Engineering Research
Express

PAPER • **OPEN ACCESS**

Rheological evaluation of xanthan gum and carboxymethyl cellulose for enhanced oil recovery: effects of concentration, salinity, and temperature

To cite this article: Muzammil Jehangir *et al* 2025 *Eng. Res. Express* **7** 045009

IOP Publishing Eng. Res. Express 7 (2025) 045009 https://doi.org/10.1088/2631-8695/ae1dc8

Engineering Research Express

OPEN ACCESS

RECEIVED
15 April 2025

REVISED
26 October 2025

ACCEPTED FOR PUBLICATION
10 November 2025

PUBLISHED
19 November 2025

PAPER

Rheological evaluation of xanthan gum and carboxymethyl cellulose for enhanced oil recovery: effects of concentration, salinity, and temperature

Muzammil Jehangir[1], **Tanveer Iqbal**[2], **Saima Yasin**[1], **Naveed Ramzan**[1] **and Asif Jamil**[2,3,*]

[1] Department of Chemical Engineering, University of Engineering and Technology Lahore, 54890, Pakistan
[2] Department of Chemical, Polymer and Composite Materials Engineering, University of Engineering and Technology Lahore (New-Campus), 39021, Pakistan
[3] Department of Mechanical Engineering, Kaunas University of Technology, Kaunas, 44249, Lithuania
[*] Author to whom any correspondence should be addressed.

E-mail: **muhammad.jamil@ktu.lt**

Keywords: xanthan gum, enhanced oil recovery, Herschel-Bulkley model, rheology, carboxymethyl cellulose

Abstract

Global energy demand continues to rise and is projected to increase by 50%–60% in the next decade. To meet this demand, enhanced oil recovery (EOR) techniques are being employed to maximize extraction from existing reservoirs. Polymer flooding is a promising EOR method, where water-soluble polymers improve sweep efficiency by increasing the viscosity of the displacing fluid. However, successful polymer flooding relies on careful polymer selection and a thorough understanding of rheological behavior. This study presents a systematic rheological evaluation of two polymers, Xanthan Gum (XG, $C_{35}H_{49}O_{29}$) and Carboxymethyl Cellulose (CMC), at varying concentrations (0.25, 0.50, 0.75, and 1 wt%) for EOR applications. Steady-shear rheology, thermal stability, and salinity effects were investigated to assess polymer performance under different conditions. The Herschel-Bulkley and Cross models were used to characterize the non-Newtonian behavior of the polymers. Results indicate that higher polymer concentrations enhance viscosity and shear-thinning behavior. However, salinity (NaCl and $MgCl_2$) reduces solution viscosity, while increasing temperature (25 °C, 50 °C, and 75 °C) further diminishes viscosity. These findings provide critical insights into polymer selection and optimization for efficient EOR processes.

1. Introduction

World energy demand is growing day by day and is expected to increase by 55%–65% in the next decade [1]. Since oil and gas are the major sources of energy, it is predicted that they will remain the primary sources in the future [2]. To meet the energy crisis, it is therefore essential to enhance oil recovery from low-productive wells or to drill new reservoirs [3]. Many methods are used to recover oil from wells. In the primary phase, oil is recovered by the natural drive, i.e., the energy stored in the reservoir due to volatile components [4]. In the secondary phase, recovery is achieved by injecting high-pressure water or gas (CO_2, N_2) into the reservoir [5]. For the recovery of the remaining heavy oil, a tertiary recovery process, also termed enhanced oil recovery (EOR), is used [6]. The EOR (tertiary phase) of oil recovery is further classified into three main categories: thermal EOR, waterflooding/gas flooding EOR, and chemical flooding EOR [7]. In chemical flooding, the most popular method is polymer flooding (PF), which is widely practiced in the field [8]. In polymer flooding for EOR applications, a high-viscosity polymer solution is injected into the reservoir to reduce the mobility ratio of trapped oil and sweep out the remaining oil [9, 10].

In chemical EOR, PF is one of the most commonly used methods that can be considered for enhancing oil recovery [11]. PF is most favorable for oil reservoirs with low salinity and low temperature [12]. Another significant mechanism of PF is the enhancement of sweep efficiency and the reduction of viscous fingering [13].

Beyond this, other factors such as the rheology of the solution, thermal stability, adsorption, compatibility, core flooding, injectivity, and cost are also important considerations for EOR using polymers [14].

Several polymers have been evaluated by researchers for chemical EOR applications [15]. Nevertheless, the polymer selection also takes into consideration the reservoir rock permeability and oil viscosity to achieve optimal performance [16]. Moreover, it is important to select a polymer that exhibits thermal stability in high-salt brine and at high temperatures [17]. Both synthetic and biopolymers can be used as injection solutions [18]. The primary advantage of most biopolymers studied for PF application is their environmental friendliness. Among the biopolymers that could be employed for EOR, carboxymethylcellulose and xanthan gum (XG) show the most promise for future applications. Given the variety of bio-based PF options available, it is critical to identify which polymer backbone properties are most significant for the application [19].

XG is a biopolymer (polysaccharide) that is widely used in chemical EOR. The polymer XG is produced through a bacterial fermentation process involving the polymerization of saccharide molecules [20]. Due to the high rigidity of its polysaccharide chain, xanthan is less sensitive to mechanical shear. Since it is essential for chemical EOR projects, especially those involving polymers, to control the viscosity of xanthan under varying salinity and temperature conditions, these factors have attracted significant research attention regarding its application in the CEOR process [21, 22].

