JPMTR 134 | 2003
DOI 10.14622/JPMTR-2003
UDC 667.5:534.2

Research paper
Received: 2020-03-26
Accepted: 2020-06-24

Impact of printing surfaces with UV-curable inks on sound absorption

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Abstract

The recent UV-curable inks, used in modern inkjet printing systems, bring several advantages and therefore a potential to expand to new applications, including décor printing. In this work, we investigate the impact of printing with UV-curable inks on sound absorption. The sound absorption curves of three different sound-absorbing decorative wall plates are calculated from the reverberation times measured in a reverberation room. The comparison between the sound absorption from unprinted and printed decorative plates showed that printing with UV-curable inks has no significant impact on the sound absorbing characteristics of materials.

Keywords: sound-absorbing plate, reverberation time measurement, décor printing, UV-curable inkjet printing

1. Introduction

Inkjet printing and UV-curing technologies have developed in parallel since the 1950s (Cahill, 2001). Inkjet printing systems based on UV-curable inks enable print service providers to offer additional value to their customers and allow designers to create more stylish and impactful finishes on various types of surfaces (Canon, 2018). They have expanded the inkjet printing technology into alternative fields and applications like packaging, publishing, décor, textile design, and outdoor display (Parraman and Ortiz Segovia, 2018, p. 96). The base of the UV-curable inks is composed of fluid monomers that, when exposed to UV radiation, polymerize into a hardened dry ink containing the pigment (Parraman, 2012).

The UV-cured inks bring several advantages: they are more reliable and have better sustainability ratings, they support extended gamut printing, they are tolerant and applicable to a variety of printing surfaces (Taylor and Cahill, 2015), and they can be used to produce a surface texture (Parraman and Ortiz Segovia, 2018, p. 96).

In this work, the focus is on the décor application, e.g., printing on materials used for decorative indoor walls or ceilings. The large surface area of walls and ceilings impacts the acoustic characteristics of the indoor space (Harris, 1991, pp. 64–66). Therefore, decorative walls and ceilings may require having certain sound-absorbing characteristics. These characteristics are closely related to the reverberation time of the indoor space, which is the time needed for the sound pressure level (SPL) to decay 60 dB after the source of the sound has stopped (Beranek and Mellow, 2012, p. 470). Several studies have been made to investigate the acoustic impact of different decorative surface coatings of objects in indoor spaces. Martellotta and Castiglione (2011) investigated the use of paintings and tapestries as sound-absorbing materials, where they among others looked at the combined effect of painted canvases covering porous materials. They found that impermeable treatments, from using oil or acrylic color, mostly influenced high-frequency absorption. Ivanova, Vitchev, and Hristodorova (2018) investigated the influence of different surface coatings on sound absorption of wood. They showed that coating improved sound absorption properties of the wood. Chrisler (1941) did measurements for sound absorption of different materials and paint, including different number of coats. The results indicated differences between the materials, as some could be painted with just one or two coats of paint before a decrease in sound absorption was detected, while others could be painted multiple times before a decrease was found. Xu, et al. (2020) investigated polyurethane coating thickness in sound absorption for four different wood species, where the results of the sound absorption is dependent on the wood species and coating thickness. Sayako and Yamamoto (2018) in their patent proposed a surface treatment liquid for porous sound-absorbing materials. The main goal was to add decorative elements to sound-absorbing materials without impairing the sound absorption capabilities of the surface. The surface treatment was in terms of an aqueous ink. Most examples showed small differences in an air permeability evaluation compared to unprinted samples.

