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PROPERTIES OF SCREEN-PRINTED FLUORESCENT MOTIVE IN A FLEXO-SCREEN COMBINED REPRODUCTION ON RECYCLED PAPER SUBSTRATES

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Abstract: *Fluorescent printing inks are utilized in graphic reproduction for their special visual impression. Because of their vividness, they are used for printing decorative elements and information that needs to be noticeable. In this research, the fluorescent motive was printed by screen printing technique on recycled paper substrates and a preprinted flexographic ink layer. Because of the importance of introducing eco-friendly and sustainable options and alternatives to all segments of graphic reproduction, the possibility of using recycled paper substrates for printing a special-effect ink initiated the research with specific materials presented in this paper. Two types of flexographic printing plates (one solvent-washable and one eco-friendly water-washable) with different surface properties and screen printing plates with different mesh counts were used. This research aimed to determine the influence of the basic flexographic and screen printing plate parameters on the reproduction quality of fluorescent prints on recycled paper substrates. Spectrophotometric measurements of prints, measurements of the thickness of screen-printed and flexographic layers, microscopy of details on fluorescent prints and the width of the fluorescent printed fine lines were analyzed. Furthermore, adhesion parameters were calculated between the paper substrates, printed flexographic ink and fluorescent screen-printed ink. The results of this research provide information on the interaction, compatibility and properties of layers printed by a combination of flexography and screen printing on recycled paper substrates.*

Key words: fluorescent inks, flexography, screen-printing, recycled paper

1. INTRODUCTION

Fluorescent inks are a type of material that can absorb UV radiation and then re-emit it at longer wavelengths. These inks are used for various printing techniques such as offset printing, flexographic printing, gravure printing, inkjet, and screen printing (Koutsioukis, Belessi & Georgakilas, 2019; Xu, Yang & Sun, 2011). When printed on a light or white surface, the fluorescence effect is enhanced (Morović et al., 2019). Fluorescent pigments are highly visible and are commonly used for safety applications like roadwork signage, safety vests, helmets, and construction materials. They are also used in various products such as sporting gear, toys, textiles, and packaging. Fluorescent inks can be activated by visible light as well, which significantly expands the range of colors achievable beyond traditional printing capabilities. They can be formulated using rare-earth elements or organic fluorescent pigments. These inks contain binders like acrylic and epoxy resins, ensuring good viscosity, adhesion fastness, light resistance, heat resistance, and corrosion resistance. They are frequently applied in security printing (Muthamma et al., 2023; Rossier & Hersch, 2011; Varatharajan et al., 2023).

Research on fluorescent materials involves studying their interactions with different printing substrates to meet specific requirements and ensure optimal functionality (Muthamma et al., 2023; Tomašegović et al., 2021). Additionally, a combination of different printing techniques, such as flexographic printing and screen printing, is often used to achieve specific visual and tactile effects in products. By combining various printing techniques, interesting production options could be obtained, with a high degree of economy for printers and added value for the customer. Different technologies can be combined with different hybrid systems, i.e. conventional printing techniques can be combined with digital technologies, or different conventional techniques can be used to print the same product (Eshkeiti et al., 2015; Cazac et al., 2018) When using hybrid printing systems, the characteristics of the printing substrate, expectations of print quality and adhesion between the printed layers are of particular importance. The combined technologies must meet the qualitative requirements and be compatible in terms of the used materials and production technology (Krzemiński et al., 2023).

In this study, three types of recycled paper printing substrates were used, and fluorescent ink was screen-printed on plain substrates and substrates preprinted with black flexographic UV-curable printing ink. The research aimed to determine the influence of the screen printing plate's mesh count on the reproduction of fluorescent ink on recycled paper substrates, with and without the layer preprinted using flexographic printing and UV-curable ink. Furthermore, the influence of the preprinted flexographic ink layer on the optical and interfacial properties of the fluorescent ink layer was investigated.

