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The effect of IPC formulation on bitumen properties – An experimental study

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ABSTRACT

Use of chemicals as an additive during steam-based bitumen recovery processes has been an active topic for research and development in the last four decades. In this study, thermo-physical properties of mixtures of bitumen with a newly developed chemical are reported. This new chemical technology (i.e. IPC as referred in this paper) is a proprietary mixture of surfactants that has been used in several techniques associated with surface extraction as well as in-situ recovery of heavy oil and bitumen. This formulation of solvents and surfactants is reusable, low foaming, non-flammable, not acutely toxic and non-carcinogenic. A series of tests were conducted to measure density and viscosity of a bitumen, IPC, and different mixtures of bitumen-IPC at several pressure, temperature and chemical composition conditions. It was observed that solubility of IPC in bitumen was small, and its effects on the oil phase viscosity and density could not be separated from its effects on bulk properties caused by dispersed emulsified droplets of IPC. The impact of IPC on viscosity of mixture was more pronounced than its effect on mixture density. A very complex emulsion was formed upon contact of IPC with bitumen. The results of these tests will be useful in designing a steam-based bitumen recovery process with IPC as the chemical additive. Details of thermal stability analysis of IPC are also presented.

1. Introduction

Fluid characterization for oil-solvent mixtures can be expressed in the form of a data analysis process by which the data associated with the mixtures of oil and solvent(s) are turned into mathematical parameters. These parameters, which describe the fluid properties over variable operating conditions of pressure, temperature and composition, can then be used in numerical simulations to describe flow behavior of oil-solvent mixtures in porous structure. At the basic level, fluid characterization provides descriptive and quantitative information and equations that represent properties of only the liquid oil phase in the absence of an associated gas or vapor phase, with some solvent composition. However, if other phases, either gaseous or solid phases, appear during interaction of the solvent with oil within the range of operating conditions of interest, compositions and properties of these evolved fluid phases in equilibrium with the oil phase are also determined using fluid properties modeling approach.

Equilibrium compositions of various phases, and the conditions at which additional phases appear, are usually characterized with help of Equations of State (EOS). Each component is treated separately in an EOS with uniquely assigned parameters, or else lump components with similar characteristics together into pseudo-components, which are thereafter treated the same as any other pure component. When constituents of a crude oil are not expected to separate into any other phases under operating conditions of interest but instead remain essentially in the liquid oil phase, then all the constituents can be lumped together and the oil phase can be regarded as a single pseudo-component. However if the constituents of the oil phase turn into separate phases of solid or gas under pertaining operating conditions, it is essential to describe the evolved phases in terms of separate pure and/or pseudo-components as appropriate. Alternatively, if all constituents of a solvent would be dissolved in the oil phase with no evolution of a secondary fluid phase, then the whole mixture can be regarded as a single pseudo-component.

To reduce viscosity of bitumen under in-situ conditions, both heat and solvent could be implemented (Mohammadzadeh, 2012; Mohammadzadeh et al., 2010, 2012a; 2012b, 2015a; Rezaei et al., 2010a, 2010b; Hernandez and Farouq Ali, 1972; Farouq Ali and Abad, 1976; Farouq Ali and Snyder, 1973; Nasr and Ayodele, 2006; Nasr et al., 2002; Nasr et al., 1991). There have been several applications of chemicals alongside thermal processes at pilot- and field-scales which prove efficacy of thermal-hybrid bitumen recovery methods (Dickson et al., 2011; Orr, 2009; Solanki et al., 2011). Although the parameters needed to describe various oil and bitumen types are different, the effects of solvents on these oil types are usually similar when it is viewed in terms of mole fractions of solvent addition. The effects and trends

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observed in terms of changes in viscosity, density, and vapor-liquid equilibrium for one oil type will be roughly similar to those in most other oil types. The least certain property among all these properties of concern is viscosity when it comes to the greater viscosity ranges of hydrocarbons, i.e. bitumen. Bitumen viscosity can vary significantly between reservoirs. Interfacial properties and their behaviors can, however, differ more broadly because they may be influenced by large differences in minor constituents, which therefore are not well reflected in the overall physical oil properties. This is why surfactant behavior needs to be tailored to each oil reservoirs.

This study investigated effects of IPC formulation, a newly developed chemical additive, on physical properties of a representative bitumen when the chemical dissolves in it. These effects and thermophysical properties of mixtures were to be quantitatively measured so that they could be subsequently portrayed with high accuracy in numerical simulation of laboratory tests and on broader scale to develop the potential for field applications of IPC formulation for in-situ recovery of bitumen. In this regard, the properties of bitumen and IPC formulation were required to be measured first over a range of temperature and pressure conditions that allows a correlation to be obtained with suitable accuracy. Of particular importance during the design stage of these fluid characterization tests are how the IPC formulation behaves at high temperature conditions associated with thermal processes for bitumen recovery, and determine chemical stability and effectiveness at these temperatures when solvency properties of the chemical is concerned, and how well it maintains capability of reducing Interfacial Tension (IFT) at higher temperatures. All this information was needed to properly design a thermal recovery method, assisted with use of the IPC formulation, for effective recovery of bitumen.

