401 N. Lindbergh Blvd.
St. Louis, MO 63141
Tel.: 314.993.1700, #546
Toll Free: 800.424.2841, #546
Fax: 800.708.1364
Cell: 314.283.1983
Send via email to: jbode@aaortho.org and cyoung@aaortho.org

AAO Foundation Final Report Form
(a/o 6/30/2020)

Type of Award
Biomedical Research Award

Name(s) of Principal Investigator(s)
F. Kurtis Kasper

Institution
The University of Texas Health Science Center at Houston

Title of Project
Characterization of 3D-Printed Esthetic Orthodontic Brackets

Period of AAOF Support
07-01-20 to 06-30-21
No Cost Extension 07-01-21 to 06-30-22

Amount of Funding
$30,000

Summary/Abstract
Objectives: A variety of considerations drive patient and clinician decisions associated with orthodontic treatment. Patients often present concern regarding the esthetics associated with fixed appliances during treatment, which has motived considerable investment over the years in the development of "esthetic brackets," including plastic and ceramic brackets. Recent advances in additive manufacturing technologies present the potential for fabrication of esthetic orthodontic brackets in-office via 3D-printing using materials cleared for intraoral use. Direct fabrication of esthetic brackets via 3D-printing could revolutionize orthodontics by enabling clinicians to design and fabricate customized brackets that satisfy patient demands for esthetics in an on-demand fashion. At the same time, in-office design and fabrication of brackets via 3D-printing would support increased clinician control and operational efficiency in orthodontic practices. As clinical cases of 3D-printed brackets emerge in the literature, a clear and urgent need exists to investigate

key properties of 3D-printed brackets, including their mechanical properties and color stability, to inform the orthodontic community regarding potential advantages and limitations. The overall objective of the project was to evaluate the mechanical properties and color stability of 3D-printed orthodontic brackets fabricated with a filled biocompatible resin composite. Overall, the information gained through this project will inform the orthodontic community regarding key mechanical and color properties of 3D-printed esthetic brackets to guide appropriate use of the emerging approach.

Specific Aim 1 – Shear Bond Strength of Orthodontic Brackets Fabricated via 3D-Printing Using Filled Biocompatible Resins: Specific Aim 1 involved investigation of the shear bond strength of orthodontic brackets fabricated via 3D-printing using filled biocompatible resins when bonded to extracted human teeth. It was hypothesized that the initial shear bond strength of 3D-printed brackets would not differ significantly from that of corresponding commercially available plastic brackets, and that the shear bond strength of the 3D-printed brackets would increase with treatment of the bracket pad to increase surface area. To this end, 20 brackets of each of 4 biocompatible resins marked for dental applications (GR- 17.1 A1, GR- 17.1 A2, GR- 17.1 A3, and GR-10 Guide) were printed with an Asiga Max UV 3D-printer using a single master standard tessellation language (STL) file matching the American Orthodontics Silkon Plus^{TM} design. Twenty Silkon Plus^{TM} brackets were also obtained. Brackets were bonded to 100 mounted extracted human premolars and placed in a 37ºC distilled water bath for 36 hours to simulate the oral environment. Brackets were then debonded using an Instron universal testing system. Maximum load was recorded and used to calculate shear bond strength. The buccal surface of each tooth was examined and photographed to evaluate the amount of adhesive remaining via adhesive remnant index (ARI) scoring. Statistical analysis included a generalized linear model with post-hoc Tukey contrasts to evaluate the effect of bracket material on shear bond strength. A Kruskal-Wallis rank sum test with post-hoc pairwise comparisons was used to evaluate the effect of bracket material on ARI score.

