Original research or treatment paper

Light-induced cracking and abrasion of inkjet prints: Damage and mitigation

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This study is part of a larger research project at the Image Permanence Institute dedicated to digital print preservation issues – the Digital Print Preservation Portal (DP3). Previous DP3 studies determined that certain digital print types are prone to cracking and/or abrasion, and that factors such as low relative humidity, pollutants, and light increase the brittleness of the ink-receiving layer of some inkjet papers. The purpose of this investigation was to explore if light also increases the propensity of inkjet prints to abrade, and to examine the potential of framing glazings to mitigate light-induced physical damage (cracking and abrasion) by attenuating some portion of the UV spectrum. Inkjet papers and prints were subjected to xenon lighting (to simulate daylight through window glass) without glazing, or in sealed framing packages with plain framing glass (soda-lime) or UV filtering glass. Before and after light exposure, brittleness, and abrasion resistance were evaluated independently using two tests: ISO 18907 (Imaging materials – Photographic films and papers – Wedge test for brittleness) and a rub test utilizing a Sutherland® Rub Tester. In this study, exposure to light increased the cracking and/or abrasion tendency of some specimens. The use of UV filtering glass reduced this light-induced propensity in all cases. Plain glass protected all samples from at least one of these two types of surface damage, but was less effective than UV glass. Light-induced brittleness and sensitivity to abrasion were mostly, though not exclusively, caused by UV radiation. It was also seen that some prints may become brittle and/or prone to abrasion in the absence of image fade. Budgeting the amount of light these objects can be exposed to, protecting them from UV radiation, and handling prints with caution especially after exhibition, is essential in order to limit physical damage.

Keywords: Digital print, Inkjet, Light, Physical damage, Cracking, Abrasion, Mitigation, UV glass

Introduction

This investigation is part of a larger research project, the Digital Print Preservation Portal (DP3), which examines digital print preservation issues and provides information and tools for the care of digitally printed collections (www.DP3project.org). This paper expands on two previous works published in *Studies in Conservation* which examined the light fastness of prints (photographs and documents) created with the most commonly used digital technologies – inkjet, electrophotography, and dye sublimation. After the first study showed that these prints undergo colorant fade, paper yellowing, and changes in paper gloss when exposed to light (Venosa *et al.*, 2011), a second study was launched to investigate the effectiveness of framing glazing to mitigate these three types of damage as well as the loss of optical brightening agent (OBA) function (Venosa *et al.*, 2015). This third study is dedicated to a different kind of damage, one that is commonly overlooked in light-fastness testing: damage affecting the physical integrity of digital hardcopy materials. Ignoring this type of damage entails great risk. The former types of damage studied (colorant fade, paper yellowing, changes in paper gloss, and loss of OBA) have not been correlated to the disruption of the physical integrity of these materials, and therefore, cannot be used as indicators of it.

Two common forms of physical damage to digital prints are cracking and abrasion. Prints that are prone to either of these types of physical damage are especially at risk during handling and transportation.

Cracking is a manifestation of the brittleness of a print. It is a discontinuity of the image-receiving layer (IRL), which sometimes extends to the subjacent polyethylene layer. When subjected to stress, brittle

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Figure 1 Real-life example of cracking and delamination of an inkjet print displayed unframed for approximately 14 years. Close-up of the damage (left).

materials break without significant deformation, i.e. they crack (like glass). Flexing a brittle print may prompt the occurrence of cracking; however, cracking can also appear without flexing the print. Sometimes, IRLs can become detached from the underlying layer and delaminate (Fig. 1). If cracking and delamination occur at the same time, the IRL may flake. Delamination and flaking can cause complete loss of the image, even when image fade is not apparent. Flexing a print may also prompt a different type of damage: buckling. Unlike cracking, buckling is not related to brittleness, as it involves the deformation of the paper support (Fig. 2). This deformation may occur with or without discontinuity of the IRL and subjacent layer (polyethylene or baryta) if present. Also unlike cracking, buckling happens only upon severe flexing of the paper. Some prints are inherently brittle and have a tendency to crack while others are more robust in this respect. Light has the potential to affect both types of prints, initiating the brittleness or exacerbating pre-existent brittleness.

