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CUTTINGS-BED EROSION IN HORIZONTAL WELLS: BIOPOLYMERS IMPACT AND ITS RHEOLOGICAL DEPENDENCE

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ABSTRACT

Efficient wellbore cleaning in highly deviated and horizontal wells is a challenge, as there are large areas where the cuttings tend to be deposited. Insufficient wellbore cleaning could cause major operational problems and vastly increase drilling costs.

Effective removal of the deposited cuttings-bed is mainly driven by flow rate, flow rheology and drill-pipe rotation, nevertheless in cases where it's not possible to have drill-pipe rotation the challenge should be accomplished by tailoring the fluid rheology to achieve turbulent flow within the maximum flow rate possible. As a common practice water-based drilling fluids are formulated with biopolymers as viscosity modifiers, such as xanthan gum and polyanionic cellulose (PAC) to adjust the drilling fluid rheology. The viscosity profile that each of these biopolymers imparts is very different, as xanthan gum produces a shear-thinning effect, the PAC behaves as a Newtonian fluid.

This paper shows how the different flow behavior of the fluids composed of biopolymers can influence the cuttings-bed erosion, in a bench-scale lab setup without drill-pipe movement. The simulated cuttings-bed is a 75cm long deposited sand bed in a horizontal section, in addition, two different types of biopolymer-based fluids with similar viscosities at a specific shear rate range are being used to compare how non-Newtonian fluids and Newtonian fluids interact with the deposited cuttings for cleaning efficiency.

Keywords: Drilling fluids, drilled cuttings, wellbore cleaning efficiency, cuttings-bed removal.

NOMENCLATURE

G^*	Complex modulus
G'	Storage modulus
G"	Loss modulus
k	Consistency index
n	Curvature exponent
PAC	Polyanionic Cellulose
XG	Xanthan gum
ε	Strain
δ	Phase angle
σ	Shear stress
σ_B	Yield stress
γ	Shear rate
η	Viscosity

1. INTRODUCTION

Drilling fluids are used during oil-well drilling operations to accomplish several needs; thus, their formulation needs to be tailored to achieve the desired properties. Among the most common additives to water-based drilling fluids that are being used and adjusted to tailor the drilling fluids are viscosity modifiers, either as their main effect or their secondary effect, such as xanthan gum, and polyanionic cellulose (PAC) respectively.

Xanthan gum is a rheology modifier that in water solution has a non-Newtonian behavior, presenting yield stress at higher concentrations and higher viscosity at low shear rates. Meanwhile, a PAC solution in water is commonly used as filtration control agent, which as a secondary effect modifies rheology. It presents a Newtonian behavior, where the viscosity is modified only by the concentration of PAC and not the applied shear rate.

Hole cleaning phenomena is governed by 3 main parameters [1]: operational parameters, including hole inclination, drill-pipe rotation, annular-eccentricity, fluid flow rate and rate of penetration (ROP). Drilling fluid properties, such as composition, density, and rheological behavior. And the last parameter are cuttings properties, such as cuttings size, shape, and type.

From these previous parameters, drilling fluids properties are the ones that can be modified the most during drilling operations, in addition the drilling fluids are responsible of transport out the drilled cuttings to the surface.

The distance for cuttings to be transported out can be long and usually the cuttings are in suspension, but due to gravity some of them settle down forming cuttings-bed during drilling operations.

Therefore is important to improve the cuttings' cleaning efficiency, especially for highly inclined and horizontal wellbores, this can be achieved by inducing high drilling fluid flow rates [2]. It is important to mention that excessive fluid velocity can cause problems such as undesired erosion to enlarge the wellbore.

It has been shown both on CFD simulations [3] and experimentally [4], that the interaction between these parameters can also modify the hole cleaning efficiency, as in the case of the combination of drilling fluid as the interstitial fluid within the cuttings-bed, where the fluid wetting the bed modifies the internal bonding forces of the bed itself.

Lately, researchers have been studies using machine learning to predict the cutting removal [5] focusing on different parameters, which intrinsically includes their interaction, but the phenomenon behind that interaction still needs to be studied further.

