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FROM PARTICLE INTERACTIONS TO SHELF LIFE

WHY ZETA POTENTIAL, PARTICLE SIZE AND STABILITY MUST BE MEASURED TOGETHER?

Context

Colloidal systems such as suspensions, emulsions, and foams are central to numerous industries, including pharmaceuticals, cosmetics, food, coatings, agrochemicals, energy materials, and advanced chemistry.

In these systems, particle size and zeta potential are essential formulation parameters. They influence product performance (e.g., UV protection, bioavailability, catalytic activity...), texture, optical properties, processability, and robustness.

Careful control of particle size and surface charge significantly contributes to dispersion quality and stability. Yet, even when these parameters are optimized, a formulation may evolve. Systems that initially meet their specifications can undergo progressive changes due to sedimentation, creaming, flocculation, coalescence, or structural rearrangements during storage and use.

To fully understand and control colloidal and formulation behavior, three complementary dimensions must be evaluated:

- **Particle Size Distribution** defining structural behavior
- **Zeta Potential (ζ)** describing particle interactions and surface charge
- Direct **Stability Measurement** over time, revealing macroscopic evolution

Beyond their role in long-term stability, particle size and zeta potential are essential formulation tools. They allow formulators to:

- Select and compare raw materials
- Optimize milling or homogenization processes
- Adjust pH and dispersant concentration
- Evaluate sensitivity to ionic strength
- Understand interparticle interactions

Each parameter provides critical and distinct information. Only their combined interpretation enables a comprehensive understanding of formulation performance and robustness.

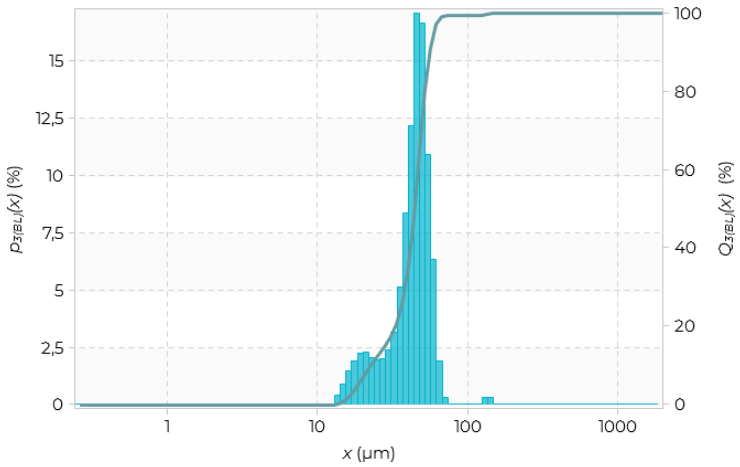
Particle Size – The Structural Framework of a Dispersion

Particle size and **particle size distribution** (PSD) are among the most fundamental parameters in colloidal systems. For the formulator, controlling size is not only a matter of stability — it is directly linked to the intrinsic properties and performance of the product.

In functional materials, smaller particles often enhance activity due to increased surface area.

From a formulation perspective, measuring particle size allows:

- Verification of milling efficiency
- Detection of agglomerates
- Monitoring of coating or surface modification effects
- Assessing emulsifier efficiency
- Optimization of homogenization parameters
- Comparison of raw materials from different suppliers
- Etc.



Example of particle size distribution

Controlling particle size also contributes to improving stability and redispersibility. Sedimentation velocity follows Stokes' law: the migration rate increases with the square of the particle radius. A modest increase in particle size can dramatically accelerate separation; smaller and well-distributed particles sediment more slowly and may form less compact sediments. However, particle size alone does not determine whether aggregation will occur.

Two dispersions may exhibit identical size distributions at the initial time and yet evolve differently depending on interparticle forces.

Why does Particle Size Distribution matter?

In real dispersions, particles are never perfectly uniform. Reporting a single mean value (e.g., D50) provides only limited information and may mask critical structural features.

The **particle size distribution (PSD)** (including its width, shape, and tails) often determines system behavior more than the average diameter.

A small population of coarse particles can dominate sedimentation kinetics. Likewise, a broad or multimodal distribution may indicate incomplete deagglomeration, raw material variability, or process instability.