Mean shear bond strength of the 3D-printed brackets ranged from 10.033 ± 1.761 to 12.766 ± 1.666 MPa, while the shear bond strength of the conventionally manufactured brackets was statistically significantly lower at 7.467 ± 1.024 MPa ($p<0.001$ for all pairwise comparisons; see Figure 1; Appendix). The GR-10 Guide group displayed statistically significantly lower shear bond strength than the GR-17.1 A1, A2, and A3 groups ($p<0.001$, $p<0.001$, and $p<0.006$, respectively). There were no statistically significant differences in shear bond strength between the GR-17.1 A1, A2, and A3 groups. The conventionally manufactured group demonstrated significantly lower ARI scores than all other groups ($p<0.001$ for all pairwise comparisons). There were no statistically significant differences in ARI scores between the 3D-printed groups (see Figure 2; Appendix). 3D-printed orthodontic brackets fabricated with GR-10 Guide and GR-17.1 (shades A1, A2, and A3) resins demonstrated clinically acceptable shear bond strengths under the conditions used in this study. 3D-printed brackets demonstrated higher ARI scores compared to conventionally manufactured brackets, indicating that less composite remained on the tooth after debond of the bracket. Overall, the results suggest that 3D-printed brackets appear to have promise for clinical applications in orthodontics, but more research is indicated to elucidate additional properties.

An additional study was completed to investigate the effect of air abrasion of bracket pads on the shear bond strength of 3D-printed plastic orthodontic brackets when bonded to the enamel of extracted human teeth. To this end, 125 deidentified extracted human premolars were divided into

6 groups of 20 premolars each. Eighty premolar brackets were 3D-printed using an American Orthodontics (AO) Silkon Plus™ bracket STL file from the manufacturer in 2 different commercially available biocompatible 3D-printing resins marketed for dental applications: Dental LT Resin (n = 40) and Dental SG Resin (n = 40). The 40 brackets 3D-printed in each resin plus 40 commercially manufactured brackets were divided into 2 groups of 20 brackets each, and 1 of the 2 groups of each resin was air abraded using 50 μm aluminum oxide at 80 pounds per square inch (psi). All brackets were bonded to the extracted premolars, and shear bond strength tests were performed on all samples with an Instron universal testing system. The failure types of each sample were classified using a 5-category modified ARI scoring system. A generalized linear model using the glm function with gamma specified error distribution was applied to evaluate effects of bracket material and air abrasion on shear bond strength, since data were not normally distributed. The POLR function was used to examine effects of bracket and air abrasion on ARI, as ARI is an ordered categorical variable.

Bracket material and bracket pad surface treatment presented statistically significant effects for mean shear bond strengths ($p=0.004$ and $p=0.005$, respectively), and a significant interaction effect between bracket material and bracket pad surface treatment was observed ($p<0.001$). The non-air abraded (NME) SG group (8.87 ± 0.64 MPa) had a statistically significantly lower shear bond strength than the air abraded (ME) SG group (12.09 ± 1.23 MPa; see Figure 3; Appendix) ($p<0.05$). In the manufactured brackets and LT Resin groups, the NME and ME groups were not statistically significantly different within each resin group ($p>0.05$). None of the samples in the study received an ARI score of 4 or 5. A significant effect of bracket material and bracket pad surface treatment on ARI score was observed ($p<0.001$ and $p<0.001$, respectively), but no significant interaction effect between bracket material and bracket pad surface was found ($p=0.067$). Within each bracket material, the group with ME surface treatment demonstrated ARI scores of 3 with greater frequency than the NME group (see Figure 4; Appendix). The traditionally manufactured brackets demonstrated low ARI scores with greater frequencies than the 3D-printed brackets. Based on the results of this study, follow-up clinical studies may further examine printing mediums and bracket pad optimization for clinically acceptable shear bond strengths to inform best practices. Overall, 3D-printed orthodontic brackets based on a Silkon Plus™ design printed in resins marketed for intraoral use (SG and LT) presented clinically sufficient shear bond strengths both with and without air abrasion prior to bonding. The effect of bracket pad air abrasion on shear bond strength depends on the bracket material. If clinicians are utilizing SG resin to print brackets, air abrasion of bracket pad bases prior to bonding could help increase shear bond strengths.

