



Investigation on the Rheological Properties of Polydimethylsiloxane

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Abstract. This paper focuses on studying the rheological properties of polydimethylsiloxane (PDMS). This polymer has been used to fabricate membranes and filters in engineering. The analysis of the rheological properties of this polymer is required for a further investigation of its mechanical behavior. In this study, the rheological behavior of PDMS is reported at different temperatures. This polymer showed steady shear viscosity during a short duration. However, this behavior changed with time and increased more with increasing temperature. The impact of the temperature increase was also observed when the shear viscosity of PDMS increased with shear strain. The increase of torque with shear strain and time was observed at different temperatures. Shear stress increased linearly with the shear rate at 20 °C and 40 °C. As expected, the deformation of the polymer required less shear stress with the increase of temperature. However, the change of shear stress with the shear rate at 60 °C was not linear, and the slope of the curve increased more at high shear rates. The results of this investigation can provide the required information for a better fabrication of membranes and filters with this polymer.

Keywords: rheology, polymer, mechanical properties, materials science, industrial growth.

1 Introduction

Polydimethylsiloxane (PDMS) is a “silicone rubber” polymer. Different steps such as hydrolysis and anionic, cationic, and radiation polymerization are used to synthesize this polymer [1, 2]. PDMS is transparent and resistant to thermal change, oxidation, and UV radiation [3–6]. It is worth noting that silicones do not produce any toxic material apart from a small amount of smoke during their combustion [3, 7]. Moreover, the thermal decomposition temperatures of PDMS are different because of significant differences in siloxane bond strength and segment flexibility in the main polymer chain, which also affect their toughening when used to prepare composites [3, 8]. The good elasticity of the siloxane chain can affect the hydrophobic properties of silicones and their low-temperature resistance. However, it can reduce the stability of these polymers at higher temperatures [9].

Different reaction mechanisms involve thermal depolymerization: random chain cleavage, attack of the PDMS chain end groups, and external reactions [10]. The type of functional groups and their positions on the chain and the molecular weight of PDMS affect the process of thermal depolymerization of the polymer [11]. It was

shown that replacing end hydroxyl groups with methyl groups could increase the thermal resistance. Cyclic siloxane oligomers were produced in this process [12]. Besides, vinyl end groups could change the polymer’s thermal degradation mechanism [13].

Silicone-based materials contain different substances, such as crosslinking systems, rheology modifiers, and adhesion promoters. [14–19]. The silicone-based framework can also be used to design nanoporous materials [20]. The surface hydrophilization of PDMS can be produced when plasma oxidation or UV radiation is applied. This can improve cell adhesion, help assemble microdevices, and improve samples’ wetting with physiological fluids [21, 22].

A study showed that the chemical treatment of PDMS can affect the rheological behavior of the nanocomposites prepared with it [23]. Another study revealed that the variations of the properties of the pressure-sensitive adhesives changed with the type and loading of filler concerning their rheological properties [24]. Another parameter that influences the nanocomposite thermal conductivity is the critical filler fraction, affecting the liquid-solid transition and interface conductance [25].

2 Research Methodology

The improvement of the mechanical behavior of PDMS depends on a better understanding of its rheological properties, which can lead to an appropriate investigation of these nanocomposites.

In this study, the rheological properties of PDMS at different temperatures are reported. This investigation allows a better understanding of the mechanical behavior of this polymer. This is the first investigation of this polymer reported with the analysis of rheological parameters at different temperatures to the author's knowledge.

PDMS (#423785) was purchased from Sigma Aldrich. The purchased polymer was in solution, and it was used in the rheological assessments without adding no other chemical.

The rheological properties of PDMS were determined with an Anton Paar MCR-302 rheometer [26–29]. The circular rheological measurements were performed in triplicate at 20 °C, 40 °C, and 60 °C [30].

The data analysis was performed with QtiPlot, a software that calculates mean values and standard deviations [31–34]. The statistical significance of the data was determined for all the graphs.

3 Results and Discussion

Figure 1 shows the viscosity of PDMS vs. the shear rate at different temperatures.

