

# A review on the stability of magnetorheological materials

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Received: 14 August 2025 / Accepted: 2 December 2025

**Abstract.** Magnetorheological materials, as a type of intelligent controllable material, have broad application prospects in the engineering field. However, stability issues (such as sedimentation, particle agglomeration, and extreme temperature adaptability) severely limit the practical application of magnetorheological materials. In this paper, the research progress on the stability of magnetorheological materials was summarized and categorized, and analyzed from three aspects: material systems, testing methods, and improvement strategies. First, the compositional characteristics and stability challenges of magnetorheological materials with different matrix morphologies were compared, and it was pointed out that sedimentation issues in magnetorheological fluids and particle migration issues in magnetorheological elastomers are key research focuses. Second, the currently available stability testing methods were summarized, including sedimentation observation, particle concentration testing, redispersibility testing, and temperature stability testing, and the applicable scenarios, advantages and disadvantages of different methods are discussed. Third, the technical measures to enhance stability were discussed in detail, such as additive optimization (surfactants, thixotropic agents, nanoparticles, etc.), magnetic particle surface modification (polymer coating, composite structure design, etc.), and matrix carrier modification (magnetic matrix carriers, fluid-solid carrier conversion, etc.), and the enhancement mechanisms and characteristics of different methods were compared. Finally, current research limitations in terms of performance trade-offs and long-term reliability were identified, and future directions such as smart responsive materials and standardized testing were proposed. This study provides theoretical references and technical guidance for the stability design and engineering applications of magnetorheological materials.

**Keywords:** Magnetorheological materials / sedimentation stability / agglomeration / temperature adaptability / additives / surface modification

## 1 Introduction

Magnetorheological materials, as intelligent materials, refer to the homogeneous dispersion of magnetic particles in a non-magnetic matrix [1]. Owing to their controllable rheological properties under magnetic fields, rapid response, and reversible reactions [2], magnetic rheological materials are widely applied in automotive engineering, mechanical manufacturing, biomedicine, and other fields, showing broad application prospects in vibration damping and cushioning, precision polishing, friction and wear, and medical rehabilitation [3–5].

However, the practical application of magnetorheological materials still faces significant challenges, with particle settling and insufficient dispersion stability being the core bottlenecks limiting their engineering applications [6–8]. When the magnetorheological material is stationary without a magnetic field, due to the significant density difference between the solid particles and the carrier, the

solid particles tend to settle under the influence of gravity. Additionally, the particles are prone to agglomeration under van der Waals forces, which further accelerates settling. Once settled, the solid particles are difficult to redisperse. Particles settling or agglomeration reduces the magnetic rheological effect of the material and causes device damage. Meanwhile, the stability of magnetorheological materials is greatly affected by temperature. High temperatures accelerate the movement of internal particles, reducing viscosity and making particles susceptible to oxidation. At low temperatures, the viscosity of the material increases sharply, leading to a stiffening behavior that renders its vibration damping and cushioning functions ineffective. Therefore, the preparation of high-stability magnetic rheological materials is crucial for further advancing magnetic rheological technology.

In recent years, faced with the stability bottleneck of magnetorheological materials in engineering applications, researchers have adopted various measures, including surface modification of magnetic particles [9–11], addition of nanoparticles [12] or additives [13–15], and modification of the base carrier [16–18], to systematically improve the

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sedimentation and dispersion stability of the materials. With the continuous development of the magnetorheological materials, higher requirements for their stability performance have emerged for different application scenarios.

This paper focuses on the latest advancements in magnetic rheological material systems, systematically reviews the characterization methods for the sedimentation, redispersion, and temperature stability of magnetorheological materials, and summarizes the strategies for enhancing their stability. It aims to provide a reference for researchers in the field. Finally, based on current research findings, this paper discusses the future trends in stability enhancement techniques and engineering applications of magnetic rheological materials, with the goal of guiding innovative developments in this field.

## 2 Classification of magnetorheological materials

After decades of development, researchers have prepared various types of magnetorheological materials with different matrix structures for different engineering applications, analyzed their mechanisms, and characterized their properties, thereby establishing a magnetic rheological material system. At present, the magnetorheological material system primarily includes magnetorheological fluids with liquid characteristics, solid-like magnetorheological greases, magnetorheological gels, and magnetorheological plastics, as well as magnetorheological foams and magnetorheological elastomers with characteristics. Table 1 shows the classification of common magnetorheological materials, and Figure 1 shows the physical images of common magnetorheological materials. Figure 2 is the schematic diagram of the working principle of magnetorheological materials.

The selection of magnetorheological materials depends on core scenario requirements:

- For applications requiring rapid dynamic response and continuous fluidity (such as real-time vibration control and precision polishing), liquid-state magnetorheological materials are preferred due to their fast rheological adjustment.
- For static/dynamic hybrid working conditions with leakage risks (such as robotic joints and valve seals), solid-state-like magnetorheological materials are suitable, as their solid-like morphology avoids fluid spillage.

For long-term solid-state service under harsh environments (e.g., high temperatures, mechanical wear, such as aircraft components or automotive suspensions), solid-state magnetorheological materials are optimal, owing to their fixed shape and excellent mechanical stability.

### 2.1 Liquid-state magnetorheological materials

Magnetorheological fluid (MRF) is the earliest liquid-form magnetorheological material, whose carrier fluid typically uses water or oil. In the absence of a magnetic field, MRF exhibits typical characteristics of Newtonian fluids and can

flow freely; once a magnetic field is applied, the magnetic particles in the material rapidly orient into chain-like structures within milliseconds, forming a high-viscosity solid-like state; after removing the magnetic field, MRF can quickly restore its original flow characteristics [19].

In 1948, the American scholar Rabinow [20] first discovered the magnetorheological effect. By uniformly dispersing ferromagnetic particles in base oil, he successfully designed an electromagnetically controlled fluid clutch based on MRF. This breakthrough not only officially initiated the exploration of MRF applications in engineering but also laid a solid foundation for subsequent in-depth research and innovative practices in mechanical manufacturing, automotive industry, aerospace, and other fields [2]. After decades of exploration by researchers, key performance indicators of MRF, including stability, rheological properties, dynamic response speed, precise control accuracy, and complex environment adaptability [12–14], have been significantly improved in diverse application scenarios [21].

However, current challenges remain unresolved: (1) The large density difference between carrier fluids and magnetic particles still leads to inevitable sedimentation, especially in long-term static conditions; (2) Solid particles are prone to oxidation and agglomeration under high temperatures or harsh environments [22], which degrades the magnetorheological effect; (3) Traditional surfactants used to improve dispersion fail at high temperatures ( $>150\text{ }^{\circ}\text{C}$ ), limiting MRF's application in high-temperature scenarios.

### 2.2 Solid-state-like magnetorheological materials

Magnetorheological grease (MRG) is a magnetorheological material between liquid and solid states, which uniformly disperses micron-scale magnetic particles in a high-viscosity grease matrix and exhibits excellent properties beyond traditional magnetorheological materials under specific working conditions [23]. In 1999, Rankin et al. [24] pioneered the dispersion of ferromagnetic particles in grease matrices with different viscosities, successfully preparing a series of magnetorheological greases with diverse zero-field viscosities. Theoretical calculations confirmed that the grease matrix not only effectively suppresses particle sedimentation but also significantly enhances material stability without compromising the magnetorheological response. Thereafter, Ye et al. [25] prepared MRG using lithium-based grease as the carrier and carbonyl iron powder as the magnetic particles, systematically investigating the influence of particle concentration, magnetic field strength, and temperature on the normal force characteristics of MRG under oscillatory shear mode. They found that under constant magnetic field strength, the normal force showed a positive correlation with the carbonyl iron content.

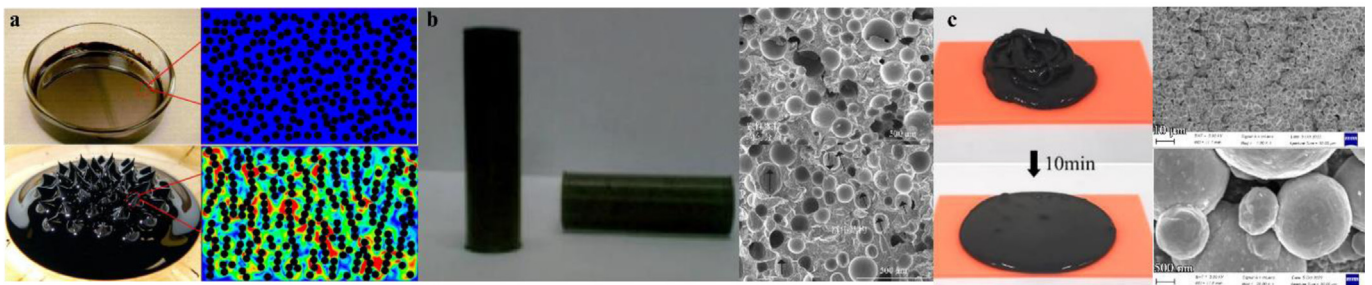
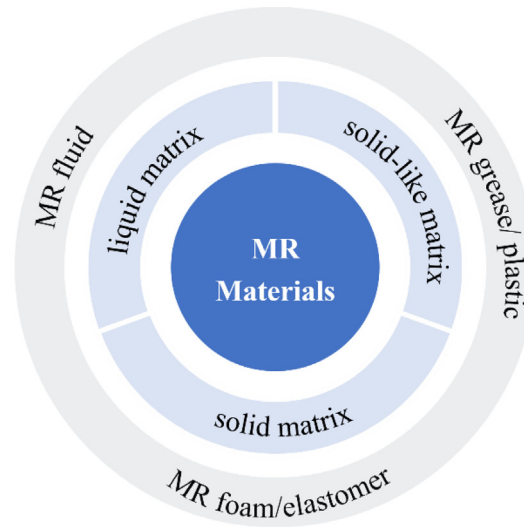
Wang et al. [26] prepared MRG using commercial lubricating grease and hydroxyl iron powder as raw materials, analyzing the rheological properties of MRG under different shear modes. When the magnetic field

