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Advance effect of magnetic field on the rheological properties of manganese zinc ferrite ferrofluid

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Abstract

The rheological characteristics of manganese zinc (Mn-Zn) ferrite magnetic nanofluid synthesized using co-precipitation technique were examined in the absence and presence of magnetic fields. The research formulates required conditions needed for the formation of a gelly-like structure. The impact of magnetic field and temperature on the rheological properties of Mn-Zn ferrite ferrofluid is investigated. When a magnetic field was applied, higher magnetoviscoelasticity and magnetoviscosity were formed. Other rheological parameters such as damping factor which is crucial for regulating and restricting vibrations in a system was also analyzed. A stiff, gel-like structure is produced when a magnetic field is applied, and the gel-like quality grows as the magnetic field increases; when the magnetic field is removed, the gel-like and rigidity of the structure is lost. At low temperatures, the liquid phase is dominated by solid-like particles, whereas at high temperatures, the liquid-like structure is dominant. This study reveals the conditions required for the creation of high viscous effect and the viscoelastic behavior induced by the field offers important insights for optimizing the Mn-Zn ferrite ferrofluid for a range of applications. Other criterial for gel-like structure formation such as low torque and deflection angle of the ferrofluid were also established.

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1. Introduction

The remarkable magnetic field responsiveness of ferrofluids, which are made up of nanoscale ferrous particles suspended in a carrier fluid, allows for precise control and manipulation in a wide range of technological applications, including damping systems and medical devices [1, 2]. Damping application of the Mn-Zn ferrite ferrofluid is reported in this study. According to recent research, Mn-Zn ferrite ferrofluid is useful for efficient heat control systems and effective damping applications because of its appropriate particle stability in the carrier medium [3]. Mn-Zn ferrite ferrofluid is underdamped, this occurred because elastic particles are dominated by the system, and the effect is ascribed to a small amount of energy being dissipated by the system [3]. Micron-sized magnetic particles found in magneto rheological fluids undergo quick viscosity changes in response to a magnetic field, providing flexible and

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reversible damping solutions for use in automotive and engineering systems [4, 5]. The magnetic nanofluid is produced as either ferrofluid or magneto rheological fluid (MR fluid), depending on the size of the magnetic fluid particles. Ferrofluid displays particle size at the nanoscale, whereas MR fluid displays particle size in the micrometer range. MR fluid, as opposed to ferrofluid, is made up of magnetic particles with a permanent dipole moment. Brownian motion and the field-induced magnetic moment of micrometer-sized particles are thought to be negligible. However, Brownian motion is not regarded as insignificant for a ferrofluid, where the magnetic particles experience thermal motion. To form a rigid structure by ferrofluid, a strong thermal motion is required to bring the particles together in order to overcome the Brownian motion effect on the nanometer scaled particles.

When a magnetic field is applied and properly diffused in a liquid medium, the magnetic fluid's particles are drawn toward the magnetic poles. It is constructed from ferromagnetic nanoparticles that have been properly dispersed in a non- magnetic liquid. Ferrofluid is thought to be a manufactured fluid that contains extremely small, nanoscale ferromagnetic particles [6]. A base medium is used to create magnetic nanofluid, which is referred to as a smart fluid material since it responds to the application of magnetic fields [6]. Mn-Zn ferrite ferrofluid's rheological characteristics are influenced by a number of factors, including temperature, shear rate, magnetic field, and others [7]. The magnetic nanoparticles coalesce and form microstructural aggregates when a magnetic field is applied to ferrofluid. The particles are connected by chains to form a chain-like microstructure in the magnetic field's direction [8]. When the magnetic field is removed, the particle aggregate and the chain-like microstructures are destroyed. The particle aggregate is partially destroyed when the magnetic field is partially removed because the magnetostatic forces holding the particles to the parent aggregates are weakening. Due to this behavior, a semi-rigid microstructure is formed, with the stiff- ness depending on the size of the aggregate and the strength of the external magnetic field used to apply it.

The rigidity is broken and the Mn-Zn ferrite fluid becomes softer when the magnetic field is removed because each particle experiences a magnetic moment, which is randomly distributed throughout the fluid medium. The magnetic links that consolidate the particles into aggregates were removed, which is what caused this to happen [8]. This is the result of higher hydrodynamic forces developing and the magnetostatic force diminishing. But if the chains are left in place, the microstructure aggregate strengthens and, in the presence of increased magnetostatic stresses, this causes the creation of an elastic dominating structure. This suggests that the magnetic domain contains robust dipole-dipole interactions. The creation of the microstructure aggregate is fundamentally caused by the dipole-dipole interactions of the MR fluid nanoparticles [9, 10]. The strength of the microstructure aggregate depends on the strength of the dipole-dipole connection. According to literature, magnetic particle interactions are related to dipolar interactions of the magnetic particles. These interactions enable the particles to group up and affix themselves, forming a top-to-bottom structure.

The size of the Mn-Zn ferrite ferrofluid thickness affects the physico-mechanical characteristics of magnetic fluid, including its elasticity, stiffness, and softness. Viscosity can be effectively controlled by using specific shear rates and magnetic fields [11]. The generation of elastic fluid is caused by the particle aggregates' significant resistance to fluid flow. Because the applied shear rate cannot overcome the magnetostatic force that bonded the particles to the parent aggregates, viscosity of Mn-Zn ferrite ferrofluid is always high at low shear rates. As a result, the fluid becomes rigid from the strong resistance to fluid movement [12]. Because the applied shear rate is somewhat resistible over the magnetostatic force and partially separates a portion of the particles from the parent aggregates, the viscosity decreases as the shear rate rises, making the fluid more semi-rigid. High shear rates cause the shear force to be stronger than the magnetostatic force, which causes the aggregates to disintegrate into smaller particle units and soften the fluid [13]. Similar results were reported by Ibiyemi *et al*. [11], Mishra *et al*. [12], Chand *et al*. [13] and Hosseini *et al*. [14].

Viscosity, one of the magnetorheological qualities, is influenced by a number of variables, including morphology, surfactant, dilution, temperature, particle size, and carrier fluid. The nanofluid can be used in a variety of device applications, including actuators, bearings, thermal medium, motors, and sensors, by carefully controlling these properties. It is helpful in medicine as a medication delivery agent and a therapy for hyperthermia [15, 16]. It has been reported that a number of crucial factors, including fluid medium stability, magnetization, and other magnetic parameters like coercivity, might affect the rheological characteristics of magnetic nanofluid. Based on the effects of superparamagnetic particles and the volume of superparamagnetic particles on the fluid rheology, experimental study findings have been made. The creation of enhanced chain-like structure in a superparamagnetic medium is strongly influenced by the particle volume [17]. Jahan *et al*. [15], explored the effect of dilution on the interaction of magnetic dipoles and reported that when a magnetic field is applied, greater magnetoviscoelastic behavior develops. According to reports, the magneto viscous effect of the nanofluid is improved by the interaction of the magnetic dipoles [17]. Paul *et al*. [18] reported on the influence of ferrite particle concentration dispersed in aqueous medium.

According to research, magnetic nanofluid particles exhibit significant thermal energy at elevated temperatures, and the particle aggregate is unable to resist this high thermal energy. Because the forces holding the particles to the aggregates diminish when high temperatures are applied across them, the particles now separate from the parent aggregate. The fluid then becomes semi-rigid due to the production of low magnetoviscosity, which causes the aggregate to be destroyed. The magnetic nanofluid's particles exhibit low thermal energy when low temperatures are applied, and the aggregate of particles is able to withstand the effects of low thermal energy. Therefore, the forces holding the particles to the aggregates cannot be dissolved when low heat is applied across the aggregates; as a result, the particles do not separate from their parent aggregates. Due to its ability to withstand the effects of low thermal energy, the aggregate does not disintegrate. However, the fluid becomes rigid as a result of the establishment of a high magnetoviscosity. The cohesiveness between the interacting particles weakens as a result of rising temperature, as evidenced by literature, which shows that viscosity decreases with increasing temperature [19]. As the temperature rises, the fluid's average kinetic energy increases, forcing the attractive binding energy to be annihilated [20]. This causes the particles to become mobile since it separates them from the parent aggregates. As the temperature rises, the chains holding the particles together fall apart, increasing the particle mobility and decreasing the magnetoviscosity.

A ferrofluid sample was created in this research project by dispersing the manganese zinc ferrite magnetic nanoparticles that were manufactured in a liquid. At temperatures of 25, 40, and 50 °C, respectively, the rheological properties of shear viscosity, complex viscosity, shear stress, loss modulus, storage modulus, relaxation modulus, transmitting torque, damping factor, and deflection angle were examined in the presence and absence of magnetic fields. Utilizing the X-ray diffraction (XRD) technique, Energy Dispersive Spectroscopy (EDX), Transmission Electron Microscopy (TEM), and High Resolution Transmission Electron Microscopy (HRTEM), the structure, elemental composition, and surface morphology of the magnetic nanoparticles were identified prior to the synthesis of the ferrofluid sample. We believe that several of the rheological characteristics of the Mn-Zn ferrite ferrofluid were just recently described.

