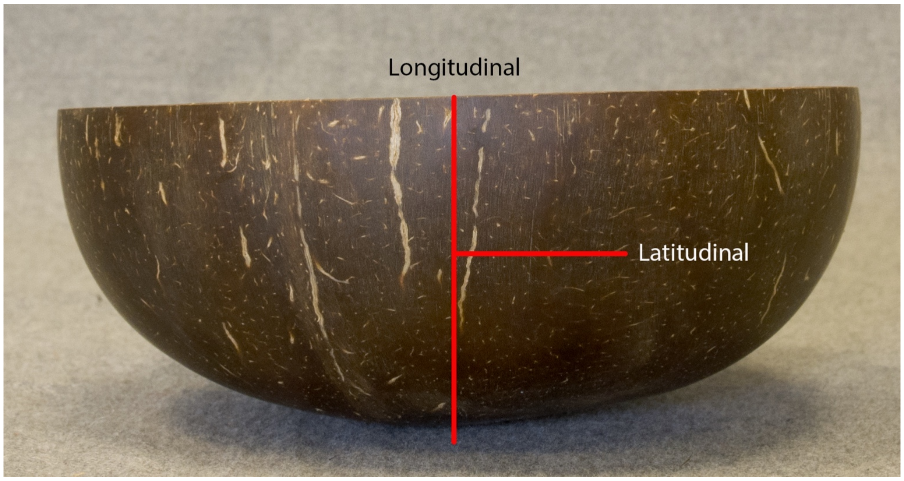


Figure 1: Indication of directional language used for coconut shell. Image courtesy of author.

Coconut morphological terminology

Exocarp - the smooth, thin outermost layer of a coconut

Mesocarp - the middle fibrous layer of a coconut

Endocarp - the hard inner shell containing the fruit (or meat) of the coconut

Coir - fibers harvested from the mesocarp of a coconut and used for cordage. This cordage is used to make netting, clothing, armor, and rope amongst other products[1]

Drupe - fruit with a hardened endocarp such as peaches, cherries, walnuts, or coconuts[2]

Terminology for survey

Good condition - the object is structurally sound, no active deterioration, can go on display, loan, and be handled

Fair condition - may have minor damage, previous repairs, must be handled carefully, and may require some intervention for display

Poor condition - physical/chemical integrity of the shell is compromised and actively deteriorating and will not permit display or extensive handling[3]

[1] Florian, M.E., D.P. Kronkright, and R.E. Norton. 1990. Plant materials used in artifact construction. In The Conservation of Artifacts Made from Plant Materials. 99-132. Marian del Rey, California: Getty Conservation Institute.
[2] Dardick, Chris, and Ann M. Callahan. 2014. "Evolution of the Fruit Endocarp: Molecular Mechanisms Underlying Adaptations in Seed Protection and Dispersal Strategies." Frontiers in Plant Science 5 (June): 1–10. https://doi.org/10.3389/fpls.2014.00284.
[3] Museum Standards Programme for Ireland, An Chomhairle Oidhreachta and Heritage Council, 2014.

Figure 2: Examples of damage observed during Fowler survey. Left: Latitudinal cracking; Right: Surface loss. Photograph courtesy of the Fowler Museum at UCLA, photograph by author.

Figure 3: Examples of damage observed during Fowler survey. Left: surface discoloration and accretions; Right: delamination. Photograph courtesy of the Fowler Museum at UCLA, photograph by author.

Acknowledgements

I would like to express my immense appreciation for the village that has supported me throughout the past three years and made this thesis research possible. First, I would like to thank my thesis advisor Ellen Pearlstein as well as my committee members Al Roberts and Stephen Acabado. My research would not have been possible without the assistance of Tom Learner, Vincent Beltran, Michal Lukomski, and David Carson at the Getty Conservation Institute. Thank you for facilitating access to a spectrodensitometer. A thank you also goes to the Getty Villa Antiquities Conservation Department for access to their digital microscope. I would also like to express my appreciation to Chris de Brer and the Fowler Museum for allowing me access to their collection.

I would like to thank Vanessa Muros, Shaharoh Chism, and William Shelley for their support over the last three years both in and out of the lab. Thank you to my family and Tamara for your love and encouragement. And of course, to my classmates, I can't imagine spending the past three years with anyone else.

1. Introduction

1.1 Coconuts; a brief historical context

A scene from one of my favorite movies, 1975's *Monty Python and the Holy Grail*, leads to a humorous discussion between King Arthur and a castle guard about what type of swallow could carry a coconut from tropical climates to the temperate zone of Great Britain. While coconuts may not have been transported across the continents by swallows, as suggested in this scene, coconut shell has found its way into the material culture of societies across nearly every continent. From carved ornate goblets thought to have curative powers (Victoria and Albert Museum 2002) to utilitarian tools such as spoons and water containers, coconut shell is a raw material with endless possibilities that at one point in history even inspired a coconut cult (Stuff You Should Know 2019). One of the unique and useful qualities of coconuts, is that every part of the coconut is useful. The inner milk and meat are nutritious components that can be consumed raw or cooked, the shell and husk are used as an efficient biofuel, and the fibers harvested from the coconut husk can be used to create rope and textiles. These are merely examples of the many uses for coconut worldwide.

Native to the Pacific and Indian Ocean basins, the coconut of modern times is now cultivated in 89 different tropical countries and has developed significant genetic diversity. In addition to *Cocos nucifera,* many types of palms produce some sort of fruit. One of those is the *Lodoicea* palm tree, which produces a coconut called the coco de mer, or coconut of the sea (Orozco-Segovia et al. 2003). Although many of these fruits are similar in appearance and have been used in material culture, the focus of this thesis will be solely on the species *Cocos nucifera* and its extensive use in material culture.

There are two documented varieties of coconut fruit; the first, *Niu kafa*, is an elongated, triangular coconut fruit with a large proportion of husk. These are found on tall coconut palms and genetically are more closely related to coconuts dispersed naturally. The second variety of coconut fruit is the *Niu vai*, which is the round, colorful coconut. These typically have a higher proportion of coconut milk, are found on the dwarf coconut palm, and are more closely associated with human dispersion and cultivation (Gunn et al. 2011).

Its usefulness as a vessel for food and water means that coconuts have been historically intertwined with human migration patterns. Fossil and textual evidence have traced coconut cultivation back almost 3,000 years in the Indian Ocean and have shown the path coconuts took from the Pacific Ocean to the Indian Ocean following ancient trade routes (Gunn et al. 2011). With all of this in mind, it is unsurprising that coconuts have been used extensively in cultural heritage throughout the globe. In this thesis, I intend to underscore that ubiquity and investigate the properties of coconut shell with the intent of providing guidelines for stewards of collections containing coconut shell objects.

1.2 Lack of Conservation Literature

During the winter quarter of my first year, I was tasked with the research and treatment of a Puerto Rican *vejigante* mask from the Connecting Cultures Mobile Museum collection. This mask, composed of a painted and carved coconut husk, posed numerous condition issues. The husk was cracking and in some areas there was paint loss. Because this mask was never used and was sold as a tourist piece for display, the condition issues were most likely from inherent material vices or the material's response to environmental changes. Research into coconut led me to find agricultural literature on the shape, size, and breeding of coconuts (Gunn 2004; Santos et al. 1996; Grimwood and Ashman 1975). The only mention of coconut materials found in conservation literature was related to the properties and usage of coir (Florian et al. 1990). Coir is easily identifiable when compared to reference samples, however there is no literature about the behavior of coir prior to being harvested from the coconut husk. Further research led me to find the only literature available on coconut shell was for its use as a biofuel (Mendu et al. 2011; Achaw and Afrane 2008; Grimwood and Ashman 1975) or for biomedical research (Gludovatz et al. 2017).

1.3 Coconuts in Cultural Heritage; Fowler Museum Survey

Prior to designing a survey form for distribution among museum professionals, a survey of the Fowler Museum at UCLA collection was done to gather preliminary information and gain a sense of the types, condition, and display histories of coconut shell objects. Key words including “coconut”, “cocoa nut”, and “coconut shell” were searched in the Museum’s online Argus database[4]. It should be noted that although cocoa nut is not the same as coconut shell, this spelling was used in some coconut object descriptions. From this search, an Excel spreadsheet was compiled including the object number, name, materials, techniques, culture, use, storage location, date, exhibition history, conservation history, condition, and notes. Where this information was not provided, cells were left blank. Exhibition history included both in-house Fowler display and loans. Following this online search, the spreadsheet was used to systematically go through storage and check the accuracy of the online database entries as well as make condition notes. Objects were labelled as in good, fair, or poor condition based on the

[4] Museum collections management software from Lucidea. 2019. https://lucidea.com/argus/.

definitions laid out by the Museum Standards Programme for Ireland (An Chomhairle Oidhreachta and Heritage Council 2014).

From the initial online database search, there are approximately 192 coconut shell-containing objects in the Fowler collection. Upon inspection of the objects in storage, it appears that many were erroneously identified as coconut shell and some identifications were not included due to the small amount of material present (beads or small fragments, for example). Visual examination confirmed that many objects made of gourd were erroneously identified as coconut shell and that small fragments do not have enough physical characteristics for identification. With this in mind only 186 total objects could be confirmed to contain coconut shell and an additional five objects found for a total of 191 coconut shell containing objects.

Of that 191, 46% are from Africa, 41% from Oceania, 6% from Southeast Asia, 3% from the Caribbean, 2% from Europe, and 2% from the Americas. Many of the objects do not have specific dates (43% unknown); of those that do, 1% were made during the 13th century, 2% during the 17th century, 2% during the 18th century, 1% from the 19th century, and 54% from the 20th century. Some objects made with coconut shell from the 21st century were found in exhibition condition reports but were not included because they were loans. So, while it seems that coconut shell is no longer being used, this is untrue and simply a representation of the Fowler Museum Collection’s holdings and history.

The majority of the coconut shell objects in the Fowler Collection are vessels or spoons, objects that could easily be manufactured due to the coconut’s natural geometry. Some bowls are incised or inlaid with mother of pearl, while others are undecorated. More unique finds within the collection were a laminated and carved coconut shell ring from China and a mannequin head fashioned out of the entire cross-section of a coconut for a blowfish helmet from Micronesia.

Only 33% of the objects have previously been on display. 95% of the objects are in good condition, while 4% are in fair condition, and 1% in poor condition. The 12% of these objects that have undergone treatment are composite objects treated for materials other than coconut. For example, two silver gilt mounted coconut goblets received treatment in 1989 with the focus being solely on polishing the silver components. Although the coconut shell was noted as being cracked, no intervention was done. Other treatments were limited to dry cleaning. With regards to condition issues observed, 16 objects were noted as having cracking (8%), seven had small surface losses (4%), six objects were delaminating (3%), and seven had discoloration or accretions on the surface (4%). The survey also helped me to gain an understanding of how the objects are used across different cultures for different uses. Coconut shell was used for utilitarian and decorative objects, in bulk with the coconut husk or cut into small beads or shapes, and was used in cultures across nearly every continent.

2. Museum Condition Survey

2.1 Museum Survey Methodology

A Google form survey was created and sent to museum professionals to collect tombstone information as well as conservation information on coconut shell objects held in museum collections. The purpose of this survey was to gather information regarding the care, treatment, and state of coconut shell materials, connect these findings to results of aging, humidity, and adhesive tests, and provide suggestions for best practices. The usage and long-term success of reported treatment protocols for coconut shell will provide real-life data, which can then be compared to the success or failure of adhesives from this study.

The survey itself is divided into four sections: 1. an introduction to the survey and an area to capture participants' contact information; 2. collection information including the institution name, respondent name, number of objects in the collection, number of coconut shell objects in the collection, how this information was retrieved by the respondent, and general tombstone information; 3. coconut shell manufacture techniques; and 4. condition of the objects and treatment documentation.

Information such as the type of museum database, searchable terms, and how the information was collected (i.e. database search, physical counting, or from memory) can provide insight into the accuracy and type of information provided. It is also useful to know whether the information was gathered by a conservator or another museum professional as this will affect their access and knowledge of condition issues. Approximate manufacture dates and geographic origins can provide important insights into trade, general aging properties of coconut shell, and confirm the ubiquitous use of coconut shell in cultural heritage.

Detailed data regarding specific object condition issues can help to anchor the lab tests from this thesis to physical examples. Knowing the type and source of damage found in coconut shell can provide conservators and collection managers with guidelines for preventative storage, handling, and display of coconut shell objects, information that currently does not exist in the conservation literature.

The types of questions chosen for the survey were narrowed down and refined after a rough pilot survey of the Fowler Museum collection. In order to be very precise about the terminology of condition issues observed, images of various condition issues were included. For the overall condition of the objects, definitions from the Museum Standards Programme for Ireland were chosen because of their clear outlining of good, fair, and poor condition using allowable movement of the object, amount of previous repair, and ability to be displayed safely (An Chomhairle Oidhreachta and Heritage Council 2014).

The survey was disseminated to 21 museums that were identified as having coconut shell materials from an online collections search. Search terms “coconut shell” and “museum” were used for a Google search to draft a general list of museums containing coconut shell objects. Professional contacts in conservation departments were utilized where possible and, where not possible, contact information from individual museum websites and the American Institute for Conservation of Historic and Artistic Works (AIC) member search function were employed. The survey was also posted to the AIC Objects Specialty Group distribution list and a Facebook group called Art Conservation Advocates.

The survey was sent out in early November with a deadline of mid-December. Due to the low number of responses and the deadline falling right before the holidays, it was decided to extend the deadline to mid-January and a second posting was sent out in mid-December. This prompted a few more responses before the survey officially closed in mid-January.

2.2 Survey Results

By mid-January, the survey had received six unique responses. One respondent submitted answers twice for the same institution and so the duplicate responses were removed. While the survey was distributed to conservators across the US and around the globe, respondents represented museums and one personal collection from the Northwest, Northeast, and Mid-Atlantic US as well as a respondent from New Zealand. However, due to the small number of responses, more wide-spread conclusions cannot be drawn from this information.

The collections of these museums range from 36,000 to around four million total objects. In all cases, besides the personal collection, the term coconut was searchable in the museum database. Databases used include Vernon Systems, Axiell EMu, and The Museum System (TMS). All museum-based respondents calculated the number of coconut shell objects in their collections through a database search or approximation. All respondents found that their coconut shell holdings comprised less than 1% of the total museum collection with the largest percentage being 0.04% in an archaeological collection. Surprisingly the natural history museum collection contained the lowest percentage of coconut shell holdings with 0.003%. Of course, the percentage of the total institution collection does not reflect how many total coconut shell objects exist in the collection. This number ranged from two in the personal collection (six in an encyclopedic collection, the lowest of the museum responses), to approximately 1000 in a history collection. While the percentages appear small, the total number of objects (137, 6, 2, 365, 1000, and 13 respectively) is significant and can provide general conclusions about the condition of coconut shell objects in museum collections.

Table 1: Coconut Shell Objects by Collection Type

Institution	Type of Institution	Total Number of Objects	Number of Coconut Shell Objects	% of Collection
Museum	Natural History	4.1 million	137	0.003
Museum	Encyclopedic	> 36000	6	0.02
Personal Collection	--	--	2	--
Museum	Archaeology	~ 1 million	365	0.04
Museum	History	~ 3.5 million	1000	0.03
Museum	Encyclopedic	> 200,000	13	0.007

The majority of coconut shell objects that had inscribed dates were made post-17th century with the largest group made in the 20th-21st century. It would be interesting to see a breakdown of these dates by culture type to see if there is a pattern of use over time and across geographical regions, although this is not within the scope of this thesis. All collections contain decorative objects, four contain utilitarian and ceremonial objects, two have musical instruments made of coconut shell, and one collection has coconut shell folk art[5]. One respondent included a write-in response of modern art/tourist art. In these collections respondents reported carved, painted, inlaid, cut, shaped, lacquered, and metal attachments in their coconut shell objects.

Table 2: Manufacture Date of Coconut Shell Objects

Institution	Type of Institution	20th – 21st c.	17th - 19th c.	Before 17th c.
Museum	Encyclopedic	< 20%	50-75%	<20%
Museum	Natural History	--	--	--
Personal Collection	--	< 20%	80-100%	<20%
Museum	Archaeology	80-100%	<20%	<20%
Museum	History	80-100%	<20%	<20%
Museum	Encyclopedic	50-75%	50-75%	<20%

Of the six responses, four reported that less than 20% of the coconut shell objects had been displayed. Only the private and encyclopedic collections reported more than 50% of their coconut shell objects had been on display at some point. It should be noted, however, that in the process of disseminating this survey, email exchanges with larger institutions revealed a lack of knowledge of museum holdings. Multiple conservators from the same institution reported that they had never seen any coconut shell objects in the collection while a quick online search revealed more than ten ornate coconut shell goblets and tankards that are currently on display

[5] Categories were created from descriptions given for individual objects in various museum databases. Utilitarian objects were defined as undecorated bowls, plates, and spoons/ladles for non-ceremonial purposes. Decorative objects were defined as jewelry, statues, and other similar objects. Folk art was described as masks, dioramas, and other similar objects. Musical instruments were self-explanatory and therefore not described in the survey form. Ceremonial objects were described as objects used for cultural performances and could include containers or adornments. It should be noted that objects could fall into multiple categories, so this question was just to get an overall view of uses for coconut shell.

and should have at least been condition checked or prepared for exhibition in their recent history. It should be noted, therefore, that larger institutions were not well represented in survey results.