**Table 1.** Classification and scenario-specific applications of common magnetorheological materials.

Matrix type	Characteristics	Research focus	Application field
Liquid matrix (magnetorheological fluid)	Using water or oil as a carrier, the magnetic particles are uniformly dispersed, with good fluidity and rapid response speed for continuous, reversible rheological properties	Prevent particle settling and agglomeration to improve anti-aging properties; optimize dispersants to extend the service life of materials; study the effects of temperature, magnetic field, and other factors on material properties	<ol style="list-style-type: none"> <li><b>Automotive:</b> Shock absorbers for passenger cars (improving ride comfort), brakes/clutches (smooth torque control)</li> <li><b>Precision Manufacturing:</b> Magnetorheological polishing of hard materials (e.g., sapphire, optical lenses)</li> <li><b>Aerospace:</b> Vibration isolation systems for satellite components (reducing micro-vibrations)</li> <li><b>Civil Engineering:</b> Damping devices for high-rise building sway (wind/earthquake resistance)</li> </ol>
Solid-like matrix (magnetorheological grease, magnetorheological plastic)	With a morphology between liquid and solid, exhibiting certain viscoelasticity, and capable of undergoing significant rheological properties under the influence of a magnetic field	Controlling the range of material viscoelasticity; improving the compatibility of solid-like substrates with magnetic particles; enhancing the fatigue resistance of materials	<ol style="list-style-type: none"> <li><b>Sealing:</b> Intelligent seals for industrial valves (preventing leakage under variable pressure)</li> <li><b>Robotics:</b> Driving joints for bionic robots (precision motion control without fluid leakage)</li> <li><b>Construction:</b> Seismic reinforcement for prefabricated building connections (absorbing impact energy)</li> <li><b>Medical Equipment:</b> Flexible grippers for minimally invasive surgical tools (gentle tissue handling)</li> </ol>
Solid matrix (magnetorheological foam, magnetorheological elastomer)	Rubber/polymer-based matrix with embedded magnetic particles, maintaining fixed shape, excellent mechanical properties, and high stability	Optimization of the interfacial bonding strength between particles and matrix; enhancement of the wear resistance of the material; improvement of the magnetorheological properties of the material under complex stresses	<ol style="list-style-type: none"> <li><b>Aerospace:</b> Solid-state dampers for aircraft engine mounts (withstanding high temperatures/vibrations)</li> <li><b>Automotive:</b> Suspension bushings (adapting to road conditions for stability/comfort)</li> <li><b>Protective Equipment:</b> Intelligent helmets (absorbing impact energy during collisions)</li> <li><b>Acoustics:</b> Active sound-absorbing panels for high-speed trains (reducing interior noise at different speeds)</li> <li><b>Medical:</b> Tactile sensors for prosthetics (simulating human skin pressure perception)</li> </ol>

strength was 0.96T, the relative magnetorheological effect of MRG with 70% hydroxyl iron powder content reached 3814%, which provides the theoretical support for the application of MRG buffers in artillery recoil mechanisms. Ju et al. [22] further developed MRG using low-viscosity damping lubricating grease as the matrix and carbonyl iron powder as soft magnetic filler particles, deeply analyzing the internal correlation between particle concentration and material response characteristics under rotating magnetic fields. These studies indicate that MRG, by virtue of the synergistic effect between the grease matrix and magnetic particles, exhibits outstanding advantages in stability control, dynamic response accuracy, etc. [27–29], laying a solid foundation for its application in complex working conditions.

In 1995, Shiga [30] first proposed the concept of magnetorheological gel, preparing a gel-like magnetic fluid by thoroughly mixing magnetic particles with silicone resin and conducting preliminary studies on its properties. Magnetorheological gel is a type of magnetic fluid using high-viscosity non-magnetic polymer colloid as the carrier matrix. Compared with magnetorheological fluid, magnetorheological gel has a higher carrier viscosity, which mitigates magnetic particle sedimentation and ensures better stability. The viscoelastic properties of magnetorheological gel can be correspondingly adjusted under a magnetic field, enabling intelligent regulation of its rheological behavior [31]. Sun et al. [32] analyzed the micro-mechanical behavior of magnetorheological gel and applied it to dampers, achieving control over impact loads in dampers.



(a) Magnetorheological Fluid (b) Magnetorheological Elastomer (c) Magnetorheological Grease

Fig. 1. Common magnetorheological materials [33,34,22].

In 2011, Xu et al. [33] pioneered the concept of magnetorheological plastomer (MRP) by preparing a polyurethane-based magnetorheological plastomer, which can flexibly change shape under external forces while retaining its original magnetorheological properties. Subsequently, Pang et al. [36] analyzed the variation of shear storage modulus of MRP in magnetic fields, designed a buffer utilizing the rheological properties of MRP, and tested its anti-vibration and impact performance. Due to their excellent mechanical properties, MRP have found extensive applications in dampers [17,37]. Xu et al. [38] constructed a flexible sensor using MRP combined with graphite and other substances, which has a fast response speed. However, the MRP are prone to deformation under the action of external forces, and the stability cannot be maintained during the work, which limits their application to some extent.

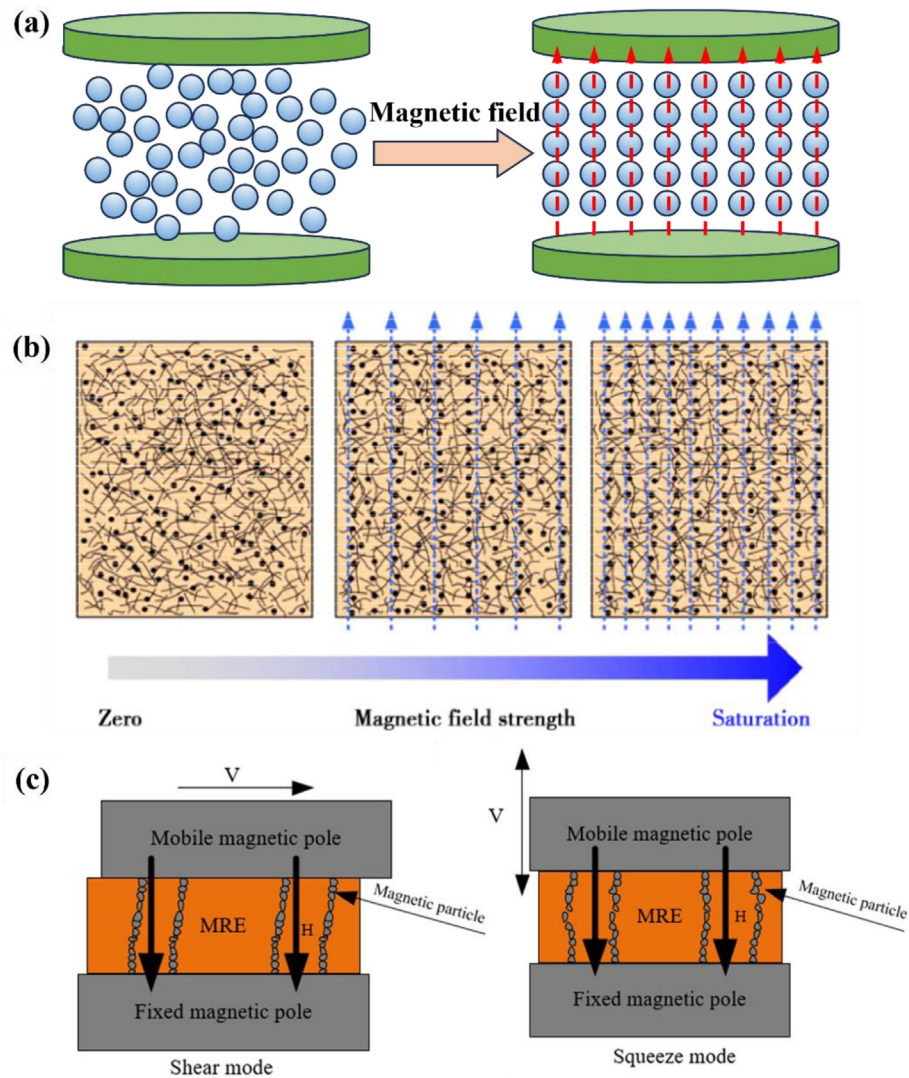
In summary, solid-state-like magnetorheological materials represented by MRG and MRP have effectively addressed the sedimentation issue of liquid MRF by replacing low-viscosity carrier fluids with viscoelastic matrices such as greases and plasticizers, and have demonstrated application potential in static/low-dynamic scenarios such as precision valves and deformable sensors. However, their current development is still constrained by two core bottlenecks: first, MRG faces a trade-off between stability and response efficiency—high-viscosity matrices

improve anti-sedimentation performance but result in a response speed 5-10 times slower than that of MRF, while low-viscosity matrices lead to compromised anti-sedimentation capability; second, the correlation mechanism between matrix-particle interface interactions and long-term fatigue performance remains unclear.