2. Methodology

The three aqueous solutions required for the production of manganese zinc ferrite magnetic nanoparticles are manganese (II) chloride tetrahydrate ($MnCl_2.4H_2O$), zinc (II) chloride hexahydrate ($ZnCl_2.6H_2O$), and iron (III) chloride ($FeCl_3$). Prior to the creation of the Mn-Zn ferrite sample, the reagent beakers were thoroughly cleaned with distilled water, isopropyl ethanol, and later rinsed with acetone. The beakers were properly cleaned inside and out to remove any contaminants. The required quantity of the aqueous solutions was weighed using a computerized weighing scale. We start the synthesis by using a magnetic stirrer to heat the aqueous solutions of $ZnCl_2.6H_2O$, $MnCl_2.4H_2O$, and $FeCl_3$ for 30 minutes at 60 °C. Magnetic stirring of the solution produces homogeneous solutions. Then, in a single reagent beaker, the solutions of $ZnCl_2.6H_2O$, $MnCl_2.4H_2O$, and $FeCl_3$ were combined. Once the solution has been blended, the reagent beaker is placed on the heater and is continuously stirred. Up till the pH level of 11, drops of ammonia solution are applied to the precipitate. Oleic acid, a surfactant that helps prevent particle agglomeration, was added to the solution. The precipitate is cleansed with distilled water after being decanted. To clean the precipitates and remove any impurities, acetone was utilized. To make a ferrofluid made of $MnZnFe_2O_4$, the formed wet slurry was combined with kerosene, centrifuged at 12,000 rpm to separate the bigger size particles from the medium. Rheological parameters were assessed using a rheometer at temperatures of 25, 40, and 50 °C after the nanofluid had formed. The Rigaku powder X-ray diffractometer was used to obtain X-ray diffraction patterns. The particle morphology, microstructure, shape, and lattice information were obtained using the Transmission Electron Microscopy (TEM) and High-resolution Transmission Electron Microscopy (HRTEM). Using an MCR-301 rheometer, the sample's viscoelastic characteristics were examined.

3. Result and Discussion

3.1. Structural and Morphological Analysis of Mn-Zn ferrite Nanoparticles

Figure 2a's XRD diffraction patterns demonstrate the creation of numerous peaks without a phase transition. The peak positions for the diffraction patterns at 2θ = 30.654°, 34.869°, 43.684°, 51.498°, 57.242°, and 62.719°, respectively, correspond to the diffraction planes (220), (311), (400), (422), (511), and (440). All of the relative diffraction peaks that could be linked to ferrite spinel crystallites are visible in the Mn-Zn ferrite sample. Face-center cubic crystal (FCC) framework and single phase spinel development are visible in the crystallites. Contrary to $NiFe_2O_4$, which exhibits additional reflections, the diffraction pattern does not show the production of new reflection planes, negating the formation of additional phases [21]. The cubic spinel structure of manganese zinc ferrite is represented by the diffraction peaks (ASTM card no. 22-1086). According to the XRD pattern, many peaks were generated, which indicates the emergence of polycrystalline microstructure. Ibiyemi *et al.* [11], Mishra *et al.* [12] and Chand *et al.* [13] all observed similar results. The suggested orientation of the sample is given along the reflection plane of (311). Derby Scherer's equation was used to examine the average crystallite size.

Figure 2b displays a SEM image of nanomagnetic Mn-Zn ferrite particles. The surface structure is made up of grains of various sizes that are closely packed together. The SEM morphology reveals the development of spherical nanomagnetic particles. We see that the grain sizes are not randomly distributed and that the smaller particles are aggregated to generate bigger grain sizes. The SEM picture showed an uneven surface morphology and no signs of surface fracture. Similar technique was used by Abba *et al.* [22], and Omatola *et al.* [23], to examine the surface morphology of material. The Mn-Zn ferrite sample was ultrasonically processed prior to the TEM investigation. To separate any aggregated or coalesced particles in the sample, it was sonicated. The sample's particle structure and distribution were revealed by the TEM investigation. The particles are evenly dispersed and there is no particle aggregation. Because the particles of the synthesized Mn-Zn ferrite particles were stirred at ultrasonication frequency before SEM analysis was done agglomerations of particles exhibited by SEM samples are not disclosed by TEM samples. By submitting the sample to ultrasonication at a specific frequency of 100 Hz, agglomerated particles disintegrate into simple particles. The smaller particles are better able to disseminate in the liquid medium due to the breakdown of the larger particles into

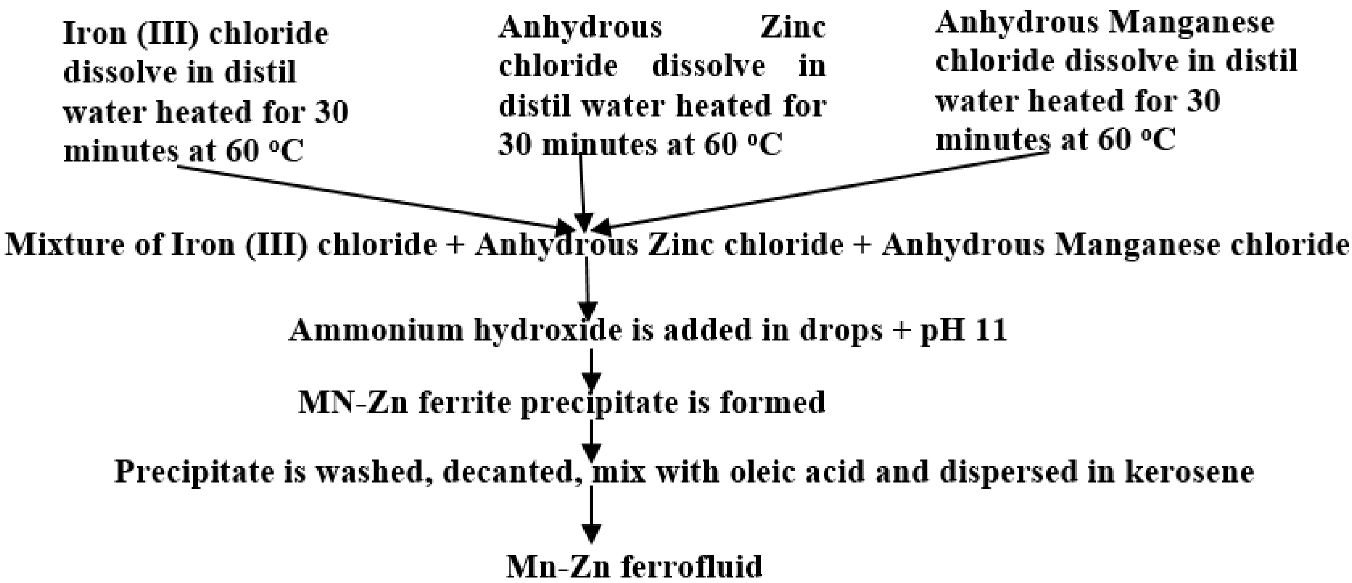

Figure 1. Schematic diagram of experimental procedure of manganese zinc ferrite ferrofluid.

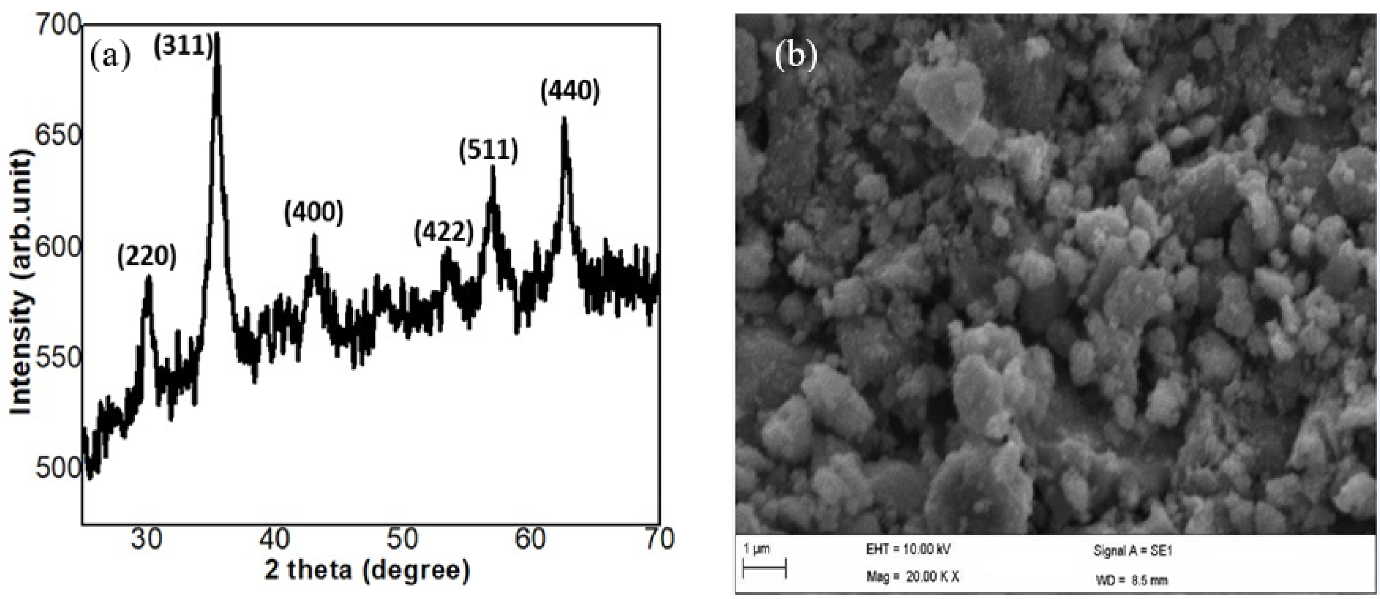

Figure 2. X-ray diffraction (XRD) and (b) Scanning Electron Microscope (SEM) image of Mn- Zn ferrite magnetic nanoparticles.