2. MATERIALS AND METHODS

2.1 Preparation of the samples

For this study, three different types of recycled papers were utilized as printing substrates. Each substrate was certified by the Forest Stewardship Council, promoting environmentally sound, socially beneficial, and economically sustainable forest management. All substrates were uncoated types of papers, and were denoted A, B, and C. Their properties are presented in Table 1.

Table 1: Properties of the used paper substrates

	A	B	C
Brand	MOHAWK	FLORA	SCHOELLERS
Grammage (g/m^2)	220	130	140
Caliper (µm)	200	140	155
Bekk smoothness (s)	52.00	3.80	4.10
Surface free energy (mJ/m^2)	29.20	29.76	22.38

Papers were cut to dimensions of 5 x 70 cm and conditioned 24 hours before printing. The flexographic printing process was carried out using IGT Printability Tester F1 in the laboratory conditions, at a relative humidity of 55% and 23±2˚C. Anilox roller of 90 l/cm and 18 ml/m^2 was used. Anilox pressure was set to 300 N, and printing speed was 0.3m/s. For the flexographic printing, UV-curable ink, Solarflex Integra SINT 46 process black was used. The printing pressure was set to 300 N. Kodak Flexcel NX printing plate, with the micro-pattern on the surface for improving the ink transfer was used, as well as a water-washable and therefore environmentally friendlier printing plate, Toyobo Cosmolight QS. Full-tone flexographic prints were cured using the Technigraph Aktiprint L 10-1 device.
Screen printing was carried out using fluorescent ink Sebastar neon pink from SEBEK inks, and two polyester screens with different mesh counts: 60 l/cm and 100 l/cm. In that way, different amounts of the ink were transferred to the substrates, affecting the qualitative properties of the fluorescent prints. Screen printing was carried out on plain papers, as well as on the papers preprinted using flexography. The details on the prints are presented in Figure 1.

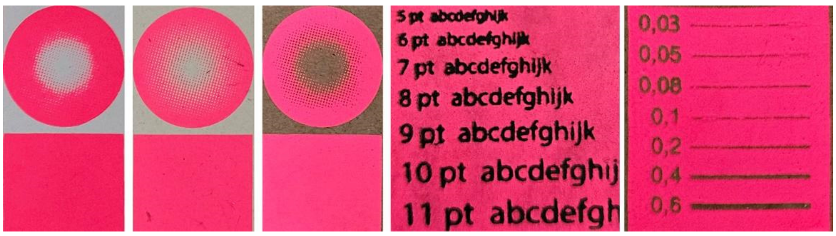


Figure 1: Details on the fluorescent prints (screen 60 l/cm), from left to right: on paper A, on paper B, on paper C, on pre-printed paper C and on plain paper C

2.2 Measurement and analysis

Paper smoothness was measured using the Bekk method on a PTI-Line Bekk device, following the TAPPI standard T 479. Samples were placed on a glass plate, and a measuring head pressed the sample with a 10 kg weight. The pressure between the paper surface and the glass plate was adjusted to 50.7 kPa and then released until it reached 48.0 kPa. The time it took for 10 mL of air to reach 48.0 kPa provided the smoothness value in seconds. Smoothness was measured five times on each printed paper side, and the average values were presented.
Printed ink thickness was measured using the SaluTron D4-Fe, which works based on magnetic induction to measure nonmagnetic layers. Measurements were conducted ten times on each paper, and average