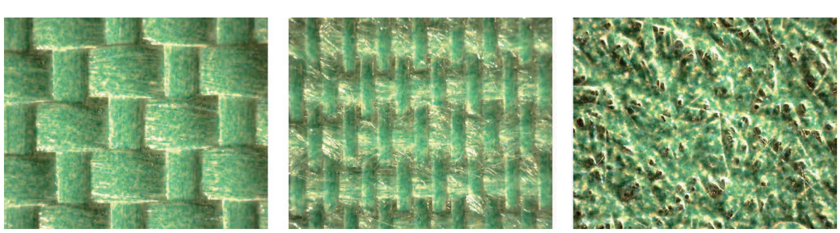
In summary, the previous related works show that the sound-absorbing characteristic of a material can be influenced by the surface of that material. It is interesting to see whether depositing hardened UV-cured inks on indoor décor surfaces has an impact on the sound absorption, and therefore, on the acoustic characteristics of the indoor space. In fact, the potential of using UV-curable inks for printing on a wide range of materials used for decorative walls or ceilings is connected to their acoustic impact. To the best of our efforts, we were unable to find a study regarding the acoustic impact of surfaces printed with hardened UV-cured inks. One of the reasons for that could be the interdisciplinarity of the issue. The main goal of this work is to investigate this impact, i.e., to answer the question whether printing with UV-cured inks influences the sound-absorbing property of a material.

2. Methodology

The evaluation of the acoustic impact from printed surfaces is based on comparing the sound absorption between unprinted and printed sound-absorbing materials. When sound propagates in a closed space, the level to which the sound builds up as well as the decay of the reverberant sound after the sound source is stopped depends on the sound-absorbing characteristics of the boundary surfaces and objects filling the closed space (International Organization for Standardization, 2003). A closed space that is specifically designed so that the average sound pressure level is essentially uniform, i.e., the sound field is diffuse, is referred to as reverberation room (Vér and Beranek, 2006, p. 85). Measurement of the sound absorption of a given material is performed by measuring the reverberation time when the material is mounted in a reverberation room (International Organization for Standardization, 2003). As mentioned before, the reverberation time itself is a measure of the time needed for the stationary and diffuse sound to fade out, or more accurately, for the SPL to fall 60 dB after the sound source has stopped (Beranek and Mellow, 2012, p. 470). In the following subsections, the materials and equipment used for the measurements as well as the method for calculating the sound absorption are described.

2.1 Materials and equipment

We used three different sound-absorbing materials for the evaluation, Ecophon Akusto™ wall Super G™, Ecophon Akusto™ wall Texona, and Ecophon Akusto™ wall Akutex™ FT. They are to be used as decorative wall plates, and they are all made of glass wool but with different front-facing surface finishing. In the rest of the text we refer to them as three different quality types, from one to three. Their dimensions are 2.4 m × 1.2 m × 0.04 m (cut from the original 2.7 m × 1.2 m × 0.04 m), and their main purpose is providing thermal isolation and sound absorption in indoor spaces (Ecophon, 2020). The printer we used is a flatbed Canon Arizona 2280XT, enabled with the VarioDot technology for variable size of the deposited ink drops (Canon, 2020a), and the Touchstone elevated (also known as 2.5D) printing technology (Canon, 2020b). It is a piezoelectric inkjet system; it uses the IJC-257 inks that are polymerized (cured) using UV light right after being deposited on the printing substrate. The elevated print production is achieved through adding up ink layers in several print-and-cure cycles (Canon, 2018). In this work, we investigate the acoustic impact from only one ink layer – as in the con-



1 2 3

Figure 1: Microscopic surface of the printed sound-absorbing plates of three quality types marked 1, 2, and 3; the physical size of the area shown in all three images is 8 mm × 6 mm

ventional 2D print reproduction. The whole area of the testing plates was printed with one layer of uniform green at 200 % ink – we used full coverage levels of both cyan and yellow. The amount of deposited ink was selected so that it emulates 2D prints with moderate-to-high ink coverage; the uniformity of the print was to ensure uniform sound-absorbing properties of the printed surface and contribute towards reducing the measurement noise. Figure 1 shows microscopic view of each of the three printed plates.

