JOURNAL OF
EMERGING INVESTIGATORS

Article

Role of environmental conditions on drying of paint

Deepti Aggarwal, Riya Dutta, Bhaskar Dutta
Troy High School, Troy, Michigan

SUMMARY

Most manufacturing industries paint their products to protect them from environmental degradation and enhance aesthetics. Reducing paint drying time is an important step in improving production efficiency and reducing costs. To find the most effective way to dry paint, we performed a series of 60 experiments by varying different environmental conditions: humidity, lighting, substrate roughness, and paint color. We hypothesized that decreased humidity would lead to faster drying, ultraviolet (UV) light exposure would not affect the paint colors differently, white light exposure would allow for longer wavelength colors to dry at a faster rate than shorter wavelength colors, and substrates with higher roughness would dry slower. We constructed a custom paint booth to control the environmental conditions for a variety of painted samples and regularly weighed the samples to monitor the drying rate. Our experiments showed that trials under high humidity dried slightly faster than trials under low humidity, contrary to the hypothesis. We found that white paint had the slowest drying rate compared to red, yellow, and blue paints under ambient and white light, while under UV light the drying rate of all paints were similar to one another. Colored paints dried the fastest on a metal substrate followed by canvas and then wood, following the increase in roughness of the substrate. Overall, our studies show that the paint drying process is very much dependent on its surrounding environment, and optimizing the drying process requires a thorough understanding of the environmental factors and their interactive effects with the paint constituents.

INTRODUCTION

Manufacturing industries, whether they deal with cars, toys, refrigerators, or anything in between, all have one thing in common: they paint their products. This painting process involves the essential step of paint drying following its application on the products during mass production. The time it takes for paint to dry varies for these products; if the time is reduced, the production to market time would be reduced with important financial implications and an increase in efficiency (1-2). Currently, some companies place painted products in ovens to quickly dry them or use radiation heaters. In the case of automobiles, paint tunnels with low humidity hot air are often used for accelerating the paint drying process (3).

Paints are made of microscopic colloidal particles in a liquid. As paint dries, the liquid evaporates, and the paint particles move at different speeds according to their size and settle into layers. Various environmental factors, such as temperature, air flow, and humidity can affect the evaporation rate of liquids (4). These changes can affect the chemical and physical boundary conditions in the drying paint layer and further affect the forces and accelerations on the colloidal particles. The interaction forces acting between these colloidal particles in suspension play an important role in the process of paint drying (1). There are four stages of paint drying (**Fig. 1**). The first stage is known as settling. In this stage, the particles of the paint fit into place and begin to stop moving; no noticeable differences in weight or paint dryness are evident here. The second stage, known as squashing, is used to measure the rate of paint drying, as this is where paint rapidly declines in weight and the solvent evaporates quickly. The third stage is called inversion. This stage results in a small increase in weight for the paint samples due to air becoming trapped in the now solid paint. This stage may or may not be present in all paint drying processes. The fourth and final stage of paint drying is known as diffusion. From here, the paint gradually declines in weight, and continues evaporating solvent until no more evaporation is possible, at which point the sample is considered "cured" (5-6). Paint

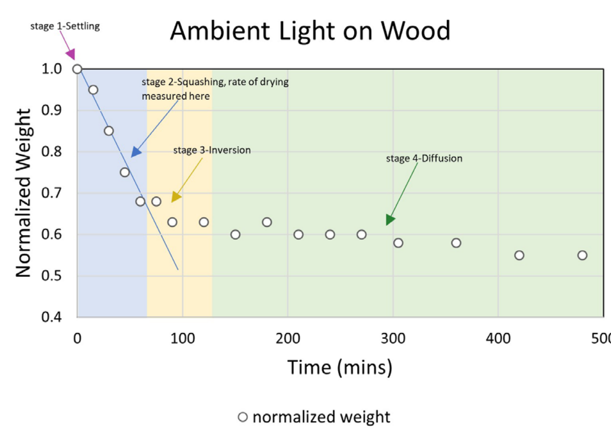

Figure 1. Four independent stages of paint drying as indicated by preliminary testing. The rate of drying was measured from the slope of the blue section of the plot in stage 2 (Squashing). Most of the solvent evaporated in this stage. The yellow section represents stage 3, inversion, and the green section represents stage 4, dispersion.

