

Effect of Fiber on Rheological Properties and Flow Behavior of Polymer Completion Fluids

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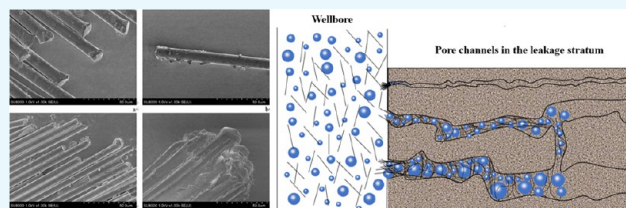
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ABSTRACT: The application of fiber in the completion fluid can improve the rheological properties of the completion fluid and the plugging quality of the production layer by the completion fluid and reduce the damage of the filtrate to the reservoir formation. However, there are few studies on the influence of fibers on the rheological properties of completion fluids and the flow behavior in pores. In this paper, plant fiber, mineral fiber, and synthetic fiber are discussed. Carbon fiber, bamboo fiber, polypropylene fiber, and polyester fiber are selected as research objects. The dependence of the rheological property of polymer solution on fiber type, fiber concentration, temperature, and shear rate is evaluated. The evaluation is carried out by observing the microscopic state of the fiber through a microscope and a scanning electron microscope, testing the rheological property parameters of the fiber with an OFITE 900 rheological tester, and fitting with the Herschel–Bulkley model. The results show that polypropylene fiber and carbon fiber have the best dispersion in polymer solution. The higher the fiber content, the greater the influence of fiber on the rheological properties of the solution. Compared with the other three fibers, carbon fiber has the greatest influence on the rheological properties of polymer solution. When the temperature is lower than 70 °C, the influence of the fiber on the rheological properties of the solution is not affected by the temperature. When the temperature exceeds 70 °C, the carbon fiber and polypropylene fiber are affected by the temperature, and the viscosity of the polymer solution is increased. The flow behavior of fiber suspensions in pores varies with the flow factor n . Carbon fiber suspensions are most conducive to the transition of polymer solution to plate laminar flow, which can improve the bearing capacity of plugging materials.



1. INTRODUCTION

Drilling fluid and completion fluid are important parts of the oil-drilling process. Fiber is widely used in drilling fluid and completion fluid as the main additive, which helps to solve complex engineering problems onsite, improves the efficiency of drilling and exploration, and reduces reservoir damage. The introduction of fiber helps the downhole working fluid carry the solid phase. Studies have shown that in the process of wellbore cleaning, fibers are added to the drilling fluid. The fibers increase the drag force on drilling cuttings and improve the carrying capacity of drilling cuttings in the drilling fluid. Fiber-based drilling fluids are very effective in cleaning high-inclination and high-displacement wells, helping to increase the rate of mechanical drilling and reduce fluid loss, improve wellbore cleaning efficiency, and reduce the thickness of cutting beds.^{1–4}

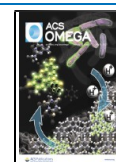
The application of fibers can effectively change the rheological properties of fluids.⁵ In fracturing fluids, Elgaddafi found that fiber-containing fluids had a stronger bearing capacity on the proppant than fiber-free fluids, which could hinder the settlement movement of the proppant^{6–9} and improve the proppant transport efficiency during the fracturing process, further carrying the proppant into the fracture.¹⁰ Kang proposed a set of temporary plugging technologies for naturally

fractured formations in tight gas reservoirs in western Sichuan.^{11,12} With the synergistic effect of rigid particles, fibers, and elastic particles, effective plugging is formed in the fractured stratum and the plugging pressure is increased. Ramasamy found a new type of fiber ecological loss circulation material (LCM), which was developed with natural jujube tree waste as raw material.¹³ The experiment under high temperature and high pressure proved that the fiber material is an ideal leakage material to resist moderate leakage. Kefi proposed rigid and flexible fibers dispersed in water-based drilling fluid and mixed with solid particles.¹⁴ In the water-based drilling fluid, the composite mixture of fibers and particles is bridged in the blockage loss zone to maintain the blockage and optimize the cracks. Xu established the strength analysis model for the friction and shear failure of the crack plugging zone, reflecting the tensile strength of the fiber, the aspect ratio, and the

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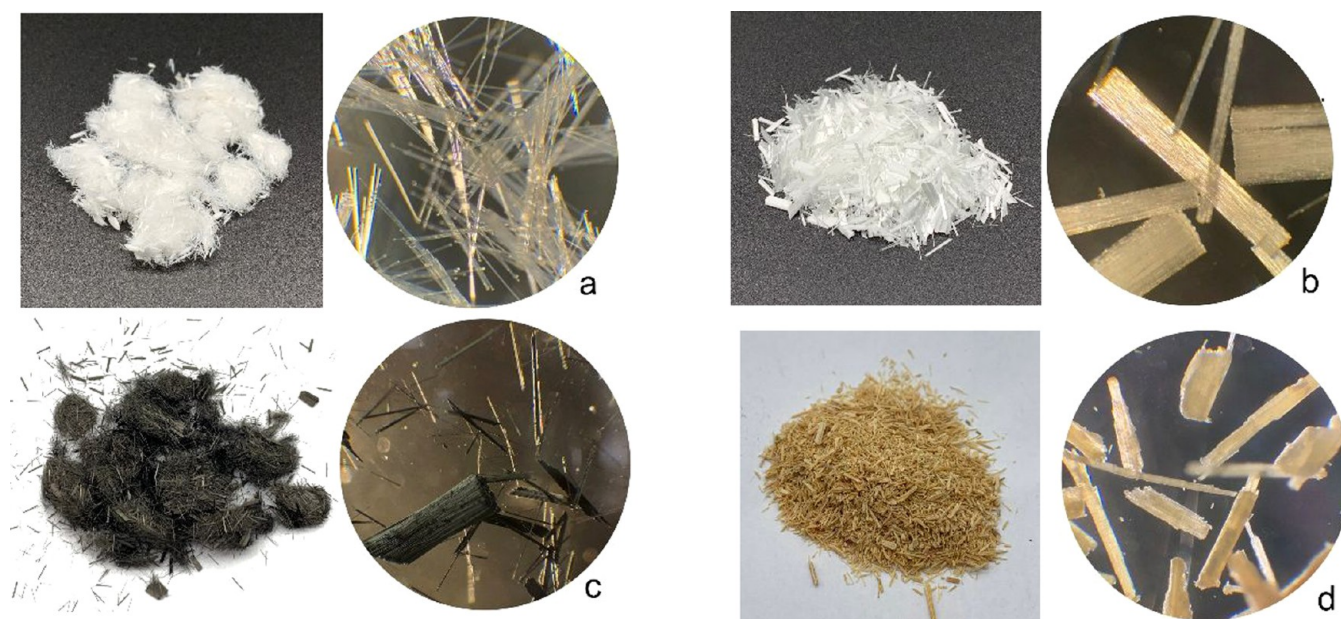


Figure 1. Macroscopic and microscopic states of four kinds of fibers. (a) Polyester fiber, (b) polypropylene fiber, (c) carbon fiber, and (d) bamboo fiber.

reasonable combination of fibers and particles.¹⁵ The strength and damage prevention effect of the blockage zone has a great influence. Zhang proposed that the combination of degradable fibers and particle plugging behaviors can increase the acidizing temporary plugging transfer pressure, increasing the productivity of complex carbonate reservoirs.^{16–19}

Therefore, in polymer completion fluids, fibers are often added to change the rheological properties and carrying capacity of the completion fluid, and the concentration of the polymer base fluid can also be reduced to reduce operating costs. Jiang showed that the carrying capacity of high-concentration polymer solutions without fibers to solid particles is less than the carrying capacity of low-concentration polymer solutions with fibers.²⁰ Herzhaft and Guazzelli explained the variation of fiber sedimentation velocity and direction distribution with particle concentration and fiber aspect ratio.^{21,22} At the same time, fibers and temporary plugging particles of different particle sizes cooperate with each other to form a skeleton through bridging, connecting, supporting, and retaining in the missing pores, sealing the pores and reducing the damage of the filtrate to the reservoir base block. Rajabian established a fiber–polymer suspension model, which describes the interaction between fibers in the fiber–polymer suspension and between the fibers and the polymer solution.²³ The effects of various characteristics of fiber–polymer interaction on the rheological properties of fiber suspension in simple shear flow were explored.

In general, the rheological behavior of the fiber–polymer suspension is mainly affected by the four aspects of fiber type, concentration, temperature, and shear rate. Polymer fluids are generally non-Newtonian fluids. The increase in fiber concentration enhances the non-Newtonian behavior of the fiber suspension. The effect of fiber materials on the viscosity of the suspension mainly depends on the type of the fiber material, especially the flexibility of the fiber material. The shear viscosity of rigid fiber–polymer suspensions is similar to that of polymer suspensions, while the more flexible fibers deepen the non-Newtonian effect of polymer suspensions.