Specific Aim 2 – Investigation of Color Stability of 3D-Printed Orthodontic Brackets: Specific Aim 2 involved investigation of the color stability of 3D-printed orthodontic brackets. It was hypothesized that the composite resins applied in the fabrication of 3D-printed brackets would present initial color and translucency within acceptable limits, but that accelerated aging and staining solutions would each induce changes in the color and translucency beyond acceptable limits. To this end, GR-17.1 (shades A1, A2, and A3) and GR-10 Guide resins were printed on an Asiga MAX UV printer into discs 2 mm thick, with a diameter of 10 mm, and then post-processed as per manufacturer's instructions. Discs were immersed in 5 mL of coffee, tea, red wine, or distilled water for 1 week. Another group was subjected to artificial accelerated aging as per ISO Standard 4892-2. Ten samples were produced per resin, per treatment condition. Color measurements were taken on the discs before and after treatment using a spectrophotometer against white and black reference tiles to assess color and translucency. Statistical analysis included a generalized linear model with post-hoc Tukey contrasts to evaluate the effect of bracket material and treatment condition on total change in color (ΔE_{00}) and translucency (ΔTP_{00}).

A statistically significant effect of the treatment ($p < 0.001$) and the disc material ($p<0.001$) were found for ΔE_{00}, while only the treatment produced a significant change in ΔTP_{00} ($p<0.001$), with the type of resin having no significant effect on the change in translucency parameter. An interaction effect between the treatment effects and the material was present for ΔE_{00} ($p<0.001$), but not for ΔTP_{00}. Among the treatment conditions, immersion in red wine produced the greatest change in color (ΔE_{00}), except in shade A2 resin, which experienced the greatest change with coffee (see Figure 5; Appendix). Red wine also produced the greatest change in translucency parameter (ΔTP_{00}) for all materials except the A3 resin, where coffee also had a greater effect (see Figure 6; Appendix). Qualitatively, red wine and coffee had the largest effect on resin color. Immersion in tea caused staining in the resin samples to a lesser degree than coffee or red wine, but more than exposure to artificial aging, which had the least effect on color of any experimental treatment tested in this study (see Figure 7; Appendix). Artificial aging was not shown to have a significant effect on translucency. The control for the study was immersion in distilled water, which itself produced a mild color change for GR-17.1 filled resin samples, and a moderate color change for GR-10 Guide resin. The effects of distilled water on the samples were not apparent qualitatively. The three GR-17.1 resin materials – shade A1, A2, and A3 – had similar magnitudes of ΔE_{00} in response to the treatment conditions. The unfilled GR-10 Guide resin underwent significantly more color change than the GR-17.1 resins for all treatment conditions except for immersion in coffee. This resin was also the most variable in its response to treatment condition, with the standard deviations much wider than that of the other groups. Overall, while initial color of the printed resin discs was acceptable, all resin groups underwent significant color change during the experiment. Red wine and coffee produced the greatest color and translucency change, followed by tea, with artificial aging producing the least change in color and translucency. The 3D-printed resins tested underwent significant changes in color and translucency following exposure to endogenous and exogenous sources of staining, and are not recommended for esthetic orthodontic bracket applications.

<u>Respond to the following questions</u>:

1. **Were the original, specific aims of the proposal realized?**
   Yes

2. **Were the results published?**
   a. **If so, cite reference/s for publication/s including titles, dates, author or co-authors, journal, issue and page numbers**
      Hanson, M. S. (2021). Effect of Pad Abrasion on Shear Bond Strength of 3D-Printed Orthodontic Brackets (Order No. 28650314). Available from Dissertations & Theses @ University of Texas School of Dentistry at Houston. (2562790237). Retrieved from https://libdb.db.uth.tmc.edu/login?url=https://www.proquest.com/dissertations-theses/effect-pad-abrasion-on-shear-bond-strength-3d/docview/2562790237/se-2?accountid=7127

b. **Was AAOF support acknowledged?**
Yes, as appropriate, AAOF support was acknowledged in each publication.

c. **If not, are there plans to publish? If not, why not?**
Yes, the project involved contributions from 3 residents in partial completion of the requirements of the degree of Masters of Science in Dentistry. Some project results were published in a thesis detailed above and other results will be published in planned theses, as follows:

1. Siller J. Shear Bond Strength of Orthodontic Brackets Fabricated via 3D-Printing Using Filled Biocompatible Resins. Masters of Science in Dentistry Thesis, Department of Orthodontics, The University of Texas School of Dentistry at Houston, Houston, Texas. (in preparation).

