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Research articles

Temperature dependency of magnetorheological fluids' properties under varying strain amplitude and rate

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ABSTRACT

The temperature dependencies of the rheological and viscoelastic properties of magnetorheological (MR) fluids were investigated experimentally using a rotary rheometer. The shear flow and oscillatory shear strain experiments were conducted over a wide temperature range (−5 to 50 °C) for different levels of magnetic flux density, and strain amplitude and rate. The temperature effect is also investigated considering three different MR fluids with varying solid particles concentration. The measured shear stress-strain data were used to evaluate the effects of temperature and magnetic field on the pre- and post-yield properties of the MR fluids. The acquired data under harmonic strain excitations swept in the 0.005–100% strain amplitude and different levels of steady temperatures in the −5 °C to 50 °C range were analyzed to identify storage and loss moduli as functions of the temperature, shear strain amplitude and frequency. The results suggested strong influence of temperature on the mechanical properties of the fluids in the absence of the magnetic field, especially at temperatures below 10 °C. The magnetic field, however, constituted the dominant effect. In the presence of a magnetic field, the temperature effect could be observed only at low strain levels. The temperature dependency of the mechanical properties also varied considerably with the iron particle fraction of the MR fluid. The critical strain amplitude also increased with increasing magnetic field density, while the linear storage modulus approached saturation with magnetic flux density above 0.2 T.

1. Introduction

Magnetorheological (MR) fluids are categorized as smart materials whose rheological properties can be controlled by varying the applied magnetic field. This inimitable feature has prompted numerous studies on MR fluids in varying applications such as MR dampers, valves, brakes and clutches [1], MR sandwich structures [2], finishing devices [3,4] and medical applications [5,6]. Considering the diverse range of applications, a number of studies have studied rheological behavior of MR fluids under different operating conditions, namely, flux density, strain amplitude and strain rate. These have employed widely different methods for rheological characterizations considering different operating modes such as dynamic squeeze, compression and impulsive [7,8], shear [9–18], tensile [19,20], and mixed modes [21–29]. For instance, Weiss et al. [9] investigated the elastic and viscoelastic properties of electrorheological (ER) and MR fluids using a strain controlled rheometer. The study reported strong dependency of the storage modulus and loss factor of the fluids on the strain amplitude in the 0–10% range and excitation frequency in the 1–16 Hz range, apart from the intensity of the applied electric/magnetic field. The critical strains of the ER and MR fluids, separating the linear and nonlinear viscoelastic regions, were also identified. Kim and Park [12] employed wave transmission test method to measure shear stress-strain properties of MR fluids under high frequency excitations (50–100 kHz), and evaluated storage and loss moduli from the measured speed of sound and attenuation data. The effect of the magnetic field direction was also investigated by applying the field in parallel and perpendicular to the direction of wave propagation. The study concluded that the storage modulus of the MR fluid increases linearly with frequency. Gudmundsson et al. [13] conducted experiments to quantify off-state rheological properties of MR fluids with different volume fractions of iron particles and average particle size, ranging from a few microns to nano, for application to a MR prosthetic knee. The study showed considerable negative influence on the performance of the bimodal MR fluid due to added nano particles, while the bimodal MR fluids with micron-sized particles revealed relatively lower off-state viscosity and higher field-induced shear stresses. Guth and Maas [16] investigated the effect of shear rate on rheological properties of MR fluids and demonstrated significance of the Taylor vortex flow for limiting particle centrifugation, irrespective of the applied magnetic flux density. The

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results showed reduced MR effect and torque at higher rotational speeds and thus the shear rates. A few studies have also investigated the performance of MR fluids operating in the mixed modes. Tang et al. [21] showed that the shear yield stress of the MR fluid can be increased by compressing the MR fluid along the applied magnetic field direction, which was attributed to formation of a thicker column of the particle chains. Experimental characterizations of the MR fluids in the flow and shear modes have also shown notably higher flow and shear mode yield stress even under low pressures [23,24]. Wahed et al. [22,27] conducted characterization of a MR fluid in the squeeze and shear flow modes, applied independently or simultaneously, under different loading and magnetic fields. From the comparisons of performance in the dynamic squeeze, shear flow and mixed squeeze and shear flow modes, it was shown that operation in the mixed modes significantly enhances the transmitted force. Bigué et al. [25] conducted small amplitude oscillatory shear tests under combined squeeze-shear conditions and magnetic field intensity and demonstrated the squeeze-strengthening of the MR fluids under combined squeeze-shear mode. The squeeze-strengthening effect was correlated with the Péclet number. The effects of squeeze geometry, fluid composition and rotational speed on the performance of MR fluids have also been reported in [28,29].

Apart from the operating modes and the magnetic field intensity, the variations in operating temperature is known to affect the rheological properties of the MR fluids [30–44]. Table 1 summarized the studies that have been done on the influence of temperature on the rheological and viscoelastic properties of MR fluids. One of the first studies on temperature dependency of the post-yield properties of MR and ER fluids revealed nearly 10% lower dynamic yield stress of the MR fluid when temperature increased from −40 °C to 150 °C in the presence of 3000 Oersted magnetic flux density [30]. This reduction was attributed to thermal expansion of the carrier fluid leading to lower particle volume fraction at a higher temperature. Li et al. [31,32] investigated the rheological and viscoelastic behavior of MR fluids in the 20 °C to 60 °C temperature range, and observed thinning of the fluid with increasing temperature. The studies evaluated temperature dependency of the Herschel-Bulkley parameters, and the storage and loss moduli of the MR fluid via oscillatory shear tests in both amplitude and frequency sweep modes. Chooi and Oyadiji [33] investigated viscoelastic behavior of MR fluids in the pre-yield region in the −20 °C to 50 °C temperature range, and concluded relatively greater temperature dependency of the loss modulus compared to the storage modulus. This tendency has been observed irrespective of the magnetic field intensity, and attributed to relatively higher temperature sensitivity of the carrier fluid compared to the solid particles [34,35].

A study on the yielding behavior of a novel MR suspension in the 19 °C to 55 °C temperature range demonstrated notable effects of temperature on both the storage and loss moduli, especially in the absence of the magnetic field [41]. The temperature dependency of the moduli, however, diminished with increase in the magnetic field intensity. The temperature dependency of five different MR fluids including their viscosity, shear stress and thermal stability were investigated by Wang et al. [37] in the 10–120 °C temperatures range using parallel disk test method. The observed temperature dependencies of the mechanical properties were primarily attributed to reductions in the off-field viscosity and shear stress with increasing temperature. Rabbani et al. [38,39] investigated the stability and rheological properties of a suspension of carbonyl iron microparticles in the silicone oil in the 10 °C to 85 °C temperature range. The study concluded that intensifying the magnetic field or decreasing the temperature significantly increases the maximum yield stress. The diminishing MR effect under increasing temperature has also been reported for a CoNi microcluster-based MR fluid [40].

Through experimental characterizations of a MR fluid in the 30–120 °C temperature range, it was shown that an increase in temperature yields relatively higher static yield stress under a low magnetic field [42]. The yield stress, however, decreased with further increase in the temperature. Most recently, Bahiuddin et al. [43] presented constitutive models for the MR fluids using the feed-forward neural network approach for predicting shear and dynamic yield stress as a function of the temperature. The results obtained from the model compared reasonably well with the modified forms of the Herschel-Bulkley and the power law models.

The aforementioned studies have primarily focused on the influence of temperature on the rheological properties of the MR fluids, namely, the yield stress and viscosity, considering temperatures above 10 °C. Although the viscosity of the carrier fluid is strongly affected at lower temperatures, only a single study could be found on the influence of low temperatures on rheological properties of MR fluids [30] in which just the temperature response of the yield stress in absence and presence of 3000 Oersted magnetic field have been compared. Thus, first of all, the present study investigates the effect of temperature on the shear stress-shear rate responses of the MR fluids under various levels of applied magnetic field to show how the magnetic field and temperature together affect the yielding behavior of the MR fluid. Moreover, as it can be seen in Table 1, the temperature dependency of the viscoelastic properties has not been adequately inspected. Limited studies investigated the influence of temperature on viscoelastic properties of MR fluids [31–33,41] which mainly focused on the variation of the storage and loss moduli at temperatures above 20 °C under few selective magnetic fields. As it was previously shown by authors [44] and it will be shown in the present study, the moduli are almost temperature independent at temperatures above 20 °C, while the influence of low temperatures on them cannot be ignored. Therefore, another contribution of this article is the characterization of the temperature effect

Table 1
Summary of the studies that have been presented on the effect of temperature on the rheological and viscoelastic properties of MR fluids.