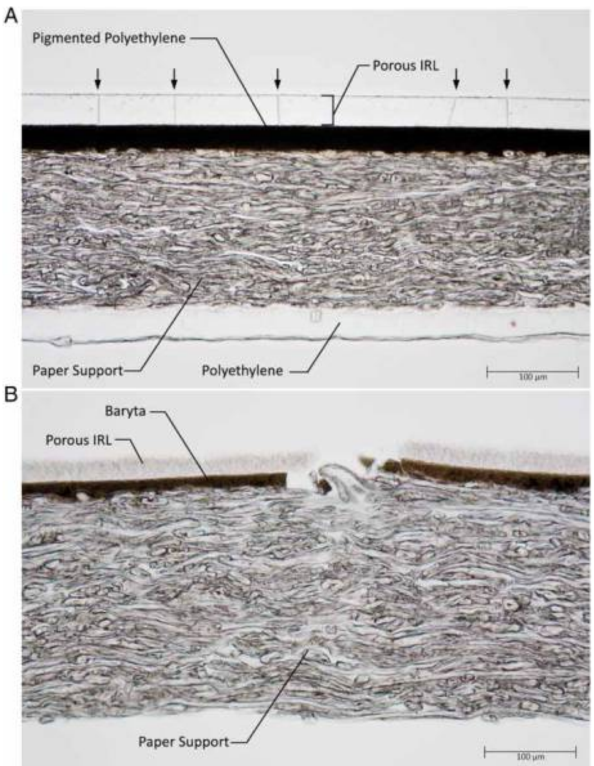

Figure 2 Micrographs of cross sections of a photo-porous inkjet paper showing cracks (A) and a fine-art inkjet paper showing buckling (B). Illuminated with transmitted light. (IRL: image receiving layer.)

Abrasion damage is the number one problem observed in collections of digitally printed materials according to a survey of the field undertaken as part of the DP3 project in 2008 (Burge *et al.*, 2009). It can appear in several forms: colorant loss, colorant smear from dark areas to light areas, colorant transfer from the print to the abrading surface, increase in gloss over a large area of the print (polishing), or a localized increase in gloss (scuff) (Fig. 3). Abrasion is caused by the motion of a broad surface over a large area of a print (or vice versa) and is prone to occur when a print is mishandled, pulled from a stack, or inserted or removed from enclosure materials. Even seemingly harmless materials frequently used with the intention of protecting prints, such as interleaving tissue, can be abrasive (Holden, 1988; Nishimura *et al.*, 2009). Prints with colorants that sit on top of the paper surface, such as pigment inkjet prints, are especially at risk.

Previous DP3 studies determined that certain digital print types are prone to cracking (Salesin *et al.*, 2009) and abrasion (Nishimura *et al.*, 2009), and that factors such as low relative humidity (RH), pollutants, and

Figure 3 Abraded inkjet print. Notice colorant loss in printed area and colorant smear from dark to light areas (especially border of the print).

light increase the tendency to crack of the IRL in some inkjet prints (Salesin *et al.*, 2009; Burge *et al.*, 2010; Salesin & Burge, 2012a). The purpose of this investigation was to explore if light also increases the propensity of inkjet prints to abrade, and to examine the potential of framing glazings (plain glass and UV-filtering glass) to mitigate light-induced physical damage (cracking and abrasion) by attenuating some portion of the UV spectrum. In a previous study Salesin and Burge (2012b) reported that the use of plain glass reduced the light-induced brittleness in two inkjet photo papers tested. However, the efficiency of UV-filtering glass was not assessed in that study. The results of this investigation will help establish the best practices for exhibiting digitally printed objects.

Experimental

Inkjet samples were exposed to high-intensity light in different framing configurations. Then brittleness and abrasion resistance were evaluated independently using two tests: ISO 18907 (Imaging materials – Photographic films and papers – Wedge test for brittleness) and a rub test utilizing a Sutherland® Rub Tester, respectively.