Zhao showed that the effect of fiber addition on the apparent viscosity and elastic modulus of fracturing fluid was that the elastic modulus of cross-linked fracturing fluid increased significantly under high fiber concentration and long fiber length.²⁴ A study of fiber suspensions showed that at a relatively low fiber concentration, the relative viscosity of the fiber suspension is a monotonically increasing function of fiber composition.²⁵ The study by Goto showed that the rheological properties of fiber–polymer solutions are related to fiber concentration, aspect ratio, and diameter, similar to suspensions in Newtonian fluids.^{26–28} However, the influence of fiber materials on the viscous properties of the suspension mainly depends on the type of the fiber material, especially the flexibility of the fiber material. The shear viscosity of the rigid fiber–polymer suspension is roughly equivalent to that of the polymer, while the more flexible fiber deepens the non-Newtonian effect of the polymer suspension. Khalil studied the temperature dependence of completion fluid rheology, indicating that the Arrhenius equation can better describe the change of Saraline-based super lightweight completion fluid (SLWCF) viscosity with temperature.²⁹ The sensitivity of different fibers to temperature is different.³⁰ Li studied the effect of high temperature on the microstructure of different fibers. Through multiscale morphology observation and microstructure analysis of the fiber microstructure by a digital camera and an optical microscope, the thermal stability results of different fibers were obtained.³¹ The viscosity of the fiber suspension is a function of the shear rate. When the shear flow has just started, the rotation of the fiber with the suspension is hindered by adjacent fibers, and the resulting strengthening of the fiber network causes a sharp increase in viscosity. At low shear rates, the rheological properties of fiber suspensions are affected more by factors such as fiber structure and concentration. But with the increase of shear rate, the influence of these factors on rheological properties gradually becomes weaker. At high shear rates, shear-thinning occurs, and the shear stress increases with the increase of shear rate and then decreases. The reason for this is that due to the high-

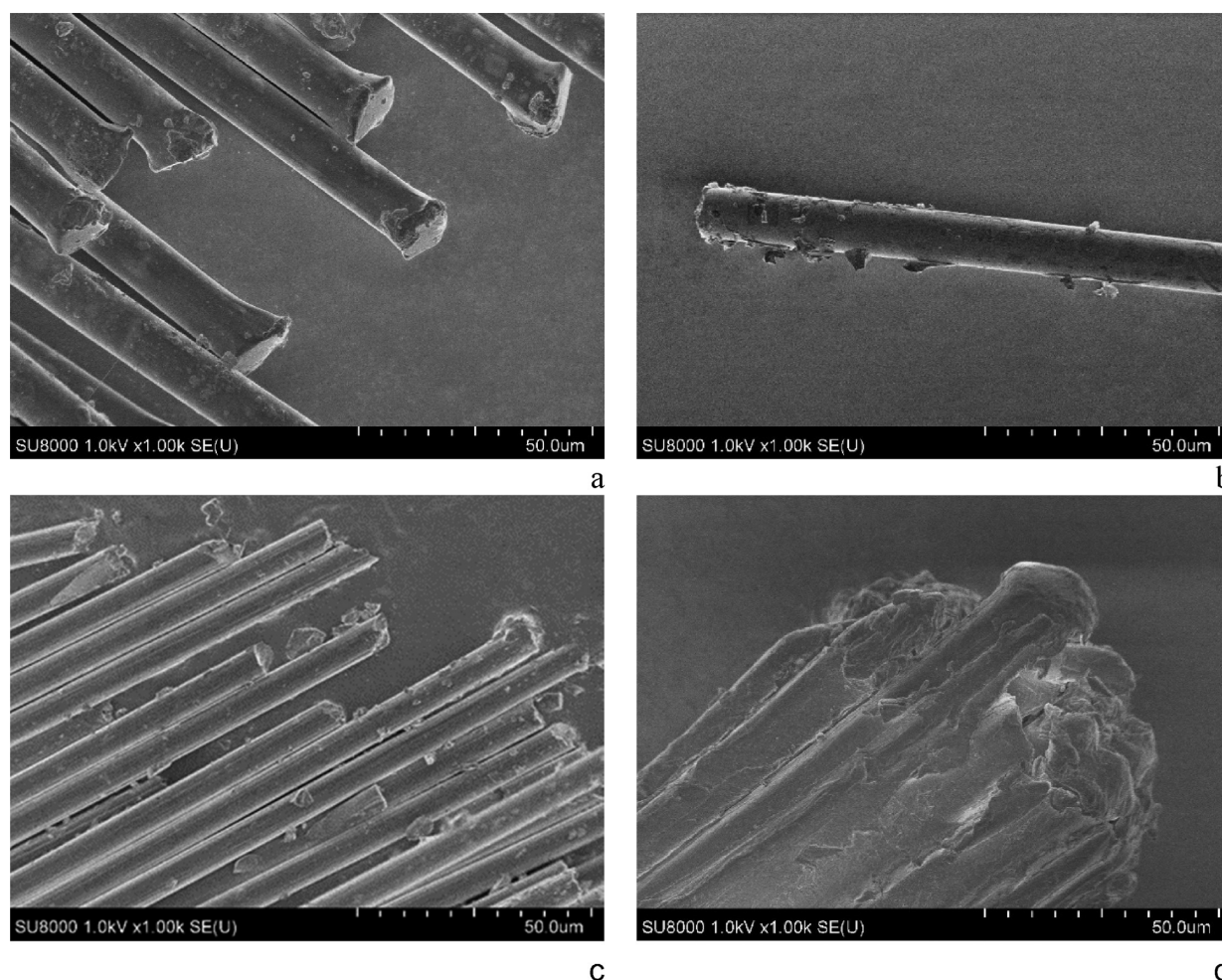


Figure 2. Scanning electron micrographs of fibers. Cross-sectional morphologies of (a) polyester fiber, (b) polypropylene fiber, (c) carbon fiber, and (d) bamboo fiber enlarged 1000 times.

speed shear rate, the fiber gradually tends to the same direction from the state of chaotic dispersion in the solution, the fiber network is destroyed, and the viscosity of the fiber suspension reaches an equilibrium value.³²

The introduction of fibers promotes the formation of fiber networks, improves the rheological properties of the completion fluid, and improves the plugging of the production layer by the completion fluid, which can significantly reduce the amount and depth of filtrate invasion and the damage of the filtrate to the reservoir block. However, considering that the influence of fibers on the rheological behavior of fluids is complicated, the introduction of different types of fibers has different effects on the rheological properties and flow behavior of polymers. With the recent widespread application of fibers in completion fluids, however, there are few studies on the effects of fibers on the rheology of completion fluids. Therefore, it is necessary to consider the effect of fiber on polymer rheological properties and flow behavior in the formulation design of polymer completion fluids.

This paper discusses three types of fibers: plant fibers, mineral fibers, and synthetic fibers. Four types of fibers, carbon fiber, bamboo fiber, polypropylene fiber, and polyester fiber, are selected as research objects. The fiber type, concentration, temperature, and shear are discussed. The effect of speed on the rheological properties and flow behavior of fiber-containing polymer solutions are also discussed. The power-law model is

used to describe the rheological parameters of fiber-containing polymer completion fluids. To describe the microscopic characteristics of different types of fibers, an optical microscope is used to characterize the microstructure of the fibers at 100 times magnification. At the same time, the dispersion and suspension behavior of the fiber in the polymer solution are compared. The flow states of different types of fibers in tiny pores are described. This paper aims to better understand the influence of fibers on the rheological properties and flow behavior of polymer completion fluids.

2. RESULTS AND DISCUSSION

2.1. Fiber Appearances. The appearance of the fiber is shown in Figure 1. Under 100 times magnification of the optical fiber mirror, polyester fibers are milky white with mercerization, and they are dispersed in the natural state. Carbon fiber is black and flocculent in the natural state. In the natural state, polypropylene is distributed like a cluster, and the fiber segment has a close aggregation structure. Under natural conditions, bamboo fibers are dispersed with each other, the surface structure is rough and uneven, the cross-sectional shape is irregular, and the diameter is the largest.