smaller ones. According to the TEM image seen in Figure 3a, the particles are equally disseminated throughout the liquid media. Due to the creation of a steady magnetic fluid, ultrasonication also helps control the rate at which particles settle in the medium and prevents them from sedimenting. Basic particle clusters with a diameter of 12 to 16 nm make up the magnetic fluid. The (311) reflection plane is represented by some aggregated stacked layers with an interlayer distance of 0.87 nm in the HRTEM as shown in Figure 3b. Lattice d-spacing is expected to be 0.22 nm. The lattice fringe is shown inset in Figure 3a. The atomic structure and lattice spacing were revealed by lattice fringes. According to the HRTEM image, it also aids in the examination of grain boundaries.

3.2. Shear Viscosity of Manganese Zinc Ferrite Ferrofluid

The Mn-Zn ferrofluid's fundamental capabilities in dynamic and static rheological systems are evaluated, along with its transient response. The results demonstrate that the magnetoviscosity of Mn-Zn ferrofluid depends on both temperature and magnetic field. Experimental evidence for a decrease in magnetoviscosity of Mn-Zn ferrite ferrofluid with increased shear rate is presented in Figure 4. Figure 4 clearly illustrates how the magnetic field, temperature, and shear rate affect magnetoviscosity. Because the low shear effect of Mn-Zn ferrite ferrofluid cannot withstand the magnetostatic force, higher magnetoviscosity is produced by applying a high magnetic field at a low shear rate. As a result, stiff structures start to emerge in the

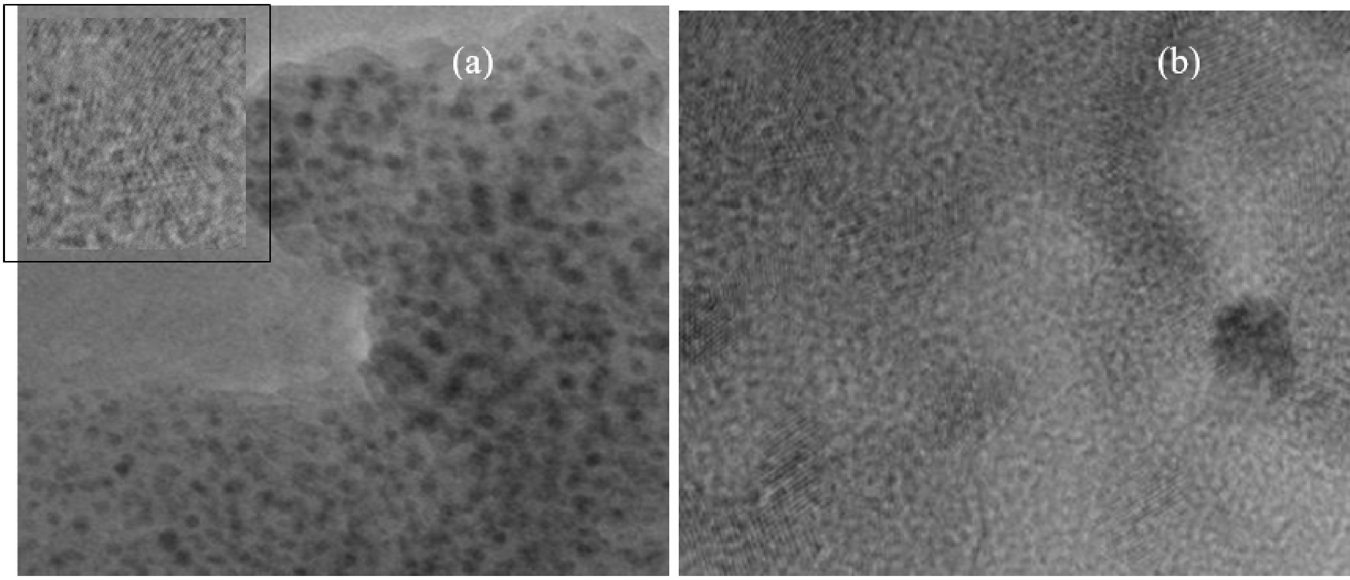

Figure 3. Transmission Electron Microsccope (TEM) image and (b) High Resolution Transmission Electron Miroscope (HRTEM) image of Mn-Zn ferrite magnetic nanoparticles.

liquid phase. In rheological medium, magnetic field and shear rate competes. The competition between the magnetic field and the shear rate affects the production of stiff structures in the liquid phase [24].

The force known as magnetostatic force is responsible for aggregating and holding together small particles. Enhanced magnetoviscosity typically forms in the presence of large particle aggregates and strong magnetostatic forces. Particles could not be separated from aggregates at low shear rates between 1 and 5 s^{-1} because the low shear is not resistible over the magnetostatic force of Mn-Zn ferrite particles. The magnetostatic force somewhat weakens as the shear rate rises between 10 and 20 s^{-1} because it is unable to fully withstand its effects. As a result, the particle aggregate is partially destroyed. Certain fractions of the Mn-Zn ferrite particles separate or dissociate from the particle aggregates when the aggregate is partially destroyed. This explains why the magnetoviscosity of Mn-Zn ferrite ferrofluid decreases as the shear rate rises. The magnetoviscosity of the synthetic Mn-Zn ferrite ferrofluid is completely lowered at shear rates above 20 s^{-1}, owing to large destruction of the magnetic aggregates. This occurs because the magnetostatic force is insurmountable at such high shear rates.

High viscous effect forms in the presence of a magnetic field at low shear rates because the Mn- Zn ferrite ferrofluid particles are properly aligned along the magnetic field direction, as shown in Figure 4d. This is because the particles' orientation is not reversed from the direction of the applied magnetic field. As seen in Figure 4e, the particles become misaligned as the shear rate increases. The high shear supports the particles from orienting themselves in the direction of shear, which destroys the particle aggregates and reduces the viscous effect [25]. Chain-like aggregates and the magneto viscous effect are destroyed when the fluid particle alignment is off at high shear rates. At low shear rates, the fluid showed shear thinning Newtonian fluid, however at high shear rates, a non-Newtonian fluid is produced.

Mn-Zn ferrite ferrofluid becomes softer as a result of the loss of the elastic microstructure and the establishment of the low viscous effect when there is no magnetic field because the magnetization of the nanoparticle relaxes and the solid-like structure is destroyed [26]. This happened as a result of the particle's magnetostatic interaction being forced into a constrained relaxation cycle. The fluid phase forms a localized dominating induced elastic structure when a magnetic field is present because the magnetic field aligns the fluid particles and arranges them in a chain-like pattern. As can be seen in Figure 3, the results demonstrate that the magnetoviscosity of Mn-Zn ferrite ferrofluid increases with increasing magnetic field. As the shear rate is raised, a quick decrease in magnetoviscosity is created; this is consistent with studies by researchers Mishra *et al*. [12] and Chand *et al*. [13]. When we compared the greatest magnetoviscosity we obtained 50 pa.s to other values that have been published, we saw that the results of the current experiment had produced greater magnetoviscosity. The maximum values of 2 pa.s, 1.2 pa.s, 9.5 pa.s, and 20 pa.s that were published by Linke *et al*. [25], Jahan *et al*. [17], Hosseini *et al*. [14], and Borin *et al*. [26] are significantly lower than the value that we reported.