particles also coalesce in the final stage of drying. Companies may use latex paints or short-wave infrared curing to increase paint drying speed and efficiency (7). The current study aims to investigate the role of the above-mentioned environmental factors on paint drying in order to better understand the drying process and, in turn, aid in improving the efficiency of the process.

For these experiments, the drying rates of household acrylic paints were tested under different environmental conditions to evaluate the effect of individual factors (8). The goal of this study was to find out how the environmental conditions such as humidity, lighting, paint color, and substrate affect the rate of drying of household acrylic paint. For each of the various independent variables to be tested, we formulated a different hypothesis. We hypothesized that a decrease in room humidity will promote faster evaporation of the liquid solvent in the paint and result in a higher paint drying rate. We predicted that painted samples exposed to ultraviolet (UV) light would not exhibit a correlation between the color of the paint and rate of paint drying. Under white light, however, we hypothesized that colors characterized by shorter wavelengths will dry at a slower rate than colors characterized by longer wavelengths because shorter wavelengths have more energy. If shorter wavelengths of light are reflected, then less energy is being absorbed. Finally, we hypothesized that a higher substrate roughness will mean thicker layers of paint at the troughs and would result in a slower drying rate. The goal of this study was to find the environmental conditions that could increase the speed of paint drying and potentially increase efficiency of the relevant manufacturing processes. Trials under high humidity dried slightly faster than trials under low humidity. We also found that white paint had the slowest drying rate compared to red, yellow, and blue paints under ambient and white light. However, under UV light, the drying rate of all paints were similar. Colored paints dried the fastest on a metal substrate followed by canvas and then wood, following the increase in roughness of the substrate.

RESULTS

In this study, we conducted a series of experiments to investigate how environmental conditions such as humidity, lighting, paint color, and substrate affected the rate of drying of household acrylic paint. We performed a total of 60 trials, each spanning a total test time from 500 minutes to up to 1700 minutes. Each experiment involved applying paint of a specific color on either a canvas, wood, or metal substrate, and subsequently measuring the weight of the substrate at periodic time intervals. The rate of the drying process is expressed as the normalized weight loss per unit time (**Equation 1**) during the squashing stage of the paint drying

$$\text{Normalized weight loss at time 't'} = \frac{\text{Initial paint weight} - \text{Paint weight at time 't'}}{\text{Initial paint weight}} \quad \textbf{(1)}$$