values were presented. The paper caliper values (200 µm for paper A, 140 µm for paper B, and 155 µm for paper C) were subtracted from the measured average thickness values of the paper with print.
Spectral reflectance of the printed coatings was measured using the Ocean Optics USB 2000+ spectrometer and Deuterium-Tungsten Halogen UV light source DH-2000. This allowed observation of the reflectance of fluorescent inks when exposed to UV and daylight radiation.
Microscopy of the printed lines with a nominal width of 600 µm was performed using an Olympus BX51 microscope. Microscopic images were captured at a 50× magnification, and the Stream Motion program was used to measure the width of the fine lines from the captured images.
The contact angles of the reference liquids and consequently the surface free energy (SFE) of the samples were analyzed using the Data Physics OCA 30 goniometer. Three reference liquids with known SFE (water, diiodomethane, and glycerol) were applied on the paper substrates and prints. The SFE of the reference liquids and their contact angles on the samples were used to calculate the SFE of the solid substrates. Contact angles were measured using the sessile drop method, ten times on each sample at different positions. The shape of the drop was a spherical cap, and the volume of the drop was 1 µl. All measurements of the contact angles were performed at 0.4 s (10 frames) after the drop had touched the sample surface, due to the fast absorption of the liquids on unprinted papers. The SFE was calculated using the OWRK method. From the calculated SFE components, the adhesion parameters between the layers in the contact were calculated. Interfacial tension (γ_{12}), work of adhesion (W_{12}), and wetting coefficient (S_{12}) between the layers in contact were defined to assess the strength of interfacial interactions (Mahović Poljaček et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Spectral reflectance of substrates and fluorescent prints

The results of spectral reflectance of the papers A, B, C; and of fluorescent prints on plain and preprinted papers, are presented in Figure 2 "F_" denotes the fluorescent print, "Bl_" denotes the black flexographic print, and "60" or "100" denotes the mesh count.
In Figure 2a, spectral reflectance of paper A and the corresponding prints can be seen. The reflectance over 100% for paper A in the area between 400 and 520 nm could be assigned to the optical brighteners in the paper (Mahović Poljaček et al., 2021; Mustalish, 2000). Furthermore, the reflectance over 100% is also usual for the spectra of fluorescent inks (Tomašegović et al., 2021).

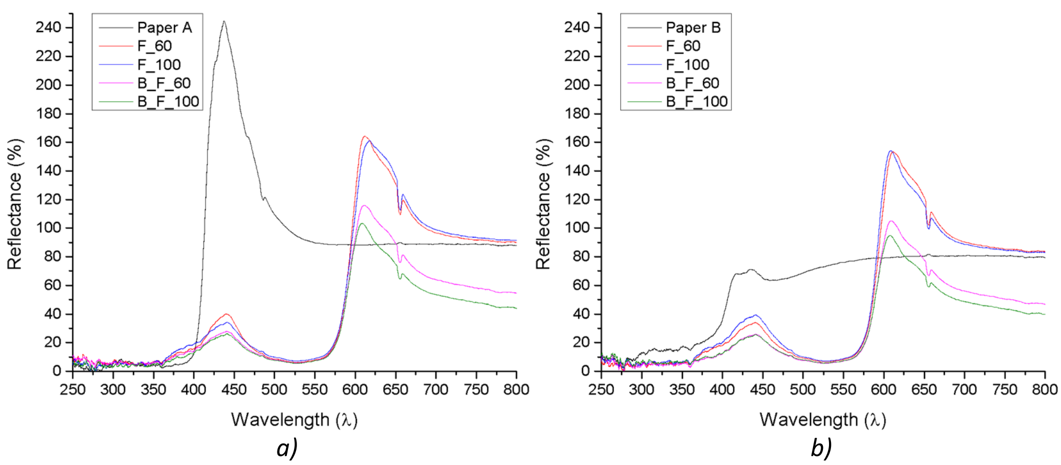


Figure 2 (part 1): Spectral reflectance of paper substrates and fluorescent prints: a) paper A, b) paper B

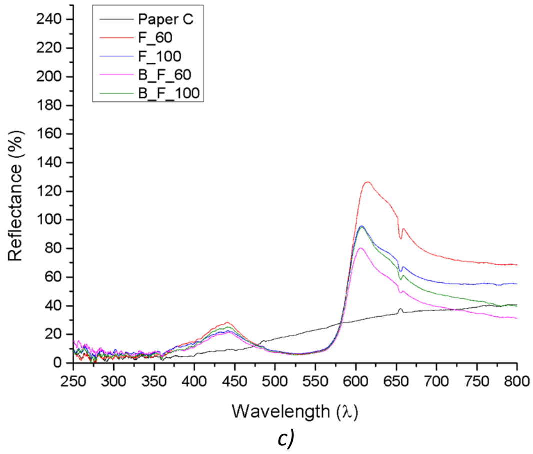


Figure 2 (part 2): Spectral reflectance of paper substrates and fluorescent prints: c) paper C

