Comparative Analysis of Dispersants for Water-Based Paint

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Keywords:

Paint formulation

Dispersant

Free monomers

Water-based paint

Abstract

Water-based paints are more environmentally friendly than their oil-based counterpart, but they present challenges such as pigment dispersion due to high surface tension and longer drying times. To address these challenges, polymeric dispersants are used to help disperse and stabilize pigments. Polymeric dispersants are synthesized by polymerizing monomers; however, not all monomers are consumed during synthesis, resulting in free monomers remaining in the dispersant. These monomers play a significant role in water-based paints by influencing odor, film formation, water resistance, and environmental impact.

Two common polymeric dispersants used in water-based paints are Dispersant 4140 and Dispersant 4141. Dispersant 4140 has a lower concentration of free monomers, making it more suitable for environmentally conscious applications. In contrast, Dispersant 4141, with a higher monomer concentration, presents challenges such as odor control, high volatile organic compound (VOC) emissions, and potential environmental risks. This comparative analysis of dispersants highlights the critical role of monomer concentration in the overall performance and environmental sustainability of paint formulations. Additionally, it underscores why Dispersant 4140 is better suited for modern coatings, offering benefits for environmental sustainability.

1. Introduction

Paints or coatings are complex chemical mixtures available in liquid, paste, or powder form, intended to be applied to a surface using various methods and equipment in given thicknesses. These create a tight bond on the surface of the substrate. When applied to a substance, these mixtures form a thin, solid coating that provides protective and functional benefits [1]. For instance, painting a car can improve its appearance by offering a variety of colors and finishes, such as gloss, while also providing essential protection against corrosion, especially if the car's body is made from mild steel [2]. Today, the U.S. paints and coating industry is continuing to grow. The 2024 production of paints is expected to reach approximately 789 million gallons, a 2.9% increase from the 2023 output [3]. The four typical components of paints are pigments, binders, solvents, and additives [4].

The pigment is a material that can be classified as organic or inorganic [5]; the primary function of the pigment in painting is to create color. Pigment also played a significant role throughout history in decorating, conveying emotions, and communicating social messages and culture [6]. The binder is the essence of the coating, which provides various chemical and physical properties of the paint. The binder adheres any particulate component together and to provide a continuous coating film [7]. The additives in a paint composition greatly influence the various paint properties by increasing the viscosity and making it more stable and spread voluntarily [8]. The solvent is the medium that carries the solid components of paints. During the drying process, evaporation ensures that the paint adheres appropriately [9]. There are two main categories of paint: Water-based paint and Oil-based paint.

Oil-based paints are popular due to their durability, gloss, and resistance to wear, making them suitable for surfaces that need a robust finish, such as woodwork and high-traffic areas [10]. A key component of oil-based paint is turpentine, which is used as the primarily organic solvent for thinning oil-based paint. It is also a base material for creating productive coatings and waxes for wood. Turpentine ($C_{10}H_{16}$) is a transparent and volatile liquid obtained from the resin of the trees with a heavy odor [11]. The chemical structure of the oil-based paint is defined as polymetric through the evolution of unsaturated fatty acids in the drying oil. That plays a critical role in the stability and longevity of the paint film [12]. In oil-based paint, dispersion involves breaking down pigment particles and evenly distributing them within the solvent medium. This process is essential for achieving the desired optical properties, such as color, gloss, and hiding power, by ensuring that pigment is adequately de-agglomerated. Proper dispersion also optimizes the paint's viscosity, which is crucial for its application and overall performance [13]. A chemical view of traditional and modern oil paint sees it as a durable composite material consisting of complex metal salts or organic pigments, a polymerized triglyceride-based drying oil, and various additives. This composition contributes to the long-lasting stability and resilience of the paint [14]. However, oil-based paints are also well known for their conservation issues. This is because they also show sensitivity when reacting with water. The paint layers have been the factor in accelerated aging under high humidity and light. High humidity has been showing a form of oxidation in the paint films [15,16]. Nowadays, many modern oil paintings are unvarnished. That cause arises from their exposure to atmospheric impacts like air pollution, light, and moisture. The main factors trigger degradation processes, such as efflorescence, water sensitivity, and the formation of water-soluble salts. Over time, those reactions weaken the paint's polymer structure, making the surface more vulnerable to damage and complicating conservation efforts. Temperature, humidity, and atmospheric composition further influence these degradation processes [16]. Furthermore, many Volatile Organic compounds (VOCs) are produced in paint manufacturing. Benzene, toluene, ethylbenzene, and xylene are among the most common VOCs. They pose severe risks to human health, especially for respiration. Short-term exposure can irritate the eye, nose, throat, lungs, kidneys, and central nervous system. Long-term exposure is linked to severe health issues like asthma, cardiovascular disease, and cancer. Some VOCs, such as benzene and styrene, are classified as carcinogens by health agencies, making occupational exposure particularly hazardous [17].