According to published research, interaction parameters can be used to assess a particle's propensity to form a certain magnetic structure when a magnetic field is applied [27]. The ratio of the energy of the dipole interaction of two particles in contact with one other to their thermal energy determines the interaction parameter. It is calculated using:

$$\lambda = \frac{\mu_0 M_0^2 V_0}{4\pi l^3 k_B T}, \tag{1}$$

where M_0 is the spontaneous magnetization of the magnetic

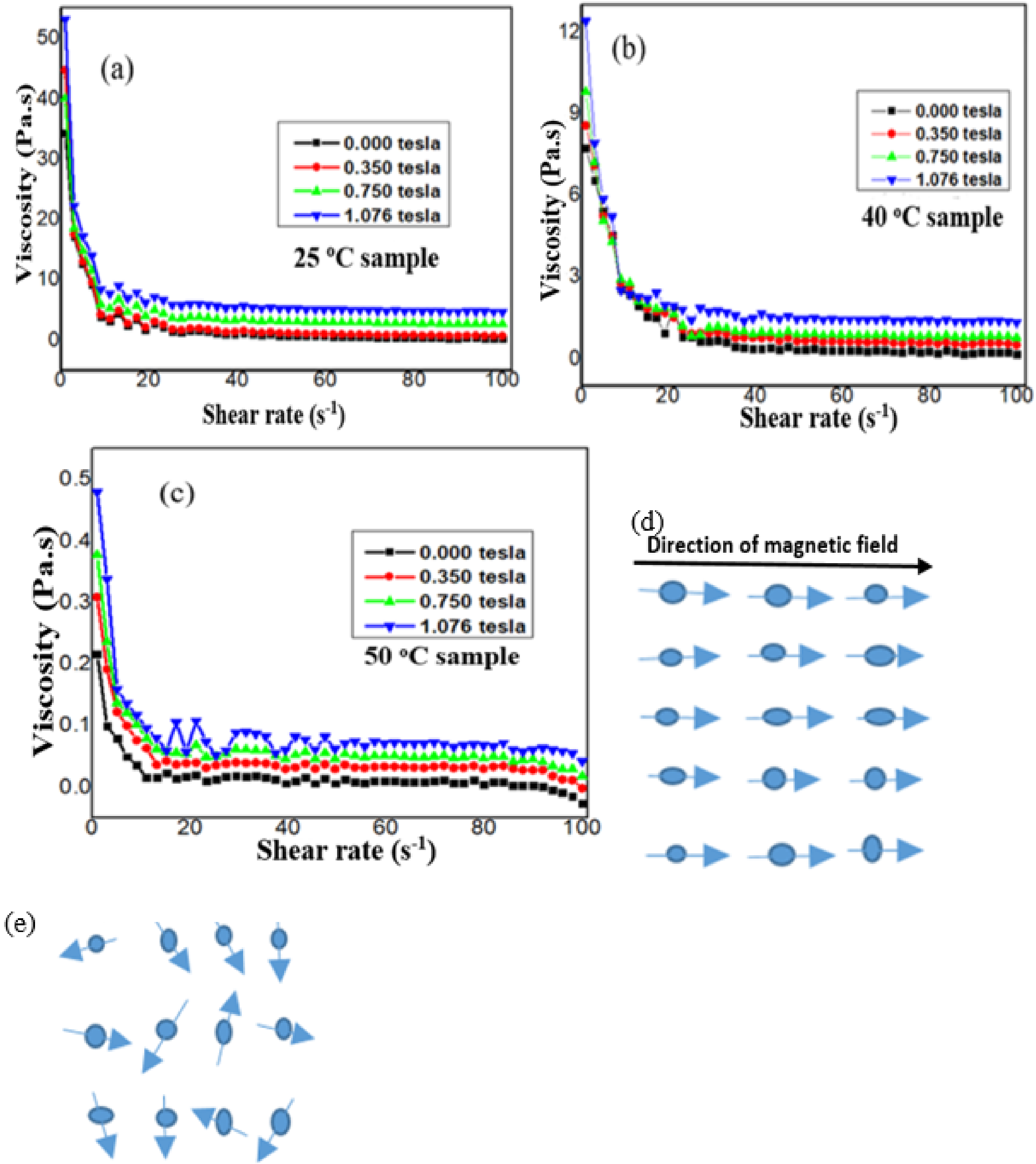

Figure 4. Shear viscosity of manganese zinc ferrite ferrofluid at temperature (a) 25 ^oC, (b) 40 ^oC and (c) 50 ^oC (d) particle orientation at low shear rate.

particle, $_0$ is the vacuum permeability, T is the absolute temperature, V is the volume of the nanoparticle, $k_B$is the Boltzmann constant, and l is the length distance of two particles. For spheroid particles, the length l is the diameter of the par-

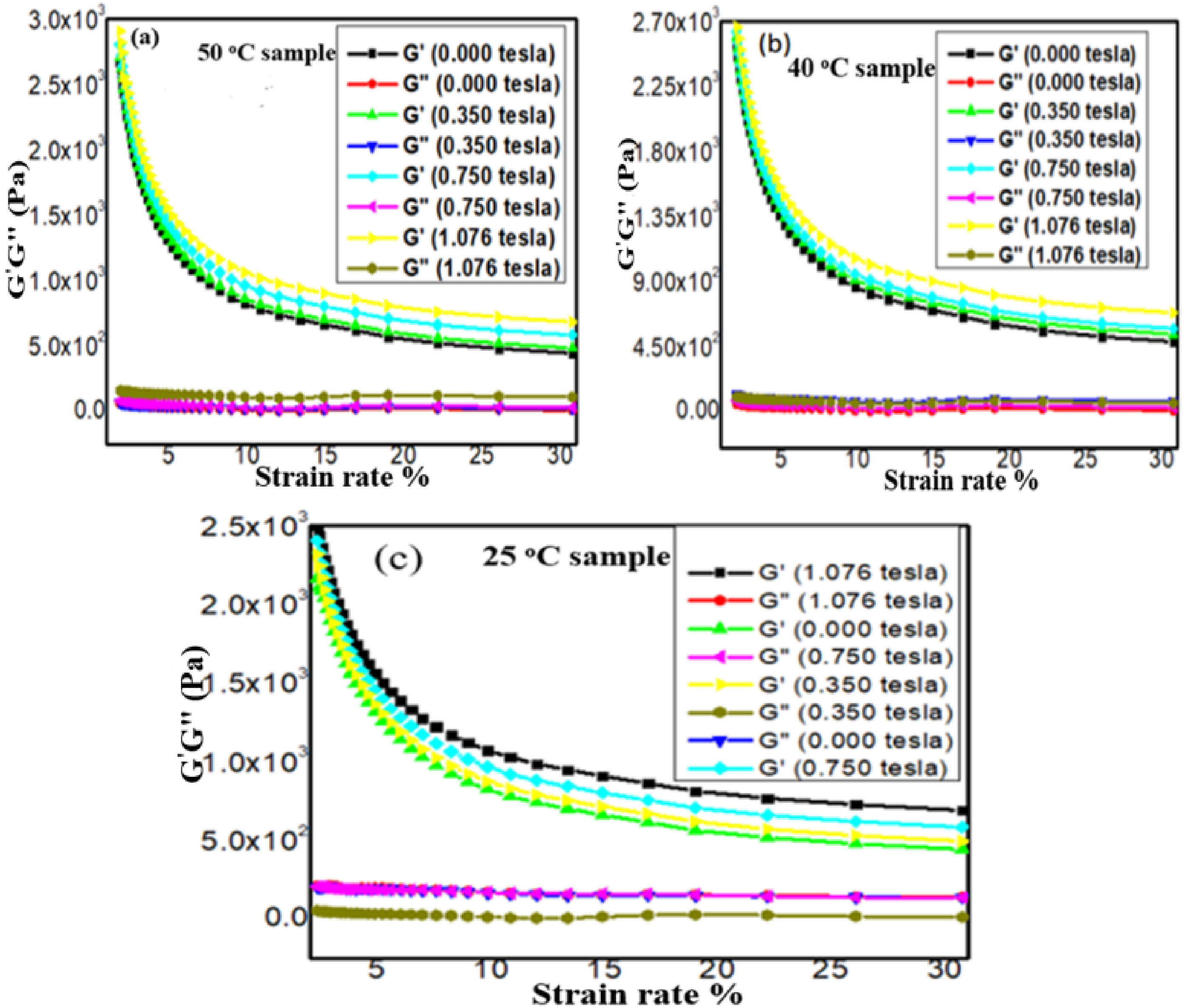

Figure 5. Storage modulus and loss modulus of manganese zinc ferrite ferrofluid at temperature (a) 50 ^oC, (b) 40 ^oC and (c) 25 ^oC.

ticles. To form magnetic structures via the application of magnetic field, the strength of the dipole interaction must be greater than or not less than the thermal energy, so that the interaction parameter $\lambda 1$. For spherical nanoparticles, the interaction parameter is modified as:

$$\lambda^* = \lambda \left(\frac{d}{d + 2s} \right)^3, \tag{2}$$

where s represent the thickness of the coated material and d is the diameter of the particles [27]. For the fluid under study, the interaction parameter 'λ' of the fluid is greater than one only in the presence of magnetic field and is increased with increasing magnetic field and decreased with temperature. It was assumed that magnetoviscous effect of manganese zinc ferrite fluid exhibit field induced structured. The high magnetoviscous effect of the Mn-Zn fluid is evidently due to high dipole interaction. The shape of the fluid nanoparticles does not actually play an important role toward the modification of the fluid magnetoviscosity [28]. It is shown that the application of a magnetic field causes a high viscous effect, which increases with the strength of the applied magnetic field. However, the viscous effect decreases with the removal of the applied magnetic field as shown in Figure 4 (a-c).