Two wavelength regions associated with the reflectance of the fluorescent pink ink utilized in this study are evident on all spectra of fluorescent prints, regardless of the used printing substrates (Figure 2a – c): one between 400 and 500 nm peaking at approximately 440 nm, and the other above 550 nm, peaking at around 620 nm. This leads to the conclusion that the fluorescent ink layer is opaque and has completely covered all substrates. However, the spectral reflectance of the fluorescent prints was influenced by the different optical properties of the papers. Darker paper C (Figure 2c) caused a reduction in the reflectance of the fluorescent print compared to prints on papers A and B (Figures 2a - 2b). Additionally, the mesh count also affected the reflectance - a higher mesh count resulted in a thinner ink layer on the substrate and therefore lower reflectance. Furthermore, the existence of the black flexographic ink layer under the fluorescent prints resulted in decreased reflectance, as well. This is particularly true for the fluorescent prints obtained using a 100 l/cm mesh: the effect of the black flexographic ink on the reflectance was significant due to the thin fluorescent print.

3.2 Thickness of the printed ink layers

In Figure 3 the thicknesses of the black and fluorescent layers printed on all substrates (papers A, B, and C) are presented.

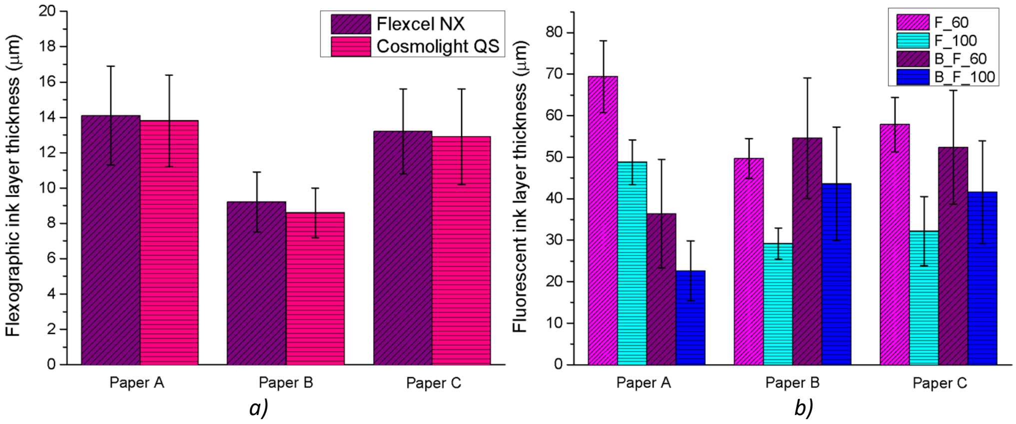


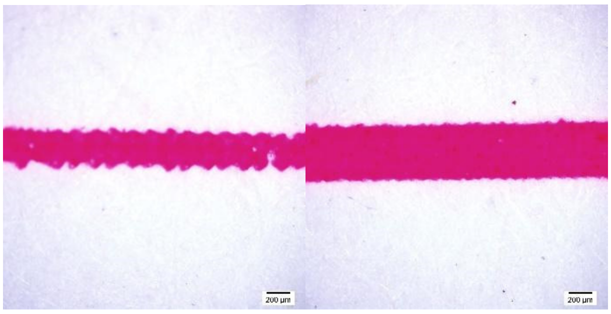
Figure 3: Thickness of the printed ink layers on different paper substrates: a) flexographic ink, b) fluorescent ink on plain and preprinted papers

The thickness of the black flexographic ink layer (Figure 3a) did not present with any significant differences as a result of different flexographic printing plate used. Although the Flexcel NX printing plate should transfer more ink to the substrate than the conventional flexographic printing plate due to the micro-patterned surface, water-washable Cosmolight QS plate performed similarly. It can be concluded that water-washable printing plate used in this research can be utilized to preprint a UV-curable ink layer on the recycled paper substrates rather than the solvent-washable plate due to its ecological favourability.