Occupational exposure to organic solvents, common in industries like paint production and printing, contributes to 15% of adult asthma cases, with 20% of affected adults experiencing worsened symptoms due to their work environment. Solvents' irritating and sensitizing properties can trigger or aggravate asthma. In France, it was reported that 15% of workers were exposed to solvents in 2013, highlighting the widespread nature of this risk [18]. Beyond health risks, organic solvents also contribute to environmental damage by emitting volatile organic compounds (VOCs). When released into the atmosphere, VOCs play a crucial role in forming ground-level ozone, a potent greenhouse gas thereby exacerbating global warming. According to data from 2010, 13% of VOC originated from the organic solvent, such as exposure of the oil-based paint [19].

Water-based paint utilize water as the primary solvent, making it an eco-friendlier option compared to oil-based paints. Studies have found that VOC content in water-based coating is average 50.8% lower than in oil-based counterparts. By 2030, adopting low-VOC water-based paints could reduce emissions by up to 75.2 Gg, achieving a reduction rate of up to 56.1% compared to 2020 [20,21].

The challenge of the water-based paint is the pigment dispersion, Titanium dioxide (TiO_2) is the most widely used pigment in water-based paints and a crucial white pigment in various industries globally due to its inertness, non-toxicity, and thermodynamic stability, available in multiple crystalline forms. Including TiO_2 in paint formulations significantly enhances opacity, but its application in water-based paints presents several challenges. One primary challenge is maintaining stable dispersion in water, which is essential for ensuring consistent opacity, gloss, and overall paint film performance. TiO_2 particles can agglomerate as the paint dries, leading to defects in the final film. This issue is exacerbated by the higher surface tension of water compared to oil-based paints, where the lower surface tension facilitates easier pigment dispersion. Consequently, the higher surface tension in water-based systems makes it challenging to keep the pigment evenly dispersed throughout the paint, potentially reducing the effectiveness of the pigment, and leading to a compromised final product [22]. One of the most effective approaches to addressing the challenge of pigment distribution in water-based paints is dispersants. *Dispersants* enhance the distribution of pigment particles within the paint formulation by interacting with the pigment surface to stabilize dispersion and prevent particle agglomeration. The final coating produces a more uniform color, gloss, and opacity [23]. Studies have shown that dispersants effectively reduce surface roughness and increase gloss in the dry paint film, with specific types significantly improving pigment dispersion, consistent with findings from aqueous suspension studies [24].

BASF's Dispex AA 4140 and Dispex AA 4141 are two wide utilized water-based paint formulations. They are exceptional dispersing agents for a wide range of water-based coating. It offers excellent stability and performance across various formulations, making it a go-to choose for formulators seeking to enhance pigment dispersion and improve the overall quality of their coating. This dispersant can be used as supplied, simplifying the formulation process while ensuring consistent results. Its effectiveness in reducing viscosity and preventing pigment agglomeration makes it particularly valuable in producing coating with superior smoothness, gloss, and color intensity [25,26]

4140 and 4141 are polymeric dispersants. *Polymers* are substances made up of long chains of repeating units of monomers. Monomers are individual molecules that can chemically bond with any other monomers to form a larger molecule, a polymer. The process by which monomers connect to form polymers is called polymerization when monomeric units link together by sharing electrons [27]. Polymer chains can consist of identical or different units and come from various materials, including synthetic organics, plastics, and resins. Polymers can be categorized based on their molecular structure, their process, and their physical properties [28]. Both 4140 and 4141 are polymers of sodium polyacrylate synthesized from the same monomer such they the molecular structures of each are almost identical. The critical difference between 4140 and 4141 is content unreacted with monomers.