To address these issues, future research should focus on the following key aspects: developing “smart adaptive matrices” to realize dynamic viscosity regulation, like temperature-sensitive or shear-thinning composites, thereby resolving the conflict between response speed and stability; and establishing a “mechanism-application correlation model” by combining interface characterization with long-term fatigue testing to clarify failure mechanisms and improve material durability. These efforts will ultimately promote the transition of solid-state-like magnetorheological materials from laboratory optimization to large-scale engineering applications.

### 2.3 Solid-state magnetorheological materials

Magnetorheological foam is a functional composite material formed by uniformly adsorbing magnetorheological fluid onto porous substrates such as sponges, open-cell foams, felts, or fiber fabrics through capillary action [39]. Xu et al. [40] filled magnetorheological fluid into the pores



(a) Liquid-state Magnetorheological Materials (b) Solid-state-like Magnetorheological Materials (c) Solid-state Magnetorheological Materials

**Fig. 2.** Schematic diagram of the working principle of magnetorheological materials [41].

of open-cell foam and utilized the skeletal support properties of porous polymer materials such as sponge to achieve high elasticity, light weight, and uniform dispersion of magnetic particles within the matrix, significantly enhancing the material's sedimentation stability. The application of magnetorheological foam in dampers not only reduces material consumption and usage costs but also enhances the service life of dampers through the confinement effect of the matrix on the magnetorheological fluid [42]. Additionally, magnetorheological foam exhibits excellent actively controlled sound absorption properties, enabling efficient absorption and regulation of sound waves at different frequencies by dynamically adjusting the internal pore structure and rheological state via an external magnetic field [43,44].

Magnetorheological elastomer is a common type of solid-state magnetorheological material, prepared by uniformly dispersing magnetic particles in elastic polymeric material such as rubber [18]. In the absence of a magnetic field, magnetic particles are pre-arranged in chain-like structures within the matrix; when a magnetic field is applied, the magnetic particles inside the elastomer are constrained by the matrix and cannot move freely. With the dynamic variation of magnetic field strength, magnetorheological elastomers exhibit significant stiffness-tunable characteristics at the macroscopic level [45]. Operating primarily in the pre-yield stage, magnetorheological elastomers enable dynamic control of their shear modulus and damping properties through precise adjustment of magnetic field strength, thus achieving the desired

regulation objectives. By introducing liquid metal EGeIn into magnetorheological elastomer, Chang et al. [46] successfully prepared a liquid metal-filled magnetorheological elastomer composite material with piezoresistive properties, and developed a flexible tactile sensor based on this material. It has the advantages of simple preparation process, high sensitivity and small hysteresis error. Magnetorheological elastomer possesses remarkable advantages such as low sedimentation tendency of magnetic particles, environmental friendliness, and convenient storage and packaging [47,48], showing promising application prospects in aerospace, civil engineering, automotive industry [49–51], and other fields.

In summary, solid-state magnetorheological materials, including magnetorheological foam and magnetorheological elastomer, have become important branches of smart magnetorheological materials due to their unique structural advantages. However, solid-state magnetorheological materials still face several key issues: for magnetorheological foam, the porous structure is prone to deformation under long-term mechanical loading, which destroys the uniform dispersion of internal MRF and weakens the magnetorheological effect; for MRE, the interface bonding between magnetic particles and the elastic matrix is insufficient, leading to particle detachment during cyclic deformation and reducing material durability, and the low magnetic particle content limits the maximum adjustable range of stiffness. To address these problems, targeted measures can be taken: for magnetorheological foam, modifying porous substrates with wear-resistant and anti-deformation materials can improve structural stability, such as adding glass fiber reinforcements to sponges; for MRE, using surface-modified magnetic particles to enhance matrix-particle interface adhesion to expand stiffness tunability. These improvements will further promote the practical application of solid-state magnetorheological materials in more complex engineering scenarios.

### 3 Stability classification and testing methods of magnetorheological materials

Under ideal conditions, magnetic particles in magnetorheological materials are uniformly distributed throughout the matrix. Especially in magnetorheological fluids, the significantly higher density of magnetic particles compared to the matrix fluid causes them to settle rapidly in the suspension. When magnetorheological materials are left stationary, gravity gradually forms multiple zones with different concentration gradients, making sedimentation a key factor affecting the practical application of magnetorheological materials [52]. Meanwhile, in the sedimentation zone, particles agglomerate and tend to become compacted, causing magnetorheological devices to fail in restoring their rated performance when restarted, or even leading to functional failure. Therefore, the redispersibility of the material has become another core indicator for its practical application [1]. With the widespread application of magnetorheological materials in high-end fields such as automotive, exploring the normal operating temperature

range of magnetorheological devices and their performance under high and low temperature environments has become a current research hotspot.

Thus, the stability testing system for magnetorheological materials mainly includes sedimentation stability testing, redispersibility evaluation, and temperature stability testing. Establishing recognized quantitative monitoring methods and scientific evaluation systems is not only the foundation for accurately characterizing the stability of magnetorheological materials but also a key technical link urgently needing breakthroughs in promoting their engineering applications. Forming standardized testing procedures and quantitative evaluation indicators can provide reliable technical support for the research, development, optimization, and engineering application of magnetorheological materials.