Carboxymethyl cellulose (CMC) is a derivative of cellulose used as a solution viscosifier in various industries [23]. It has been reported that the rheological properties of CMC solutions with concentrations of 1%–5% are nearly Newtonian and exhibit viscoelastic and pseudoplastic behavior [24]. Abdelrahim *et al* studied the rheological properties of CMC solutions with concentrations of 2%–5% over a temperature range of 30–90 °C using a rotational rheometer [25]. Planas *et al* also investigated the rheological behavior of CMC solutions in the range of 1%–2.5%, analyzing the properties in terms of concentration differences, temperature changes, and storage time durations [26].

This paper presents the rheological evaluation of XG and CMC for EOR applications. This study specifically evaluates XG and CMC for EOR, testing their stability and rheology directly in saline water to simulate reservoir conditions, which represents a critical and application-focused advancement over previous general rheological studies. In the rheological evaluation, steady shear and viscosity behavior experiments are performed at different temperatures and polymer concentrations. To ensure stability against salinity, the polymers are dissolved in saline water before performing rheological tests. The thermal behavior of the polymers was studied over different temperature ranges using a rheometer. The Herschel–Bulkley and Cross models are then used to analyze the rheological parameters and characterize the non-Newtonian behavior.

2. Experimental

2.1. Materials

High molecular weight (MW) and high-quality industrial-grade XG ($C_{35}H_{49}O_{29}$, 100% through 60 mesh, $\geqslant$95% through 80 mesh) was purchased from Shanghai Tianjia Biochemical Co., Ltd, a local distributor, in powder form and used in its pure form without any alteration. XG is an extracellular polymer characterized by high resistance to shear degradation, shear-thinning behavior, stability over a wide range of temperatures, and high viscosity at low shear rates.

CMC (MW 263, 100 mesh size) was also procured from Shanghai Tianjia Biochemical Co., Ltd, a local distributor, in powder form and used in pure form. Moreover, CMC presents a lower environmental hazard and is a semicrystalline anionic polymer capable of forming strong bonds with oppositely charged materials. Distilled water with a pH of 6.5–7.5 was used for solution preparation.

The salts sodium chloride (NaCl), in white crystalline form with a density of 2.165 g mL^{-1} and a boiling point of 1413 °C, and magnesium chloride ($MgCl_2$), in colorless crystalline form with a density of 2.32 g/cm^3 and a boiling point of 1412 °C, were also procured from a Sigma Chemical Firm local distributor in pure form.

2.2. Polymer solution preparation

The solutions of both polymers, XG and CMC, were separately prepared in distilled water at concentrations of 0.25, 0.50, 0.75, and 1 wt% using a magnetic stirrer operating at 600 rpm. To prevent the formation of lumps, the polymers were gradually poured onto the shoulder of the vortex created in the deionized water. After 3–4 h of stirring, the completely dissolved polymer solutions were kept in sealed jars at room temperature for 24 h to allow full hydration. After complete hydration, steady shear rheology and thermal stability tests were performed using a rotational rheometer.

To investigate the effect of salinity on the rheological properties of polymer solutions, salt solutions (NaCl and $MgCl_2$) with different molar concentrations (0.25 M, 0.50 M, 0.75 M, and 1 M) were prepared at room temperature using a magnetic stirrer operating at 300 rpm. The polymers XG and CMC, each at 1 wt%, were then added separately to the brine solutions and placed in airtight sealed beakers for 24 h to allow hydration. After complete hydration of the samples, rheological tests were performed.

2.3. Rheological properties measurements

The rheological tests of the solutions were performed using a LAUDA RE-620 rotational rheometer equipped with a sample filling cup and cone geometry (rotor diameter: 35.04 mm, rotor length: 52.56 mm, filling cup capacity: 38 mL, sample volume: 30 mL). This instrument is used for the characterization and measurement of rheological properties of both Newtonian and non-Newtonian fluids. In this study, the rheometer was used to assess apparent viscosity versus shear rate and steady shear rheology at different polymer concentrations and temperatures (25 °C, 50 °C, and 75 °C). To evaluate the effect of salinity, polymer solutions were prepared with different molar concentrations of salt, and their rheological properties were observed. For measuring rheological parameters; shear stress (τ), viscosity (η), and shear rate (γ); a 30 mL sample was loaded into the rheometer. After completing the experimental work, two rheological models, the Cross model and the Herschel–Bulkley model, were used for evaluation.

2.4. Models

The rheological characteristics of various polymer solutions were examined using the Cross model. The experimental rheological data were fitted to the Cross model to obtain the corresponding rheological parameters, as described in the literature.

$$\mu = \frac{(\mu 0 - \mu\infty)}{(1 + (\mathrm{k}\check{\ddot{Y}})\hat{}\,\mathrm{n})} + \mu\infty \tag{1}$$

The Herschel–Bulkley model was employed to investigate the behavior of the polymer compositions. The shear stress versus shear rate values were fitted to the Herschel–Bulkley model. According to the literature, most polymers fit well with this model.

$$\tau = \tau 0 + k(\gamma)n \tag{2}$$

Nonlinear regression analysis was used to determine the rheological parameters in Excel using the SOLVER tool. Shear stress (Pa), flow consistency index k (Pa·s$^{\mathrm{n}}$), shear rate (1/s), flow behavior index (n), and yield stress (Pa) are all represented in the equations above.

2.5. Shear degradation

One of the most serious concerns, particularly for biopolymers, is the material's potential for shear degradation. During PF, the polymer solution is typically exposed to high flow rates (and consequently high shear stresses) and sudden pressure fluctuations, both of which can cause backbone breakdown. As a result, the MW of the polymer decreases, leading to a reduction in viscosity and overall effectiveness of the polymer solution. According to the literature, high-MW polymers offer several advantages for EOR, including improved viscosity modification.

2.6. Thermal stability of polymers

The first step is to recognize the importance of selecting thermally stable polymeric materials. It is also essential to understand the resistance of the polymeric material to thermal decomposition. Short-term temperature effects and long-term temperature effects are the two main approaches used to determine how the thermal degradation of a polymer solution changes with temperature.

