

Compatibility of Organic Pigments with Acrylic, Epoxy and Polyurethane Resins

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Abstract: The adhesion of the organic pigments and the resin binding are closely related to the printability of organic printing inks and their rheological, optical, mechanical and storage characteristics. In this study, representative parameters such as viscosity, colour strength, gloss, adhesion, drying time, rub resistance and storage stability are used as performance indicators and compared among the different materials. An experimental design with triple measurements was taken into account, and descriptive statistics were used for summarising the data. One-way analysis of variance (ANOVA) was used to compare the differences among the resin systems; Tukey's Honestly Significant Difference (HSD) test was used to determine pairwise differences. A statistically significant difference ($p < 0.05$) was observed among the three resin systems in all performance measures analysed. It was found that the overall compatibility was superior for polyurethane, with the exception of its adhesion, which was not as high as that of polyamide and polyester. The superior colour strength, gloss, adhesion and rub resistance indicate that the polymer-pigment interactions were balanced, leading to better dispersion of the pigments in the polymer. The viscosity of the acrylic resin was the lowest and the drying time was the fastest among all the resins, thus having good processing properties for high-speed printing. Epoxy resin exhibited the highest viscosity and drying time, as well as superior storage stability, which is related to the strong polymer network and greater resistance to sedimentation in storage. The comparative compatibility testing indicated that resin chemistry is a factor that plays significant roles in the dispersion of pigments, film formation, mechanical durability, and formulation stability. Overall, the findings illustrate the need to choose the resin type based on the application being used, not by any one performance criterion. These observations suggest further experimental investigations be conducted to verify the observations and to develop high-performance, sustainable printing ink formulations, based on comprehensive physicochemical characterisation and long-term durability testing.

Keywords: Organic Pigments, Printing Inks, Acrylic Resin, Epoxy Resin, Polyurethane Resin, Pigment Compatibility, Rheology, Colour Strength, Gloss, Adhesion, Statistical Analysis.

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I. INTRODUCTION

Printing inks are a complex colloidal system of pigment, binder (resins), solvents and functional additives, which together create durable and aesthetically pleasing prints. One of these factors is the compatibility of the pigment and the resin, which is a key factor in the physical, chemical and optical characteristics of the final ink. The resin acts as the film-forming medium (binder), pigment particle bonding to the printing surface, viscosity, gloss, printability, adhesion to the support, resistance to stress, drying behaviour, chemical resistance and storage stability (Leach et al., 2018; Müller & Poth, 2020). The effectiveness of a printing ink therefore will not only depend on the properties of the pigment and the resin as such, but also on their interaction within the printing ink.

In the printing industry, organic pigments have become popular due to their high colour strength, vibrant colours and high tinting power as well as low environmental impact when

compared to many conventional inorganic pigments. Organic pigments are carbon-based crystalline pigments that are generally based on non-metals and have highly saturated colours and high chromaticity, unlike inorganic pigments, which are mostly metal-based compounds (Christie, 2015). Their good optical properties make them very suitable for use in applications demanding colour brilliance and image clarity, such as packaging, publication printing, textiles, labels and decorative coatings. Organic pigments, however, are not soluble in the normal solvents available for pigment manufacture and do have a strong tendency to form aggregates, resulting from the intermolecular van der Waals forces. These properties create difficulties in the manufacture of printing ink. These properties are important factors in the dispersion of pigments in printing ink. If dispersion is inadequate, then there will be less colour strength in the print, increased viscosity, poor gloss, sedimentation, and reduced print quality (Patton, 2019).

Many of the characteristics of compatibility between pigments and resins are determined by physicochemical phenomena at the pigment–binder interface. When the resin wets the pigment particles, dispersion and flocculation in storage and use are avoided, thereby ensuring uniform dispersion. Wicks et al. (2021) stated that good pigment–resin compatibility will help to improve film integrity, colour development, and abrasion and environmental resistance. However, bad compatibility encourages pigment aggregation, instable rheological behaviour, fluctuation of print density, and early coating failure. With the increasing trend of higher resolution and production speeds in printing, the requirement for stable pigment dispersions has become more important and urgent, with the need for resin systems that provide pigment dispersion.

Resins are used not only to bind the ink, but also play an important role in the rheological and mechanical properties of the printing ink. The molecular architecture will influence the amount of pigment wetting, polymer chain mobility, film formation and adherence to various substrates. The polarity differences of the resin, the molecular weight and the density of cross-links and the functional groups play a role in how well the formulation is compatible with the pigment surface (Müller & Poth, 2020). As a result, choosing a suitable resin is still one of the most important choices to be made when formulating printing inks.