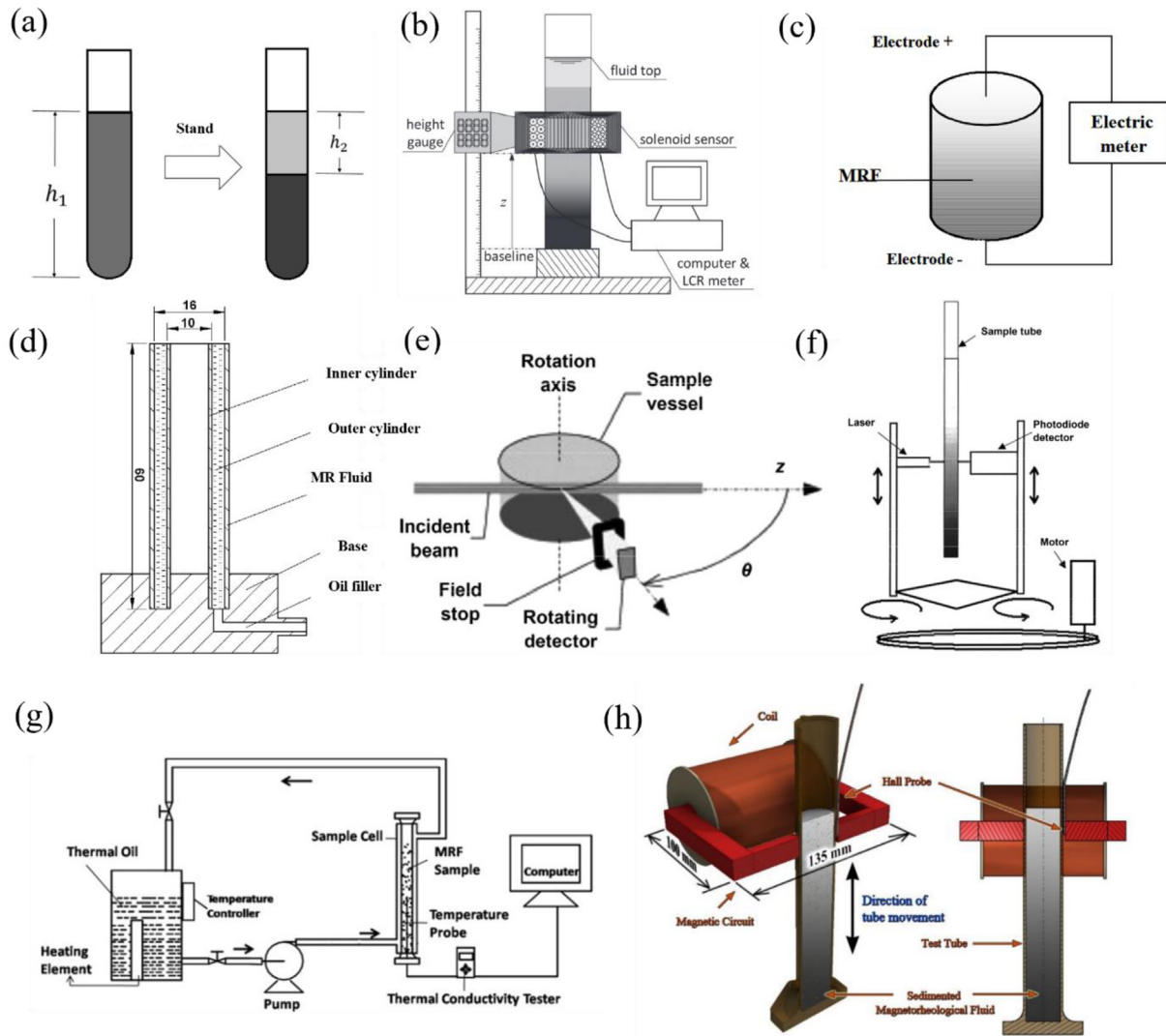
#### 3.1 Sedimentation stability

Sedimentation stability is a key indicator for evaluating the stability of magnetorheological materials, particularly for magnetorheological fluids, where a significant density difference exists between the carrier fluid and solid particles. Particles are prone to sedimentation under gravity, leading to stratification in magnetorheological fluids. The sedimentation rate [53] is an important parameter for characterizing the sedimentation stability of magnetorheological fluids. The principle of testing sedimentation stability via natural sedimentation is shown in Figure 2a. The sample is injected into a test tube and sealed, with the initial solution height measured as  $h_1$ . After the solution is left stationary, the height of the clear liquid layer  $h_2$  is recorded at regular intervals, from which the sedimentation rate can be obtained:

$$V = \frac{h_2}{h_1} \times 100\%. \quad (1)$$

The sedimentation rate is generally measured by the visual observation method [54,55] and the multiple light scattering method [56,57]. The visual observation method uses a ruler to measure the height change of the solution, featuring fast and simple operation, but its measurement accuracy is significantly affected by human judgment. The multiple light scattering method is a detection technology that studies the particle size distribution and concentration of magnetorheological materials by analyzing the signal changes of light after multiple scattering in the sample. Using the Turbiscan optical stability analyzer, real-time monitoring of the intensity of backscattered and transmitted light can be achieved. By calculating parameters such as particle migration rates and sediment layer thickness, sedimentation rate indicators can be obtained. Meanwhile, the multiple light scattering method can also enable early prediction of material sedimentation behavior, providing more comprehensive dynamic data support for the stability evaluation of magnetorheological materials.

In addition to traditional methods, researchers have utilized particle concentration changes to characterize sedimentation stability, developing technical approaches such as the capacitance methods [58,59], inductance



(a) Natural Sedimentation Method (b) Inductance Method (c) Potentiometric Method

(d) Permeability Method (e)(f) Optical Detection Method (g) Thermal Conductivity method (h) Inductance Method

**Fig. 3.** Principle of sedimentation stability testing methods [53,60,61,62,63,64,65].

methods [66–71], potentiometric methods [61], permeability methods [72], thermal conductivity methods [68], and optical detection methods [63–64]. When magnetorheological material sediments at rest, the concentration of magnetic particles exhibits a gradient distribution along the depth direction, and such distribution changes induce alterations in physical parameters like capacitance, inductance, and potential in the measuring device. Thus, by detecting the dynamic changes in the above physical quantities of the sample, the concentration variation can be reflected, thereby characterizing the sedimentation stability of magnetorheological materials.

Zhao et al. [58] proposed a method for measuring the sedimentation stability of magnetorheological fluid using capacitance, leveraging the relationship between

capacitance and particle content. Based on the principle that particle sedimentation induces changes in the dielectric properties of the system, a capacitive sensor was used to capture real-time capacitance changes, precisely correlating electrical signals with the sedimentation process to provide a novel stability detection method. Ju et al. [59] designed a capacitive experimental testing system using magnetorheological elastomer as the dielectric medium, systematically investigating the magnetically controlled electrical properties of magnetorheological elastomer under magnetic fields. Meanwhile, they analyzed the relationship between magneto-capacitive characteristics and viscosity, as well as magnetic particle content, providing a theoretical basis for material property regulation and optimization.

Chen et al. [66] first discovered the linear relationship between sedimentation rate and inductance, thereby designing a magnetorheological fluid sedimentation measurement device based on permalloy inductors. Iglesias et al. [67] developed a fully automated vertical scanning device to measure inductance intensity changes in samples, generating time-evolution images of particle concentration to further verify the linear correlation between inductance and concentration. Xie et al. [60] developed a Vertical Axis Inductance Monitoring System (VAIMS) for evaluating the sedimentation stability of magnetorheological fluids with high-viscosity linear polysiloxane carrier fluid over 365 days. The system enables real-time monitoring of carrier fluid viscosity and particle concentration by recording inductance data of the scanned sample in a vertical liquid column as functions of height and time. Subsequently, Choi et al. [68] also used this Vertical Axis Inductance Monitoring System to accurately detect particle concentrations in different zones of magnetorheological fluid: clear liquid zone, original concentration gradient zone, variable concentration gradient zone, and sediment zone. Wen et al. [69] further optimized the technology by designing an Automated Vertical Axis Inductance Monitoring System (AVAIMS) with low-aspect-ratio sensor coils, tracking particle movement in the sample via vertical translation of inductance sensors to effectively improve the detection accuracy of magnetorheological fluid sedimentation stability. Meanwhile, the complementarily designed low-aspect-ratio solenoid (LARS) sensor precisely captures vertical distribution changes in carbonyl iron particle concentration. Roupec et al. [70] built a test bench using inductance-concentration characteristics, innovatively achieving dynamic monitoring of magnetorheological fluid concentration variations by combining the magnetically active region generated by magnetic circuit coils with Hall probes for magnetic flux density measurement. The inductance method enables real-time monitoring of sedimentation states in magnetorheological materials [71], distinguishing each sedimentation zone, and unlike capacitance testing, inductance measurements are less susceptible to interference from non-magnetic particles.

The sedimentation potentiometric method [61] evaluates sedimentation performance by utilizing the potential changes generated during the settling of solid particles in magnetorheological materials, the principle is shown in Figure 2. While this method enables automatic measurement of material sedimentation, it can only determine the overall sedimentation rate between the upper and lower electrodes, failing to measure local sedimentation rates. Roupec et al. [72] experimentally found that the sedimented portion of magnetorheological materials exhibits higher magnetic permeability than the non-sedimented region with fewer iron particles. Thus, magnetic permeability measurement can real-time monitor the sedimentation of magnetorheological materials, as illustrated in Figure 2. Characterizing sedimentation properties via magnetic permeability enables non-contact measurement, but introducing a strong magnetic field may interfere with natural sedimentation. Thermal conductivity, which correlates with particle concentration, can also characterize the sedimentation rate of magnetorheological materials. Cheng et al. [62] monitored particle concentration in magnetorheological fluid samples

by measuring thermal conductivity at fixed positions, thereby obtaining material sedimentation characteristics. The thermal conductivity method offers simplicity and flexibility, but it fails to acquire global sedimentation information during measurement.

Hoffman et al. [63] developed a laser light scattering device translatable along the z-axis, which accurately deduces the sedimentation state of particles in suspension by establishing a calibration curve to correlate particle concentration values with measured scattering data. The principle of the laser beam deflection method, as shown in Figure 2, measures the sedimentation stability of magnetorheological materials based on optical transmittance. This method offers high measurement accuracy, but high-concentration samples are prone to saturation, limiting its measurement range [74]. Similar to laser beam scattering, a turbidity meter is a device that measures scattered light passing through a sample fluid, with the detector positioned at a specific angle to the incident light direction, thus measuring the intensity of scattered light rather than light transmitted through the sample. For turbid samples, the amount of scattered light exceeds that of transmitted light, making turbidity meters more sensitive than spectrometers for measuring particle concentration [64]. The measurement principle of the turbidity meter is shown in Figure 3. The testing methods for sedimentation stability are shown in Table 2.

The sedimentation stability of magnetorheological materials varies significantly with their matrix morphologies, primarily determined by the synergistic effect of matrix viscosity, particle confinement, and density difference between particles and carriers. Magnetorheological fluids (MRFs) with liquid matrices face the most severe sedimentation challenges: the low viscosity of water or oil carriers cannot effectively counteract the gravity-induced settling of magnetic particles, leading to obvious stratification and compacted sedimentation in long-term static conditions [CE1]. Figure 4 is the results of visual observation of magnetorheological fluid, the final sedimentation ratio is about 67%, i.e. the mudline descent is about 54.2 mm after 8,662 h. In contrast, solid-like magnetorheological materials exhibit improved sedimentation resistance due to their viscoelastic matrix networks, which mechanically trap magnetic particles and reduce their mobility—nevertheless, the trade-off between matrix viscosity and response speed still limits their anti-sedimentation performance under dynamic shear. Solid-state magnetorheological materials achieve the optimal sedimentation stability: the porous skeleton of foams or the elastic polymer matrix of elastomers physically immobilizes magnetic particles, minimizing density-driven settling and agglomeration even in harsh environments such as high temperatures or cyclic mechanical loads. However, the sedimentation behavior of solid-state materials can be compromised by matrix deformation or interface debonding under long-term mechanical stress.

