Development of High-performance Inorganic Pigment and Lacquer Pastes for UV-Curable Coating Systems

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This work presents an optimized formulation strategy for UV-curable pigment pastes based on seven inorganic pigments and six lacquers for nail coating systems. The composition was systematically adjusted by varying the monomer–oligomer ratio, pigment loading, and dispersant concentration. Dispersion efficiency was assessed through wetting tests, controlled mixing and three-roll milling. Final performance was characterized by viscosity, grind value and opacity measurements. Viscosity increased with oligomer content and pigment concentration, while dispersant 1 substantially reduced viscosity and enabled stable formulations at practical pigment loadings. Three-roll milling at 20/10 μm roll gaps and 160 rpm improved opacity (ΔOP = 12.81%), confirming the need for high shear energy to achieve efficient deagglomeration. The results establish a practical parameter set for producing UV-compatible inorganic and lacquer pigment pastes with viscosities suitable for automated manufacturing.

Keywords: UV-curable nail coatings, inorganic pigments, lacquers, viscosity, dispersion.

1. INTRODUCTION

UV-curable gel polishes are widely used due to rapid curing, high gloss, and durable performance [1]. The market for these systems continues to grow, driven by demand for long-lasting and visually diverse nail coating products.

The main ingredients of UV-curable nail coatings are acrylate-derived monomers and oligomers, photoinitiators, and functional additives such as wetting agents and pigments [2]. Among these components, pigments play a critical role, as they determine color, opacity and product differentiation [3, 4].

Pigments cannot be incorporated directly as dry powders. Their use in UV-curable systems requires effective wetting and dispersion to ensure stability and uniform distribution [4, 5]. For this reason, pigments are commonly introduced as pre-dispersed concentrates in acrylate-based media. Such dispersions improve chemical compatibility with the reactive matrix and enhance pigment stabilization within the polymer network [4, 5].

A major challenge in pigment paste formulation is achieving a balance between high pigment loading and optimal paste viscosity. Excessive viscosity hinders application and limits process automation [6, 7], whereas low pigment content reduces color intensity and opacity [4, 5]. To ensure functionality, the pigment paste must exhibit appropriate flow behavior and provide sufficient optical intensity in the final product [5].

During development, dry pigments are combined with selected base components to achieve controlled viscosity, appropriate particle size distribution, opacity, stability and color saturation [4, 8].

Test films (applications) of defined thickness are commonly prepared to evaluate the functional properties of pigment pastes. This allows visual and instrumental assessment of color uniformity, particle agglomeration (graininess) and opacity, prior to incorporation into the final product [8].

Pigments used in UV-curable nail coatings are generally classified as organic pigments, inorganic pigments, and lacquers based on their chemical nature [9]. The present study focuses on inorganic pigments and lacquers.

Inorganic pigments are mineral or metal oxide compounds [10]. They are widely used in gel polish formulations due to their high refractive index, which results in excellent coverage and low transparency [9]. These pigments also exhibit good environmental stability and dispersibility [8].

Lacquers are produced by precipitating water-soluble organic dyes onto a metal hydroxide substrate (typically aluminum hydroxide), forming insoluble colored particles [11]. They combine bright color with stability comparable to inorganic pigments.

In this work, seven inorganic pigments and six lacquers were selected for their high quality and compliance with EU Cosmetic Regulation, according to the supplier's documentation. All pigments were supplied by Sensient, the leading EU manufacturer of cosmetic-grade pigments.

Commercially available dispersions often exhibit very high viscosity, limiting their use in automated production [12]. Such systems are typically suitable only for manual processing. To ensure better control and enable automation, manufacturers increasingly aim to produce pigment pastes in-house. However, standardized methodologies tailored to

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their sector remain limited. Therefore, this study focuses on developing and optimizing formulations for inorganic pigments and lacquer pigment concentrates suitable for controlled industrial processing.

This study aims to develop optimal composition and manufacturing technology for inorganic pigment and lacquer pastes. The objectives were to investigate the relationship between pigment paste composition and its physico-chemical properties, examine the influence of different dispersion techniques on pigment distribution, and evaluate the resulting formulations in terms of viscosity, pigment particle size, and opacity.