Hence, it is important to understand the combined behavior and properties of the drilled cuttings, the formed cuttings-bed, and the drilling fluid and not only to study the behavior of the parameters by themselves.

2. MATERIALS AND METHODS

2.1 Materials

Two types of biopolymers were analyzed as viscosity agents of the fluids, making the interstitial fluid wetting the drilled cuttings bed: Polyanionic Cellulose (PAC) ultra-low viscosity, in water solution at the following concentrations: 0.75%w/w, 1%w/w and 1.25%w/w, and xanthan gum (XG), in water solution at the following concentrations: 0.15%w/w, 0.25%w/w and 0.5%w/w.

Water was circulated to remove the formed cuttings bed. Quartz sand grains of irregular shape with particle size of 1.3 mm +/- 0.2 mm were used to simulate the cuttings particles.

2.2 Rheological characterization

Rheological characterization of the different polymeric fluids and their concentrations has been made using an Anton-Paar MCR 301 rheometer with grooved Couette geometry, maintaining the temperature at 25°C, both on rotational shearing to measure the flow and viscous behavior, and oscillatory shearing to measure the static yield strength and viscoelastic behavior.

The protocol used to perform the rotational viscosity testing was: pre-shearing at 1000 s^{-1} for 120 s achieving steady-state shear viscosity. Then measuring 2 s per point it was ramped down from 1200 s^{-1} to 60 s^{-1} in 100 linear steps, 5 linear steps from 60 s^{-1} to 10 s^{-1}, and finally 100 linear steps from 10 s^{-1} to 0.1 s^{-1}.

The protocol to perform the oscillatory rheology testing was as follows: Angular frequency set to 10 rad/s, increasing amplitude logarithmically from 0.001 to 100% strain in 60 measuring points.

The measured points of the xanthan gum solutions are curve fitted using the Hershel-Bulkley model described by Eq. 1, as the fluid presents a yield stress and shear-thinning behavior, meanwhile, the Polyanionic Cellulose solution is best fitted to the Newtonian model, described by Eq. 2.

$$\sigma = \sigma_B + k\dot{\gamma}^n \tag{1}$$

$$\sigma = \eta\dot{\gamma} \tag{2}$$

The Newtonian model is based only on the shear stress (σ) as a function of the viscosity (η) of the fluid and the shear rate (γ), and the Hershel-Bulkley model is based on three parameters, the Herschel-Bulkley flow behavior index or curvature exponent (n), the consistency index (k), and the dynamic yield stress (σ_B).

Complex modulus (G*) is used to describe viscoelastic behavior or the resistance of a sample to deform, as the ratio of the applied stress (σ) to the measured strain (ε), as shown in Eq. 3.

$$G^* = \frac{\sigma}{\varepsilon} \tag{3}$$

From the complex modulus, the elastic and viscous components, also named as storage (G') and loss (G") modulus respectively, can be described in terms of the phase angle (δ) as follows:

$$G' = G^* \cos\delta \tag{4}$$

$$G'' = G^* \sin\delta \tag{5}$$

For a pure viscous material phase angle (δ) is equal to 90 degrees, there is no elastic component and tan(δ) approaches infinity.

Storage modulus (G') and loss modulus (G") curves from the oscillatory testing, are taken into consideration and its ratio helps to understand the behavior of the fluid. When G' > G", the fluid has elastic behavior during the length of the linear viscoelastic region (LVER) until the minimum strain is reached to break the inner structure, this strain point shows the static yield strength and is usually defined as the point when linearity reaches 10% of deviation. In this case the biopolymer solution shows a solid-like character.

In the moment where G' = G", is the crossing point and is known as the flow point. In the case where G" > G', the fluid behaves completely liquid-like as it only presents viscous properties.

2.3 Bed-wetting fluid characterization

Experiments were conducted to analyze the erodibility to water of formed cuttings-beds on a bench scale setup (see FIGURE *1*), where the cell has the top and sides are built with transparent acrylic.