Materials and sample preparation

Brittleness

This portion of the study tested the brittleness of four inkjet papers commonly used for creating digitally printed photographs: a photo-porous paper (porous IRL, resin-coated (RC) base), a photo-polymer paper (polymer IRL, RC base, also known as swellable paper) and two fine-art papers (porous IRL). Unprinted strips of each paper were cut to measure 1.5×21.5 cm (0.625×8.5 inches). Given that some inkjet papers show a reduced brittleness tendency when printed (Salesin *et al.*, 2009), unprinted samples were used. Actual prints may include a wide range of colorant densities as well as unprinted areas, therefore examining what appears to be the worst-case scenario (unprinted area), was considered the most sensible approach. All papers were cut along the width of the sheet discarding at least 25 mm (one inch) from the edge of the paper.

Abrasion

For this portion of the study, targets consisting of a 2.5×3 cm (1×1.25 inches), 80% composite gray patch were printed. A composite gray patch (sRGB 52, 52, 52) was selected as the target with the purpose of including all colors of a colorant set (cyan, magenta, yellow, and black) in the abrasion area, rather than a maximum density black, which is all or mostly black colorant. Two inkjet printers were used in combination with the same substrates used in the brittleness test to produce the following four samples: Pigment/Photo-porous, Dye/Photo-polymer, Pigment/Fine Art 1, Pigment/Fine Art 2. Because pigments sit on top of the paper surface, they are good candidates for abrasion (Nishimura *et al.*, 2009). Dyes, on the other hand, are absorbed into the polymer layer, which makes them more resistant to abrasion.

Samples were conditioned to 21°C/50% RH for two weeks before light exposure.

Light exposure

Samples were exposed to 50 kilolux (klx) xenon arc light for six weeks in the following framing arrangements: without glazing, in sealed frames with plain glass (soda-lime), and in sealed frames with UV-filtering glass.

The glazings used in this experiment were identical to the ones used in our previous work (Venosa *et al.*, 2015). The spectral power distributions obtained in that study show that this UV glass eliminates all of the UVB radiation (280–315 nm), most of the UVA radiation (315–400 nm), and as much visible light (400–750 nm) as the plain glass. That study also established the stability of the glazings' ability to filter UV radiation. After six weeks of exposure to 50 klx xenon arc light, the UV glass showed very little change in the spectral transmission in the UV region, while the plain glass showed no change at all, therefore both glazings were considered suitable for the study. The thickness of the glazing was 2 mm.

Sealed frames served the purpose of isolating the samples from atmospheric pollutants, which contribute to the physical deterioration of certain digital print types after extended periods of time (Burge *et al.*, 2010). In sealed packages, the air was not evacuated, nor replaced with inert gas; any atmospheric pollutants trapped inside are predictably consumed without further ingress of pollutants. Given that only the intensity of the light was enhanced to simulate the long-term exposure, and not the concentration of pollutants, the effects of external pollutants after six weeks are thought to be negligible.

Control samples were kept in the dark in the same framing arrangements as test samples.

A Q-Sun Xenon Test Chamber (Westlake, USA) with Window-Q filters with an illumination intensity of 50 klx was used to simulate diffuse daylight through window glass.

Brittleness samples in their respective framing arrangements were positioned on the specimen tray. All samples were window-matted using 100% cotton cellulose 4-ply white mat board. Sealed frames had a polyester sheet on the back of the mat board, glazing in front of the window mat, and were sealed with polyester tape with acrylic adhesive all around the edges. The mat board, the polyester, and the tape were non-reactive in accordance to ISO 18916 (Imaging materials – Processed imaging materials – Photographic activity test for enclosure materials).

Abrasion samples were positioned on the specimen tray in metal holders with metal backings. The glazing was separated from the print by a window mat, and then sealed with polyester tape with acrylic adhesive. The mat board and tape were the same as those used for the brittleness test.

The samples' location on the tray was rotated weekly to account for the asymmetry of the position of the light source with respect to each sample. The temperature and humidity across the specimen plane were set to 25°C and 50% RH.