The microstructure and cross-sectional morphology of the four fibers are shown in Figure 2. It can be seen that the surface of polyester fiber is very smooth, and the cross section is flat and round. The surface of polypropylene fiber is smooth,

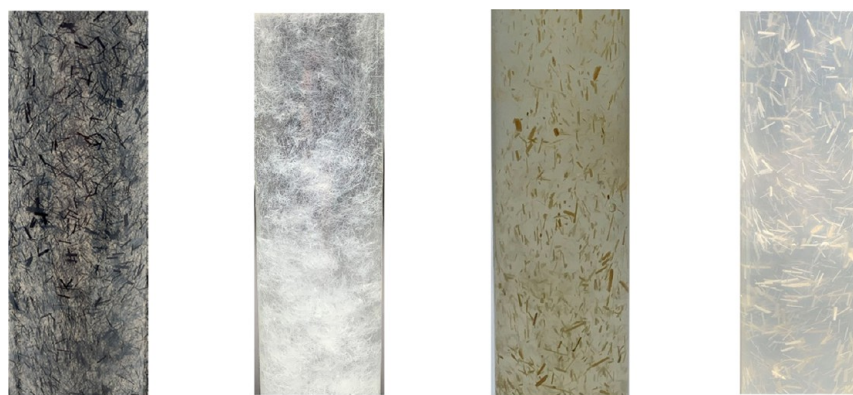


Figure 3. Dispersion state of four kinds of fibers in solution.

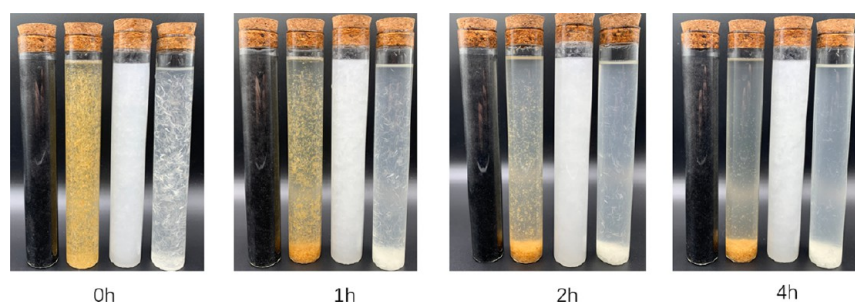


Figure 4. Settling state of four kinds of fiber at different times.

and the surface is small and uneven, but the cross section is flat. The surface of carbon fiber is regular and uneven, and the cross section is not smooth. Bamboo fiber is a kind of fiber of clusters and strips, which are closely combined with each other, and its surface is the roughest and the cross-sectional shape is irregular.

2.2. Dispersion and Sedimentation of Fibers in XC Solution. **2.2.1. Dispersion of Fibers in Solution.** To better observe the dispersion state of fiber in xanthan gum solution, a fiber concentration of 0.5 wt %, as shown in Figure 3, was selected and stirred at a low speed for 1 h to observe the dispersion state of fiber in xanthan gum solution. It can be seen from Figure 4 that due to the different surface physical properties, densities, stiffnesses, and length diameters of different fibers in the solution, the dispersion state of the four fibers in the solution is different. It can be seen that polyester fiber and carbon fiber are highly dispersed in the solution and form a monofilament state, but fiber flocculation occurs to a small extent. Schmid introduced the phenomenon of fiber flocculation due to friction and repulsion between fibers in the shear flow of fiber suspensions.³³ Bamboo fiber and polypropylene fiber are in a poor dispersion state in the solution, resulting in fiber bundle integration, which reduces the influence on the rheological properties of the solution. The different dispersions of different fibers lead to different effects of fibers on the rheological properties of suspensions. Therefore, the dispersion of different fibers in solution has different influences on the rheological properties of fibers.

2.2.2. Sedimentation of Fibers. It can be seen from Figure 4 that the settling speed of polypropylene fiber is the fastest, and it settles completely within 4 h. The second is bamboo fiber, most of which settles within 4 h. The suspension stabilities of polyester fiber and carbon fiber are the best, and there is no settlement. The results show that the suspension stabilities of

polyester fiber and carbon fiber in xanthan gum solution are much better than those of bamboo fiber and polypropylene fiber.

2.3. Rheological Performance Test Results. To study the effect of different fiber concentrations on the rheological properties of xanthan gum solution, we measured the different shear stresses of carbon fiber, bamboo fiber, polyester fiber, and polypropylene fiber at 25 °C at room temperature. The different shear stresses of the fiber suspension at different shear rates were in the range of 0.5–3 wt %. The results are shown in Figures 5–9. It can be seen that xanthan gum XC solution is a polymer solution, which is a non-Newtonian fluid. The flow

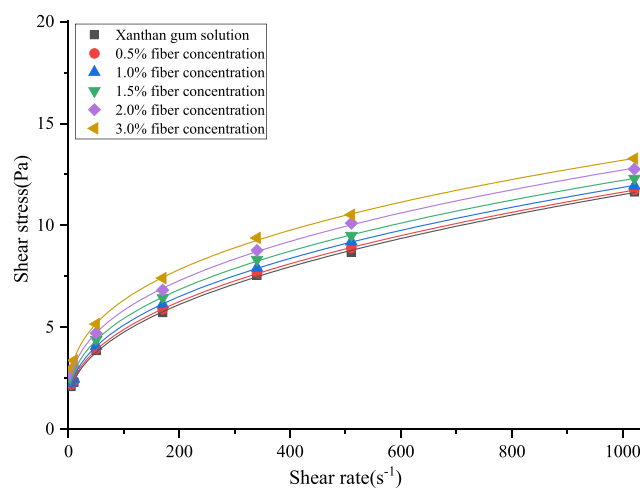


Figure 5. Fitting curves of shear stress and shear rate of polypropylene fiber at different concentrations and at room temperature based on the Herschel–Bulkley model.

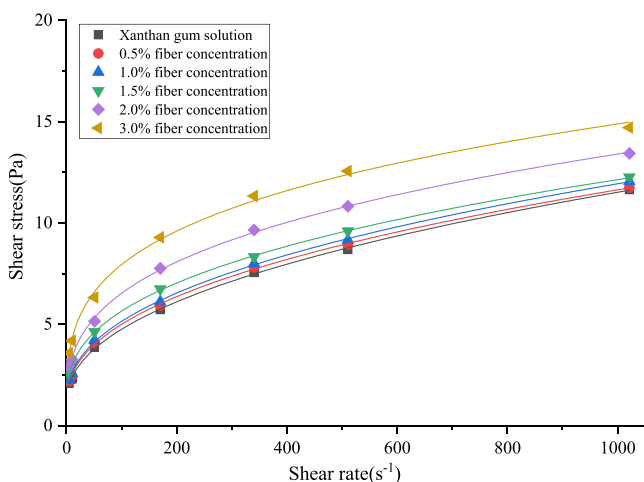


Figure 6. Fitting curves of shear stress and shear rate of polyester fiber at different concentrations and at room temperature based on the Herschel–Bulkley model.

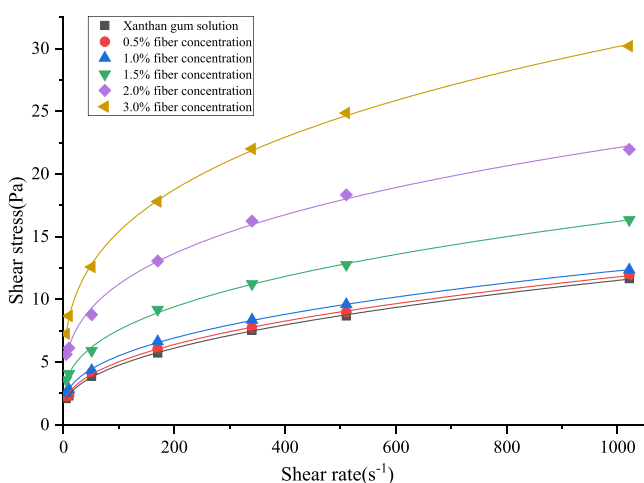


Figure 7. Fitting curves of carbon fiber shear stress and shear rate at different concentrations and at room temperature based on the Herschel–Bulkley model.

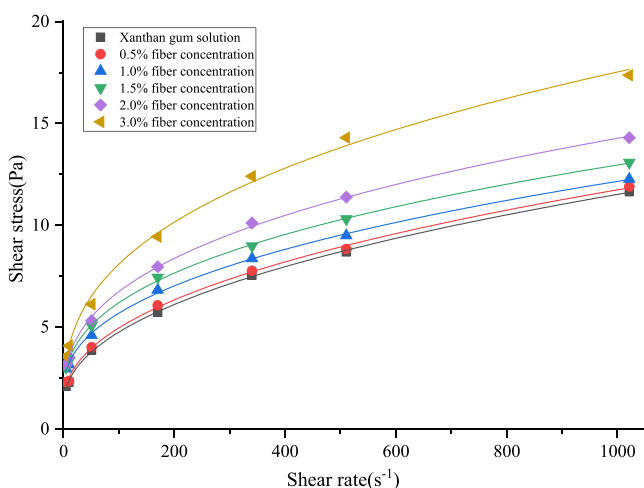


Figure 8. Fitting curves of shear stress and shear rate of bamboo fiber under different concentrations at room temperature based on the Herschel–Bulkley model.