2. MATERIALS AND METHODS

2.1. Materials

All coating ingredients were selected to comply with the requirements of the EU Cosmetics Regulation. The pigment paste base was prepared using the following materials: aromatic monofunctional methacrylate (monomer, purity > 98 %), supplied by Sartomer [13]; bifunctional aliphatic urethane acrylate (oligomer), supplied by Sartomer; type I photoinitiator – phosphine oxide, supplied by IGM Resins; silicon dioxide (> 99.8 %), supplied by Sensient [14]; wetting agent supplied by BYK Additives; dispersant 1 – fatty acid-modified polyester (~100 %), supplied by BYK Additives [15]; dispersant 2 – high molecular weight polymer (~100 %), supplied by BYK Additives [16]; dispersant 3 – acrylic block copolymer (~100 %), supplied by BYK Additives [17]; inorganic pigments and lacquers (see Table 1), identified by their Color Index (CI) numbers and supplied by Sensient.

Table 1. Inorganic and lacquer pigments selected for this study

Material/trade name	Chemical identifier (CI No.) /description
Inorganic pigments	
Unipure Violet LC581	CI 77742 and CI 77004
Unipure Yellow LC182	CI 77492
Unipure Red LC386	CI 77491, CI 77499, and iron oxide
Unipure Red LC381	CI 77491 and CI 77499
Unipure Black LC998	CI 77499
Unipure Blue LC689	CI 77510
Oxyde De Titane Standard TiO_2	CI 77891
Lacquers	
Unipure Red (Red 33 Lake) LC323	CI 17200
Unipure Blue LC621	CI 42090
Unipure Red (RED 7) LC3075	CI 15850
Unipure Red (Unipure Rubine) LC414	CI 15880
Unipure Red (Red 30 Lake) LC300	CI 73360
Unipure Red (RED 7) LC3071	CI 15850

2.2. Equipment

A precision laboratory balance (PR 1000.R, Radwag, Poland) was used for weighing raw materials. Pigment pastes were mixed using a planetary mixer (Hauschild SpeedMixer® DAC 250.3 FVZ, Hauschild GmbH & Co KG, Germany) and a high-speed disperser (Palpostrast 56 KK-300, Dispermill, Netherlands). Milling was performed using three-roll mills (S65, Shandong Sayhi Machinery Co., China; ZYTR-BOE, ZYE, China).

Rheological measurements were obtained using a Kinexus KNX5112 rheometer (NETZSCH-Gerätebau GmbH, Germany). Films with controlled thicknesses were prepared using an automatic film applicator (Byko-drive, BYK-Gardner, Germany). UV curing was performed under a UV/LED lamp (KP800LED, YI Liang Electron Technology Co., China). The light stability of the pigmented coatings was evaluated using a Xenon test chamber. Coating quality was evaluated using a digital microscope (ANESOK® 321, Inskam, USA), a Hegman grind gauge (BYK, Germany), and a Datacolor 200 spectrophotometer (Datacolor, Switzerland).

2.3. Wetting test

The wetting performance of dry pigments was evaluated by placing a small amount of pigment powder on a glass plate and applying a drop of liquid beside it. The liquid was gently drawn toward the pigment using a wooden spatula. Wetting behavior was assessed visually. To reduce subjectivity, wetting was evaluated using a semi-quantitative five-point scale (1-5), where: 1 – pigment remains dry (very weak); 5 – liquid rapidly spreads over the pigment surface and fully penetrates the agglomerates within a few seconds (very good). A representative example is shown in Fig. 1.

a b

Fig. 1. Pigment wetting: a – very good (score 5); b – very weak (score 1)

2.4. Preparation of pigment pastes

Four paste bases were prepared (Table 2).

Table 2. Proportions of paste base components

	A	B	C	D	E
Monomer, %	40.0	50.0	75.0	81.0	80.9
Oligomer, %	55.7	45.0	20.0	15.0	14.1
Photoinitiator and silicon dioxide, %	4.3	5.0	5.0	4.0	5.0

Dry pigment powder was added to each base and premixed using a Hauschild SpeedMixer (4 min, 1800 rpm). The dispersant was then incorporated and mixed again under identical conditions. In selected experiments, additional

dispersion was performed using a high-speed disperser (Palpostrast). Mixing was carried out in 100 mL, 1 L, or 3 L containers. The impeller diameter was set to approximately one-third of the container diameter.