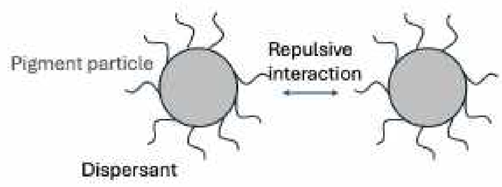

Figure 1

In this paper, we will investigate how the difference in free monomer concentration between dispersants 4140 and 4141 affects the functional properties of paints. This study will compare dispersant 4140 and 4141 formulations to determine which is more suitable for modern building applications. We will achieve this by incorporating various materials into both formulations, with the dispersant type as the variable. The experiment will assess key performance areas in different aspects to facilitate comparative analysis. By systematically testing these parameters, the study aims to comprehensively understand how each formulation responds under controlled conditions, contributing to determining their suitability for specific applications. Additionally, we will explore the impact of monomers on the coating's overall performance.

2. Methodology

The methodology for this experiment focuses on comparing the performance of two dispersants, 4140 and 4141, in water-based paint formulations. These formulations were systematically developed and evaluated to ensure that consistent variables were maintained, with the primary difference being the dispersant used. The characterization process followed was designed to assess key paint properties such as viscosity stability, solid content, dispersion quality, thermal storage stability, and odor impact, each contributing to the overall quality and functionality of the paint.

The goal of this methodology is to establish a thorough understanding of how these dispersants affect the final properties of the paint. This approach provides a controlled environment to study the interaction between dispersants and the other components of the paint formulation, offering insights into their suitability for modern applications in the paint industry.

2.1. Paint Formulation

The paint formulation was prepared systematically to ensure consistency and accuracy across the two formulations: one containing the 4140 dispersants and another containing the 4141 dispersants. The process began by adding a measured amount of deionized water to a clean, temperature-controlled mixing vessel. Cellulose ether was then incorporated into the water to adjust the viscosity and provide the necessary rheological properties for the formulation. Dispersants 4140 and 4141 were added to the mixture. The role of each dispersant is essential, as it ensures the even distribution of pigment and prevents aggregation, which is essential for maintaining the stability and quality of the final paint product. A wetting agent was subsequently added to improve the pigment's ability to integrate with the water phase, enhancing overall dispersion. A pH regulator was introduced to maintain the correct pH balance, which is crucial for the stability and performance of the paint. A deodorizing agent was also included to minimize any potential odor during the formulation and final paint application. Pigment and fillers were added, beginning with titanium dioxide, providing the primary white color and opacity. Additional fillers such as wollastonite, kaolin, and calcium carbonate were included to enhance the paint's texture, coverage, and durability. Bentonite was added to adjust viscosity further and prevent the settling of solid components, ensuring a uniform mixture. After incorporating these solid ingredients, additional deionized water was added to adjust the consistency of the formulation before introducing the styrene acrylic emulsion. This emulsion acts as a binder, proving adhesion and flexibility and forming a durable paint film. Finally, film-forming agents, preservatives, and antimicrobial agents were added to enhance the durability and shelf-life of the paint. The entire mixture was thoroughly homogenized using a high-speed mixer, ensuring even distribution of all components. The final formulation was then allowed to rest, facilitating complete interaction between the components before testing.

Name of the Term	Function in the Experiment	Quantity Needed (grams)
DI Water	**Solvent, dilutes and dissolves materials**	**379.8**
Cellulose Ether	**Thickener, stabilizes the mixture**	**4.5**
4140 dispersants	**Helps in distributing particles evenly**	**7**
4141 dispersants	**Alternative dispersant**	**7**

Wetting Agent	**Lower surface tension, improve spread**	**1.5**
PH Regulator	**Adjust the pH of the solution**	**1.2**
Defoaming Agent	**Reduce or eliminates foam**	**3**
Titanium Dioxide	**White pigment, provide opacity**	**25**
Wollastonite	**Filler, enhances durability**	**20**
Kaolin	**Filler, increase stability**	**75**
Calcium Carbonate	**Filler, reduce cost and improve properties**	**300**
Bentonite	**Thickening agent, stability the mixture**	**20**
Styrene-Acrylic Emulsion	**Binder, provides film-forming properties**	**140**
Film Forming Agent	**Enhance film formation**	**20.5**
Preservative and Antimicrobial	**Prevents microbial growth**	**2.5**

2.2. Paint Characterization

Paint characterization experiment was carried out to compare the performance of the two dispersant 4140 and 4141 in the water-based paint formulation. This process involved the systematic evaluation of several critical properties that influence the overall quality and functionality of the paint. Key properties such as viscosity stability, solid content, dispersion condition, thermal storage, and odor were analyzed using well-defined methods and specific equipment tailored to each measurement.