2. Wallach R. Color Stability of 3D-Printed Orthodontic Brackets Using Filled Resins. Masters of Science in Dentistry Thesis, Department of Orthodontics, The University of Texas School of Dentistry at Houston, Houston, Texas. (in preparation).

In addition, three research manuscripts based on the results of the project are presently under preparation for submission to peer-reviewed journals. In each case, the submissions will acknowledge AAOF support, as appropriate.

3. **Have the results of this proposal been presented?**

a. **If so, list titles, author or co-authors of these presentation/s, year and locations**
Siller J, Hanson M, English JD, Harrington D, Ontiveros J, Wirthlin J, Cozad B, Kasper FK. Effect of Pad Abrasion on Shear Bond Strength of 3D-Printed Orthodontic Brackets. American Association of Orthodontists Annual Meeting, Miami, FL. May 21-24, 2022. (E-Poster Presentation)

b. **Was AAOF support acknowledged?**
Yes, as appropriate, AAOF support was acknowledged in each presentation.

c. **If not, are there plans to do so? If not, why not?**
The results will continue to be included in presentations, as appropriate, with proper acknowledgement of support from AAOF for the work. Planned presentations include the following:

Kasper FK. Leaving the Stone Age: Applying Biomaterials and 3D Printing to Meet Clinical Needs. American Institute of Oral Biology 79th Annual Meeting, Palm Springs, CA. October 21-23, 2022. (Invited Oral Presentation)

4. **To what extent have you used, or how do you intend to use, AAOF funding to further your career?**
As a bioengineer, I am thrilled to explore exciting new frontiers at the intersection of engineering and orthodontics, and funding from the AAOF has been vital to enable my investigations in these areas that traditionally are not targets for funding from federal sources. The funding from AAOF

provides me with opportunities to expand my exposure to the challenges of clinical orthodontics, to collaborate with clinicians and researchers in the field, to increase my research profile, and to broaden my professional network. Indeed, support from the AAOF has been instrumental in my career advancement through the academic ranks from an Assistant Professor to a recently approved promotion to Professor (Tenured). The benefits enabled by AAOF support provide a firm foundation upon which I plan to continue to build my research program in topics of relevance to orthodontics.

Accounting for Project

Approximately $26,004 of the $30,000 project budget was expended or encumbered to-date in completion of the project.

Appendix

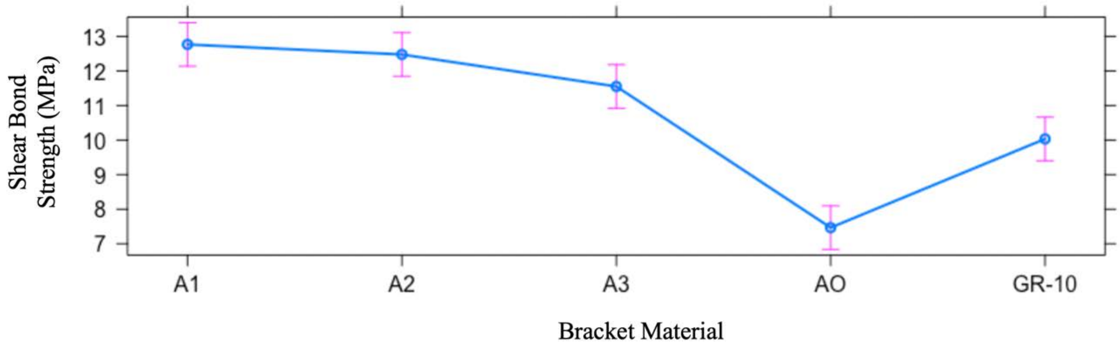

Figure 1. Mean shear bond strength and 95% confidence interval of each bracket material. A1 = GR-17.1 A1 resin group; A2 = GR-17.1 A2 resin group; A3 = GR-17.1 A3 resin group; GR-10 = GR- 10 Guide resin group; AO = American Orthodontics conventionally manufactured bracket group.