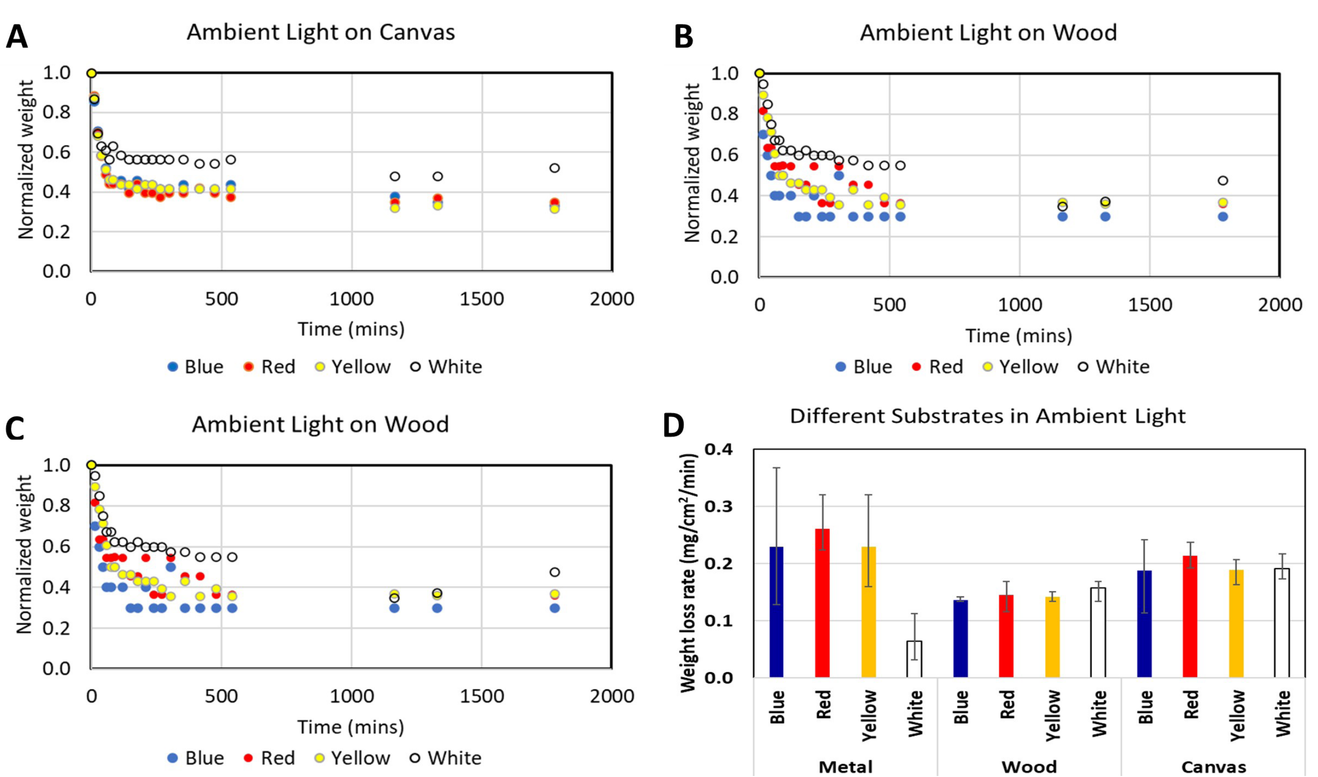

Figure 2. Control and modified roofs. Craft store birdhouse roofs were modified with different mitigation devices. **a)** Control roof with no mitigation device. **b)** Rounded edge mitigation device. **c)** Barrier edge mitigation device. **d)** Upright airfoil mitigation device.

