Identification of best fit crude oil of upper Assam basin for pipeline transportation

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Abstract

This paper attempts to identify a crude oil (CO) from eight different CO samples with a wide range of °API gravity from 13 to 43 belonging to Upper Assam Basin, India, to formulate the identified CO for pipeline transportation. Studies were conducted to understand the physical, rheological, and viscoelastic properties of the CO samples where physical properties included pour point (PP) and °API gravity, the rheological properties included viscosity (η), kinematic viscosity (K.V.), viscosity gravity constant (VGC), shear stress (τ) and shear strain (γ') and the viscoelastic properties were elastic modulus (G') and viscous modulus (G''). This research aims at achieving PP < 9 °C for CO for the ease of flow through pipeline even during the extreme winter season in Assam when the ambient temperature drops below 10° C. SKO in 0%, 5%, 10%, and 15% was added with all CO samples to determine the physical, rheological and viscoelastic properties at 30 °C, since PP of most of the CO samples was near 30 °C. However, the important properties of SKO, i.e. smoke point, flash point and boiling point, were not addressed here as SKO was used for improving flowability through pipeline. Correlation coefficients (CC) were determined using CORREL function in Microsoft Excel to investigate the relationship between °API gravity and the other properties for all the CO samples to identify the best fit CO. CO3 and CO8 were identified from the relationships as the most desired CO samples and CO3 was obtained as the best fit CO for the pipeline transportation.

Keywords Physical property · Rheological property · Viscoelastic property · Correlation coefficient

Nomenclature

CO	Crude Oil
γ'	Shear Strain
RPM	Revolutions Per Minute
K.V.	Kinematic Viscosity
S	Second
LCO	Light Crude Oil
Sp. gr.	Specific Gravity
VGC	Viscosity Gravity Constant
SKO	Superior Kerosene Oil
PP	Pour Point
API	American Petroleum Institute
G'	Elastic Modulus
°API gr.	API gravity
G''	Viscous Modulus
τ	Shear Stress
τ_y	Yield Stress

Pa	Pascal
η	Viscosity
G^*	Dynamic Modulus
m	Meter
Cm	Centimeter

Introduction

Identification of crude oil (CO) of Upper Assam Basin was studied to determine the ease of flow through the pipeline. Various authors have investigated the problems encountered during CO flow through pipelines which are related to composition, solid deposition, wax formation, and altering climatic conditions (Jamaluddin et al. 2001; Jha et al. 2014). Assam CO is mainly from the Barail formation of Upper Assam Basin, which is an intermountain basin, surrounded by fold and thrust belts, being one of the most seismic active areas of the world (Jha et al. 2014). The physical properties of Assam CO do not exhibit a consistent trend (Sarmah et al. 2017). Physical, rheological, and viscoelastic properties of CO depend on the chemical composition of the oil

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and dissolved natural gases (Ilyin et al. 2016). The economic value of CO transportation is mainly influenced by °API gravity (°API gr.), pour point (PP), and viscosity (η) (Santos et al., 2014). The properties of CO play an important role in understanding their flow behavior through the pipeline. The flow behavior can be understood from Reynolds number (R_e), as $R_e > 2300$ is desirable which leads to transition and turbulent flow (Wyslouzil, 1987). PP of CO reveals the influence of low temperature on pumpability and provides information about paraffin wax content in CO (Chinenyeze and Ekene, 2017). Jaafar et al. 2015 and Srivastava et al. 1993 described waxy COs having aliphatic hydrocarbon of high molecular weight paraffin consisting of both straight and branched chains with carbon number in the range of C18 to C65 (Jaafar et al. 2015; Srivastava et al. 1993). The PP of Upper Assam CO shows significant variation which reflects a change in the most abundant group of HCs contained in the CO, and this was also observed by Frankle and Cordvy 1967 for the Nigerian CO (Robidas and Gogoi 2020; Frankle and Cordvy 1967).

Paraffin deposition occurs in the cold inner wall of the pipeline, mainly during the winter season when the ambient temperature is lowest compared to the core of the pipeline, because of this radial temperature gradient, wax deposition rate increases toward the wall of the pipelines, mainly when the PP and η of CO is high (Jaafar et al., 2015; Singh et al. 2001; Rønningsen et al. 1991). If remedial measures are not taken to maintain the temperature throughout the pipeline, an increase in the wax deposition will continually reduce the effective diameter of the pipeline and a situation may arise that the wax deposition finally clogs the pipeline (Robidas and Gogoi 2020). Temperature decline beyond the Wax Appearance Temperature (WAT) results in a gel-like structure of high yield stress leading to non-Newtonian behavior of CO (Kok et al. 2018). To prevent the consequences of paraffin deposition and maintain an easy flow of CO through pipeline, a better understanding of the physical, rheological, and viscoelastic properties of CO is necessary, which are attempted in this research. Based on various literature, research was conducted to scientifically understand the influence of PP, °API gr., τ , γ' , η , K.V., VGC, G' and G'', on the flow of CO through the pipeline (Dong et al. 2020; Dimitriou and McKinley 2014). The results of various authors on the effect of viscous CO for pipeline transportation vary due to variation in considering different geometries and Standard Operating Procedure (SOP) of the rheometers be it rotational or oscillatory type, because of these reasons contradictory findings may occur in this area of research (Rønningsen et al. 1991; Chang et al. 1998; Venkatesan 2005, Jaafar et al. 2015). The empirical formula for VGC was generated by Kurtz et al. 1956 which was used in characterizing CO based on paraffinicity, naphthenicity or aromaticity (Kurtz et al. 1956; Hill and Coats 1928; Houghton and Robb 1931).