### 3.2 Redispersibility

During the mutual contact of solid particles, they are prone to attract each other and undergo agglomeration under the action of van der Waals forces and magnetostatic forces. Agglomeration increases particle size, making

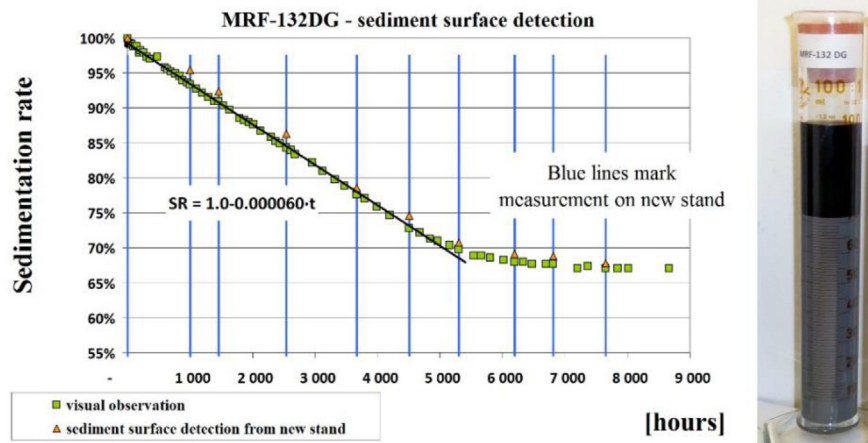


Fig. 4. Results of visual observation of magnetorheological fluid [65].

sedimentation more likely. Over time, the agglomerated and sedimented solid particles form compact clusters, which are difficult to redisperse uniformly in the matrix. This directly affects the mechanical properties of the material and, in turn, the normal operation of magnetorheological devices. Therefore, in addition to sedimentation stability, the redispersibility between particles is also a key indicator of the stability of magnetorheological materials [75]. The redispersibility of magnetorheological materials refers to the ability of the post-sedimentation concentration distribution to recover to the initial distribution after a certain mechanical dispersion. After solid particles sediment, traditional methods such as mechanical stirring and ultrasonic oscillation are used to redisperse the particles and carrier medium. In most application scenarios, the uniform dispersion of the material can be restored through the motion of the device itself, such as the shearing action of the brake disc in magnetorheological brakes and the reciprocating motion of the piston in magnetorheological dampers. The redispersibility coefficient [9] is commonly used to characterize redispersibility stability, defined as the ratio of the sedimentation rate of the redispersed sample to the initial sedimentation rate within a fixed time period.

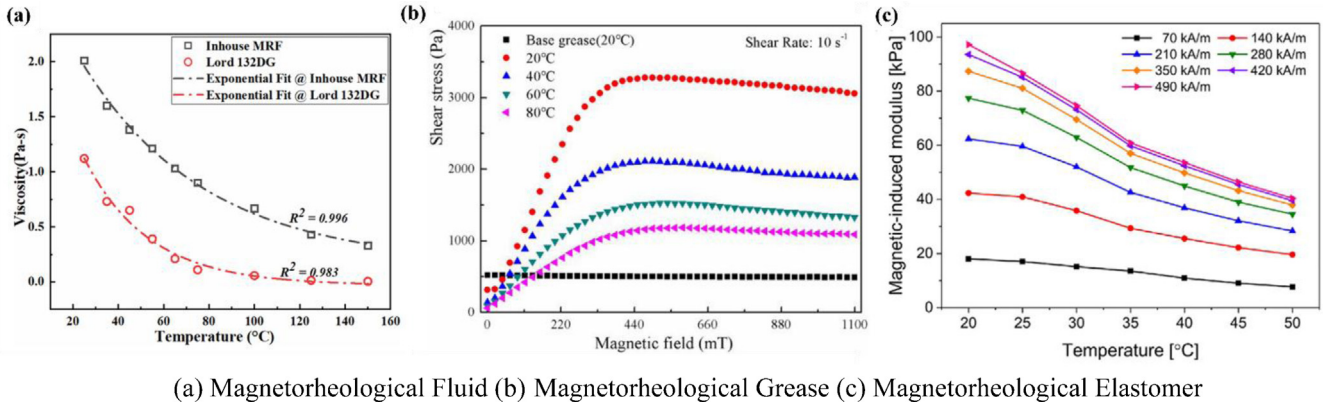
Current research on characterizing redispersibility stability mainly employs methods such as optical analysis [76] and electrochemical methods [3]. Bonn et al. [76] measured the shear yield stress of materials via stress scanning to characterize particle redispersibility. The magnitude of Zeta potential determines the repulsive force between particles, thereby influencing inter-particle agglomeration. Xu et al. [77] characterized redispersibility stability by measuring the Zeta potential and particle size distribution of solid particles in aqueous suspensions using a microelectrophoresis apparatus. They proposed that adding dispersants enhances electrostatic and steric hindrance stability, which collectively improve electrosteric stability. It was concluded that higher Zeta potential on particle surfaces leads to greater repulsive forces, resulting in better dispersibility in water. The QXP-type scraping method [78] can also rapidly evaluate particle size distribution or maximum particle size of samples, while qualitative characterization can be performed using the ASTM rating method for pigment sedimentation [79]. The QXP fineness

gauge is widely used due to its simple operation and low cost, but it should be noted that it reflects the particle size upper limit rather than the complete distribution. For on-line detection and evaluation of material redispersibility during sedimentation, dynamic light scattering (DLS) or electron microscopy (SEM/TEM) should be combined.

### 3.3 Thermal stability

In engineering applications, extreme high or low temperature environments often exist. During the operation of magnetorheological devices, heat generation occurs. As temperature rises, the movement of internal particles in magnetorheological materials intensifies, leading to weakened segment strength within the material under magnetic fields, causing “shear thinning” phenomena. The shear yield stress of the material decreases, and the magnetorheological effect is reduced to varying degrees [80]. High temperatures can also cause oxidation of magnetic particles. Meanwhile, at high temperatures, the supporting force of the matrix on magnetic particles weakens, which further reduces the sedimentation stability of magnetorheological materials [81].

Pan et al. [41] investigated the rheological characteristics of magnetorheological grease under different temperatures and magnetic field intensities, and conducted an in-depth study on the magnetic properties of carbonyl iron powder (magnetic particles) at various temperatures. They analyzed the relationship between the evolution of the magnetorheological grease structural system under thermomagnetic coupling and changes in its rheological properties. The structural system of magnetorheological grease under magnetic fields consists of carrier fluid soap fibers and magnetic chains. Soap fibers can enhance the structural strength of magnetorheological grease, while temperature affects the winding degree of soap fibers, thereby influencing material stability. Li et al. [82] performed static heat treatment on magnetorheological grease and found through experiments that after thermal exposure at 180 °C for 24 h, the shear stability of magnetorheological grease decreases. Although magnetic fields can mitigate this stability reduction to some extent, sustained thermal effects still pose significant challenges to the service performance of magnetorheological grease.



(a) Magnetorheological Fluid (b) Magnetorheological Grease (c) Magnetorheological Elastomer

**Fig. 5.** Temperature effects on the performance of magnetorheological materials [41,83,84].

On the other hand, at low temperatures, the viscosity of magnetorheological materials increases drastically, and stiffness significantly rises, leading to a substantial decrease in dynamic response speed [83]. This characteristic severely limits the application of magnetorheological materials in vibration reduction and buffering fields. Specifically, magnetorheological devices lose their original functionality under low temperatures. For example, magnetorheological shock absorbers exhibit stiffness characteristics due to the disappearance of damping properties at low temperatures. To address this issue, Liang et al. [85] proposed a novel temperature-dependent parameterized hyperbolic hysteresis model for magnetorheological shock absorbers. This model not only enables temperature compensation but also effectively improves current control accuracy. Qi et al. [86] designed a low-temperature operation performance testing system for magnetorheological retarder braking devices based on a low-temperature test chamber, testing the startup stability of the device at low temperatures. Experiments show that startup impacts in low-temperature environments significantly affect the service life of the device. Currently, research on the low-temperature failure mechanism of magnetorheological materials is relatively limited, and studies can be considered from two aspects: material composition optimization and external excitation heating.

The thermal stability temperature ranges of different magnetorheological materials are closely tied to their matrix compositions; Figure 5 presents the curve diagram illustrating the effect of temperature on the performance of the three types of magnetorheological materials. Water-based MRF exhibit stable rheological properties within 0~60 °C, above 60 °C, water evaporation causes viscosity spikes; below 0 °C, freezing destroys particle dispersion; oil-based MRF extend the range to -20~120 °C, but surfactant degradation above 120 °C leads to particle agglomeration [65]. The operating temperature range of solid-state-like and solid-state magnetorheological materials is wider than that of liquid-state magnetorheological materials, while an increase in temperature will lead to a decrease in their storage modulus and magnetorheological effect.