For the sound absorption measurement, we followed guidelines from the ISO 354:2003 standard (International Organization for Standardization, 2003). This standard specifies the room characteristics, the mounting of the measured plates, the methods for measurement of the reverberation time as well as the subsequent calculation of the sound absorption curve. The size of our reverberation room is 2.7 m × 3.84 m, and it is 2.6 m high. The testing plates were mounted on a wall in the reverberation room by tiling two plates to an effective area of 2.4 m × 2.4 m. Metal fasteners were used to ensure they fit tightly to the wall. An example of the mounted plates in the reverberation room is shown in Figure 2.

Figure 2: One of the printed plates mounted on the wall in the reverberation room; the omnidirectional loudspeaker and microphone are also shown

The volume of the reverberation room (27 m^3) is considerably below the recommended minimum of 150 m^3 (International Organization for Standardization, 2003) and it is the main limitation of our measurement setup. While the measurements of the reverberation time in this work may therefore not be absolutely correct, we believe that this has limited impact on our study – it is a comparative analysis of sound absorption of different materials, calculated using repeated measurements in the same conditions. Furthermore, given that “the minimum volume of the room depends on how low in frequency valid measurements are to be taken” (Vér and Beranek, 2006, p. 85), the potential measurement errors due to spatial non-uniformities in the sound intensity are expected for the lower frequencies. For example, if measurements are to be done down to the 200 Hz band, then a room volume of 70 m^3 would be acceptable (Vér and Beranek, 2006, p. 85).

The reverberation time is measured using the interrupted noise method (International Organization for Standardization, 2003). The reverberation room is excited for around 5 s with a pink noise with continuous spectrum from an omnidirectional loudspeaker, Norsonic Nor276, driven by the power amplifier Norsonic Nor280, to create a diffuse sound field in the room. A free-field microphone, Norsonic Nor1225, coupled with the sound analyzer Norsonic Nor140, is used to record the SPL during the excitation and for 10 s after the excitation stops. The sound analyzer estimates the decay curve of the SPL and subsequently the reverberation time. As recommended in the ISO 354:2003 standard, we used 20 dB as an evaluation range for the SPL decay; therefore, we label the measured reverberation time as T_{20dB}. The reverberation time itself is normally dependent on frequency. As recommended in the ISO 354:2003 standard, we performed measurements at 18 third-octave frequency bands, ranging from 100 Hz to 5 000 Hz. During the measurements, both temperature and humidity were controlled to reduce variability in sound absorption caused by air at different atmospheric conditions. The number of spatially independent measured reverberation times is six – we used two different positions for the loudspeaker and three different positions for the microphone. In order to reduce the occurrence of acoustical resonances, there were no spatial symmetries regarding the loudspeaker and microphone positions, and their distance from each other and to the surrounding walls, for all of the six different configurations. To obtain statistically independent measurements and avoid non-representative measurements, the microphone positions should be at least half-wavelength apart (for the lowest measured frequency) from each other and also half-wavelength away from any reflecting objects (Vér and Beranek, 2006, p. 210). In our six different configurations, the minimum of the distances between the different microphone positions and between the microphone positions and the nearest reflecting objects was 0.6 m – which is the half-wavelength of a wave at frequency of approximately 286 Hz. According to this requirement, our measurements of the reverberation time for the frequency bands lower than 286 Hz may not be representative.

2.2 Calculation of the sound absorption curve

The reverberation time is calculated as an average of the reverberation times measured for the six different loudspeaker/microphone positions. For calculation of the sound absorption coefficient at each frequency band, two different measurements of the reverberation time are needed – one of an empty reverberation room, and another with the testing plate mounted inside the room. The sound absorption curve $\alpha(f)$ is calculated as a ratio between the equivalent sound-absorbing area, $A_T(f)$, and the actual area of the testing plate, S:

$$\alpha(f) = \frac{A_T(f)}{S} \qquad [1]$$

The equivalent sound-absorbing area of the testing plate is calculated (International Organization for Standardization, 2003) as

$$A_T(f) = 55.3V\left(\frac{1}{c(t_2)T_2(f)} - \frac{1}{c(t_1)T_1(f)}\right) - 4V(m_2 - m_1) \qquad [2]$$