2.7. Salinity impact

When selecting the composition and microstructure of a polymer, consideration must be given to the composition of the brine used for PF or the types of salts present in the reservoir. Moreover, the mechanical, thermal, and chemical stability of EOR polymers can be affected by the ions present in the solution. The reduction in polymer viscosity is often caused by salinity and hardness, the new polymeric materials being developed for EOR must be 'brine-friendly' or 'salt-tolerant.'

3. Results and discussions

The experimental results of XG and CMC are presented in this section. Various concentrations of both polymers (0.25, 0.50, 0.75, and 1 wt%) were selected for evaluation. The effects of polymer concentration on rheological properties, steady shear rheology, temperature dependency of viscosity, and salinity impact on both polymers are discussed. After the experiments, the data were further analyzed using rheological models, namely

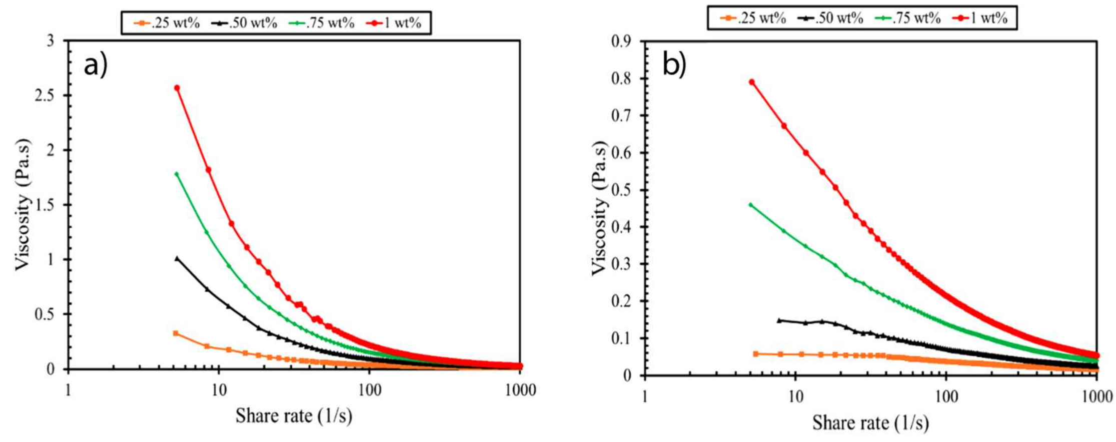

Figure 1. Effect on viscosity by changing the concentration of , (a) Xanthan, and, (b), CMC at 25℃.

the Cross model and the Herschel–Bulkley model. Rheological parameters were obtained using Excel's SOLVER tool and nonlinear regression analysis.

3.1. Effect of polymer's concentration on the rheological properties

The rheological properties of the natural polymers XG and CMC were investigated at varying weight-per-unit-volume concentrations. At 25 °C, 50 °C, and 75 °C, shear stress and viscosity curves were obtained using variable shear rates (1/s to 1000/s). The viscosity of the polymer solutions increased as the concentration increased from 0.25 wt% to 0.50 wt%, 0.75 wt%, and 1 wt% in distilled water, and the behavior of the polymer solutions changed from Newtonian to pseudoplastic.

Figures 1(a) and (b) shows the viscosity versus shear rate plots of polymers XG and CMC in distilled water at 25 °C, 50 °C, and 75 °C for different weight-per-volume percentages (w/v%). Shear-thinning behavior was observed in all polymer solutions at these temperatures. The viscosity of all polymer solutions is strongly influenced by their molecular structure and concentration. The viscosity of a polymer under shear force is determined by factors such as functional group distribution, MW, ionic strength, surface charge, degree of hydrolysis, and molecular chain network. However, in this study, only the polymer's MW was considered to determine its stable shear viscosity.

As shown in figure 1(b), there is a significant difference in the viscosities of polymers XG and CMC at low shear rates, and this difference becomes more pronounced as the shear rate increases. The main reason for this is that, at lower shear rates, polymer XG with its higher MW has more molecular chains per unit volume, resulting in shorter intermolecular distances and stronger bonding strength compared to polymer CMC with lower MW. XG solutions exhibit strong pseudoplastic behavior, and although shear-thinning occurs when shear rate is applied, the initial viscosity is quickly restored when the shear rate is reduced. A similar observation was reported by Zheng *et al* when analyzing the effect of polymer addition on viscosity at different shear rates [27].

When the shear rate is increased, the molecular chains align in the direction of flow, making it easier to break the stretched molecular structures [28]. Several researchers have noted that polymer concentration has a greater effect at low shear rates than at high shear rates [29]. As the concentration of a high-MW polymer in the solvent increases, the molecular chains per unit volume become denser and more entangled. The intermolecular interactions between the molecules strengthen, leading to an increase in the apparent viscosity of the solution, making it more stable under lower shear forces.

To solidify the shear-thinning behavior of both polymers Xanthan and CMC solution, the experimental data was evaluated by Cross-Model which is used for viscosity data of solution analysis.

$$\mu = \frac{(\mu 0 - \mu\infty)}{(1 + (\mathrm{k}\check{\mathrm{Y}})\hat{\ }\mathrm{n})} + \mu\infty$$

where μ (Pa.s) is the viscosity at shear rate (y), μ_o is zero shear viscosity and μ_∞ (Pa.S) is infinite shear rate viscosity. The other parameter of the Cross-Model is the Flow Consistency Index (K) and the Flow Behavior Index (n). Figures 2 (a), and (b) shows the Cross-model fitting of Xanthan and CMC solution, respectively. Their rheological parameter is listed in tables 1 and 2.