3.3. Storage Modulus (G') and Loss Modulus (G") of Manganese Zinc Ferrite Ferrofluid

To investigate the magnetoviscoelastic behavior of Mn-Zn ferrite ferrofluid, we employed oscillatory sweep test. As shown in Figure 5 (a-c), different viscoelastic responses are created at various applications of magnetic field and temperature. The results of the study demonstrate that the design of the desired viscoelastic system depends on the size of the system's

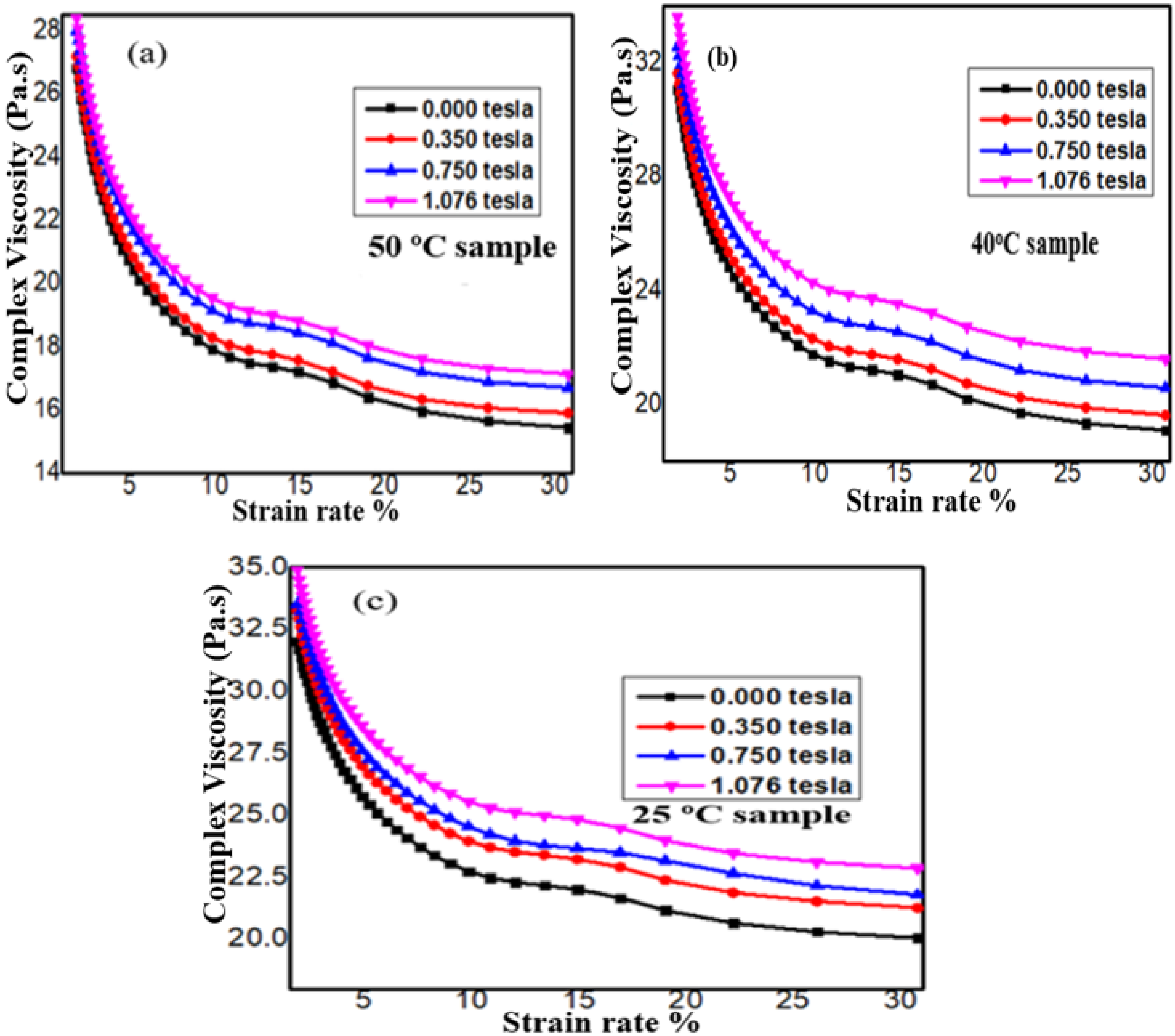

Figure 6. Complex viscosity of manganese zinc ferrofluid at temperature (a) 50 ^oC, (b) 40 ^oC and (c) 25 ^oC.

storage modulus (G') and loss modulus. According to the current experimental results, the production of high storage modulus and low loss modulus indicates the formation of high energy storage capacity with big solid-like structure in the liquid phase. At low strain rates, the loss modulus of Mn-Zn ferrite ferrofluid is drastically lower than the storage modulus, which suggests the production of low viscous systems with minimal energy dissipation. At low strain region, there is less liquid-like structure in the liquid phase than there is solid-like structure, this is demonstrated by the production of low viscous effects. Magnetic nanoparticles coalesce and produce field-induced microstructure when a magnetic field is applied to fluid particles [29]. The strength of the applied magnetic field affects how strong the coalesce structure is. Results reveal that both in the absence and presence of a magnetic field, G' is higher than G"; this finding denotes the production of a massive elastic microstructure. A rise in G' with increasing magnetic field suggests the emergence of improved elastic microstructure with significant energy storage potential.

The literature demonstrates that the conflict between the magnetostatic and hydrodynamic forces determines the rheology of Mn-Zn ferrite ferrofluid. The fluid particles interact during rheology experiments on the basis of a conflict between magnetostatic force and hydrodynamic force [30, 31]. Due to the creation of solid structures and the fact that the alignment of the particles is not deviated from the direction of the magnetic field, the magnetostatic force is clearly dominating over the hydrodynamic force in the low strain rate area. The development of a stronger magnetic force over the hydrodynamic force results in the production of a stiff elastic microstructure. As the

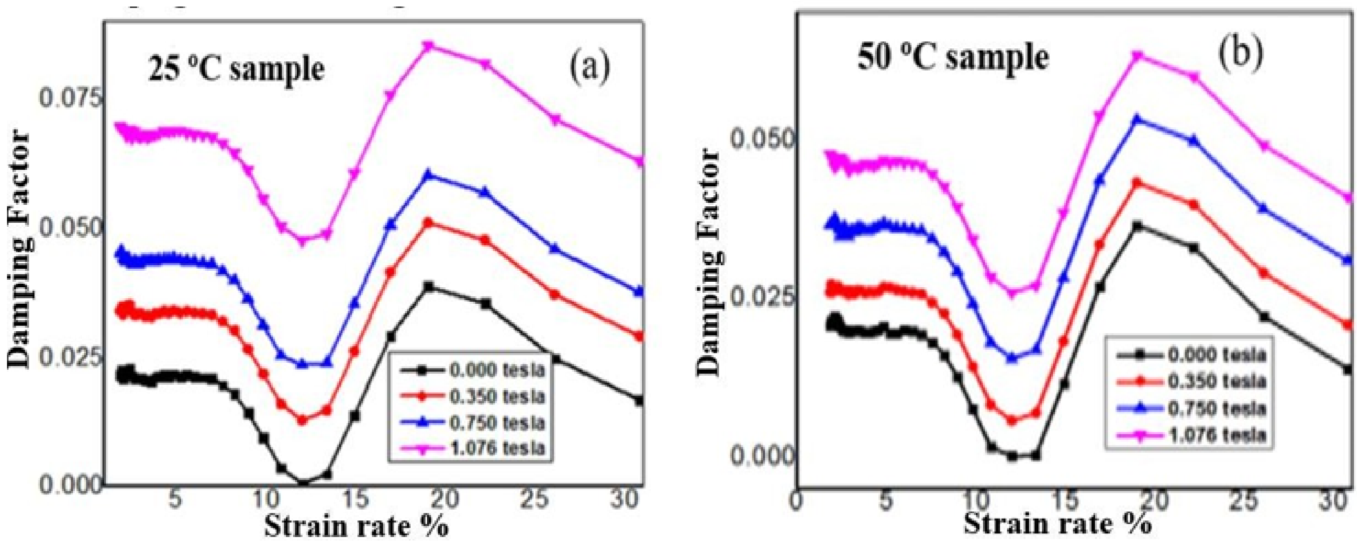

Figure 7. Damping factor of manganese zinc ferrite ferrofluid at temperature (a) 25 ^{o}C, (b) 50 ^{o}C.

strain rate rises, the storage modulus of Mn-Zn ferrite ferrofluid decreases, resulting in a region of low storage modulus where the values are almost identical to those of the loss modulus. We can observe that even when the strain rate increases, the chains do not entirely snap, and the magnetostatic force is still able to overcome the hydrodynamic force in the high strain rate zone. This is proof that the liquid phase still retains an elastic structure. At high strain rates, the volume of solid particles is almost equal to the volume of liquid particles in the liquid phase. We can see that any further increase in strain rate has the potential to destabilize the current elastic system and cause a phase transition from rigid fluid to semi-rigid fluid [32]. It is noteworthy that the increasing magnetic field leads to the formation of enhanced magneto-viscoelastic structure.