Reference	Studied Parameters	Temperatures	Magnetic Fields
Weiss and Duclos [30]	Dynamic yield stress	−40 to 150 °C	0 and 3000 Oersted
Li et al. [31]	Shear stress vs shear rate, yield stress	10 to 80 °C	0.4 T
	Storage modulus vs frequency	20 to 60 °C	0.27 T
Li et al. [32]	Storage and loss moduli vs frequency	20 to 60 °C	0.34 T
Chooi and Oyadiji [33]	Storage and loss moduli vs frequency	−20 to 50 °C	1.0 T
Resiga [34].	Viscosity	20 to 60 °C	0.1 to 3 A (electric current)
Sherman et al. [35].	Viscosity	5 to 55 °C	
Guo et al. [36]	Normal force vs strain amplitude, normal force vs angular frequency	10 to 85 °C	0.12 and 0.72 T
Wang et al. [37]	Yield stress, viscosity	10 to 120 °C	0 to 1.2 T
Rabbani et al.[38]	Maximum yield stress, shear viscosity	10 to 85 °C	0, 136, 198, and 234 $kA.m^{-1}$
Rabbani et al. [39]	Shear stress vs shear rate	10 to 85 °C	0, 136, 198, and 234 $kA.m^{-1}$
Arief et al. [40].	Shear stress vs shear rate, dynamic yield stress, viscosity vs shear rate	25 to 55 °C	0.04, 0.125, 0.24, 0.4, and 0.6 T
Arief and Mukhopadhyay [41]	Storage and loss moduli	19 to 55 °C	0, 0.1, 0.2, 0.3, 0.4, and 0.5 T
Laherisheth and Upadhyay [42]	Shear stress vs shear rate, yield stress	40 to 120 °C	0.26, 0.42, and 0.94 T
Bahiuddin et al. [43]	Yield stress, shear stress vs shear rate	25 to 40 °C	0, 0.1, 0.21, 0.33, 0.44, and 0.54 T
Hemmatian et al. [44]	Storage and loss moduli vs frequency, Storage and loss moduli vs strain amplitude	−5 to 50 °C	0, 0.4, and 0.8 T

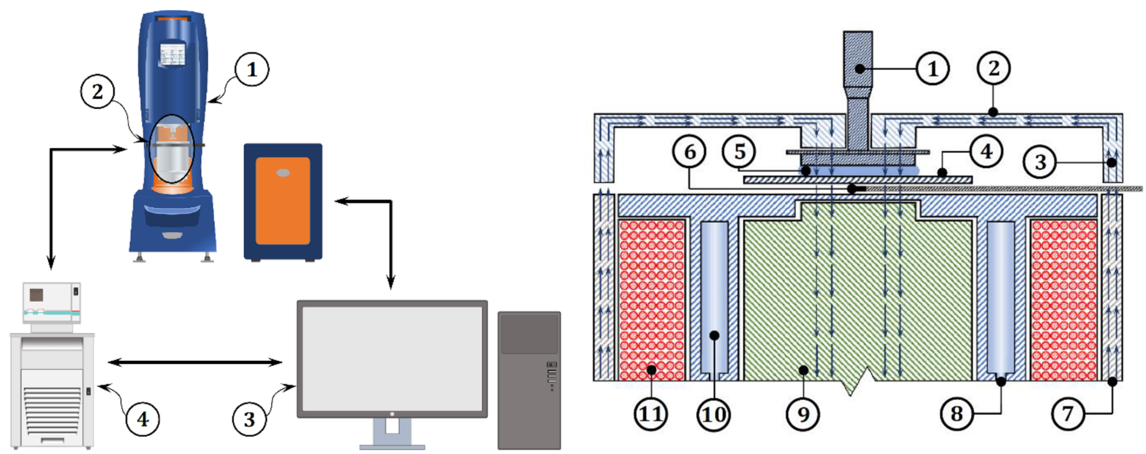

Fig. 1. (a) Schematic of test setup: 1. DHR-3 rheometer; 2. magneto-rheology accessory and parallel geometry; 3. Computer; and 4. Julabo circulator and (b) schematic of magneto-rheology accessory: 1. upper geometry; 2. upper cover; 3. magnetic flow; 4. bottom geometry; 5. MR sample; 6. Hall probe; 7. external cover; 8. heat exchange inlet/outlet; 9. cylindrical core; 10. chamber for recirculating heat exchange fluid; 11. solenoid.

on the behavior of the MR fluids considering a wide range of the operating temperature and magnetic flux density. Unlike the previous studies, both the flow and viscoelastic properties of the MR fluids are investigated. In addition, the properties are investigated with respect to both the frequency and strain amplitude and the effect of the temperature on the critical strain is evaluated.

2. Experimental setup

The rheological behavior of a MR fluids in shear is known to strongly depend on the temperature apart from the magnetic field, and shear strain amplitude and rate. The fluid may exhibit linear viscoelastic to nonlinear viscoelastic (viscoplastic) behavior with increasing shear strain and frequency. Considering this, the experiments were designed to investigate the effects of temperature on rheological properties considering broad ranges of excitation frequency and amplitude as well as flux density. The experiments were conducted using an advanced rotational rheometer (Discovery HR-3, TA instruments) (Fig. 1). The rheometer is equipped with a circulator (Julabo F32-HE) that permits controlled temperature of the sample over a relatively wide range (−10 °C to 70 °C) and the magneto-rheology accessory that permits homogenous and closed-loop controlled magnetic flux density up to 1.0 T applied in a direction perpendicular to the flow direction. The controlled magnetic field created by the solenoid is guided through the sample by means of the upper cover assembly, as shown in Fig. 1(b). The measurements were conducted using the parallel-plate geometry (diameter = 20 mm with 1 mm plate-gap). Sufficient amount of a MR fluid was placed in the gap, which was subjected to controlled shear strain rate as well as oscillatory shear strain using the amplitude and frequency sweep modes.

The experiment design involved three different hydrocarbon-based MR fluids (MRF-122EG, MRF-132DG and MRF-140CG; Lord Corporation, USA) with different concentration of micron-sized iron particles as it is presented in Table 2. It is noted that the type of carrier fluid is synthetic oil and ferromagnetic particles are in the range of 3–10 μm. A fluid sample was thoroughly stirred for about 10 min at above 2000 rpm prior to measurements in order to minimize the sedimentation effect.

Table 2
Solid content of the MR fluids considered in the study [45].

	Solid Content by Weight (%)	Density (g/cm^3)
MRF-122EG	72	2.28 – 2.48
MRF-132DG	80.98	2.95 – 3.15
MRF-140CG	85.44	3.54 – 3.74

Four types of experiments have been conducted on the three aforementioned MR fluids to investigate the temperature dependency of rheological and viscoelastic properties of MR fluids operating in shear mode. First, the flow ramp analysis was performed measuring the torque while the shear rate increases from 0.001 to 1000 s^{-1} over 60 s and the applied flux density and temperature were maintained steady. The test has been done under different levels of applied flux density (0.0, 0.05, 0.1, 0.2, 0.4, 0.8 and 1.0 T) and temperature (−5, 0, 10, 20, 30, 40, 50 °C) and the measured stress-strain rate data were analyzed to obtain the field dependent shear yield stress of the fluids for each operating temperature. Second, the viscoelastic properties of the MR fluids were investigated using strain amplitude sweep mode analysis (0.005 to 100%) maintaining the driving frequency at 1.0 Hz. The storage and loss moduli were evaluated from the measured stress-strain data under the same magnetic field and temperature as those of the flow ramp analysis. Strain frequency analysis is the third analysis that was performed using sweep frequency mode in the frequency range of 0.1 to 100 Hz at 0.01% strain amplitude to investigate the storage and loss moduli frequency response for different temperatures and applied flux densities. Finally, the off-state temperature ramp analyses have been performed on the fluids by continuously varying the temperature from −5 to 50 °C in 30 min while maintaining the strain amplitude (0.01, 0.1, 1, 5, 10 and 50%) and frequency (0.1, 1, 10 and 50 Hz) steady.