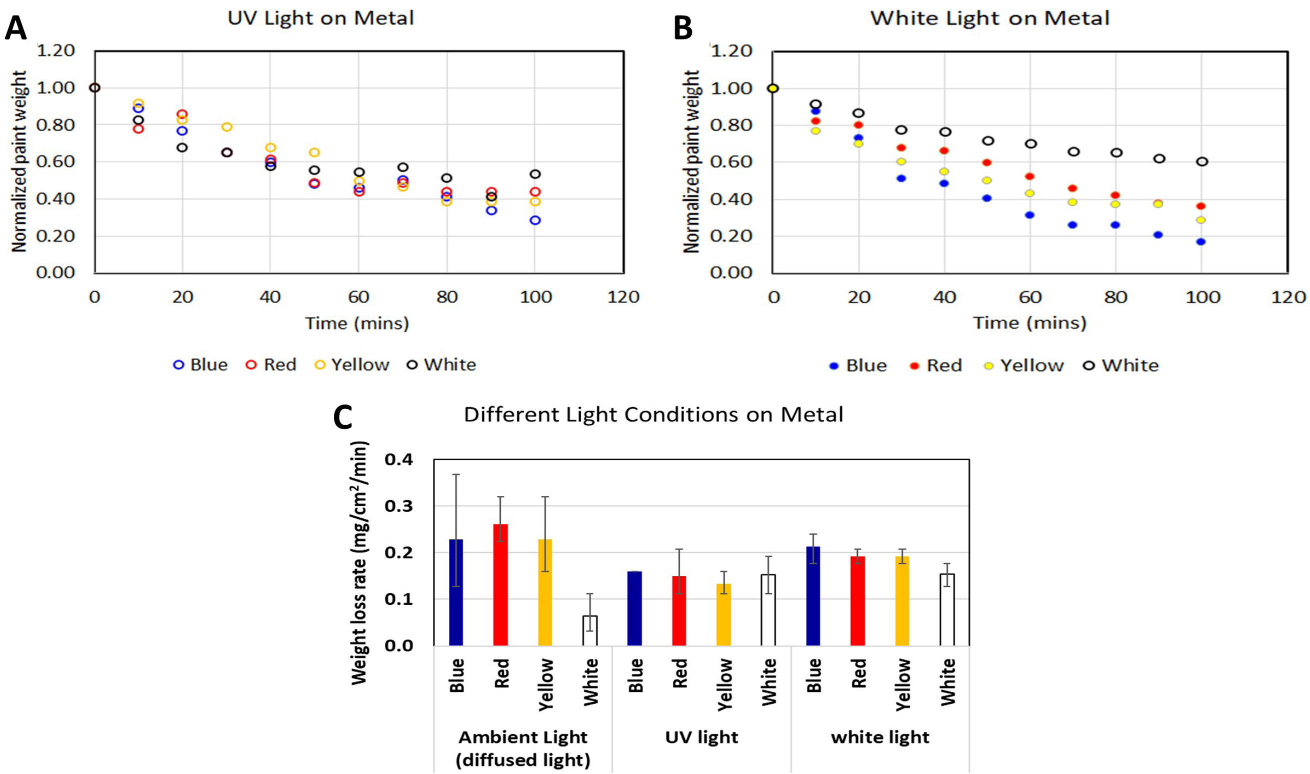

Figure 3. Drying rates (squashing stage) of different paint colors in A) UV light, **B)** white light, and **C)** ambient light on a metal substrate. Under UV light, there was no observable difference between the drying rates of the different colors. Under white light and diffused light, white paint dried at a slower rate compared to the other colors. The error bar shows the max and min of each data set.

process:
The overall trend of the normalized weight loss for all the samples during drying was exponential decay (**Fig. 1**). The normalized weights declined from 1.0 down to between 0.3 and 0.5 until the plateau at about 100 minutes (**Figs. 2 and 3**). Almost 80% of the total weight loss occurred within the first 100 minutes, and the remainder over the next 400 minutes. Since paint samples on different substrates had different surface area, we calculated the drying rate as weight loss per unit area per unit time to allow proper comparison between different substrates.

Next, we analyzed the effect of several variables on the rate of paint drying. Since we hypothesized that the drying rates of different painted substrates under ambient light would be influenced by surface roughness, we used a surface profilometer to determine roughness of canvas, metal, and wood substrate samples. The mean (standard deviation) of the surface roughness in the z direction from peak to valley of the canvas was 26.79 μm (2.73 μm). The roughness of the wood was the greatest at 34.17 μm (2.56 μm), and metal roughness was the least at 0.56 μm (0.06 μm) (**Table 1**). The drying rates of paint in ambient light on these substrates varied depending on which substrate we used (**Fig. 2**). For blue, red, and yellow paint, the metal had the highest drying rate (blue: 0.23 mg/cm²/min, red: 0.26 mg/cm²/min, yellow: 0.23 mg/cm²/min), followed by canvas (blue: 0.19 mg/cm²/min, red: 0.21 mg/cm²/min, yellow: 0.19 mg/cm²/min) and then wood (blue: 0.14 mg/cm²/min, red: 0.15 mg/cm²/min, yellow: 0.14 mg/

Table 1. Substrate sizes, average amount of paint applied on each substrate, average paint area and approx. paint weight per unit area on different substrates.