The premixed material was then processed using a three-roll mill. The paste was manually fed between the first and second rolls using a wooden spatula. Temperature of the pigment pastes was monitored to prevent excessive heating caused by the roll rotation speed. Milling was performed in several stages, with progressive reduction of the roll gaps: 150/75 µm at 200 rpm; 80/40 µm at 200 rpm; 20/10 µm at 160 rpm; 10/5 µm at 120 rpm.

At each stage, the paste was passed through the rolls twice.

2.5. Rheology and grind gauge measurement

For each pigment system, the milled dispersion was incorporated into the coating base (10 wt%). The corresponding unmilled formulation served as the control sample. Dispersion fineness was evaluated using a Hegman grind gauge. A drop of the pigmented coating was placed at the deepest end of the grooved channel and drawn across the scale using a standardized steel scraper. The point at which streaks or visible agglomerates first appeared was recorded as the degree of dispersion. Each sample was measured in triplicate, and the mean value was reported.

Rheological measurements were performed using a parallel-plate geometry, suitable for high-viscosity materials. The measurement gap was fixed at 0.2 mm and tests were conducted at 25 °C. Viscosity was measured at shear rates of 0.1, 1, 10, and 100 s^{-1}. Each sample was tested in triplicate, and mean values were reported.

2.6. Optical and mechanical evaluation

To assess dispersion quality, two coating films were prepared for each formulation – before and after three-roll milling. The pigmented base was prepared by incorporating 0.5 wt.% dispersion and 2 wt.% TiO_2 white pigment into the coating base. The mixture was homogenized for 4 min in the planetary mixer and applied onto a substrate using an automatic film applicator Byko-drive to obtain a 200 µm film thickness. Films were cured for 60 s under a UV/LED lamp (λ = 400 – 410 nm).

Visual evaluation was conducted with the naked eye and under magnification to detect agglomerates. Samples showing noticeable graininess were further analyzed using a digital microscope to estimate particle size and distinguish between flocculated and agglomerated structures.

Opacity was measured using a spectrophotometer by determining CIE Y reflectance values on black (Y_b) and white (Y_w) backgrounds. Opacity was calculated according to Eq. 1.

$$OP\ (\%) = (Y_b / Y_w) \times 100\%. \quad (1)$$

Each sample was measured in triplicate, and the mean values were reported. Tinting strength was assessed by preparing pigmented base formulations using the developed dispersions and comparing the resulting color intensity with equivalent formulations prepared from commercial reference pastes.

2.7. Accelerated stability testing

Stability was evaluated using three approaches: stability of pigment pastes and pigmented bases; color stability after thermal aging; light stability under Xenon exposure.

For thermal evaluation, samples were stored in a temperature - controlled laboratory oven at 50 °C. Pigment dispersions were analyzed after 2 weeks, while pigmented base formulations were assessed over 3 months. Viscosity was measured at defined intervals, and samples were inspected visually for sedimentation or phase separation.

Color stability was determined by comparing coatings prepared from thermally aged samples (50 °C, 3 months) with freshly prepared references. Color differences were measured spectrophotometrically.

Light stability was evaluated by exposing coated films to a Xenon test chamber for 2 h. Color differences were then measured using a spectrophotometer.

3. RESULTS AND DISCUSSION

3.1. Viscosity dependence on the base

To assess the effect of base composition on viscosity, the inorganic pigment Unipure Yellow LC182 was incorporated into bases C, D, and E (Fig. 2).