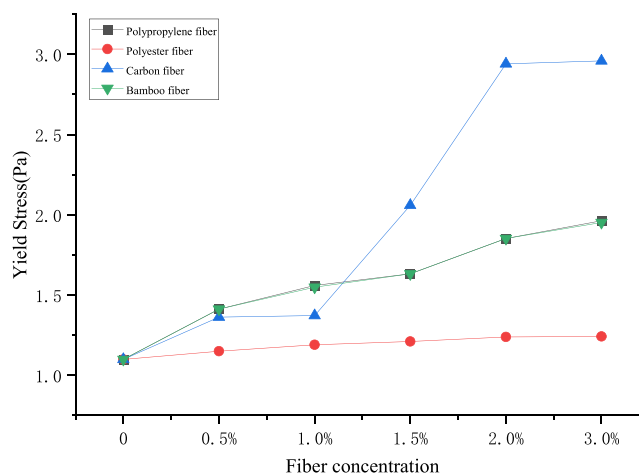


Figure 9. Variation trend of yield stress of fiber suspension caused by the fiber content.

pattern of xanthan gum solution does not change after adding 0.5–3 wt % fiber.

2.3.1. Selection of the Rheological Model. Due to the universality and complexity of non-Newtonian fluids, some rheological models have been developed to describe the relationship between shear rate and shear stress of non-Newtonian fluids. The power-law model and Herschel–Bulkley model describe a wide range of fluids. According to the relationship between shear stress and shear rate in rheological data, by fitting the data with power-law model and Herschel–Bulkley model, it is found that the Herschel–Bulkley model is closer to the actual rheological model of fiber suspensions. Therefore, the Herschel–Bulkley model (modified power-law model) is used to describe the rheological properties of fiber suspensions.

$$\tau - \tau_y = K\dot{\gamma}^n \quad (1)$$

where τ is the shear stress of fiber suspension (dyn/cm^2), τ_y is the dynamic shear stress (dyn/cm^2), K is the consistency coefficient ($\text{dyn}\cdot\text{s}^n/\text{cm}^2$) and its value is related to the viscosity of fluid at shear rate, and n is the popularity index and its value represents the degree of deviation of the fluid from Newtonian fluids. For the meaning of all model and equation symbols, please refer to the nomenclature section.

2.3.2. Influence of Four Types of Fiber Concentrations on the Rheological Properties of Fiber Suspension at Room Temperature. It can be seen in Figures 5–8 that the experimental data of the rheological curve of fiber suspensions are fitted using the Herschel–Bulkley model formula. It can be seen in Table 1 that all variances R^2 are above 0.99, indicating that xanthan gum solution containing fiber conforms to the modified power-law model. It can further be observed from the rheological curves in Figures 5–8 that with the increase of fiber concentration, the non-Newtonian behavior of the fiber suspension gradually increases, and the shear stress changes with the same shear rate. Among the four fibers, carbon fiber has the greatest influence on the rheological properties of xanthan gum. Carbon fiber significantly improves the viscoelasticity of xanthan gum XC solution, which is higher than that by other fibers. Polypropylene fiber has the least effect on the rheological properties of xanthan gum. When the concentration of polypropylene fiber is 3%, the viscoelastic property of xanthan gum solution is still less pronounced, and

Table 1. Power-Law Model Parameters of Fiber Suspensions with Different Concentrations

type	0.5%			1%			1.5%			2%			3%		
	K	n	R ²	K	n	R ²	K	n	R ²	K	n	R ²	K	n	R ²
bamboo fiber	4.9066	0.44456	0.99875	5.6509	0.42183	0.99917	8.2591	0.38197	0.99942	9.8493	0.37396	0.99915	13.05603	0.36743	0.996
polyester fiber	5.4928	0.42832	0.99954	5.6538	0.42759	0.99972	7.5424	0.38782	0.99988	12.9668	0.33206	0.99911	22.66826	0.27243	0.997
polypropylene fiber	4.9393	0.44312	0.99965	5.8524	0.42281	0.99975	6.5217	0.41031	0.99972	7.4403	0.39647	0.99975	9.46072	0.36779	0.999
carbon fiber	5.1702	0.43816	0.99889	6.5821	0.40911	0.9995	9.7108	0.39204	0.99881	19.8888	0.33579	0.99723	28.7696	0.32836	0.999

its viscoelastic property is not increased compared with xanthan gum solution. The viscoelasticity of the solution is obviously improved when the addition of polyester fiber reaches 2 wt %. When the addition of carbon fiber and bamboo fiber reached 1.5 wt %, the viscoelasticity of the solution was significantly improved. When the fiber content is 0.5–1.5 wt %, the fiber concentration has little effect on the flow state of xanthan gum XC solution. When the fiber content increases by 0.5 wt %, the shear stress increases by 0.1–0.6 Pa. When the fiber content reaches 2%, the shear stress increases by 1.5–9 Pa for every 0.5 wt % increase of the fiber content. When the fiber concentration in the suspension reaches a certain value, each fiber in the solution can contact with other fibers many times, which makes the fiber form a spatial network structure, showing a certain mechanical strength and viscoelastic behavior.

In the range of low shear rates, the shear stress of the polymer xanthan gum solution changes greatly with the shear rate, while in the high-shear-rate range, the shear stress increases slightly with the increase of shear rate. This shows that the interaction between fibers is small and has little effect on the rheological properties of fiber suspensions at low fiber concentrations. When the fiber concentration reaches a certain value, the fibers in xanthan gum XC solution can contact each other and form a spatial network structure, which can significantly improve the shear stress of the fiber suspension. In the low-shear-rate range of 5–50 s⁻¹, the shear stress of the fiber suspension is more sensitive to the shear rate. With the increase of the fiber shear rate, the corresponding shear stress increases rapidly, which is from 6 to 8 times as much as the high-shear-rate range. At low shear rates, the rapid increase of shear stress is beneficial to the fiber suspensions and plugging particles. In the high-shear-rate range of 600–1000 s⁻¹, the increase of the shear stress of fiber suspensions decreases with the increase of shear rate, and obvious shear dilution occurs. As shown in ref 32, the higher the shear rate is, the narrower the fiber orientation distribution is, and it is difficult for the fiber to form a network structure at a higher shear rate. Therefore, the fiber does not change the shear dilution of xanthan gum XC solution. When the fiber concentration is 3%, the shear stress of carbon fiber suspension is 167.08% higher than that of xanthan gum solution at a shear rate of 1000 s⁻¹. Under the corresponding conditions, the shear stress of bamboo fiber suspension increased by 49.12%, polypropylene fiber suspension by 14.03%, and polyester fiber suspension by 18.77%.

The yield stress and surface viscosity of fiber suspension increase with the increase of fiber content. It can be seen from Figure 9 that the yield stress of carbon fiber suspension increases fastest with the increase of fiber concentration, which is significantly higher than those of the other three fibers. The increase of polyester fiber concentration has little effect on the fiber suspension. This shows that the spatial network structures formed by different fibers in polymer solutions are also different. The higher the yield stress is, the more favorable it is for the fiber suspension to carry the solid particles and the flow state of the fiber suspension in the leakage channel.

The above fully shows that the influence of fiber length to diameter ratio, dispersion degree, surface condition, and density on xanthan gum rheology is very different. Therefore, it is necessary to consider the influence factors of fiber type on polymer solution in the formulation design of completion fluids.

In polymer completion fluids, the effect of fiber on the rheological properties of the completion fluid can be reflected by the viscosity coefficient “ K ” and the flow pattern index n . The Herschel–Bulkley model (modified power-law model) is used to characterize the relationship between shear stress and shear rate of fiber suspensions. The parameters of the power-law model, consistency coefficient “ K ”, and popularity index n of four different types of fiber suspensions at different concentrations are calculated. It can be seen from Figures 10

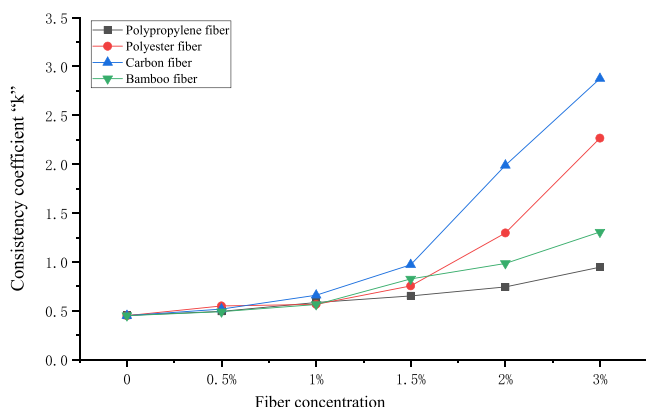


Figure 10. Effect of the fiber content on the “ K ” value at room temperature.