Table 3: Display History of Coconut Shell Objects

Institution	Type of Institution	Percentage Displayed
Museum	Natural History	--
Museum	Encyclopedic	50-75%
Personal Collection	--	80-100%
Museum	Archaeology	< 20%
Museum	History	< 20%
Museum	Encyclopedic	< 20%

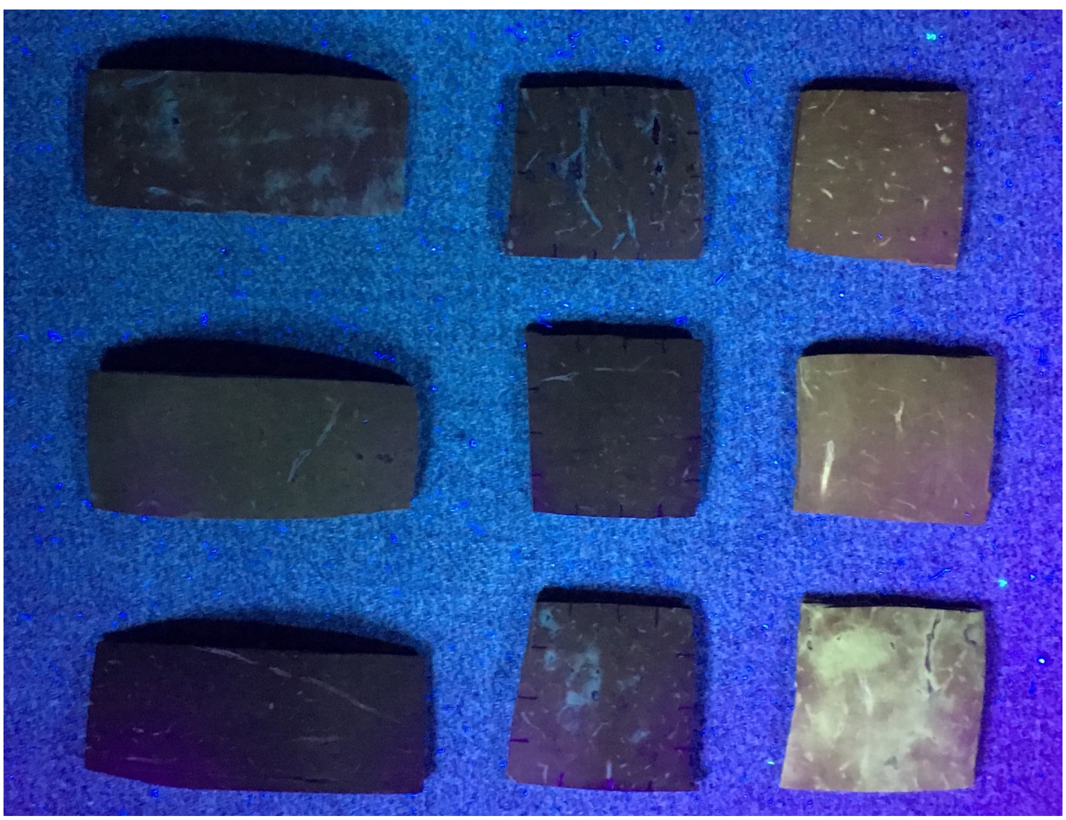
The survey results for object condition are encouraging for the durability of coconut shell. Five of the six respondents answered this question and placed at least 50% of their coconut shell objects in the good condition category. This means that the majority of their coconut shell holdings are structurally sound, have no active deterioration, and can be safely handled, displayed, and transported. Less than 45% of the remaining objects (and mostly reported as less than 20%) were in fair or poor condition. For more precise results, the categories here should have been refined to include a 0% choice as well as smaller percent ranges. For many responses, the sum of Good, Fair, and Poor condition objects adds up to greater than 100% and therefore can be confusing to interpret. Of the condition issues generally identified by respondents structural loss, cracking, and surface grime appeared the most. This was followed by distortion, surface chipping/loss, color change, and insect infestation. Only one respondent marked delamination as being present in any of their objects.

Table 4: Condition of Coconut Shell Objects

Institution	Type of Institution	Good	Fair	Poor
Museum	Natural History	--	--	--
Museum	Encyclopedic	80-100%	20-45%	< 20%
Personal Collection	--	80-100%	< 20%	< 20%
Museum	Archaeology	50-75%	20-45%	< 20%
Museum	History	50-75%	< 20%	< 20%
Museum	Encyclopedic	80-100%	20-45%	< 20%

Some respondents provided reports detailing treatment of coconut shell objects to further describe condition issues and interventions. Of these, the majority of treatments involved dry and wet cleaning of the coconut shell as well as the creation of storage mounts. Solvents used for wet cleaning included ethanol, water, and saliva. Two institutions reported four different methods of crack repair. Two of these repairs involved the use of Japanese tissue bridges adhered with methyl cellulose or wheat starch paste and toned to match the surrounding areas. The methyl cellulose and tissue mend was checked six years after the initial repair and found to be intact. A third repair method reported was the use of cellulose nitrate for structural cracks. The fourth method of crack repair reported was the use of a copper alloy shim and rivets with some sort of adhesive. In addition to crack repairs the use of a wax coating was also noted by one institution on the coconut shell surface. One report also mentioned the identification of coconut shell by its orange fluorescence under long-wave ultraviolet (UV) light. While I did not initially observe this in my coconut bowl samples, comparison of unaged, humidity cycle samples, and light aged samples indicated that light aged coconut shell shows an orange-yellow fluorescence under UV (λ_{exc} = 365 nm). The modification of the coconut shell properties as it is exposed to light could be interesting future research and a way of identifying light damage in coconut shell objects.

Figure 4: Coconut samples in diffuse light (above, captured with a Nikon D90 camera) and UV-induced visible fluorescence (below, λ_{exc} = 365 nm, captured with an iPhone camera). The three coconut shell samples in the left of each image are unaged samples, in the center are three humidity cycle samples, and on the right are three light aged samples. Pieces were chosen to represent the range of color of the coconut shell in diffuse light. Images by author.



3. Coconut Morphology

3.1 Sample Preparation

Coconut bowls were purchased online from *Coconut Bowls*, which is a company that repurposes discarded coconut shells from coconut palm farmers. These are then made into bowls and utensils in workshops in Vietnam and Indonesia. The shells are cut, cleaned, and refined by local craftsmen in workshops. According to the company website, bowls are sanded and cleaned before being polished with organic coconut oil.

Ten bowls were purchased for sampling. Upon arrival, each bowl was photographed under diffuse light and UV (λ_{exc} = 365 nm) light, measured, and weighed. It was noted that in UV-induced visible fluorescence images there was a green fluorescence mainly around the lighter brown areas of the bowls. Once imaged, measured, and weighed the bowls were placed into a desiccator cabinet with silica gel conditioned to 50% RH.

A small pie-shaped piece was cut from one of the bowls using a Lenox® hacksaw with a bimetal blade. It was noted that paint from the blade was being transferred to the coconut and so prior to continuing to cut samples, the paint layer was removed from the blade using acetone and a paper towel. The bottom of the piece was cut in the latitudinal direction to ensure there was one longitudinal cross-section and one latitudinal cross-section. This piece was then labelled on the interior with pencil to ensure clarity when imaging. When viewed under low magnification markings from the coconut shell processing and sampling obscured much of the morphology on the outer, inner, and freshly cut surfaces. To attempt to reduce this effect, the sample surfaces were polished with a sequence of 1500, 3600, and 8000 grit Micro Mesh® abrasive sheets and imaged again.

An attempt was made to thin-section the coconut shell using a metal razor-blade as one would sample wood sections (Von Arx et al. 2016). However, the coconut shell proved too hard to sample in this way. Using the Schweingruber method for sampling dry and hard wood, a piece of coconut shell was placed in a beaker of deionized water and brought to boil on a hot-plate. This was allowed to boil for approximately two hours with a watch glass placed on top of the beaker to prevent water evaporation. After two hours, the coconut shell was removed and sampled using a metal razorblade (Schweingruber 2007). A section was sampled from both the longitudinal and latitudinal cross-sections. These thin sections were then temporarily mounted on a glass slide by placing a drop of water and glass coverslip over the samples. Imaging was done on a Keyence VHX 6000 digital optical microscope using transmitted light. Discussion of the morphology visible in these thin-sections is discussed in section 3.2.

Prior to testing, attempts were made to contact the *Coconut Bowls* company for more information about the manufacture and production of these bowls in order to ensure nothing that was applied to the surfaces of the bowls would interfere with humidity and adhesive testing. The company never responded to contact attempts. In order to check the oil content of the bowls, Fourier-transform infrared (FTIR) spectroscopy was performed with a portable handheld spectrometer, model 4300 from Agilent, equipped with a deuterated triglycine sulfate detector (DTGS) and an attenuated total reflectance (ATR) diamond crystal attachment. Every ten minutes a background reading was taken to ensure there were no artifacts in the spectra.

One reading was taken for each bowl and run against an internal library provided by Agilent. Readings of the interior and exterior of the bowl samples were identical so only one spectrum is included for each sample. Because the internal library provided by the company was created for industrial purposes, the references provided are not a 100% match but similar cellulosic and oil materials within the database can provide a general sense of the composition (cellulosic materials within the reference library include cardboard, wood, and paper while olive oil is the main oil result from the reference library). All samples were a 93% or higher match with the wood or cardboard reference samples and did not show any additional peaks indicating the presence of oil. The spectra and subsequent reports generated by the Agilent software for each sample can be found in the appendices. Based on this analysis, it can be said with confidence that the coconut oil used in the manufacture of these bowls is either no longer present or is so minimal that it would not skew any mechanical or chemical testing of the samples significantly.

3.2 Coconut Morphology

Although there is little information on coconut shell structure for the purposes of conservation, the microstructure and main components of coconut shell have been discussed in biomedical, botanical, and materials engineering literature. Due to its use as a precursor for activated carbon as well as a bulking agent in polymeric materials for industry use, understanding the porosity and structure of the material is extremely important (Gludovatz et al. 2017; Achaw and Afrane 2007). It is useful to use wood as a point of comparison to coconut shell as it contains similar components (Table 5) and presumed similar physical and chemical properties. As research has shown with wood treatment, understanding how the microstructure of coconut shell relates to its macroscopic properties and responsivity to environmental changes is key in understanding coconut shell’s response to conservation treatment. In comparison with wood, coconut shell contains nearly double the amount of lignin, although the reported amount of lignin in coconut shell is not consistent in the literature.

Table 5: Approximate Chemical Compositions of Cellulosic Materials (Wood and Coconut)

		Cellulose		Lignin	Pentosans	Ash	Other
		Hemi[6] [Holo] [Crude] [Amorphous]	Alpha[7] [True] [Crystalline]				
Wood[8]	Hardwood	71.7 ± 5.7	45.5 ± 3.5	23.0 ± 3.0	19.3 ± 2.2	0.5 ± 0.3	--
	Softwood	64.5 ± 4.6	43.7 ± 2.6	28.8 ± 2.2	9.8 ± 2.2	0.3 ± 0.1	--
Coconut	Fleck et al. 1937[9]	44.98	27.31	33.30	17.67	0.23	Methoxyl groups: 5.39
	Child & Ramanathan 1938[10]	53.06	32.52	36.51	20.54	0.61	
	Phillips & Gross 1940[11]	33.52	28.26	27.26	5.26	0.55	Methoxyl groups: 5.84
	Mendu et al. 2011	29.7[12]		44.0	--	0.5	
	Husseinsyah & Mostapha 2011	26.6		29.4	27.7	0.6	Moisture: 8.0 Solvent extractives: 4.2 Uronic anhydrides: 3.5

[6] Fleck et al. refer to this as holocellulose, Child & Ramanathan refer to this as simply cellulose, and Grimwood & Ashman refer to this as crude cellulose. Some authors refer to this as hemicellulose or amorphous cellulose.
[7] Grimwood & Ashman refer to this as true cellulose. This can also be referred to as crystalline cellulose.
[8] Nilssona, T. and Rowell, R. 2012, Historical wood– structure and properties, Journal of Cultural Heritage, 13:3, Supplement, S5-S9.
[9] As cited in Grimwood & Ashman 1975.
[10] As cited in Grimwood & Ashman 1975.
[11] As cited in Grimwood & Ashman 1975.
[12] Mendu et. al and Husseinsyah & Mostapha refer only to cellulose without distinction between amorphous and crystalline cellulose.

In both the latitudinal and longitudinal views, one can see the significant network of porosity of the shell. These elongated pores run both longitudinally and latitudinally as can be seen in Figure 3. In the latitudinal cross-section, one can see the long channel-like sclerenchyma fibers running parallel to each other as was noted by Gludovatz et al. (2007) in their coconut shell research. What is interesting is that these longer fibers are more prominent in the latitudinal view than the longitudinal view, suggesting coconut shell might have anisotropic responsivity to environmental changes or external stressors. In their research of microcracking propagation of young and old (i.e. more mature) coconut shell, Gludovatz et al. found that older coconut shell lacks the nanoscale porosity of less mature coconut shell and develops more pronounced anisotropy as it matures. This would make sense because as drupes mature, their cell walls lignify and harden (Dardick and Callahan 2014). With the structure of the long, hollow sclerenchyma fibers in one direction and the shorter channels in the longitudinal direction, it would make sense that these hardened walls would be tougher but also more anisotropic as a consequence.

In contrast to coconut shell, wood is distinctly directional in its behavior. Wood anatomy consists of axial and radial parenchyma cells and, depending on the type of wood (i.e. soft or hardwood), resin canals and tracheid in softwoods or vessels and fibers in hardwoods (Wiedenhoeft 2013). This anatomy, when viewed in the conventional three planes for identification (tangential, radial, and transverse), appears distinct in each view (Wiedenhoeft 2013). A tangential view of a wood sample shows the elongated parenchyma running parallel to the axis of the tree, the radial view of a wood sample reveals the horizontal ray parenchyma and vertical tracheid, and in the transverse view one can see the ends of axial parenchyma and rays (Fig. 5). Because of the directionality of these cells, changes in relative humidity affect wood more drastically in the tangential direction, allowing conservators to predict how wood will deteriorate under certain conditions (Erhardt et al. 1996).

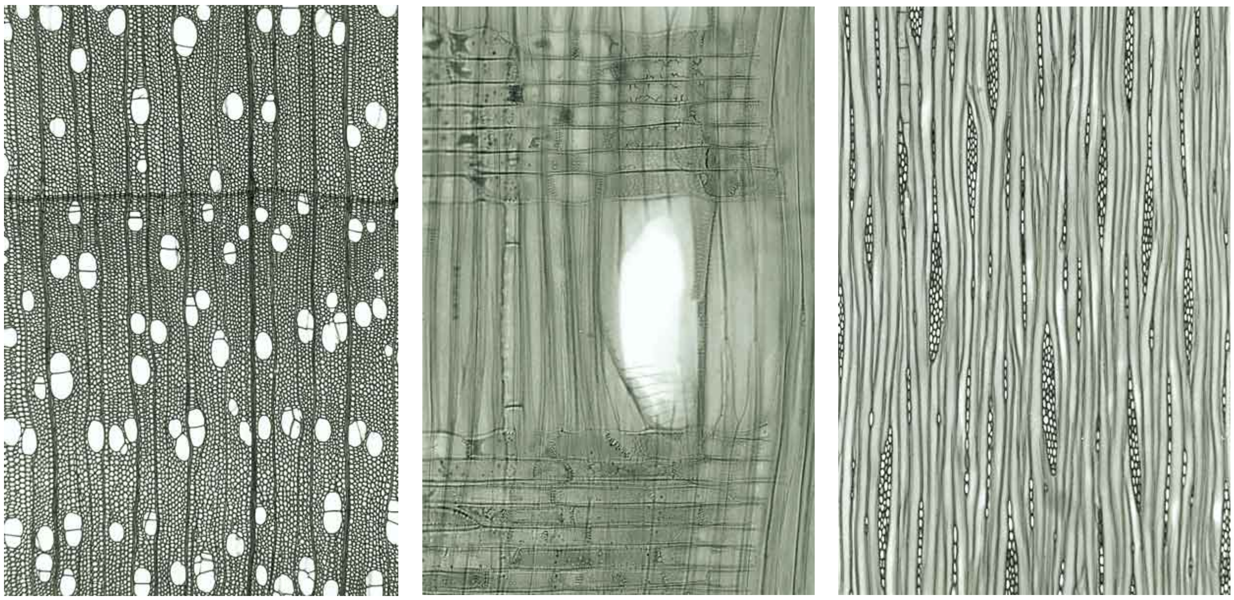


Figure 5: Transverse, radial, and tangential (left to right) cross-sections of common birch (*Betula alba*). Images from *Betula alba*, www.woodanatomy.ch/.

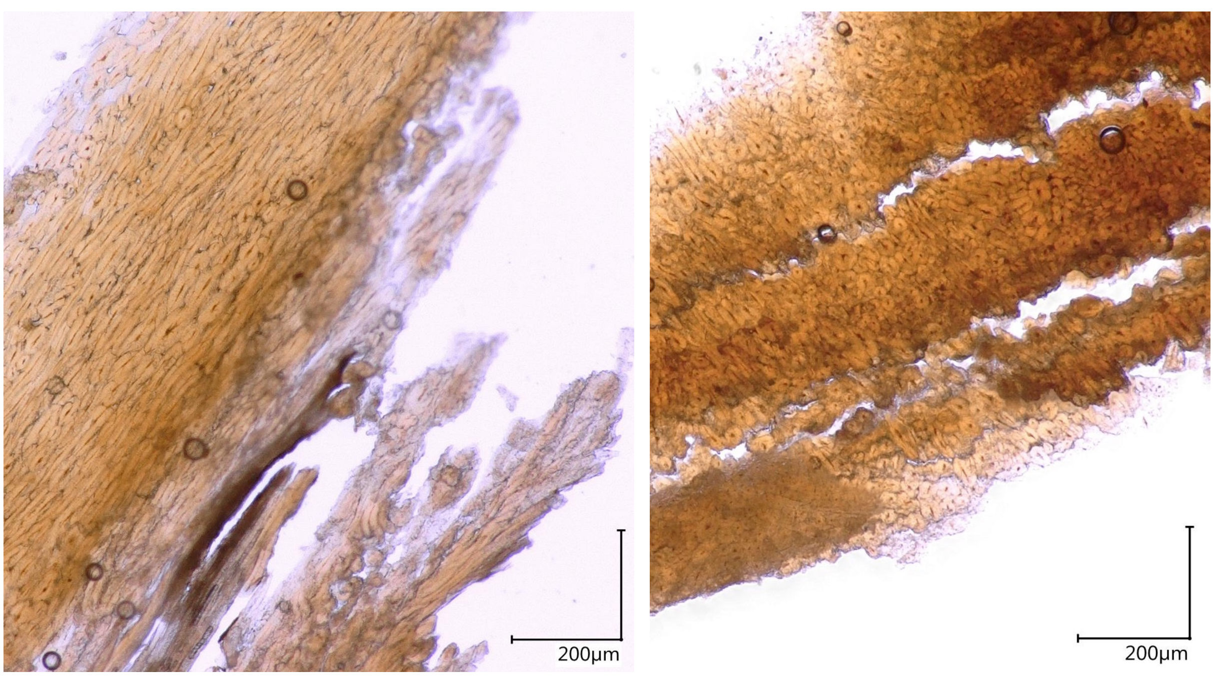


Figure 6: Latitudinal (left) and longitudinal (right) thin-sections of the coconut shell bowl showing unique morphological characteristics unlike wood morphology. Images by author.

4. Sample Testing

4.1 Sample Preparation

To create standardized samples for testing, each coconut shell bowl was cut into approximately 16 pieces using a combination of the Lenox hacksaw with bimetal blade and a WEN® 2305 rotary tool with a Baban® 3-centimeter diameter diamond-coated wheel blade. Once cut, these pieces were placed into a polyethylene bag labelled with the bowl number and returned to the 50% RH microclimate chamber. For humidity cycling and light aging, these sections were cut into approximately 2.5 by 2.5 centimeter squares using the hacksaw. These were then labelled on the interior with pencil, bagged, and placed back into the 50% RH chamber (mentioned in section 3.1) until testing commenced. This was done to ensure no dimensional changes would occur, as is common with hygroscopic organic materials, between initial measurements and testing.