Assuming a typical display intensity of 450 lx for 12 hours per day (Wilhelm, 1993, pp. 107–11), six weeks of constant 50 klx exposure is approximately equivalent to 25 years of typical domestic display. This prediction also assumes that all degradation is caused only by light, and excludes the simultaneous effects of atmospheric pollutants, humidity, and heat, which also occur during typical display, and that the reciprocity law holds true. According to the reciprocity law, the total chemical change is constant for a given exposure, independent of the intensity, where exposure equals intensity multiplied by time (Bunsen & Roscoe, 1862). A number of external factors and intrinsic properties of the material in question can cause deviations from this law (Feller, 1994, pp. 50–54).

The mentioned assumptions as well as the light source are not optimal museum display conditions; they were selected to create a worst-case scenario for exhibits in institutions. Limiting the exposure to 25 simulated years allowed for time to complete the experiments during the project's duration.

Treatments

Brittleness

Samples exposed to light in each framing configuration were tested in triplicate according to the wedge brittleness method described in ISO 18907. The wedge brittleness device (Fig. 4) used in the test consists of two non-parallel plates or jaws that form a wedge. The separation between the jaws is adjustable. The device has a clamp at the narrow opening of the wedge that holds the sample. The test procedure consists of clamping one end of the specimen, then looping and pulling it rapidly through the narrow end of the wedge. Specimens were looped with the side intended for printing on the outside to replicate flexing of the print during handling. The unclamped end of the sample had a leader attached to provide enough length to carry out the process.

Subsequently, specimens were examined visually under magnification, with the aid of raking light, to determine the diameter (wedge separation) at which the samples first crack. In samples that buckled rather than cracking, the diameter at which buckling first occurred was recorded. Larger diameters indicate greater brittleness or susceptibility to buckle. To eliminate variations between individuals, a single operator carried out the procedure for all samples, and a single observer did the visual evaluation of all samples.

Abrasion

Currently, the International Organization for Standardization (ISO) does not have a standard abrasion test method for digitally printed material. However, in a previous study in which Salesin investigated a variety of abrasion testing devices, the Sutherland® Rub Tester (San Antonio, USA) was

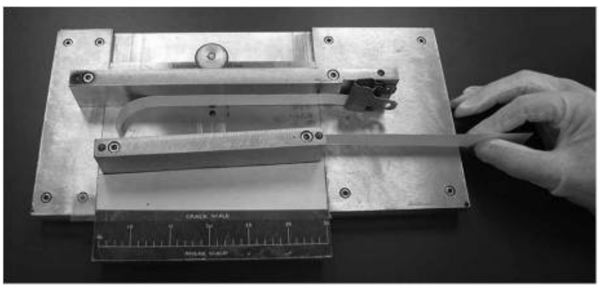

Figure 4 Wedge brittleness device.

considered the best (Salesin *et al.*, 2008). This motorized device consists of a fixed base to secure the test sample, and a movable arm to mount the abrading surface. The arm sweeps back and forth producing the rubbing motion. The speed and number of cycles of the sweeping motion are programmable. The pressure of the abrader on the test sample can also be varied using weights supplied by the manufacturer. Unexposed samples and samples exposed to high-intensity light in each of the framing configurations described above were subjected to the Sutherland® Rub Tester. The abrader of choice was the reverse side of an unexposed paper that matched the print being tested. The tester was set up with a 907 g (2-lb) weight producing a pressure of 1.7 kPa (0.25 psi) and programmed to abrade for 20 cycles at a speed of 42 cycles per minute.

ImageXpert® image analysis software was used to calculate the average gray value of a region of interest (ROI). The software assigns an eight-bit brightness level to each pixel of a ROI, ranging from 0 (black) to 255 (white), and then averages the brightness level of all pixels. This average is the average gray value. Two ROIs were examined (Fig. 5). The first ROI was within the printed gray patch, and was intended to detect colorant loss (rubbed off). The second ROI was located in an unprinted area adjacent to the gray patch, and was intended to detect smear of colorant from the printed area to the unprinted area. Average gray values were determined for unexposed samples, before and after abrasion, and for light-exposed samples before and after abrasion.