## 4 Methods for enhancing stability

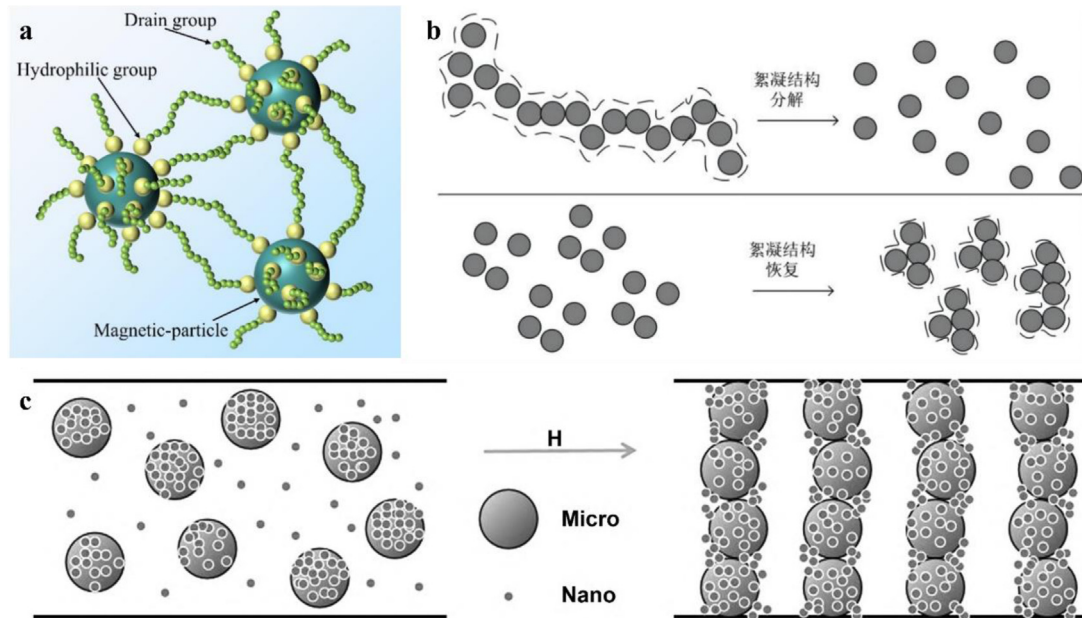
From a microscale system perspective, the primary factors causing particle agglomeration in magnetorheological materials are van der Waals forces and magnetostatic interactions, while Brownian motion, electrostatic repulsion, collision repulsive force, and steric hindrance effect are key factors hindering particle agglomeration. The size, shape, and content of magnetic particles, as well as the additives, can all affect the magnitude of inter-particle forces, thereby altering the material structure. Existing studies have shown that methods such as adding additives [87–98], modifying the surface of magnetic particles [99–106], and modifying the carrier medium for different types of magnetorheological materials [16] can optimize the inter-particle force distribution to a certain extent, effectively enhancing the stability of magnetorheological materials.

### 4.1 Addition of additives

Commonly used additives mainly include surfactants, thixotropic agents, and nanoparticles. The working principles of these three types of additives are illustrated in Figure 6.

#### (1) Surfactants

After ionic surfactants dissolve in water, their hydrophilic groups enable surfactant molecules adsorbed on particle surfaces to carry the same charge, thereby forming an electrical double layer structure on the particle surface. Adjacent particles generate electrostatic repulsion due to the same charge, effectively preventing particles from approaching and coalescing, thus maintaining a dispersed state [87]. Compared to water-based magnetorheological fluids, when the carrier fluid is oil, solid particles have higher surface potential energy, making particle dispersion significantly more difficult [15]. However, oil undergoes polymerization and degradation over time and also promotes bacterial growth, leading to performance deterioration of magnetorheological fluids. When water is used as



(a) Surfactants (b) Thixotropic agents (c) Nanoparticles

**Fig. 6.** Schematic diagram of adding additives [9,88,89].

the carrier, nonionic surfactants exist in a non-ionic state in the solution, exhibiting high stability and insensitivity to pH changes, thus having broader applicability [13].

Xiong et al. [88] experimentally found that the effect of surfactants on materials depends on their hydrophilic or hydrophobic properties: the smaller the hydrophilic-lipophilic balance (HLB) value, the stronger the sedimentation stability of magnetorheological fluids. Dorosti et al. [89] used cetyltrimethylammonium bromide as a dispersant and added potassium bromide to prepare magnetorheological fluids with high sedimentation stability. Their study showed that worm-like micelles formed in the carrier fluid significantly enhance the yield stress of the material. The hydrophilic segments of nonionic surfactants (e.g., polyoxyethylene) or polymeric surfactants (e.g., polyacrylamide) exist in an extended state in solution, forming a relatively thick adsorption layer. When particles approach each other, overlapping of the adsorption layers reduces the entropic repulsion of the segments, while solvation causes the adsorption layers to swell, generating steric hindrance repulsion. This dual mechanism prevents particle coalescence. Song et al. [90] coated surfactants on the surface of hydroxylated iron powder, which not only increased the powder volume but also effectively inhibited agglomeration caused by particle collisions by enhancing inter-particle repulsion. Surfactants form a three-dimensional interaction framework inside the material, which can minimize particle sedimentation caused by density differences between particles and the carrier fluid, providing multiple guarantees for material stability.

Commonly used surfactants in magnetorheological materials include organic fatty acids such as lauric acid, polyacrylic acid, stearic acid, and oleic acid. Studies have shown that the introduction of surfactants can significantly

increase the viscosity of magnetorheological materials and improve the anti-sedimentation effect of particles by enhancing steric hindrance or electrostatic repulsion between particles. However, such surfactants are prone to failure at high temperatures, leading to decreased stability and durability of magnetorheological materials, which limits their application under high-temperature working conditions.

## (2) Thixotropic agents

Thixotropic agents enable non-solid magnetorheological materials to form a network structure under static or low shear rate conditions. This network mechanically “traps” solid particles within its grids, effectively preventing both particle sedimentation due to gravity and aggregation caused by Brownian motion [91]. After adding thixotropic agents, the material exhibits high viscosity or gel-like properties. Under high shear forces, the network structure is disrupted and viscosity decreases rapidly; when shear forces are removed, the structure gradually recovers. Through this dynamically reversible physical cross-linking mechanism, thixotropic agents can inhibit particle sedimentation or aggregation in the system, thereby enhancing the stability of magnetorheological materials.

Zhang et al. [14] formed a stable organic coating layer on the surface of nano-fumed SiO<sub>2</sub> particles using xanthan gum, preparing a composite thixotropic agent. When added to magnetorheological suspensions, it forms a robust spatial thixotropic network structure, which limits direct contact between magnetic particles through physical barrier effects, effectively inhibiting particle agglomeration and sedimentation. James et al. [92] coated natural gums

**Table 2.** Testing methods for sedimentation stability.

Testing methods	Basic principle	Specificities
Visual Observation	Sedimentation Rate $V = \frac{h_2}{h_1} \times 100\%$	Fast and easy to operate, but the measurement accuracy is greatly affected by human judgment
Multiple Light Scattering Method	Parameters such as the migration rate of particles and the thickness of the sedimentation layer are calculated to obtain an index of the sedimentation rate	High precision, real-time monitoring and early prediction of material settlement behavior can be achieved
Capacitance Method	Particle settling induces changes in the dielectric properties of the system	Susceptible to interference from non-magnetic particles
Inductance Methods	Relationship between inductance and magnetic particle concentration characteristics	Distinguish between sedimentation zones, less susceptible to interference from non-magnetic particles
Sedimentation Potentiometric Methods	Comparison of the settling properties of solid-phase particles in magnetorheological materials using the potential change generated during their settling	Automatic measurement of material settlement is possible, but only the overall settlement rate between the upper and lower electrode plates can be measured, while the local settlement rate cannot be measured
Thermal Conductivity Method	Measurement of thermal conductivity at a fixed location to monitor particle concentration in a sample	Measurement is simple and flexible, but global settlement information is not captured during measurement
Magnetic Permeability Method	Measurement of the change in permeability of the deposited and undeposited portions to detect the concentration of magnetic particles	Enables non-contact measurements, but introduces strong magnetic fields that can interfere with true settling
Optical Detection Methods	Settling stability of magnetorheological materials can be measured based on the optical transmittance principle	High measurement accuracy, but high concentration samples are easily saturated and the range is limited

such as guar gum on the surface of magnetic particles and added grease and other thixotropic additives to the carrier fluid of the material. This composite strategy not only significantly improves the sedimentation issue of magnetorheological fluids but also inhibits microbial degradation of natural gums through the bacteriostatic effect of grease, simultaneously alleviating corrosion issues.

The network structure formed by thixotropic agents can slow down particle sedimentation by increasing the yield stress of the material, thereby enhancing stability. Roupec et al. [70] systematically studied the influence of clay-based additive concentration on the sedimentation stability of magnetorheological fluids, conducting sedimentation tests on magnetorheological fluids with different carrier fluids and particle sizes. They found that yield stress shows an upward trend under the action of clay-based additives. Di et al. [93] utilized the network structure formed by ionic bond interactions between bentonite and the carrier, successfully preparing a bidisperse magnetorheological grease with

excellent magnetic suspension stability and thixotropy for the first time. Experimental data showed that the addition of bentonite improved suspension stability by 17.873%, and this achievement has significant engineering application value for the precise control and stable operation of damping braking and transportation systems.