Non-Newtonian viscoelastic (NLV) MN-Zn ferrite ferrofluid forms in regions with low strain rates, whereas Newtonian viscoelastic (NV) fluid forms in regions with high strain rates. Since there isn't a crossover point between the storage modulus and loss modulus, there hasn't been a phase transition in the liquid phase. The lack of a transition from a solid-like structure to a liquid- like structure suggests that there hasn't been any structural rearrangement. Our findings are in line with those previously published by Mahesh *et al.* [33], who similarly did not report the occurrence of a phase transition. At 25 ^{o}C, the fluid displayed insufficient magnetoviscoelasticity, but adequate magnetoviscoelastic amount is generated at 50 ^{o}C. The entire strain rate region forms a linear loss modulus, and when the value of the loss modulus approaches 0, it indicates that no structural rearrangement has taken place. Low energy dissipation and a sufficient solid-like structure are indicators of the production of low loss modulus. Improved magnetoviscoelastic microstructure with maximum storage modulus of order 10^3 is generated [34]. This value is roughly three times higher than that reported by Balaji *et al.* [34] and about four times higher than that reported by Ankur Chattopadhyay *et al.* [24]. Because G' is greatly more dominating than G", the results provided by Yongbo *et al.* [35] are exactly in line with the results of the current experimental discoveries. This indicates the production of a system with a bigger elastic structure and ferrofluid that resembles solids. According to Mitsumata and Okazaki's report on the dependence of storage modulus on strain rate, the storage modulus decreases as the strain rate rises [36]. This conclusion is in perfect agreement with the findings of our investigation.

3.4. Complex Viscosity of Manganese Zinc Ferrite Ferrofluid

In both the presence and absence of a magnetic field, the complex magnetoviscosity of Mn-Zn ferrite ferrofluid is studied. Magnetic particles that are distributed in Mn-Zn ferrite ferrofluid are brought together and form field-induced microstructure as a result of their interaction with a magnetic field. When shear is applied, the magnetic structures are resistant to shear deformation at low strain amplitude, which results in the creation of increased elastic fluid [6]. MN-Zn ferrite ferrofluid is shown to be toughened and extremely elastic at low strain rates between 0 and 3% due to the production of a high complex magnetoviscosity. This occurred because the fluid particles generated strong field induced structures that are aligned in the direction of the applied magnetic field. At low strain applications, the dipolar interaction and the magnetostatic force are larger than the hydrodynamic force. The structural rearrangement is caused by applied strain, which distorted the magnetically induced structures by partially breaking the chains structure that connects Mn-Zn ferrite particles as the strain rate is increased from 3% to 8%. This results in a reduction in the complex magneto-viscosity and a softening of the fluid. Within this area, the fluid displayed non-Newtonian shear action. The chains of the field-induced structure are totally destroyed when a strain rate greater than 10% is applied, and MVE is reduced. At this strain area, the MR fluid exhibits Newtonian behavior.

As a result of the distinct dipolar interactions at various magnetic field applications, the complex magnetoviscosity of Mn-Zn ferrite ferrofluid is higher at high magnetic fields of

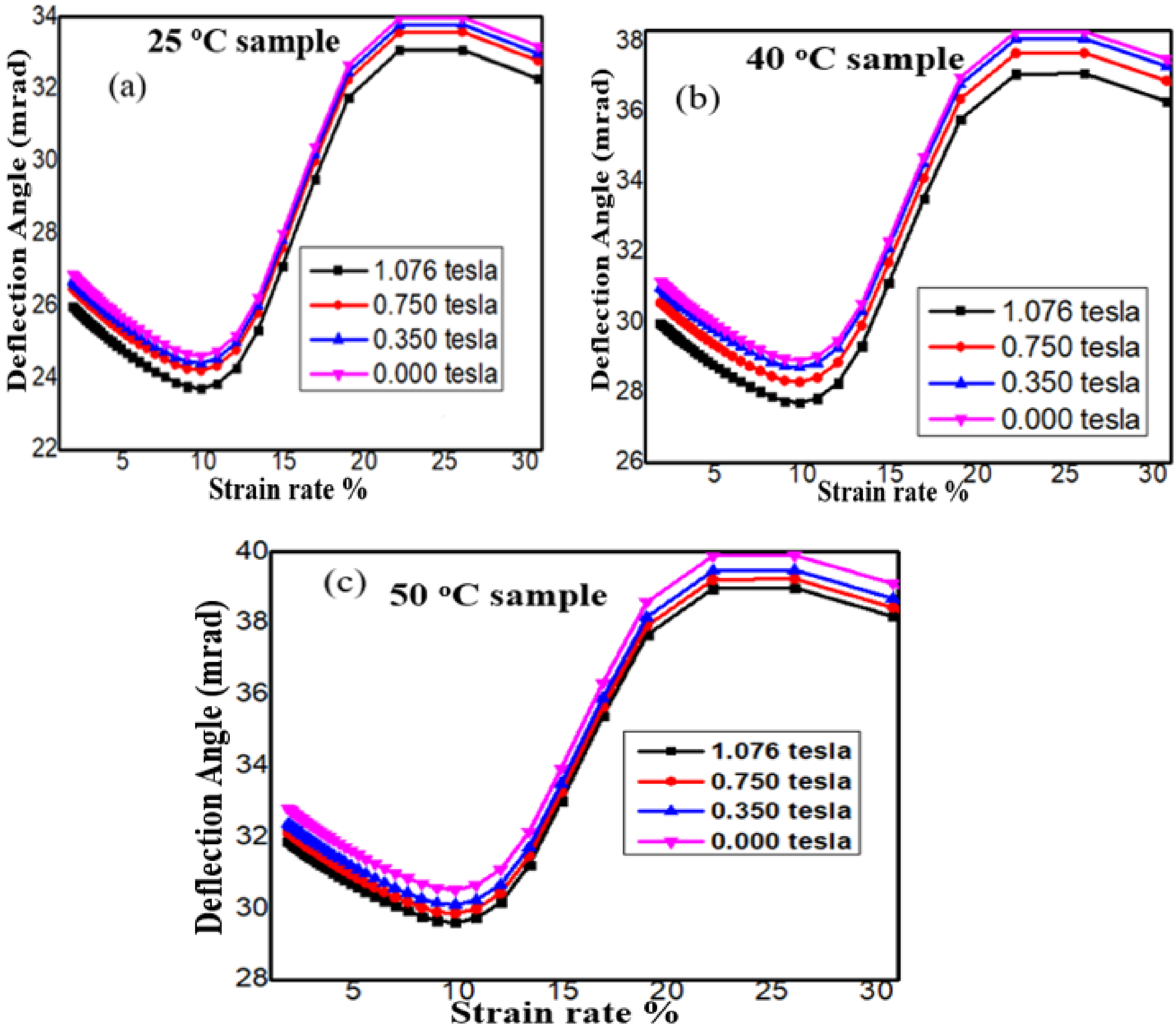

Figure 8. Deflection angle of manganese-zinc ferrite ferrofluid at temperature (a) 25 ^{o}C (b) 40 ^{o}C and (c) 50 ^{o}C.

1.076 tesla than it is when magnetoviscosity is created at low magnetic fields. When a high magnetic field and little strain are applied, the chain of field-induced structures is stronger. Due to weak magnetic interaction, lengthy chains form when low strain is applied, but they shorten or totally break down when high strain and low magnetic field are applied [37]. Low magnetic fields provide a short chain, which significantly lowers the complex magnetoviscosity on a wide scale [38]. As shown in Figures 6(a-c), the decrease in complex magnetoviscosity of Mn-Zn ferrite ferrofluid with rising temperatures is also experimentally studied. At 25 ^{o}C, a large complex magnetoviscosity forms as a result of low particle mobility and high binding energy. At a low temperature of 25 ^{o}C, the Mn-Zn ferrite particles are tightly bound together, but as the temperature rises to 50 ^{o}C, the binding energy weakens, allowing Mn-Zn ferrite particles to separate from their parent aggregates. As a result, there are fewer actively interacting particles, which reduces the complex magnetoviscosity. Particle aggregates disintegrate at high temperatures, and numerous particles separate from the aggregates to become individual particles. Due to the low thermal state that the MN-Zn ferrite particles experienced at 25 ^{o}C, the chains that link the field-induced structures do not break and the particles do not separate from their aggregates. One of the reasons low complex magnetoviscosity forms at high temperature is because of the particle's high thermal state at 50 ^{o}C, which causes the particle to get separated from the aggregate. The complicated magneto-viscosity decreases as temperature rises [39].