The fluorescent ink layer thickness was highest at an average value of 69.4 µm on paper A using a 60 l/cm screen and lowest at 22.6 µm on preprinted paper A using a 100 l/cm screen (Figure 3a). The mesh count had an impact on the thickness of the printed layers on all substrates, and an influence of the preprinted flexographic ink layer was discernible only on paper A. As expected, the relationship between ink layer thickness and mesh count was inversely proportional.
When fluorescent ink was directly printed onto paper, the prints on paper A had the highest thickness among the prints on different substrates. The preprinted black flexographic layer also significantly affected the thickness of the printed fluorescent ink layer on paper A. Compared to the fluorescent layers printed directly on the papers, prints on the black flexographic ink layer had a lower thickness. This can be attributed to the smoothness of the paper A - a significantly smoother substrate than papers B and C (Table 1). The flexographic ink filled out the pores of the paper A, which led to less fluorescent ink being transferred to the substrate due to reduced substrate roughness. However, due to the deviations in the printed layer thicknesses, resulting from the substrate roughness, fluorescent ink consistency, mesh structure and fast ink drying, the influence of the black flexographic ink layer on the thickness of the fluorescent ink on papers B and C could not be precisely defined.

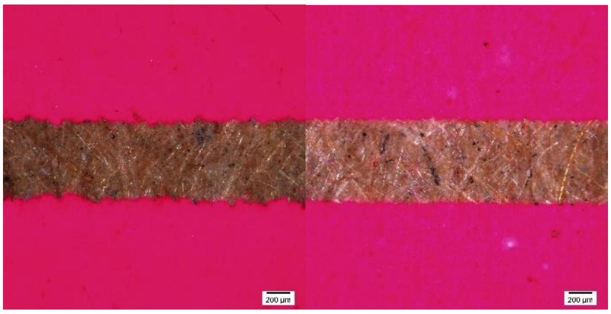
3.3 Width of the printed lines

Figures 4-7 present microscopic images of the lines on the print (nominal width of 600 µm). Image magnification was 50×. Figure 4 presents a clear difference in the width of the lines printed on paper A using different mesh counts. The line printed using the 60 l/cm mesh has irregular edges and is thinner than the line printed using the 100 l/cm mesh. Differences in the width can be attributed to less pronounced deformation during the production of the printing plate occurring due to the incidence and scattering of the light in the emulsion layer, and to the usual irregularity of the line edge in screen printing at lower l/cm. In Figure 5, there is a less pronounced difference between the printed lines in the negative on paper C.



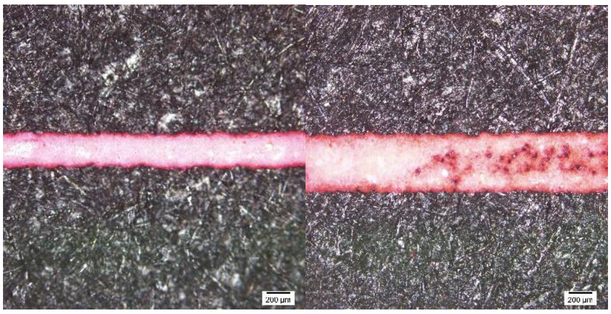
a) b)

Figure 4: Microscopic images of the fluorescent printed lines (positive) on paper A: a) 60 l/cm, b) 100 l/cm



a) b)

Figure 5: Microscopic images of the fluorescent printed lines (negative) on paper C: a) 60 l/cm, b) 100 l/cm



a) *b)*

Figure 6: Microscopic images of the fluorescent printed lines (positive) on preprinted paper B: a) 60 l/cm, b) 100 l/cm