4.2 Humidity Testing

In order to test the coconut shell's susceptibility to humidification and water vapor, one of the cut samples was chosen to be placed into a humidity chamber. A humidity chamber was made using a polyethylene bag propped up with Ethafoam® blocks and with a Coroplast base. 30 mL of deionized water was divided into four 10 mL glass beakers. A previously calibrated hygrometer dial was placed into the chamber to monitor the humidity level. This was constructed on a Friday afternoon and left to build up humidity over the weekend. By the following Monday, the chamber had reached 90% relative humidity (RH). A coconut sample was weighed to the ten thousandth place using a precision balance and the curve of the sample photographed. The flex of the sample before humidification and after humidification was also documented by pressing down with one finger on the center of the sample and taking a photograph. This method of documentation, however, was deemed too inconsistent as there was no way to measure the actual force being placed on the sample and photos did not accurately represent the flex. The sample was then placed in the 90% RH chamber and monitored every few days. The same measurements done prior to placing the sample into the chamber were repeated at each check-in. After two weeks in the chamber, the sample had gained 0.1444 grams, or about 5% of its total weight. At this point there was a large amount of mold growth on the surface of the coconut shell sample and so it was removed from the chamber. Although not part of the scope of this study, it should be noted that coconut shell is susceptible to biological growth at high relative humidity.

Table 6: Initial Humidity Testing of a Coconut Shell Sample

Date	Weight (grams)	Time elapsed (days)	Weight change (grams)	Percent weight change
1/21/19	2.8678	0	0	0.00
1/23/19	2.9969	2	0.1291	4.50
1/24/19	2.9999	3	0.1321	4.61
1/25/19	3.0014	4	0.1336	4.66
1/29/19	3.0078	8	0.1400	4.88
2/1/19	3.0093	11	0.1415	4.93
2/2/19	3.0104	12	0.1426	4.97
2/4/19	3.0122	14	0.1444	5.04

Due to this propensity for mold growth around the two week mark and noticing that the weight gain plateaued near 5% at eleven days, it was decided that for humidity cycling a time frame of ten days would be enough for the samples to adjust. The two extremes of relative humidity selected were 0% RH and 75% RH. Although it would be interesting to study the effect of higher humidity ranges on coconut shell, 75% relative humidity was chosen to avoid mold growth during the humidity cycling and due to the accessibility of the salt solution (sodium chloride) needed to maintain this humidity.

Ten pre-cut samples were selected for humidity cycling, one from each bowl. On the exterior of each sample, three pencil marks were made along the length and along the width. These marked areas designate where each sample will be measured between humidity cycles to measure dimensional change. All samples were then weighed to the ten thousandth place using a precision balance and recorded in a spreadsheet. Each sample was then imaged using a Keyence VHX 6000 digital optical microscope at twenty times magnification (the lowest magnification on the microscope). Due to the size of the samples this was done using stitched images. Using the linear measurement tool on the Keyence, the three width and length marks were measured to the hundredth millimeter. Each measurement (W1, W2, W3, H1, H2, H3) was taken as an average of three readings to mitigate human error.

Once all measurements were taken and recorded, the samples were placed into a prepared desiccator at 0% RH. These were allowed to adjust for ten days before being removed, weighed, and measured exactly as done prior to the ten day cycle. While the samples were being desiccated at 0% RH, a humidity chamber was made to approximately 75% RH. This was done using beakers of a saturated salt solution made of sodium chloride in deionized water and calculated for the volume of the chamber (Piechota 1992). The relative humidity inside the chamber was monitored with cobalt strips and a dial hygrometer to ensure a consistent RH. The samples were immediately transferred to the 75% RH chamber following inter-cycle measurements and allowed to adjust for another ten days. Once this cycle was completed, measurements were taken and the samples were transferred back to the 0% RH chamber. After another ten days, the samples were removed from the desiccator and final measurements were taken.

Table 7: Humidity Cycling Averages

		Average	Average change	Percent change
Before cycling	Weight (grams)	1.83	--	--
	Width (mm)	24.90	--	--
	Length (mm)	24.23	--	--
After 10 days at 0% RH	Weight (grams)	1.75	-0.08	-4.51
	Width (mm)	25.21	0.31	1.23
	Length (mm)	24.44	0.21	0.86
After 10 days at 75% RH	Weight (grams)	1.89	0.14	7.99
	Width (mm)	25.22	0.01	0.06
	Length (mm)	24.70	0.26	1.05
After 10 days at 0% RH	Weight (grams)	1.75	-0.14	-7.17
	Width (mm)	24.88	-0.34	-1.36
	Length (mm)	24.17	-0.54	-2.17

4.2.1 Humidity Cycling Results

Photographs taken under low magnification prior to and following humidity cycling showed no visible change to the samples themselves. No shrinkage was observed following desiccation nor was any expansion noted following exposure to high humidity. The expected macroscopic or microscopic cracks that appears in wood from anisotropic reactions to fluctuating humidity was also not observed in the coconut shell samples (Mecklenburg, et. al. 1998).

With regards to the dimensional measurements, minimal to no change was observed in the length and width of the samples. This stands in stark contrast to the significant average 5-8% percent weight change. It is possible there is dimensional change in the thickness of the sample, however this was not measured. Rather than causing dimensional change, the rigid yet porous network of the coconut shell may be able to absorb and desorb water vapor without causing stress to the structure. Due to the fact that the shell serves to hold coconut water, this is likely the case; even when in constant contact with moisture, the shell structure must retain its integrity. Knowledge of this property of coconut shell by many civilizations can be evidenced by its wide usage as a vessel for water, ink, and other liquids (Pitt Rivers Museum 2015; Penn Museum 2019).

4.3 Light Aging

Due to the lack of literature on the response of coconut shell to light and UV, samples were light aged for a total period of 15 days. This was done using a Q-SUN Xenon Test Chamber Model Xe-1-B with a Window Q filter, which allows for conditions similar to a window-lit room without UV filtration. Samples were exposed to a range of light similar to that allowed through a typical single-pane window on a summer afternoon with a cutoff of 310nm. For light aging cycles, the chamber was set to 0.26 W/m^2 at 420 nm and a temperature of 40°C for five days at a time. According to calculations done by Ellen Pearlstein and Sean Fowler (Q-Lab Technical Marketing Specialist), these settings would expose samples to an average of 20,700 incident lux, measured in the visible range, or 116 W/m^2 per hour. Over the course of a day, this would be approximately 496,800 lux per day (24 hours) , 90% the amount of light a moderately sensitive material (ISO 4, 5, and 6), such as wood, would be exposed to over a year at the recommended 150 lux maximum museum lighting (Michalski 2018). A blue wool standard card was placed into the chamber with the samples as another way of measuring the light dosage.

In order to examine the effects of museum lighting on coconut shell color and appearance, qualitative evaluation of the shell surface prior to and following light aging was done using the colorimeter function of a Spectro densitometer. A colorimeter applies the CIE*LAB (International Commission of Illumination) system to describe reflected or transmitted color mathematically through the use of a defined light source and a characteristic response. In the CIE*LAB System, color is described in three dimensions with the values of L*, a*, and b*.

The instrument used for these measurements was an X-Rite®939 Spectro densitometer. In this instrument, the illumination/detection angle is fixed to 0/45 ° and the spot site is 1cm. Due to the geometry and size of the coconut shell, the Spectro densitometer was opened like a stapler to take measurements. Each measured L*, a*, and b* value is the result of 6 averaged measurements. All values were recorded in an Excel spreadsheet. These measurements were taken before placement in the light aging chamber and subsequently after 5, 10, and 15 days of light aging. Individual Mylar templates were used for each sample to ensure all measurements were being taken in the same area each time.

The overall change in L*, a*, and b* values was calculated after each aging cycle (5, 10, and 15 days, respectively). These values were calculated to determine the overall color change referred to as ΔE. In 1976, the CIE published a color difference formula that is referred to as the CIE*76 or CIE*LAB. Since the original equation in 1976, the formula has been updated, once in 1994 (CIE'94) and again in 2000 (CIE'00). In order to provide more comprehensive results, the ΔE values for each CIE formula were plugged into a free spreadsheet provided by Color Conversion Center, http://ccc.orgfree.com/ and are reported in the appendix.

In order to assess the significance of change recorded by these values, research was done into what constitutes a perceptible change to the human eye. Based on this literature search (Michalski 2018; Beltran 2018), three categories were created: a ΔE'00 below two, a ΔE'00 from two to three, and a ΔE'00 of three and above. The first category will be considered acceptable color change, the second category represents just noticeable change, and the third category represents significant and unacceptable color change. These numerical results were then compared to photographs taken of the samples before light aging, after five days, after ten days, and after fifteen days of light aging.

4.3.1 Light Aging Results

Based on the average ΔE'00 calculations seen in Table 8, significant visual change occurred in the coconut shell samples after ten days of light exposure, the equivalent of 4.97 Mlx hours. After five days of light aging, four of the 10 samples had surpassed the threshold of a ΔE_{00} of two, five after 10 days, and eight after 15 days. Based on Michalski's (2018) research into the dosing necessary to just noticeably fade ISO blue wool standards with UV present, this would place coconut shell between ISO 4 (3.5 Mlx to fade) and ISO 5 (8 Mlx to fade). In the images taken of the samples between cycles (seen in Appendix) a perceptible amount of fading can be observed, reinforcing the numerical results. Based on the raw data, which is reported in the Appendix, a general trend of lightening can be seen in all samples as the L* value increased for all samples after each cycle with the exception of sample ten, which decreased or darkened slightly after each light aging cycle. Although this was not investigated, this darkening could be related to the amount of lignin in this sample in relation to the other samples. Both a* and b* values also showed general increasing trends, although less consistently than the L* values across all samples.

Table 8: Average Light Aging Data

	ΔE_{76}			ΔE_{94}			ΔE_{00}		
	5 days	10 days	15 days	5 days	10 days	15 days	5 days	10 days	15 days
Average	2.30	3.29	4.37	1.96	2.81	3.65	1.75	2.54	3.27
Minimum	0.66	0.64	1.47	0.65	0.53	0.96	0.53	0.73	1.13
Maximum	3.94	7.38	9.24	3.24	5.71	6.98	3.17	5.77	7.01

(green) Acceptable color change	(yellow) Noticeable color change	(red) Unacceptable color change

4.4 Oddy Test

During my survey of museum objects in the Fowler Museum and online, I encountered many worked coconut shell composite objects including ornately decorated vessels from Europe and the Americas. Many of these vessels are made of a whole carved coconut shell cut open at the top and mounted on worked silver, gold, or gilt copper. Because of the coconut's close proximity to these metals and display in enclosed vitrines with other metalwork, I was curious if the coconut releases any volatile organic compounds (VOCs). In order to explore this research question, I decided to conduct an Oddy test using samples from the coconut shell bowls. All Oddy test steps were done following the Brooklyn Museum guidelines and placed in the oven for 28 days at 60°C. In order to achieve two grams of sample for each test jar, approximately six to eight 1x1cm shell pieces were needed per bowl. All metal coupons were laid out and imaged prior to testing for comparison.

4.4.1 Oddy Test Results

Initial observations of the coupons were that the lead coupons had a large amount of white, pink, and yellow corrosion products compared to the control sample. Only five jars could be opened and one lid was broken in order to retrieve a lead coupon that had fallen off of the beaker rim and was being compromised by abrasion. These six coupons were laid out and imaged in the same manner as before the test. The copper and silver coupons all appeared identical to the control coupons. The copper coupons appear darker on the side that was folded inside the small beaker, but this was consistent across all samples and the control. The exposed lead coupons consistently showed more corrosion products than the control and is cause for concern. Samples of the lead corrosion products were taken for analysis using x-ray diffraction (XRD).

All six samples (including the control) were run on a Rigaku R-AXIS Spider powder diffractometer at 50 kV, 40 mA, for a run time of 20 minutes and using a Cu-α target. The sample was mounted on a glass spindle using Apiezon N grease. Data was processed using Rigaku's 2D software and identified using the program Jade 8.3, which contains a database of reference spectra from the International Center for Diffraction Data (ICDD). The resulting spectra can be found in the appendix. In these samples, a lead carbonate hydroxide, plumbonacrite ($Pb_5O(OH)_2(CO_3)_3$) was identified as a possible corrosion product. This product is very similar to hydrocerussite ($Pb_3(CO_3)_2(OH)_2$.

5. Compatible Conservation Materials

5.1 Bond Strength Testing

To begin assessing compatible adhesives for coconut shell, a literature review of wooden object conservation treatments was done (Rice 1989; Young et al. 2002; Williams 2015; Tsetskeou, Platanianki, and Pournou 2018). Because wood is a similar organic material to coconut shell that has undergone extensive research for identifying compatible conservation materials, four adhesives popular for wood repairs were chosen for testing: Paraloid B72 (an ethyl methacrylate and methyl acrylate copolymer resin), Jade R (a polyvinyl acetate and ethylene vinyl acetate copolymer aqueous emulsion modified to be reversible in water), hide glue, and Lascaux 360 (a water-based dispersion of butyl acrylate and methyl methacrylate thickened with acrylic butyl ester). Four comparable 5 x 2 cm samples were cut and breaks were made in the middle of each sample in the latitudinal direction by pushing down on the center until it broke in half. Attempts to cut the samples in half did not work as the hacksaw removed too much material during the cutting process, creating a gap not found in naturally produced breaks. Once broken, each sample was adhered with a different adhesive, clamped in place, and allowed to set for four days. When removing the clamps from the samples adhered with hide glue and Lascaux, the joins immediately failed and so these adhesives were eliminated from the study. This left the Paraloid B72 and Jade R for continued testing.

Initially, the adhered samples were to be tested for bond strength using a tensile testing instrument, most likely the three-point bend test. However, the joins easily failed by simply pressing down on top of the curved sample and the general curved geometry of the coconut shell samples would not allow for the samples to remain in place for an accurate quantitative tensile test. Because of this, research was done to find a bond strength test that would give qualitative results and could be done on the coconut shell samples regardless of their geometry. Additionally, it was decided that the more realistic test for bond strength would be one that pulled on the join parallel to the surface rather than pushed the join perpendicular to the surface.

A conservation literature search led to the tests done at Kaman-Kalehöyük by Ida Pohoriljakova and Sara A. Moy to assess adhesives used for ceramics mends at the site's conservation lab (Pohoriljakova and Moy 2013). Although their studies were focused on finding appropriate adhesives for an inorganic material in fluctuating environmental conditions, their test is one that could be adapted to measure bond strength of adhesives to coconut shell.

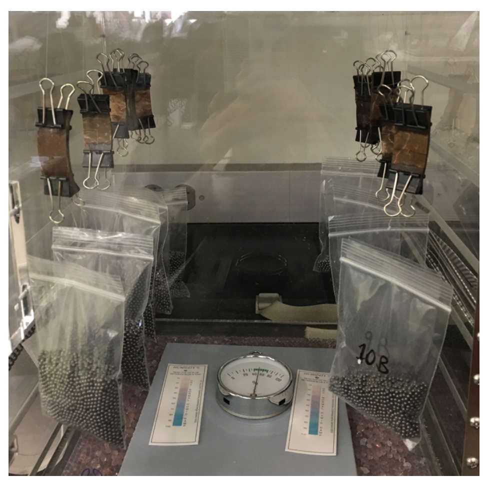


Figure 7: Set up of coconut shell samples for adhesive testing. Image by author.

Two trial runs were done to determine a good starting weight for each adhesive. Two samples, one per adhesive, were cut and then sanded to a consistent size before being mechanically broken in half. One binder clip was then adhered to each half of the sample with the Buehler EpoxiCure™ 2 epoxy system. Once this had cured, one sample was adhered with 30% Paraloid B-72 in acetone and one was adhered with Jade R. After a week of curing, these samples were hung in a 50% RH chamber using monofilament and a polyethylene bag filled with a specific weight of lead shot was attached to the bottom binder clip using another strand of monofilament. The weight load on each B-72 sample was increased by 50g every 24 hours and every hour for the Jade R sample. Unfortunately, only the approximate day of failure for the Paraloid B-72 trial is known. The results of these two trials can be seen in the tables below.

Table 9: Paraloid B-72 Adhesive Strength Trial

Hours	Weight	Observations
0	150g	No change
24	200g	No change
29	250g	No change
48	300g	No change
145	350g	No change
169	400g	No change
170 > x > 385	400g	Completely detached

Table 10: Jade R Adhesive Strength Trial

Hours	Weight	Observations
0	100g	No change
1	150g	No change
2	200g	Slight deformation of the join almost immediately
3	250g	Severe deformation of the join
4	300g	No change
5	350g	No change
6	400g	No change
23	400g	Completely detached

Based on these results, it was decided to conduct two trials for each adhesive. Five samples were tested with a consistent weight over a longer period of time while five additional samples were tested over a day with increasing loads. All of these tests were done at a consistent RH of 50%. For each adhesive, ten samples were prepared in the same manner as the trial. To ensure consistent application of the adhesives on all samples, Jade R and Paraloid B-72 (40% in acetone) were placed into polyethylene squeeze bottles and the adhesive applied to the join in one single line. All samples were allowed to set for a week before testing began. Additionally, the thickness of each coconut sample was recorded to see how thickness plays a role in the strength of the join.

Table 11: Thickness of Coconut Test Samples

	1	2	3	4	5	6	7	8	9	10
a (B-72)	2.0 mm	2.5 mm	1.5 mm	3.5 mm	3.1 mm	1.1 mm	2.5 mm	2.0 mm	1.2 mm	2.0 mm
b (Jade R)	1.5 mm	2.5 mm	1.5 mm	3.0 mm	2.1 mm	1.5 mm	2.7 mm	2.0 mm	2.0 mm	2.5 mm

Sample numbers 1-5 were tested over the short-term, while sample numbers 6-10 were tested over the long-term. Based on the trial runs, 375g was chosen as the weight for long-term testing of B-72 while 175g was chosen as the weight for long-term Jade R testing. The B-72 short-term tests started with a weight of 250g while the Jade R short-term tests started with a weight of 150g. The weight was increased in increments of 25g for both short-term trials. For these tests, any deformation of the join was considered failure although the tests were continued to determine the point of complete detachment.

5.2 Bond Strength Test Results:

Three observation categories were made: green– "OK", no deformation of the join; orange – deformation of the join, failure point; red – complete detachment. The results of these tests can be seen in the tables below. With Paraloid B-72, none of the samples failed in the short-term test. By the end of the day, the weights were increased more frequently to try and induce failure, however there was still no observed deformation of the joins. The 600g weight was left overnight to see if any deformation would occur overnight. The next morning, the joins were all still intact and so the test was terminated at that time. It is clear that Paraloid B72 would provide the strength necessary to adhere structural breaks in coconut shell without deforming.