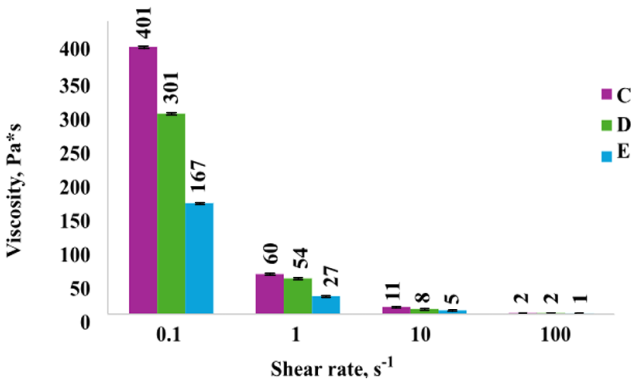

Fig. 2. Viscosity of LC182 pigment pastes prepared with different bases (C, D, and E) at 30 % dry pigment content

Base C, containing the highest proportion of oligomers, exhibited the greatest viscosity. In contrast, Base E, with the lowest oligomer content, showed the lowest viscosity. This trend can be explained by the molecular structure of the oligomer. Oligomers have higher molecular weight and bulkier chains than monomers. This increases intermolecular interactions and reduces molecular mobility, leading to higher internal friction and viscosity. This behavior is consistent with fundamental polymer rheology, where viscosity increases with molecular weight and chain overlap due to enhanced molecular interactions [18]. These results demonstrate that the oligomer-to-monomer ratio is a key parameter in controlling rheological behavior. Excessively viscous bases hinder homogenization and limit pigment loading, while overly fluid systems may promote sedimentation. Having established the role of base composition, the effect of pigment loading was subsequently examined.

3.2. Viscosity dependence on pigment concentration

The effect of pigment concentration on viscosity was evaluated by dispersing LC182 pigment in base E (Fig. 3).

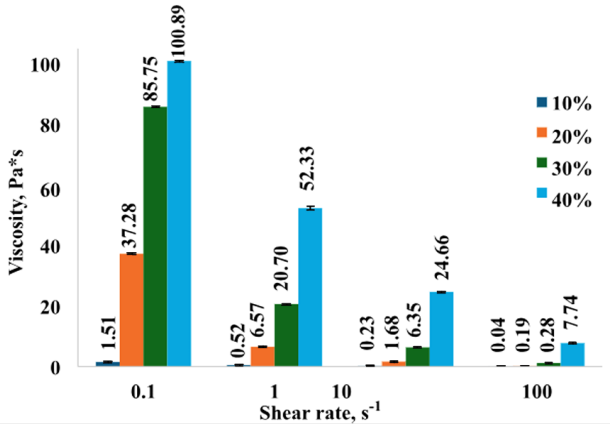

Fig. 3. Viscosity of LC182 pigment pastes in base E with varying dry pigment contents (10 %, 20 %, 30 %, and 40 %)

It was observed that increasing the pigment concentration led to a noticeable increase in viscosity. At low shear rates, viscosity increased from 1.51 Pa·s at 10 % pigment to 100.89 Pa·s at 40 % pigment, indicating strong solid-solid interactions at higher loadings. This behavior is characteristic of particle-filled systems. Increasing pigment content raises the effective solid volume fraction and enhances particle-particle interactions. As a result, transient particle networks form and restrict deformation under low shear conditions [19, 20]. Similar trends have been reported in coating and polymer systems, where increasing pigment concentration leads to higher viscosity or reduced melt flow index due to decreased flowability of the filled matrix [19]. These findings confirm that pigment concentration must be optimized to balance color strength and processability. Since solid interactions strongly affect rheology, the role of dispersing agents was subsequently investigated.

3.3. Effect of dispersant on paste viscosity

To optimize rheological performance, the effect of dispersant addition on paste viscosity was systematically evaluated. Pigment pastes were first prepared without dispersing agents to assess their processability. A formulation containing 50 wt.% of lacquer LC3075 in the base produced a semi-solid, unworkable paste. In contrast, the addition of 2.5 wt.% dispersant resulted in a creamy, workable paste. This confirmed that dispersant addition is necessary to achieve suitable consistency at high pigment loading. To quantify this effect, the influence of dispersant concentration was studied using LC182 dispersions (Fig. 4). Viscosity strongly depended on dispersant 1 concentration. As shown in Fig. 4, viscosity decreased with increasing dispersant concentration and reached a minimum value of 0.24 Pa·s at approximately 8 wt.%. This concentration was considered optimal for this system. The initial viscosity reduction is attributed to improved adsorption of the dispersant onto the pigment surface. This reduces particle-particle interactions and promotes deagglomeration. Beyond this point, viscosity increased again, indicating a non-linear relationship between dispersant amount and viscosity.