The Cross-model parameters for XG and CMC are listed in table 1 and table 2, respectively. As expected, the zero-shear viscosities increased for both polymers with increasing concentration. All infinite-shear viscosities

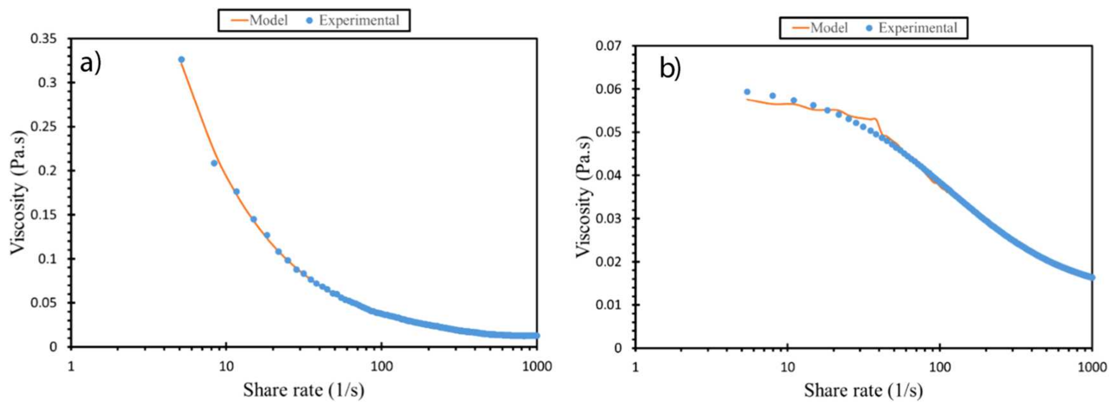

Figure 2. Cross-Model curve fitting of polymer at 0.25 wt% of, (a) Xanthan, (b) CMC at.

Table 1. Cross-model parameter of Xanthan solution at 25℃.

Concentration (w/v)%	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
0.25%	0.33	0	0.05	0.98
0.50%	1.6	0.02	0.10	0.81
0.75%	2.8	0.03	0.09	0.67
1.00%	6.1	0.01	0.13	0.43

Table 2. Cross-model parameter of CMC solution at 25℃.

Concentration (w/v)%	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
0.25%	1.06	0.01	0.006	0.95
0.50%	1.17	0.01	0.030	0.87
0.75%	1.00	0	0.471	0.57
1.00%	1.50	0	0.329	0.43

were within a factor of two, indicating that at higher flow rates, the solutions converge toward similar viscosity values. The values of '*K*' also showed a slight increase. The exponential parameter '*n*' (flow behavior index) exhibited a decreasing trend with increasing concentration.

3.2. Steady shear rheology of CMC and Xanthan solutions

The flow behavior of XG and CMC aqueous solutions was characterized at all temperatures under varying shear rates. Figures 3(a) and (b) shows the experimental results of shear stress (Pa) versus shear rate (1/s) for different concentrations (0.25, 0.50, 0.75, and 1 wt%) at room temperature. The flow curve data for both polymers, which have distinct compositions, are illustrated in the graphs. Both XG and CMC exhibit non-Newtonian flow behavior with shear-thinning characteristics. However, an initial yield stress appears in the solutions just before flow begins.

The rheological data for the flow curves were analyzed by using the Herschel-Bulkley model because this model is satisfactory and explains the flow curves very well.

$$\tau = \tau 0 + k(\gamma)n$$

In the above equations, the notations are for the shear stress, *k* is for flow consistency (Pa.s^{n}), is for shear rate (1/s), *n* is for flow behavior index, and γ (Pa) is for the yield stress. Figures 4 (a), and (b) show the good fit of Herschel-Buckley in the graphic position. For both polymers, the curves of the experiment and model fit very well.

The rheological parameters for the Herschel–Bulkley model are presented in table 3 and table 4. All parameters show a good fit to the Herschel–Bulkley model and indicate pseudoplastic behavior with yield stress. As the concentration increases, the flow consistency index (K) value rises, while the flow behavior index (n) value decreases. All n values are less than one, confirming that both xanthan and CMC exhibit pseudoplastic fluid behavior. The magnitudes of yield stress (τ_0) and consistency index (K), as determined by the Herschel–Bulkley model, increase with the polymer concentration. Moreover, the tables show that the value of τ_0

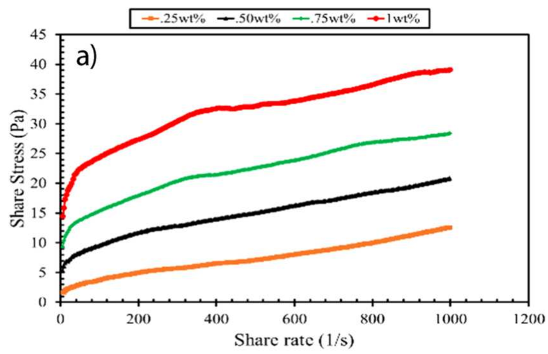

Figure 3. Effect of, (a) Xanthan, and (b), CMC, concentration on shear stress at 25℃.

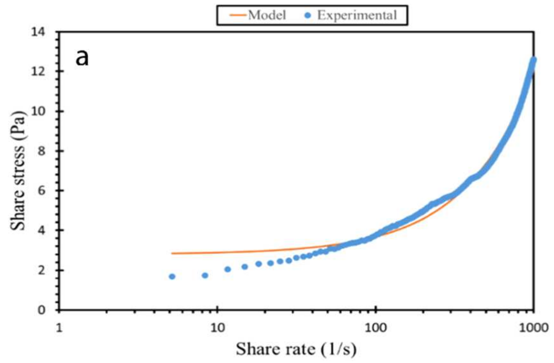

Figure 4. Flow Curve Herschel-Bulkley model fitting of 0.25 wt%, (a) Xanthan, and (b) CMC.