Type of Substrate	Substrate roughness (μm)	Sample area (mm x mm)	Average paint weight at start (g)	Average paint surface area (mm²)	Paint weight per unit area (mg/mm²)
Metal	0.56	25 x 25	0.142	625	0.23
Wood	34.17	45 x 40	0.268	1120	0.24
Canvas	26.79	65 x 65	0.468	2025	0.23

cm²/min). These results support our hypothesis that rougher surfaces (wood in this case) dry more slowly. However, the drying rate of white paint was much lower on metal, while the drying rates of white paint on both wood and canvas were much higher. This indicates that the surface roughness is not the only influencing factor in the process of paint drying.

Next, we investigated the effect of various lighting on the drying rates of the four colors on metal substrates. Metal substrates were chosen because metal is commonly used in a wide range of industrial manufacturing processes. Under ambient light, the blue, red, and yellow paints dried at similar rates (0.23, 0.26, and 0.23 mg/cm²/min, respectively), while the white paint dried much more slowly (0.06 mg/cm²/min). Under direct white light, all three colors had similar drying rates, with blue at 0.21 mg/cm²/min, and red and yellow both at 0.19 mg/cm²/min, but white at a slightly lower rate of 0.15 mg/cm²/min. The drying rate of all paints were similar under UV light (blue: 0.16 mg/cm²/min, red: 0.15mg/cm²/min, yellow: 0.13 mg/cm²/min, white: 0.15 mg/cm²/min) (**Fig. 3**). These results show that slower drying of white paint occurs under white light and ambient light, but not in the presence of UV light.

Finally, we studied the effect of humidity on the drying rate of blue paint on various substrates because the average paint drying time of blue paint was in between the rest of the drying times (**Fig. 4**). In lower humidity (31%), the average drying rates were approximately 0.16, 0.11, and 0.16 mg/cm²/min for metal, wood, and canvas, respectively. In higher humidity (43%), the average drying rates were slightly higher (0.23, 0.14, and 0.19 mg/cm²/min for the metal, wood, and canvas substrates, respectively).

DISCUSSION

In the three experiments conducted, the four stages of paint drying were clearly visible when the normalized weights were plotted over time (**Fig. 1**). In the present experiments, the second drying stage or the squashing period varied from 60 to 100 minutes, while we observed the complete drying between 500 to 1700 minutes for various conditions.

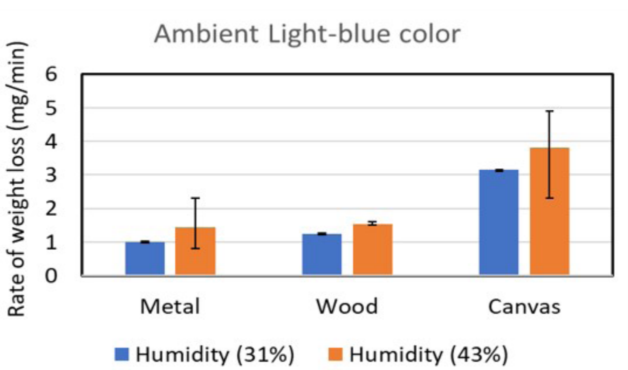

Figure 4. Drying rates (squashing stage) of blue paint on different substrates in ambient light at high (43%) and low (31%) humidity levels. At both humidity levels, drying rate is fastest on metal, followed by canvas and slowest on wood. On all three substrates, blue paint dries faster under higher humidity. The error bar shows the max and min of each data set.

When analyzing and comparing the weight loss data of various paints under different conditions, we normalized the weight of the paint by taking the weight change as a fraction of the original paint weight (**Equation 1**). As seen in **Figs. 1-3**, the starting point was 1.0 and over time the weight decreased until it reached a plateau, indicating the fraction of solids in a particular paint. We tried to apply a similar amount of paint per unit area of substrate in all the experiments (**Table 1**), the actual weight of each sample varied marginally from one to another. Normalizing the paint weight helped to eliminate the effect of this weight variation between different experiments and allowed a direct comparison between various experiments.