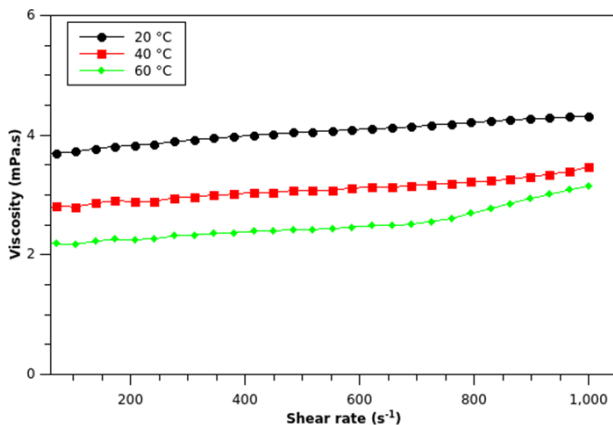


Figure 1 – Viscosity of PDMS vs. shear rate

As shown in Figure 1, the viscosity of PDMS increased with the increase of shear rate with a slight change. It was observed that the increase of viscosity was more at 60 °C at high shear rates, and the increase of viscosity with the shear rate was less at lower temperatures.

Figure 2 shows the change of viscosity of PDMS vs. shear strain at different temperatures.

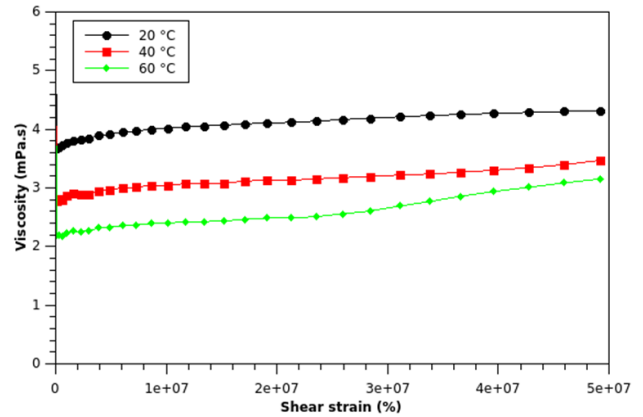


Figure 2 – Viscosity of PDMS vs. shear strain

As seen in this figure, the viscosity of PDMS increased with shear strain at all temperatures. The shear-thickening behavior of this polymer was more at 60 °C than in lower temperatures. The viscosity of the polymer became constant and reached a plateau at lower shear strain values. As the variation of viscosity with shear rate, in this case, also the shear thickening was stronger at 60 °C at high shear strain values. Although the variation of viscosity vs. shear strain of PDMS was almost linear at 20 °C at high shear strain values, it showed a slight increase at 40 °C. These results were attributed to the effect of temperature on the mobility of the polymer chains that led to its deformation.

The viscosity of PDMS vs. time curves at different temperatures is displayed in Figure 3. As shown in this figure, the changes in the viscosity of the polymer with time were similar to its changes with shear rate and shear strain, as shown in Figures 1, 2.

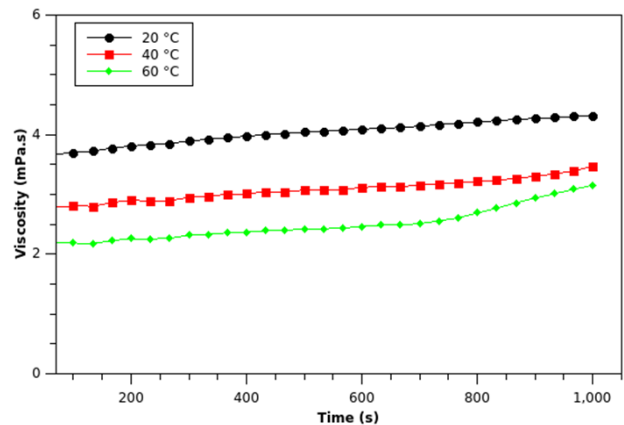


Figure 3 – Viscosity of PDMS vs. time

The viscosity values of PDMS vs. time at different temperatures are presented in Table 1. As observed in this table at 20 °C, the increased value of 0.28 mPa·s in viscosity was observed for PDMS between 600 s and 200 s. This increase was 0.23 mPa·s between 1000 s and 600 s. At 40 °C, this increase was 0.22 mPa·s between 600 s and 200 s and 0.35 mPa·s between 1000 s and 600 s, respectively, whereas it was 0.21 mPa·s in the first period and 0.68 mPa·s in the 2nd period, respectively. Therefore, the consistency between the results of this table and those of Figure 3 was observed.