It was observed in this research that there exists a strong correlation among the different properties and a combined effect of all these properties affects the flowability of CO through the pipeline. Jain and Bihani 2014 correlated the physical properties using the regression methodology, while the CORREL function in Microsoft Excel was attempted in this research, which is the first of its kind to obtain the CC of the properties of various CO (Jain and Bihani 2014). Superior kerosene oil (SKO) was used in this research as a diluent to observe the physical, rheological, and viscoelastic behavior. Basic properties of SKO are such as PP of -18°C , specific gravity ranges from 0.78 to 0.82, and °API gravity of ranges $40^\circ\text{--}46^\circ\text{API}$ gravity. The CO flowability in pipeline transportation is determined by understanding the physical, rheological and viscoelastic properties of various CO with and without the addition of SKO. A systematic study of CC of CO not only helps to assess the overall CO quality but also helps to find the relationship between the properties and to identify the best suitable CO for pipeline transportation.

Experimental

Sampling and preparation of CO

Eight CO samples from different wellheads of Upper Assam Basin were collected in dried gallons with necessary precautions. Each CO sample was kept steady in a conical flask for 48 h to separate the free water by gravity, while the emulsified water was separated by heating the CO up to the experimental temperature of 30°C and filtered. SKO was added to the CO free from water in different % as shown in Table 1.

Materials and equipment

The materials used to conduct the experiments and the geometry of the viscometer are in Table 2 and Table 3, respectively.

Table 1 Preparation of different CO samples

Sl. No.	CO sample	CO samples prepared with & without adding SKO (%)			
		0	5	10	15
1	CO1	CO1+0	CO1+5	CO1+10	CO1+15
2	CO2	CO2+0	CO2+5	CO2+10	CO2+15
3	CO3	CO3+0	CO3+5	CO3+10	CO3+15
4	CO4	CO4+0	CO4+5	CO4+10	CO4+15
5	CO5	CO5+0	CO5+5	CO5+10	CO5+15
6	CO6	CO6+0	CO6+5	CO6+10	CO6+15
7	CO7	CO7+0	CO7+5	CO7+10	CO7+15
8	CO8	CO8+0	CO8+5	CO8+10	CO8+15

Table 2 Materials used for the experiments

Sl. No.	Materials	Source
1	8 CO samples	Oil and Natural gas corporation (ONGC), Oil India Limited (OIL)
2	SKO	Locally purchased

Table 3 Measurement range of the viscometer

Sl. No.	Rotor Bob	R1 B1
1	Rotor radius (cm)	1.8415
2	Bob height (cm)	3.800
3	Bob radius (cm)	1.7245
4	Shear gap in annulus (cm)	0.1170
5	Radii ratio (R_1/R_o)	0.9365
6	Maximum use temperature (°C)	93
7	Minimum use temperature (°C)	0
8	Shear Stress Range (dynes/cm ²)	1 ~ 2,000
9	Shear Rate Constant k_3 , sec ⁻¹ per rpm (Shear Rate Range, sec-1 $\gamma = k_3 N$)	1.7023
10	$N = 100$ rpm	170.23
11	$N = 600$ rpm	1021.38
12	Minimum viscosity (cp)	0.098
13	Maximum viscosity (cp)	10,000,000

(Rotor sleeve and bob, i.e. R1B1 of the viscometer was selected for the work)

Methodology

Fundamental laws for crude oil flow through pipeline

The basic fluid mechanics principles related to fluid flow are the continuity equation (or conservation of mass), the momentum principle (or conservation of momentum), and the energy equation which was applied here to describe the flow of CO through a pipeline. To solve a CO flow problem as in this research, the mass and momentum conservation or Navier–Stokes equations as in Eqs. (1a), (1b), (1c) was used,

but the energy conservation equation was kept for future research.

In a flow of CO through a pipeline, the CO velocity changes from zero at the surface because of the no-slip condition to a maximum value at the center of the pipeline as in Fig. 1. In the heating or cooling process, the average velocity may change to some extent due to the changes in density with temperature. But, generally, the CO properties are evaluated at a certain average temperature and considered as constants because it usually justifies the insignificant loss in accuracy (Çengel and Cimbala 2004). Also, the temperature of the CO increases because of the friction between the CO components in the pipeline, but this increase in temperature due to frictional heating is generally too little that can be neglected. Flow may be laminar or turbulent and in the case of turbulent flow, because of the rapid fluctuations causes the momentum transfer between the CO compositions, which leads to raise the friction force on the surface and hence more pumping power is required. The friction factor reaches a maximum when the flow becomes fully turbulent. When CO enters through the inlet of the pipeline at uniform velocity, due to the no-slip condition, the velocity of the CO particles near the surface is zero and this layer gradually decreases its velocity as an effect of friction. So, to maintain this velocity reduction, the velocity of the CO at the centreline of the pipeline increases to keep the mass flow rate constant throughout the pipeline. The viscous shearing force caused by CO viscosity is observed at the boundary layer and the irrotational, i.e. the core flow region is observed where the frictional effects are insignificant and the velocity remains constant in the radial direction. The distance from the inlet of the pipeline to the point at which the boundary layer reaches the centreline is called the hydrodynamic entrance region, where the velocity profile develops and beyond which the fully developed region is obtained as shown in Fig. 1. The shear stress at the wall of the pipeline is associated with the slope of the velocity profile at the surface and this shear stress remains unchanged in the hydro-dynamically fully developed region and accordingly the physical, rheological and viscoelastic properties of the CO change.