Due to a change in the approach of the test, duplicates were not available for all samples/configurations. The initial approach was to abrade the light-exposed unframed (no glazing) version of each sample until it showed a substantial amount of damage, then abrade the light-exposed framed (with glass or UV glass) versions and the controls for the same number of cycles used in the unframed version to see if the use of glazings during exposure reduces the amount of damage produced by the rubbing action. In doing this, the number of cycles used for some samples was excessive and the decision was made to abrade all samples for a lower, more realistic number of cycles (20 cycles). This change in the number of cycles left three out of four samples without duplicates. Unfortunately, the limited space in the xenon arc unit did not allow the simultaneous exposure of extra samples, which could have been used to replace the misused ones.

Results

As mentioned above, the data is based on worst-case scenario display conditions. Therefore objects exposed to lower light levels or low-UV light sources may undergo less change.

Brittleness

The Fine Art 1 paper was not prone to cracking or buckling before or after the light exposure. The Fine Art 2 paper was prone to buckling before exposure, but this tendency was not exacerbated by light. The Photo-porous paper had an inherent tendency to crack without exposure to light, while the Photo-polymer paper was resistant. However, both underwent an increase in brittleness when exposed to light. This light-induced brittleness was greatly mitigated by the use of UV glass during exposure, but was not prevented completely (Fig. 6).

Abrasion

Of the four samples tested, Dye/Photo-polymer was the only one that was not sensitive to abrasion before or after the exposure. However, by the end of the exposure, this print had undergone physical damage

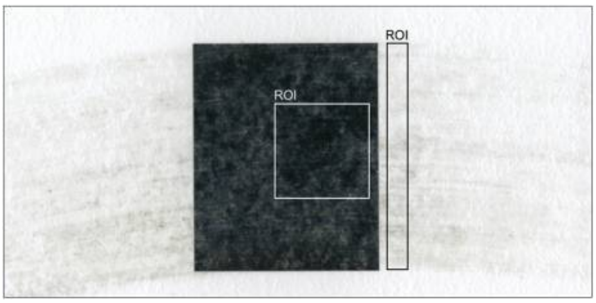

Figure 5 Abrasion target with superimposed regions of interest (ROI). The ROI within the printed gray patch was used to detect colorant loss (rubbed off). The ROI located in the unprinted area adjacent to the gray patch was used to detect smear of colorant from the printed area to the unprinted area.

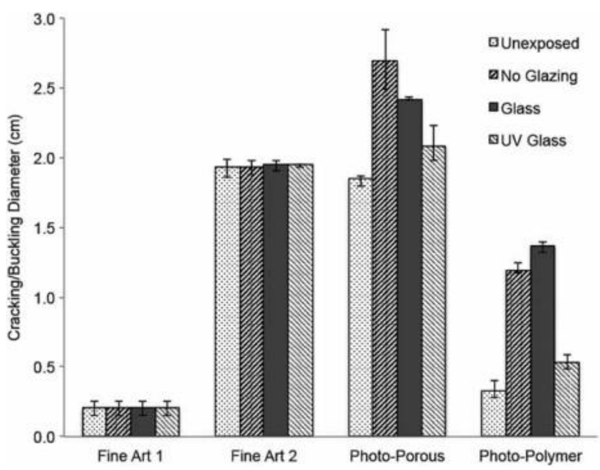

Figure 6 Average diameter at which cracking or buckling first occurs in papers subjected to the wedge brittleness tester after exposure to 50 klx xenon arc light for six weeks in different framing configurations: without glazing, in a sealed frame with plain glass, and in a sealed frame with UV glass. The error bars indicate the range of values for each paper/framing configuration.

of another type: when exposed without glazing, the IRL completely disappeared. In losing this layer, the print lost its gloss and appeared matte. For this material, the use of either type of glazing prevented the damage to the IRL.

The other three samples – the pigment samples – showed a light-induced increase in their tendency to abrade. In all cases, the use of UV glass prevented this increase almost entirely, meaning that the increased sensitivity of these prints was due almost exclusively to UV radiation. The use of plain glass had mixed results ranging from being as effective as UV glass (Pigment/Fine Art 2) to being completely ineffective (Pigment/Photo-porous) (Fig. 7A).