In Equation [2], V is the volume of the reverberation room, expressed in m^3; $c(t_1)$ and $c(t_2)$ are the speed of sound in air at the measurement room temperatures t_1 (during the measurement of an empty room) and t_2 (during the measurement with the testing plates mounted), expressed in m/s. For temperatures t in the range of 15 °C to 30 °C, the speed of sound c is calculated as: $c = 331(1 + 0.6t)$ (International Organization for Standardization, 2003). Furthermore, $T_1(f)$ is the measured reverberation time (T_{20dB}) of the empty room at frequency f, while $T_2(f)$ is the measured reverberation time with the testing plates mounted, both expressed in s. The variables m_1 and m_2 are power attenuation coefficients (expressed in m^{-1}) that account for the climatic conditions in the empty room and with the testing plate mounted, respectively (International Organization for Standardization, 1993). If the climatic conditions in the room (temperature, relative humidity) remain constant during the two measurements, then m_1 and m_2 will cancel out in Equation [2].

In order to reduce the measurement uncertainty, we performed ten measurements of the reverberation time for each loudspeaker/microphone position in all measurement scenarios for the three different plates, i.e., empty room, an unprinted plate mounted, and a printed plate mounted in the room. The average reverberation time of these repeated measurements was used in Equations [1] and [2] for calculating the sound absorption as a function of frequency.

3. Measurement procedure, results, and discussion

The T_{20dB} reverberation time was measured in seven different measurement settings: one for the empty reverberation room, three for the three types of the unprinted sound-absorbing plates mounted on the measurement wall, and another three for the printed ones. The measurements were performed ten times for each of the six different loudspeaker/microphone positions, and for the following third-octave bands (Hz): 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, and 5000. The total measurement time including mounting/dismounting the plates in the reverberation room was around 3.5 hours. For a very small number of measurements at the lowest two frequency bands (100 Hz and 125 Hz), the sound analyzer did not report the T_{20dB} times, or the reported times were unusually very high (at least twice the median value) – those measurements were not included in the analysis. The reason for this could lie in the size of our reverberation room – as mentioned before, its volume is below the recommended minimum. This may have resulted in a non-diffuse sound field for the lower frequencies during the excitation (Vér and Beranek, 2006, p. 85), and subsequently, in errors for the estimated reverberation times at these frequency bands.

The average of all 60 measured T_{20dB} times per frequency band for each of the seven setups was used in Equations [1] and [2] for calculating the sound absorption curve. In order to determine the measurement uncertainty, we calculated 10 different sound absorption curves using the average T_{20dB} time for the six loudspeaker/microphone positions; these 10 values were assumed to be samples of a Student's t-distribution, and the confidence intervals were calculated at a 95 % confidence level. The sound absorption curves for the unprinted and printed plates are shown separately for the three quality types of plates in Figures 3–5, respectively. The confidence intervals at each measured frequency band are denoted with dots. They are noticeably larger for the lowest two frequency bands mostly because of the excluded measurements for the reverberation time, which lead to less than 10 calculated values for the sound absorption. In general, for all of the six absorption curves plotted in Figures 3–5, the confidence intervals calculated for the frequency bands in the lower half are larger than those for the higher half. Therefore, we can infer that measurements for the higher frequencies were made with higher precision. It can be seen that the two sound absorption curves for the unprinted and printed plates are very close to each other for each of the three quality types. The confidence intervals overlap at each measured frequency band, and therefore, there is no significant difference in the sound absorption of the plates due to the printing one layer with two inks at full coverage. The same conclusion can be obtained using another test – we performed a two-sided sign test to check whether the difference in sound absorption between unprinted and printed plates came from a distribution whose median is not zero. For all three quality types, the sign test could not reject the null hypothesis ("the median difference is zero") as the *p*-values were above 0.7 in all three cases.