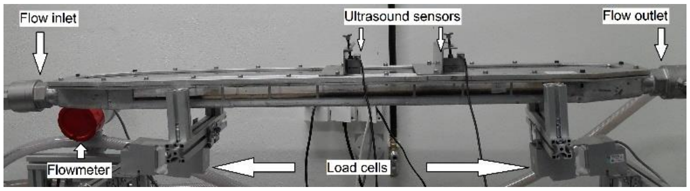

FIGURE 1. BENCH-SCALE SETUP.

The setup is 1.2 m long and the test section where the cuttings-bed wetted with the different interstitial fluids, were formed is 0.75 m long, 0.15 m wide and 0.02 m high, the gap between the top of the cuttings-bed and the lid of the setup is 0.03 m, for water to flow as the cleaning fluid.

The complete experimental setup is shown in detail in FIGURE *2* and a more detailed list of its components can be found in previous work [4].

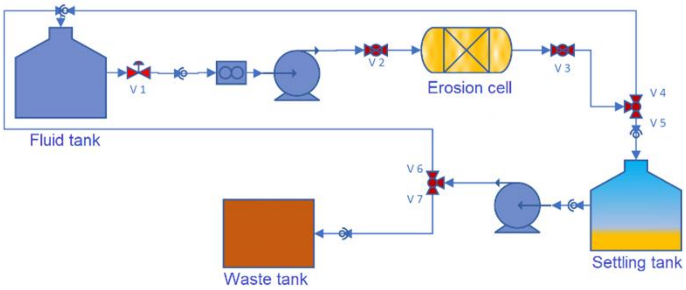

FIGURE 2. BENCH-SCALE SETUP SCHEMATIC

To form the cuttings-bed, the cuttings particles were placed in the test section and submerged to be fully wetted in the different PAC or xanthan gum solutions. Immediately water was circulated at a controlled flow rate, to erode the formed bed during periods of time between 1 to 3 minutes. The cuttings-bed erosion was measured by change in weight.

Statistical analysis of the results using the Ordinary Least Squares method (OLS) in Python was done to describe better the behavior and significance to influence the cuttings-bed removal of the different parameters; the two biopolymers as interstitial fluids, the flow rate and time of flow.

3. RESULTS AND DISCUSSION

Flow curves of the different biopolymer solutions are shown in FIGURE *3*, where the xanthan gum solutions are colored in black and the PAC solutions in blue.

From these curves is possible to conclude that the solutions containing xanthan gum can be represented by the Hershel Bulkley model, regardless of their concentration, while the solutions containing PAC fits the Newtonian fluid behavior, where the slope increases along with the concentration.

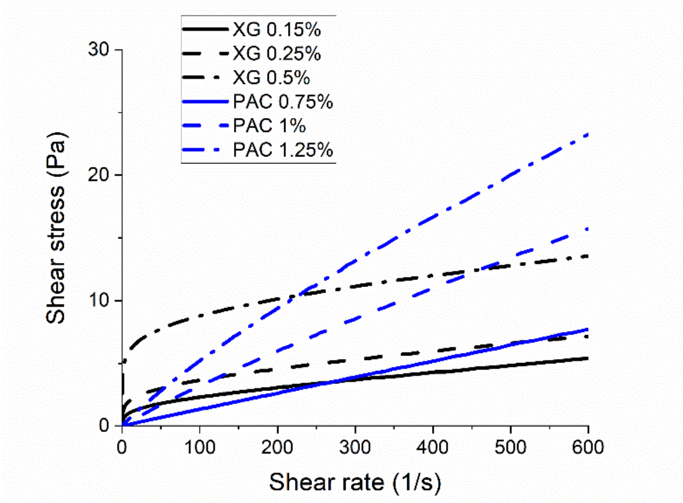

FIGURE 3. PAC AND XANTHAN GUM SOLUTIONS' FLOW CURVES.

As can be seen in the flow curve plot and the oscillatory test, xanthan gum solutions have an apparent yield stress, and it rises as the concentration increases.