Abrasion damage was evident in the gray printed area as well as the unprinted white area (Fig. 7). This explains why, in spite of the visibly extensive signs of abrasion, the average change in gray value in the white area of the Pigment/Fine Art 2 print is minimal (Fig. 7b). The prints created on fine-art papers underwent the most damage. These two samples are a good example of how abrasion can manifest in different ways. In Pigment/Fine Art 1, the colorant was rubbed off of the printed area and smeared onto the unprinted area (Fig. 8A). In Pigment/Fine Art 2, the gray patch presented some lighter streaks, but the white area did not show signs of smear; rather, the unprinted IRL became chalky and loose (Fig. 8B). This explains why, in spite of the visibly extensive signs of abrasion, the average change in gray value in the white area of the Pigment/Fine Art 2 print is minimal (Fig. 6B).

Abrasion results are based on numerical data confirmed by visual assessment.

It is important to point out that these pigment prints were sensitive to abrasion damage, but did not show signs of colorant fade during the extent of the test. Similarly, previous work showed that, when exposed to light, inkjet photo-porous papers printed with pigments can crack and/or delaminate before colorant fade is noticeable (Salesin & Burge, 2012a). The lack of visible signs of change may lead the user to assume a print is undamaged; this increases the risk of physical damage to the print during handling.

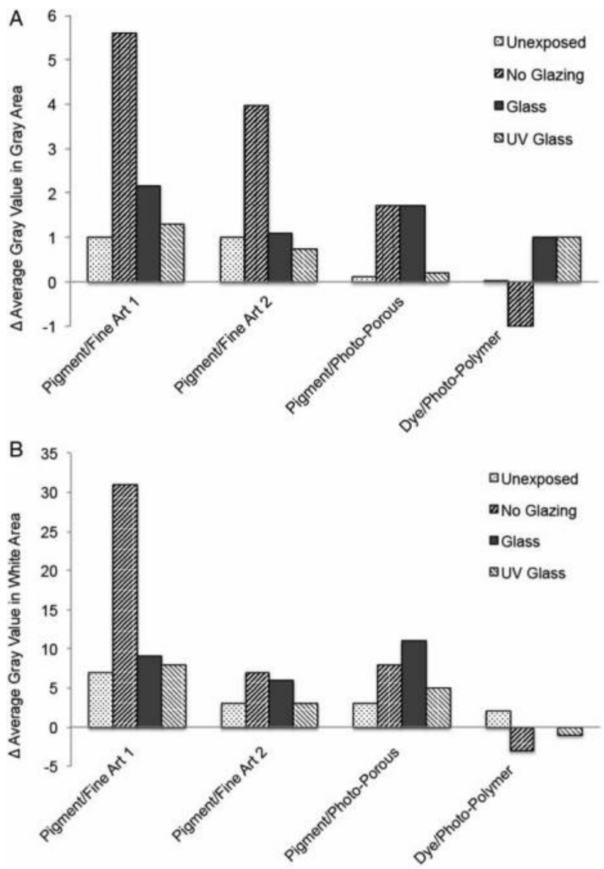

Figure 7 **Abrasion calculated as change in average gray value for a printed gray patch (A) and an unprinted area (B). Abrasion of unexposed prints and of prints exposed to 50 klx xenon arc light for six weeks in different framing configurations: without glazing, in a sealed frame with plain glass, and in a sealed frame with UV glass. Abrasion carried out with a Sutherland® Rub Tester (cycles: 20; speed: 42 cycles per minute; weight: 2 lb).**