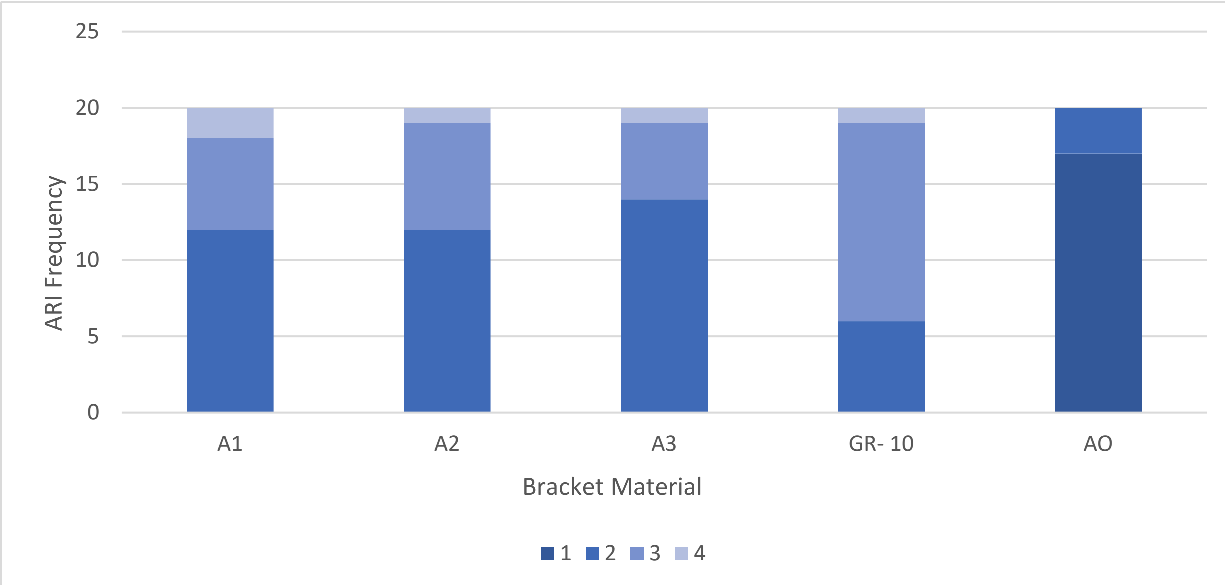

Figure 2. Frequency of ARI score by bracket material. A1 = GR-17.1 A1 resin group; A2 = GR-17.1 A2 resin group; A3 = GR-17.1 A3 resin group; GR-10 = GR-10 Guide resin group; AO = American Orthodontics conventionally manufactured bracket group.