Fig. 1 Velocity profile through pipeline

Semi-empirical laws

When CO flow through pipeline system is considered, the rate at which the mass enters the system is equal to the summation of the rate at which the mass leaves the system and the accumulation of mass that takes place within the system.

The continuity equation for CO with variable density is

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{\vartheta} = 0$$

where ρ is density, t is time, and $\vec{\vartheta}$ is the flow velocity vector.

Now the Navier–Stokes Equation in 3-D is obtained as

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial \rho}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho g_x \quad (1a)$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial \rho}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho g_y \quad (1b)$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial \rho}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho g_z \quad (1c)$$

The summation of the Navier–Stokes Equation is shown in Fig. 2.

Determination of physical, rheological, and viscoelastic properties of CO samples

Physical Properties °API gr

The specific gravities (Sp. gr.) of CO samples were determined by using ASTM D1298—12b (2017) which was used to calculate the °API gr. of the samples using Eq. (2) (Awadh and Mimar, 2015).

$$^{\circ}\text{API} = \frac{141.5}{\text{Sp.gr.at } 15.6^{\circ}\text{C}/15.6^{\circ}\text{C}} - 131.5 \quad (2)$$

Pour point

The PPs of CO samples in Table 1 were determined by ASTM D 97 (Dong et al. 2013; Wang 2013).

Rheological properties Shear Stress (τ), Shear Strain (γ') and Viscosity (η).

τ , η were determined using viscometer as in Table 3. γ' was calculated by using Eq. (3) as per Laun et al., where the viscometer geometries were used from Table 3 (Laun et al. 2014).

$$\gamma' = \frac{2\varphi_o R_o R_i}{R_o^2 - R_i^2} \quad (3)$$

where,

R_o = Outer cylinder radius (m)

R_i = Inner cylinder radius (m)

φ_o = amplitude of angular deflection (radian) which is as follows:

$$\varphi_o = \sin^{-1} \left(\frac{T}{R_o * \tau * A} \right)$$

Kinematic viscosity (K.V.)

Cannon–Fenske Viscometer was used to measure the K.V. of CO samples of Table 1.

K.V. was calculated by using Eq. (4)

$$\text{K.V.} = k \times t \quad (4)$$

where,

k = Viscometer constant in cSt/sec, which varies with the diameter of the Cannon–Fenske tube.

t = time in sec.

Fig. 2 Navier–Stokes Equation in vector form for incompressible fluid flow

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P + \rho \mathbf{g} + \mu \nabla^2 \mathbf{v}$$

MASS
Density of the fluid

ACCELERATION
How velocity experienced by a particle changes with time

FORCE
All the forces that are acting on the fluid

Change in velocity over time

The speed and direction which the fluid is moving

Internal pressure gradient of the fluid (the change in pressure)

External forces acting on the fluid (such as gravity)

Internal stress forces acting on the fluid (taking into consideration viscous effects)

Viscosity Gravity Constant (VGC)

The VGC of the CO samples of Table 1 was calculated by using semi-empirical Eqs. (5) and (6) (Kurtz et al., 1956). For the calculation of VGC, Sp. gr. and Saybolt viscosity (SSU) are required. So, Sp. gr. was determined as mentioned in Sect. 2.3.3.1 and K.V. was determined by using Eq. (4). After calculating K.V., Saybolt viscosity (SSU) was determined by using Eq. (7) which was required to calculate the VGC values in Eq. (5) or Eq. (6) as given below.

For light and medium COs

$$VGC = \frac{\{10d - 1.0752 \log(v - 38)\}}{\{10 - \log(v - 38)\}} \quad (5)$$

For heavy COs

$$VGC = \frac{\{d - 0.24 - 0.022 \log(v - 35.5)\}}{0.755} \quad (6)$$

where

d = Sp. gr. at 15.6 °C/15.6 °C.

v = Saybolt viscosity (SSU) at 37.78 °C.

Saybolt viscosity can be expressed as follows:

$$v = B\eta/\text{Sp.gr.}$$

$$= B\nu_{\text{centiStokes}} \quad (7)$$

where

$\nu = \text{K.V. (SSU)}$

$B = 4.632 \text{ at } 37.78^\circ \text{C}$

$\nu_{\text{centiStokes}} = \text{K.V. (cSt)}$

Viscoelastic properties The viscoelastic properties of the CO samples were calculated by using the following equations.

Dynamic Modulus (G^*)

G^* was calculated by applying Eq. (8) (Shenoy 1999).

$$G^* = \tau/\gamma' \quad (8)$$

Elastic Modulus (G') and Viscous Modulus (G'').

G' and G'' were calculated by Eqs. (9) and (10) respectively (Sheony 1999, Andrade 2018).

$$G' = G^* \times \cos \theta \quad (9)$$

$$G'' = G^* \times \sin \theta \quad (10)$$

where

θ = angular velocity (ω) x time (t).

ω in rad/s and t in s.

Correlation

The CC is the relationship and association between properties, which refer to the extent to which a property changes in quantity or quality in response to a change in another property. The CC was determined to find how strongly the properties are related to each other by using the CORREL function in Microsoft Excel. In this work, the CC was determined to find how °API gr. was related to the physical, rheological, and viscoelastic properties of CO samples of Table 1 to identify the best fit CO for pipeline transportation. A CC of “+1” indicates a perfect positive correlation and a CC of “-1” indicates a perfect negative correlation while a CC of “0” implies that there is no correlation between the two properties.