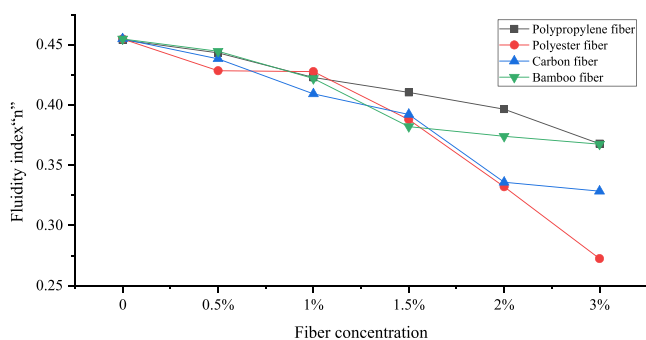


Figure 11. Effect of fiber addition on the “ n ” value at room temperature.

and 11 that the K value increases and the n value decreases with the increase of fiber concentration. The results show that the addition of fiber in the middle of the solution enhances the structural strength between solutions, increases the viscosity of fiber suspension, and enhances the non-Newtonian property of the suspension. When the fiber concentration is less than 1.5 wt %, the K value curve rises gently. When the fiber concentration reaches 1.5 wt %, the K value curve rises sharply.

The results show that when the fiber concentration increases to 1.5%, the contact opportunities between fibers increase significantly, which leads to the enhancement of the interaction force of fiber structures and the thickening of polymer solution. Among the four kinds of fibers, the consistency coefficient K of carbon fiber is the highest, which indicates that carbon fiber can significantly increase the consistency of polymer solution. Therefore, it is necessary to control the amount of carbon fiber in the use of carbon fiber to prevent the fiber suspension from being too thick and resulting in poor liquidity. The decrease of n value is beneficial to the carrying of plugging particles by

fiber suspension. According to the curve of popularity index n and fiber concentration, it can be seen that the curve of polyester fiber decreases fastest, which is most conducive to the increase of non-Newtonian behavior of suspension. This shows that the addition of polyester fiber is conducive to the suspension to maintain a good suspension state and carry solid particles better.

Generally speaking, when carbon fiber and polyester fiber are used in polymer completion fluid, it is necessary to avoid excessive addition of carbon fiber and polyester fiber, resulting in excessive viscosity of completion fluid, and thus affecting downhole pumping. When polypropylene fiber and bamboo fiber are used in polymer completion fluid, because the influences of polypropylene fiber and polyester fiber on the rheological property are small, the amount of fiber can be increased to improve the plugging performance of completion fluid.

2.3.3. Influence of Fiber Addition on the Rheological Properties of Fiber Suspension at a Shear Rate of 170 s^{-1} . In the drilling process, the fiber suspension carries particles to flow in the annular space of the wellbore. The shear rate of the drilling fluid in the annular space is generally from 50 to 250 s^{-1} , and the fiber suspension carries materials into the formation pores. Therefore, when the shear rate is 170 s^{-1} , the effect of fiber concentration on the rheological properties of suspension was analyzed.

It can be seen from Figure 12 that with the increase of fiber concentration, the viscosity of fiber suspension gradually

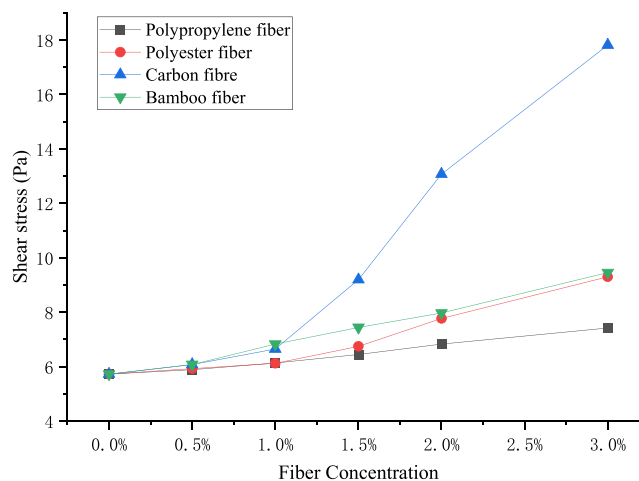


Figure 12. Dependence of shear stress of fiber suspensions on fiber concentration at a shear rate of 170 s^{-1} .

improves. When the shear rate is 170 s^{-1} , the increase rate of shear stress is small when the concentration is less than 1.5 wt %. When the concentration of fiber suspension is 1.5 wt %, the increase rate of fiber shear stress is obviously increased. This shows that the spatial network structure is formed in the suspension with the increase of fiber concentration to a certain extent. The results show that the increase of polypropylene fiber concentration has little effect on the shear stress of suspension. However, the viscosity of the suspension was significantly increased by carbon fiber, and the shear stress of the suspension was increased by 3–5 times with the addition of 3 wt %. Therefore, carbon fiber is more conducive to improve the rock carrying capacity of fiber suspension. However, the shear stress of carbon fiber, bamboo fiber,

polyester fiber, and polypropylene fiber increased by 128.46, 39.28, 35.71, and 19.31%, respectively, at 2 wt % concentration. It can be concluded that the influences of fiber type and concentration on the rheological properties of fiber suspension are very different. Therefore, in the process of drilling, to control the rheological properties of the fluid in the annular space and improve the suspension and carrying capacity of the fluid to the plugging particles, it is necessary to select the corresponding completion fluid formula based on the above analysis of the fiber characteristics according to the field needs.

2.3.4. Influence of Temperature on Rheological Properties of Fiber Suspension. The rheological properties of fiber suspensions are influenced by the ambient temperature to the underground temperature. Therefore, to better understand the effect of temperature change on the shear rate of fiber suspensions, we studied the effect of temperature on the rheological properties of fiber suspensions. In this study, we measured the relationship between shear stress and shear rate of fiber suspension at seven different temperatures from 30 to 90 °C. According to the above experimental study, the fiber concentration of 2% was selected. Figures 13–17 show the

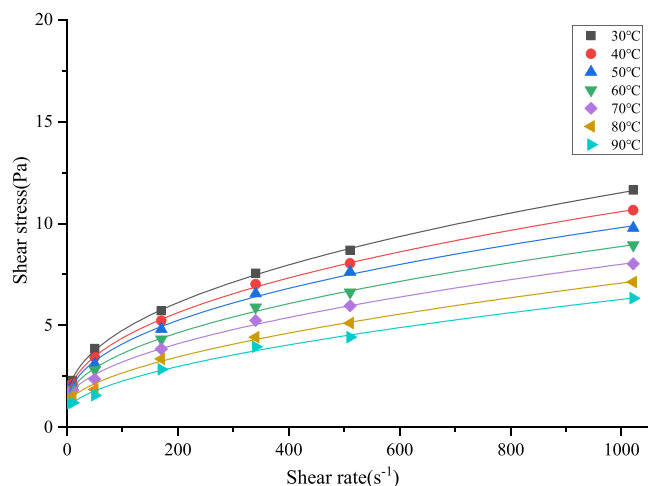


Figure 13. Fitting curves of shear stress and shear rate of xanthan gum solution at 30–90 °C based on the Herschel–Bulkley model.

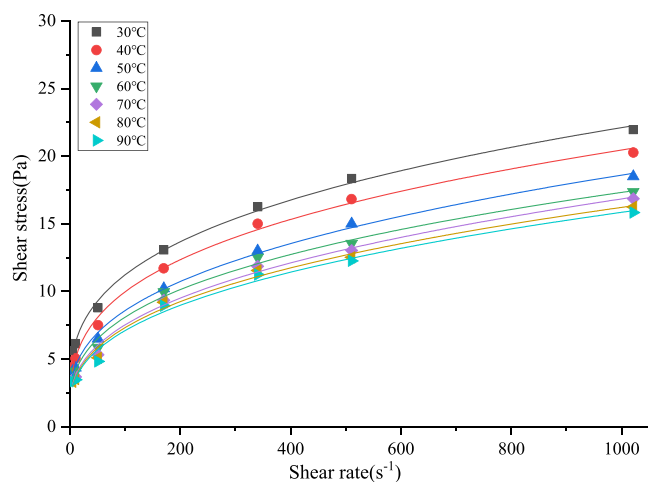


Figure 14. Fitting curves of shear stress and shear rate of carbon fiber suspension at 30–90 °C based on the Herschel–Bulkley model.