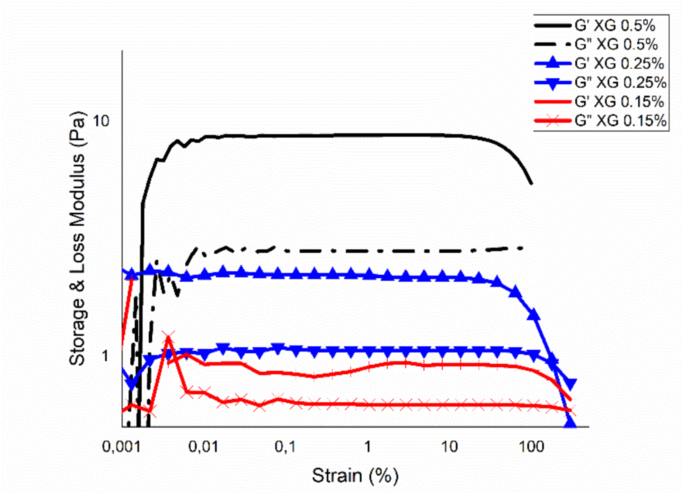

FIGURE 4. STORAGE AND LOSS MODULUS AT DIFFERENT CONCENTRATIONS OF XANTHAN GUM SOLUTIONS.

In addition, in FIGURE *4* is observed the viscoelastic behavior of the xanthan gum solutions, where the elastic modulus represented by the storage modulus (G') increases accordingly with the concentration.

In the other hand, while measuring the PAC solutions the rheometer was obtaining values of zero for the storage modulus or very low and erratic in the case of the 1.25% concentration, therefore only loss modulus (G") seems to be present in the PAC solution as shown in FIGURE *5*, indicating that it has no elastic modulus, supporting the Newtonian behavior seen in the flow curves, where no yield stress is present.

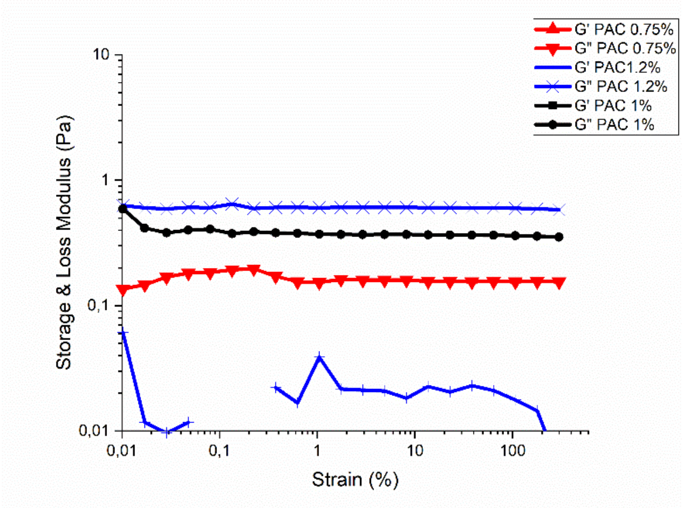

FIGURE 5. STORAGE AND LOSS MODULUS DIFFERENT CONCENTRATIONS OF PAC SOLUTIONS.

In the bench scale setup, removed weight is used to study water erodibility of the formed cuttings-bed with the different biopolymer solutions as interstitial fluids, prior to this a baseline of pure water as interstitial fluid was obtained and labeled as 0% concentration. The results are shown in Table 2, in appendix 1.