Measurement of correlation coefficients The following formula is used in the CORREL function in Microsoft Excel.

=CORREL (array1, array2).

Where, array1 and array2 represent the values of two properties.

In excel, Array 1 defines the value of the property in row1, i.e. R1 and Array 2 defines the value of the property in column1, i.e. C1.

So, the CORREL function in Microsoft Excel can be written as

=CORREL (R_{1-n} , C_{1-n}).

Where the physical, rheological, and viscoelastic properties of COs considered in this work are in rows from R_1 to R_n (R_{1-n}) and in columns from C_1 to C_n (C_{1-n}), respectively. The number of the total rows and columns should be the same for both the arrays, i.e. ‘n’ should be same for both; otherwise it will give an error. The correlation process is given in Table 4.

Results and discussion

Results

The results of physical properties PP and °API gr. of the CO samples are in Table 5. The results of rheological properties of the samples as mentioned in Sect. 2.3.3.2 are in Tables 6, 7, and 8. The viscoelastic values are in Table 9. The CC values obtained from the correlations are in Tables 10, 11, 12, 13, 14, 15, 16, 17 and from these correlations; equations are obtained from equation (11) to equation (18). From these relationships, two CO samples CO3 and CO8 were identified, and then the identified CO for the determination of the best fit CO is in Fig. 3 and Table 18.

Table 4 Correlation process

	$^{\circ}\text{API gr}$	Pp	τ	γ'	H	K.V	VGC	G'	G''
$^{\circ}\text{API gr}$	CORREL($^{\circ}\text{API gr.}, ^{\circ}\text{API gr.}$)								
PP	CORREL(PP, $^{\circ}\text{API gr.}$)	CORREL(PP, PP)							
τ	CORREL(τ , $^{\circ}\text{API gr.}$)	CORREL(τ , PP)	CORREL(τ , τ)						
γ'	CORREL(γ' , $^{\circ}\text{API gr.}$)	CORREL(γ' , PP)	CORREL(γ' , τ)	CORREL(γ' , γ')					
η	CORREL(η , $^{\circ}\text{API gr.}$)	CORREL(η , PP)	CORREL(η , τ)	CORREL(η , γ')	CORREL(η , η)				
K.V	CORREL(K.V, $^{\circ}\text{API gr.}$)	CORREL(K.V., PP)	CORREL(K.V., τ)	CORREL(K.V., γ')	CORREL(K.V., η)	CORREL(K.V., K.V.)			
VGC	CORREL(VGC, $^{\circ}\text{API gr.}$)	CORREL(VGC, PP)	CORREL(VGC, τ)	CORREL(VGC, γ')	CORREL(VGC, η)	CORREL(VGC, K.V.)	CORREL(VGC, VGC)		
G'	CORREL(G', $^{\circ}\text{API gr.}$)	CORREL(G', PP)	CORREL(G', τ)	CORREL(G', γ')	CORREL(G', η)	CORREL(G', K.V.)	CORREL(G', VGC)	CORREL(G', G')	
G''	CORREL(G'', $^{\circ}\text{API gr.}$)	CORREL(G'', PP)	CORREL(G'', τ)	CORREL(G'', γ')	CORREL(G'', η)	CORREL(G'', K.V.)	CORREL(G'', VGC)	CORREL(G'', G')	CORREL(G'', G'')

Table 5 $^{\circ}\text{API gr.}$ and PP of CO samples

Sl. No.	CO	$^{\circ}\text{API}$				PP ($^{\circ}\text{C}$)			
		CO+0	CO+5	CO+10	CO+15	CO+0	CO+5	CO+10	CO+15
1	CO1	32	36	28	25	9	24	27	27
2	CO2	21	22	26	33	12	27	24	27
3	CO3	34	38	39	35	24	21	18	24
4	CO4	26	18	24	24	3	-15	-12	-9
5	CO5	43	13	11	14	21	21	9	-9
6	CO6	13	29	32	21	12	27	30	30
7	CO7	24	28	26	34	24	30	30	27
8	CO8	33	18	23	26	21	30	33	30

Table 6 η and τ of CO samples at 30 $^{\circ}\text{C}$

Sl. No.	CO	CO+0		CO+5		CO+10		CO+15	
		η (Pa s)	τ (Pa)	η (Pa s)	τ (Pa)	η (Pa s)	τ (Pa)	η (Pa s)	τ (Pa)
1	CO1	0.0269	26.4	0.0031	3.2	0.0054	5.5	0.0052	5.3
2	CO2	0.0401	41	0.0033	3.4	0.0038	3.9	0.0065	4.5
3	CO3	0.0068	6.9	0.0065	6.6	0.0069	7	0.0068	6.9
4	CO4	0.1119	114.3	0.0433	44.2	0.0259	26.4	0.0166	17
5	CO5	0.0096	9.8	0.0249	25.4	0.0312	31.9	0.0213	21.8
6	CO6	0.1005	60.1	0.0053	5.4	0.0070	7.1	0.0307	31.4
7	CO7	0.0327	33.4	0.0043	4.4	0.0002	0.2	0.0056	5.7
8	CO8	0.0232	23.7	0.0244	24.9	0.0144	14.7	0.0090	9.2

In Table 5 the samples were prepared as per Sect. 2.1 and $^{\circ}\text{API gr.}$ and PP of CO samples were tabulated. It was observed that as SKO was added, the $^{\circ}\text{API gr.}$ increases

gradually for CO2. But except for CO2, irregularities were observed in all the samples as % of SKO increases in the sample, $^{\circ}\text{API gr.}$ also fluctuates indicating the effects of SKO

