INTRODUCTION

The Strange Case of Dr. Jekyll and Mr. Hyde, initially published in 1886 by R. L. Stevenson, captivated readers and amateur sleuths as a masked character showed two personalities: one with positive attributes and the other one, not so positive. The story reported here has similarities: it is one of sleuthing, of hide and seek. It is that of a thin, water-impermeable membrane masquerading as wallpaper.

It all started with a phone call: “We have hundreds of feet of failing wallpaper; can you help?” Failure consisted of the tendency of the wallpaper to “bubble up” within 24 hours of application over some 10-20% of the surface—that is to say, to debond from the wall surface in areas 5 to 20 mm (.2 to .8 inch) in size in myriads of locations across the paper. Failure was inconsistent, as some product lots seemed to perform better than others. Several attempts to fix the problem had been made by the client, including changing the glue source, its consistency, the application method, and the use of a primer. Although these attempts were well-executed problem-solving exercises, they did not solve the failure problem.

This is when we answered, “Yes, we can help.” Equipped with goniometers, microscopes, and chemical analyzers, we found an issue of material incompatibility that led to adhesive failure. Key findings are highlighted in this article.

The failure investigation looked into the three components involved in the performance of wallpaper: the wallpaper itself, the primer, and the adhesive. We looked at two wallpaper lots—a purportedly acceptable one and a failing performer—respectively labelled “Corridors” and “Suites”; two water-based primers, A and B; and three water-based adhesives, A, B, and C.

The investigation started with the basic assumption that failure was related to less-than-perfect installation, or product(s), or both. The client had already looked in depth at installation issues, so we focused on the materials and products aspects, along with issues related specifically to adhesion phenomena. This included the wetting propensity of the adhesive onto the wallpaper, primer and adhesive viscosity, adhesive coverage, adhesion strength, and product composition.

MOISTURE DIFFUSION

All three adhesives were water based. For the adhesive to dry and set, water thus had to escape from under the wallpaper, either by diffusion into wallpaper or into the gypsum paper on the wall. Results of wetting tests showed that water would bead on both the Suites and Corridors.
only after several minutes would it wet the backing of the wallpaper, likely through water wicking along the wallpaper fiber strands, which we will discuss below. This simple wetting analysis by goniometry showed that water did not penetrate well into the wallpaper backing, be it the Suites or the Corridors wallpaper. On this basis alone, it would be expected that adhesive drying rates due to water penetration into the wallpaper back surface would be slow in both cases.

Water permeability through the wallpaper was determined using a simple water ponding test. Samples of the two wallpapers were sealed with wax between two plexiglass dishes. A 5-mm head of water was put into the upper dish. The wallpaper was placed in such a way that the side facing the wall was exposed to water. The opposite side was brushed with bromo-cresol blue, a powder indicator that turns dark blue in the presence of water. After 24 hours of exposure, neither the Corridors nor the Suites wallpapers had shown any evidence of water permeating through the wallpaper, as no dark-blue color had developed from the yellow indicator.

The lack of water permeation through the wallpapers indicated that in practice, when the wallpapers are applied to the wall, the water of the water-based adhesive could not go through the wallpaper to evaporate and dry. The only way for the adhesive to dry was for the water to diffuse through the primer and drywall. This diffusion may be very slow, and it could delay the complete drying of the adhesive and contribute to early bubbling.

**WALLPAPER STRUCTURE**

The wallpaper underside structure was studied by microscopy, and the results are shown in Figure 3. It shows that the reinforcing grids were different in the Corridors and Suites products. In the Corridors wallpaper, the sizes of horizontal and vertical fiber strands were comparable and ranged from 250 to 335 microns, with fairly little difference between them. This was in contrast with the Suites wall, which showed much wider horizontal than vertical strands. As a result of the differences in strand sizes, the inter-fiber space was half as large in the Suites wallpaper as in the Corridors wallpaper. Thus, microscopy results showed that the structures of the Suites and Corridors wallpapers were different.

**ADHESIVE VISCOSITY, STRENGTH, AND COVERAGE**

A measure of the tendency of the wallpaper adhesives to spread under pressure was obtained by measuring the shear viscosity against the shear rate. Figure 4 shows...
that upon an increase in shear rate, each adhesive showed a decrease in viscosity, but the rates of decrease were not the same. In general, the greater the slope, the easier it is to spread an adhesive under pressure. Adhesive A would spread the least at shear rates from 100 to 1000 s\(^{-1}\) (typical of blade coating), which would potentially affect the wallpaper coverage. As will be seen later with microscopy, Adhesive A does show slightly less coverage than the other adhesives.