Comparison of particle characterization methods

Two formulations with identical mean particle sizes can therefore exhibit significantly different:

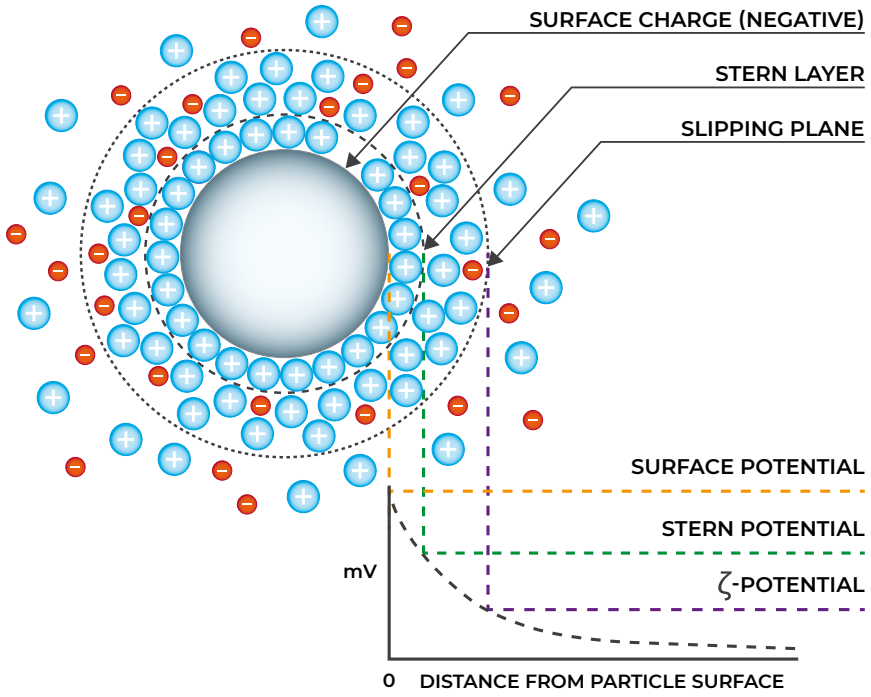
- Separation rates
- Redispersibility
- Optical properties
- Mechanical stability
- And many more

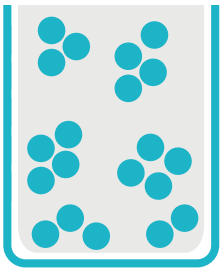
Particle size and particle size distribution, therefore, define the **structural framework** — but they do not describe interaction forces nor predict long-term macroscopic evolution.

Zeta Potential – Understanding Interparticle Interactions

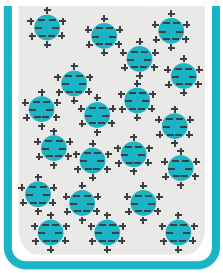
While particle size defines the geometric framework, zeta potential characterizes the electrostatic properties that determine the interaction between particles.

Zeta potential (ζ) represents the electrical potential at the hydrodynamic slipping plane of a particle or droplet. It reflects the effective surface charge environment within the electrical double layer and is directly related to electrostatic repulsion between dispersed entities.





Electrically neutral particle agglomeration



Electrically charged particles No agglomeration

According to classical colloidal science (DLVO theory), colloidal stability results from the balance between:

- Attractive van der Waals forces
- Repulsive electrostatic double-layer interactions

The total interaction potential between particles is the sum of these opposing contributions. When the repulsive energy barrier is sufficiently high relative to thermal energy (kT), particle collisions remain reversible. When the barrier decreases — due to pH adjustment, electrolyte addition, or surface chemistry changes — aggregation becomes thermodynamically favorable and the probability of irreversible aggregation increases.

For the formulator and chemist, zeta potential is particularly valuable during development because it helps:

- Optimize pH conditions
- Select and dose dispersants or surfactants
- Compare raw materials for Quality control
- Determine the isoelectric point (IEP)
- Understand salt sensitivity and electrolyte concentration

Zeta potential is particularly valuable during formulation development because it helps prevent unwanted aggregation. A sufficiently high absolute value of ζ generally indicates stronger electrostatic repulsion, reducing the probability of particle collision leading to irreversible aggregation.

This contributes to improved dispersion robustness, reduced flocculation, better redispersibility after sedimentation and enhanced long-term product consistency.

Zeta potential, therefore, provides critical insight into the **interaction energy landscape** of a dispersion. At the same time, stability in real formulations results from a combination of interaction forces and kinetic phenomena, and zeta potential does not provide information on **sedimentation** rate, **creaming** behavior, **phase separation** kinetics and structural rearrangements **over time**.

For example:

- A system may exhibit high |ζ| yet sediment rapidly if particles are large or density differences are significant
- Increasing ionic strength can compress the electrical double layer and reduce repulsion, sometimes before major ζ changes are apparent.
- Steric stabilization or increased continuous-phase viscosity may maintain stability even at moderate ζ values.