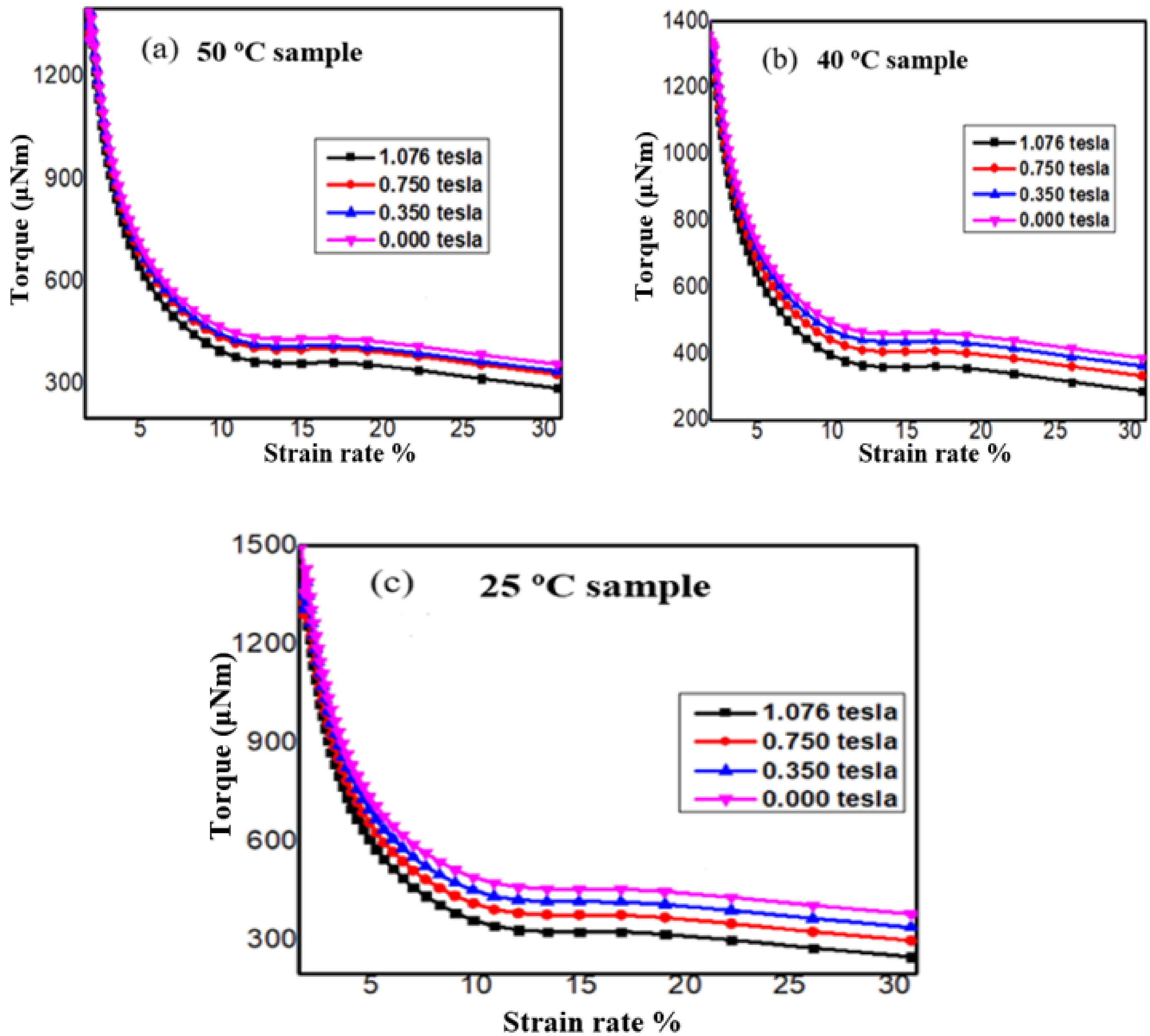

Figure 9. Torque of manganese zinc ferrite ferrofluid at temperature (a) 50 ^{o}C, (b) 40 ^{o}C and (c) 25 ^{o}C.

3.5. *Impact of Damping Factor on the Rheology of Manganese Zinc Ferrite Ferrofluid*

Because magnetic fluid exhibit strong fluid stability, zero leakages, enhanced longetivity, and respond to applied magnetic field, several magnetic fluids, such as ferrofluid and MR fluid, have been successfully used to perform active damping operation and heat control activities. Non-magnetic fluids, such as water, were adopted and used as heat control media prior to the existence of magnetic fluid. Non-magnetic fluid is used to reduce heat loss from a system. The non-magnetic fluid had poorer thermal conduction properties, which reduced its ability to regulate temperature. Magnetic fluids have been used on numerous occasions to regulate thermal activity and damping operation in a variety of devices in order to achieve very effective heat control. Flexible and exhibiting nanosize particles are magnetic fluids [40]. Due to the fact that their rheological properties might change over time, non-magnetic fluids perform less effectively [41].

The formation of an underdamped rheological system by MN-Zn ferrite ferrofluid is depicted in Figure 7(a–b). Due to the development of a sufficient elastic microstructure and limited heat dissipation, underdamping develops. Due to the fluid structure's dominant elastic nature, very little energy is lost. The development of very low loss modulus and high storage modulus is thought to be the cause of this phenomenon. It has been clearly proven that damping depends on the microstructure that the field induces. Underdamping is found to be high when 1.076 Tesla is applied, but it is found to be low when

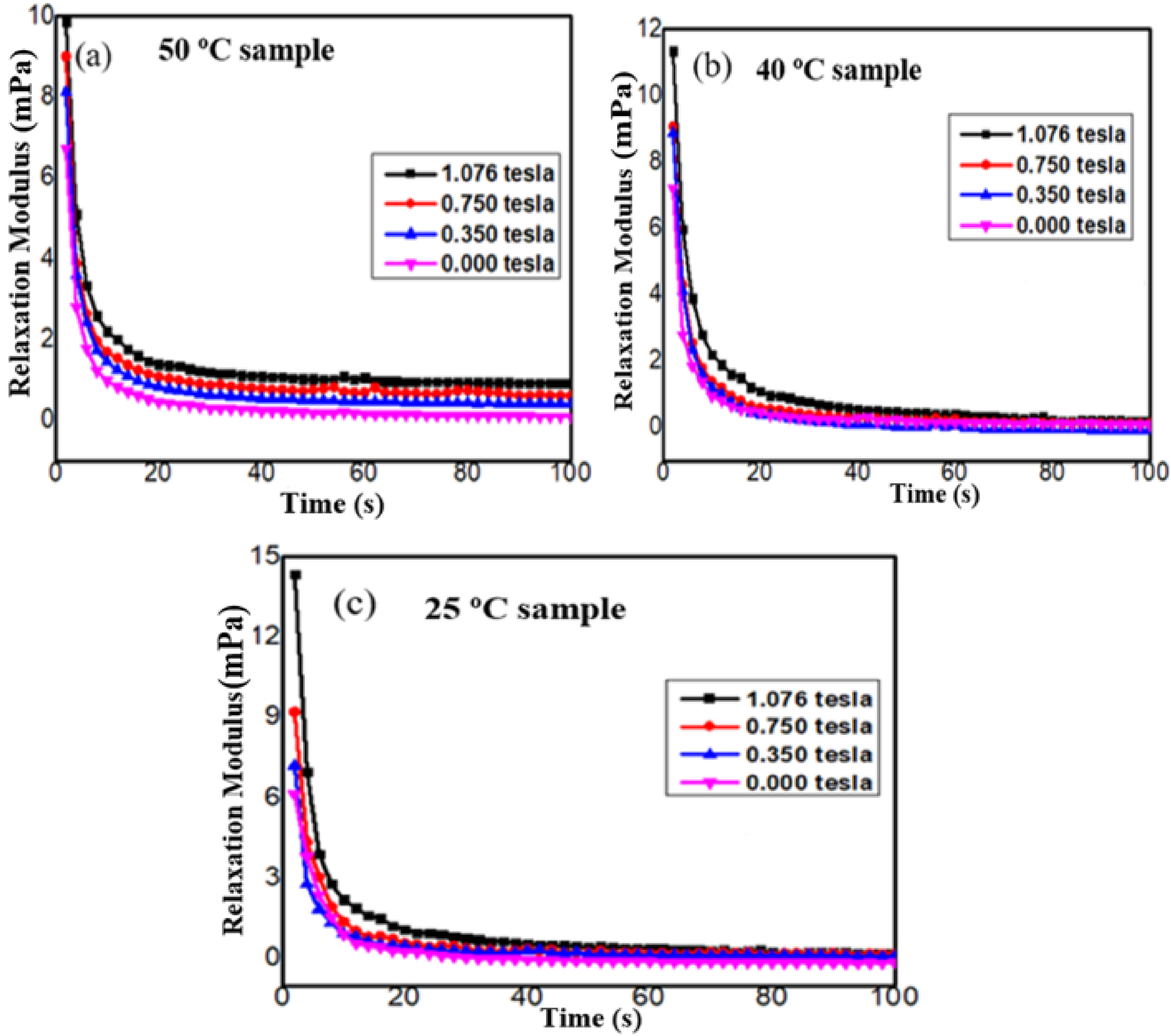

Figure 10. Relaxation modulus of manganese zinc ferrite ferrofluid at (a) 50 ^{o}C, (b) 40 ^{o}C and (c) 25 ^{o}C.