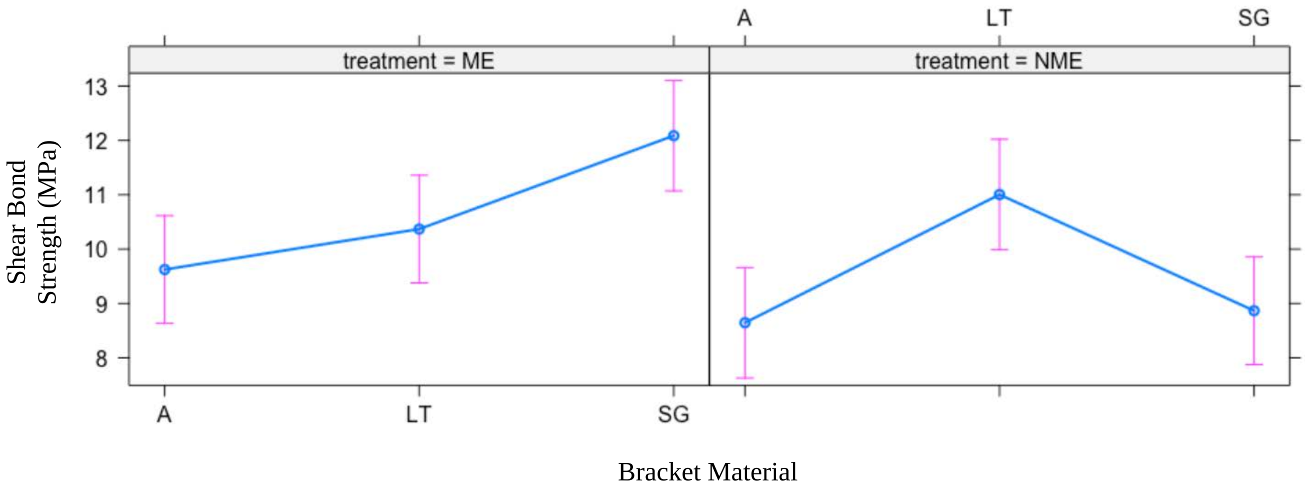

Figure 3. Mean shear bond strength and 95% confidence interval of each bracket material with air abrasion (ME) and without air abrasion (NME) of the bracket pad. A = American Orthodontics conventionally manufactured bracket group; LT = Dental LT Resin group; SG = Dental SG Resin group.

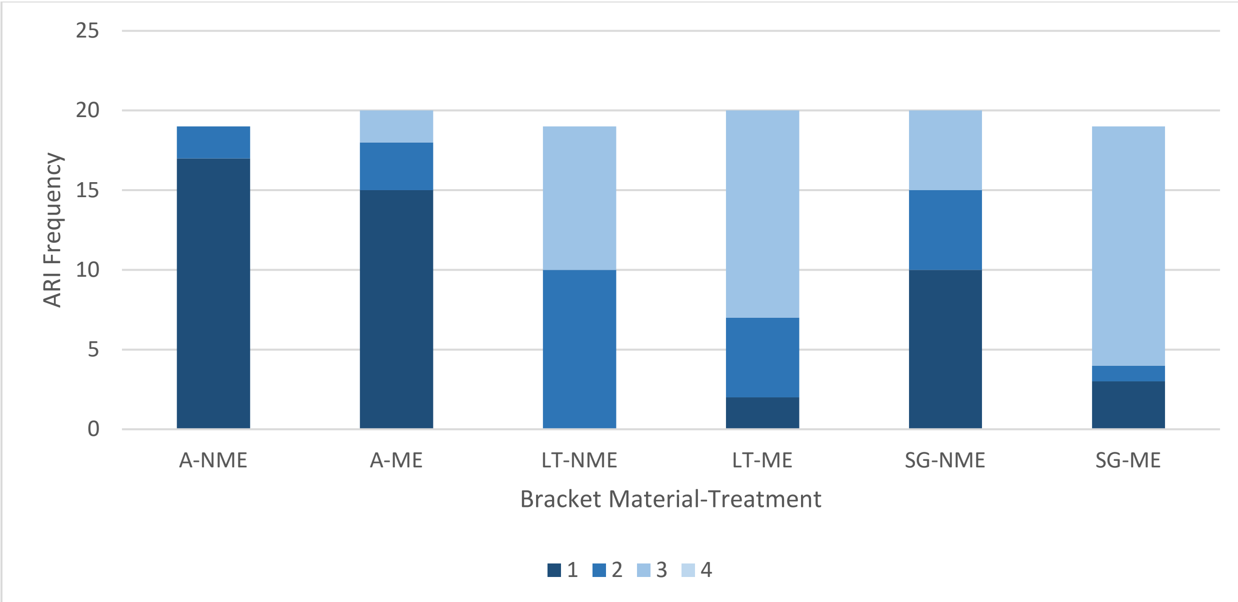

Figure 4. Frequency of ARI score by bracket material. A = American Orthodontics conventionally manufactured bracket group; LT = Dental LT Resin group; SG = Dental SG Resin group. NME = no air abrasion of the bracket pad; ME = air abrasion of the bracket pad.