3. Results and discussion

The acquired data were analyzed to evaluate temperature dependency of various mechanical properties of the MR fluids such as the yield stress, storage and loss moduli, and critical strain under a wide range of excitation frequencies and amplitudes as well as flux density. The results obtained from the analyses are discussed below.

3.1. Yield stress analysis

Fig. 2 presents the effect of temperature on the shear stress versus shear rate properties of the MRF-132DG. The results are presented for magnetic field density ranging from 0 to 0.2 T and temperature ranging from −5 °C to 50 °C. These results were obtained using flow ramp procedure in which the shear rate was permitted to vary from 0.001 to

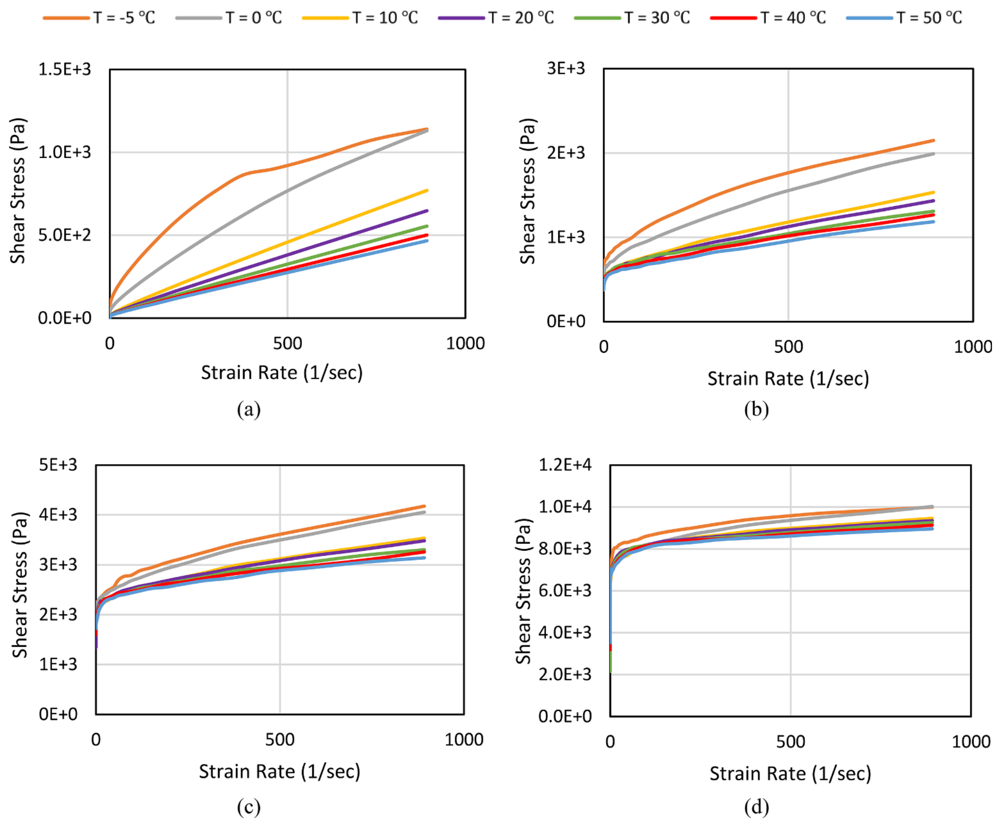

Fig. 2. Effect of temperature on variations in the shear stress of the MRF-132DG with the shear strain rate under different levels of magnetic flux density: (a) 0.0 T, (b) 0.05 T, (c) 0.1 T, and (d) 0.2 T.

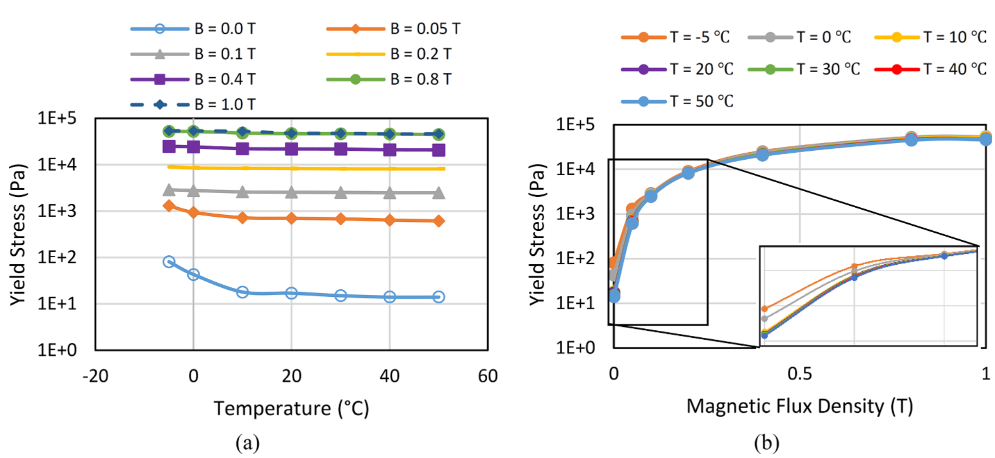

Fig. 3. Variations in yield stress of the MRF-132DG with (a) temperature and (b) magnetic flux density.

$1000\ s^{-1}$ in a controlled manner over a duration of 60 s. The resulting shear stress was computed from the measured torque. The results suggest MR fluid behavior similar to that of a Newtonian fluid in the absence of the magnetic field (B = 0.0 T), especially at temperatures above 10 °C, as seen in Fig. 2(a). At temperatures above 10 °C, the shear stress increases nearly linearly with the shear strain rate. The results also suggest similar temperature dependency of the shear stress under 0.05 T magnetic field, although the effect of temperature diminishes with increasing magnetic field, as seen in Fig. 2(c) and (d). It is evident that the shear stress is dominantly affected by the magnetic field compared to the temperature. For a Newtonian fluid, the slope of the stress-strain rate curve represents the viscosity [34]. The results in Fig. 2(a) and (b) suggest greatest viscous effect at the lowest temperature of −5 °C considered in the study, especially in the lower strain rate range, while the viscosity of the MR fluid decreases considerably with increase in the temperature. This can be mostly attributed to temperature dependency of the carrier fluid. With increasing temperature, thermal expansion of the carrier fluid leads to relatively lower volume fraction of iron particles and thereby lower shear stress and overall viscosity, which has also been reported in [30]. Thinning of the carrier fluid with increasing temperature has also been reported by Li et al. [31,32], which contributes to lower viscosity. This trend is more pronounced when the magnetic field intensity is very low. The MR fluid considered in the study exhibits shear-thinning (pseudoplastic) tendency when the temperature is below 10 °C, as seen in Fig. 2(a), where the viscosity decreases at a higher shear strain rate. This trend is even more pronounced at −5 °C. In the presence of very low magnetic flux density (≈0.05 T), the MR fluid revealed properties similar to Bingham plastic materials at temperatures above 10 °C and Herschel-Bulkley (Bingham pseudoplastic) materials at temperatures below above 10 °C.

The Bingham plastic-like material behavior under relatively higher magnetic flux (0.1 and 0.2 T) is evident in Fig. 2(b) to (d), irrespective of the temperature.

Fig. 3(a) further illustrates variations in the shear stress with the temperature for different values of the magnetic flux density. Considering that the yield stress is defined as a threshold of the shear stress after which the flow starts and shear stress increases with the flow rate, either linearly (Bingham plastic) or non-linearly (Herschel-Bulkley) [46], the results suggest that the yield stress is mostly temperature independent. This is particularly evident in the presence of the magnetic field and temperature above 10 °C. The significant temperature dependency of the yield stress, however, is evident at low temperatures (below 10 °C), especially in the absence of the magnetic field. Similar tendency has also been presented in previous studies [30,38,40]. This behavior is attributed to relatively higher temperature dependency of the carrier fluid properties at lower temperatures compared to the higher temperatures. Silicone and synthetic oils, particularly, exhibit substantially higher viscosity at temperatures below 0 °C and relatively smaller change in viscosity above 10 °C [47]. Weiss and Duclos [30] also reported substantially higher plastic viscosity of a MR fluid at temperatures below 0 °C, which rapidly declined in the −50 °C to 0 °C range. Furthermore, the yield stress of the MR fluid is highly dependent on the applied flux density, as seen in Fig. 3(b). The results suggest that the yield stress increases exponentially with the applied magnetic flux density, irrespective of the temperature, and it tends to saturate as the flux density approaches near 0.8 T.