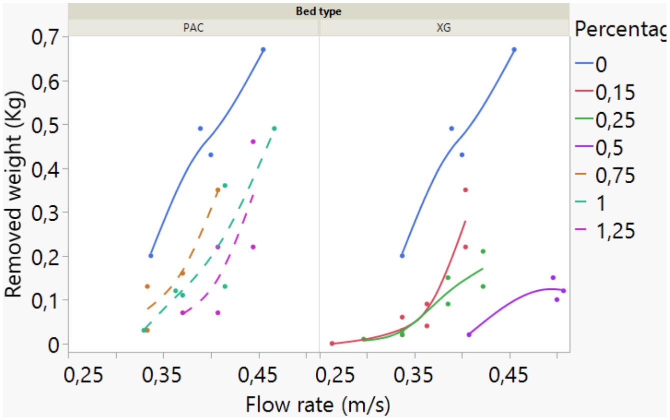

FIGURE 6. REMOVED WEIGHT VS FLOW RATE FOR EACH BIOPOLYMER.

In FIGURE *6*, is plotted the removed weight of the cuttings-bed and their trendlines versus the flow rate for each bed wetted by the different interstitial fluid, PAC in the left and xanthan gum in the right.

The baseline, cuttings-bed wetted by water, colored in blue has shown the best performance in terms of cuttings-bed erodibility, where the highest bed removal was achieved at different flow rates.

Cuttings-bed wetted by PAC solutions showed lowered cuttings-bed removal along the different flow rates, in comparison to the baseline, and showed that the erodibility decreases as the PAC concentration increases.

Cuttings-bed wetted by the xanthan gum solutions show the least bed erosion as their concentration increases and higher flow rates are required to obtain some eradibility. In the case of the concentration of 0.5% the erodibility is very low even at high flow rates.

The setup data was analyzed using the Ordinary Least Squares (OLS) model to obtain the relevance of the variables and likelihood of model fitting and predictive behavior. The obtained results are described in detail in Table *1*:

Table 1. Ordinary least squares results.

Dep. Variable:	Removed weight	R-squared:	0.786
Model:	OLS	Adj. R-squared:	0.759
Method:	Least Squares	F-statistic:	29.39
No. Observations:	46	Prob (F-statistic):	2.1e^{-12}
Df Residuals:	40	Log-Likelihood:	53.772
Df Model:	5		
Covariance Type:	Nonrobust		

===

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	-0.5858	0.117	-5.027	0.00	-0.821	-0.350
Biopolymer (XG)	-0.1082	0.061	-1.787	0.082	-0.231	0.014
Concentration	-0.2519	0.041	-6.106	0.000	-0.335	-0.169
Concentration* Biopolymer (XG)	-0.5572	0.164	-3.404	0.002	-0.888	-0.226
Flow rate	2.4501	0.277	8.860	0.000	1.891	3.009
Time	0.0005	0.000	3.937	0.000	0.000	0.001

The number of observations was 46 with 40 residual degrees of freedom. The R-squared value obtained of 0.786 is a possible fit. A lower adjusted R-squared implies low relevance from one of the parameters.

A good linear relationship between the model and the parameters is supported by the F-statistic of 29.39 and P-Value of the F-statistics close to 0, in our case 2.1e^{-12}.

The parameters that improve the cuttings-bed removal are positive and the parameters that decrease the removal efficiency are negative. Only the xanthan gum solution appears as the

Biopolymer (XG) parameter, as it is compared automatically by the system against the PAC solution wetted bed.

T-test values for all parameters including the intercept, are greater than 0. In addition, the P-value corresponding for each t-test except the Biopolymer (XG) are lower than 0.05 and close to 0. which means that these variables are significant and independent in the model.

Biopolymer (XG) variable, even with a t-test higher than the unit of magnitude, has a P-value higher than 0.05, which means that it is not significant by itself in the model, nevertheless the interaction effect between the Biopolymer (XG) and concentration is significant, which means that by modifying the biopolymer from being wetted by PAC to xanthan gum or vice versa, wouldn't be very substantial unless the concentration of the solution is considered.

$$y = -0.5858 - 0.1082XG - 0.2519C + 2.4501v + 0.0005T \qquad (6)$$

where y is the dependent variable, removed bed weight in Kg, and the independent variables are; XG for the usage of xanthan gum solutions as interstitial fluid, as it is a categorical variable it is 0 when is not present and 1 when used, C is the concentration of the biopolymer, v is the flow rate in m/s and T is the time in seconds, these last three are continuous variables.