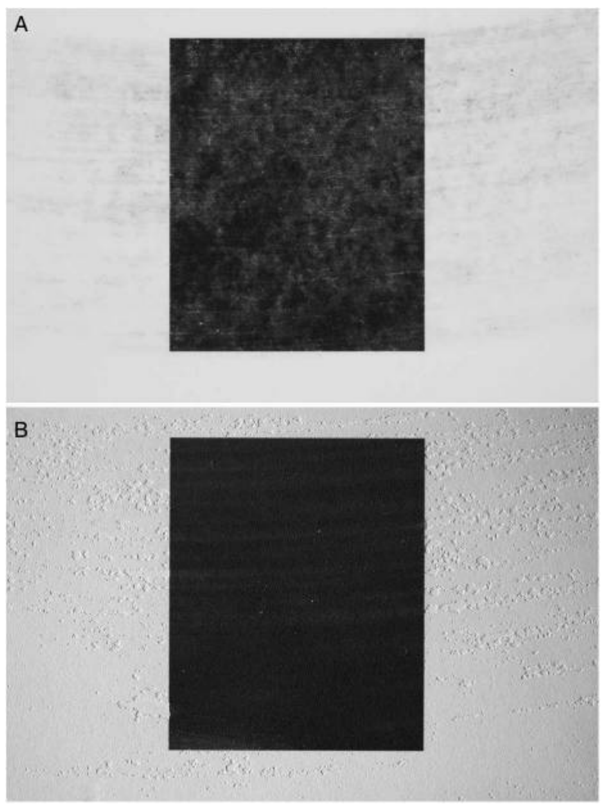

Figure 8 **Examples of different manifestations of abrasion. Pigment/Fine Art 1 print (A) and Pigment/Fine Art 2 print (B) exposed without glazing, and then abraded. Print (B) was photographed illuminated with raking light to reveal its topography.**

Conclusions

It is important to understand that due to their physical structure and/or the chemical formulation of their IRLs, some prints may be inherently prone to crack or to abrade without exposure to light, and that these natural tendencies cannot be avoided. In this study, the use of UV filtering glass greatly reduced the light-induced or light-intensified tendency to cracking and abrasion of all samples tested. Plain glass provided a lower level of protection and was not able to protect all samples from both types of damage. Therefore, the light-induced brittleness and sensitivity to abrasion of the prints used in this study were mostly, though not exclusively, caused by UV radiation.

Mitigation of the light-induced damage may be even greater in unsealed frames (versus sealed frames). In a study carried out by Salesin and Burge (2012b) the light-induced brittleness of a sample was reduced when the sample was exposed in an open frame rather than in a sealed frame. That same study showed that some inkjet photo papers exposed to light generate redox agents, and suggests that these reactants could be responsible for an increase in the brittleness of these papers. This is not the first time light-induced generation of reactants has been described. In 1979, Parson reported that when titanium dioxide (TiO_2), the opaque whitener used in the polyethylene layer of RC papers, is exposed to light, it can lead to the formation of highly reactive oxidants which react with the polyethylene breaking it down and causing brittleness. In this case too, sealed frames intensified the effect, likely by trapping the volatile oxidants and increasing the reaction time. Since then anti-oxidants, scavengers, and/or stabilizers were incorporated into RC papers slowing down the appearance of cracking enormously from a few years to decades even after continuous display in UV-containing light (Wagner, 1999). The chemical mechanisms behind the light-induced brittleness of inkjet photo papers are unknown. A study including a larger set of samples exposed in sealed as well as unsealed frames would help broaden our understanding on the usefulness of sealed versus unsealed frames.

Damage affecting the physical integrity of digital hardcopy materials is not limited to abrasion and cracking. Scratch, which is technically different from abrasion, is also commonly observed. It is caused by a point (rather than a broad surface) pushed or pulled across the surface of a print, such as the corner of another print or a fingernail. Scratches can appear as discrete furrows where IRL material and/or colorant has been removed, cuts in the print surface, or micro-scratches that mainly affect the gloss of the print. Opposed to what one may expect, there is no correlation between a print's sensitivity to abrasion and its sensitivity to scratch (Salesin & Burge, 2011). For all these reasons, scratch is considered a separate manifestation of physical damage. The ability of light to induce or exacerbate the tendency of digital hardcopy materials to scratch is unknown. Further work in this area is needed.

Physical damage is irreversible. Therefore it is crucial to budget the amount of light these objects can be exposed to, to protect prints from UV radiation, and to handle prints with extra caution regardless of their appearance in order to limit physical damage.

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