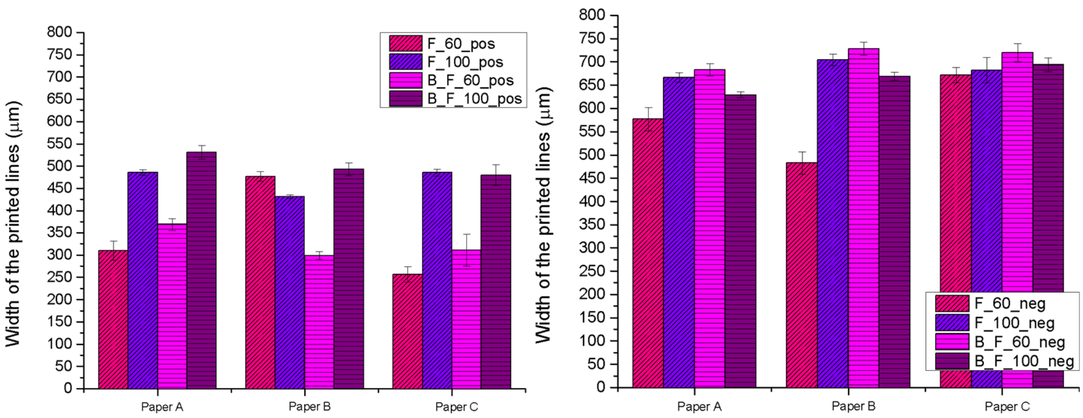
a) *b)*

Figure 7: Microscopic images of the fluorescent printed lines (negative) on preprinted paper A: a) 60 l/cm, b) 100 l/cm

In Figure 6, fluorescent lines that were printed on the flexographic ink layer (on paper B) can be seen. An obvious difference between these two lines is visible; again, the line printed using a 100 l/cm mesh is wider than the line printed using a 60 l/cm mesh.

Both lines in Figure 7 are somewhat irregular with an uneven edge. They are printed on a flexographic ink layer on paper A and are in negative. The line printed using a mesh of 60 l/cm has a more irregular edge and is wider than that printed using a mesh of 100 l/cm, which corresponds to the negative deformation present during the printing plate production. It can be concluded that the adjustment of the film, and/or shortening the exposure should be performed, in order to increase the width of the lines printed in positive, especially for the motives on the 60 l/cm screen.

In Figure 8, the diagrams present the width of the printed lines in micrometres. Their nominal width was 600 µm. Figure 8a presents the lines printed in the positive. It can be seen that the lines printed using a mesh of 100 l/cm are generally wider. The scattering of light inside the emulsion during the exposure of the screen, as well as the effect of the incidence of light rays, proved to be more pronounced on a thicker layer of emulsion, i.e., the one with 60 l/cm.



a) *b)*

Figure 8: Width of the printed fluorescent lines (nominal width of 600 µm): a) positive, b) negative

In Figure 8b, the lines printed in the negative are shown. It can be seen that most lines exceeded the nominal width of 600 µm, with the exceptions being the lines printed directly onto papers A and B, using a 60 l/mesh. Generally, the variations in the line thickness among the samples are significantly lower than for the lines printed in positive. The adjustment of the motive on the film would be needed for achieving the intended printed line width (600 µm).

3.4 Adhesion between the printing substrates and printed layers

Table 2 presents the adhesion parameters between the surfaces in the contact, i.e., papers and prints, as well as between the flexographic and screen prints. There was no difference in the contact angles (and therefore surface free energy) on the printed ink layers obtained using different flexographic and screen printing plates, since the thickness of all ink layers was high enough to uniformly cover all substrates.