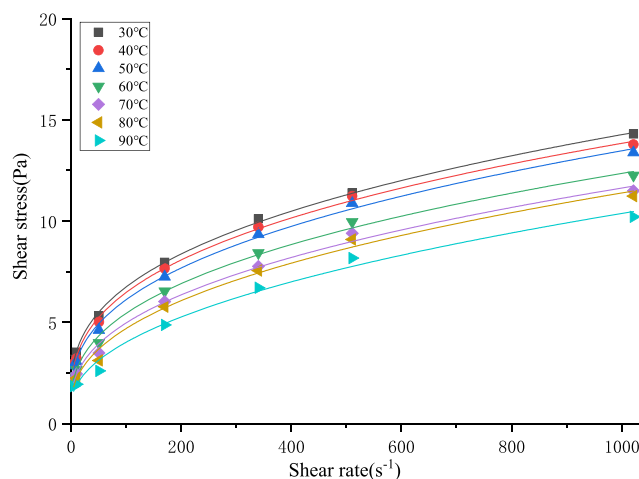


Figure 15. Fitting curves of shear stress and shear rate of bamboo fiber suspension at 30–90 °C based on the Herschel–Bulkley model.

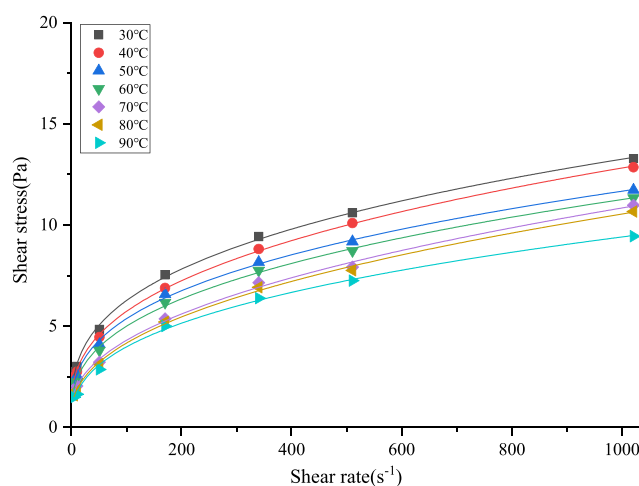


Figure 16. Fitting curves of shear stress and shear rate of polyester fiber suspension at 30–90 °C based on the Herschel–Bulkley model.

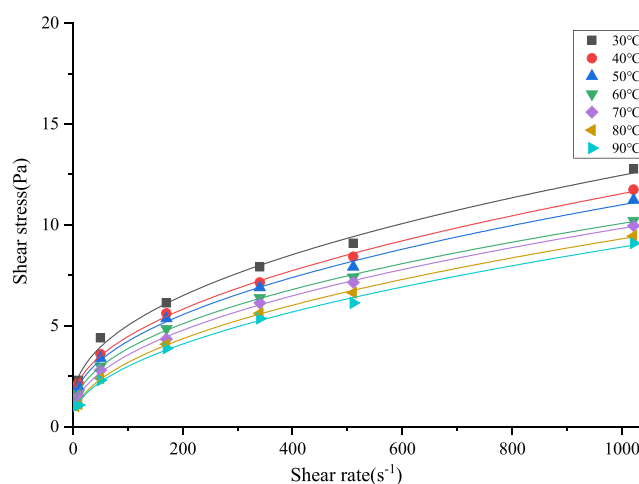


Figure 17. Fitting curve of shear stress and shear rate of polypropylene fiber suspension at 30–90 °C based on the Herschel–Bulkley model.

effect of temperature on the shear stress of fiber suspensions. Figure 13 shows the curve of shear stress changing with temperature at different shear rates of xanthan gum solution.

The results show that the shear stress curve decreases with the increase of temperature. In the range of 30–90 °C, the shear stress curve of the fiber decreases uniformly with the temperature, and the shear stress decreases by about the same extent when the temperature increases by 10 °C. Figures 13–17 show the results of rheological properties' tests of 0.3% base xanthan gum solution at four 2% fiber concentrations. The results show that the shear stress curve of fiber suspension decreases with the increase of temperature. This is because the temperature accelerates the irregular movement of molecules, which reduces the force interaction between molecules and particles and weakens the mechanical strength of the polymer chain and the spatial network structure of the fiber. These molecules are more likely to move freely, resulting in a decrease of the shear stress of the fluid.

By comparing the curves, the decreasing trend of shear stress curve of fiber suspension is different from that of xanthan gum solution without fiber. The results show that the addition of fiber slows down the downward trend of fiber suspension, and different fibers have different sensitivities to temperature, resulting in different downward trends. The shear stress curves of polyester fiber and bamboo fiber suspensions decreased slowly with the decrease of temperature in the range of 30–70 °C. However, in the range of 70–90 °C, the shear stress curves of polyester fiber and bamboo fiber decrease obviously with the decrease of temperature. This is due to the poor heat resistance of polyester fiber and bamboo fiber. The shear stress curves of carbon fiber suspensions and polypropylene fiber suspensions decrease rapidly with the increase of temperature in the range of 30–70 °C. When the temperature reaches 70 °C, the decrease amplitude decreases obviously. The reason for this is that the flexibility of the fiber is enhanced due to the temperature, which increases the viscosity of the fiber suspension and slows down the decreasing speed of the fiber suspension.

Figure 18 shows that the yield stress of fiber suspension is sensitive to the change of temperature and obviously decreases

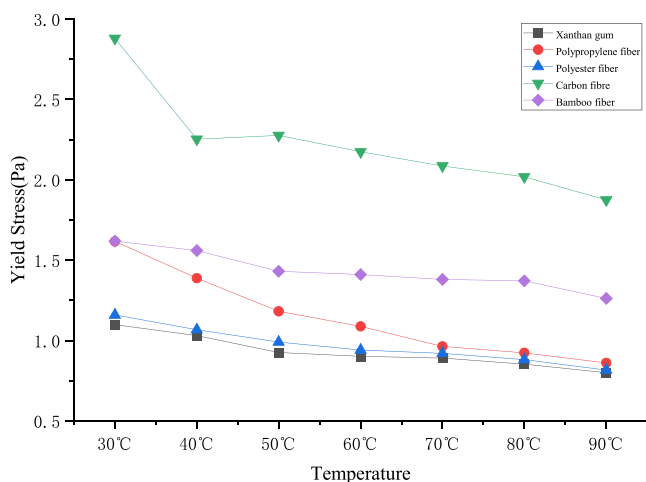


Figure 18. Variation trend of yield stress of fiber suspension at 30–90 °C.

with the increase of temperature, indicating that the addition of fiber cannot increase the yield stress of polymer solution but can only slow down the reduction rate of yield stress. The decreasing trend of bamboo fiber and polyester fiber is similar to that of xanthan gum solution, which indicated that bamboo

fiber and polyester fiber were less sensitive to temperature and less affected by temperature. The yield stress of carbon fiber and polyester fiber decreased fastest, which indicated that carbon fiber and polyester fiber were sensitive to temperature. As the temperature increases, the yield stress decreases and the carrying capacity of fiber suspension to solid particles is weakened.

2.3.5. Effect of Temperature on the Rheological Properties of the Fiber Suspension at a Shear Rate of 170 s⁻¹. To understand the flow state of fiber suspensions in the annulus, the rheological properties of fiber suspensions were tested at a shear rate of 170 s⁻¹. It can be seen from Figure 19 that the

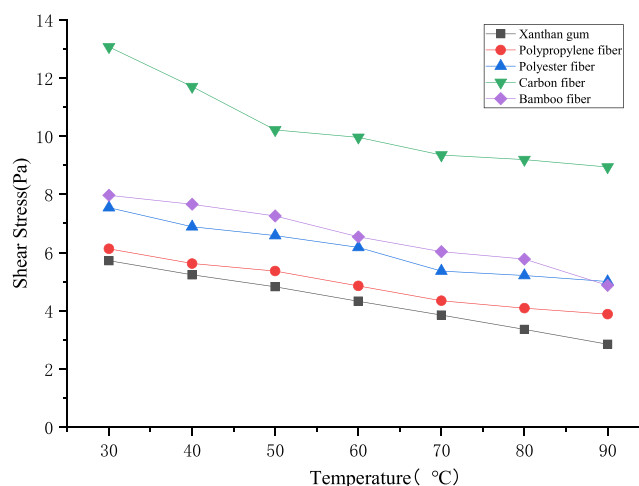


Figure 19. Temperature dependence of shear stress of fiber suspensions at a shear rate of 170 s⁻¹.