Table 1 – Viscosity values of PDMS vs. time

Polymer/viscosity, mPa·s	Time (s)		
	200	600	1000
20 °C	3.81 ± 0.03	4.09 ± 0.01	4.32 ± 0.01
40 °C	2.90 ± 0.03	3.12 ± 0.01	3.47 ± 0.01
60 °C	2.26 ± 0.06	2.47 ± 0.01	3.15 ± 0.01

Figure 4 shows the torque vs. shear strain of PDMS at different temperatures. The torque values increased with shear strain at 20 °C, 40 °C, and 60 °C. However, an increase in the curve slope was observed at high shear strains at 60 °C. Moreover, as expected, the application of less amount of torque was required when the temperature increased.

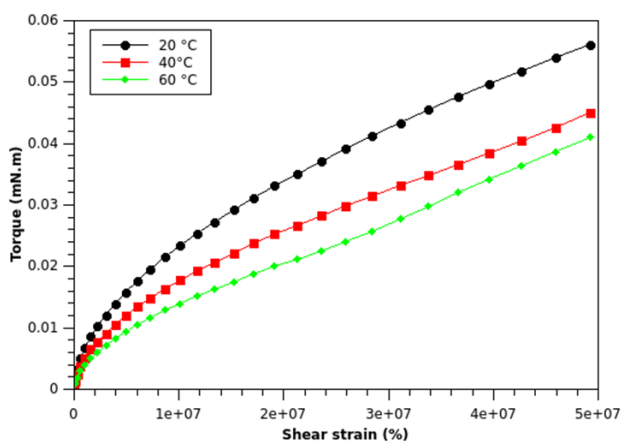


Figure 4 – Torque vs. shear strain of PDMS

The changes in the torque values for PDMS vs. time at different temperatures are displayed in Figure 5.

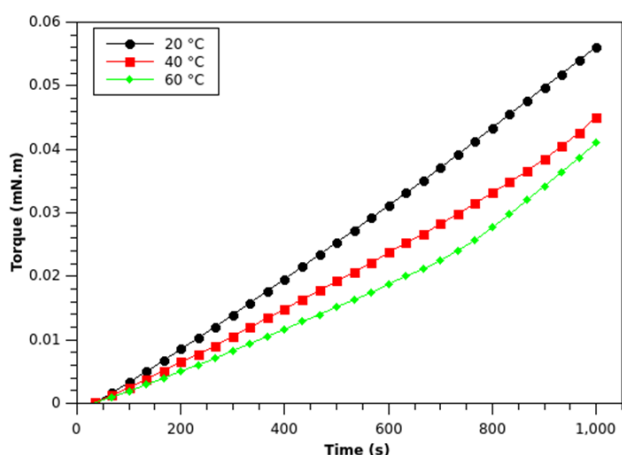


Figure 5 – Torque vs. time for PDMS

As shown in Figure 5, the torque values increased linearly with time at 20 °C and almost linearly at 40 °C, but the slope of the curve increased at 60 °C.

Figure 6 shows the shear stress vs. shear rate curves of PDMS at different temperatures. As observed in this figure, a linear increase and almost a linear increase of shear stress with the increase of shear rate were observed at 20 °C and 40 °C. However, this change was not linear at 60 °C.

Figure 7 shows the shear stress vs. shear strain curves of PDMS at different temperatures. The same shear stress changes were observed in Figure 7 as in the torque in Figure 4.