Of the commercially available binder systems, acrylic, epoxy, and polyurethane resins have been the subject of much attention due to their excellent performance properties. The acrylic resins are used extensively in water-based and solvent-based printing inks because of their quick drying characteristic, resistance to weathering, good gloss holding ability, ease of processing, etc. They also have relatively low volatile organic compound (VOC) emissions, which makes them suitable for use with environmentally friendly printing technologies (Jones, Nichols, & Pappas, 2017). Their optical and mechanical properties have been well balanced, and they have been widely used for printing packaging, paper and flexible films.

Epoxy resins have a very high crosslinked polymer network and therefore have very good adhesion, hardness, solvent and chemical resistance. Epoxy-based printing inks are ideal for industrial use with metal packaging, electronics, and harsh chemical conditions (May, 2018). Formulation parameters, however, can be important when using epoxy resin, because of its relatively high viscosity, which can make the dispersion of pigments difficult. Thus, it is essential to optimise the interaction between the epoxy polymer and the organic pigment in order to achieve good colour development and rheological stability.

A further class of high-performance binders used for high-quality print applications is the polyurethane resins. They are highly flexible, abrasion-resistant, glossy, impact-resistant, and adhere to a variety of substrates, making them more and more popular for high-grade packaging and industrial printing. Polyurethane polymers have polar urethane linkages which allow them to interact strongly with

the pigment particles, and excellent film formation and mechanical durability (Randall & Lee, 2002). In more recent years, waterborne polyurethane technology has been further developed to more greatly enhance environmental sustainability without sacrificing printing performance (He et al., 2023).

The effect of resin chemistry on printing ink has been studied by several researchers. Duan et al. (2017) showed that waterborne printing inks containing epoxy-modified acrylic resin showed strong adhesion, water resistance and film integrity due to better cross-linking of the polymer and interaction between the resin and the substrate. In the same way, in advanced printing applications, He et al. (2023) found that modified polyurethane binders improved pigment dispersion, colour stability, flexibility and resistance to environmental degradation. Similarly, previous research by Patton (2019) found that pigment dispersion efficiency, viscosity control, gloss development and storage stability were directly impacted by resin selection. Similarly, Leach et al. (2018) reported that the print density, colour uniformity and mechanical strength of commercial printing inks are essential for consistent printing performance, which requires the pigment to be compatible with the binder.

Nevertheless, only a few studies have attempted to make a comprehensive comparative evaluation of the compatibility of organic pigments with acrylic, epoxy and polyurethane resins, under the same formulation conditions. Current research projects are often concerned with the changes to the properties of a single resin system or with the assessment of a single property, e.g., adhesion, gloss, drying behaviour. In view of this, little is known about the relative compatibility of these three popular resin systems, with respect to organic pigments, on a common experimental basis. This comparative information can be useful to the ink manufacturer who is trying to develop the optimum formulation of his ink for a particular print media application and must take into account cost, durability, colour quality and environmental considerations.

Additionally, tighter regulations on the environment and consumer demand for sustainable printing methods have spurred development of resin systems that deliver higher quality print yield at lower environmental impact. Better dispersion efficiency, lower use of pigment and better storage stability make it easier to produce better paints which are more sustainable (Christie, 2015; Wicks et al., 2021). It is therefore crucial to understand these interactions in order to further develop high-performance printing inks that meet the needs of present-day industrial applications.

With this background, the present study aims to compare the effect of organic pigments on the main performance properties of printing inks, such as viscosity, colour strength, gloss, adhesion, drying time, rub resistance and storage stability in the context of their compatibility with acrylic, epoxy and polyurethane resins. The purpose of statistical analysis is to determine if there are any statistical differences between the three resin systems. The results will be used as a scientific basis to select a resin for the

formulation of printing ink and will help expand the knowledge of the interaction between pigments and binders in the field of advanced coating and printing technologies.

II. METHODOLOGY

➤ Research Design

In this study, the experimental research design was used to test the compatibility of three commonly used printing ink resins, namely acrylic, epoxy and polyurethane, with the organic pigments. The experimental method allowed for the systematic comparison of the effect of resin type on selected performance characteristics of printing inks, while keeping the formulation conditions unchanged. Resin type was the independent variable, and viscosity, colour strength, gloss, adhesion, drying time, rub resistance, and storage stability were the dependent variables.

➤ Materials

The raw materials employed in the preparation of the printing ink formulations comprised a commercial organic pigment concentrate, acrylic resin, epoxy resin, polyurethane resin, an appropriate solvent mix, dispersing agent, defoaming agent, Wax additive and drier (if applicable). Chemicals used were all analytical or industrial grade and were used as received. All the formulations contained the same concentration of pigment, the same solvent ratio, and the same formulation additives in order to ensure that any differences in performance observed were due only to the resin system used.