shear stress of fiber suspension decreases with the increase of temperature. The shear stress curves of bamboo fiber suspension, polyester fiber suspension, and polypropylene fiber suspension can roughly coincide with xanthan gum curve through up and down translation. It can be concluded that the influence of temperature on fiber suspension is similar and that the changing trend and range of rheological curve are similar to that of basic xanthan gum. The changing trend of liquid with temperature is the same. It can be seen from Figure 20 that at

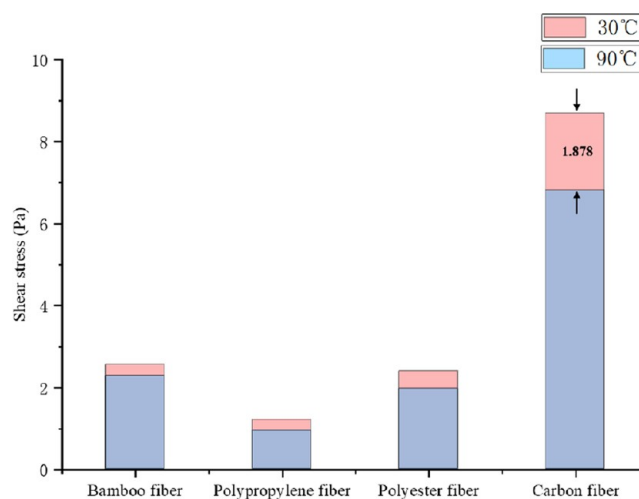


Figure 20. Influence of fiber on xanthan gum solution at 30 and 90 °C at a shear rate of 170 s⁻¹.

the shear rate of 170 s^{-1} , the shear stress increase of xanthan gum suspension is slightly lower than those at 30 and $90 \text{ }^\circ\text{C}$, except for carbon fiber, which is greatly affected by temperature. It can be concluded that the effect of temperature on the rheological properties of bamboo fiber suspension, polyester fiber suspension, and polypropylene fiber suspension is mainly due to the effect of temperature on the rheological properties of xanthan gum solution. After the temperature rises, the downward trend of carbon fiber suspension changes from steep to gentle gradually, which indicates that the physical properties of carbon fiber change after the temperature rises to $70 \text{ }^\circ\text{C}$, which improves the viscosity and shear force of fiber suspension to a certain extent, thus maintaining the rheological stability of fiber suspension.

2.4. Flow Behavior of Fiber Suspension in Low-Permeability Pores. Figure 21 shows the plugging

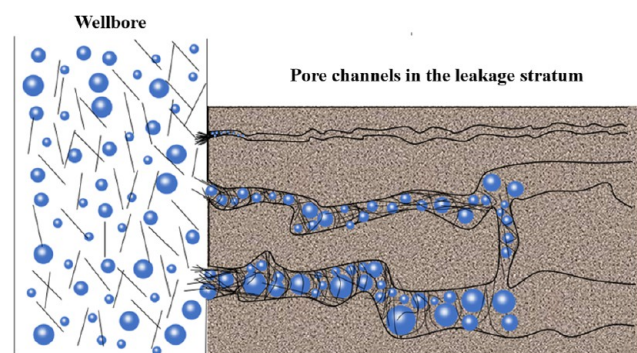


Figure 21. Schematic diagram of plugging mechanism formed by fiber and solid particles in the pore channel of leakage formation.

mechanism of completion fluid in the pore channel of leakage formation. As shown in Figure 21, fibers exist as a three-dimensional dispersed phase in completion fluid, which are randomly distributed and overlapped with each other, twining the plugging particles and carrying the plugging particles into pore channels of different sizes. Fibers and plugging particles gather, bridge, and form a plugging layer in the channel. The completion fluid has a great influence on the strength of the plugging layer of plugging particles and fibers in pores under different flow conditions. To understand the flow behavior of plugging particles in completion fluid, the flow pattern of completion fluid in pores was described and characterized.

At the same time, Shah et al.¹⁰ established a functional relationship between the n value and the non-Newtonian pseudoplastic fluid model. It was found that the fluid behavior index “ n ” had a significant effect on the proppant settling velocity, which decreased with the increase of Reynolds number. As the completion fluid is a pseudoplastic fluid, the flow core also exists in its velocity profile similar to plastic fluid. The flow core occurs because the shear rate in the center of the pipe decreases. When the n value is decreased, the core size of completion fluid increases, and the flow core changes from peak laminar flow to flat laminar flow. When the polymer

completion fluid enters into the leakage formation, the fiber carrier temporary plugging particles become more conducive to the completion fluid carrying the temporary plugging particles into the lost circulation formation when the fluid tends to be in flat laminar flow. The relationship between the flow state of completion fluid and n value can be expressed by eq 2.

$$\frac{v}{\bar{v}} = \frac{1 + 3n}{1 + n} \left[1 - \left(\frac{r}{R} \right)^{(n+1)/n} \right] \quad (2)$$

where v is the velocity at radius r , \bar{v} is the mean velocity, R is the tube radius, and n is the fluidity index.

The change of n value can change the flow state of completion fluid in pores. Figure 22 shows the relationship between the velocity profile of pseudoplastic fluid and fluidity index n . Through comparison, it is not difficult to see that by adjusting and reducing the n value, the diameter of the drilling fluid core can be increased, the velocity distribution of the peak shape can be “flattened”, and the fluid flow state can be changed from the peak laminar flow to the flat laminar flow. For low solid polymer completion fluid, flat laminar flow can effectively carry plugging particles at low viscosity and low velocity. Therefore, to control the rheological properties of polymer completion fluid, the n value should be controlled in the required range, and the peak laminar flow should be changed to flat laminar flow as far as possible, so as to change the annular flow to flat laminar flow and improve the carrying capacity of solid particles.

To understand the flow state of different types of fiber suspensions entering micropores at different concentrations, we assume that the pore radius is 0.5 mm , then the flow velocity of completion fluid in the pore is 0.5 mm/s . Combined with the flow pattern index n of different fiber suspensions, the flow behaviors of four kinds of fiber suspensions at different temperatures were calculated by eq 2.

The flow pattern index n of different concentrations and different types of fiber suspensions was basically in the range of 0.27 – 0.45 . Figure 23 shows the flow pattern of fiber suspensions in pores with n values of 0.27 , 0.36 , and 0.45 . The larger the fiber concentration is, the smaller the n value is. The flow state of fiber suspension in pores tends to be a flat flow state. When the fiber dosage is 1.5% , the n value is about 0.39 , the flow state is closer to the state when $n = 0.36$, and the flow core size is relatively small. When the fiber concentration increases, the n value decreases from 0.39 to 0.27 . The flow pattern of fiber suspension in the pores changes obviously, the flow core size becomes larger, and the annular flow state is more similar to the plate laminar flow. This reduces the erosion of fluid on the well wall and forms a better flow pattern. Through the comparison of the four fibers, the flow patterns of bamboo fiber suspension and polypropylene fiber suspension in pore are similar, and the flow core size is the smallest. The flow core size of polyester fiber suspension is relatively large, while that of carbon fiber suspension is the

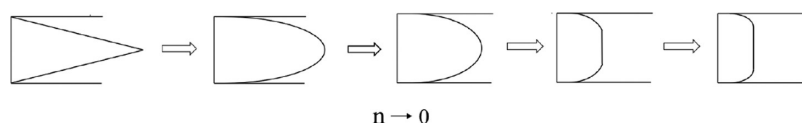


Figure 22. Relationship between the velocity profile and fluidity index n of pseudoplastic fluid.

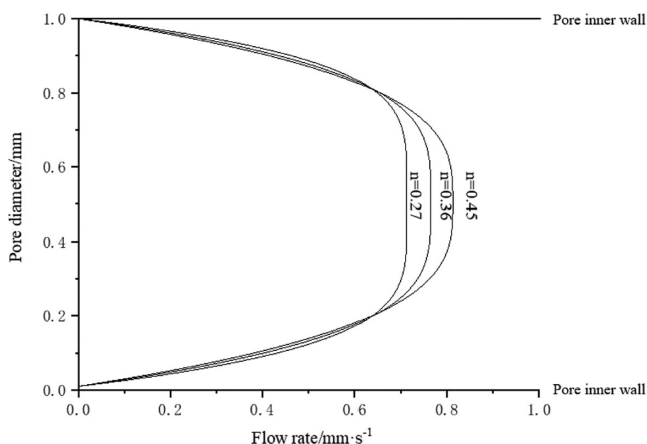


Figure 23. Effect of fiber concentration on the flow behavior of four kinds of fiber suspensions in pore space.

largest, which is most conducive to the conversion of suspension to plate laminar flow.