After we established the general trend for paint drying, the effects of specific variables were tested. We first considered the substrate type. Using a surface profilometer, we determined that the order of substrate roughness from least to greatest was metal, canvas, then wood (**Table 1**). For the blue, red, and yellow paints, the drying rate was the highest on metal, followed by canvas, and the rate was the slowest on wood substrates (**Fig. 2D**). This observation supports our hypothesis that the increased roughness of the substrate decreases the rate of paint drying. It is possible that a surface with higher roughness reduces the rate of solvent evaporation due to higher surface asperity in these samples. However, it is important to note that the drying behavior of white paint did not support this hypothesis and showed that the metal substrate had the lowest drying rate compared to wood and canvas. This clearly indicates that there are possibly other factors, such as the volume of solids in different types of paints, the paint composition, and the interaction of the paint with the substrate material, that may play a more important role in paint drying than surface roughness alone. This could be a potential future study.

We expected the lighting exposure to affect the paint drying rate because different colored paints would reflect different amounts of visible light energy. In addition, acrylic paints are known to absorb UV light very slowly (7) and consequently result in slow drying under UV light. The light that is absorbed by the paint provides additional energy for evaporation of the paint solvent, mainly water. It is well known that light colors in the visible spectrum are associated with specific wavelengths and energies, starting with blue (475nm wavelength), yellow (550nm wavelength) and red (680nm wavelength) in the order of increasing wavelength and decreasing associated energy (9). Red paints reflect red light wavelengths and absorb the rest and are therefore expected to absorb the highest amount of energy among the three colors. This is followed by yellow paint that reflects only yellow wavelength and therefore absorbs the second highest amount of energy. The third is the blue paint that reflects only blue wavelength, and therefore absorbs the least amount of energy among the three colors. White paints reflect all colors and therefore is expected to absorb the least amount of energy among all the paints in the current study. We expect that a higher amount of absorbed energy promotes a higher rate of evaporation and faster rate of paint drying.

Our hypothesis was that under white light, paint colors with increasing wavelength (blue, followed by yellow, and then red) would be associated with a decrease of drying rate because colors characterized by shorter wavelengths would reflect wavelengths of light with higher energy and therefore dry slower. We found this to be incorrect, as under white light as well as under ambient light drying rate of all three colors, blue, yellow and red were similar to each other even though blue has the shortest wavelength and red has the longest (**Fig. 3B**) wavelength. This apparent contradiction of the hypothesis and the drying rate of different paint colors indicates that the paint constituents possibly play a bigger role than the light reflection of individual colors in the process of paint drying. However, all the studies under white light and ambient lighting clearly show that white paint dries more slowly than the colored paints as predicted by our current hypothesis (**Fig. 3C**). The relatively slower drying rate of the white paint may be attributed to the reflection of most of the light by white paint. Studies in the literature have reported that white paints containing titanium dioxide (TiO_2) and acrylic can reflect up to 92% of incident light (10). Under UV light on metal, all paints seemed to dry at the same rate, which is possibly due to the fact that UV radiation is not reflected differently by any visible paint colors (**Fig. 3A**).

Finally, we studied the role of humidity on the rate of drying. We hypothesized that in ambient lighting, reduced humidity will increase paint drying rate. This is expected as reduced humidity will promote convection and aid evaporation of solvents from the paint. However, our humidity experiments with blue paint on metal showed that higher humidity yielded marginally higher drying rates (**Fig. 4**). These results do not line up with published literature (1, 6) and our hypothesis. As indicated in literature, air flow is a critical factor in the process of paint drying and possibly the most dominant factor (8). In the current experiments, the low humidity trials were performed in the closed paint booth with minimal air movement to isolate the paint booth from the rest of the room and to prevent the ambient humidity altering the humidity of the paint booth. While this allowed the paint booth to have lower humidity than the rest of the room, it also shut out air circulation and reduced convection and evaporation. Thus, we attributed this as the cause of lower drying rate at lower humidity levels during the current study. In conclusion, air movement and humidity are inter-related in the paint drying process and need to be tested independently.