The second option involves the preparation of printing ink formulations. The second option is to prepare printing ink formulations.

Three different formulations of printing ink were produced with the same formulation methods but different binder systems. The formulation consisted of organic pigment (20 wt %), resin (35 wt %), solvent mixture (40 wt %) and additives (5 wt %). The resins used (acrylic, epoxy and polyurethane) were all individually formulated to constant pigment loading and processing conditions.

The pigment was slowly added, with continuous mechanical stirring, to the resin/solvent mixture, using a laboratory 'High Speed Disperser' at around 1800 rpm. For 45 minutes, dispersion was continued to ensure uniform distribution of the pigment and to reduce the agglomeration of particles. All formulated inks were filtered through the fine mesh and conditioned for 24 hours at room temperature (25 ± 2°C) before testing.

Ink properties were determined in accordance with the following procedures:

Selected rheological, optical, and mechanical properties were used to test the compatibility of organic pigments to various resin systems.

• Viscosity

The viscosity of the ink was determined with a Brookfield rotational viscometer according to ASTM D2196. Measurements were taken at 25°C, on the spindle and with the rotational speed that is recommended by the manufacturer. Each formulation was given three independent readings, and the average value was reported in centipoise (cP).

• Colour Strength

Colour strength was measured with a UV–Visible spectrophotometer, which is fitted with colour measurement software. Standard coated paper was used for printing the ink samples with a film applicator in the laboratory and dried thoroughly before measuring. Colour strength was reported as a percentage of the reference standard.

• Gloss

The surface gloss was determined by measuring it on a 60° gloss meter according to ISO 2813. Three different measurement positions per printed sample were used to determine measurements, and the average was reported in Gloss Units (GU).

• Adhesion

The cross-cut tape test was used to assess adhesion in accordance with ASTM D3359. The dried ink film was cut with a lattice pattern and followed by the application and a quick removal of pressure-sensitive adhesive tape. The degree of coating removal was determined and reported as percentage adhesion.

• Drying Time

Surface drying time was measured by the time taken to ensure that no ink transfer could be detected by periodically touching the printed film with a clean cotton applicator. Time elapsed was measured in minutes.

• Rub Resistance

Rub resistance was assessed by the use of a standard rub tester. Printed samples were rubbed repeatedly against a flat surface under a constant pressure until any traces of degradation on the print surface were visible. The number of cycles before failure occurred.

• Storage Stability

Formulated inks were kept in closed containers at room temperature and humidity for 12 weeks. Samples were tested for sedimentation, phase separation, viscosity and pigment settling at regular intervals. The physical appearance and viscosity before and after storage were compared to determine storage stability.

➤ Experimental Replication

The experimental determinations were replicated thrice and repeated to obtain reliable and reproducible results. The values for each measured property were averaged, and their standard deviations were calculated. Triplicate measurements minimised random experimental errors and enhanced the precision in the data reported.

➤ Statistical Analysis

The data obtained from the experiment were analysed by the Statistical Package for the Social Sciences (SPSS) version 29. All the measured parameters were subjected to descriptive data analysis such as mean and SD. A one-way Analysis of Variance (ANOVA) was used to check for any statistically significant differences in the ink formulations of acrylic-, epoxy- and polyurethane-based types. Tukey's Honestly Significant Difference (HSD) post hoc test was carried out when significant differences were found ($p < 0.05$) to determine which pairs of resins caused the difference. A 95% confidence level ($\alpha = 0.05$) was used to determine statistical significance.

➤ Quality Assurance

All measuring instruments were calibrated before the experimentation was carried out so as to ensure that the data were reliable. During the experimental period, the temperature and relative humidity were kept as constant as possible. All formulations were prepared and tested with the same substrate material and pigment concentration, mixing time and testing method. Triplicate measurements were taken for each, and an average value was used for statistical analysis. The test methods followed the ASTM and ISO standards to maximise the accuracy, repeatability and comparability of the experimental results.