Table 2: Adhesion parameters between the surfaces in contact (paper substrates and prints)

Surfaces in contact	Adhesion parameters (mJ/m^2)		
	γ_{12}	W_{12}	S_{12}
Paper A - Black	2.44	60.26	-6.74
Paper A - Fluorescent	1.58	64.24	-9.00
Paper B - Black	2.12	61.14	-5.86
Paper B - Fluorescent	1.31	65.07	-8.17
Paper C - Black	2.54	53.34	-13.66
Paper C - Fluorescent	2.35	56.65	-16.59
Black - Fluorescent	0.31	69.81	-3.43

By observing Table 2, it can be concluded that the differences in the surface properties of the papers and inks were enough to have an impact on the adhesion parameters. Specifically, while the interfacial tension (γ_{12}) between all papers and printed ink layers was low, values closer to zero were obtained between the papers and fluorescent inks, while γ_{12} for paper-flexographic ink interface was a bit higher. Lowest and therefore closest to optimal γ_{12} for the paper-ink interface was calculated between paper B and fluorescent ink (1.31 mJ/m^2). Work of adhesion (W_{12}) was higher between papers and fluorescent screen-printed ink than between the papers and flexographic ink. Furthermore, papers A and B displayed higher W_{12} with both inks than paper C, which pointed to the poorest adhesion between paper C and both types of inks. The values of the wetting coefficient (S_{12}) were negative for all interfaces, with paper C again displaying the poorest result in terms of the optimal adhesion with the ink layers. Finally, most favourable adhesion parameters were obtained between the flexographic black and fluorescent screen ink: γ_{12} was the lowest among all tested interfaces, W_{12} was the highest, and S_{12} did not express significantly negative value. This points to the conclusion of the optimal interactions between these two types of printed ink layers and their compatibility.

4. CONCLUSION

This research aimed to determine the effect of using different types of recycled printing substrates and printing plates with varying properties on the characteristics of fluorescent screen prints when combining flexography and screen printing. To carry out the research, black UV-curable ink was pre-printed on three different types of recycled papers using flexography, and then screen-printed using fluorescent printing ink. Referent samples of fluorescent prints were also printed, without the pre-printed black ink. The results showed differences in the characteristics of fluorescent prints on unprinted and pre-printed paper substrates. Specifically, the fluorescent ink layer was thicker on unprinted paper A than on paper with pre-printed black flexographic UV-curable ink. The lowest thickness of the fluorescent ink layer was obtained on paper A after preprinting with flexographic ink, which can be attributed to its smoothness. Thickness of the prints on papers B and C, however, deviated significantly. Nevertheless, the mesh count still had a decisive influence on defining the thickness of the fluorescent ink on the print. Furthermore, similar flexographic ink layer thickness was obtained when printing with a patterned solvent-washable flexographic plate and a water-washable one, which was noteworthy, since a water-washable flexographic printing plate has an advantage in the ecological aspect of the production. Although the spectral reflectance of fluorescent print can typically exceed 100% at specific wavelengths, it was significantly reduced on paper

C due to its optical properties. The black pre-printed ink layer and mesh count also influenced the results, with a higher mesh count of the screen resulting in a thinner layer of the ink on the paper substrate and therefore lower spectral reflectance. Furthermore, microscopy showed that the mesh count significantly affected the quality of the fluorescent print in terms of the reproduction of details, as expected. However, this influence did not significantly depend on the pre-printed black layer. Microscopic images of print details revealed that the prints obtained with a mesh of 100 l/cm had clearer edges and a higher width. Most favorable adhesion parameters were obtained between the flexographic black and fluorescent screen ink: interfacial tension was the lowest among all tested interfaces, work of adhesion was the highest, and the wetting coefficient did not express a highly negative value; which pointed to the optimal interactions between these two types of inks on the print and their compatibility, i.e., adequate applicability in the real system. In conclusion, the research provided information on the compatibility and features of layers printed with a combination of flexo and screen printing techniques on different recycled paper substrates. It was shown that it is possible to achieve adequate reproduction of fluorescent motifs on recycled and pre-printed paper substrates by carefully selecting the printing substrate, printing inks, and printing plate for screen printing, ensuring adequate mechanical resistance of such prints on a pre-printed flexographic ink layer.

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