One important factor in the drying process was the relationship between the paint color and underlying solvent, or the ratio of the paint to solid volume (11). Solid content in a paint mainly refers to the residue that is retained in the paint after drying and this mainly consists of pigments, binders and certain additives. In comparison to the other colors, we found the white paint had a higher volume of solids (50% vs. 30-40% for blue, red, and yellow) in the present study. This variation in the solid volume was unavoidable even though we used the same brand and type of paint across all the trials. The colored paints simply require less volume of solid than the white paint. Higher volume of solid in the white paint means lower solvent content and this further highlights the fact that the drying rate of white paint was slower even with lower solvent content.

In the current study, the experiments were conducted under a controlled environment, with only one variable intentionally being altered in each variable trial. We repeated each experimental condition three times and used an average value for further analysis of data. Nonetheless, there were some instances where experimental error may have affected the data. One example is that each time we opened the paint box to perform weight measurements the paint box environment may have been affected by outside air flow. Another potential source of error is the drying rate calculation from the recorded weight loss data. As mentioned in the introduction and results section, we calculated the drying rate from the slope of the weight loss graph during the squashing stage. Weight loss is typically linear in this stage and end of squashing is marked by a significant change in the slope of the plot (**Fig. 1**). We took care to calculate drying rate from this section of the plot. Large sample size and repeated trials helped to reduce the impact of these errors.

In the future, this study could be expanded in multiple ways. Two lessons learned from the current experiments are the importance of accounting for as many confounding variables as possible and examining the hypotheses in light of unexpected findings. An experimental scheme based on the design of experiments and a detailed statistical analysis using analysis of variance could be employed to examine the effect of different variables that interact with each other. A future study isolating the effect of humidity from the effect of air flow is needed to better understand the effect of humidity on the paint drying process. In addition, various types of paints could be tested, such as back paints vs white paints, and water-based paints vs. oil-based paints that have different pigments and different solvents and/or different concentrations of solvents to understand the effect of the pigments and solvents on drying. Since paint drying has a very important application in the manufacturing industry, studies involving the drying of paint on curved vs. flat surfaces and on larger samples may be of significant interest to the industrial community. The research question is broadly applicable to all manufacturing products from refrigerators to airplanes and across various industries. Shortening the paint drying process through environmental changes will help to improve drying efficiency and be easy to implement.

METHODS

The experiments were performed in a paint booth measuring 0.9m (length) x 0.5m (width) x 0.9m (height), built from a used cardboard box. The paint booth included a

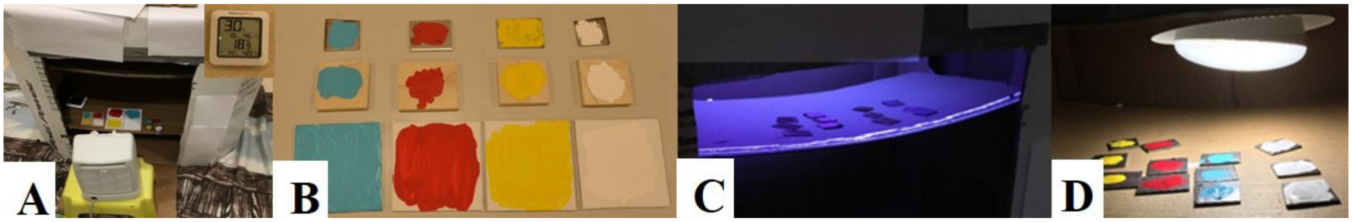

Figure 5. Experimental design. A) Paint booth with thermometer and hygrometer. **B)** Substrates and colors used. Bottom to top: canvas, wood, and metal. Left to right: blue, red, yellow, and white paint. **C)** UV light inserted into the top of the paint booth. **D)** White light inserted into the top of the paint booth.