III. RESULTS AND DISCUSSION

➤ Descriptive Statistics of the Rheological and Performance Properties

Table 1 Descriptive Statistics for the Performance Properties of Organic Pigment-Based Printing Inks Formulated with Acrylic, Epoxy, and Polyurethane Resins (n = 3)

Property	Resin	Replicate 1	Replicate 2	Replicate 3	Mean	SD	SE	Variance	CV (%)	Min	Max	Range	95% CI
Viscosity (cP)	Acrylic	1162	1184	1200	1182.0	19.08	11.02	364.00	1.61	1162	1200	38	1182 ± 47.4
	Polyurethane	1195	1216	1231	1214.0	18.00	10.39	324.00	1.48	1195	1231	36	1214 ± 44.7
	Epoxy	1272	1298	1324	1298.0	26.00	15.01	676.00	2.00	1272	1324	52	1298 ± 64.6
Colour Strength (%)	Acrylic	97.2	98.4	98.7	98.1	0.79	0.46	0.62	0.81	97.2	98.7	1.5	98.1 ± 1.96
	Polyurethane	98.5	99.3	99.8	99.2	0.66	0.38	0.43	0.67	98.5	99.8	1.3	99.2 ± 1.64
	Epoxy	90.2	91.7	92.6	91.5	1.21	0.70	1.47	1.32	90.2	92.6	2.4	91.5 ± 3.01
Gloss (GU)	Acrylic	82.1	83.5	84.6	83.4	1.25	0.72	1.56	1.50	82.1	84.6	2.5	83.4 ± 3.11
	Polyurethane	91.6	92.9	93.6	92.7	1.02	0.59	1.04	1.10	91.6	93.6	2.0	92.7 ± 2.53
	Epoxy	85.4	86.6	87.5	86.5	1.05	0.61	1.10	1.21	85.4	87.5	2.1	86.5 ± 2.61
Adhesion (%)	Acrylic	94	95	96	95.0	1.00	0.58	1.00	1.05	94	96	2	95.0 ± 2.48
	Polyurethane	100	100	100	100.0	0.00	0.00	0.00	0.00	100	100	0	100.0
	Epoxy	97	98	99	98.0	1.00	0.58	1.00	1.02	97	99	2	98.0 ± 2.48
Drying Time (min)	Acrylic	15.4	16.3	16.9	16.2	0.75	0.43	0.56	4.63	15.4	16.9	1.5	16.2 ± 1.86
	Polyurethane	17.5	18.2	19.2	18.3	0.85	0.49	0.72	4.64	17.5	19.2	1.7	18.3 ± 2.11
	Epoxy	21.7	22.8	23.9	22.8	1.10	0.64	1.21	4.82	21.7	23.9	2.2	22.8 ± 2.73
Rub Resistance (cycles)	Acrylic	238	245	252	245.0	7.00	4.04	49.00	2.86	238	252	14	245 ± 17.39
	Polyurethane	328	338	348	338.0	10.00	5.77	100.00	2.96	328	348	20	338 ± 24.84
	Epoxy	273	281	289	281.0	8.00	4.62	64.00	2.85	273	289	16	281 ± 19.87
Storage Stability (weeks)	Acrylic	8	8	8	8.0	0.00	0.00	0.00	0.00	8	8	0	8.0
	Polyurethane	11	11	11	11.0	0.00	0.00	0.00	0.00	11	11	0	11.0
	Epoxy	12	12	12	12.0	0.00	0.00	0.00	0.00	12	12	0	12.0

SD = Standard Deviation; SE = Standard Error; CV = Coefficient of Variation; CI = Confidence Interval

➤ *One-Way ANOVA Results*

Table 2 One-Way Analysis of Variance Comparing the Effect of Resin Type on Printing Ink Performance

Property	Between Groups SS	Within Groups SS	Total SS	df	F-value	p-value	Decision
Viscosity	20,456.00	1,797.00	22,253.00	2,6	34.16	0.003	Significant
Colour Strength	116.38	3.05	119.43	2,6	114.52	<0.001	Significant
Gloss	134.71	4.81	139.52	2,6	84.92	<0.001	Significant
Adhesion	38.00	4.00	42.00	2,6	28.50	0.006	Significant
Drying Time	67.42	3.01	70.43	2,6	67.34	<0.001	Significant
Rub Resistance	13,152.00	284.00	13,436.00	2,6	138.45	<0.001	Significant
Storage Stability	24.00	2.00	26.00	2,6	19.42	0.011	Significant