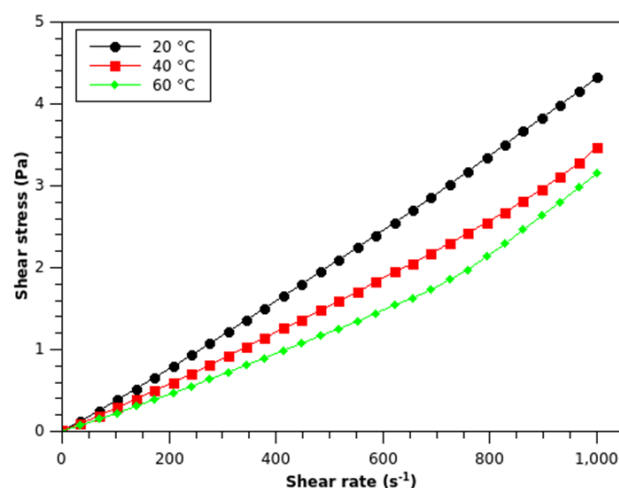


Figure 6 – Shear stress of PDMS vs. shear rate

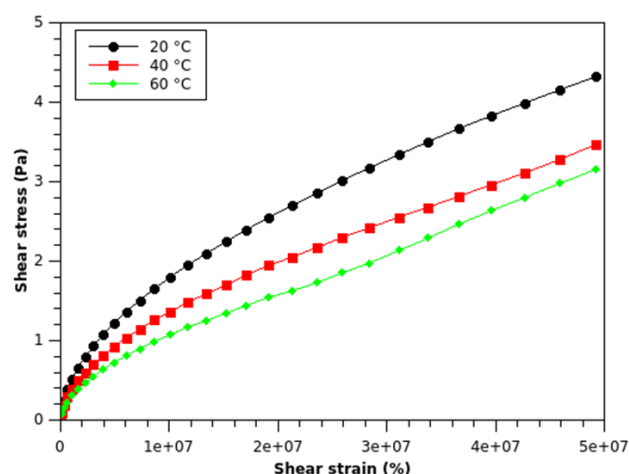


Figure 7 – Shear stress of PDMS vs. shear strain

Table 2 represents the shear stress values of PDMS vs. shear strain at different temperatures. As expected, the shear strain increase of the polymer from $1 \cdot 10^6$ to $2 \cdot 10^7$ would require more increase in the shear stress at 20 °C than 40 °C or 60 °C. However, closer shear stress values were required when the shear strain increased from $2 \cdot 10^7$ to $4 \cdot 10^7$.

Table 2 – Shear stress values of PVA and PEG vs. shear strain

Polymer/ shear stress, Pa	Shear strain, %		
	$1 \cdot 10^6$	$2 \cdot 10^7$	$4 \cdot 10^7$
20 °C	0.52 ± 0.01	2.70 ± 0.01	4.00 ± 0.01
40 °C	0.39 ± 0.02	2.05 ± 0.02	3.11 ± 0.01
60 °C	0.31 ± 0.01	1.63 ± 0.02	2.80 ± 0.01

4 Discussion

The pace of applications of PDMS in the preparation of the membranes and filters is expected to accelerate as this polymer has shown appropriate properties in new rubbers [35–42]. Various materials have been investigated with previous applications in materials science, pure sciences, and engineering [43–51].

These materials could modify the properties of PDMS in the mentioned applications. This could be directed toward the exploration of its novel applications.

Recently the properties of some polymers have been investigated that can be used to prepare blends with PDMS [52–60]. It is worth noting that adding some nanomaterials without or with other polymers to PDMS can prepare diverse nanocomposites with interesting properties [61–68].

Carbon nanotubes, polyamide with metal-organic framework nanoparticles, poly (vinylidene fluoride), and poly (ether ketone) have been used for the preparation of new membranes [69–74].

More investigations on these materials, including PDMS, can improve the quality of new membranes and filters [75–77].

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5 Conclusions

This investigation reported the rheological properties of PDMS at different temperatures. The polymer showed viscosity stability at 20 °C and 40 °C vs. shear rate. However, at 60 °C more significant viscosity increase was observed at high shear rates. Moreover, the viscosity of PDMS increased at all temperatures with shear strain, which revealed its shear thickening behavior. The changes in the viscosity of the polymer were like its changes with shear rate and shear strain vs. time. The increase of torque with shear strain and time and shear stress with shear rate and time were observed in this investigation. However, the patterns of the change of these parameters were different at 60 °C in comparison with lower temperatures. This study can better prepare membranes and filters with this polymer regarding its rheological properties.

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