- Viscosity Stability Measurement:

This was a crucial parameter to determine how the paint maintains consistency over time. Using a rotational viscometer, model STM-V (manufactured by Brookfield Engineering Laboratories), viscosity changes were tracked over days to assess how stable each formulation remained. This stability ensures the paint can be applied easily without affecting its performance or appearance during storage and application. For dispersant 4140, the temperature was 33°C, and for 4141, the temperature was set at 34°C. the viscometer’s spinning rate was set at 60 rpm for both formulation, and measurements were taken at regular intervals over one day. Each measurement session lasted 5 minutes, which is sufficient time for the reading to stabilize and provide a clear indication of how each paint formulation would behave during storage and application.

- Solid Content Determination:

The paint's solid content directly impacts its opacity, durability, and coverage. A higher solid content generally means better coverage and durability. A gravimetric method was used to measure the proportion of non-volatile materials in the paint formulation, helping to quantify its performance capabilities. The process involved placing a measured amount of paint into a pre-weighted aluminum pan, the heating it in an over 105°C for 1 hour to remove any liquids that could evaporate. After letting it cool in a desiccator to prevent moisture, the pan was weighted again. The difference in weight before and after heating showed how much solid material was left, giving a percentage of the paint's solid content.

- Dispersion Condition Evaluation:

A grind gauge is an essential tool used to measure the fineness of pigment dispersion, particularly in industries that deal with paint, coating, and ink. It provides a clear indication of how well the pigment, or solvent particles have been dispersed in a liquid medium, which is crucial for achieving consistency in the final product. The measurement scale of this tool ranges from 0 to 100 microns. A value of 0 microns indicates poor pigment dispersion, signifying uneven distribution of particles, which can lead to inconsistent color and performance. On the other hand, when the value exceeds 50 microns, the pigment dispersion is moderately good, with particles broken down more thoroughly and distributed more evenly. This even distribution is vital for optimizing the paint’s viscosity, which enhances visual quality, such as color vibrancy and gloss, as well as the overall performance of the final paint product. Ensuring fine particle dispersion also contributes to better durability, smoothness, and resistance to settling during storage, making it an indispensable quality control parameter in the industry.

Figure 2

- Thermal Storage Testing:

This test evaluates to assess the stability and durability of the paint formulation by simulating storage condition. During the thermal storage testing, the paint is subjected to controlled temperature variations over an extended period to observe how it withstands environmental changes. This process involves cycling the paint between -10°C to 50°C. This test aimed to determine whether the paint could retain its key properties, such as viscosity, texture, and color. By ensuring the paint remains stable during long-term storage, this test helps confirm that the product will perform reliably and consistently when eventually applied.

- The durability and protective qualities:

The durability and protective qualities of the paint are key factors in its performance, particularly in its ability to withstand wear, weather, and environmental stressors. Tests focused on the paint's resistance to factors like abrasion, UV exposure, moisture, and chemical corrosion. These tests help ensure the paint can provide long-lasting protection to surfaces, maintaining its appearance and protective function over time. High durability ensures that the paint can effectively safeguard structures against harsh conditions, extending the lifespan of the coated surfaces.

3. Result

Viscosity Stability Measurement:

On the first day, dispersant 4140 recorded a viscosity of 83.8 KU (Krebs), which is slightly higher than dispersant 4141 which is 83.2 KU. By the second day, both of 4140 and 4141 has increasing significantly in viscosity. Despite this, the temperature variations had very little impact on the overall viscosity, which demonstrates that both dispersant maintained stability under the given conditions. Viscosity plays a critical role in paint formulations as it directly influences the quality and performance of the application. Higher viscosity ensures that the paint is thick enough to prevent sagging or running during application, while remaining fluid enough to spread evenly. Consistent viscosity over time also indicates that the paint will perform reliably during storage and application, maintaining surface uniformity, color retention, and texture integrity. A stable viscosity ensures ease of use and enhances the overall finish of the paint, which is vital for both consumer satisfaction and product quality.

Solid Content Determination:
After being heated to 105°C for one hour, the data indicates that dispersant 4140 contains 51.03% solids, slightly higher than the 49.8% solids in dispersion 4141. However, overall, the solid content in both paint formulations is very close. Having a higher solid content is more beneficial as it contributes to a thicker and more durable paint film after drying. A paint with higher solid content provides better coverage and opacity. Additionally, the increased solid content improves the paint's resistance to wear, abrasion, and environmental impact, such as moisture, enhancing the overall longevity and protection of the painted surface.