Table 7 K.V. of CO samples at 30 °C

Sl. No.	CO	K.V. (10^{-6} m ² /s) of samples with different % of SKO			
		CO+0	CO+5	CO+10	CO+15
1	CO1	11.55	9.75	7.75	20
2	CO2	48	21.81	40.25	48
3	CO3	5.95	20.25	14.75	11.5
4	CO4	53.5	67.75	76	50.75
5	CO5	8	141	78.8	42.8
6	CO6	27	16	52	17.5
7	CO7	12.3	35	15	60
8	CO8	6.5	22	12.5	50.5

Table 8 VGC of CO samples at 30 °C

Sl. No.	CO	VGC of CO samples with different % of SKO			
		CO+0	CO+5	CO+10	CO+15
1	CO1	0.86	0.83	0.87	0.87
2	CO2	0.89	0.89	0.86	0.82
3	CO3	0.86	0.79	0.79	0.81
4	CO4	0.84	0.91	0.86	0.88
5	CO5	0.81	0.94	0.96	0.94
6	CO6	0.96	0.85	0.81	0.88
7	CO7	0.89	0.86	0.87	0.80
8	CO8	0.86	0.92	0.89	0.83

on the CO samples. It was also observed by several authors that SKO has an influential effect on CO properties (Ghanam and Esmail 2006; Kandwal et al. 2000; Dong et al. 2020; Verma et al. 2016). When SKO was added, the °API gr dropped to 18° C which may be due to the instrumental error which can be rectified in future research work.

The equations generated from Tables 10, 11, 12, 13, 14, 15, 16, 17 are as follows

For CO1, based on Table 10,

$$o_{API} \alpha \frac{(P.P.)\tau\gamma'\eta G'G''}{(K.V.)(VGC)} \quad (11)$$

For CO2, based on Table 11,

$$o_{API} \alpha \frac{(P.P.)\gamma'(K.V.)}{\tau\eta(VGC)G'G''} \quad (12)$$

For CO3, based on Table 12,

$$o_{API} \alpha \frac{\gamma'(K.V.)G'}{\tau\eta(P.P.)(VGC)G''} \quad (13)$$

For CO4, based on Table 13,

Table 9 G' and G'' values of CO samples at different γ' and 30 °C

Sl. No.	CO	CO + %SKO	γ'	G'	G''
1	CO	CO1+0	11.7946	1.599423	1.565852
		CO1+5	97.50541	0.032575	0.003994
		CO1+10	56.65216	-0.08121	-0.0532
		CO1+15	58.79316	-0.06774	-0.05948
2	CO	CO2+0	7.594433	4.740689	2.582971
		CO2+5	91.74788	0.035848	-0.00939
		CO2+10	79.94982	0.025061	-0.04185
		CO2+15	69.26563	-0.0105	-0.06411
3	CO	CO3+0	45.14593	-0.15048	0.026751
		CO3+5	47.19998	-0.13971	0.005732
		CO3+10	44.50042	-0.15357	0.034073
		CO3+15	45.14593	-0.15048	0.026751
4	CO	CO4+0	2.724132	41.28829	7.46841
		CO4+5	7.044597	5.614395	2.800991
		CO4+10	11.7946	1.599423	1.565852
		CO4+15	18.3171	0.333482	0.866112
5	CO	CO5+0	31.77926	-0.15237	0.268105
		CO5+5	12.25898	1.435647	1.493953
		CO5+10	9.76095	2.619002	1.954857
		CO5+15	14.28357	0.902253	1.230982
6	CO	CO6+0	5.180859	10.93503	3.872223
		CO6+5	57.70279	-0.07456	-0.05656
		CO6+10	43.87312	-0.15641	0.041533
		CO6+15	9.916386	2.518072	1.919866
7	CO	CO7+0	9.322567	2.931614	2.059467
		CO7+5	70.84328	-0.00364	-0.062
		CO7+10	1138.06	0.000261	-0.00019
		CO7+15	54.66171	-0.09393	-0.04528
8	CO	CO8+0	13.13838	1.172719	1.370656
		CO8+5	12.50516	1.356283	1.457836
		CO8+10	21.18357	0.123715	0.682817
		CO8+15	33.85283	-0.16512	0.215851

$$o_{API} \alpha \frac{(P.P.)\gamma'\tau\eta G'G''}{(K.V.)(VGC)} \quad (14)$$

For CO5, based on Table 14,

$$o_{API} \alpha \frac{(P.P.)\gamma'}{\tau\eta G'G''(K.V.)(VGC)} \quad (15)$$

For CO6, based on Table 15,

$$o_{API} \alpha \frac{(P.P.)\gamma'(K.V.)}{\tau\eta G'G''(VGC)} \quad (16)$$

For CO7, based on Table 16,

$$o_{API} \alpha \frac{(P.P.)(K.V.)}{\tau\eta\gamma'G'G''(VGC)} \quad (17)$$

Table 10 Correlation of the physical, rheological, and viscoelastic properties of CO1

	°API	PP (°C)	τ (Pa)	γ'	η (Pa s)	K.V.(m ² /s)	VGC	G'(Pa)	G''(Pa)
°API	1								
PP(°C)	0.47	1							
τ (Pa)	0.16	−0.94	1						
γ'	0.29	0.69	−0.89	1					
η (Pa s)	0.16	−0.94	1	−0.89	1				
K.V.(m ² /s)	−0.60	0.18	−0.06	−0.10	−0.06	1			
VGC	−0.91	0.16	0.18	−0.61	0.18	0.35	1		
G'(Pa)	0.29	−0.98	0.99	−0.81	0.99	−0.10	0.03	1	
G''(Pa)	0.28	−0.98	0.99	−0.83	0.99	−0.10	0.05	0.10	1