Table 3. Herschel-bulkley model parameter of Xanthan solution at 25℃.

Concentration (w/v)%	Yield stress (t_0)	Flow behavior index (n)	Flow consistency index (k)	R^2
0.25%	2.80	0.96	0.007	1.01
0.50%	6.24	0.63	0.178	1.00
0.75%	8.96	0.48	0.707	1.00
1%	10.1	0.29	3.06	1.01

Table 4. Herschel-Bulkley Model Parameter of CMC Solution at 25℃.

Concentration (w/v)%	Yield stress (t_0)	Flow behavior index (n)	Flow consistency index (k)	R^2
0.25%	0.06	0.99	1.02	1.01
0.50%	0.12	0.49	1.66	0.93
0.75%	0.35	0.45	1.79	0.96
1%	1.13	0.40	3.37	1.00

increases gradually from 2.80 to 10.1 for XG and from 0.06 to 1.13 for CMC as the concentration increases from 0.25 wt% to 1 wt%, respectively. The higher yield stress of the xanthan solution compared to the CMC solution indicates that xanthan molecules are more strongly bound to each other, forming a stronger network in solution.

3.3. Temperature dependency on the viscosity of XG and CMC solution

The temperature or salinity of the solution can cause XG and CMC molecules to undergo an order–disorder transition. This transition is characterized by a significant reduction in viscosity as the transition temperature is approached. The rheological properties of 0.25 wt% XG and CMC polymer solutions were investigated at three

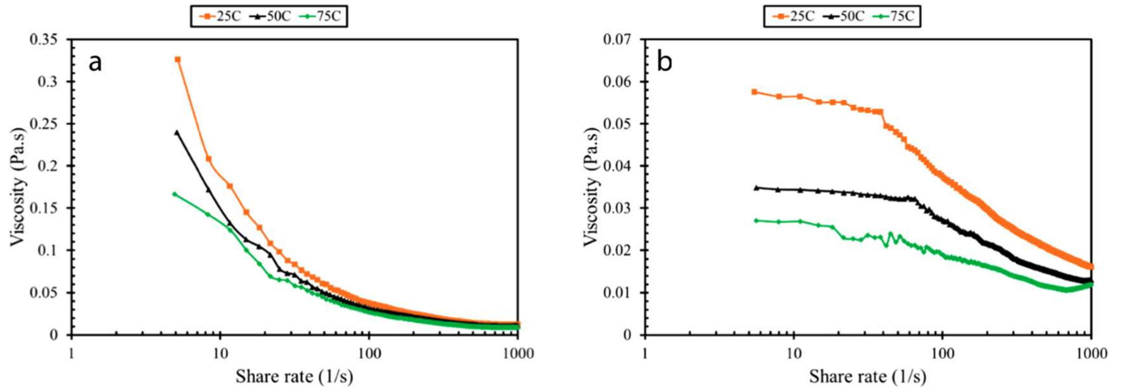

Figure 5. Viscosity variations for, (a) Xanthan and, (b) CMC, at various temperatures.

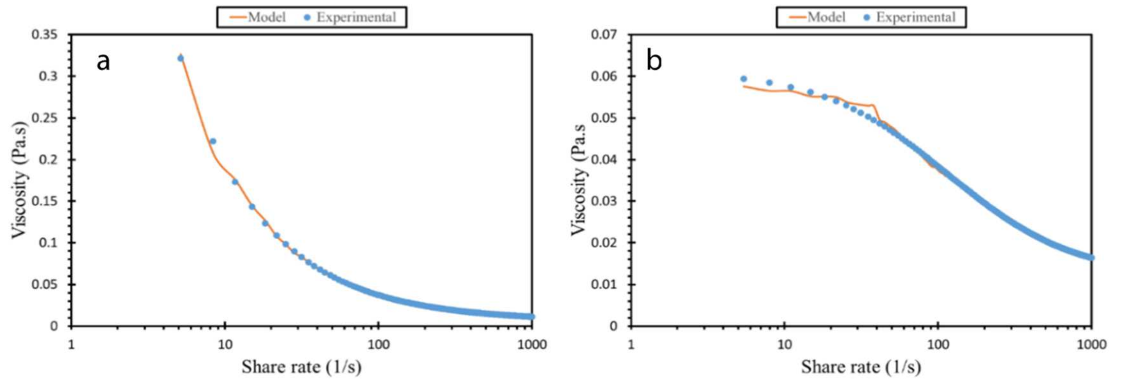

Figure 6. Cross Model Temperature effect on, (a) Xanthan and (b) CMC.

Table 5. Cross model parameter of XG solution at 25 °C, 50 °C and 75 °C.

Temperature (℃)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
25	0.99	0.01	0.90	0.78
50	0.90	0	0.98	0.79
75	0.87	0	1.00	0.82

different temperatures, as shown in figure 5(a) and b). At higher temperatures, the rheological properties of the polymers are affected primarily due to the loss of viscosity. As the temperature increases, the viscosity of the XG and CMC solutions decreases, particularly in the low shear rate range, where a notable reduction is observed. As the shear rate increases, the change in apparent viscosity at various temperatures remains consistent. This phenomenon is attributed to structural changes in the polymer macromolecules, where the structure transitions from an ordered state at low temperatures to a disordered state at high temperatures.

For further investigation of the temperature dependence on the rheological properties of both polymers, the data were analyzed using the Cross model, and the corresponding parameters were calculated. The curve-fitting graphs for the Cross model of both polymers are shown in figure 6(a) and (b).