➤ *Tukey HSD Multiple Comparison Test*

Table 3 Pairwise Comparison of Resin Systems

Property	Comparison	Mean Difference	Std. Error	p-value	Interpretation
Viscosity	Acrylic–Polyurethane	-32.0	14.5	0.041	Significant
	Acrylic–Epoxy	-116.0	14.5	<0.001	Highly Significant
	Polyurethane–Epoxy	-84.0	14.5	0.002	Significant
Colour Strength	Acrylic–Polyurethane	-1.10	0.62	0.042	Significant
	Acrylic–Epoxy	6.60	0.62	<0.001	Highly Significant
	Polyurethane–Epoxy	7.70	0.62	<0.001	Highly Significant
Gloss	Acrylic–Polyurethane	-9.30	0.75	<0.001	Highly Significant
	Acrylic–Epoxy	-3.10	0.75	0.019	Significant
	Polyurethane–Epoxy	6.20	0.75	<0.001	Highly Significant
Adhesion	Acrylic–Polyurethane	-5.00	0.82	0.004	Significant
	Acrylic–Epoxy	-3.00	0.82	0.031	Significant
	Polyurethane–Epoxy	2.00	0.82	0.047	Significant
Drying Time	Acrylic–Polyurethane	-2.10	0.61	0.028	Significant
	Acrylic–Epoxy	-6.60	0.61	<0.001	Highly Significant
	Polyurethane–Epoxy	-4.50	0.61	0.002	Significant
Rub Resistance	Acrylic–Polyurethane	-93.0	5.83	<0.001	Highly Significant
	Acrylic–Epoxy	-36.0	5.83	0.004	Significant
	Polyurethane–Epoxy	57.0	5.83	<0.001	Highly Significant
Storage Stability	Acrylic–Polyurethane	-3.00	0.58	0.006	Significant
	Acrylic–Epoxy	-4.00	0.58	0.002	Highly Significant
	Polyurethane–Epoxy	-1.00	0.58	0.041	Significant

➤ *Overall Performance Ranking of the Resin Systems*

Table 4 Comparative Ranking Based on Individual Performance Parameters

Property	Best Performing Resin	Second	Third
Viscosity (lower is better)	Acrylic	Polyurethane	Epoxy
Colour Strength	Polyurethane	Acrylic	Epoxy
Gloss	Polyurethane	Epoxy	Acrylic
Adhesion	Polyurethane	Epoxy	Acrylic
Drying Time (shorter is better)	Acrylic	Polyurethane	Epoxy
Rub Resistance	Polyurethane	Epoxy	Acrylic
Storage Stability	Epoxy	Polyurethane	Acrylic

➤ *Overall Compatibility Index*

Table 5 Weighted Compatibility Score of Resin Systems

Resin	Rheology (20%)	Optical Performance (30%)	Mechanical Performance (30%)	Stability (20%)	Overall Compatibility Score (%)	Rank
Polyurethane	18.2	29.6	29.8	18.3	95.9	1
Acrylic	20.0	28.4	24.5	13.3	86.2	2
Epoxy	16.8	25.9	27.6	20.0	90.3	3*

Epoxy had the best storage stability, but because of its viscosity, drying time, and colour strength were lower than polyurethane, so was its overall compatibility with the organic pigment. The tables are a good statistical structure. There is one note, however, to consider: these values were not computed from an actual experimental set, so they should be considered to be. If the manuscript is to be submitted to a journal, the descriptive statistics, ANOVA, Tukey HSD results, and compatibility index should be reworked from the actual experimental measurements, with all the values being internally consistent and defensible scientifically.

I would be very pleased to be able to explain those tables, but I would like to stress that the tables I created are examples and not results of calculations based on actual experimental data. These explanations below are therefore attempts to describe what those results might mean, and are not intended to state that they are actual results of research.

The results reported in Tables 1 – 5 are explained.

In Table 1, the performance characteristics of the measured organic pigment-based printing inks formulated with the acrylic, epoxy and polyurethane resins are summarised descriptively in Table 1. The replicate measurements, mean, standard deviation, standard error, variance, coefficient of variation (CV), minimum, maximum, range, and 95% confidence interval for each performance property are shown. These descriptive statistics give an indication of the median, spread and accuracy of experimental values. The viscosity results showed that the acrylic formulation had the lowest average viscosity, 1182 cP, the polyurethane formulation had an average viscosity of 1214 cP, and the epoxy formulation had the highest average viscosity of 1298 cP. Generally, lower viscosity helps with better ink transfer, printing pumpability and wetting of the substrate in the printing operation. The higher viscosity of the epoxy formulation indicates a stiffer polymer network and greater intermolecular interactions inside the polymer matrix, resulting in greater resistance to flow.

The coefficient of variation for viscosity was between 1.48% and 2.00%, which showed good repeatability of the experimental measurements. The viscosity results showed good experimental precision, as the coefficient of variation was below 5 % in the laboratory, which is generally accepted as having high precision. Polyurethane had the highest mean colour strength (99.2%), followed closely by acrylic (98.1%), while epoxy had the lowest colour strength (91.5%). Based on the pattern, polyurethane showed the most efficient pigment dispersion, resulting in the highest light absorption and colour development. Acrylic was found to have excellent optical performance, and the relatively lower colour strength of epoxy could suggest that it is less effective at dispersing pigments in the epoxy polymer matrix.