window for easy access to samples and shelves to hold the samples (**Fig. 5A**). The goal of this paint booth was to control as many environmental factors as possible. Temperature and humidity were measured using a ThermoPro TP50 digital hygrometer (**Fig. 5A**). The average temperature during all the experiments was recorded between 20ºC and 24ºC, approximately room temperature. Acrylic paints from the same brand (Apple Barrel) were used for all experiments (**Fig. 5B**). A Zeiss Surfcom130A profilometer was used to measure substrate surface roughness prior to painting. The weight of the paint samples was measured in an AMIR digital weighing scale with 500g maximum capacity at 0.01g increments. The independent variables tested included the lighting, humidity, substrate type, and paint color. All experiments were performed in ambient light, white light (**Fig. 5D)**, and UV light (**Fig. 5C**). Normal humidity and low humidity conditions were achieved by placing silica gel desiccants in the paint booth for the low humidity and leaving the box unaltered for the normal humidity. Three substrates (wood, canvas, and metal) were used in the experiments. Four paint colors were tested: Caribbean blue, yellow, white, and apple red. Details of the substrate size, initial paint weight, paint area, and paint weight per unit area are given in **Table 1**. We attempted to maintain similar values for 'paint weight per unit area' for all experiments to allow a better comparison of results among the various experiments.

The first step of our experiments was to measure and record the weight of each unpainted sample of wood, canvas, and stainless steel (**Fig. 5**). We used this to normalize the weight in calculations, so the mass of the original sample does not affect the rate (**Equation 1**). Each substrate was then hand painted using nylon/polyester 3-inch brushes with either acrylic Caribbean blue, yellow, white, or apple red paint (**Fig. 5B**). The weight of the painted samples of wood, canvas, and metal (with different colors) was recorded as a function of time (**Fig. 2**). New samples were used for each experiment and experiments for every variable were repeated three times.

The samples were placed in the paint booth and weighed every 15 minutes for the first 90 minutes. Measurements were taken at longer intervals for up to 500 minutes in all cases and continued up to 2000 minutes if the normalized weight continued to decline. However, in later experiments, since the second stage (squashing) was the focus of interest for this study, strict measurements were taken only up until the point of inversion. Prior to each trial, the temperature and humidity in the paint booth were recorded using a thermometer and hygrometer. Experiments (total of 60) were repeated to test varying conditions of lighting, humidity, substrate, and paint color. The data were calculated as the mean of three trials and plotted along with the error bars, showing the max and min of each data set, and analyzed. Paint weight loss was plotted as the normalized weight at time t, defined as the ratio of the difference between the initial weight and weight at time t to the initial weight. By applying regression analysis in the linear "squashing" region, the slope of the plot (mg/min) was calculated, and this was used to determine the rate of paint drying (**Fig. 1**).

Received: September 23, 2020
Accepted: February 14, 2021
Published: February 20, 2021

REFERENCES

1. Saranjam, Nazli. "Transport Phenomena in Drying Paint Films", tspace.library.utoronto.ca/bitstream/1807/76813/1/Saranjam_Nazli_201611_PhD_thesis.pdf, Accessed 12/17/2019.
2. "Paint", www.britannica.com/technology//paint, Accessed 12/17/2019.
3. www.beccainc.com/dry-paint-technologies-available/, accessed 12/29/2020.
4. justpaint.org/technical-notes-on-drying/, Accessed 12/29/2020.
5. Drying of Water-based Paints, www.maths-in-industry.org/miis/312/1/Drying-of-water-based-paints.pdf, Accessed 1/12/2019.
6. Heat and mass transfer in latex paints during drying, Stuart G Croll, J. of Coatings Technology, Vol 59, No 751, Aug 1987. pp. 81-92.
7. The effects of temperature and air humidity on drying of waterborne paint products, Hong Diep Bui, Ph.D. Thesis, Industrial Management, Centria University of Applied Sciences, October 2017
8. "Drying Parameters Application Guidelines." *Teknos*, www.teknos.com/globalassets/teknos.uk/industry/industrial-