Table 12: Paraloid B-72 Short-Term Adhesive Bond Strength Test

	9:30 AM: 250g	10:30 AM: 275g	11:30 AM: 300g	12:30 PM: 325g	1:30 PM: 350g	2:30 PM: 375g	3:30 PM: 400g	4:30 PM: 425g	5:00 PM: 450g	5:30 PM: 475g	5:45 PM: 500g	6:00 PM: 525g	6:05 PM: 550g	6:20 PM: 600g	11:00 AM: 600g
1a	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
2a	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
3a	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
4a	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
5a	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

No deformation visible   Deformation of the join (fail)   Complete detachment

For the long-term testing, again none of the Paraloid B-72 samples failed. After almost two weeks, 375g of consistent weight had failed to deform any of the joins. At this point, the test was terminated. Future research should examine longer time frames to ensure the complete stability of these joins over time as the trial run samples failed in less than 16 days with a 400g load.

Table 13: Paraloid B-72 Long-Term Adhesive Bond Strength Test with 375g

	0 days	1 day	2 days	3 days	4 days	5 days	7 days	8 days	12 days
6a	OK	OK	OK	OK	OK	OK	OK	OK	OK
7a	OK	OK	OK	OK	OK	OK	OK	OK	OK
8a	OK	OK	OK	OK	OK	OK	OK	OK	OK
9a	OK	OK	OK	OK	OK	OK	OK	OK	OK
10a	OK	OK	OK	OK	OK	OK	OK	OK	OK

No deformation visible   Deformation of the join (fail)   Complete detachment

The results for the Jade R tests, were significantly different from the Paraloid B-72 tests; all joins failed in both tests. In the short-term test, all but one sample (4b) had failed, showing signs of both slight and significant deformation of the join. The one sample which did not deform, 4b, was also the thickest sample (3.0 mm). The two samples that deformed the most, 1b and 3b, were among the thinnest of the samples (1.5 mm). At a weight of 175g, all joins had failed through deformation of the join and with a weight of 275g all joins had completely detached. The last two samples to completely detach were 4b (the thickest sample) and 5b. Due to the rapid failure of joins at relatively low weights, Jade R could be used for surface cracks or for adhering Japanese tissue bridges, as was mentioned in Section 2.2, but would not be appropriate for a structural join.

Table 14: Jade R Short-Term Adhesive Bond Strength Test

	150g	175g	200g	225g	250g	275g
1b	ED	ED	CD	--	--	--
2b	IG	ED	ED	ED	CD	--
3b	ED	CD	--	--	--	--
4b	OK	IG	ED	ED	ED	CD
5b	IG	ED	ED	--	--	CD

No deformation visible (OK)

Deformation of the join (fail)
IG – interior gapping
ED – extreme deformation

Complete detachment (CD)

For the long-term testing of Jade R, all but one sample (7b) failed immediately with 175g. This also happened to be the thickest of the coconut shell pieces. After three days, this sample failed and after seven days, all five samples had completely detached. These findings reinforce the short-term Jade R test results and show that even at a low weight, joins are vulnerable to failure.

Table 15: Jade R Long-Term Adhesive Bond Strength Test with 175g

	0 days	1 day	2 days	3 days	4 days	5 days	7 days
6b	ED CD after 3 hrs.	--	--	--	--	--	--
7b	OK	OK	OK	IG	ED	CD	--
8b	IG	IG	IG	IG	IG	ED	CD
9b	ED CD after 1 hr.	--	--	--	--	--	--
10b	IG	ED	ED	ED	CD	--	--

Green	No deformation visible
Yellow	Deformation of the join (fail) IG – interior gapping ED – extreme deformation
Red	Complete detachment

6. Conclusions and Future Research

From this research, I hope to begin to show how coconut shell objects can be cared for in museum collections and where future research might fill in the gaps to better understand and care for this material. As was shown in the museum survey, coconut shell can be found in museum collections across the globe. Apart from coconut goblets popular in medieval Europe, many coconut shell objects have a limited display history and could provide an interesting baseline for future research in comparison with the goblets, which have an extensive display history. An examination and comparison of these objects could provide further evidence of the light fading I observed through testing. From humidity testing results, coconut shell is stable even in fluctuating environments and can be held at standard museum humidity guidelines (50 +/- 5%) without the need for a specific microclimate. Oddy test results indicate that further research needs to be done into the compounds released from coconut shell, and if this interaction between coconut shell and lead has been observed previously. This could perhaps be the reason coconut shell and lead composite objects are uncommon. Until this research can be done, as a precautionary measure coconut shell-containing objects should not be stored in close proximity to lead objects. Compatible adhesive testing and survey results indicate that adhesives such as Jade, methylcellulose, or wheat starch paste can be used with Japanese tissue bridges for surface or smaller cracks while a stronger adhesive such as Paraloid B72 would be necessary for structural repairs.

Appendix A: Coconut Bowl Sample Photos and Dimensions

Fig. 1: Exterior of coconut bowl samples (Group 1) in diffuse light. Taken with a D90 Nikon camera and color corrected.

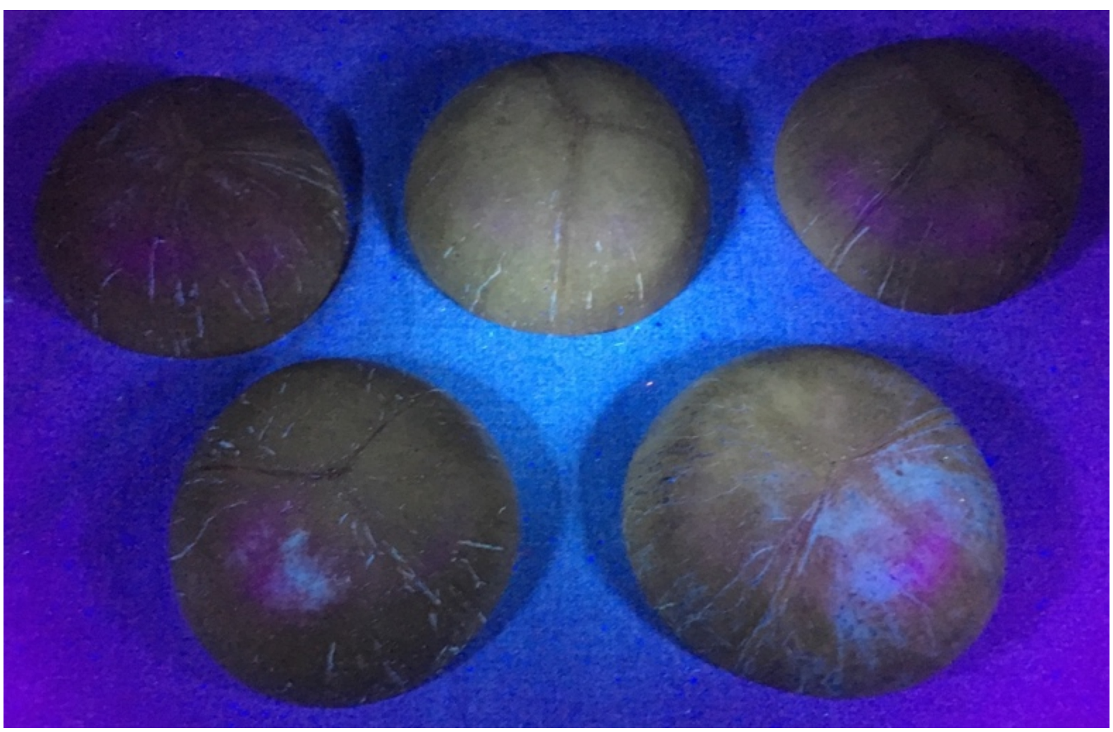


Fig. 2: Exterior of coconut bowl samples (Group 1) viewed under UV light (λ_{exc} = 365 nm). UV-induced visible fluorescence image was taken with an iPhone to capture fluorescence colors visible to the naked eye.

Fig. 3: Interior of coconut bowl samples (Group 1) in diffuse light. Taken with a D90 Nikon camera and color corrected.

Fig. 4: Interior of coconut bowl samples (Group 1) viewed under UV light (λ_{exc} = 365 nm). UV-induced visible fluorescence image was taken with an iPhone to capture fluorescence colors visible to the naked eye.

Fig. 5: Exterior of coconut bowl samples (Group 2) in diffuse light. Taken with a D90 Nikon camera and color corrected.

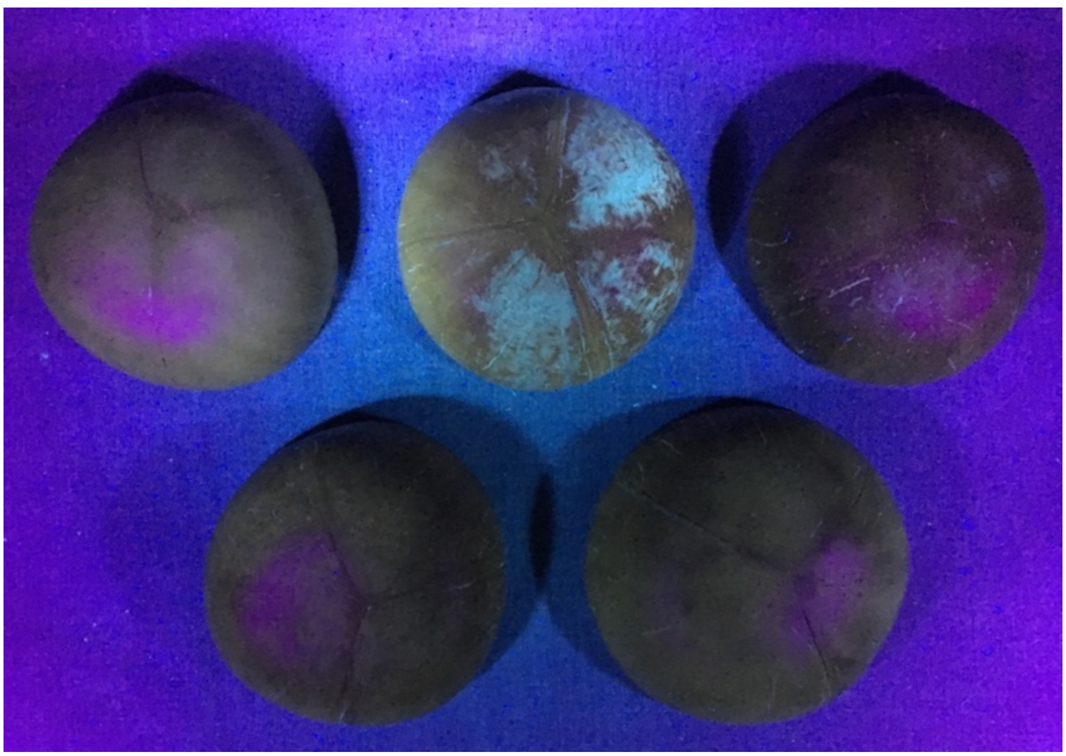


Fig. 6: Exterior of coconut bowl samples (Group 2) viewed under UV light (λ_{exc} = 365 nm). UV-induced visible fluorescence image was taken with an iPhone to capture fluorescence colors visible to the naked eye.

Fig. 7: Interior of coconut bowl samples (Group 2) in diffuse light. Taken with a D90 Nikon camera and color corrected.

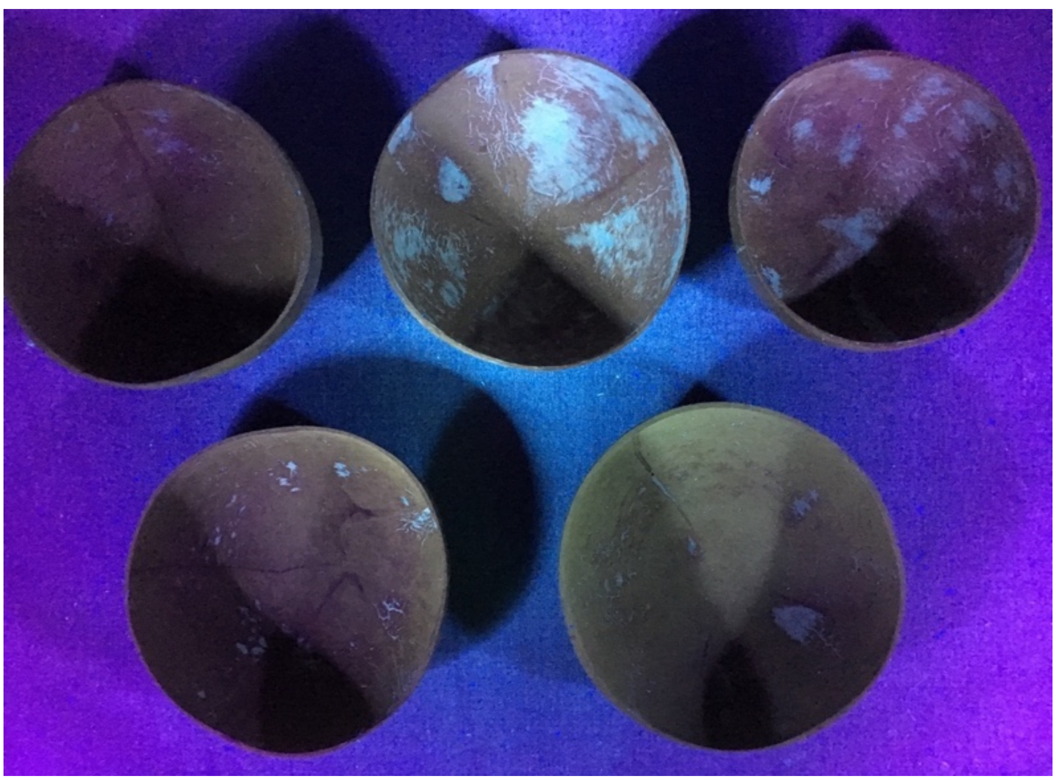


Fig. 8: Interior of coconut bowl samples (Group 2) viewed under UV light (λ_{exc} = 365 nm). UV-induced visible fluorescence image was taken with an iPhone to capture fluorescence colors visible to the naked eye.

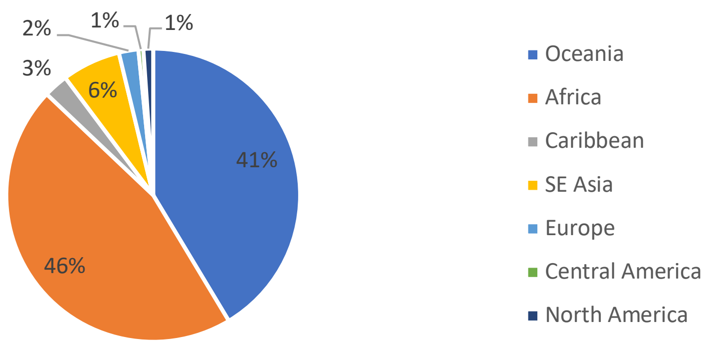
Table 1: Physical Properties of the Coconut Bowl Samples

Bowl Number	Diameter (cm)	Circumference (cm)	Height (cm)	Thickness (average) (cm)	Weight (grams)	Density* (g/cm^3)
1	14.3	43.5	5.5	0.2	71	1.17
2	14.2	42.7	5.6	0.2	62	1.03
3	14.4	43.1	6.2	0.2	61	0.97
4	14.2	42.5	6	0.3	88	0.98
5	13.5	40.7	6	0.2	77	1.39
6	13.9	42.1	5.5	0.2	60	1.04
7	14.8	44.3	6.6	0.2	97	1.46
8	15.4	46.7	5.9	0.2	72	1.02
9	13.3	40.2	5.3	0.2	64	1.21
10	15.3	45.3	6	0.3	105	1.01
Average	**14.3**	**43.1**	**5.9**	**0.2**	**75.7**	**1.13**

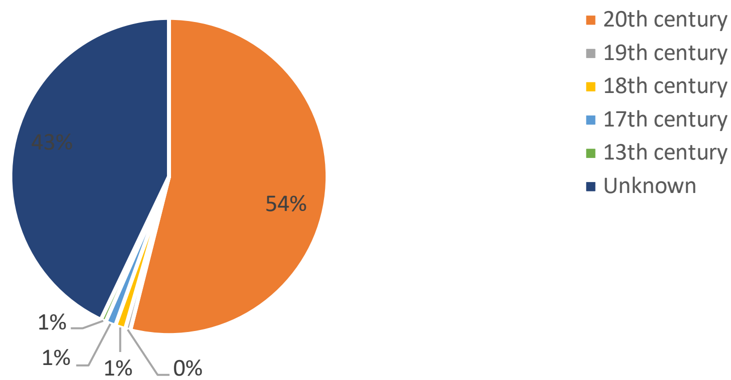
* Densities are approximate given the variability in thickness of the coconut shell and variation in geometry. The volume was calculated using the partial hemisphere volume formula to calculate total volume of the exterior measurements and then subtracting out the inner volume of the bowl. This calculated volume was then divided by the overall weight to calculate approximate densities.

Appendix B: Fowler Museum Survey Graphs

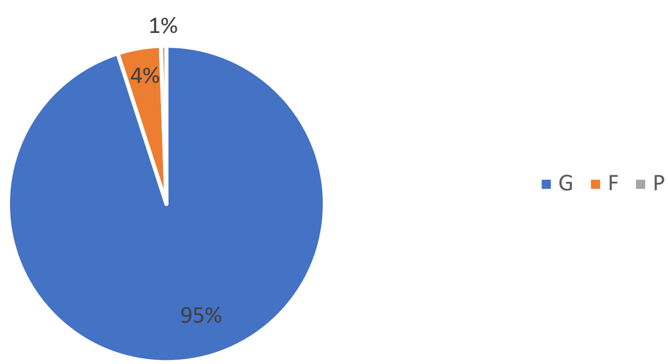
Fowler Coconut Objects by Region



Century of Manufacture of Fowler Objects



Condition of Fowler Coconut Material



Appendix C: Museum Survey Google Form

Coconut Shell Masters Thesis Survey

I am a current second-year student at the UCLA/Getty Masters Program in the Conservation of Archaeological and Ethnographic Materials. For my thesis research, I am seeking to address the lack of literature on the use, condition, and conservation protocol for coconut shell material in cultural heritage. In addition to examining the number, cultural context, and condition of coconut shell objects in the museum environment, I will be conducting mechanical testing on unaltered coconut shell samples and coconut shell samples adhered with different adhesives and bulking agents to fill the conservation knowledge gap. Please share as much information about the coconut shell materials in your institution as possible by January 18, 2019*. Thank you in advance for your participation!

*Please note the deadline has been extended!

* Required

Email address *

Your email

NEXT

Collection Information

The goal of this section is to assess the amount of objects utilizing coconut shell as a material, how these objects are categorized and searchable, and their cultural context.