As previously mentioned, due to the small distances between the microphone locations and the surrounding reflective walls in the room, our measurements for the bands lower than 286 Hz may not be representative. Another property of our room that indicates inaccurate measurements for the lower bands is the Schroeder frequency (Schroeder, 1962). This frequency is considered as a transition frequency between the low-frequency region, where acoustical resonances in the form of standing waves at the discrete room's natural frequencies are dominant, and the high-frequency region, where the sound field is spatially more uniform and can be statistically described (Vér and Beranek, 2006, p. 209). The reverberation time of our empty room averaged over 10 measurements and all frequency bands is 3.05 s, resulting in an estimated Schroeder frequency of 673 Hz. This value is relatively high mostly because of the small room volume that is used in the calculation. For small rooms, the statistical properties of the frequency response even at half of the Schroeder frequency can be indistinguishable from that of the high-frequency region (Skålevik, 2011). However, the impact of acoustical resonances in our room appears to be significant, and it may be the reason behind the larger differences in measured sound absorption between adjacent bands lower than 800 Hz, which can be observed for all six plates in Figures 3–5. These differences are similarly distributed across the low-frequency region for all of the plates – most probably because of the same measurement conditions (regarding the positions of the plates, the loudspeaker and the microphone) which resulted in specific and consistent statistical properties of the sound field during our measurements.

In general, non-diffuse sound field is the reason behind high variability in sound absorption measurements according to the ISO 354:2003 standard (Vercammen and Lautenbach, 2016). This variability can be reduced, e.g., by calibration that uses a reference absorber (Vercammen, 2010). While not meeting the recommendations from the ISO 354:2003 standard regarding the size of our room may have led to incorrect values calculated for the absorption curves, we think that this has limited relevance for our goal – we are comparing the absorption curves between printed and unprinted plates, i.e., investigating the difference between them.

Even though our measurements were not performed in fully diffuse conditions, we believe that the statistical properties of the non-diffuse sound field did not vary significantly between and during both measurements – as they were performed in the same conditions regarding the positioning of materials and equipment. The average error we make in absolute sense due to the non-diffuse conditions during the measurements of $T_{20\text{dB}}$, and therefore on the sound absorption coefficients, are expected to be the same for both measurements and effectively cancel out in our analysis that looks only at the difference in sound absorptions. The small and insignificant differences in sound absorption between printed and unprinted plates for the higher frequencies (for which the small size of the room had less contribution to a non-diffuse sound field, and therefore, to inaccurate measurements of the reverberation time) was also observed for the lower frequencies (that are more affected by the small size of the room). From our measurement setup and analysis, we do not have a strong reason to believe that there might be a significant difference in sound absorption for the lower frequencies, which was not able to be detected with our limited setup. However, such claim can be supported by performing the measurements in full compliance with the ISO 354:2003 standard.

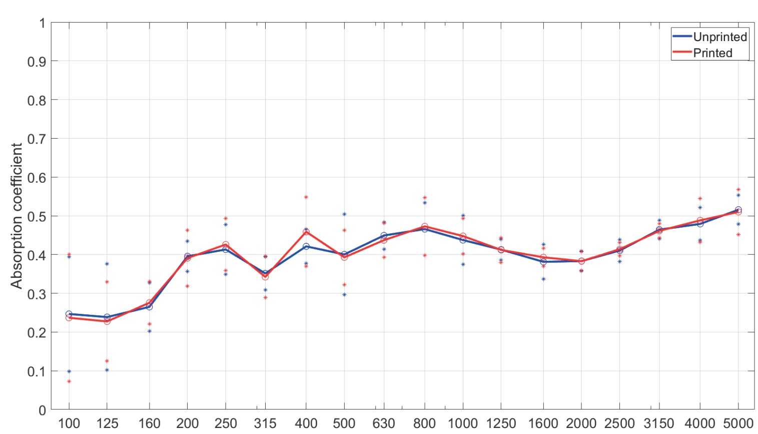


Figure 3: Average sound absorption coefficients with 95 % confidence intervals for the unprinted and printed plates for quality type 1; the averaged measured values are shown with circles