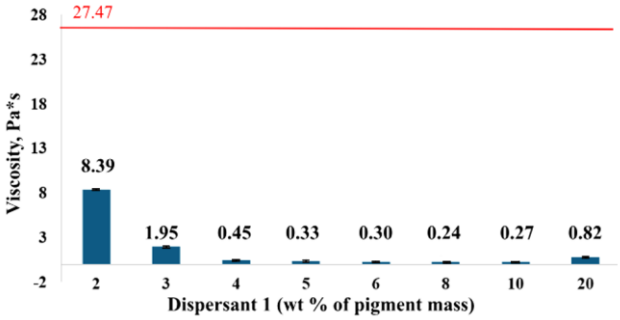

Fig. 4. Viscosity at a shear rate of 10 s^{-1} for LC182 pigment pastes with varying dispersant 1 contents, where the red line represents the viscosity of the paste without added dispersant 1

The rise in viscosity at higher concentrations is likely due to excess non-adsorbed dispersant in the continuous phase, which increases intermolecular interactions within the system [8]. Similar trends have been reported in other studies, supporting the validity of these results [21].

Dispersants 2 and 3 did not substantially reduce viscosity. At higher concentrations, they caused a rapid increase in viscosity. In contrast, dispersant 1 produced a clear decrease in viscosity and was therefore selected for further formulations. The better performance of dispersant 1 is likely related to its fatty acid-modified polyester structure [15]. This structure allows effective adsorption onto the pigment surface and provides steric stabilization in the polymer medium. As a result, pigment particles remain separated without excessive viscosity increase [22, 23]. Since dispersion efficiency depends not only on stabilization but also on initial wetting, wetting behavior was subsequently examined.

3.4. Wetting test

Effective wetting is the first essential step in pigment dispersion, enabling penetration of agglomerates and subsequent deagglomeration. The monomer without additives achieved the highest wetting score (5), spreading rapidly over the dry pigment surface. Systems containing dispersing agents showed slower spreading and lower wetting scores. Wetting occurs when the liquid replaces the pigment/air interface with a pigment/liquid interface. It is favored when interfacial compatibility between the liquid and pigment surface is high. Efficient wetting reduces agglomeration and facilitates uniform dispersion [8]. The observed behavior suggests favorable surface interactions between the monomer and the pigment. Effective wetting in the early stage improves processability and reduces the mechanical energy required for further deagglomeration.

3.5. Three-roll mill

After optimizing wetting, the effect of three-roll milling was evaluated. The optimal milling regime involved roll gaps of 20 µm (first-second roll) and 10 µm (second-third roll). Milling was performed at 160 rpm and repeated twice. During three-roll milling, pigment agglomerates are subjected to intense shear stress within the narrow gap

between rotating rolls. When the applied shear stress exceeds the cohesive forces holding the agglomerates together, particle clusters are progressively deagglomerated. The gradual reduction of roll gaps increases stress intensity, enabling more efficient breakup of remaining aggregates and resulting in improved dispersion homogeneity [22].

The optimized base composition, pigment loading, and dispersant 1 concentration were applied to seven inorganic pigments and six lacquers. These pastes were milled using a three-roll mill, and their consistency was evaluated visually (Table 3).

Table 3. Optimal base, pigment concentration and dispersant 1 concentration for different milled pigment pastes

Base	Pigment	Pigment, wt.% of total mass	Dispersant 1, wt.% of total mass	Consistency
Inorganic pigments				
B	LC581	49	2.4	liquid/cream-like
B	LC182	49	2.4	liquid/cream-like
B	LC386	49	2.4	liquid
B	LC381	49	2.4	liquid/cream-like
B	LC998	49	2.4	liquid
D	LC689	33	3.3	liquid/cream-like
B	TiO_2	49	2.4	liquid/cream-like
Lacquers				
B	LC323	43	4.0	cream-like
B	LC621	43	4.0	liquid/cream-like
D	LC3075	49	2.4	cream-like
D	LC414	33	3.3	liquid/cream-like
D	LC300	44	4.1	cream-like
D	LC3071	33	3.3	cream-like

Dispersion efficiency depends not only on mechanical energy but also on paste viscosity. Suitable viscosity allows effective stress transfer between the rolls, while excessively high viscosity increases flow resistance and reduces milling efficiency. Similar behavior has been reported in dispersion studies, where grinding time and energy must be carefully optimized to achieve stable dispersion [24].