Table 11 Correlation of the physical, rheological, and viscoelastic properties of CO2

	°API	PP (°C)	τ (Pa)	γ'	η (Pa s)	K.V.(m ² /s)	VGC	G'(Pa)	G''(Pa)
°API	1								
PP (°C)	0.57	1							
τ (Pa)	−0.53	−0.98	1						
γ'	0.33	0.95	−0.98	1					
η (Pa s)	−0.49	−0.97	0.10	−0.98	1				
K.V.(m ² /s)	0.44	−0.49	0.48	−0.66	0.51	1			
VGC	−0.10	−0.51	0.48	−0.28	0.44	−0.50	1		
G'(Pa)	−0.57	−0.98	0.10	−0.97	0.10	0.44	0.52	1	
G''(Pa)	−0.57	−0.98	0.10	−0.97	0.10	0.44	0.52	0.10	1

Table 12 Correlation of the physical, rheological, and viscoelastic properties of CO3

	°API	PP(°C)	τ (Pa)	γ'	η (Pa s)	K.V.(m ² /s)	VGC	G'(Pa)	G''(Pa)
°API	1								
PP(°C)	−0.95	1							
τ (Pa)	−0.16	−0.10	1						
γ'	0.18	0.09	−0.10	1					
η (Pa s)	−0.17	−0.09	0.10	−0.10	1				
K.V.(m ² /s)	0.82	−0.61	−0.64	0.65	−0.63	1			
VGC	−0.87	0.69	0.38	−0.39	0.37	−0.95	1		
G'(Pa)	0.19	0.07	−0.10	0.10	−0.10	0.66	−0.40	1	
G''(Pa)	−0.15	−0.11	0.10	−0.10	0.10	−0.63	0.37	−0.10	1

Table 13 Correlation of the physical, rheological, and viscoelastic properties of CO4

	°API	PP(°C)	τ (Pa)	γ'	η (Pa s)	K.V.(m ² /s)	VGC	G'(Pa)	G''(Pa)
°API	1								
PP(°C)	0.77	1							
τ (Pa)	0.36	0.84	1						
γ'	0.04	−0.47	−0.87	1					
η (Pa s)	0.36	0.84	1	−0.87	1				
K.V.(m ² /s)	−0.41	−0.63	−0.34	−0.10	−0.34	1			
VGC	−0.94	−0.81	−0.57	0.28	−0.57	0.22	1		
G'(Pa)	0.48	0.91	0.99	−0.79	0.99	−0.43	−0.66	1	
G''(Pa)	0.35	0.83	0.10	−0.88	0.10	−0.33	−0.57	0.99	1

Table 14 Correlation of the physical, rheological, and viscoelastic properties of CO5

	$^{\circ}\text{API}$	$\text{PP}(^{\circ}\text{C})$	$\tau(\text{Pa})$	γ'	$\eta(\text{Pa s})$	$\text{K.V.}(\text{m}^2/\text{s})$	VGC	$G'(\text{Pa})$	$G''(\text{Pa})$
$^{\circ}\text{API}$	1								
$\text{PP}(^{\circ}\text{C})$	0.46	1							
$\tau(\text{Pa})$	-0.93	-0.26	1						
γ'	0.99	0.40	-0.96	1					
$\eta(\text{Pa s})$	-0.93	-0.26	1	-0.96	1				
$\text{K.V.}(\text{m}^2/\text{s})$	-0.71	0.25	0.69	-0.73	0.69	1			
VGC	-0.10	-0.48	0.94	-0.10	0.94	0.68	1		
$G'(\text{Pa})$	-0.83	-0.16	0.98	-0.88	0.98	0.62	0.86	1	
$G''(\text{Pa})$	-0.94	-0.28	0.10	-0.97	0.10	0.70	0.95	0.97	1

Table 15 Correlation of the physical, rheological, and viscoelastic properties of CO6

	$^{\circ}\text{API}$	$\text{PP}(^{\circ}\text{C})$	$\tau(\text{Pa})$	γ'	$\eta(\text{Pa s})$	$\text{K.V.}(\text{m}^2/\text{s})$	VGC	$G'(\text{Pa})$	$G''(\text{Pa})$
$^{\circ}\text{API}$	1								
$\text{PP}(^{\circ}\text{C})$	0.81	1							
$\tau(\text{Pa})$	-0.98	-0.83	1						
γ'	0.89	0.52	-0.91	1					
$\eta(\text{Pa s})$	-0.95	-0.93	0.98	-0.80	1				
$\text{K.V.}(\text{m}^2/\text{s})$	0.41	0.13	-0.23	0.19	-0.15	1			
VGC	-0.98	-0.89	0.96	-0.78	0.95	-0.44	1		
$G'(\text{Pa})$	-0.94	-0.94	0.97	-0.78	0.10	-0.16	0.96	1	
$G''(\text{Pa})$	-0.99	-0.82	0.10	-0.92	0.97	-0.25	0.95	0.96	1

Table 16 Correlation of the physical, rheological, and viscoelastic properties of CO7