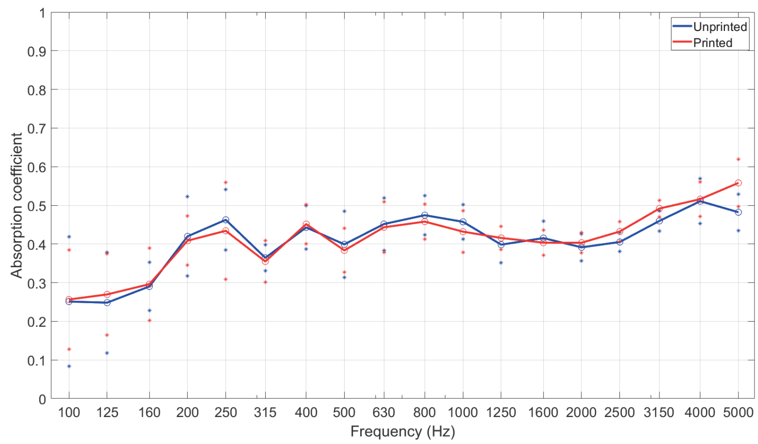


Figure 4: Average sound absorption coefficients with 95 % confidence intervals for the unprinted and printed plates for quality type 2; the averaged measured values are shown with circles

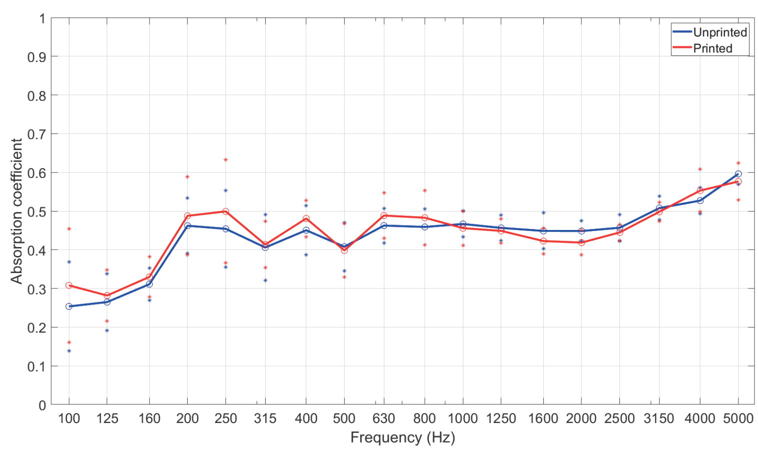


Figure 5: Average sound absorption coefficients with 95 % confidence intervals for the unprinted and printed plates for quality type 3; the averaged measured values are shown with circles

4. Conclusion

In this work, we investigated the impact on sound absorption from printed UV-cured inks on sound-absorbing plates with three different types of surface finishing. We printed only one layer with moderate ink amount – which is sufficient for creating colored décor designs. The sound absorption curves for both printed and unprinted plates were calculated from the reverberation times that were measured in a reverberation room. Our measurement setup was not in full compliance with the ISO 354:2003 standard for measurement of sound absorption, and therefore, the sound absorption measurements are not accurate in absolute sense. However, due to the same measurement conditions, the difference in sound absorption between printed and unprinted plates should still be valid. It was found to be very small, and according to our analysis not significant. We conclude that there is no impact on sound absorption from printing one layer with UV-cured inks.

Potential directions for future work may be taken towards confirming our conclusion in other reverberation rooms, or towards investigating the impact of printing elevated designs using multiple layers of UV-cured ink on sound absorption.

Acknowledgements

We would like to thank Alf Dalby for providing logistics support regarding the reverberation time measurement, to Pål Jacobsen for providing us with the printing equipment, and to Odd Kr. Pettersen and Guillaume Dutilleux for the useful discussions regarding sound absorption measurement.

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