The temperature dependence of the rheological parameters for both polymers, XG and CMC, is shown in tables 5 and 6, respectively. The flow behavior index (n) for both polymers increases steadily with temperature, indicating a slight shift in the system toward pseudoplastic behavior. While the value of n, derived from the Cross model, fluctuated slightly but generally decreased with increasing temperature for both polymers, the magnitude of the consistency index (k) decreased as the temperature increased. This behavior indicates that the microstructure of the xanthan solution is temperature-sensitive, allowing some shear-thinning behavior to persist even at elevated temperatures.

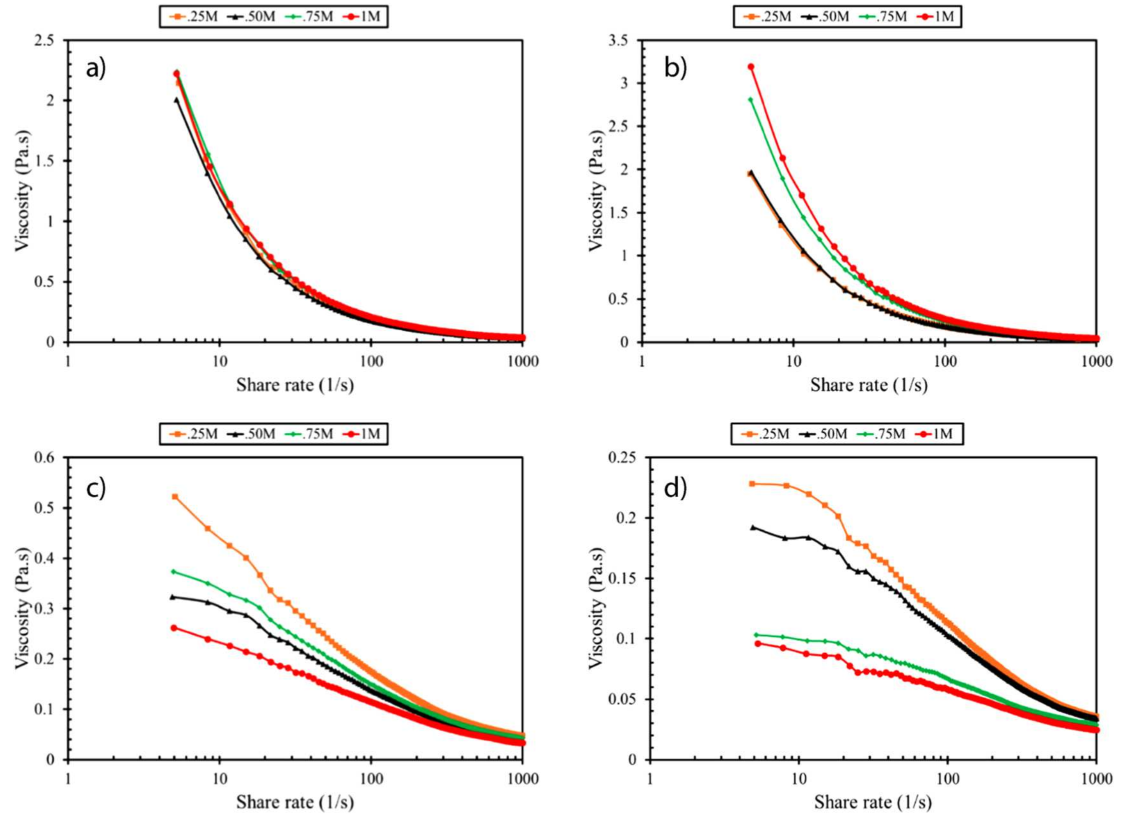

Figure 7. Effect of Xanthan gum with, (a) NaCl, (b) MgCl, and CMC solution with, c) NaCl, d) MgCl.

Table 6. Cross Model Parameter of CMC Solution at 25 °C, 50 °C and 75 °C.

Temperature (℃)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
25	0.06	0.01	0	0.87
50	0.04	0	0.02	0.93
75	0.02	0	0	0.98

3.4. Salinity effects on the viscosity of CMC and Xanthan solutions

High temperature and salinity are two major challenges in EOR, as polymer solutions lose viscosity significantly when exposed to these conditions. To investigate the influence of salinity on the polymer solutions of XG and CMC, molar solutions of NaCl and $MgCl_2$ were prepared in the laboratory. Salt solutions with molar concentrations of 0.25 M, 0.50 M, 0.75 M, and 1 M were used to evaluate the performance of 1 wt% polymer solutions. At 25 °C, the effect of salt content on both polymer solutions is shown in figure 7. The viscosity of both polymers decreases as the salt molarity increases, with the greatest reduction occurring at higher molar concentrations for both polymers. However, the key difference between the two polymers is that xanthan exhibits greater resistance to salinity due to its macromolecular structure, whereas the viscosity of the CMC solution is more severely affected by salt, as shown in the graphs.

The data were evaluated using the Cross-model, and the corresponding parameters were calculated to further examine the salinity dependence of the rheological properties of both polymers. The curve-fitting graphs for the Cross-models of both polymers are presented in figure 8.

The rheological parameters calculated for the XG and CMC polymer solutions in saline water (NaCl and $MgCl_2$) are listed in table 7 and table 8. In saline water, the flow behavior index (n) increases, while viscosity decreases as the molar concentration of salts increases. The decrease in μ_0 from 0.25 M to 0.50 M NaCl is likely due to the salt ions screening the charges on the xanthan chains, causing them to coil and consequently lowering the viscosity. At higher salt concentrations (0.75–1.0 M), weak chain–chain associations or aggregations may form, resulting in a slight increase in viscosity. Thus, the observed non-monotonic trend reflects a balance between charge screening (which reduces μ_0) and aggregation (which increases μ_0). At a high salt concentration (1 M NaCl), electrostatic repulsion between xanthan chains is completely screened, leading the chains to collapse into compact coils and reduce entanglement and network formation. With minimal structural resistance to shear, the solution behaves more like a Newtonian fluid.