The model created shown in Equation 6 is specific for these setup conditions, such as geometry, cuttings-bed interstitial fluid, cleaning fluid and it is recommended not to use it directly with other conditions for calculations, only for possible qualitative comparisons. To analyze other conditions a new model should be created by performing another OLS test with the required conditions and parameters.

With the coefficients obtained from the OLS model, the impact of each parameter to improve the cuttings removal from the bed are plotted in a pareto chart (see FIGURE *7*). This chart shows that in this scenario, flow rate is the most significant parameter to erode a cuttings-bed with water, followed by the interaction between two parameters; having as interstitial fluid xanthan gum solutions and their concentration.

Considering the coefficient value and that it is negative, it can be concluded that the usage of xanthan gum solutions as the interstitial fluid is the most significant factor to reduce bed erodibility, getting even lower removal efficiency as the concentration of the xanthan gum solution increases.

It is know that drill-string rotation increases the cuttings transport efficiency significantly [6] and might be the most influential factor, but it is not always possible to have rotation during drilling operations. With these results we corroborate that in absence of drill string rotation the factor that affects the cuttings removal the most is the flow rate [7].

The parameter that showed the least influence was time, meaning that the difference on flowing a fluid between 1 minute to 3 minutes is not very significant, but it should be analyzed for longer periods of time.

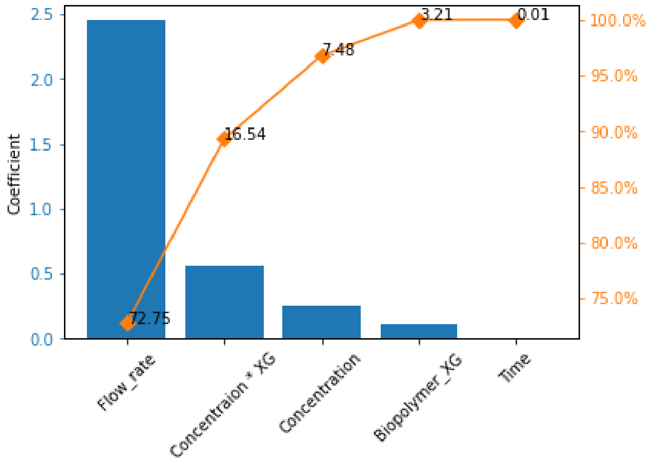

FIGURE 7. FACTORS AND MODEL INTERACTION.

4. CONCLUSION

The rheological behavior of the interstitial fluid affects the bonding strength of the cuttings' particles forming a bed. Showing that the interstitial fluid with yield strength and non-Newtonian behavior, namely xanthan gum solution, forms more cohesive cuttings-beds than the Newtonian fluid, in this case Polyanionic Cellulose solutions. Therefore, water erodibility at similar flow rates is lower with xanthan gum solution as the interstitial fluid.

As the concentration of the biopolymers increases, their viscosity increases and the erodibility of the formed beds tend to decrease, thus we hypothesis that there is a relationship between the adhesion forces imparted by the interstitial fluid and its viscosity at the wall shear rate.