Dispersion Condition Evaluation:
The results show that Dispersants 4140 and 4141 achieved a fineness level of 50 microns, demonstrating stable dispersion throughout the observation period. There was no significant difference observed between the two dispersants, indicating their comparable effectiveness. When the fineness level exceeds 50 microns, it indicates a relatively well-dispersed pigment, showing high-quality formulation. The efficiency of both dispersants ensures that pigment particles are thoroughly dispersed and evenly distributed. This is crucial for maintaining color uniformity, gloss retention, and opacity in the final product. These properties are essential for producing consistent and visually appealing paint, highlighting the reliability of Dispersants 4140 and 4141 in achieving uniform performance and appearance across applications.

Thermal Storage Testing:
The thermal storage stability of Dispersants 4140 and 4141 was tested over a one-day period under controlled temperature conditions, ranging from -10°C to 50°C. This was done to simulate potential environmental stresses during storage. Both dispersants showed normal thermal stability, with no signs of degradation such as separation, coagulation, or changes in viscosity. This means that both formulations can maintain their integrity and performance under thermal stress, ensuring that the paint remains reliable and effective even when exposed to varying temperatures. This stability is

crucial for ensuring the paint's long-term performance and ease of application across different storage conditions.

The durability and protective qualities:
In the test, Dispersant 4140 demonstrated superior protective qualities. It showed enhanced resistance to abrasion and moisture, ensuring better protection of surfaces from wear and environmental factors over time. It effectively prevents issues such as peeling, blistering, and damage caused by prolonged exposure to moisture, making it ideal for humid or wet environments. Furthermore, Dispersant 4140 exhibited excellent UV resistance, maintaining its structural integrity and experiencing minimal fading or degradation under extended sunlight exposure. These attributes make it particularly well-suited for outdoor applications, where durability against sunlight, weather, and physical stress is crucial for maintaining the paint's appearance, color stability, and long-term performance.

The odor assessment:
The odor assessment revealed a noticeable difference between the two formulations. Dispersant 4141 has a much stronger odor compared to Dispersant 4140, which has a milder scent. The low odor of 4140 makes it more suitable for environmentally friendly applications, especially in sensitive environments such as schools, hospitals, or homes, where health and air quality are crucial. On the other hand, the strong odor of 4141 may limit its use in areas where odor control is important, as it could pose health and environmental risks, especially in poorly ventilated spaces. Therefore, Dispersant 4140 is better suited for low-odor applications.

4. Summary

In conclusion, the evaluation of dispersion 4140 and 4141 in water- based formulation highlights both their similarity and difference in the final performance. while both dispersants demonstrated comparable results in term of dispersion condition and thermal storage stability, the main difference emerged in their viscosity stability, solid content, and odor characteristics. Dispersant 4140 demonstrated higher value of viscosity stability and solid content, which giving the advantage that maintaining the paint’s structural integrity and ensuring better coverage, durability, and resistance. The lower odor level in dispersant 4140 also makes it particularly more suitable for environmentally sensitive applications, such as residential or commercial interiors where odor control and low VOC emission are essential. These advantages making dispersant 4140 become the superior choice for all the coating industry and building application, making it ideal for the environmental sustainability. On the other hand, dispersion 4141, with slightly lower solid content and stronger odor, may be more appropriate for high performance ration, serve as viable alternative, particularly in situation where budget constraints are priority, and stringent environmental standards are less critical. This results in improved water resistance, as fewer unreacted monomers mean fewer weak spots in the paint film where moisture can penetrate [29]. Monomers also play a critical role in wet adhesion, particularly in latex paints, and are essential for maintaining adhesive properties under moist conditions, addressing the common issue of adhesion loss when exposed to moisture. These monomers enable the paint to retain its bond even in high humidity or humid environments, such as during rain or in moisture-prone areas like kitchens and bathrooms [30].

The role of monomers in the formulation further underscores these findings, as they significantly influence the paint's durability, odor, and overall performance. Higher free monomer content can lead to more pungent odors and increased VOC emissions. During polymerization, monomers chemically bond to form a stable film that provides the structural integrity of the paint. When the concentration of free monomers is lower, as seen in dispersant 4140, the polymerization process is more complete, leading to a more cohesive film. Overall, dispersant 4140 merges as the superior option for the modern architectural coating, offering enhanced environmental benefits. Better water resistance is a priority, but its stringer odor and slightly lower performance metrics may limit its use in more environmentally stringent settings. This comparison highlights the importance of selecting the appropriate dispersant based on performance needs and environmental considerations.

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