Name of Institution

Your answer

Name of respondent

Your answer

Today's Date

MM DD YYYY

/ / 2019

Total number of objects in the collection.

Your answer

Is the term "coconut" or "coconut shell" searchable in your institution's database?

- ◯ Yes
- ◯ No
- ◯ Other:

What database does your museum use?

Your answer

Total number of coconut shell-containing objects in the collection.

Your answer

How did you come to this number?

- ◯ Database search
- ◯ Manual counting
- ◯ Approximation
- ◯ Other:

Please mark which general geographic areas these coconut shell objects originate from (check all that apply).

- ☐ Oceania
- ☐ Europe
- ☐ Americas
- ☐ Africa
- ☐ Asia
- ☐ Other: ____________________

Approximately what percentage of these objects were manufactured in the 20th-21st centuries?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

Approximately what percentage of these objects were manufactured between the 17th and 19th centuries?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

Approximately what percentage of these objects were manufactured before the 17th century?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

Approximately what percentage of the coconut shell objects have received conservation intervention (to the best of your knowledge)?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

If conservation intervention has occurred, what types of materials were utilized (adhesives, fill materials, etc.)? Please be specific.

Your answer

BACK NEXT

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Coconut Shell Manufacture Techniques

What type of objects are represented in this group? Check all that apply.

- [ ] Utilitarian (undecorated bowls, plates, spoons/ladles, for non-ceremonial purposes)
- [ ] Decorative (jewelry, statues, etc.)
- [ ] Folk Art (masks, dioramas, etc.)
- [ ] Musical Instruments
- [ ] Ceremonial (objects used for performances: containers, adornments)
- [ ] Other: ________________

What techniques have been applied to the coconut shell in these objects? Check all that apply.

- [ ] Carving
- [ ] Painting
- [ ] Inlay
- [ ] Gilding
- [ ] Other: ________________

For composite objects, what other materials are used in conjunction with coconut shell? Check all that apply.

- [ ] Plant/animal fiber
- [ ] Wood
- [ ] Paint
- [ ] Metal
- [ ] Glass/ceramic
- [ ] Plastic
- [ ] Other: ____________________

BACK NEXT

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Condition of Objects

Approximately what percentage of these objects have been on display in the past 50 years?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

What are the approximate temperature and relative humidity guidelines for your institution (gallery and/or storage)?

Your answer

Approximately what percentage of the coconut shell objects are in good condition (the object is structurally sound, no active deterioration, can go on display, loan, and be handled)?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

Approximately what percentage of the coconut shell objects are in fair condition (may have minor damage, previous repairs, must be handled carefully, and may require some intervention for display)?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

Approximately what percentage of the coconut shell objects are in poor condition (physical/chemical integrity of the shell is compromised and actively deteriorating and will not permit display or extensive handling)?

- ○ 80-100%
- ○ 50-75%
- ○ 20-45%
- ○ Less than 20%

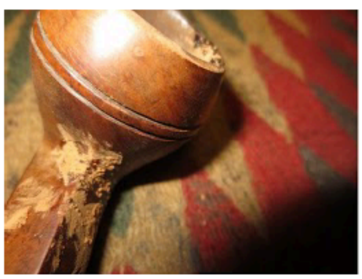
If you have observed deterioration of the coconut shell, which of the following conditions have you observed? Check all that apply.

☐ Cracking

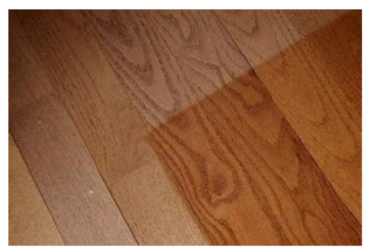
☐ Distortion

☐ Structural loss

☐ Delamination



☐ Surface chipping or loss



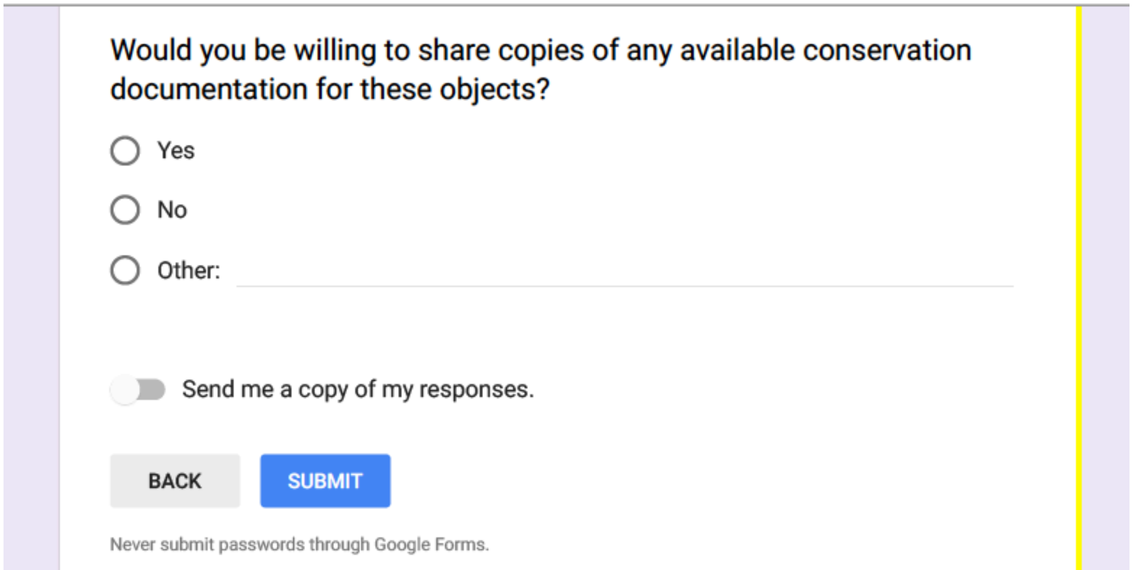
☐ Color change (fading, darkening, staining, etc.)

☐ Surface grime

☐ Insect infestation

☐ Biological damage (mold,

☐ Other:



Would you be willing to share copies of any available conservation documentation for these objects?

- Yes
- No
- Other: ______

Send me a copy of my responses.

BACK SUBMIT

Never submit passwords through Google Forms.

Appendix D: Portable FTIR Reports with Spectra

<u>Contents of this Appendix:</u>

<u>**Report and Spectrum A: Exterior of Coconut Shell Bowl 1**</u>

Agilent Technologies

Sample ID:B1_outside_2

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 1:33:43 PM

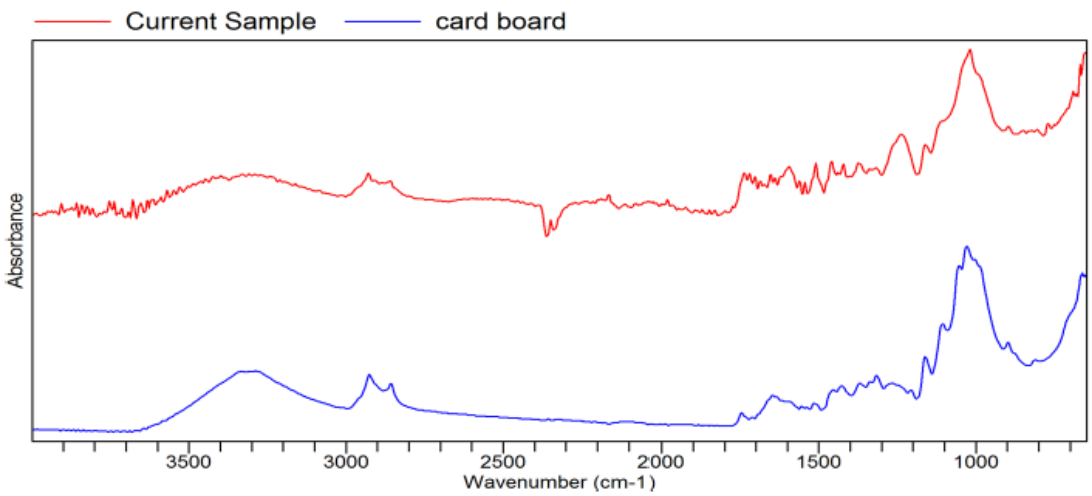
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB1_outside_2_2019-04-26T13-33-43.a2r



Quality	Library	CAS#	Name
0.92092	ATR Demo Library (19)		card board
0.89478	ATR Demo Library (53)		wood
0.89452	Agilent Elastomer Oring and Seal Handheld ATR Library (99)		Ethylene Propylene EPR 618337 Run#5

4/26/2019 1:34:40 PM

Spectrum B: Interior of Coconut Shell Bowl 2

Agilent Technologies

Sample ID:B2_inside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 1:44:08 PM

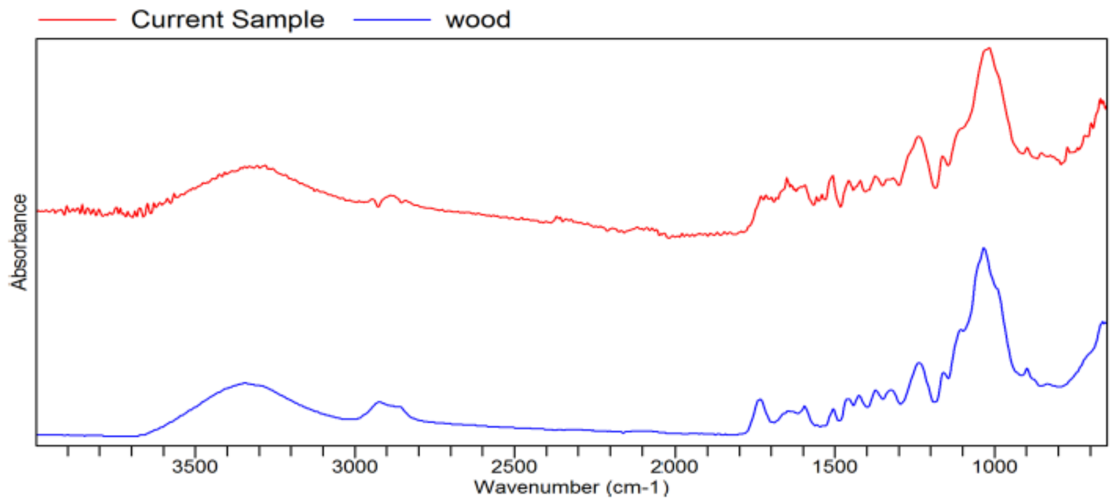
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB2_inside_1_2019-04-26T13-44-08.a2r



Quality	Library	CAS#	Name
0.93016	ATR Demo Library (53)		wood
0.89821	ATR Demo Library (19)		card board
0.87628	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

4/26/2019 1:44:53 PM

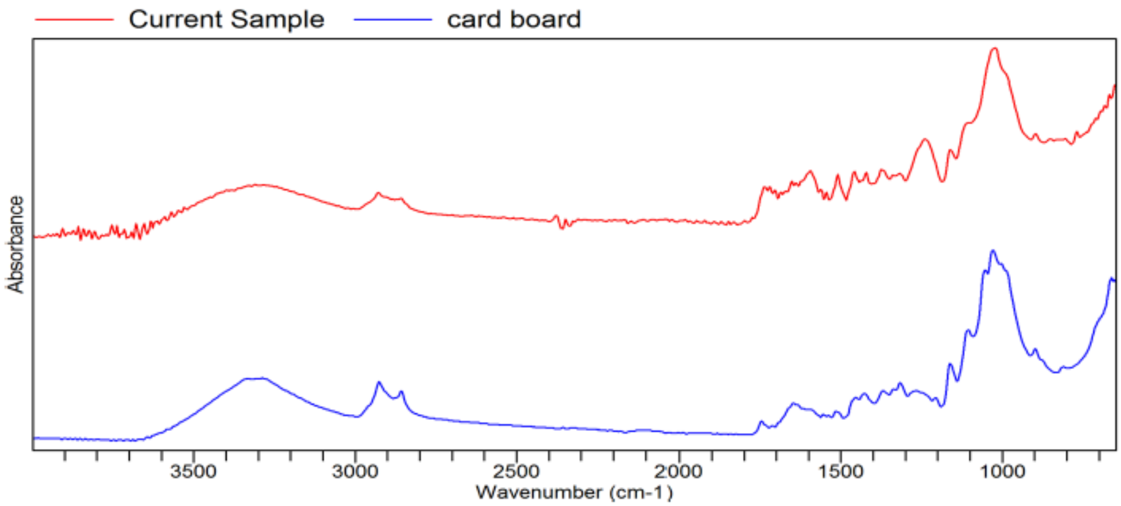
page 1 of 4

<u>**Spectrum C: Exterior of Coconut Shell Bowl 2**</u>

Agilent Technologies

Sample ID:B2_outside_1	Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m
Sample Scans:32	User:admin
Background Scans:32	Date/Time:04/26/2019 1:37:48 PM
Resolution: 8	Range:4000 - 650
System Status: Good	Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB2_outside_1_2019-04-26T13-37-48.a2r



Quality	Library	CAS#	Name
0.92061	ATR Demo Library (19)		card board
0.90712	ATR Demo Library (53)		wood
0.89710	Agilent Elastomer Oring and Seal Handheld ATR Library (99)		Ethylene Propylene EPR 618337 Run#5

Spectrum D: Exterior of Coconut Shell Bowl 3

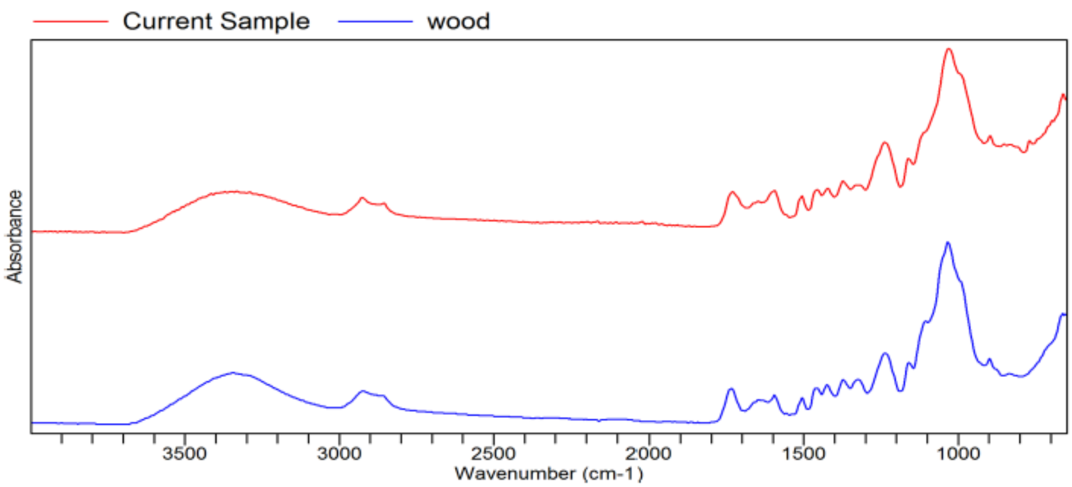
Agilent Technologies

Sample ID:B3_outside_2

Sample Scans:32
Background Scans:32
Resolution: 8
System Status: Good

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m
User:admin
Date/Time:04/26/2019 1:53:08 PM
Range:4000 - 650
Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB3_outside_2_2019-04-26T13-53-08.a2r



Quality	Library	CAS#	Name
0.93556	ATR Demo Library (53)		wood
0.93369	ATR Demo Library (19)		card board
0.90232	Agilent Elastomer Oring and Seal Handheld ATR Library (99)		Ethylene Propylene EPR 618337 Run#5

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Spectrum E: Exterior of Coconut Shell Bowl 4

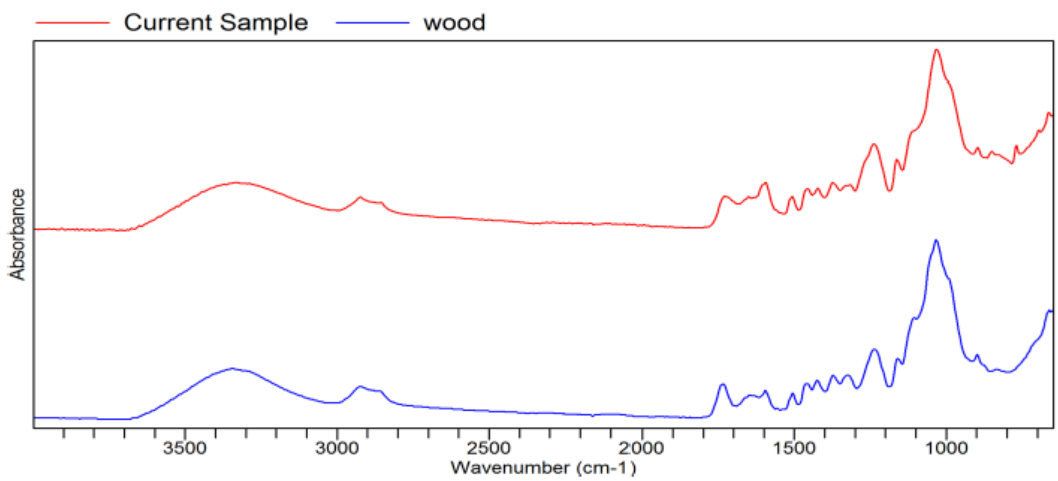
Agilent Technologies

Sample ID:B4_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32
User:admin
Background Scans:32
Date/Time:04/26/2019 1:55:23 PM
Resolution: 8
Range:4000 - 650
System Status: Good
Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB4_outside_1_2019-04-26T13-55-23.a2r



Quality	Library	CAS#	Name
0.96499	ATR Demo Library (53)		wood
0.94357	ATR Demo Library (19)		card board
0.91270	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