5. ACKNOWLEDGEMENTS

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Appendix 1

Table 2. Setup experimental data

Biopolymer	Concentration (%)	Flow rate (m/s)	Removed weight (Kg)	Time (s)
PAC	0	0.389	0.49	144
PAC	0	0.337	0.2	70.5
PAC	0	0.455	0.67	114
PAC	0	0.4	0.43	89
PAC	0.75	0.4074	0.53	169
PAC	0.75	0.4074	0.35	100
PAC	0.75	0.3704	0.16	303.5
PAC	0.75	0.3333	0.13	346
PAC	0.75	0.3333	0.03	100
PAC	1	0.4148	0.36	346.5
PAC	1	0.4148	0.13	100
PAC	1	0.363	0.12	100
PAC	1	0.3296	0.08	325
PAC	1	0.3296	0.03	100
PAC	1	0.3704	0.11	100
PAC	1	0.4667	0.49	154.5
PAC	1.25	0.4444	0.46	277
PAC	1.25	0.4444	0.22	100
PAC	1.25	0.4074	0.22	295
PAC	1.25	0.4074	0.07	100
PAC	1.25	0.3704	0.07	100
XG	0.25	0.2963	0.01	100
XG	0.25	0.337	0.03	294
XG	0.25	0.337	0.02	100
XG	0.25	0.4222	0.21	231
XG	0.25	0.4222	0.13	100
XG	0.25	0.3852	0.15	200.5
XG	0.25	0.3852	0.09	100
XG	0.15	0.4037	0.35	183.5
XG	0.15	0.4037	0.22	100
XG	0.15	0.337	0.06	176.5
XG	0.15	0.337	0.02	100
XG	0.15	0.363	0.09	183.5
XG	0.15	0.363	0.04	100
XG	0.15	0.263	0	100
XG	0.5	0.496	0.15	60.5
XG	0.5	0.5	0.1	61.5
XG	0.5	0.507	0.12	66.5
XG	0.5	0.4074	0.02	100
XG	0	0.389	0.49	144
XG	0	0.337	0.2	70.5
XG	0	0.455	0.67	114
XG	0	0.4	0.43	89

Appendix 2

Python code

```
import pandas as pd
import numpy as np
import scipy, pylab
import matplotlib.pyplot as plt
from scipy import stats
import statistics as stat
import statsmodels.formula.api as smf
import statsmodels.api as sm
from matplotlib.ticker import PercentFormatter

df = pd.read_csv('databiop.txt', delimiter='\t')
df

#Separating data by bed type
DF_p=np.array(df[df["Biopolymer"]=="PAC"])
DF_x=np.array(df[df["Biopolymer"]=="XG"])

XP=DF_p[:,2]
YP=DF_p[:,4]
ZP=DF_p[:,3]
XX=DF_x[:,2]
YX=DF_x[:,4]
ZX=DF_x[:,3]

res1=smf.ols(formula='Removed_weight~Concentration+Biop
olymer+Concentration*Biopolymer+Flow_rate+Time',data=df)
.fit()
sm.stats.anova_lm(res1, typ=3)
print(res1.summary())

df1=pd.read_html(res1.summary().tables[1].as_html(),header
=0,index_col=0)[0]
C_1=abs(df1['coef'].values[0])
C_2=abs(df1['coef'].values[1])
C_3=abs(df1['coef'].values[2])
C_4=abs(df1['coef'].values[3])
C_5=abs(df1['coef'].values[4])
C_6=abs(df1['coef'].values[5])
print (C_1)

df_par=pd.DataFrame({'Coefficient':[C_2,  C_3,  C_4,  C_5,
C_6]})
df_par.index=['Biopolymer_XG','Concentration','Concentraion
* XG','Flow_rate','Time']
df_par = df_par.sort_values(by='Coefficient',ascending=False)
df_par["cumpercentage"]                                =
df_par["Coefficient"].cumsum()/df_par["Coefficient"].sum()*1
00
df_par["percentage"]                                   =
df_par["Coefficient"]/df_par["Coefficient"].sum()*100

fig, ax3 = plt.subplots()
ax3.bar(df_par.index, df_par["Coefficient"], color="C0")
ax4 = ax3.twinx()
ax4.plot(df_par.index,  df_par["cumpercentage"],  color="C1",
marker="D", ms=7)
ax4.yaxis.set_major_formatter(PercentFormatter())
#ax4.set_ylim([0,105])
for i, txt in enumerate(df_par["percentage"]):
   ax4.annotate("{:.2f}".format(txt),            (df_par.index[i],
df_par["cumpercentage"][i]))

ax3.tick_params(axis="y", colors="C0")
ax3.tick_params(axis="x", labelrotation=45)
ax4.tick_params(axis="y", colors="C1")
ax4.set_ylabel("Cummulative percentage")
ax3.set_ylabel("Coefficient")
plt.show()
```