Zeta potential should therefore be viewed as a **predictive interaction parameter** — a powerful tool for guiding formulation strategy and minimizing instability risks — while recognizing that macroscopic stability ultimately depends on additional structural and kinetic factors.

Stability - Observing What Happens Over Time

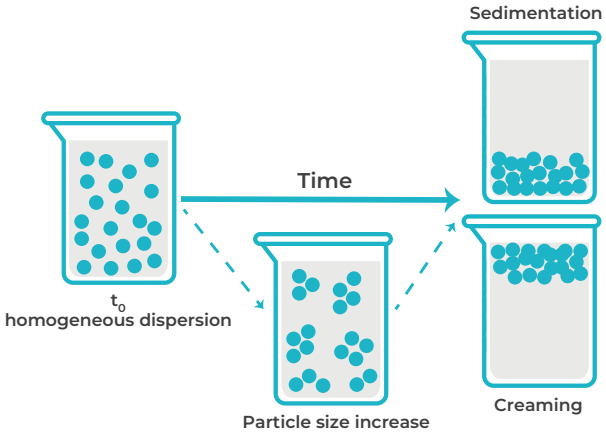
Colloidal and dispersed systems are, by nature, **thermodynamically unstable,** and they will ultimately evolve into phase separation.

What we call a “stable formulation” is therefore not an equilibrium system, but a **kinetically stabilized one**.

Stability is not a “static” property; it is a time-dependent process. A dispersion may initially exhibit an optimal particle size distribution, a sufficiently high absolute ζ value, and acceptable rheological properties, yet over time, the system can undergo progressive changes that ultimately affect performance, appearance, texture, etc.

Destabilization typically occurs through one or more of the following mechanisms:

- **Sedimentation** – downward migration of denser particles
- **Creaming** – upward migration of lighter droplets or particles
- **Flocculation** – reversible aggregation without fusion
- **Coalescence** – irreversible droplet fusion
- **Phase separation**
- **Structural rearrangements or compaction**



These mechanisms depend heavily on particle size and surface charge, but also on:

- Density differences
- Viscosity
- Interparticle forces
- Ionic environment
- Possible chemical reactions
- Storage & use conditions

Because these phenomena develop over time, they must be **directly monitored** rather than inferred, and measuring stability provides the ultimate validation of the formulation structure and robustness.

Linking Particle Size, Zeta Potential, and Stability

Particle size and zeta potential are formulation levers; stability is the outcome:

- Particle size defines the structural and end-use properties of the formulation
- Zeta potential governs electrostatic interactions and aggregation tendencies
- Stability measurement reveals the macroscopic evolution and kinetic reality.

Optimizing size and ζ helps reduce the risk of instability:

- Smaller particles generally migrate more slowly.
- Higher absolute ζ values reduce flocculation probability.
- Proper surface chemistry improves dispersion robustness.

However, even when both parameters are optimized, instability may still occur due to density differences, viscosity effects, steric interactions, chemical reactions, storage conditions, etc.

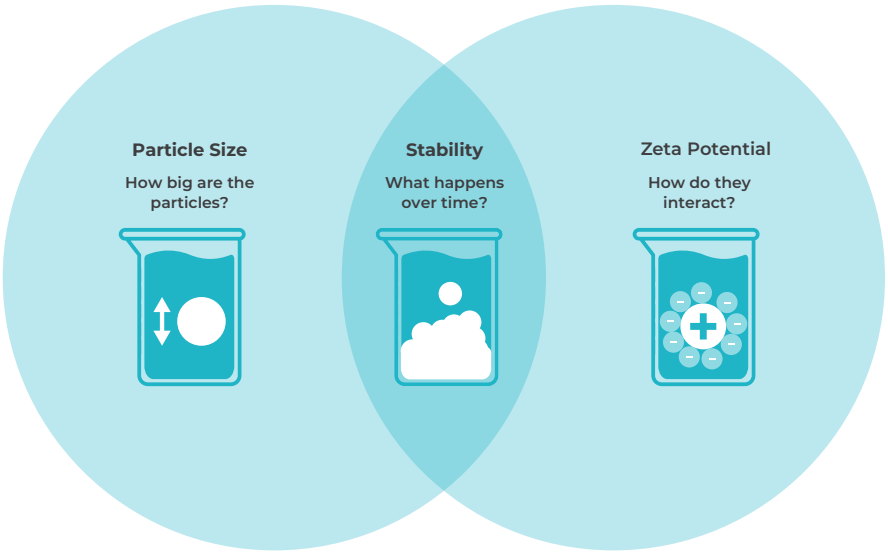
A single-parameter approach is incomplete:

Measuring ONLY	You may miss
Particle size	Interaction forces and kinetic evolution
Zeta potential	Migration and kinetic evolution
Stability only	Root cause of failure

Therefore:

- Particle size and zeta potential help design a stable system.
- Direct stability measurement confirms whether the system remains stable over time.