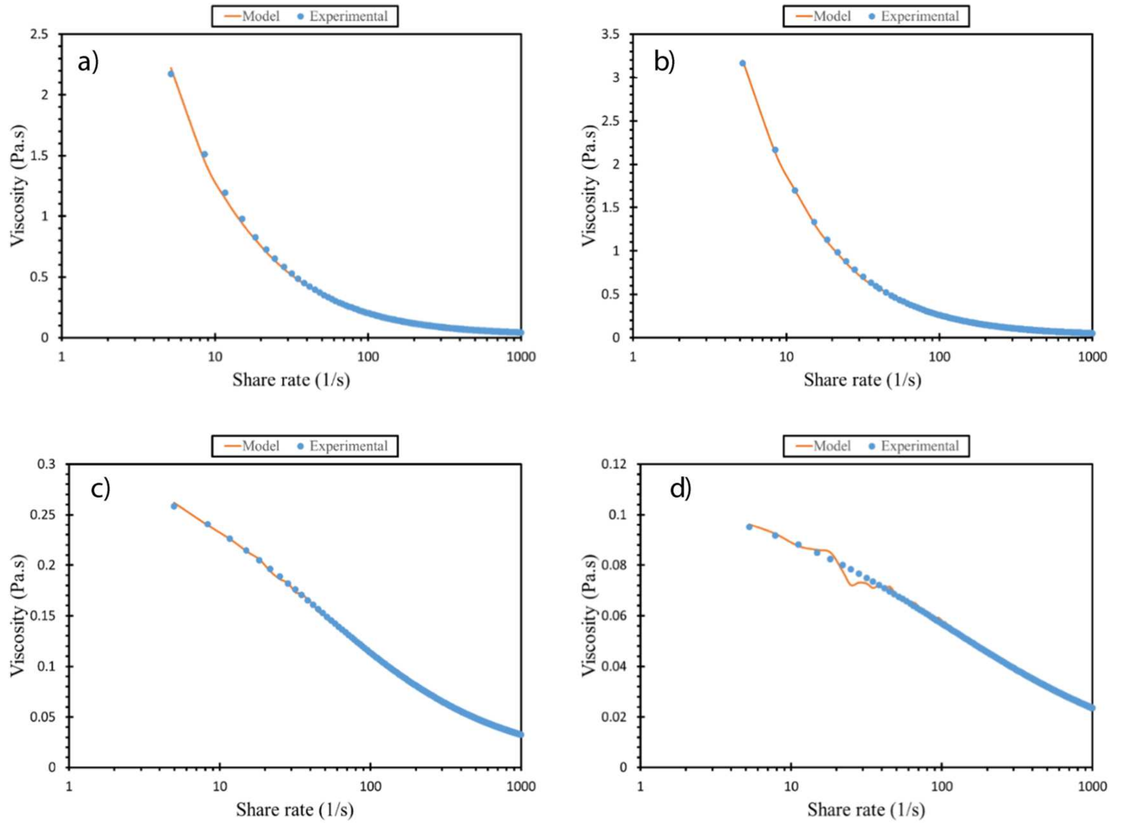

Figure 8. Cross-Model fitting for Xanthan with, (a) NaCl, (b) MgCl, and, for CMC, (c) NaCl, and (d) MgCl.

Table 7. Rheological Parameter of Cross-Model for NaCl molar concentration.

	XG				CMC			
Molar Conc. (M)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
0.25	9.71	0.02	0.73	0.94	0.96	0	0.27	0.46
0.50	7.08	0.02	0.50	0.98	0.78	0	0.45	0.52
0.75	7.83	0.02	0.49	0.99	0.84	0	0.39	0.54
1	8.26	0.02	0.45	1	0.87	0	0.06	0.71

Table 8. Rheological parameter of cross-model for MgCl molar concentration.

	XG				CMC			
Molar Conc. (M)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)	Viscosity (μ_0)	Infinite viscosity (μ_∞)	Flow consistency index (k)	Flow behavior index (n)
0.25	4.78	0.02	0.28	1.00	0.25	0.01	0.02	0.87
0.50	4.82	0.02	0.26	1.00	0.22	0	0.04	0.71
0.75	13.7	0.02	0.83	0.98	0.10	0.01	0	1
1.00	15.2	0.02	0.85	0.99	0.11	0	0.06	0.90

4. Conclusion

This study evaluated the rheological properties of XG and CMC for EOR. Increasing polymer concentration enhanced viscosity, shifting the system from non-Newtonian to pseudoplastic behavior, with both polymers exhibiting shear-thinning characteristics. XG demonstrated greater shear resistance than CMC due to its robust macromolecular structure. The flow behavior index (n) correlated with shear-thinning intensity, while the yield stress and consistency index increased with concentration. At higher shear rates, all solutions exhibited similar behavior, whereas viscosity at lower shear rates depended strongly on concentration. Temperature and salinity significantly influenced performance. Heating reduced viscosity; XG showed a 20% decrease at 50 °C and 40% at 75 °C, while CMC declined by 35% and 70%, respectively. Salinity tests using NaCl and $MgCl_2$ solutions revealed that increased ionic concentration further reduced viscosity due to charge shielding effects. These findings highlight critical considerations for polymer selection in EOR applications.