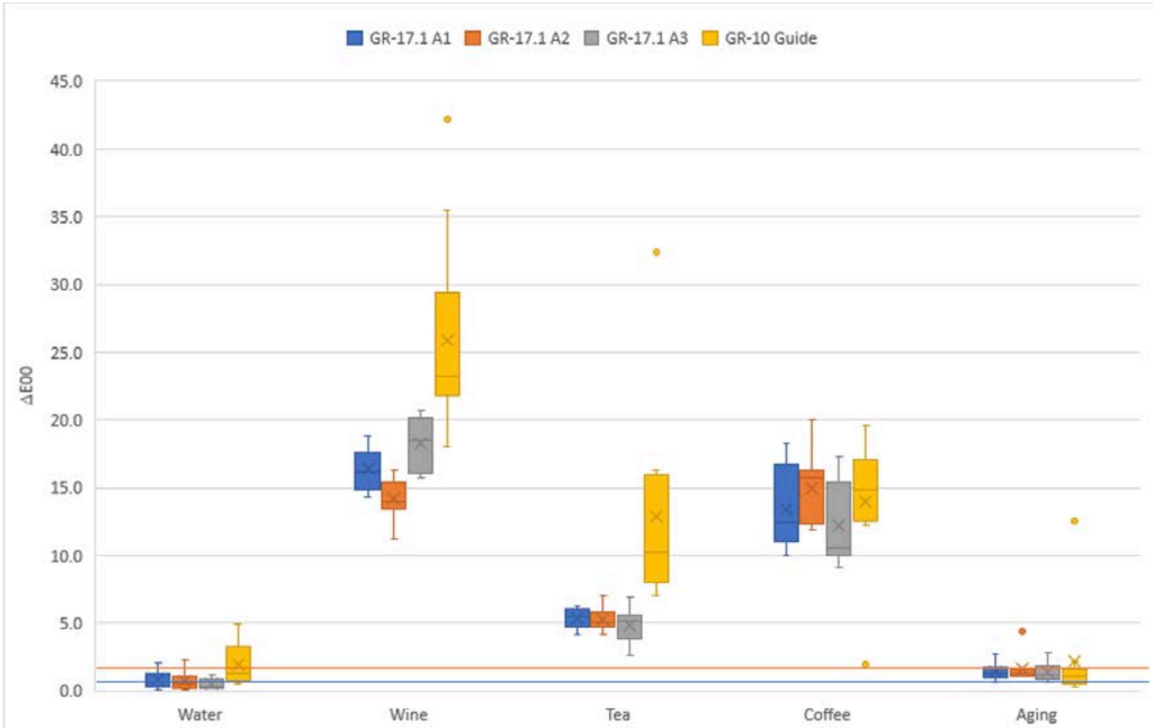

Figure 5. Box and whisker plot showing the distribution of color change (ΔE_{00}) observed for each material under experimental conditions. Blue line indicates the perceptibility threshold, and the orange line indicates the acceptability threshold.