4/26/2019 1:55:38 PM page 1 of 4

Spectrum F: Exterior of Coconut Shell Bowl 5

Agilent Technologies

Sample ID:B5_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 1:46:12 PM

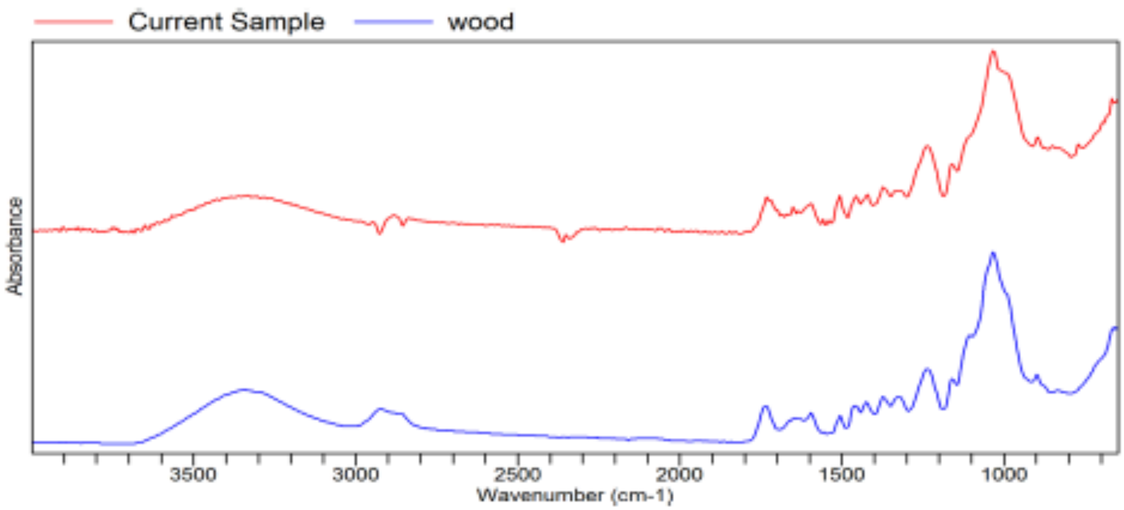
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB5_outside_1_2019-04-26T13-46-12.a2r



Quality	Library	CAS#	Name
0.92227	ATR Demo Library (53)		wood
0.91274	ATR Demo Library (19)		card board
0.88220	Agilent Elastomer Oring and Seal Handheld ATR Library (99)		Ethylene Propylene EPR 618337 Run#5

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<u>**Spectrum G: Exterior of Coconut Shell Bowl 6**</u>

Agilent Technologies

Sample ID:B6_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

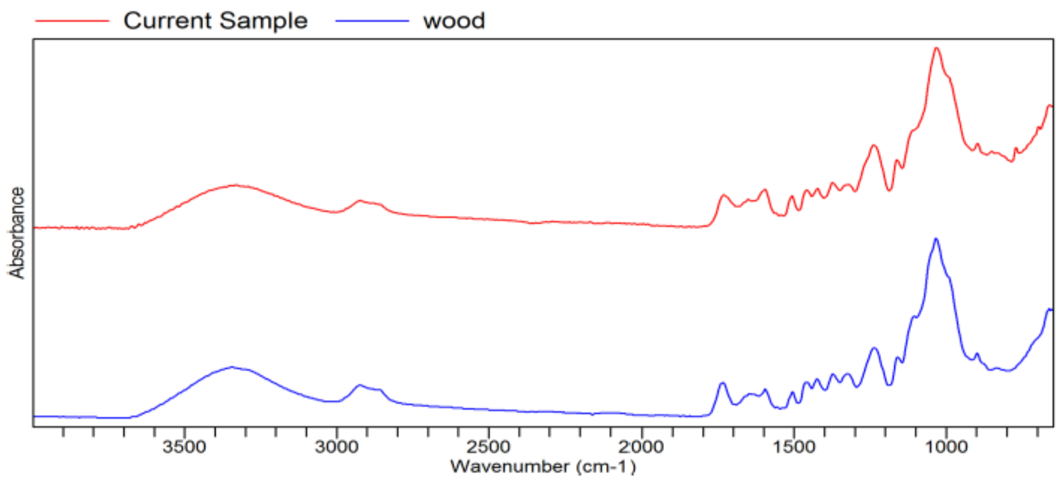
Sample Scans:32
User:admin

Background Scans:32
Date/Time:04/26/2019 1:56:12 PM

Resolution: 8
Range:4000 - 650

System Status: Good
Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB6_outside_1_2019-04-26T13-56-12.a2r



Quality	Library	CAS#	Name
0.96399	ATR Demo Library (53)		wood
0.94554	ATR Demo Library (19)		card board
0.91348	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

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Spectrum H: Exterior of Coconut Shell Bowl 7

Agilent Technologies

Sample ID:B7_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 1:57:33 PM

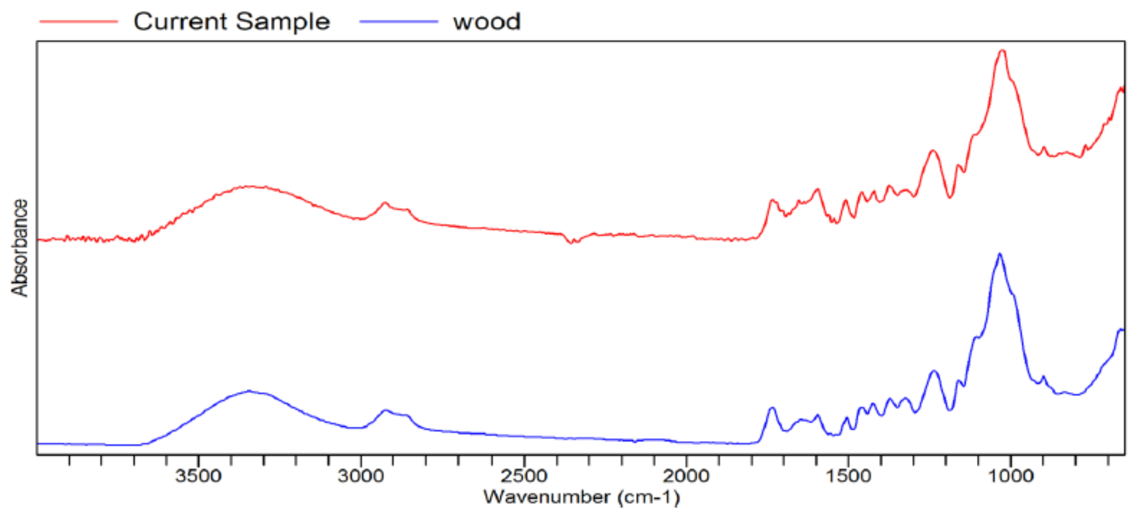
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB7_outside_1_2019-04-26T13-57-33.a2r



Quality	Library	CAS#	Name
0.94961	ATR Demo Library (53)		wood
0.94851	ATR Demo Library (19)		card board
0.90568	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

4/26/2019 1:57:47 PM

Spectrum I: Exterior of Coconut Shell Bowl 8

Agilent Technologies

Sample ID:B8_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 1:58:46 PM

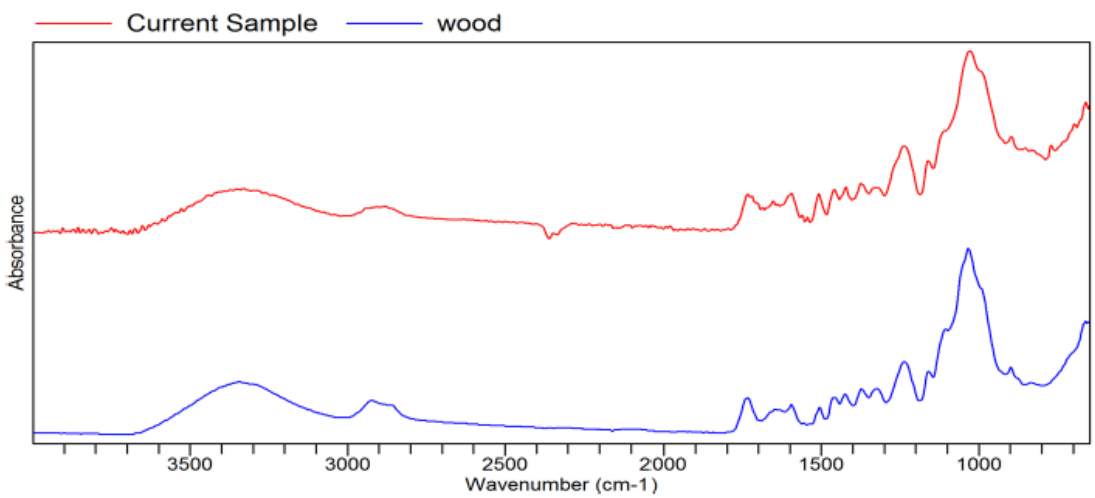
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB8_outside_1_2019-04-26T13-58-46.a2r



Quality	Library	CAS#	Name
0.94704	ATR Demo Library (53)		wood
0.93709	ATR Demo Library (19)		card board
0.90065	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

Spectrum J: Exterior of Coconut Shell Bowl 9

Agilent Technologies

Sample ID:B9_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

Sample Scans:32

User:admin

Background Scans:32

Date/Time:04/26/2019 2:00:13 PM

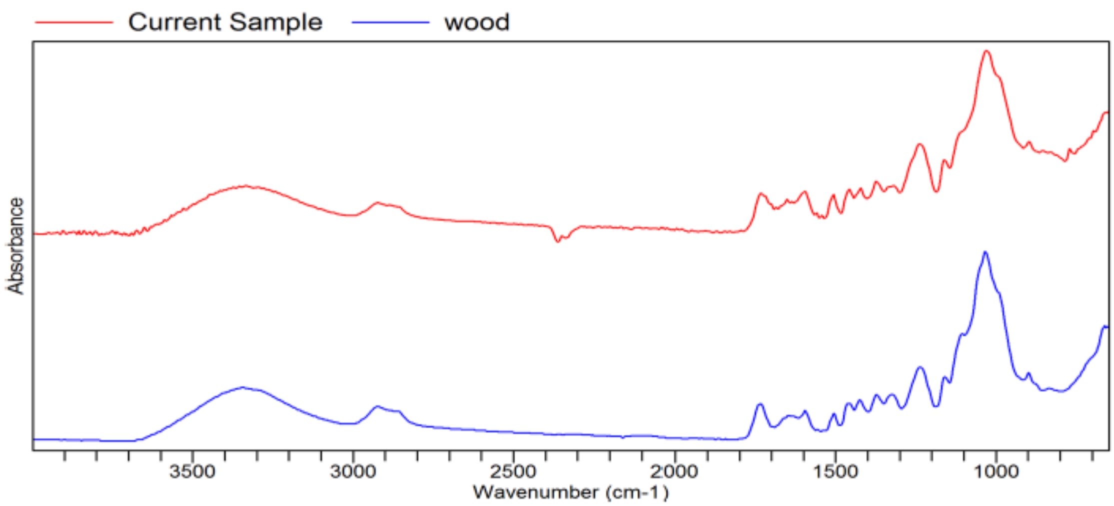
Resolution: 8

Range:4000 - 650

System Status: Good

Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB9_outside_1_2019-04-26T14-00-13.a2r



Quality	Library	CAS#	Name
0.95600	ATR Demo Library (53)		wood
0.93642	ATR Demo Library (19)		card board
0.90304	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

4/26/2019 2:00:29 PM page 1 of 4

Spectrum K: Exterior of Coconut Shell Bowl 10

Agilent Technologies

Sample ID:B10_outside_1

Method Name:C:\Users\Public\Documents\Agilent\MicroLab\Methods\Elena.a2m

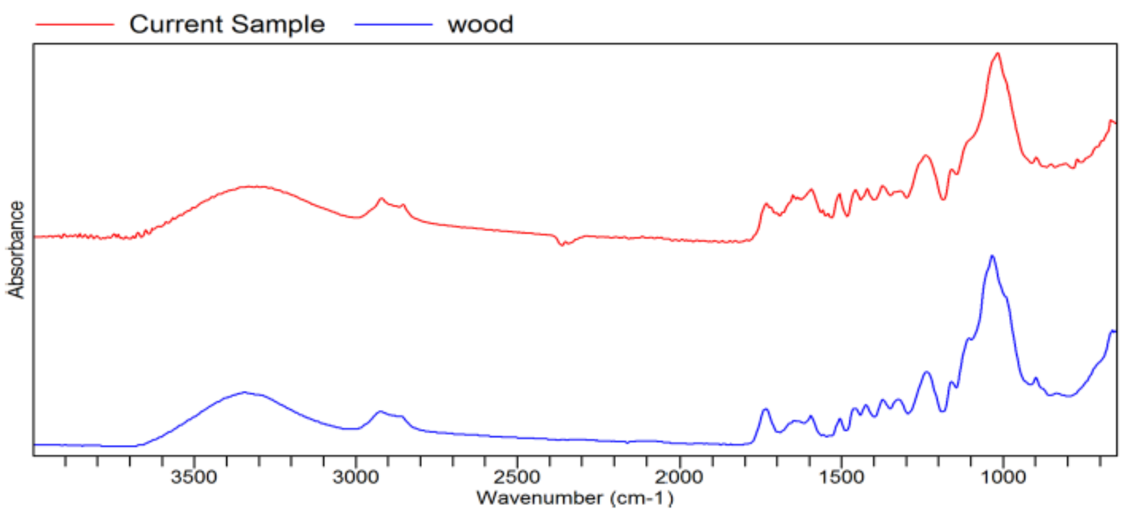
Sample Scans:32
User:admin

Background Scans:32
Date/Time:04/26/2019 1:47:57 PM

Resolution: 8
Range:4000 - 650

System Status: Good
Apodization:Triangular

File Location:C:\Users\Public\Documents\Agilent\MicroLab\Results\\FileLocationB10_outside_1_2019-04-26T13-47-57.a2r



Quality	Library	CAS#	Name
0.95586	ATR Demo Library (53)		wood
0.93830	ATR Demo Library (19)		card board
0.90470	Agilent Polymer Handheld ATR Library (12)		Cellulose Filter Paper

Appendix E: Humidity Cycling Images, Results Table, and Graphs

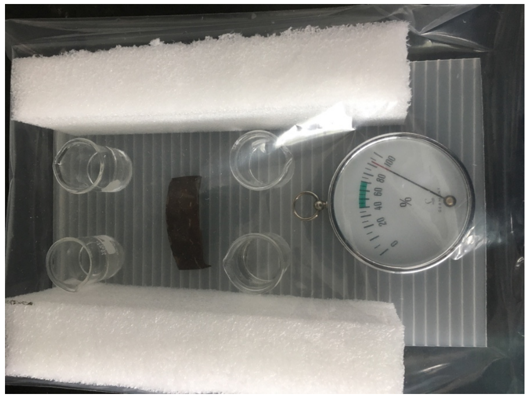


Fig. 1: Humidity chamber test set up at 90% RH.

Fig. 2: Coconut sample prior to humidification.

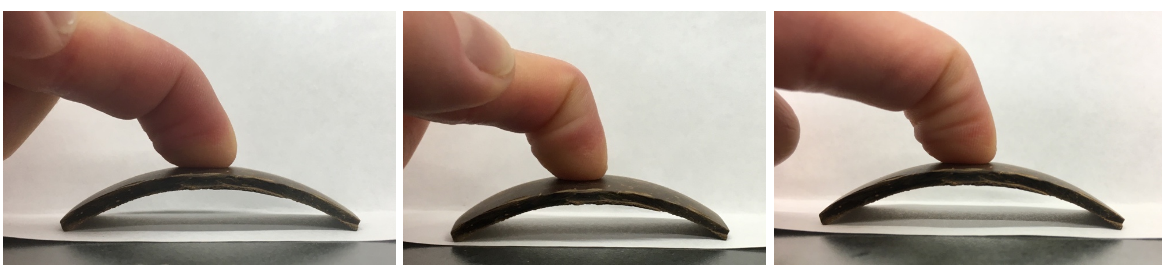


Fig. 3: Coconut sample after 2, 3, and 4 days of humidification. There was no apparent change in flexibility and due to the different camera angles and human error, it was determined that this was not a good measure of flexibility.

Table 1: Humidity Cycling Raw Data

	Sample	1	2	3	4	5	6	7	8	9	10
Before Cycling	Weight (grams)	1.7091	1.6073	1.6147	2.2222	1.8214	1.9846	2.0819	2.0499	1.6227	1.5809
	W1 (mm)	25.21	24.68	26.62	24.99	23.57	25.19	26.07	27.05	24.12	25.70
	W2 (mm)	24.83	24.16	26.91	24.04	24.53	24.68	25.71	25.87	23.61	25.48

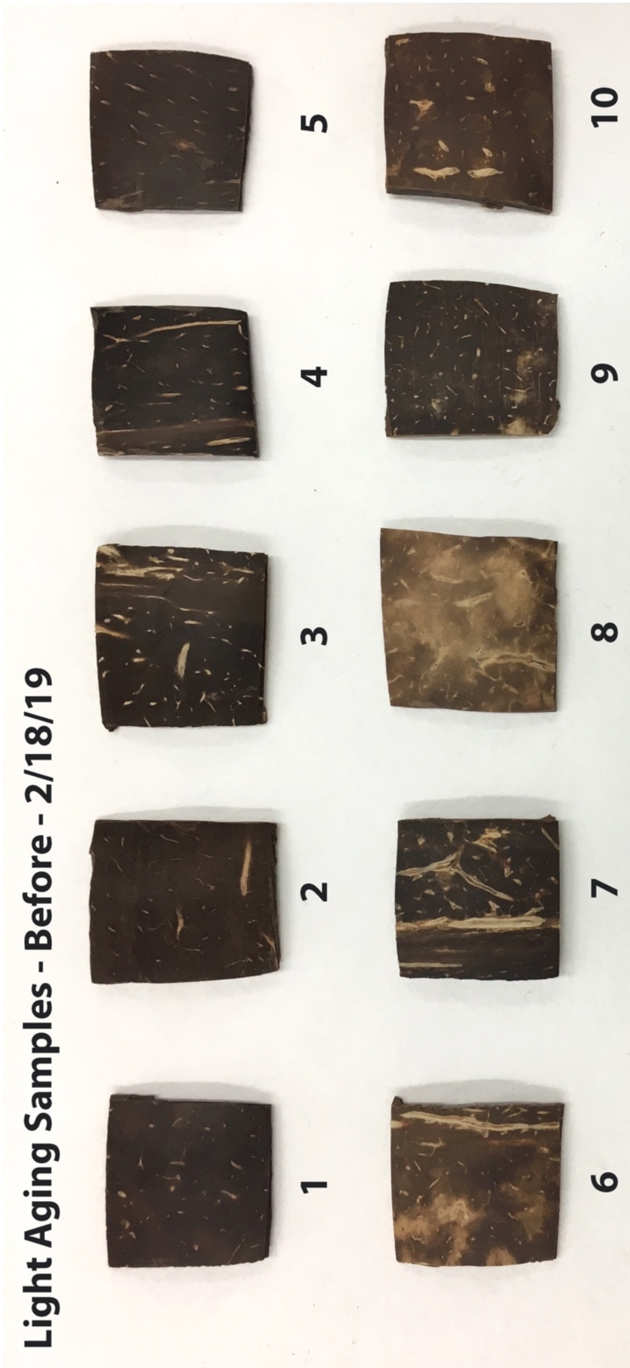
	W3 (mm)	24.92	23.83	26.81	23.18	24.26	22.82	25.54	25.45	22.32	24.80
	L1 (mm)	23.28	24.24	23.12	23.93	23.22	25.64	24.20	23.92	24.42	25.14
	L2 (mm)	23.92	24.62	23.17	24.29	23.49	25.88	24.53	24.01	24.55	25.07
	L3 (mm)	23.80	24.80	23.16	24.09	23.64	25.56	24.54	23.72	24.72	24.34
After 10 Days at 0% RH	Weight (grams)	1.6295	1.5347	1.5422	2.1214	1.7413	1.8945	1.9872	1.9541	1.5540	1.5112
	W1 (mm)	25.26	25.16	26.83	24.56	24.05	25.46	26.66	27.26	24.76	25.79
	W2 (mm)	25.14	24.52	27.01	23.63	24.74	25.18	26.42	25.99	24.22	25.64
	W3 (mm)	25.28	24.35	26.87	23.64	24.63	23.24	26.09	25.93	22.92	25.01
	L1 (mm)	23.45	24.05	23.34	23.99	23.43	25.56	24.28	24.24	24.8	25.27
	L2 (mm)	24.02	24.63	23.4	24.27	23.6	25.72	25.3	24.42	25.2	25.1
	L3 (mm)	23.82	24.87	23.62	24.1	24.03	25.83	25.17	23.81	25.29	24.7
After 10 Days at 75% RH	Weight (grams)	1.763	1.6576	1.6664	2.2899	1.8791	2.0489	2.1451	2.1141	1.6747	1.6265
	W1 (mm)	25.08	25.05	27.11	24.68	24.04	25.61	26.33	27.74	24.72	25.76
	W2 (mm)	24.73	24.57	27.08	23.73	24.74	25.14	26.07	27.12	24.06	25.90
	W3 (mm)	24.74	24.34	26.88	23.69	24.62	23.22	25.85	26.16	22.65	25.29
	L1 (mm)	23.22	24.37	23.54	24.63	23.46	25.79	24.77	24.63	25.36	25.34
	L2 (mm)	23.86	25.09	23.66	24.94	23.97	26.38	25.25	24.83	25.85	25.28
	L3 (mm)	23.78	24.94	23.35	24.42	23.98	26.24	25.07	24.37	26.08	24.68
After 10 Days at 0% RH	Weight (grams)	1.634	1.5386	1.5466	2.1266	1.7462	1.899	1.9915	1.9586	1.5568	1.5144
	W1 (mm)	24.94	24.64	26.78	24.29	23.5	25.19	26.15	27.18	24.16	25.61
	W2 (mm)	24.54	24.46	26.97	23.86	24.31	24.67	25.62	26.74	23.55	25.44
	W3 (mm)	24.62	23.8	26.82	23.11	24.18	22.77	25.46	25.76	22.34	24.89
	L1 (mm)	22.90	24.05	23.02	23.75	22.99	25.43	24.07	24.03	24.59	25.01
	L2 (mm)	23.50	24.42	23.04	24.00	23.52	25.69	24.53	24.08	24.73	25.12
	L3 (mm)	23.52	24.61	23.20	23.75	23.55	25.24	24.63	23.86	25.49	24.70