The shear stress and thus the yield stress of a MR fluid also depend on the weight fraction of the iron particles. Fig. 4 illustrates the flow behavior of three different MR fluids, MRF-132DG, MRF-122EG and MRF-140CG, in terms of the measured shear stress-strain properties under 0 T and 0.1 T magnetic flux density and temperature of 20 °C. It should be noted that the iron particle weight fraction of MRF-122EG (72%) is lower than that of the MRF-132DG (80.98%), while that of the MRF-140CG (85.44%) is higher. The results suggest that all the fluids behave as a Newtonian fluid in the absence of magnetic field (B = 0.0 T). These, however, exhibit close to the Bingham plastic behavior in the presence of the relatively small magnetic field (B = 0.1 T). The results show notably higher shear stress of the fluid with relatively higher solid content. Increasing the weight fraction beyond 80% revealed substantially greater influence on the rheological property of the MR fluid, while lowering the solid particle fraction resulted in relatively smaller change, especially in the presence of the magnetic field. For instance, in presence of 0.1 T magnetic flux density, the shear stress of the MRF-140CG with higher solid particle fraction is 68% higher than that of the MRF-132DG fluid under B = 0.1 T. The shear stress of the MRF-122EG fluid with lower solid particle content, however, is only slightly smaller than that of the MRF-132DG. Table 3 summarizes the approximate yield stresses of the MR fluids for B = 0.0 T and B = 0.1 T. The results show nearly 68% higher yield stress of the fluid, when solid particle content is increased from about 81% to 85% (MRF-132DG vs MRF-140CG) under B = 0.1 T. Reducing the particle content from 81% to 72% (MRF-122EG), on the other hand, caused only about 8% reduction in the yield stress. The results thus suggest superior performance of the MR fluid with solid particle content in excess of 80%.

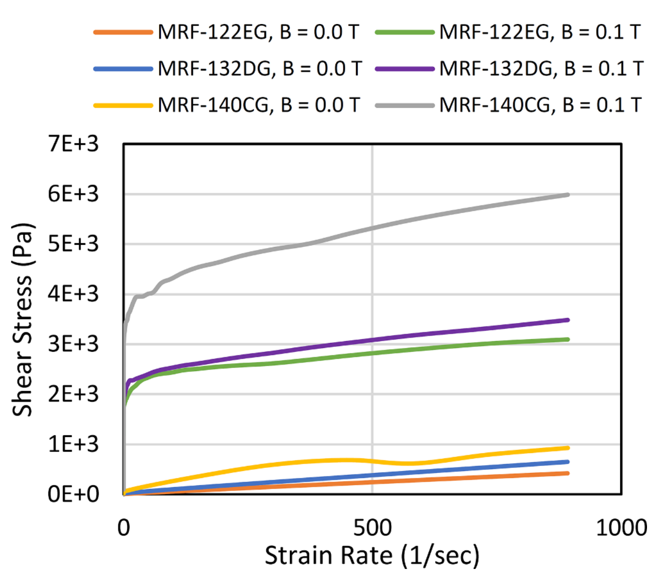

Fig. 4. Shear stress vs shear strain rate characteristics of for three different MR fluids under 0 and 0.1 T magnetic flux density.

Table 3
Approximate yield stress of three different MR fluids with varying weight fractions of the solid particles.

Applied Magnetic Flux Density (T)	Yield Stress (Pa)		
	MRF-122EG (72%)	MRF-132DG (80.98%)	MRF-140CG (85.44%)
0	5	17	60
0.1	2350	2550	4300

3.2. Strain amplitude analysis

The data acquired from the oscillatory tests were analyzed to study the effect of large shear amplitude on the stress-strain characteristics of the MR fluids. The measurements were performed under varying amplitudes of harmonic shear strain amplitude, while maintaining the desired frequency, magnetic flux density and temperature. The data acquired in the steady-state condition were used to evaluate storage and loss moduli of the MR fluid. Fig. 5 shows the variations in the storage modulus of the MRF-132DG as a function of the strain amplitude, ranging from 0.005% to 100%, at an excitation frequency of 1.0 Hz. The results are presented for different magnitudes of the magnetic flux density (0.0, 0.05, 0.1 and 0.2 T) and different temperatures. In the absence of the magnetic field, the storage modulus of the fluid is nearly constant under low strain amplitudes representing the linear viscoelastic region, as seen in Fig. 5(a). The storage modulus decreases sharply with increasing strain amplitude as it exceeds the critical strain amplitude (γ_{lin}), defined as the limiting shear strain amplitude corresponding to the linear viscoelastic behavior. It is noted that, for small strain amplitudes (less than γ_{lin}) the MR fluid nearly behaves as an elastic material in which the particle chains deform without destruction and the storage modulus does not vary with the strain amplitude. However, the chains break as the fluid operates at higher strain amplitudes (greater than γ_{lin}) which results in yielding and drastic reduction in the storage modulus. This tendency was also reported in other studies [32,36]. Moreover, in the absence of the magnetic field, increasing the temperature from −5 °C to 10 °C yields notably lower storage modulus, while the modulus does not varies significantly by further increase of the temperature. This behavior of the MR fluid could be interpreted with respect to the variation of the entropy of the fluid by temperature. The entropy of a material is a logarithmic function of temperature at each phase (i.e. liquid) [48], such a way that, initial increase of temperature causes a rapid enhancement in the entropy while further rise of temperature does not considerably affect it. Therefore, less force is required to deform the MR sample as its entropy increases with temperature and thus the storage modulus decreases. The effect of temperature, however, diminishes in the presence of even low level magnetic field, as seen in Fig. 5(b) thru (d). It is thus deduced that the linear and nonlinear viscoelastic behaviors of the MR fluid together with the critical strain are not notably affected by the temperature in presence of magnetic field, as observed earlier in Fig. 2. The linear viscoelastic region and thus the critical strain amplitude of the

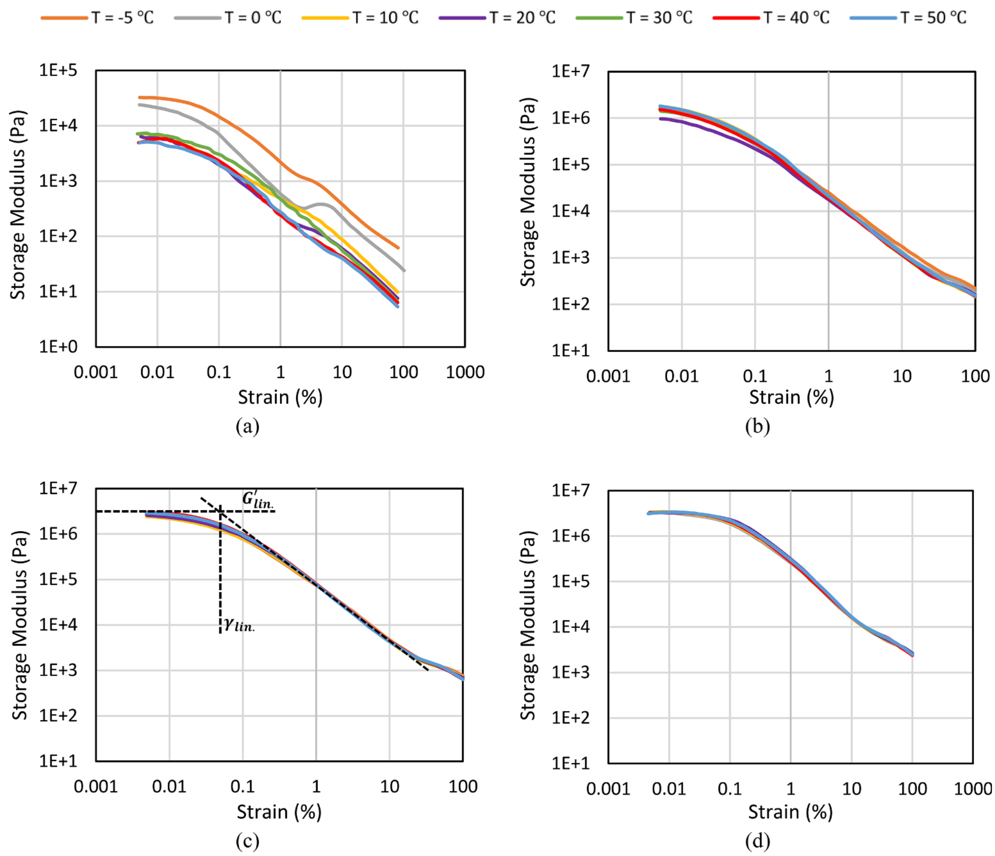

Fig. 5. Effect of temperature on variations in the storage modulus of MRF-132DG fluid with the shear strain amplitude at an excitation frequency of 1.0 Hz and different levels of magnetic field intensity: (a) 0.0 T, (b) 0.05 T, (c) 0.1 T, and (d) 0.2 T.