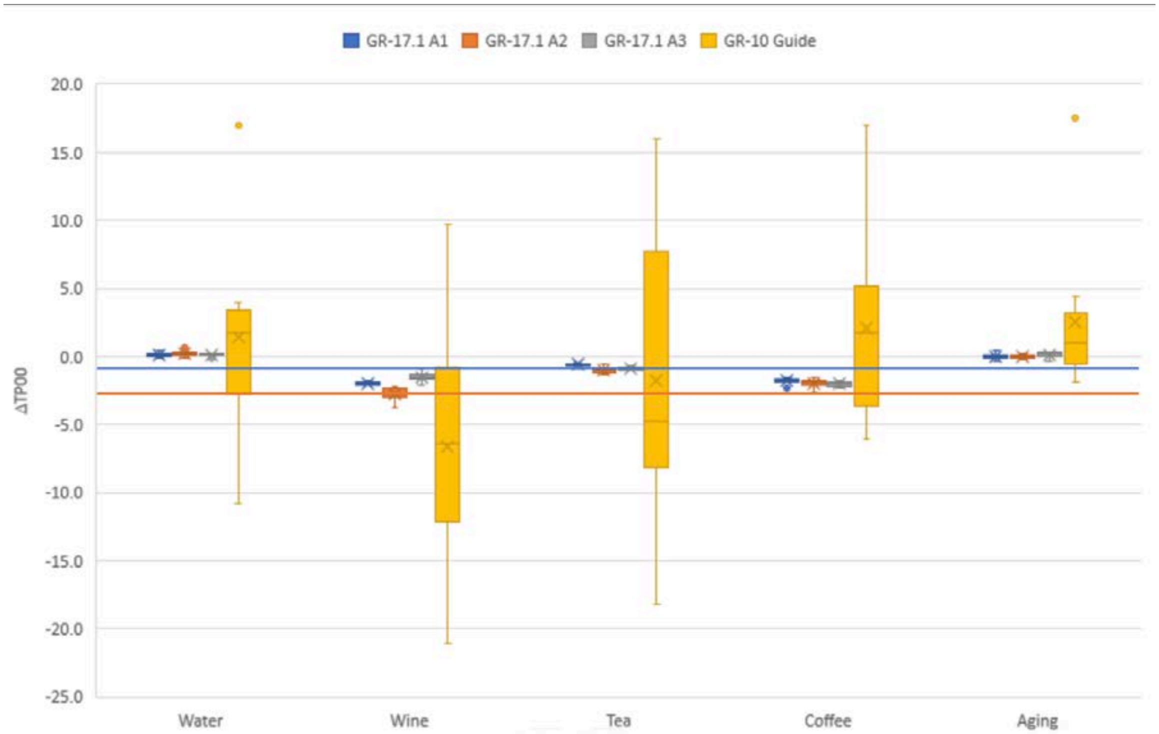

Figure 6. Box and whisker plot showing the distribution of translucency parameter change (ΔTP_{00}) observed for each material under experimental conditions. Blue line indicates the translucency perceptibility threshold, and the orange line indicates the translucency acceptability threshold.

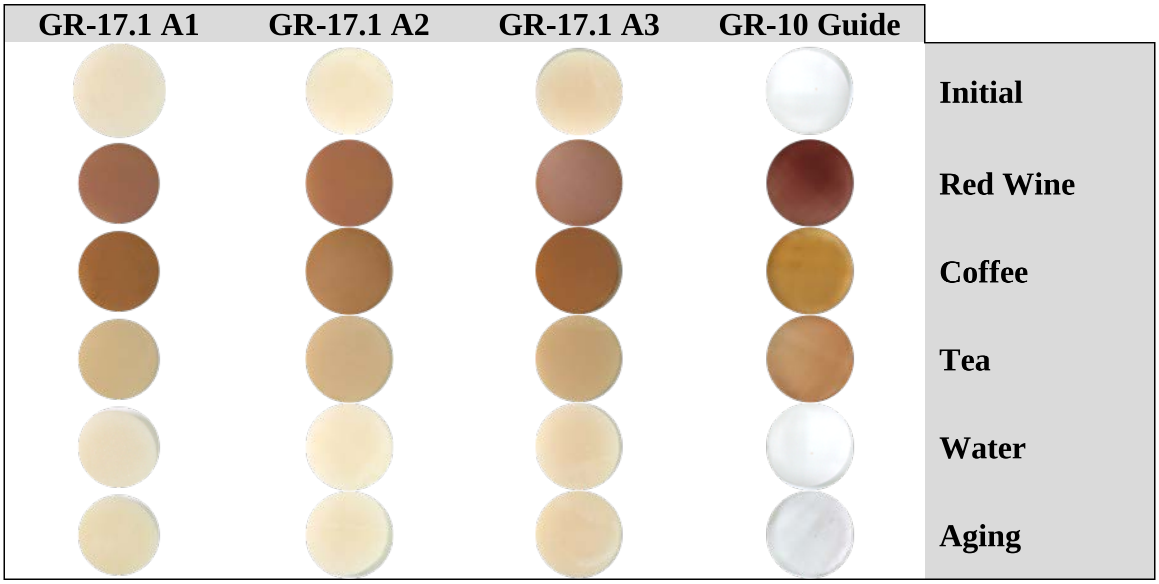

Figure 7. Representative photographs of 3D-printed resin samples pre- and post-treatment.