Acknowledgments

The work is supported by the National Research Program for Universities (NRPU), Higher Education Commission Pakistan, No. 20-15709/NRPU/R&D/HEC/2021.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

References

[1] Guo H *et al* 2021 Recent advances in polymer flooding in China: Lessons learned and continuing development *SPE J.* **26** 2038–52
[2] Sheng J J, Leonhardt B and Azri N 2015 Status of Polymer-Flooding Technology, *Journal of Canadian Petroleum Technology* **54** 116–26
[3] Mogensen K and Masalmeh S 2020 A review of EOR techniques for carbonate reservoirs in challenging geological settings *Journal of Petroleum Science and Engineering* **195** 107889
[4] Malik I A, Al-Mubaiyedh U A, Sultan A S, Kamal M S and Hussein I A 2016 Rheological and thermal properties of novel surfactant-polymer systems for EOR applications *Can. J. Chem. Eng.* **94** 1693–9
[5] Li X, Zhang F and Liu G 2021 Review on polymer flooding technology *IOP Conf. Ser.: Earth Environ. Sci.* **675** 012199
[6] Joshi D, Ramesh D N, Prakash S, Saw R K, Maurya N K, Rathi K B, Mitra S, Sinha O P, Bikkina P K and Mandal A 2025 Formulation and characterisation of polymer and nanoparticle-stabilized anionic surfactant foam for application in enhanced oil recovery *Surfaces and Interfaces* **56** 105615
[7] Alagoz E 2023 Enhanced oil recovery (EOR) screening criteria: at a glance *International Journal of Earth Sciences Knowledge and Applications* **5** 405–11
[8] Dong Z, Pan X, Li W, Wei X, Qian S, Hou B, Zou L, Lin K and Yi H 2024 Using polymer-alternating-water to maximize polymer flooding performance *Journal of Petroleum Exploration and Production Technology* **14** 1589–604
[9] Bealessio B A, Blánquez Alonso N A, Mendes N J, Sande A V and Hascakir B 2021 A review of enhanced oil recovery (EOR) methods applied in Kazakhstan *Petroleum* **7** 1–9
[10] Bai Y, Wang F, Shang X, Lv K and Dong C 2021 Microstructure, dispersion, and flooding characteristics of intercalated polymer for enhanced oil recovery *J. Mol. Liq.* **340** 117235
[11] Salem K G, Tantawy M A, Gawish A A, Salem A M, Gomaa S and El-hoshoudy A N 2024 Key aspects of polymeric nanofluids as a new enhanced oil recovery approach: a comprehensive review *Fuel* **368** 131515
[12] Ding L, Wu Q, Zhang L and Guérillot D 2020 Application of fractional flow theory for analytical modeling of surfactant flooding, polymer flooding, and surfactant/polymer flooding for chemical enhanced oil recovery *Water (Switzerland)* **12** 2195–223
[13] Song K *et al* 2022 Recent advances in polymer flooding in China *Molecules* **27** 6978
[14] Seright R S, Seheult M and Talashek T 2008 Injectivitv characteristics of EOR polymers *Proc. - SPE Annu. Tech. Conf. Exhib* **2** 767–80
[15] Gbadamosi A, Patil S, Kamal M S, Adewunmi A A, Yusuff A S, Agi A and Oseh J 2022 Application of polymers for chemical enhanced oil recovery: a review *Polymers* **14** 1433
[16] Xia S, Zhang L, Davletshin A, Li Z, You J and Tan S 2020 Application of polysaccharide biopolymer in petroleum recovery *Polymers (Basel)* **12** 1–36
[17] Sun Y, Zhang W, Li J, Han R and Lu C 2023 Mechanism and performance analysis of nanoparticle-polymer fluid for enhanced oil recovery: a review *Molecules* **28** 4331
[18] Wei Q, Deng N N, Guo J and Deng J 2018 Synthetic polymers for biomedical applications *Int. J. Biomater* **2018** 1–2
[19] Pu W, Shen C, Wei B, Yang Y and Li Y 2018 A comprehensive review of polysaccharide biopolymers for enhanced oil recovery (EOR) from flask to field *J. Ind. Eng. Chem.* **61** 1–11
[20] Onofre-Rentería K, Cabrera-Munguía D A, Cobos-Puc L E, Claudio-Rizo J A, Morales-Oyervides L and Oyervides-Muñoz E 2024 Xanthan gum production and its modifications to obtain novel applications: a review *Polym. Adv. Technol.* **35** e70004
[21] Sofia G B and Djamel A 2016 A rheological study of xanthan polymer for enhanced oil recovery *J. Macromol. Sci. Part B Phys.* **55** 793–809
[22] Arabani M and Shalchian M M 2024 A review of the use of bio-based substances in soil stabilization *Environment, Development and Sustainability* **26** 13685–737
[23] Nowrouzi I, Khaksar Manshad A and Mohammadi A H 2020 Effects of tragacanth Gum as a natural polymeric surfactant and soluble ions on chemical smart water injection into oil reservoirs *J. Mol. Struct.* **1200** 127078
[24] Benchabane A and Bekkour K 2008 Rheological properties of carboxymethyl cellulose (CMC) solutions *Colloid Polym. Sci.* **286** 1173–80
[25] Abdelrahim K, Ramaswamy H, Doyon G and Toupin C 2007 Effects of concentration and temperature on carboxymethylcellulose rheology *Int. J. Food Sci. Technol.* **29** 243–53

[26] Dolz-Planas M, Roldan-Garcia C, Herraez-Dominguez J V and Belda-Maximino R 1991 Thixotropy of different concentrations of microcrystalline cellulose: sodium carboxymethyl cellulose gels *J. Pharm. Sci.* **80** 75–9

[27] Zheng W, Wu X and Huang Y 2020 Impact of polymer addition, electrolyte, clay and antioxidant on rheological properties of polymer fluid at high temperature and high pressure *J. Pet. Explor. Prod. Technol* **10** 663–71

[28] Czernek K, Ochowiak M and Włodarczak S 2020 Effect of rheological properties of aqueous solution of na-cmc on spray angle for conical pressure-swirl atomizers *Energies* **13** 6309

[29] Ghannam M and Esmail N 2002 Flow behavior of enhanced oil recovery Alcoflood polymers *J. Appl. Polym. Sci.* **85** 2896–904