MR fluid, however, increase with increasing magnetic field. This is likely due to strengthening of the chains of particles under a higher magnetic field. By increasing the applied magnetic field, MR fluid behaves more solid-like with increased yield strength thus wider linear region.

Fig. 6 illustrates the effect of temperature on the critical strain considering different levels of the magnetic flux density. The critical strain corresponding to each test condition is identified from the intersection of asymptotes drawn for the linear (low strain) and nonlinear (high strain) regions, as shown in Fig. 5(c) [49]. The results suggest that the critical strain amplitude similar to the yield strength increases with increase in the applied magnetic field density, irrespective of the sample temperature. As discussed before, this is due to the expansion of linear viscoelastic region as the applied magnetic field increases. Moreover, the critical strain is generally insensitive to the temperature, irrespective of the magnetic field density, although the critical strain increases slightly with temperature. This is also evident from the relatively lower temperature insensitivity of the yield strength of the MR fluids in the presence of the magnetic field (Fig. 3). Fig. 7 further illustrates variations in the storage modulus of the MR fluid in the linear

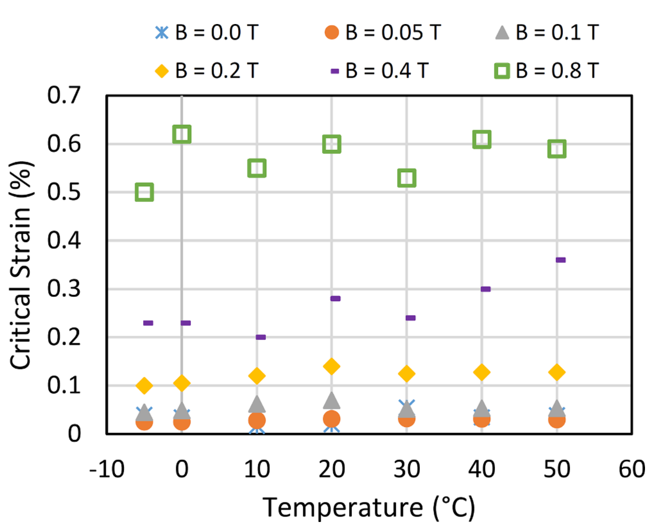

Fig. 6. Variations in the critical strain with temperature under different levels of magnetic flux density.

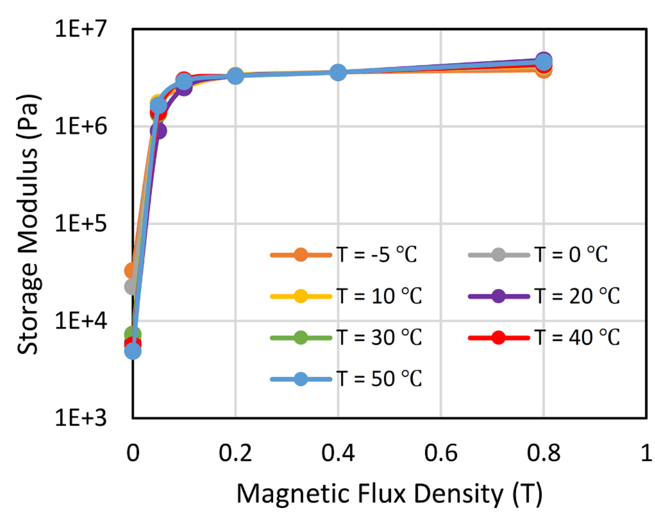

Fig. 7. Effect of magnetic flux density on the storage modulus in the linear region at different temperatures.

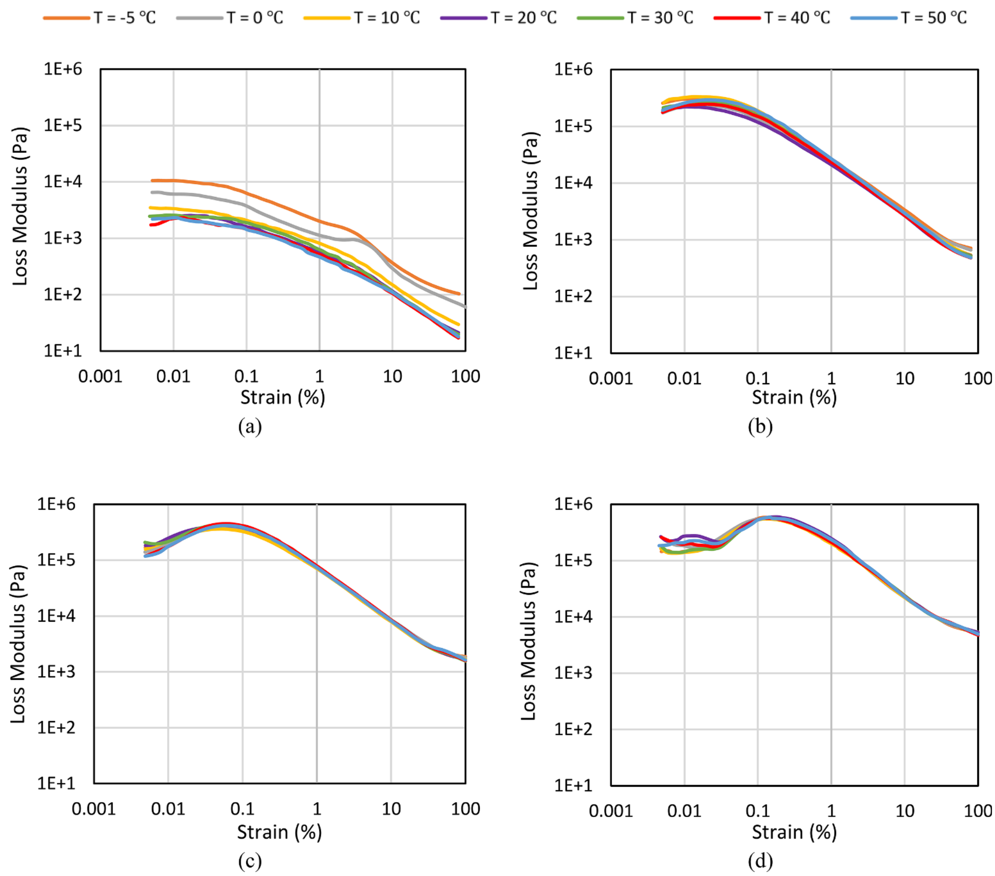

Fig. 8. Effect of temperature on variations in the loss modulus of MRF-132DG with the shear strain amplitude at an excitation frequency of 1.0 Hz and different levels of magnetic field intensity: (a) 0.0 T, (b) 0.05 T, (c) 0.1 T, and (d) 0.2 T.

region corresponding to γ_{lin}, as seen in Fig. 5(c), for different temperatures and intensities of the magnetic field. The linear storage modulus is observed to be independent of the temperature, except in the absence of the magnetic field. The linear storage modulus increases with the magnetic flux density and saturates around 0.2 T.

The loss modulus of the MRF-132DG fluid also decreases with increase in the strain amplitude, as seen in Fig. 8. The results were obtained for different sample's temperature and magnetic flux densities, and strain amplitudes at 1.0 Hz. Similar to the storage modulus, the loss modulus is nearly constant under low strain amplitudes in the absence of the magnetic field, while it decreases rapidly as the strain amplitude exceeds the critical strain, as seen in Fig. 8(a). The loss modulus also decreases with increase in the fluid temperature from −5 °C to about 10 °C and it remains almost constant for higher temperatures. The loss modulus basically represents the energy dissipation of the material mostly as a heat. Increasing the temperature of the MR sample reduces its heat capacity and consequently the loss modulus decreases. Fig. 8(b) to 8(d) show that in the presence of magnetic field the loss modulus is strain dependent, while the effect of temperature is insignificant. In the linear region, the loss modulus increases with strain amplitude up to the critical strain, and decreases with further increase in strain amplitude, irrespective of the magnetic field and temperature.