Pigmented base formulations were prepared using either 5 wt.% individual pigment or a combination of 0.5 wt.% pigment and 2 wt.% TiO_2. Similar trends in opacity changes were observed after milling across all samples. The inorganic pigment LC689 is presented as an example (Table 4).

Table 4. Opacity (OP) measurements of LC689 pigment pastes before and after three-roll milling

Pigmentation in the color base	OP of pigmented color base applications, %				
	Mean value before milling OPb	SD, %	Mean value after milling OPa	SD, %	ΔOP (OPa-OPb)
5 %	62.21	1.85	75.02	1.46	12.81
0.5 %+2% (white pigment)	83.58	1.46	89.68	0.73	6.10

A considerable increase in opacity was observed after milling, highlighting the importance of this step. Microscopic evaluation showed visible agglomerates before milling, while no distinct particle clusters were observed after processing. Hegman gauge measurements also indicated finer dispersion. The increased opacity further supports improved pigment distribution, as smaller and more uniformly dispersed particles scatter light more efficiently. The addition of white TiO_2 pigment further increased opacity due to its high refractive index, which enhances light scattering and reduces light transmission through the material [20]. Color-matching confirmed that the developed dispersions provided tinting strength comparable to commercial products.

Although bead or ball milling is commonly used for low-viscosity systems [8], the present results confirm that three-roll milling is suitable for high-viscosity dispersions. Milling efficiency depends on both viscosity and pigment surface properties.

3.6. Accelerated stability testing

Following dispersion optimization, accelerated stability testing was performed. After storage at 50 °C, both pigment pastes and pigmented base formulations remained physically stable. No visible sedimentation or phase separation was observed. Viscosity changes remained within the predefined acceptance range (10 % to 20 %).

Thermal aging at 50 °C for 3 months resulted in color differences within acceptable quality limits and comparable to those of commercial reference formulations. Similarly, light exposure in a Xenon chamber caused no noticeable color degradation, and all measured color differences remained within accepted industry tolerance ranges.

Accelerated testing at elevated temperature, commonly used to predict long-term storage behavior in coatings [21], confirmed the stability of the developed systems. The pigment dispersions maintained rheological, thermal, and photostability under the applied conditions.

These results indicate that efficient dispersion is achieved through three interconnected steps: wetting, dispersant adsorption, and high-shear milling. Wetting ensures effective contact between the pigment and the matrix. Dispersant adsorption reduces particle–particle interactions and prevents re-agglomeration. Three-roll milling breaks down remaining agglomerates. Together, these steps govern final rheology, optical performance, and long-term stability.

4. CONCLUSIONS

This study provides a systematic and reproducible parameter set for producing automation-compatible inorganic pigment and lacquer dispersions for UV-curable nail coatings. High dispersion quality was achieved using a defined three-step process: planetary mixing for uniform component distribution, high-speed mixing for intensive mechanical action, and three-roll milling to break down pigment agglomerates. The rheological and optical properties of the pastes were strongly governed by base composition, pigment concentration, and dispersant loading. Increasing oligomer or pigment concentration increased viscosity. This confirms the need to balance pigment loading with flow behavior suitable for automated production. At optimized dispersant levels, the dry pigment

content in the paste could be increased up to 20 wt% without noticeably altering the final product viscosity. The main contribution of this work is the development of a stepwise formulation algorithm under regulatory and raw material constraints. The workflow integrates compliant pigment selection, dispersant optimization, and defined milling parameters. The proposed workflow provides a reproducible strategy for producing stable, high-opacity dispersions.

This approach is transferable to other UV-curable systems used in digitally controlled coating technologies, such as 3D printing resins, dental materials and medical coatings. In these systems, precise rheology, high opacity and regulatory compliance are critical. Overall, the study connects fundamental dispersion science with practical implementation in advanced functional coatings. The proposed framework supports scalable and reproducible manufacturing under regulatory constraints, facilitating reliable industrial application.

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