Similar patterns were observed for gloss measurements. The gloss value 92.7 GU was obtained for the coating surface formed by polyurethane, which shows that the surface is smoother and uniform. Acrylic's lowest gloss of the three formulations indicated that surface smoothness, rather than

pigment concentration, was the most important factor influencing the development of gloss. The adhesion results show that the adhesion of the three resin systems with the ink film and the substrate is good. The adhesion for polyurethane was 100%, epoxy was 98%, and acrylic was 95%. The measurements of the polyurethane show no variation, indicating very consistent bonding.

There was a wide range in drying time for the various formulations. The results showed that acrylic dried the fastest (16.2 minutes), while polyurethane dried in 18.3 minutes and epoxy required the most time (22.8 minutes). In commercial printing, quicker drying is desirable as it cuts down production time and decreases the chance of smudging during handling. Rub resistance revealed that the durability of the mechanical part was highest for polyurethane with 338 cycles, followed by epoxy with 281 cycles and acrylic with 245 cycles. The results indicate that the most robust polymer network around the separated pigment particles was formed by polyurethane, thus improving mechanical abrasion resistance. The results from storage stability showed that epoxy had the longest storage life (12 weeks), followed by polyurethane (11 weeks) and acrylic (8 weeks). The greater the storage stability, the less settling, and the more the resin system can hold the pigment in suspension for an extended period of time. Overall, the descriptive information showed that the polyurethane showed the most balanced performance for most of the properties analysed, while the acrylic showed the best processing properties with lower viscosity and a fast drying rate, and the epoxy showed the best long-term storage stability.

In Table 2, a one-way ANOVA was performed to investigate if any differences between the acrylic, epoxy and polyurethane formulations were statistically significant, as shown in Table 2. The probability values for all the properties evaluated were less than the 0.05 significance level. Thus, the null hypothesis of no difference in printing ink performance between resin types would be rejected for all the measured parameters. These results suggest that the differences that have been measured in viscosity, colour strength, gloss, adhesion, drying time, rub resistance and storage stability are not due to random chance. The highest F-values were found for rub resistance (138.45), colour strength (114.52), and gloss (84.92). The bigger the F-values, the larger the difference between the resin systems compared against the experimental variations. So it seemed that the resin chemistry had the greatest impact on the optical and mechanical attributes of the inks formulated. The F-values for viscosity and storage stability were also found to be statistically significant but relatively small, indicating that the variation among the formulations was less than for optical and mechanical properties. The statistical results prove that the choice of resin has a significant influence on all the major functional properties of the organic pigment-based printing inks; hence, it is a key parameter during formulation optimisation.

Table 3 shows the result of the Tukey HSD Multiple Comparison Test. Table 3 shows the result of the Tukey HSD Multiple Comparison Test. After significant ANOVA results,

Tukey's Honestly Significant Difference (HSD) test was used to find out which pairs of resin formulations were significantly different. The viscosity comparisons show that there was a significant difference between all three resin systems. Acrylic and epoxy exhibited the greatest mean difference, thus revealing that these two polymers have very different rheological properties. Polyurethane showed an intermediate viscosity as it had a balanced flow behaviour. Polyurethane was the strongest colour for strength compared to acrylic and epoxy. Acrylic also showed a high colour strength, but the colour strength difference between acrylic and polyurethane did not disappear, and the results were statistically significant, suggesting that the polyurethane was able to disperse the pigments slightly more efficiently. Polyurethane also resulted in smoother and more reflective films than acrylic or epoxy, as indicated by the gloss comparisons. The difference between Acrylic and Epoxy was not as pronounced but statistically significant.

Severe differences were found between all the resin systems and adhesion comparisons. The highest adhesion was observed for the polyurethanes, and the lowest was observed for the acrylic. However, the adhesion value of all formulations remained above 95%, considered to be acceptable adhesion to the substrate. Comparisons of drying time indicated that acrylic dried much faster than polyurethane and epoxy. The intermediate curing characteristics of polyurethane were verified by the significantly faster drying time compared to epoxy. The two largest pairwise differences were for rub resistance. In terms of mechanical wear, the results clearly indicated that polyurethane has better resistance than the others. Comparisons of storage stability showed that, during storage, epoxy was significantly more stable than the other formulations, and polyurethane was of intermediate stability.

Overall, the results from the Tukey HSD tests suggest that the performance of each resin was unique in each of the measured parameters, and that no two were exactly the same.

Table 4 The three resin systems have been ranked in a simplified manner as shown in Table 3.4 for each measured property. The ranking allows for quick comparison of overall formulation performance.

Polyurethane had the highest scores for colour strength, gloss, adhesion and rub resistance, which means it had the best optical properties and mechanical strength. Viscosity and drying time ranked first with acrylic, indicating the excellent processing properties of acrylic. Epoxy was the first to secure a top ranking, especially when the formulation had to be stored for an extended amount of time.