Both the loss and storage moduli of the MR fluid are also dependent on the solid particles weight fraction, as shown in Fig. 9 for the three different fluids subjected to B = 0.0 T and B = 0.1 T. The results are obtained for different strain amplitudes at a fixed frequency of 1.0 Hz and 20 °C temperature. The results suggest that increasing the weight fraction of iron particles enhances both the storage and loss moduli of the MR fluid for both the magnetic field conditions considered. Moreover, results also show that an increase in the weight fraction of iron particles yields relatively lower critical strain amplitude but substantially higher linear storage modulus. In presence of 0.1 T magnetic flux density, increasing the weight fraction from 72% (MRF-122EG) to 80.98% (MRF-132DG) and 85.44% (MRF-140CG) respectively reduces the critical strain amplitude from about 0.08% to 0.07% and 0.055% while the linear storage moduli increased from 1600 Pa to 2500 Pa and 3500 Pa. This suggests that increasing the weight fraction reduces the region in which the MR fluid behaves as a linear viscoelastic material and increases the nonlinear properties of the fluid in shear motion. This could be attributed to the effect of the weight fraction of iron particles on the density of the particle chains in the carrier fluid. By increasing the iron particles percentage, the distance between the particle chains decreases and consequently the rearrangement of the chains occurs at lower strain amplitudes.

3.3. Time response analysis

The experiments were performed under varying magnitudes of strain excitation, and the data were analyzed to investigate transient shear stress behavior of the MR fluid. The data were acquired under a 28 s excitation cycle comprising four equal duration segments of different amplitudes of the harmonic strain (0.01, 0.1, 1.0 and 10%), such that:

$$\begin{cases} \gamma = 0.01\,\sin(\omega t) & t < 7 \\ \gamma = 0.1\,\sin(\omega t) & 7 \le t < 14 \\ \gamma = 1\,\sin(\omega t) & 14 \le t < 21 \\ \gamma = 10\,\sin(\omega t) & 21 \le t < 28 \end{cases} \tag{1}$$

where ω is the excitation frequency. Fig. 10(a) and (b) show time-histories of the strain excitation and stress response of MRF-132DG considering excitation frequency of 1.0 Hz, and B = 0.0 T and B = 0.1 T.

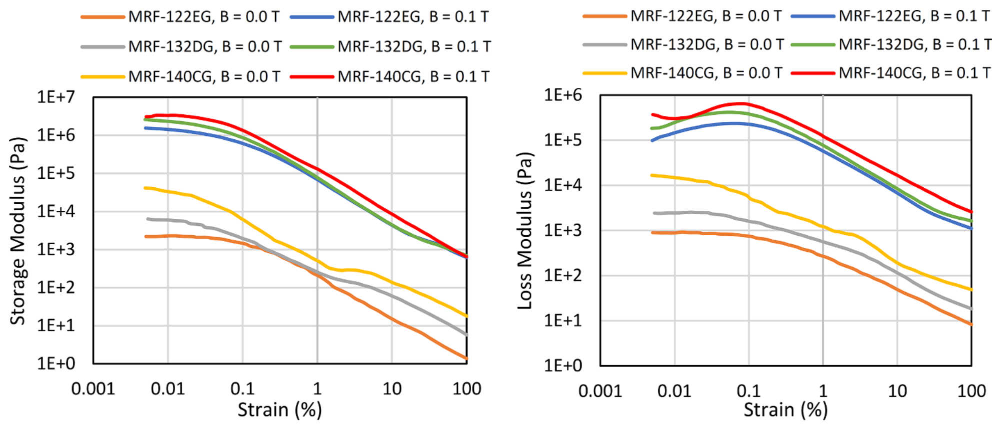

Fig. 9. (a) Storage and (b) loss moduli of three different MR fluids with varying solid particles fractions with respect to strain amplitude at 1.0 Hz (Temperature = 20 °C).

Both the strain and stress measures were normalized with respect to the peak values observed during each excitation segment. The stress is observed to be nearly sinusoidal under low strain amplitude excitations of 0.01% and 0.1%, suggesting linear viscoelastic behavior of the MR fluid under low strain excitations. Notable distortions of the stress response oscillations are evident under higher strain amplitudes of 1.0% and 10%, especially in the absence of the magnetic field. The stress response under 10% strain excitation suggests presence of higher frequencies. This tendency is attributable to the nonlinear viscoelastic behavior of the MR fluid under higher strain excitations. The results also show that the stress response approaches steady-state after about three initial cycles.

Moreover, the effect of applied magnetic field and temperature on the hysteresis stress-strain responses of the MRF-132DG have been investigated and results for excitation frequency of 1.0 Hz and linear strain amplitude range are presented in Fig. 11. As it can be realized the hysteresis responses are generally in elliptical shape for all the applied magnetic flux densities and temperatures showing that the MR fluid operates in the linear viscoelastic region as expected. Fig. 11(a) clearly shows that enhancing the applied magnetic field causes both the slope and the area bounded by the stress-strain loops to increase suggesting that the stiffness and damping, and thereby the storage and loss moduli of the sample, increase. Fig. 11(b) also compares the hysteresis stress-strain responses of the MR fluid at different temperatures in the absence of applied magnetic flux density. From the results, it is evident that the equivalent stiffness and damping property are substantially higher at −5 °C compared to those obtained for the higher temperatures. This is attributable to the substantially higher plastic viscosity of the fluid at the lower temperature. The equivalent stiffness decreases considerably with increase in temperature, which causes the hysteresis loops to rotate clockwise with increasing temperature, as seen in Fig. 11(b).

3.4. Strain frequency analysis

The data acquired from the frequency sweep tests were analyzed to study the frequency dependency of the viscoelastic behavior of the MR

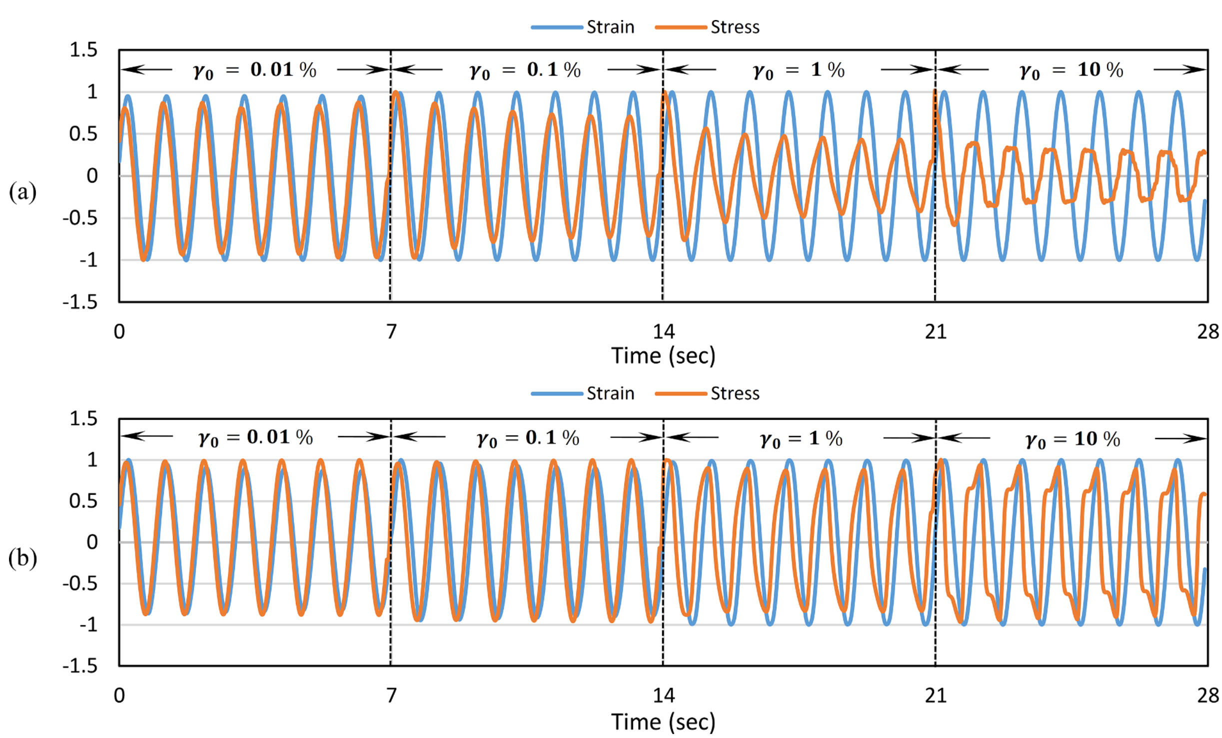

Fig. 10. Time histories of varying amplitude strain excitation at 1.0 Hz and the resulting shear stress response under (a) B = 0.0 T and (b) B = 0.1 T.