Appendix F: Light Aging Results Table and Sample Photos

Table 1: Raw Light Aging Data and CIE Calculations

		1	2	3	4	5	6	7	8	9	10
After 5 Days	L*	31.31	32.19	29.98	28.21	30.9	38.65	30.18	51.18	34.02	26.9
	a*	7.51	8.44	7.86	6.27	6.83	8.76	7.38	8.41	5.96	11.11
	b*	11.92	12.13	12.58	8.93	10.59	16.46	12.3	25.28	11.02	14.6
	ΔL	1.47	1.26	2.55	0.72	0.64	2.85	2.17	2.66	1.59	-0.97
	Δa	0.63	-0.16	0.44	0.69	0.17	-0.04	0.62	-0.5	0.19	0.2
	Δb	0.88	0.52	2.82	1.09	-0.01	2.46	2.16	2.86	0.9	-0.62
	ΔE_{76}	1.83	1.37	3.83	1.48	0.66	3.77	3.12	3.94	1.84	1.17
	ΔE_{94}	1.62	1.32	3.18	1.14	0.65	3.24	2.61	3.09	1.7	1.07
	ΔE_{00}	1.37	1.1	2.75	1.11	0.53	2.93	2.22	3.17	1.42	0.9
After 10 Days	L*	29.83	32.36	29.37	29.54	32.01	40.75	30.13	53.56	36.27	26.61
	a*	7.45	8.74	8.31	6.29	6.93	8.96	7.59	8.7	5.94	11.57
	b*	10.75	12.34	12.11	9.29	11.59	18.06	12.29	27.81	11.91	14.39
	ΔL	-0.01	1.43	1.94	2.05	1.75	4.95	2.12	5.04	3.84	-1.26
	Δa	0.57	0.14	0.89	0.71	0.27	0.16	0.83	-0.21	0.17	0.66
	Δb	-0.29	0.73	2.35	1.45	0.99	4.06	2.15	5.39	1.79	-0.83
	ΔE_{76}	0.64	1.61	3.17	2.61	2.03	6.4	3.13	7.38	4.24	1.65
	ΔE_{94}	0.53	1.51	2.52	2.33	1.87	5.53	2.58	5.71	4.03	1.5
	ΔE_{00}	0.73	1.23	2.21	1.95	1.53	4.98	2.21	5.77	3.37	1.37
After 15 Days	L*	30.13	33.97	31.77	31.57	32.6	39.91	31.19	54.65	35.03	26.7
	a*	7.95	9.18	8.92	6.61	7.32	8.74	8.01	8.91	6.59	11.82
	b*	12.01	14.13	14.74	10.8	11.96	16.89	13.25	29.33	11.49	14.65
	ΔL	0.29	3.04	4.34	4.08	2.34	4.11	3.18	6.13	2.6	-1.17
	Δa	1.07	0.58	1.5	1.03	0.66	-0.06	1.25	0	0.82	0.91
	Δb	0.97	2.52	4.98	2.96	1.36	2.89	3.11	6.91	1.37	-0.57
	ΔE_{76}	1.47	3.99	6.77	5.14	2.79	5.02	4.62	9.24	3.05	1.59
	ΔE_{94}	0.96	3.44	5.43	4.6	2.53	4.49	3.81	6.98	2.79	1.44
	ΔE_{00}	1.13	2.93	4.7	3.82	2.09	4.01	3.26	7.01	2.38	1.37

(green)	Acceptable color change	(yellow)	Noticeable color change	(red)	Unacceptable color change


Light Aging Samples - Before - 2/18/19
1
2
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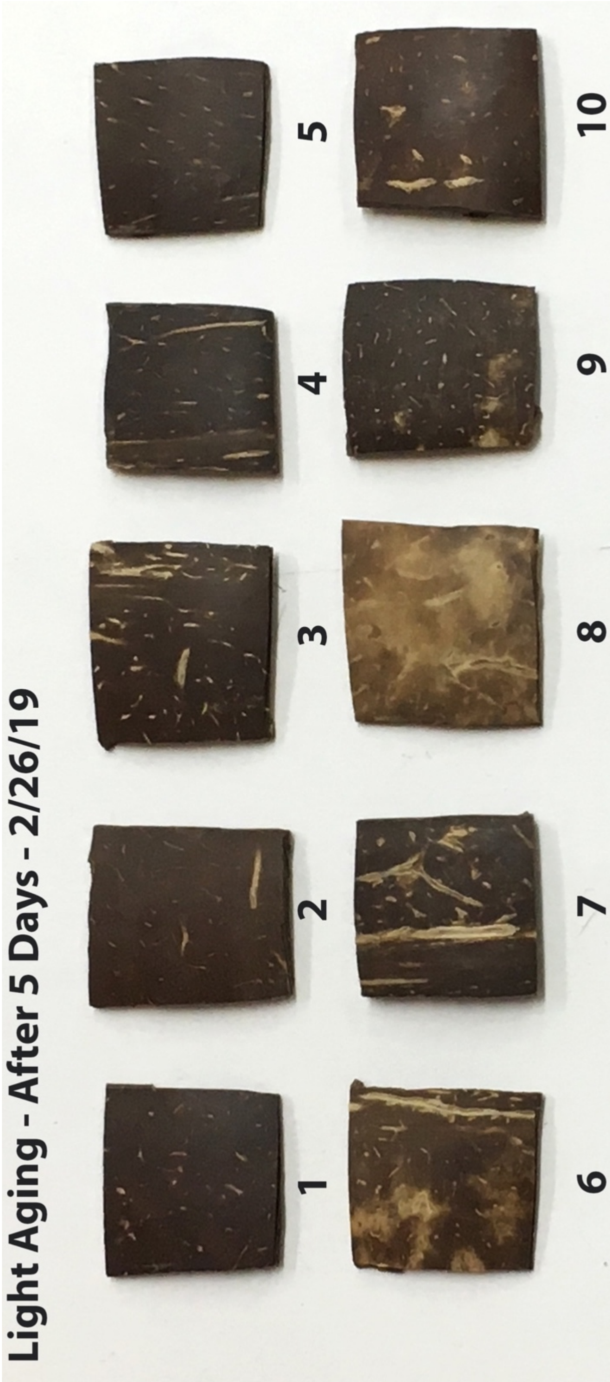
10



Light Aging - After 5 Days - 2/26/19
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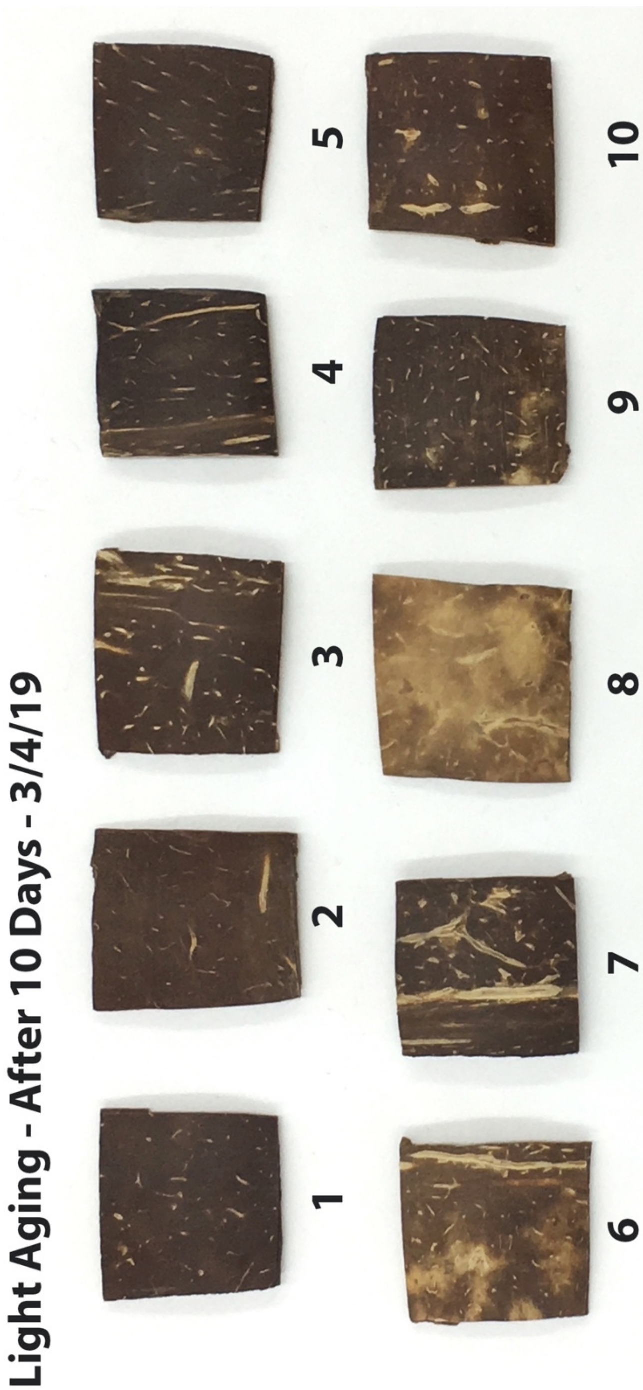
Light Aging - After 10 Days - 3/4/19
1
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4
5
6
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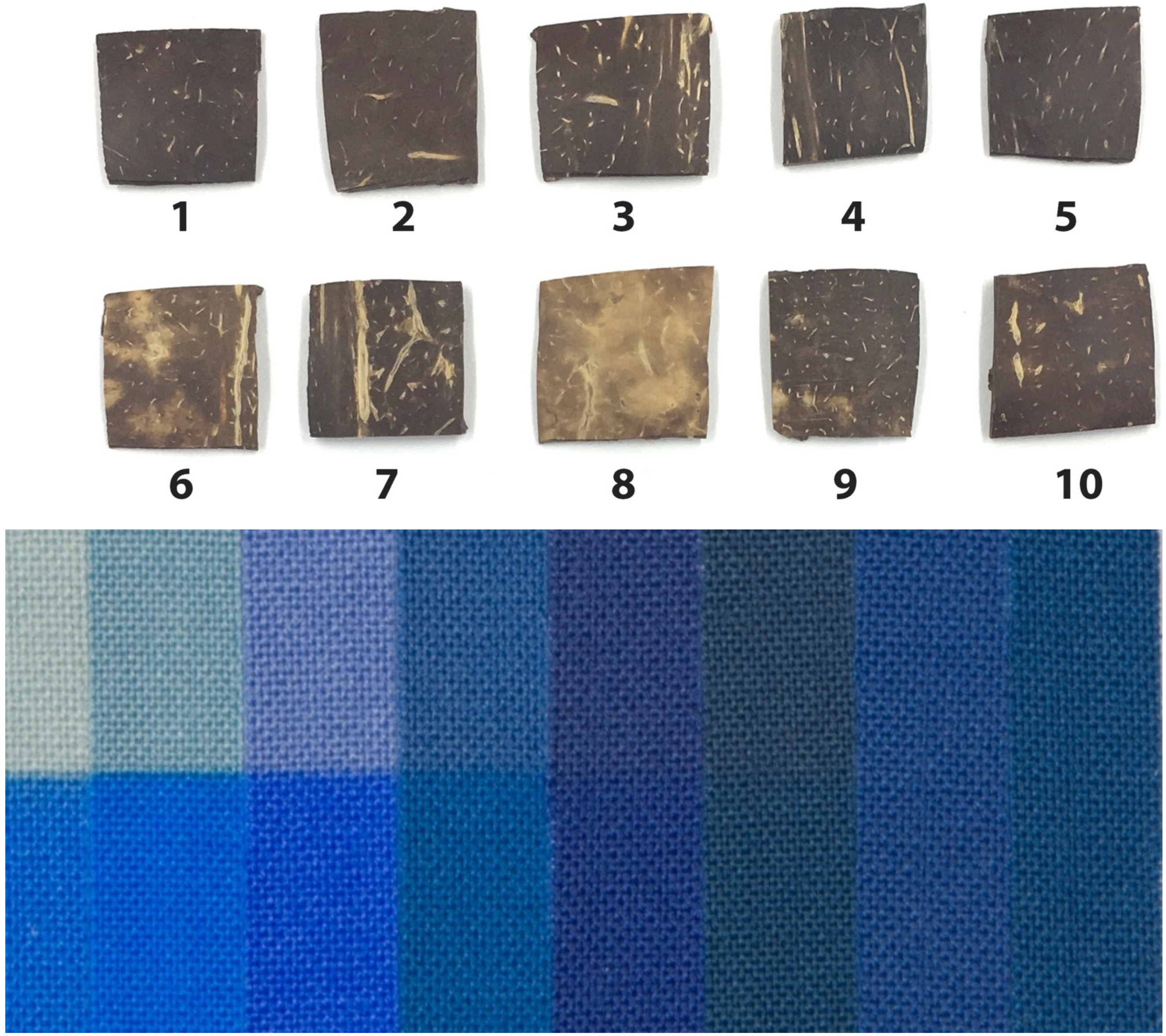
10

Light Aging - After 15 Days - 3/10/19



Appendix G: Oddy Testing Protocol and Coupon Photos

Materials:

- Samples (approximately 0.2g each)
- 45ml glass Kimax weighing bottles with ground glass outside caps. One for each sample and one control.
- 10ml beakers
- 1ml glass vials (remove plastic caps)
- Cotton
- Metal coupons (silver, copper, lead)
- Deionized water
- Acetone
- Cotton swabs
- High vacuum silicone grease (Dow Corning)
- 3 glass bristle brushes (one for each metal)
- Gloves
- Tweezers or small pliers
- Disposable plastic transfer pipette

Procedure:

1. Rinse clean glassware several times with deionized water before use.
2. Put on gloves. For the rest of the test, nothing can be contaminated with bare hands.
3. Using cotton swabs, wipe the glass containers, glass beakers, and small vials with acetone. Set these pieces aside to air dry completely.
4. Label your jars with the name of the test material, date, and initials.
5. Clean the metal coupons with glass bristle brushes (one for each metal). Work on a clean surface such as a piece of Mylar. Change the Mylar with each new coupon so they are not contaminated. After cleaning with brush, wipe the coupon surfaces with acetone and cotton swabs.
6. Place each test material into a 10ml beaker. Leave one empty as a control.
7. Use tweezers or pliers to bend the coupons into a U shape and hang one of each type on the edge of each 10ml beaker. Wipe the pliers with acetone before bending each new coupon. Do not let the coupons touch each other.
8. Pipette 0.5ml of deionized water into the small glass vial. With tweezers, stuff a small ball of cotton into the top of the vial without letting it fall into the water.
9. Carefully place the beaker (with sample and coupons hanging on the beaker lip) into the Kimax glass weighing bottle. Use tweezers to lower it in.
10. Run a light amount of grease along the outside lower lip of the Kimax ground glass fitting with the Dow Corning high vacuum grease. Place the lid on the container lightly, rotate the lid to distribute the grease evenly and then press down tight to form a good seal. Be careful not to disrupt your coupons or the water-filled glass vial. The coupons should not touch each other.
11. Place jars in oven set to 60° C.
12. Check the jars periodically (once a week) to make sure the water has not evaporated. Water evaporation indicates potential loss of VOC's from the container – nullifying the

test. Avoid moving the containers to keep any water droplets on the lid from dropping onto the coupons.

13. After 28 days, remove the tests and record the results. Compare the degree of corrosion on the metal samples to the control.