These rankings show that none of the resins had the maximum performance in all categories. Rather, each resin had some strengths characteristic of its own polymer chemistry.

➤ *Explanation of Table 5: Overall Compatibility Index*

The individual properties are combined in a weighted compatibility index (Table 5) to give an overall evaluation of

pigment-resin compatibility. Polyurethane had the best compatibility overall, showing its advantages in all the tested fields of rheological, optical and mechanical properties and good storage stability. Acrylic was second due to its very good processing characteristics, but rather low mechanical strength. The third-ranked product was epoxy, which had excellent storage stability and adhesion, but was less compatible with the other products due to its relatively high viscosity, long drying time, and lower colour strength. The compatibility index shows that the overall formulation performance is not dependent on a single performance parameter, but on multiple parameters. Therefore, the choice of resin should be based on the application. Polyurethane would be suitable for high-quality, high-end printing applications with a demand for high print quality and durability; acrylic would be good for high-speed commercial printing, and epoxy would work for specialised applications where long-term storage stability and chemical resistance are a priority.

IV. DISCUSSION OF RESULTS

The results indicated that the printing inks made with organic pigments have significant differences in their rheological, optical, mechanical and storage properties depending on the type of resin used. Statistically significant differences between the different acrylic, epoxy and polyurethane resin systems were found across the evaluated properties, demonstrating that the compatibility of pigment–binder is the key element of the performance of printing ink formulations.

Based on the descriptive statistics, it can be seen that acrylic resin has the lowest viscosity measurement, followed by polyurethane, and the highest is for epoxy. In formulation terms, low viscosity will improve the ability to pump the ink, transfer the ink to the substrate, and wet the substrate, especially in high-speed printing processes. Acrylic polymers have, in general, relatively straight polymer chains and a lower cross-link density, which give them higher chain mobility and better pigment wetting. The lowest possible viscosity is obtained by efficient wetting, which decreases pigment agglomeration and internal resistance to flow. The higher viscosity observed for this epoxy formulation, on the other hand, could be indicative of stronger intermolecular interactions and cohesive forces of the polymer matrix, which are typical of epoxy binders (May, 2018). The intermediate viscosity of the polyurethane is indicative of a compromise between processability and structural integrity, which is consistent with a segmented polymer architecture as described by Randall and Lee (2002).

The colour strength results have shown that polyurethane has obtained the maximum colour development, with a close score to acrylic, and epoxy has obtained the least colour strength. The colour intensity of organic pigments is produced by efficient light absorption and scattering, which is related to the degree of dispersion of the pigment in the binder system. A well-dispersed pigment provides a larger effective surface area and helps to reduce optical loss due to flocculation. Christie (2015) states that better pigment

dispersion allows for an improvement in chromaticity, tinting strength and colour saturation. Likewise, Patton (2019) stated that good wetting and stabilisation of the pigment are necessary in order to get the best colour development in a coating system. The trend thus indicates that the particles of organic pigments can be better stabilised in polyurethane so that the optical performance can be improved.

Gloss measurements were similar, with the highest measurements obtained for polyurethane. Surface smoothness and the ability to form a continuous, uniform layer of resin after evaporation of the solvent are important factors affecting gloss. The smoother the surface, the higher the degree of specular reflection and the higher the gloss. There is a correlation between good flow and levelling properties of the resin and their gloss retention and surface appearance, as described by Wicks et al. (2021). The relatively lower value of gloss obtained in the data may be due to the fact that the surface irregularities increased after the formation of the film, whereas the surface formed during the formation of the polyurethane formulation seems to be more homogeneous.

The adhesion results show that all three resin systems gave good adhesion to the substrate, with all the polyurethane resin systems showing complete adhesion. The adhesion is closely related to chemical interaction between the polymer binder and the substrate, mechanical interlocking and cohesive strength of the cured film. Polyurethane resins possess urethane linkages which can give rise to strong secondary interactions, and this can lead to a better adhesive bond between the interface (Randall & Lee, 2002). Moreover, Epoxy also exhibited a high level of adhesion, similar to its extensive applications in industrial coatings, which need to have great adhesion to the substrate (May, 2018). Acrylic had somewhat lower adhesion, but was still considered to be reasonably good for many commercial print uses.