It can be seen from Figure 24 that with the increase of temperature, the flow pattern profile of the liquid becomes

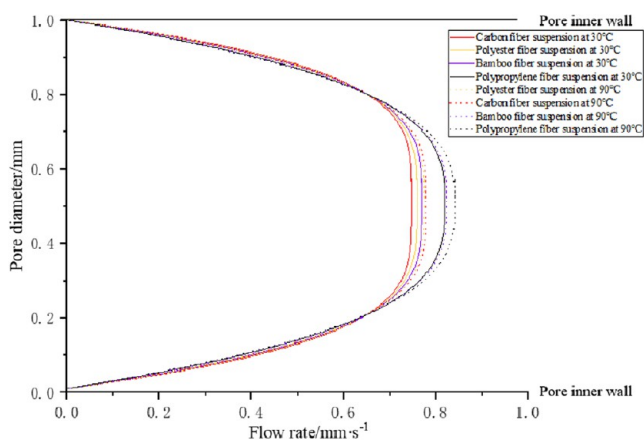


Figure 24. Flow behavior of different fiber suspensions in pore space at 30 and 90 °C.

sharper, the diameter of the flow core becomes smaller, and it becomes more unfavorable to carry the plugging particles into the pores. When the temperature changes from 30 to 90 °C, the relative change of flow core size of polyester fiber is the smallest while that of bamboo fiber is the largest. This shows that the change of temperature has little effect on the flow pattern of polyester fiber suspension. Among the four kinds of fibers, the flow core size of carbon fiber suspension is the largest, that of polypropylene fiber is the second largest, and that of polypropylene fiber is the smallest. This shows that carbon fiber can cause the annular liquid flow to be closer to the plate laminar flow at higher temperatures.

3. CONCLUSIONS

The main conclusions relating to the rheological properties and flow behavior of fiber–polymer completion fluids discussed in this paper are as follows:

- (1) Fiber type, fiber concentration, and shear rate have a great influence on the rheological properties of polymer completion fluids. Among them, carbon fiber and polyester fiber have a great influence on the increase

of viscosity and shear property of polymer completion fluid, while bamboo fiber and polypropylene fiber have little effect. The recommended concentration of fiber is 2 wt %. The viscosity of polymer completion fluid increases sharply if the fiber concentration is too high.

- (2) In the low-shear-rate range of 5–50 s^{-1} , the shear stress of fiber suspension increases rapidly with the increase of shear rate, while in the high-shear-rate range of 600–1000 s^{-1} , the shear stress of fiber suspension changes little with the increase of shear rate.
- (3) In the range of 30–90 °C, the addition of fiber helps to offset the decrease of viscosity of polymer completion fluid due to the increase of temperature. Therefore, the addition of fiber in polymer completion fluid helps to maintain the stability of viscosity at a certain temperature. Among the four kinds of fibers, carbon fiber is the most sensitive to temperature. With the increase of temperature, the viscosity of suspension increases the most.
- (4) By fitting the fiber suspension with the Herschel–Bulkley power-law model, the flow index n can reflect the carrying capacity of fiber suspension on solid particles and the flow behavior of polymer completion fluid in pores. The type, concentration, and temperature of fiber have a great influence on the n value. Compared with other fiber suspensions, polyester fiber suspensions and carbon fiber suspensions tend to have flat flow patterns in pores, which proves that they have the best carrying performance for solid plugging particles. The higher the temperature and the n value, the weaker the carrying capacity of the fiber suspension to solid particles in the pores.

4. EXPERIMENTAL MATERIALS AND METHODS

4.1. Materials. The polymer completion fluid is composed of the water phase, polymer, and the plugging material. The plugging material is selected as solid particles and short fibers that match the radius of the reservoir leakage channel. The short fibers are entangled in the solution to form a network, which improves the rheology of the polymer solution and the suspending and migration abilities of solid particles. At the same time, the short fibers act as a skeleton in the leakage channel and form a temporary plugging layer with the solid temporary plugging particles under a certain pressure difference.

To test the effect of fibers on the rheological properties of polymer solutions, the polymer xanthan gum solution (XC) was selected as the base solution, which was prepared by adding xanthan gum into fresh water, and the xanthan gum concentration commonly used in completion fluids was selected as 0.3 wt % (the ratio of XC mass to water mass). Xanthan gum (XC) was provided by Hebei Renqiu Company with a purity of 95–99%.

Generally, according to the pore size of rocks, the pores can be divided into three types: ultracapillary, capillary, and microcapillary pores. In this paper, the types of ultracapillary pores are studied. The diameter of the ultracapillary pores is greater than 0.5 mm or the crack width is greater than 0.25 mm. Large cracks, karst caves, and unconsolidated or loosely cemented sand pores in rocks mostly belong to this category. Therefore, for the microcracks of 0.25 mm, the length of the fiber is selected to be 1 mm, which is provided by Jingzhou

Table 2. Specific Properties of Fiber

fiber type	sort	length (mm)	diameter (μm)	aspect ratio	exterior	elastic modulus (GPa)	elongation (%)	density (g/cm^3)
bamboo fiber	plant fibers	1	22	91	rod-shaped needle	1900	20–50	1.49
carbon fiber	mineral fiber	1	5	400	rod-shaped needle	228	2.4	1.75
polyester fiber	synthesis fiber	1	16	125	rod-shaped needle	3.8	30–40	1.38
polypropylene fibers	synthesis fiber	1	18	111	rod-shaped needle	3500	20	0.99

Jiahua Technology Co., Ltd. The properties of the fibers are shown in Table 2.

4.2. Preparation of the Fluid and Gel. The fiber suspension was prepared by biopolymer XC solution and fiber. The polymer solution is xanthan gum (XC) solution. Xanthan gum solution is prepared by adding xanthan gum (XC) into fresh water. The concentration of xanthan gum XC is 0.3%, which is the xanthan gum concentration commonly used in polymer completion fluids. The concentration is the ratio of XC mass to water mass.

First, xanthan gum powder is slowly added into water and stirred using a JJ-1 precision timing electric stirrer at a low speed for 1 h to completely dissolve xanthan gum in water and avoid air entering into xanthan gum solution and producing bubbles, which affects the rheological properties of xanthan gum solution. Carbon fiber, bamboo fiber, polyester fiber, and polypropylene fiber were, respectively, added to xanthan gum solution and then stirred at a low speed for 1 h so that the fibers were completely evenly dispersed in XC solution. Finally, the fiber suspension of the required concentration was prepared.

4.3. Fiber Appearance Conditions and Dispersion. The length, diameter, surface morphology, concentration, type, and dispersion of the fiber can affect the rheological properties of the completion fluid. Through macroscopic observation, the fiber appearance and the dispersion state of the fiber in XC solution can be studied. Using an optical fiber mirror, we can record the appearance of the fiber at 100 times magnification, as shown in Figure 1. A scanning electron microscope was used to observe the microscopic morphology of the fiber, and the magnification was 1000 times, as shown in Figure 2.

To observe the dispersion of fiber in xanthan gum, the high concentration of fiber suspension is not conducive to the observation of the dispersion of single fibers in the solution. Therefore, the fiber concentration of 0.5% was selected to observe the dispersion state of fiber suspension, as shown in Figure 3. To observe the suspension stability of the fiber, the concentration of xanthan gum was 0.15% and the fiber content was 1.5%. After stirring at a low speed for 1 h, the suspension stability of the fiber was observed, as shown in Figure 4.

4.4. Rheological Measurement. Using OFITE's model900Vister as the testing instrument for fiber suspension, the software equipped with the instrument automatically calculates the average value of the shear stress measured under a certain shear rate and obtains reliable data. The instrument can measure the rheological properties of fiber suspensions at different temperatures.

The fiber concentration commonly used is in the field ranges of 0.5–3 wt % (the mass ratio of fiber to fluid is taken as the fiber concentration). Therefore, the fiber concentrations of 0.5, 1, 2, and 3 wt % were selected as the test concentration.

In the downhole circulation process, the flow rate and shear rate of drilling fluid are different in different parts. The higher the flow rate, the higher the shear rate. The shear rate is about

10–20 s^{-1} in the mud pit, 50–250 s^{-1} in the annular space, and 100–1000 s^{-1} in the drill pipe. To understand the rheological state of fiber suspension under different shear rates during drilling, the shear rate range of the test is from 3 to 1000 s^{-1} . The working temperature of polymer completion fluid is generally below 90 °C. The influence of temperature of fiber suspension on rheological properties of polymer completion fluid is studied at seven temperatures: 30, 40, 50, 60, 70, 80, and 90 °C.

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Conceptualization, P.X.; data curation, L.P.; formal analysis, L.P.; methodology, L.P. and J.S.; project administration, L.P. and M.H.; resources, J.S. and M.H.; supervision, P.X. and M.X.; writing: original draft, L.P.; and writing: review and editing, P.X.

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Notes

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