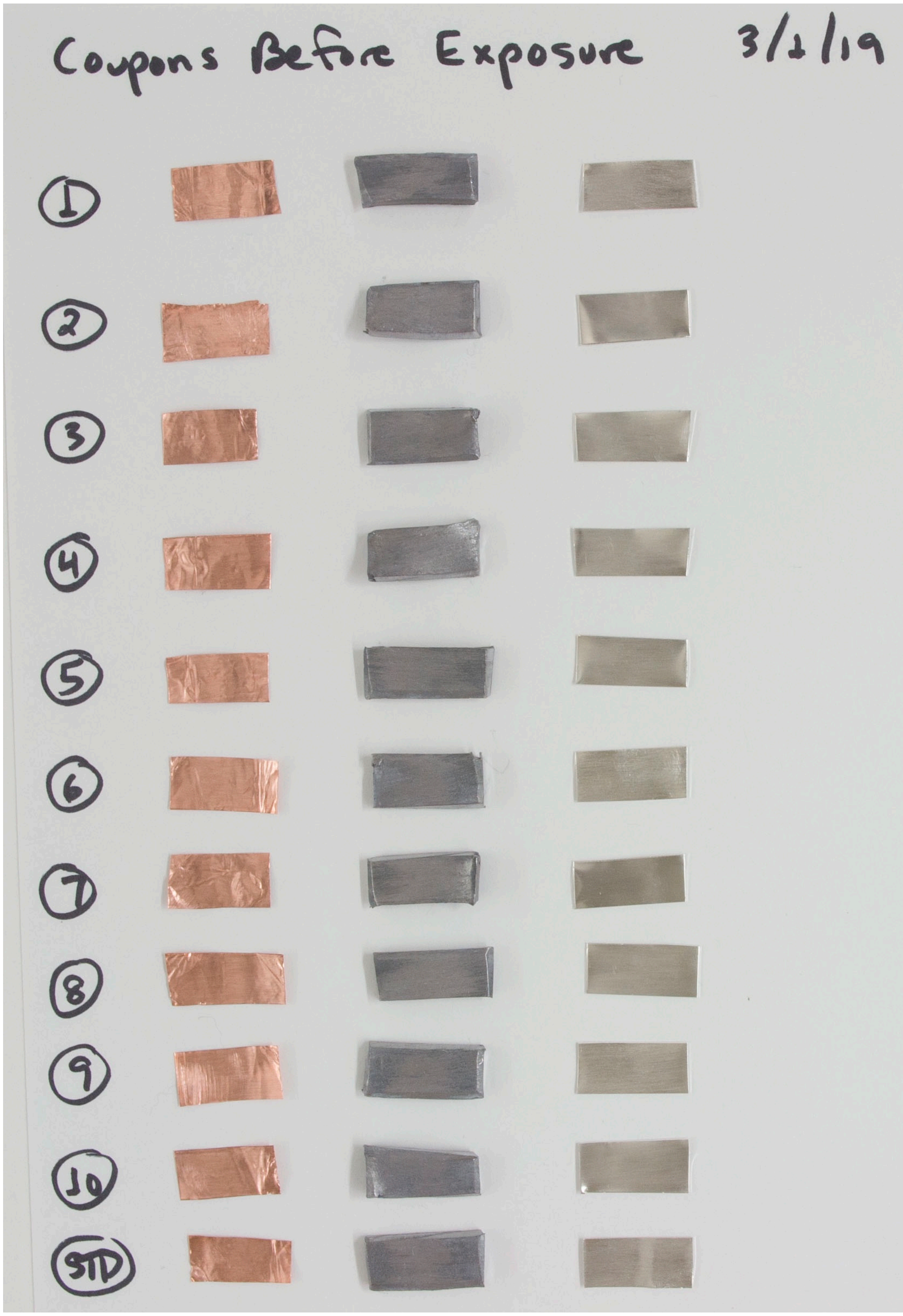


Fig. 1: Coupon image before test cycle. STD – control standard.

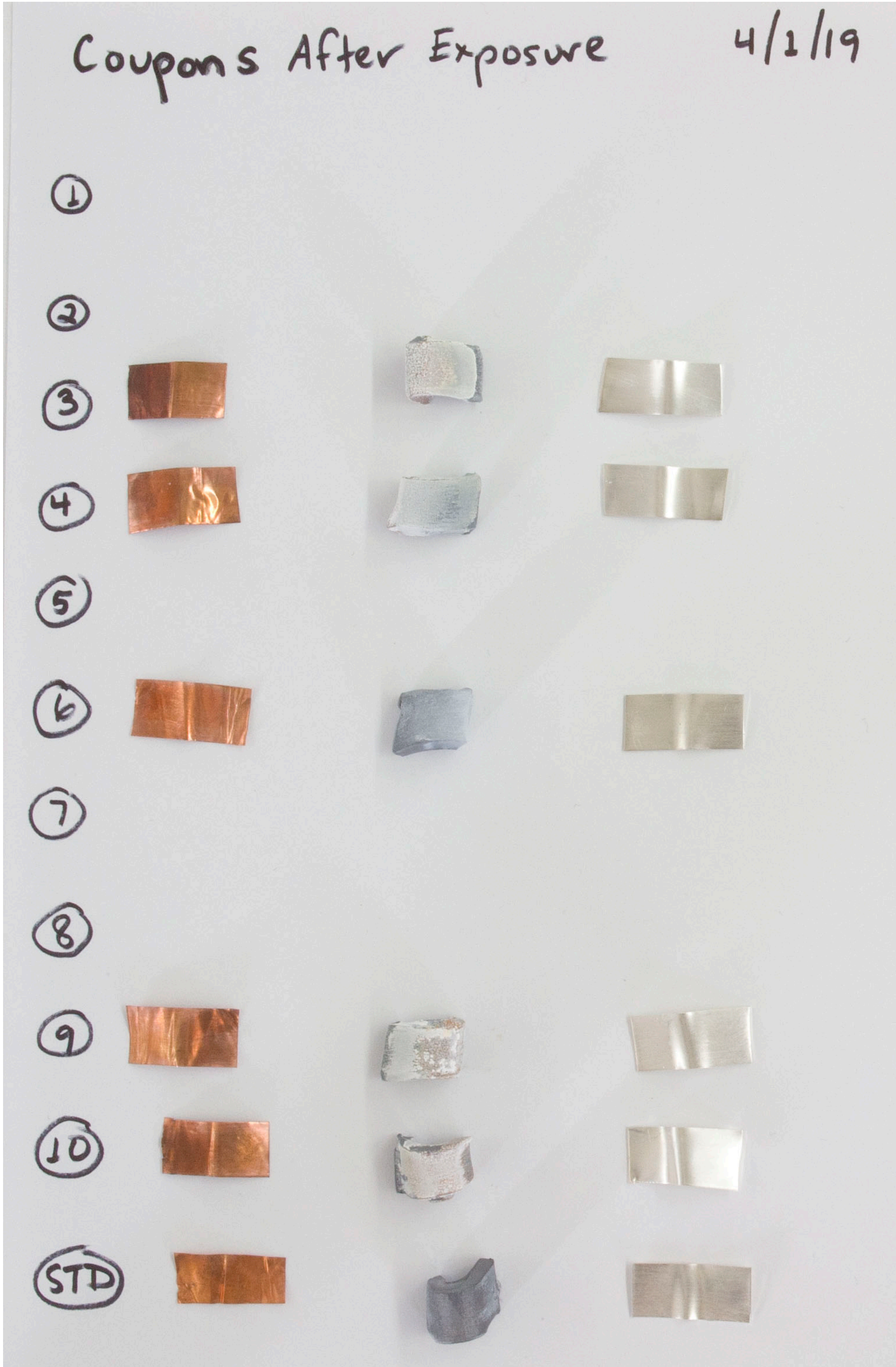


Fig. 2: Coupon image after test cycle. Image contains coupons from those jars that could be opened. All other jars remained sealed and so coupons were photographed in situ. STD – control standard.

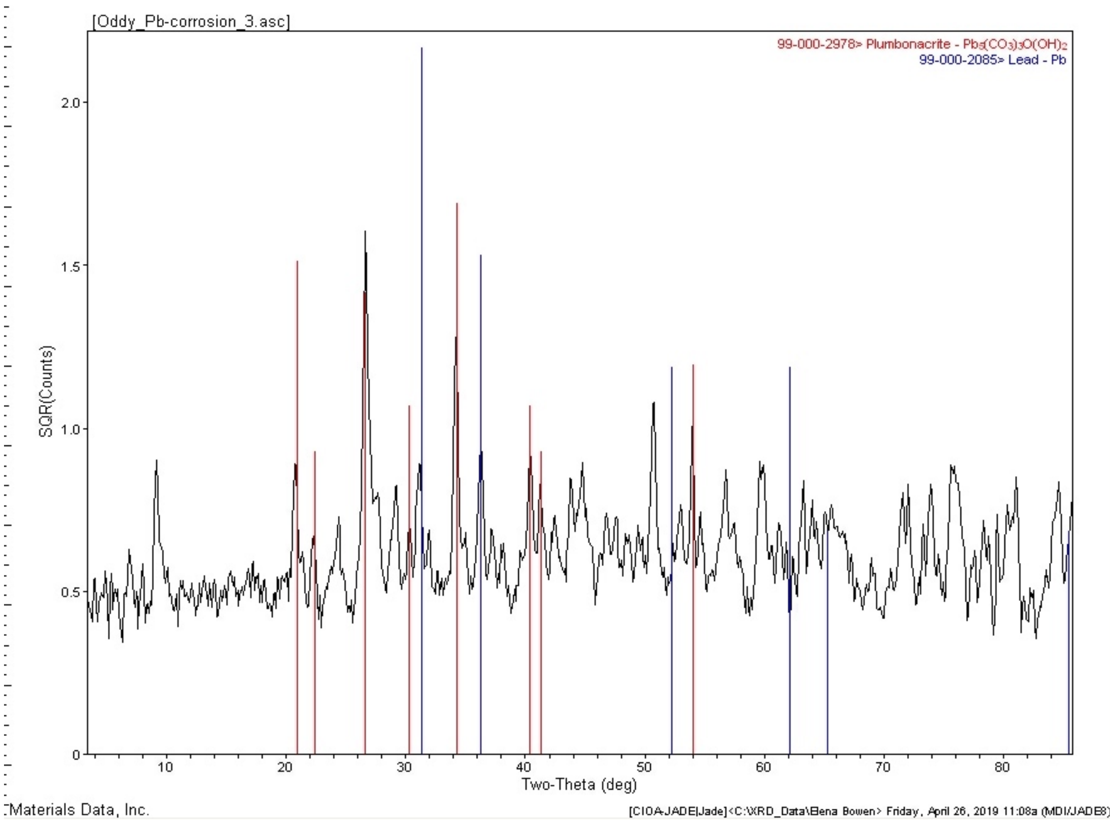


Fig. 2: XRD results from lead coupon 3.

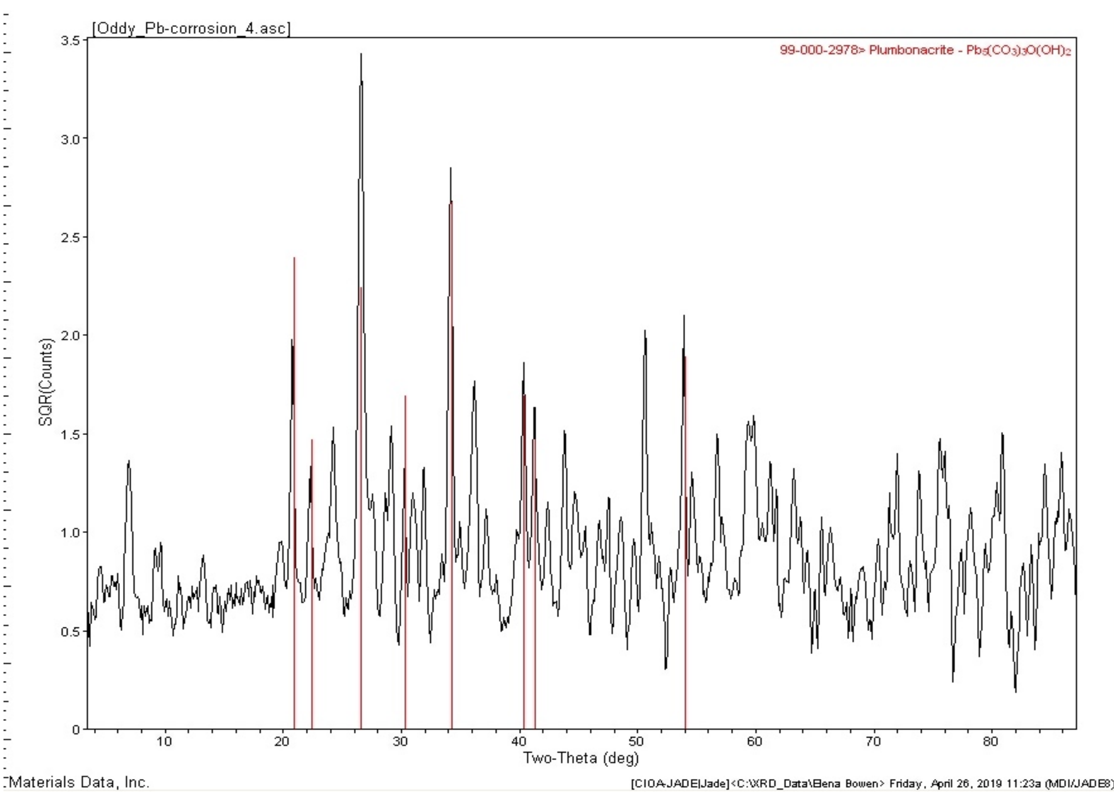


Fig. 3: XRD results from lead coupon 4.

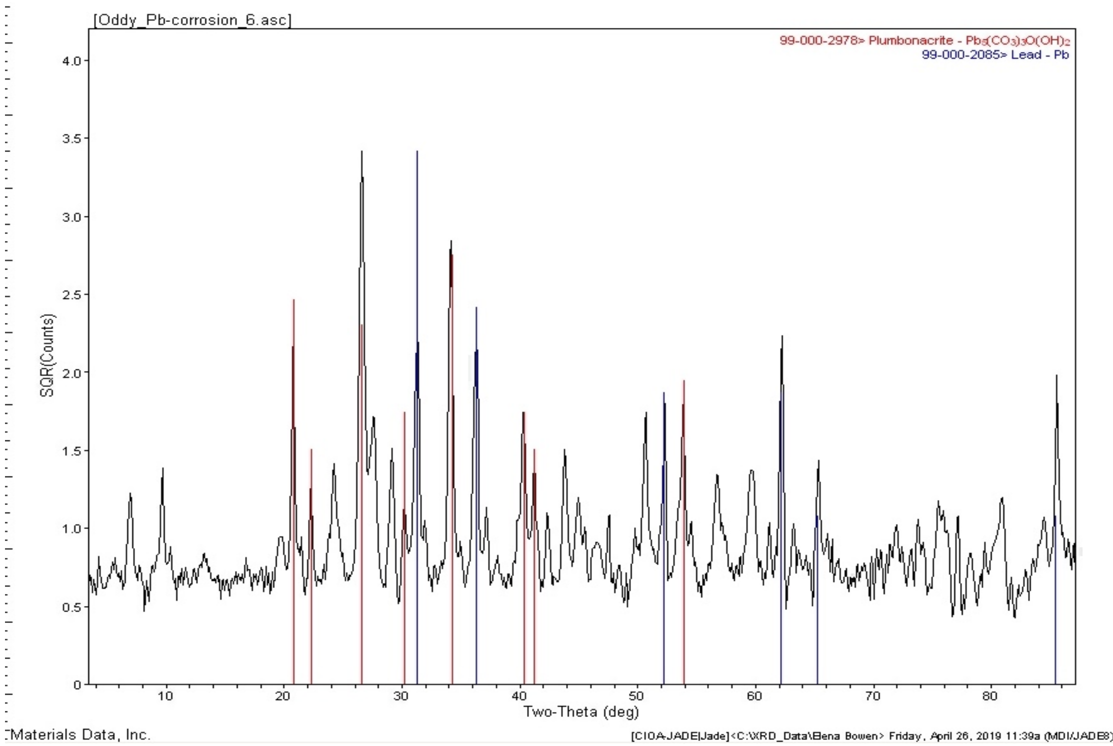


Fig. 4: XRD results from lead coupon 6.

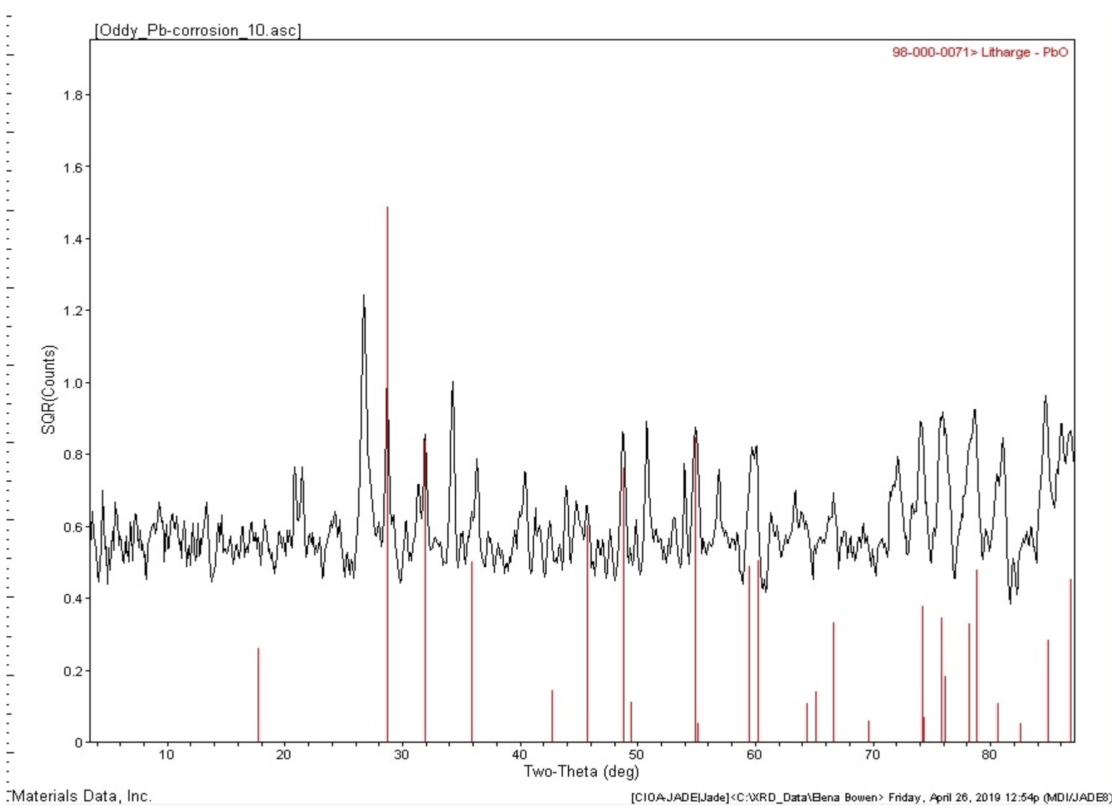


Fig. 5: XRD results from lead coupon 10.

Appendix H: Adhesive Information

Materials:

Paraloid B-72, Talas
Jade R, Talas
Hide glue, Talas
Lascaux 360, Talas

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