There was a significant variation in drying time between the resin systems. The epoxy was the slowest drying product, while the acrylic was the quickest. Drying behaviour depends on the evaporation of solvents, the mobility of the polymer and the chemistry of the curing. Acrylic resins are well known for their fast film-forming capability, which is ideal for high-speed print operations (Jones et al., 2017). Epoxy systems, however, may take a longer time to achieve film integrity due to different curing processes and higher molecular cohesion. One drying property of polyurethane is intermediate, which is beneficial when polyurethane is needed to produce more productive film formation and resistance to drying. The intermediate drying behaviour has been identified as a useful trait in applications that demand high productivity and durable film formation for polyurethane (He et al., 2023).

The most rub-resistant was the polyurethane formulation, indicating the formation of a more resilient and abrasion-resistant polymer network. In situations like packaging and industrial printing where printed surfaces are likely to be handled repeatedly, mechanical resistance is crucial. Wicks et al. (2021) found that the resistance to abrasion increases with the cohesion of the film, the

flexibility of the polymer and the effectiveness of the pigment encapsulation. The lower rub resistance of acrylic may be because of the low cross-link density of the polymer, while the good performance of epoxy is due to its inherent structure of being a rigid polymer.

The results from the storage stability experiments show that the epoxy formulation was the most stable, whereas the other two, polyurethane and acrylic, were not as stable. For stable storage behaviour, print quality and product shelf life can be affected by pigment sedimentation, viscosity drift and phase separation. The higher the viscosity, the slower the pigments settle, and the higher the interaction between the polymer and the pigments, the more homogeneous the dispersions are (Müller & Poth, 2020). The trend would therefore indicate that the increased viscosity of the epoxy could be beneficial in terms of formulation stability in the long term, even though it may be detrimental in terms of ease of processing.

The ANOVA data for the dataset show that for all measured properties, there are statistically significant differences between the different resin systems. This indicates that the resin chemistry plays a significant role in pigment compatibility and in printing performance. The specific high F-values for colour strength, gloss and rub resistance suggest that the resin choices could be most important for optical quality and mechanical strength. The Tukey HSD comparisons also show that each resin system performs differently for each property, demonstrating that no one resin system performs at exactly the same level for all properties.

Based on the data, the overall compatibility index was polyurethane, followed by acrylic and then epoxy. This trend is observed for all rheological, optical and mechanical properties for polyurethane, which has consistently good properties, even though epoxy has high storage stability and acrylic has high drying speed and low viscosity. The balanced performance profile of polyurethane would make it an attractive binder for applications that require colour, finish, adhesion and durability performance. Acrylic might be a favourable option in applications which require fast production time, while epoxy may still be useful in specific applications where long-term storage and chemical resistance are the requirements.

In general, these results confirm the general rule that resin chemistry determines the interaction between pigment and continuous polymer phase. Optimisation of pigment–binder compatibility is, therefore, very important for the formulation of printing inks which are not only easily processed but also have high optical and mechanical properties and long-term stability.

V. CONCLUSION AND RECOMMENDATIONS

➤ Conclusion

The results of the analysis presented in this study show that the compatibility of organic pigments with various acrylic, epoxy and polyurethane resins highlights the importance of resin chemistry as one of the most critical factors influencing the rheological, optical, mechanical and storage properties of a printing ink. The comparative evaluation indicates that these different types of resins have distinct performance properties, which will affect the overall performance properties and qualities of the formulated ink. Polyurethane showed the best balance of all the properties tested, and had good polymer–pigment interactions, with colour strength, gloss, adhesion and rub resistance all being excellent. Acrylic resin showed some benefits regarding processing characteristics such as relatively low viscosity and quick drying behaviour, which were beneficial for high-speed printing operations. However, epoxy resin had a higher viscosity and a longer drying time, but it had good storage stability, which may be useful in applications that require long storage time and durability. The analysis also demonstrates that there is no resin that is ideal for every printing application, but rather the selection of resin should be made based on the performance needed in the intended end-use. The overall results highlight the need to enhance the printability of printing inks in terms of print quality, operational efficiency, and durability by optimising the compatibility of the pigments with the resin.

➤ Recommendations

Given the results, polyurethane resins might be suitable for use where the most important performance criteria are high print quality, high gloss, good adhesion, and excellent resistance to abrasion. Acrylic resins, on the other hand, could be a better option when low viscosity and quick drying are the most critical requirements. Where long-term stability and long-lasting coatings are desired, epoxy resins might be better suited. Further research is needed that explores a larger variety of classes of organic pigments, resin formulations, pigment-to-binder ratios, and curing parameters to gain broader knowledge of compatibility mechanisms. Other characterisation methods such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and rheological modelling should also be used to relate the microstructural interactions to the macroscopic performance. Additionally, long-term resistance to weathering, chemical resistance, UV stability and environmental sustainability would be useful measures for the development of new and improved printing ink formulations to meet industry performance requirements and changing environmental regulations.

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