	$^{\circ}\text{API}$	$\text{PP}(^{\circ}\text{C})$	$\tau(\text{Pa})$	γ'	$\eta(\text{Pa s})$	$\text{K.V.}(\text{m}^2/\text{s})$	VGC	$G'(\text{Pa})$	$G''(\text{Pa})$
$^{\circ}\text{API}$	1								
$\text{PP}(^{\circ}\text{C})$	0.36	1							
$\tau(\text{Pa})$	-0.51	-0.93	1						
γ'	-0.28	0.35	-0.51	1					
$\eta(\text{Pa s})$	-0.51	-0.93	0.10	-0.51	1				
$\text{K.V.}(\text{m}^2/\text{s})$	0.98	0.34	-0.43	-0.44	-0.43	1			
VGC	-0.10	-0.32	0.50	0.23	0.50	-0.96	1		
$G'(\text{Pa})$	-0.64	-0.92	0.99	-0.36	0.98	-0.57	0.63	1	
$G''(\text{Pa})$	-0.63	-0.93	0.99	-0.35	0.98	-0.57	0.61	0.10	1

Table 17 Correlation of the physical, rheological, and viscoelastic properties of CO8

	$^{\circ}\text{API}$	$\text{PP}(^{\circ}\text{C})$	$\tau(\text{Pa})$	γ'	$\eta(\text{Pa s})$	$\text{K.V.}(\text{m}^2/\text{s})$	VGC	$G'(\text{Pa})$	$G''(\text{Pa})$
$^{\circ}\text{API}$	1								
$\text{PP}(^{\circ}\text{C})$	-0.65	1							
$\tau(\text{Pa})$	-0.32	-0.52	1						
γ'	0.37	0.43	-0.97	1					
$\eta(\text{Pa s})$	-0.32	-0.52	1	-0.97	1				
$\text{K.V.}(\text{m}^2/\text{s})$	0.15	0.38	-0.70	0.84	-0.70	1			
VGC	-0.91	0.30	0.66	-0.73	0.67	-0.53	1		
$G'(\text{Pa})$	-0.28	-0.55	0.99	-0.92	0.99	-0.59	0.60	1	
$G''(\text{Pa})$	-0.32	-0.51	0.10	-0.98	0.10	-0.72	0.67	0.98	1

Fig. 3 Properties of CO3 and CO8 with varying % of SKO

Table 18 Selection of best fit CO

	CO3		CO8		
	5%	10%	0%	5%	15%
°API	–	39	33	–	–
PP(°C)	–	18	21	–	–
η(Pa s)	0.00646	–	–	0.00901	–
G''	0.005732	–	–	–	0.215851

For CO8, based on Table 17,

$$o_{API} \propto \frac{\gamma'(K.V.)}{\tau \eta (P.P.) G' G'' (VGC)} \quad (18)$$

Discussion

Correlating the variation of the physical, rheological and viscoelastic properties of CO samples with °API gr. led to the identification of CO samples from the point of flowability of CO through the pipeline. As discussed by several authors that high °API gr. & G' and low PP, η, K.V., VGC, τ, γ' & G'' were the prerequisite desirable requirements in the properties for CO for flowability (Dong et al. 2020; Dimitriou and McKinley 2014; Andrade 2018). Equation (11) to Eq. (18) for the CO samples was derived from the correlations that exist between the properties as in Tables 10, 11, 12, 13, 14, 15, 16, 17. CO3 and CO8 were identified amongst all the CO samples for the selection of the best fit CO. The discussion for CO3 and CO8 was as follows:

- (a) In Eq. (13), as °API gr. increases, PP, η, VGC, τ and G'' decrease while γ', K.V. and G' increase, indicating that as the % of SKO in CO3 increases, the elastic-

ity increases showing shear thinning behavior. While the decreasing trend of VGC indicates the inclination toward paraffinicity, since the PP decreases therefore the paraffins are not crosslinkers by a linear chain.

- (b) In Eq. (18), as °API gr. increases, PP, τ, η, VGC, G' and G'' decrease while γ' and K.V. increase indicating that as the % of SKO in CO8 increases, the viscoelasticity decreases. The response toward VGC was the same as that for CO3.

Since the objective of this work is to reduce the PP of the CO samples, so CO1, CO2, CO4, CO5, CO6, and CO7 are not found to be the best fit for pipeline transportation. The discussions are as follows:

- (a) In Eq. (11), as °API gr. increases, K.V., VGC decreases while PP, τ, γ', η, G' and G'' increase. This indicates that as the % of SKO in CO1 increases, the PP and η increase and as G' and G'' increase, the viscoelastic behavior increases.
- (b) In Eq. (12), as °API gr. increases, τ, η, VGC, G' and G'' decrease, while PP, γ' and K.V. increase. This indicates that as the % of SKO in CO2 increases, it appears to be difficult to flow through a pipeline at low temperatures as PP increases.
- (c) In Eq. (14), as °API gr. increases, K.V., VGC decrease, while τ, γ', η, PP, G', and G'' increase. This indicates that as the % of SKO in CO4 increases, the viscosity, PP, and viscoelasticity also increase which creates difficulty in pipeline transportation.
- (d) In Eq. (15), as °API gr. increases, τ, η, VGC, K.V., G' and G'' decrease, while PP and γ' increase. This indicates that as the % of SKO in CO5 increases, it appears to be difficult to flow through a pipeline at low temperatures as PP increases.
- (e) In Eq. (16), as °API gr. increases, τ, η, VGC, G' and G'' decrease, while PP, γ' and K.V. increase. This indicates that as the % of SKO in CO6 increases, the CO6 appears to be difficult to flow through a pipeline at low temperatures as PP increases.
- (f) In Eq. (17), as °API gr. increases, τ, γ', η, VGC, G' and G'' decrease, while PP, and K.V. increase. This indicates that as the % of SKO in CO7 increases, it appears to be difficult to flow through a pipeline at low temperatures as PP increases.