To develop a sense of the adhesion strength for the various product combinations onto wallboard, a pull adhesion test was performed based on ASTM D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. The adhesion strength of the adhesives A, B, and C was measured with a primer and without a primer when applied to both the Corridor and Suites wallpapers. The results of adhesion strength tests (metric ton per square meter) and failure mode are presented in Table 1. With respect to the failure modes, adhesive failure indicates that failure occurred at the interface of the adhesive and wallpaper, whereas cohesive failure means failure occurred in the bulk of the material—either in the adhesive, the wallpaper, or the wallboard. The adhesion strengths, on the order of

![Figure 4 – Shear viscosity vs. shear rate for Adhesive A (square), Adhesive B (triangle), and Adhesive C (circle). Typical shear rates for application processes are shown in red bars.](image)
several T/m², readily highlighted that the issue to resolve was not that of low adhesion strength of adhesive–wallpaper–primer combinations, but more likely the adhesive coverage on the backside of the wallpaper discussed below. During the adhesion tests, failure mode 2 (no adhesion due to a bubble) was occasionally obtained when there was insufficient adhesive on the backside of wallpaper. Consequently, bubbles would not lead to wallpaper falling off the walls. This was a case of aesthetic failure as much as it was an adhesive failure.

After the adhesion test, the underside of the pulling dolly and wallboard substrate were inspected for adhesive coverage. Figure 5 shows Corridor wallpaper adhered with Adhesive C, with the image on the left being the underside of the dolly after the adhesion tests—that is, the side of the wallpaper backing. The image on the right shows the surface of the wallboard after the adhesion test. The left-side image shows three distinct regions: 1) dark brown regions of dyed adhesive (highlighted with white rectangles) still on the backing of the wallpaper (a sign of good adhesion between the wallpaper and adhesive); 2) grey areas (highlighted with red rectangles) where the adhesive had failed, which corresponds to the dark regions with adhesive on the wallboard image in the right (white rectangles), a sign of greater adhesion of Adhesive C to wallboard than to wallpaper; and 3) white isolated patches without adhesive (yellow circles). These are areas that were never covered with adhesive.

Figure 6 shows a microscopy image of the left-side photo in Figure 5, and it reveals that the area within the red rectangles, where adhesive failure had occurred, was found principally along the flat ribbon of the reinforcement (i.e., the horizontal fiber at the bottom of Figure 3). The image also reveals that areas without adhesive within the yellow circles were located in the inter-fiber area, identified by the crosses (+) in Figure 3. The qualitative results from Figures 5 and 6 were then digitized to calculate the surface areas where adhesive failure had occurred and areas without adhesive. An example of digitization is shown in Figure 8. From digitization, quantitative results were obtained, which allowed for a comparison of the effects of wallpaper, adhesive, and primer on the size of the failed areas.

Table 2 shows the percent surface area with adhesive failures (highlighted by the
long horizontal rectangles in Figure 5) and the percent areas without adhesive (highlighted by the yellow circles in Figure 5). The table shows that regardless of the adhesive or primer, the Suites wallpaper showed more adhesive failure from the pull test (32% and 18%) than the Corridors wallpaper (5% and 6%). This suggests that the smoother flat-ribbon structure of the Corridor paper (Figure 3) plays against adhesion. It could be argued that this flat structure, combined with the greater viscosity of Adhesive A, led to both the greatest areas of adhesive failure and non-wetting. However, these results did not translate into a correlation with the adhesion results in Table 1.

**CHEMICAL COMPOSITIONS**

To probe deeper into the differences between the purportedly good and poor wallpaper, Raman spectroscopy was used to determine the chemical composition of the adhesive, primer, and wallpaper backing. The analysis provided for a series of peaks (frequencies), the position of which along the wavenumber\(^3\) provides information on chemical composition (Figure 8). On this basis, the composition of Adhesives A, B, and C was found to be made of starch (exclusively), starch/kaolin, and chemically modified starch, respectively. Primer A was found to be an acrylic latex with some kaolin clay, and Primer B a styrene-acrylic latex.

The results for the wallpapers (Figure 8) revealed a slight difference (green arrows) in the composition of the Corridors and Suites wallpapers. The individual horizontal and vertical fiber strands, and inter-fiber areas were also slightly different in the two wallpapers. This confirmed the microscopy results in Figure 3: the wallpapers had not been produced from the exact same raw materials. More importantly, however, the Raman analysis revealed that both Corridors and Suites wallpaper backings were produced

<table>
<thead>
<tr>
<th>Material</th>
<th>Adhesive A</th>
<th>Adhesive B</th>
<th>Adhesive C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Strength T/m(^2)</td>
<td>Failure Mode (^c)</td>
<td>Strength T/m(^2)</td>
</tr>
<tr>
<td>Corridor wallpaper with primer a</td>
<td>12</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>Corridor wallpaper without primer</td>
<td>12</td>
<td>1, 2</td>
<td>29</td>
</tr>
<tr>
<td>Suites wallpaper with primer a</td>
<td>22</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>Suites wallpaper without primer</td>
<td>14</td>
<td>1</td>
<td>24</td>
</tr>
</tbody>
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\(^a\) Primer A was used with Adhesives A and B; Primer B was used with Adhesive C. \(^c\) Failure modes: 1) adhesive failure, 2) no adhesion (bubble), 3) cohesive failure; \(^d\) n.t.: not tested.