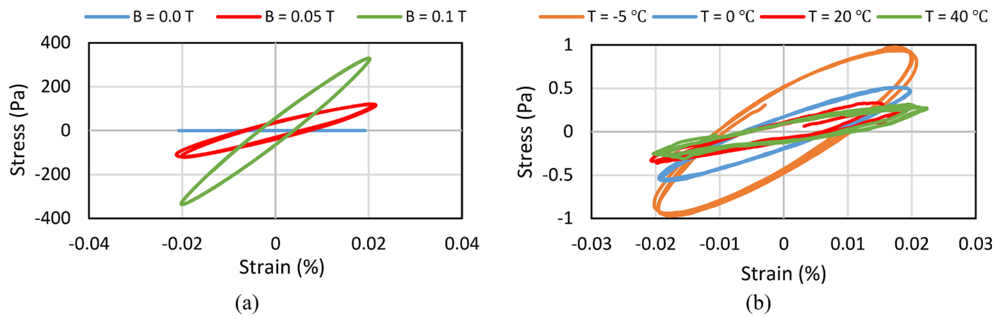

Fig. 11. Effect of (a) applied magnetic field and (b) temperature on the stress–strain responses of MR fluid at excitation frequency of 1.0 Hz.

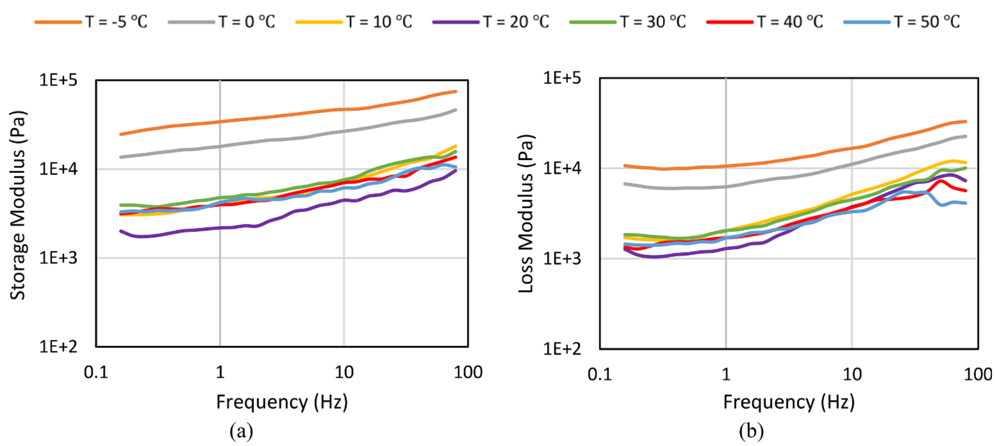

Fig. 12. Effect of temperature on variations in the (a) storage and (b) loss moduli of MRF-132DG with the excitation frequency at an strain amplitude of 0.01% and in absence of applied flux density (B = 0.0 T).

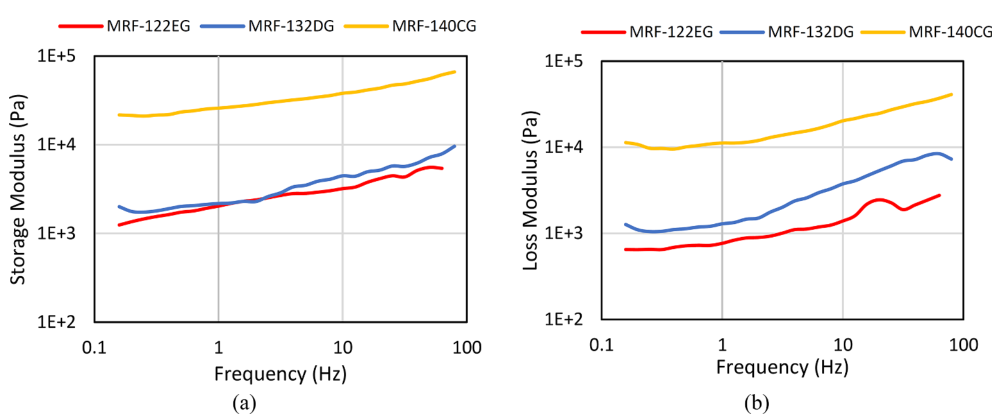

Fig. 13. (a) Storage and (b) loss moduli of three different MR fluids with varying solid particles fractions with respect to excitation frequency at 0.01% strain amplitude (Temperature = 20 °C and B = 0.0 T).

fluid considering different levels of temperature. The tests were conducted under constant strain amplitude (0.01%), while the frequency was swept in the 0.1–100 Hz range. The results revealed notable temperature effect on the storage and loss moduli only in the absence of the magnetic field, as observed in the earlier results. The results are thus limited to the storage and loss moduli frequency responses under different temperatures in absence of applied flux density (Fig. 12). The strong and nonlinear dependency of the storage modulus on the temperature is evident in the entire frequency range, which was also observed for the shear stress response in Fig. 2. The storage modulus of the MR fluid decreases considerably with temperature increasing from −5 to 20 °C. The modulus however varies only slightly with further increase in temperature. Considering the absence of magnetic field, the temperature dependency of the storage modulus should be interpreted with respect to the fluid performance rather than the chain-structure of iron particles. In this subject, reducing the temperature in the absence of the applied magnetic field results in reduction of the fluid's entropy and increase in its viscosity which subsequently demands for higher force to shear the fluid and thus higher storage modulus. Moreover, the storage modulus increased nearly linearly with the excitation frequency. For instance, the storage modulus at −5 °C increased from 20.8 kPa at 0.1 Hz to 77.8 kPa at 100 Hz, which represents an increase of about 57 kPa. The increases in the storage moduli at 10 and 40 °C in the same frequency band were only 18 kPa and 13.4 kPa, respectively. In the absence of the applied magnetic field, the loss modulus increases monotonically with increasing the frequency until it reaches to saturation as shown in Fig. 12(b). In addition, similar to the storage modulus, the loss modulus is temperature dependent in the absence of applied magnetic field and by increasing the temperature up to 20 °C the loss modulus decreases and remains constant for sample

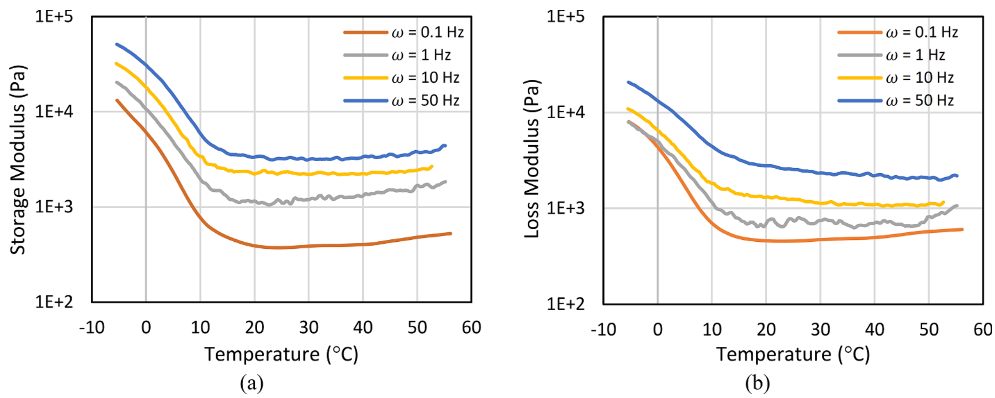

Fig. 14. Effect of excitation frequency on the variation in the (a) storage and (b) loss moduli of MRF-132DG with respect to temperature in absence of applied magnetic field at an strain amplitude of 0.01%.

temperature above 20 °C. This behavior could be attributed to the properties of the carrying oil whose apparent viscosity decreases by increasing the temperature.