The °API gr. is an important property for the flow of CO through pipeline because °API gr. is inversely proportional to sp. gr. which means that °API gr. is also inversely proportional to density (ρ). Observation from Reynolds no (R_e) Eq. (19) appears that the higher the °API gr. higher will be the R_e. Similarly, the lesser the η higher will be the R_e. R_e plays an important role in understanding the

flow behavior through a pipeline and an undisturbed flow was suggested when $R_e > 2300$, indicating a transition to turbulent flow from laminar flow (Wyslouzil, 1987).

$$R_e = \frac{\rho v D}{\eta} \quad (19)$$

where R_e = Reynolds no.

ρ = density (kg/m^3)

v = velocity (m/s)

D = Diameter (m)

η = viscosity (Pa s)

Several researchers worked with chemicals to reduce the PP, η , and yield stress of CO samples, but in this research, SKO was added for the same purpose which is also economically and environmentally viable (Mamonova 2019; Slater 1986). Souas 2020 showed that η , τ_y , G' and G'' were significantly reduced by adding surfactants for CO flowability (Souas 2020). But in this research for flowability G' increases while G'' decreases with °API gr. was desirable for flowability. Minero et al. 2014 and Szilas 1975 accepted that a CO can be transported through the pipeline only if its K.V. is less than 250 cSt at 37 °C (Minero et al. 2014). Since the K.V. values in this work are very low at 30 °C, so the effect of K.V. on °API gr. was neglected.

To determine the best fit crude equations from Eq. (11) to Eq. (18) were compared and found that in the case of CO3 and CO8, °API gr. is inversely proportional to τ as in Eq. (13) and Eq. (18) which suggests that lower τ_y was required for flow of CO through a pipeline. Plotting the values of PP, °API gr., G'' and η with varying % of SKO in Fig. 3 and tabulating the values of lowest PP, η , and G'' and highest °API gr. for the identified CO samples of CO3 and CO8 in Table 18, the best fit CO sample was found to be CO3.

Table 14 describes why the best fit was CO3; the analyses are as follows:

- °API gr of CO3 was the highest at 10% SKO which was 39, while °API gr of CO8 was the highest at 0% SKO which was 33. Therefore, w.r.t. °API gr CO3 was found to be the best fit.
- PP of CO3 was the lowest at 10% SKO which was 18 °C, while PP of CO8 was the lowest at 0% SKO which was 21 °C. Therefore, w.r.t. PP, CO3 was found to be the best fit.
- η of CO3 and CO8 was the lowest at 5% SKO but comparing both the values η for CO3 and CO8 which were 0.00646 Pa s and 0.00901 Pa s, respectively, the η for CO3 was the lowest. Therefore, w.r.t. η CO3 was found to be the best fit.

- G'' of CO3 was lowest at 5% SKO which was 0.005732, while G'' of CO8 was the lowest at 15% SKO which was 0.215851. Therefore, w.r.t. G'' , CO3 was found to be the best fit as at lower % of SKO G'' was much lower compared to the value of G'' for CO8.
- Compared from the economic point of view, for CO3 up to 10%, the desirable properties were met as compared to CO8, where the desirable properties were met when SKO % increases to 15%.

The CCs were obtained using CORREL from the physical and viscoelastic properties of the CO samples. In this work, all the CCs obtained from the correlation are in Tables 10, 11, 12, 13, 14, 15, 16, 17. The relationships of °API gr. with the other properties are from Eq. (11) to Eq. (18). The CC of +1 was observed in the case of η vs. τ in Tables 10, 13, 14, and 17, indicating a perfect positive correlation. As observed in Tables 10, 11, 12, 13, 14, 15, 16, 17, positive CC values are directly proportional and negative CC values are inversely proportional to °API gr., respectively. Taking this into consideration, Eq. (11) to Eq. (18) was generated.

Determination of best fit CO is done based on the following:

The objective of the work is to obtain the PP < 9 °C, which is a requisite parameter for pipeline transportation, but in both cases, the lowest PP for CO3 and CO8 was > 9 °C as in Table 6, CO3 sample was LCO, as its °API gr. > 31 throughout the mixing of 0% to 15% of SKO. But in the case of CO8, only at 0% SKO it behaved as LCO. In case of CO3, η and G'' were lowest at 5% of SKO. But in the case of CO8, η was lowest at 5% SKO, but loss modulus was lowest at 15% of SKO. Therefore, further upgradation of CO3 and CO8 samples was required.

Conclusion

The work was carried out to analyze the effect of SKO content on CO flow in a pipeline. The correlation between API and other physical, rheological, and viscoelastic properties has been investigated through several experiments at SKO %. A best fit CO for pipeline transportation was identified from eight different CO samples. CO3 was identified considering the correlation that exists between the properties. CO3 had a high °API gr. of 39, low PP of 18 °C, lowest η of 0.00646 Pa s, and lowest G'' of 0.005732 Pa as compared to other CO samples. Although CO8 was very close to CO3, the values of η and G'' are higher than for CO3. °API gr. was significantly enhanced and PP was reduced with an increase

in % of SKO in CO₃ to 10% at any particular 30 °C. These changes in the properties of CO₃ enhance the flowability through a pipeline. Further research is needed to study the flow behavior of CO₃ through a pipeline with special consideration to Re and frictional factors.

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Ethical approval This work is the authors' original work, which has not been published elsewhere, accepted for publication elsewhere, and the paper reflects the authors' research work.

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