### (3) Nanoparticles

The preparation methods for adding surfactants and thixotropic agents are simple, and they significantly improve the sedimentation stability of materials at low shear rates, but have little impact on the magnetorheological properties of materials. Meanwhile, the addition of these two additives makes the sediment of magnetorheological materials denser, resulting in poor redispersion stability of magnetorheological materials. Nanoparticles (typically with a particle size of 1-100 nm) exhibit characteristics such as high specific surface area,

**Table 3.** Comparison of three commonly used additives.

Additive	Mechanism	Common types	Characteristics
Surfactant	Interfacial directional adsorption, reducing interfacial tension and providing electrostatic/spatial potential resistance. Concentrates at the interface and acts on the microscopic interfacial layer.	Sodium dodecyl sulfate (SDS, anionic type), cetyltrimethylammonium bromide (CTAB, cationic type), Tween (nonionic type), and phospholipids (amphoteric type)	Stabilization is achieved through chemical interfacial interaction (reduction of interfacial tension, charge modulation), with fast onset of action but poor resistance to extreme conditions.
Thixotropic agent	Forming dynamic networks through physical cross-linking, restricting particle movement via mechanical methods, establishing three-dimensional networks throughout the system, acting on the macroscopic scale.	Polymers (e.g., hydroxyethyl cellulose), nanoparticles (e.g., fumed silica), and layered inorganics (e.g., bentonite).	Relying on the dynamic reversibility of the macroscopic network structure, it is suitable for systems where the rheological behavior needs to be regulated (e.g., shear thinning), but the stabilizing effect on nanoscale particles is weak.
Nanoparticle	Interfacial adsorption, steric hindrance, electrostatic repulsion, network construction; mainly acts at the interface or uniformly disperses in the matrix to form a “cloud” structure.	Oxides (e.g., SiO <sub>2</sub> , TiO <sub>2</sub> , Fe <sub>3</sub> O <sub>4</sub> , etc.), carbon-based materials (graphene, carbon nanotubes, etc.), polymer nanoparticles (polystyrene, polymethyl methacrylate, etc.), and bio-based nanoparticles (cellulose nanocrystals, chitosan nanoparticles, etc.).	Stabilization is achieved through interfacial physical adsorption and nanoscale steric hindrance, which is especially suitable for harsh environments (e.g., high temperature, high salt) that are difficult to be handled by traditional surfactants, and the interfacial layer has higher mechanical strength. However, the preparation process is more complicated and costly.

quantum effects, and surface activity, and are often used as solid additives to enhance the stability of magnetorheological materials. Nanoparticles adsorb on the surface of solid particles, forming a physical barrier to prevent direct contact and agglomeration of particles due to Brownian motion [94], which can weaken the short-range attractive forces between large particles, thereby forming a soft sedimentation state.

In 2001, Tohver et al. [95] proposed a new mechanism for regulating the stability of suspension particles, where the addition of nanoparticles forms a “cloud” structure in the system. Adding magnetic nanoparticles to magnetorheological materials creates bidisperse composite magnetorheological materials [96]. Zhu et al. [97] synthesized iron nanoparticles using direct current arc discharge, doped them with traditional carbonyl iron powder, and prepared magnetorheological materials with different proportions. Under the combined action of free and adsorbed iron nanoparticles in the material, the sedimentation stability significantly improved with increasing nanoparticle ratio. Nanoscale particles

aggregate around larger particles to form a “cloud” structure, preventing surface attraction and contact between large particles, thereby enhancing sedimentation and redispersion stability [98]. Additionally, under magnetic fields, nanoparticles fill pores, facilitating the formation of more regular and stable magnetic chain structures. This further increases yield stress, achieving a balance between stability and rheological properties [9], and exhibits better performance in practical engineering applications such as polishing or vibration reduction. Compared to traditional additives, the interface layer formed by nanoparticles is more robust and resistant to harsh conditions such as high temperatures and high salinity.

Table 3 shows a comparison of the action mechanisms, common types, and typical characteristics of three commonly used additives. In practical applications, multiple additives can act synergistically according to actual conditions, leveraging the advantages of each additive to prepare complex systems with high stability, special rheological properties, and environmental tolerance.

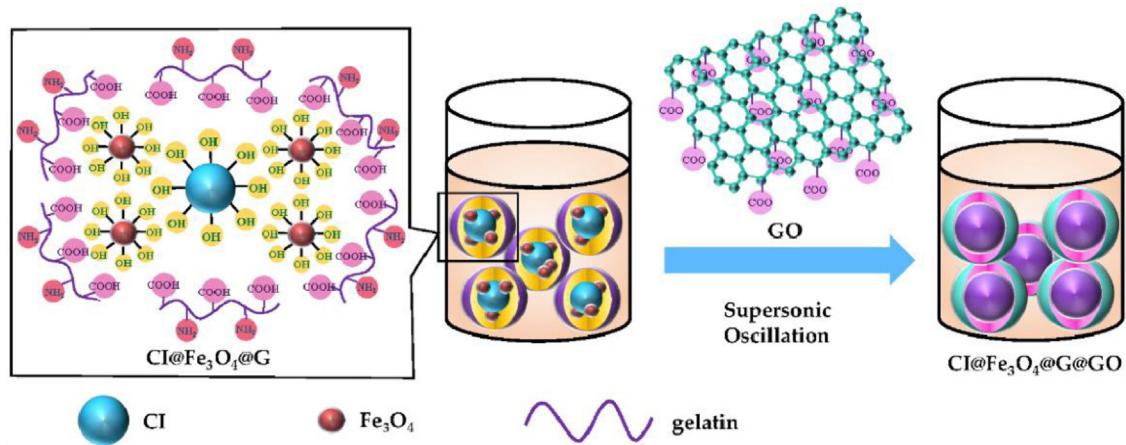


Fig. 7. Schematic diagram of the principle of surface modification of magnetic particles [99].

#### 4.2 Surface modification of magnetic particles

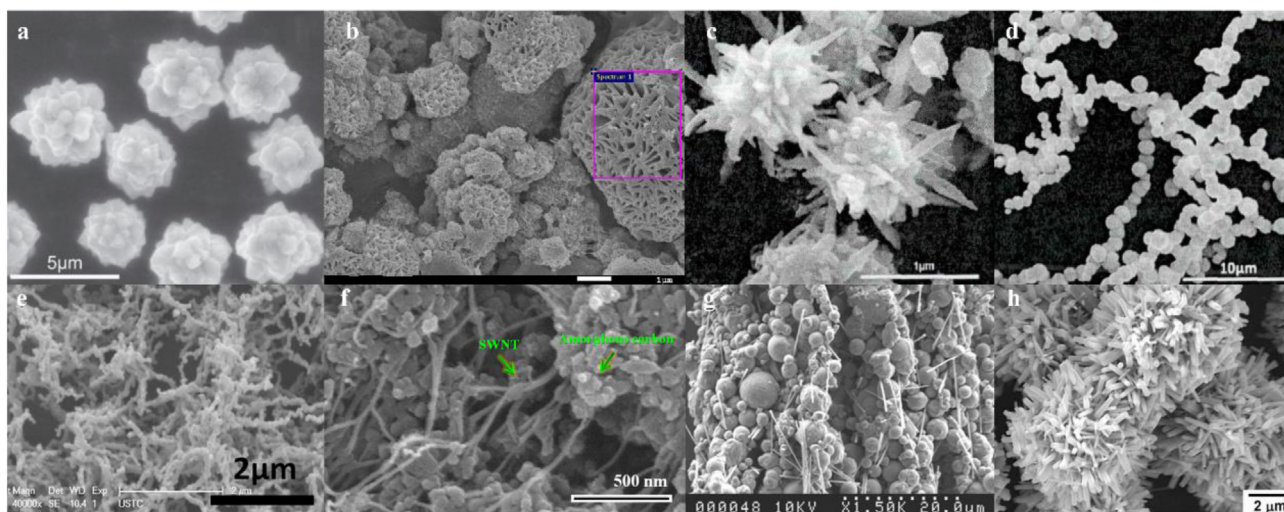
The primary cause of sedimentation and agglomeration in magnetorheological materials is the magnetic particles. Therefore, modifying the surface of magnetic particles to reduce their density, and balancing the interparticle interactions (magnetic attraction, van der Waals forces) with the steric hindrance or electrostatic repulsion of the modified layer, can achieve the goal of improving stability. Currently, researchers mainly adopt two methods: one is to change the size and morphology of magnetic particles to increase their contact area with the base carrier and alter the magnitude of interparticle interactions, thereby enhancing stability; the other is to coat low-density nanofibers on the surface of magnetic particles to form a core-shell composite structure of magnetic particles, which inhibits particle agglomeration. Figure 7 shows the common methods for improving stability through surface modification of magnetic particles.