0.350 Tesla is applied. The damping factor rises as the applied magnetic field increases, which points to a rise in thermal energy loss as magneto-dynamic activity rises. A peak damping ratio of 0.75 is created during underdamped activity, which is higher than the maximum value of 0.16 reported by Rao et al. [42]. As the strain amplitude increases, the damping activity does not exhibit a regular pattern. The Figures illustrate lowest damping ratio, which occurs between strain rates of 10% and 15%, and the largest damping ratio, which occurs at high strain rates. In this work, temperature-dependent damping is also developed. Low thermal activity at low temperatures resulted to low damping, but significant thermal activity at high temperatures is obvious and leads to high damping activity. In order to dissipate heat from a system and keep it from breaking down, magnetic nanofluid can be used. The quantity of heat that is dissipated out of the system determines the damping and heat control [6].

3.6. Impact of Deflection Angle on the Rheeology of Manganese Zinc Ferrite Ferrofluid

Experimental analysis is done to determine how fluid deflection affects the rheology of MN-Zn ferrite particles. The illustrations from literature show that deflection of fluid plays significant role in the rheology of fluid. One of the key factors that determines the magnetoviscosity of the nanofluid is the fluid deflection, which demonstrates that the physico- mechanical properties such as elasticity, hardening and softening of the fluid is dependent on the size of the deflection angle. When compared to the volume of ferrofluid deflected at low strain rates, the volume of fluid deflected at high strain rates is higher.

Figure 8 (a–c) illustrates the formation of a high deflection angle under high strain rates. As the deflection angle widens, the larger volume of Mn-Zn ferrite ferrofluid can be deflected. Only fluids of larger dimensions are possibly deflected. Low deflection angles and low strain rates prevent fluid, especially those with greater diameters from deflecting. This demonstrates how the deflection angle affects fluid deflection. The particle size and size distribution have an impact on the particle deflection as well. Low strain applications cause the deflection angle to shrink, which prevents significant amounts of fluid from deflecting and prevents the separation of the particles from their parent aggregate. High magnetoviscosity is created as a result of the aggregate's protection from deterioration. Increased strain rate causes the deflection angle to broaden, which increases the potential for large numbers of fluid to deflect. This occurs because the wide deflection angle is unable to prevent or restrict the fluid from deflecting. Large numbers of particles separate from their respective parent aggregates as a result of this. The quantity of particles reachable for contact decreased as a result of a considerable number of particles being deflected, which therefore degraded the system's rheological activity.

When a magnetic field is applied, the deflection angle of Mn-Zn ferrite ferrofluid decreases, and when the magnetic field is fully removed, the volume of fluid deflection increases. The outcome demonstrates that the volume of Mn-Zn ferrite ferrofluid deflected when a low magnetic field is applied is higher than the volume of fluid deflected when a high magnetic field is applied. As demonstrated in Figure 7(a-c), a lower deflection angle forms at high magnetic fields, which prevents a significant portion of Mn-Zn ferrite ferrofluid from deflecting; this is because when the angle narrows, small amount of fluid deflects. The field-induced structure and the particle aggregate are strengthened by the deflection of a small number of particles. Strong magnetic fields aid in the development of an improved rheological system. Large amounts of Mn-Zn ferrite ferrofluid are prevented from deflecting by the small deflection angle. The results reveal that as the magnetic field weakens, the deflection angle widens and increases, increasing the population density of deflected Mn-Zn ferrite particles because a large deflection angle cannot prevent a particle from deflecting. The large deflection angle enables the separation of the particles from their parent aggregates. When 25 ^{o}C is applied, only a small number of particles are deflected. This is because the creation of low deflection angles and low thermal effects prevented the separation of the particles from their parent aggregates. When 50 ^{o}C is applied, a large number of particles are deflected; this is because a high deflection angle and a strong thermal effect form, which can separate the particles from the aggregates. The viscous effect of the fluid caused by internal frictional force of the molecular chains that affect the fluid flow is blamed for the variation in deflection angle.

3.7. Torque of Manganese-Zinc Ferrite Ferrofluid at Different Temperatures

It is recognized that torque depends on magnetic structure and temperature. The formation of a rheological system with high torque is shown in Figure 9. In the absence of a magnetic field, higher torque is created; however, when a magnetic field is supplied, torque is lost, and this loss of torque increases as the magnetic field's intensity increases. Due to higher torque, a low magnetic field application causes a high magnetic field rotation, which limit the viscous effect of the fluid. The fluid's magnetoviscosity decreases as a result of the high rotating magnetic field destroying the aggregate of particle particles. The application of a strong magnetic field reduces the spinning magnetic field's transmitting torque, according to the results. Due to the low rotation of the magnetic field, the magnetically induced structure and particle aggregates are now kept, which improves the rheology of Mn-Zn ferrite ferrofluid by preventing the magnetic structure from becoming frustrated. When the magnetic field is low, the rotating magnetic field rotates faster because the transmitting torque increases as the magnetic field decreases. Because the magnetic field cannot withstand the impact of high spinning, it is destroyed. Consequently, the particles are separated from the parent aggregates because the disintegration of the magnetic field lowers the magnetostatic force, which in turn weakens the binding force holding the particle to the parent aggregates. This explains one of the mechanisms by which the magnetoviscosity increases as the magnetic field increases. Greater transmitting torque develops in the absence of a magnetic field, and this high torque greatly twists the magnetic field, which destroys the magnetic effect and causes the particles to separate from their parent aggregates going forward.

As the temperature rises, there is a loss in the transmitting torque of Mn-Zn ferrite ferrofluid. The fluid's ability to last longer is compromised by thermal expansion, which forms when the temperature rises [43]. The decrease in rotat- ing torque that occurs as temperature rises is thought to be the cause of thermal expansion. The loss of rotating torque affected the fluid's durability; this is consistent with findings made by Wiehe et al who reported a decline in fluid durability as temperature rose [44]. Wang et al's assertion that viscous torque decreased as temperature rose was also supported by their research [45]. As the temperature rises, the spinning torque declines. At high temperatures of 50 °C, low torque is produced, whereas high torque is produced at low temperatures of 25 °C. In order to prevent the rheological system from being frustrated, relaxation is necessary to control the shear stress acting across the fluid's particle surface. The relaxation modulus of manganese zinc ferrite ferrofluid is investigated. A rheological system is shielded from destruction and allowed to recover to equilibrium after shearing when an appropriate relaxation mod- ulus is provided to it [46, 47]. A specific amount of stress must be provided to fluid systems in order to keep them from rupturing; if the stress exceeds the allowable limit or reaches a critical point, the system will shear and eventually deform. Use of a relaxing technique that brings the system back to equilibrium can stop the system from shearing permanently. When the system reaches equilibrium, it stabilizes and achieves steady state flow. Studies demonstrate that the applied strain needs to be kept to a minimum to prevent frustration of the equilibrium state [48]. By delivering a sufficient relaxation modulus at predetermined intervals, the stress is able to relax and prevent the system from permanently deforming. After a fluid has been disrupted, the relaxation modulus helps the fluid return to a steady state flow. The fluid will permanently deform and transition from an elastic to a plastic state if the system hits a critical point and does not return to equilibrium [43]. After 20 seconds, the relaxation modulus reaches equilibrium after gradually decreasing throughout that period of time. Maximum relaxation moduli of 10.342, 8.906, 8.028, and 6.856 MPa are produced at temperatures of 50 °C with 1.076, 0.750, 0.350, and 0.000 tesla of magnetic field, respectively. With a magnetic field of 1.076 tesla and a temperature of 25 °C, the largest relaxation modulus, 14.974 m.pa, is produced. In the absence of a magnetic field, the lowest relaxation forms. With a growing magnetic field, the relaxation modulus rises. Figure 10 illustrates the formation of a non-steady state flow before the time interval of 20 seconds. Between 0 and 20 seconds, a non-linear relaxation forms, indicating the emergence of a non-steady state flow. After 20 seconds, a linear relaxation modulus forms; the emergence of linear relaxation denotes the emergence of steady state flow. Only after a 20-second interval, in all applied magnetic fields and temperatures, does steady state flow begin to occur.

4. Conclusion

The structural, magnetoviscous, and magnetoviscoelastic properties of Mn-Zn ferrite ferrofluid have been studied. The impact of temperature and magnetic field on the rheology of Mn-Zn ferrite ferrofluid is investigated. The co-precipitation technique was used to synthesize the Mn-Zn ferrite ferrofluid, and the research formulates required conditions needed for the formation of elastic structure. Elevated magnetoviscoelasticity and magnetoviscosity were formed upon application of a magnetic field. Other rheological parameters such as damping factor which is essential for controlling vibrations in a system was also analyzed. This work provides important insights for optimizing the Mn-Zn ferrite ferrofluid for various applications by revealing the conditions necessary to create a high viscous effect and the viscoelastic behavior induced by the field. Precision control and manipulation are made possible in a multitude of technological applications, such as damping systems, by the Mn-Zn ferrite ferrofluids' response to magnetic fields.

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