The storage and loss moduli of MRF-122EG, MRF-132DG and MRF-140CG are also compared in frequency domain in Fig. 13. As it can be realized both the storage and loss moduli increase as the weight percentage of solid contents increases for the entire frequency range. Moreover, it is clear in this figure that both the moduli rise with frequency and increasing the weight fraction of iron particles enhances the frequency effect. This may be attributed to the fluid-like viscous behavior of the MR fluid in the absence of magnetic field causing increase in loss modulus (damping) as the frequency increases.

3.5. Temperature ramp analysis

The temperature dependency of the storage and loss moduli at higher levels of strain amplitude and frequencies are studied in the present section. The results obtained from the oscillatory tests conducted at a defined strain amplitudes (0.01, 0.1, 1.0, 5.0, 10 and 50%) and frequencies (0.1, 1.0, 10 and 50 Hz) while the temperature linearly increases from −5 to 50 °C in 30 min. Fig. 14 shows the frequency and temperature-dependency of the off-state storage and loss moduli of MRF-132DG which acts the in linear region at γ = 0.01%. As it can be seen for all frequencies both the moduli significantly decrease when temperature rises from −5 °C to about 10 °C, and then the storage and loss moduli remain almost steady with the temperature increase.

Fig. 15 presents the off-state storage and loss moduli of the MR fluid as a function of temperature for various strain amplitudes. Results show that for all the strain amplitudes, the storage and loss moduli also decrease when temperature increases from −5 to 10 °C. As the temperature further increases, the moduli remain approximately constant for strains in the linear viscoelastic region (γ = 0.01 and 0.1%). However, when the fluid enters into the nonlinear viscoelastic region (γ = 5, 10, and 50%), the moduli gradually decreases as the temperature increases. These results show in linear viscoelastic region (below strain amplitude of 0.1%), increasing the temperature from −5 °C to 55 °C causes the MR fluids pass the glassy (less than −5 °C) and transition (−5 °C to 15 °C) temperature regions and reach the rubberlike region (15 °C to 55 °C). Whereas, increasing the strain above the critical strain amplitude (above 1%) narrows the rubberlike region in which the storage modulus decreases with temperature while the loss factor increases.

As it was shown before, the three types of MR fluids (MRF-122EG, MRF-132DG, and MRF-140CG) generally behave similarly under various loading conditions. Therefore, herein the influence of temperature on the storage and loss moduli of these fluids is investigated at a specific loading condition (γ = 0.01% and ω = 1 Hz). Fig. 16 compares the variation of the storage and loss moduli of the three types of fluids with respect to temperature in the absence and presence of 0.1 T magnetic flux density. As it can be seen in this figure, in the absence of magnetic field both the storage and loss moduli initially decrease as the temperature rises, however, the critical temperature ($T_{cr.}$) at which the storage modulus become minimum varies for different MR fluids. It is shown in Fig. 16(a) that the critical temperature of MRF-122EG is greater than that of MRF-132DG which is also greater than the critical temperature of MRF-140CG. Therefore, it can be concluded that the critical temperature of MR fluids decreases as the weight fraction of solid particles increases. Moreover, Fig. 16(a) shows that though the storage modulus of the MRF-122EG and MRF-132DG does not considerably vary for temperatures above the critical temperature, the modulus of MRF-140CG increases slightly by further increase of temperature. This behavior can be described as the effect of temperature on the particle sizes. Increasing the temperature causes the iron particles to

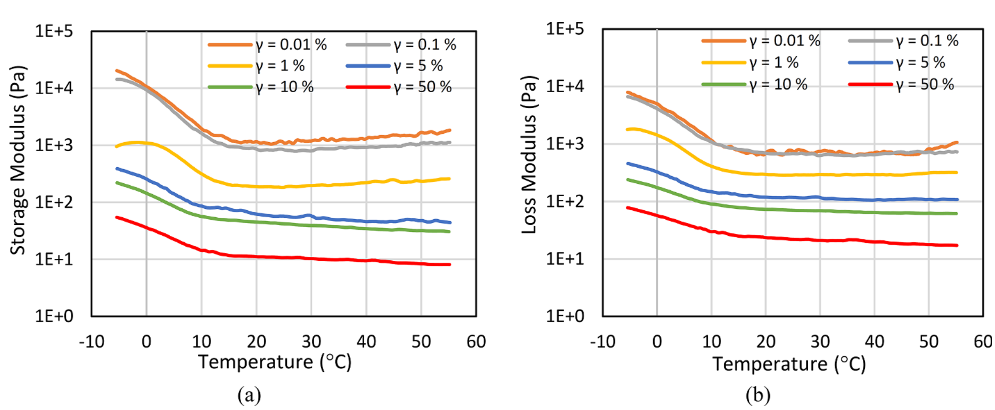

Fig. 15. Effect of strain amplitude on the variation in the (a) storage and (b) loss moduli of MRF-132DG with respect to temperature in absence of applied magnetic field at an excitation frequency of 1.0 Hz.

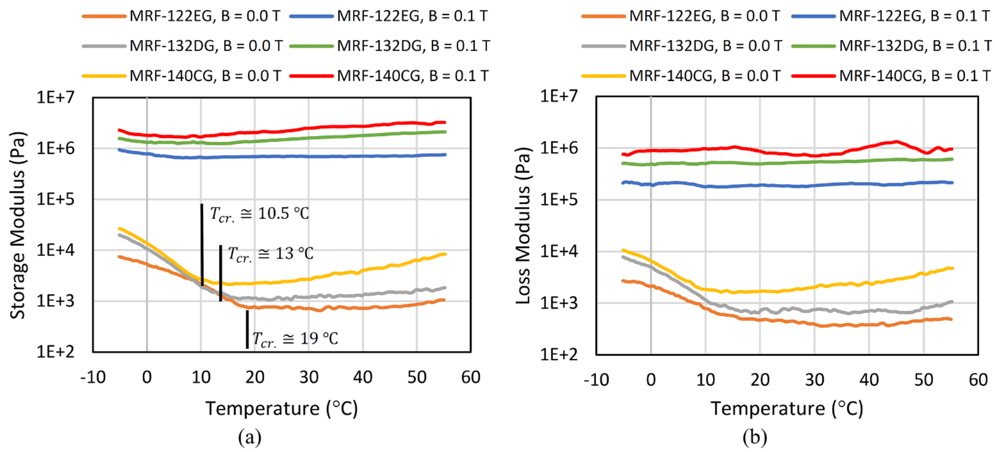

Fig. 16. (a) Storage and (b) loss moduli with respect to temperature for different MR fluids at an strain amplitude of 0.01% and excitation frequency of 1.0 Hz.

expand due to thermal expansion. The expansion of the iron particles including with the higher volume fraction of the particles in MRF-140CG reduce the space between the particles. Consequently, the friction between the iron particles increases and causes the storage moduli to increases. In addition, increasing the friction means that the material has a higher capacity to dissipate mechanical energy in terms of heat. This behavior can be seen in Fig. 16(b) in which the loss modulus of the MRF-140CG increases after the critical temperature. As also observed before, Fig. 16 also shows that the influence of temperature on both the storage and loss moduli decreases by applying magnetic field.

4. Conclusion

The present research study mainly concerns with the influence of temperature on the linear and nonlinear viscoelastic behavior of MR fluids. It has been shown that in absence of magnetic field the MR fluid is highly dependent on the temperature and shear stress increases by reducing the temperature especially below 10 °C. Moreover, it has been observed that applying the magnetic field decreases the effect of the carrier fluid and consequently the dependency of the MR fluid to the temperature decreases. The results also show the significant influence of the weight fraction of solid contents on increasing the yield stress. The storage and loss moduli of the MR fluids were carefully analyzed performing sweep strain amplitude and frequency tests. It was shown that in the linear region, the temperature mostly affects the storage and loss moduli in the absence of the applied flux density. The critical strain amplitude and associated linear storage modulus were presented with respect to the temperature and applied flux density and it was discussed that enhancing the applied magnetic field increases the critical strain amplitude while the linear storage modulus was saturated for magnetic flux densities above 0.2 T. In addition, the influence of the driving frequency on the viscoelastic properties of the MR fluids was studied and it was presented that the in absence of magnetic field both the storage and loss moduli increase with respect to the frequency. Furthermore, the time response of the MR fluid was presented for different strain amplitudes and the performance of the fluid in the linear and nonlinear regions were compared.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmmm.2019.166109.

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