This integrated approach transforms formulation from empirical adjustment into predictive science.



Individually, each parameter provides critical insight. Together, they deliver a complete understanding of colloidal behavior.

This approach supports:

- Faster time to market in product development
- Reduced reformulation costs
- Better supplier qualification
- More robust scale-up
- State-of-the-art quality control testing.

Implementing an Integrated Characterization Strategy with MICROTRAC

Understanding dispersed systems requires connecting microscopic structure, interparticle interaction forces, and macroscopic kinetic evolution. Achieving this connection demands analytical methods that provide complementary information while preserving the real state of the formulation.

A key requirement in dispersion analysis is the ability to measure systems under conditions that closely reflect their native structure. Dilution, excessive sample preparation, or structural disturbance can significantly alter particle interactions and lead to misleading conclusions. Reliable characterization, therefore, requires technologies capable of analyzing samples with minimal perturbation.

With more than **50 years of expertise** in particle characterization, **MICROTRAC** has developed a coherent portfolio designed to address the three fundamental dimensions of dispersion science: **particle size, electrokinetic properties, and direct stability monitoring**.

PARTICLE SIZE - FROM NANOMETERS TO MILLIMETERS WITH SYNC AND NANOTRAC

Particle size defines the structural framework of a dispersion and influences both functional performance and separation kinetics. Accurate measurement across a wide size range is therefore essential.

SYNC combines high-resolution laser diffraction with dynamic image analysis, enabling measurement from 10 nm to the millimeter range while also providing particle shape information for larger particles. This allows detection of coarse fractions, agglomerates, and morphological variability that may influence separation behavior.

SYNC

For **nanoscale** systems, **NANOTRAC** applies dynamic light scattering (DLS) technology to characterize particles from the nanometer range up to several microns. Its dip-and-measure approach enables analysis at concentrations where conventional optical techniques may require dilution.

Together, these technologies provide structural insight across an exceptionally broad size spectrum — from nanosuspensions to coarse dispersions — ensuring that the full particle size distribution is captured rather than reduced to a single mean value.

ZETA POTENTIAL – STABINO ZETA

STABINO ZETA measures zeta potential using a non-optical principle, enabling analysis of highly concentrated and opaque systems with minimal sample preparation.

Automatic titration capabilities allow systematic investigation of:

- pH dependent changes in zeta potential
- Isoelectric point (IEP) determination
- Electrolyte sensitivity
- Dispersant adsorption efficiency
- Polyelectrolyte titration to determine surface charge density

By mapping ζ under realistic formulation conditions, electrostatic stability windows can be defined and formulation parameters optimized with quantitative support.

DIRECT STABILITY – TURBISCAN

Even when particle size and surface charge are optimized, real stability must be validated over time.

TURBISCAN provides non-invasive optical analysis of undiluted samples, detecting early destabilization phenomena long before they become visible to the naked eye. Monitoring spatial and temporal changes within the sample, it enables the detection and quantification of:

- Sedimentation and creaming
- Flocculation and coalescence
- Early destabilization phenomena

This direct observation of kinetic evolution allows microscopic interaction parameters to be correlated with macroscopic shelf-life behavior.

Conclusion

A COHERENT ANALYTICAL ECOSYSTEM

When particle size analysis, zeta potential measurement, and direct stability monitoring are integrated within a unified workflow, dispersed systems can be understood across scales:

- **Microscopic structure** (particle size distribution)
- **Interaction energy landscape** (zeta potential)
- **Macroscopic kinetic outcome** (stability over time)

This multidimensional approach reduces reliance on empirical trial-and-error, accelerates development cycles, and strengthens scientific decision-making throughout R&D and quality control.

By integrating structural, electrokinetic, and kinetic insights, formulation development shifts from reactive troubleshooting to predictive engineering.

By preserving native sample structure and providing complementary information, MICROTRAC technologies enable formulators to connect particle interactions to real-world performance — **transforming dispersion characterization into a structured scientific methodology.**

Find out more on www.microtrac.com

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