Carbonyl iron particles, with high magnetic permeability and high saturation magnetization, are often used as magnetic particles in magnetorheological materials. Yu et al. [99] coated the surface of magnetic Fe<sub>3</sub>O<sub>4</sub> nanoparticles with a magnetic mixed coating composed of gelatin and graphene oxide. By depositing magnetic nanoparticles onto carbonyl iron particles coated with a traditional coating, they prepared a magnetorheological material with both magnetic responsiveness and dispersion stability. Gelatin, acting as a grafting agent, can reduce the aggregation and sedimentation of carbonyl iron particles and prevent the oxidation of Fe<sub>3</sub>O<sub>4</sub> nanoparticles. Meanwhile, researchers have also adopted bimetallic or alloy coating methods to improve the stability of materials. Du et al. [100] formed a micro-nano bidisperse system by mixing FeCo nanoparticles with high saturation magnetization with micron-sized carbonyl iron powder, and the experimental test showed that the 72 h sedimentation stability reached 87.3%. Craciunescu et al. [101] prepared Fe<sub>3</sub>O<sub>4</sub>/OA-FeCo/Al<sub>2</sub>O<sub>3</sub> nanocomposite magnetic clusters with high magnetization using an improved oil-in-water microemulsion method. The

magnetic clusters achieved dual stabilization of lipophilic and hydrophilic interfaces through surfactants oleic acid and sodium dodecyl sulfate, forming a core-shell structure. The surface-modified cobalt ferrite nanoparticles enhanced the overall magnetization, improved the magnetic response efficiency, and at the same time strengthened the stability of the material.

Fibrous and flaky non-magnetic particles exhibit better anti-sedimentation effects, such as carbon nanotubes and layered graphite. Rwei et al. [102] prepared a magnetorheological fluid by coating multi-walled carbon nanotubes around carbonyl iron powder using a mild ultrasonic method, which showed improved sedimentation stability. Additionally, the coating of multi-walled carbon nanotubes did not reduce the saturation magnetization of the material, nor did it weaken its rheological properties. Zhai et al. [12] fabricated a high-stability magnetorheological material with a Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub> core-shell structure, and designed a polishing device using this core-shell structured abrasive, which enhanced the polishing effect on sapphire.

Most common magnetic particles have a spherical morphology. However, studies have shown that the morphology of magnetic particles has a significant impact on the stability of magnetorheological materials. Bell et al. [103] prepared submicron iron fiber magnetic particles, and their application in magnetorheological fluids significantly improved the sedimentation stability of the system. Li Haitao et al. [104] constructed a magnetorheological fluid model based on rod-shaped particles and found that such magnetorheological fluids have both excellent magnetorheological properties and stability. Yang et al. [105] modified carbonyl iron powder particles through surface modification technology to prepare a new type of magnetorheological gel. Compared with the traditional magnetorheological gel with spherical carbonyl iron powder particles, its yield stress and sedimentation stability have been improved. In addition to iron particles, cobalt, as a magnetic material with high saturation magnetization, has a morphology that is more easily altered. Tong et al. [106] prepared magnetorheological fluids using flower-like and spherical cobalt particles as magnetic particles



(a) Flower-like Cobalt Particles (b) Core-shell Loose-structured Particles (c)(d) Needle-shaped Bimodal Magnetic Particles

(e)(f) Single-walled Carbon Nanotube-coated Particles (g) Nanowires Particles (h) Core-shell Urchin-like Particles

**Fig. 8.** SEM images of surface-modified magnetic particles [99,106–110].

respectively, and experimental verification showed that flower-like magnetic particles have higher zero-field viscosity, yield stress, storage modulus, and better sedimentation stability. Figure 8 shows the SEM images of magnetic particles with different morphologies.

### 4.3 Modification of the base carrier

In magnetorheological materials, the base carrier serves as the dispersion medium for magnetic particles. Its physico-chemical properties directly affect the dispersion state and anti-sedimentation ability of the particles. Meanwhile, compared with magnetic particles, the base carrier is more susceptible to temperature changes, so the properties of the base carrier play a key role in the stability of the material. Fluid-form magnetorheological materials, such as the most typical magnetorheological fluids, can be divided into water-based and oil-based categories. For water-based magnetorheological materials, hydrophilic polymers (e.g., polyvinyl alcohol, PVA; polyacrylamide, PAM) are introduced to adjust the viscosity of the base fluid, and hydrogen bond networks are formed through hydroxyl groups and amide groups with hydrophilic groups on the particle surface (e.g.,  $-\text{SiOH}$  in  $\text{SiO}_2$  coating layers). For oil-based magnetorheological fluid materials, polar additives (e.g., fatty acids, organic amines) can be added to enhance the polarity of the base fluid, forming hydrogen bonds or dipole interactions with the hydrophobic modified layer on the particle surface (e.g., oleic acid coating). To improve the material performance, Liu et al. [16] used magnetic liquid as the base carrier fluid, which enhanced the shear yield stress of the magnetorheological fluid.

To enhance the stability of magnetorheological materials, researchers have optimized the morphology of the base carrier. This evolution has progressed from fluid-form

magnetorheological fluids to magnetorheological greases, which exist between fluid and solid states, and further to solid-form magnetorheological elastomers. During this process, the base carrier material has upgraded from traditional water or oil systems to lipid-based and rubber-based elastomers. By embedding magnetic particles in solid materials, the technical challenge of easy sedimentation of magnetic particles in traditional fluid systems has been effectively addressed, resulting in a significant improvement in material stability. Magnetorheological materials with different matrix materials have varying ranges of engineering applications. Magnetorheological elastomers, due to their solid-state characteristics, exhibit unique advantages in the application of seals. It should be noted that this material must operate before reaching its yield stage; once the yield limit is exceeded, the chain-like ordered structure formed by magnetic particles in the material is easily destroyed, which impairs its performance.

## 5 Conclusion and perspectives

Magnetorheological materials are intelligent materials whose rheological behavior can be controlled under an external magnetic field. After years of exploration by researchers, ranging from the construction of basic theoretical models and optimization of preparation processes to the characterization of mechanical behavior, performance regulation of materials, and expansion of engineering applications, magnetorheological materials have achieved vigorous development in fields such as intelligent equipment, aerospace, automotive industry, precision manufacturing, and biomedicine. To achieve better engineering applications, more and more researchers are focusing on the performance optimization of materials. Among various performance indicators, stability is a

critical one for magnetorheological materials: it not only directly affects the reliable use of materials but also determines the application range and service life of related devices. At present, there are many methods to improve their sedimentation and redispersion stability.

Currently, there are multiple methods to improve the sedimentation and redispersion stability of these materials; however, during the optimization process, attention should also be paid to three key aspects: the long-term reliability of materials, the exploration of green and pollution-free process routes, and the realization of a dynamic balance between performance improvement and cost control.

### 5.1 Core unresolved problems in current research

- Lack of balanced stability-performance synergy: The stability of magnetorheological materials includes multi-dimensional indicators. How to accurately balance the synergistic relationship between sedimentation, redispersion, and temperature stability in the material preparation scheme, and balance stability and rheological properties, is a key issue in current research. Take thixotropic agents as an example: they form a structured network inside the material and coat solid particles simultaneously. At low shear rates, they can significantly increase the overall viscosity of the material, thereby improving its sedimentation stability. However, at high shear rates, the viscosity drops sharply, and for specific application scenarios (such as polishing, sealing, etc.), the shear stress of the material will decrease.
- Absence of standardized stability testing systems: There is no complete and comprehensive measurement system for testing the stability performance of magnetorheological materials; redispersion stability and temperature stability lack objective, universally recognized evaluation criteria, and standardized testing procedures unified assessment systems are urgently needed.
- Inadequate solution to temperature-induced sedimentation instability: The sedimentation stability of magnetorheological materials is highly sensitive to temperature fluctuations—temperature changes directly alter the viscosity of the base carrier, which in turn disrupts the dispersion state of magnetic particles and degrades the material's rheological properties. However, current research has not yet developed a targeted regulation strategy that can dynamically adapt to temperature variations to maintain stable sedimentation performance, leading to limited applicability of materials in extreme temperature environments.

### 5.2 Future research directions and application prospects

- Scenario-oriented stability optimization: Future stability improvement schemes should further integrate device working conditions (e.g., temperature range, shear rate) and application scenarios (e.g., polishing, sealing, damping), and rationally select additives (e.g., thixotropic agents, surface modifiers) or modification methods to avoid performance trade-offs.

- Establishment of standardized stability evaluation systems: Prioritize developing complete measurement systems for stability performance, and define objective, universally accepted evaluation criteria for redispersion stability and temperature stability to promote unified research benchmarks in the field.
- Intelligent design for stability regulation: With the trend of material intellectualization, introduce intelligent responsive additives (such as temperature-sensitive or magneto sensitive polymers, stimuli-responsive nanoparticles) to endow magnetorheological materials with dynamic stability response capabilities—this will open up new application paths in extreme environments like high/low temperature and complex load scenarios.

### Funding

This research was funded by the National Natural Science Foundation of China [52472464].

### Conflicts of interest

The authors have nothing to disclose.

### Data availability statement

This article has no associated data generated.

### Author contribution statement

Conceptualization, Yongbao Feng and Xiaoxia Han; Investigation, Zhen Huang and Liang Li.; Writing – Original Draft Preparation, Yuanyuan Sang and Yongbao Feng; Writing – Review & Editing, Yuanyuan Sang and Yongbao Feng; Visualization, Xinfeng Wang.

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