**Table 1 – Adhesion strength of wallpapers glued to wallboard.**
from polyethylene terephthalate (PET) and polyvinyl chloride (PVC). This came as a surprise because the material specification called for cotton-based backing, which would be compatible with a water-based starchy adhesive. This would ensure compatibility because both cotton and starch are cellulosic materials. Hence, poor adhesion was the result of a mismatch in wallpaper backing and adhesive. The adhesive is polar in nature, and it swells in water, whereas the synthetic wallpaper backing material is synthetic, with PET and PVC being impervious to water.

CONCLUSIONS AND RECOMMENDATIONS

The debonding of wallpaper led to a laboratory investigation to explain the reasons for the poor performance of the wallpaper and to help establish corrective measures. The results showed the three adhesives were mostly starch. The wallpaper backings were not cotton as expected, but blends of PET and PVC. These synthetic polymers are not compatible with starch adhesives. It must be emphasized that the wallpaper specifications indicated that the backing was cotton for both wallpapers, but it was not. It is likely that minimal performance issue would have arisen with cotton backing and starch-based adhesives. However, despite the incompatibility between the adhesives and the synthetic backings, the adhesion strength of all adhesives exceeded 12 T/m², a value larger than what is required to hold wallpaper in place. The issue with wallpaper failure was therefore not one of insufficient adhesion strength or adhesive coverage, it was one of incompatibility that led to aesthetic failure.

Wallpaper adhesion is governed by several factors. For the lack of chemical compatibility between starch-based adhesive and synthetic wallpapers, proper adhesion is maintained only by the gripping of the adhesive onto a rough surface. This

<table>
<thead>
<tr>
<th>Materials</th>
<th>Percent area</th>
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<tbody>
<tr>
<td>Corridor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corridor</td>
<td>Adhesive C</td>
<td>Primer B</td>
</tr>
<tr>
<td>Corridor</td>
<td>Adhesive A</td>
<td>none</td>
</tr>
<tr>
<td>Suites</td>
<td>Adhesive C</td>
<td>Primer B</td>
</tr>
<tr>
<td>Suites</td>
<td>Adhesive A</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 2 – Effect of material combinations on the percent adhesive failure areas and non-wetted areas.
requires that the adhesive flow easily into the rough surface to find grip. With smooth ribbon-like flat fibers in the Suites wallpapers, there is little grip, and this leads to one-third of its surface showing adhesive failure during adhesion tests when Adhesive A is used. This is more than with any other product combinations.

In conclusion, this investigation showed that four factors contributed to failure of the Suites wallpaper:

1. The wallpaper backing was not cotton, which is compatible with starch adhesives.
2. The wallpaper backing was a blend of PET-PVC, which is not compatible with starch adhesives.
3. Adhesive A does not flow well into the wallpaper backing.
4. Suites wallpaper has a relatively smooth surface compared to Corridors wallpaper.

Had there been cotton backing on the wallpapers, as expected from the product specifications, no performance issue would have been expected. However, with synthetic backing, factors 2, 3, and 4 acted in synergy to reduce performance and provide for poor adhesion of Suites wallpaper.

It is recommended that quality control procedures for both incoming materials and installation practices be established. In addition, it is recommended to verify the expected mid-term to long-term performance of the currently installed wallpaper to ensure that the product is durable enough to fulfill its designed expected service life and to mitigate the risk of premature wallpaper failure while it is in operation.

REFERENCES

1. A simple and visual method to measure contact angle and surface wetting. In this method, a drop (silhouette) is optically imaged, and the angle subtended by the drop at the point of solid-liquid contact is estimated.
2. Viscosity is resistance of a fluid against flow. Viscosity often depends on applied pressure or shear rates. Ketchup is a good example: it does not flow on standing, but it does when pressed. The viscosity of wallpaper adhesives is no different: it also depends on shear rate.
3. Defined as number of wavelengths per unit distance.

Figure 8 – Raman spectra with the signal Intensity vs. the Wavenumber for the Suites wallpaper (blue) and the Corridors wallpaper (red). The green arrows reveal close but not identical compositions.

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