The IPC formulation is a proprietary chemical that has applications in in-situ recovery of heavy oil using chemical-assisted waterflooding process (Mohammadzadeh et al., 2015b), surface extraction of bitumen from oilsand ore, froth purifications and a few other applications in the downstream oil industry. The IPC formulation (Patent US, 2013/0157920 A1) is a proprietary, liquid cleaning, degreasing, and disinfecting concentrate composition, comprised of: (1) caustic soda in a range of about 0.181% to about 5.45% by volume; (2) a de-emulsifier in a range of about 0.028% to about 9.09% by volume; (3) an alkyl glucoside surfactant of about 0.090% to about 7.27% by volume; (4) a phosphated alkyl ethoxylate surfactant of about 0.028% to about 1.81% by volume; (5) a tridecyl alcohol surfactant in a range of about 0.363% to about 9.09% by volume; (6) a non-polar bonding agent of about 0.028% to about 1.81% by volume; and, (7) water forming the remainder percentage by volume. To assess the suitability of this chemical for improving the in-situ bitumen recovery processes such as solvent aided steam assisted gravity drainage (SA-SAGD), there needs to be some thermal stability analysis of the chemical as well as fluid properties studies involving bitumen-IPC fluid system.

2. Materials and methods

2.1. Characterization of IPC formulation and thermal stability tests

In an earlier study, the IPC formulation was characterized for physical properties. The density and viscosity of IPC was measured at ambient pressure and several temperatures. A series of tests were also done to measure the threshold temperature at which IPC formulation begins to decompose. These tests specify the maximum temperature of the IPC formulation for use in thermal recovery of bitumen. Two Thermal Gravimetric Analysis (TGA) and two Differential Scanning Calorimetry (DSC) tests were conducted on the IPC formulation. The TGA and DSC tests can determine the onset and degree of thermal degradation of the chemical. For the TGA and DSC tests, baseline trials were also conducted with empty pans and with local carrier water which was used to manufacture the chemical, and the results were then used to correct the TGA and DSC tests performed using the chemical. A step rate change for temperature was implemented from the ambient temperature with 5 °C/min increments. To detect the thermal decomposition of IPC into volatile components through pyrolysis, one TGA and one DSC test were conducted under a Nitrogen atmosphere. The other two TGA and DSC tests were conducted in the presence of air which results in measuring the thermal degradation of the chemical due to oxidation of the constituents.

In addition to classic thermal stability tests, some distillation tests were also conducted to obtain some understanding on partitioning and thermal stability of the surface-active ingredients of IPC formulation. A certain volume of IPC was distilled at different temperature and vacuum pressure conditions, and the IFT of solutions of distillation products (i.e. distillate and remaining bottom phases) in brine with a heavy oil was measured. Using these tests, the contribution of surface active agents in different fractional cuts associated with distillation of IPC was qualitatively identified. A 100-cc sample of IPC formulation was heated under 100 °C and 67 kPa vacuum conditions. The vacuum pressure was then increased at constant temperature until the chemical started boiling. The evaporated portion was directed to a separate vessel for condensation while the bottoms (i.e. residues subject to heating at vacuum conditions) boiled continuously. The distillation process was stopped when phase separation of the bottoms occurred after about 20% of the original volume of the chemical was distilled off. The remainder of the chemical was separated, and formed two distinct liquid phases. These three distinct cuts of IPC (distillate, top and bottom liquid phases of remainder) were separated, and their densities were measured at lab conditions. A 2 wt% solution of each of these cuts in 1 wt% NaCl brine were prepared. The IFT between these three solutions and a heavy oil sample were measured at 20 °C.

To test the thermal stability and IFT reduction ability of IPC at elevated temperatures associated with solvent assisted thermal recovery processes, a second distillation test was conducted. One liter of a solution composed of 2 wt% IPC in 1 wt% NaCl was poured into a 2 L stainless steel vessel. The vessel was vacuumed and flashed with nitrogen to remove the air, and was then sealed and placed inside an oven at 200 °C for 24 h. After cooling down, the IFT between the heated solution and Heavy Oil C was measured at 20 °C. Results from the distillation tests helped in designing proper phase behavior and fluid characterization studies for IPC-oil mixtures.

2.2. Design of fluid characterization tests

Considering the results obtained from thermal stability analysis of the IPC formulation, its use as a solvent additive for thermal recovery of bitumen seemed promising. The role of a solvent additive for steam-based processes of bitumen recovery is to further reduce bitumen's viscosity by dilution. Therefore, a series of fluid characterization tests were needed to study solubility and partitioning of IPC in bitumen, as well as to quantify its effects on reducing the viscosity and density of bitumen-IPC mixture as a function of pressure, temperature and mole fractions of IPC.

A series of bench-top volumetric partitioning tests were conducted previously to measure how much IPC partitions between aqueous and oleic phases at ambient temperature. In these tests, measured volumes of a heavy oil, deionized water, toluene, and IPC were added to a 100 mL centrifuge test tube and mixed by vigorous shaking until a homogeneous phase was formed, then centrifuged for 30 min. The volumes were measured and photographs were taken (Mohammadzadeh et al., 2015b). Several standard methods such as infrared spectrometry and gas chromatography were used to measure the concentration of active ingredients of IPC in solution. They all failed to identify the characteristic peaks necessary to measure concentration of active ingredients in IPC. Titration methods could not be used due to very small concentrations of active components in IPC. These difficulties made it challenging to measure the solubility parameter and gas-liquid or liquid-liquid equilibria and partitioning coefficients for the oil-IPC mixture.

Since the main purpose of characterizing fluids was to obtain fluids properties for material balance and flow modeling of the solvent aided bitumen recovery process, the base characterization tests are needed to be conducted on pure bitumen extracted from the oilsands. Toluene is mostly used as a solvent to extract the bitumen content of oilsands ore; therefore, it needs to be removed from the extracted bitumen prior to being used for the characterization tests. Of particular concern is separating toluene from bitumen after extraction from ore because there is always the possibility of some traces of residual toluene in the extracted bitumen. A gas purging method was successfully used to remove the residual traces of toluene to ensure that no detectable solvents remained in the bitumen, which is very important for viscosity measurements and subsequent flow modeling purposes. A bitumen sample, representative of Northern Alberta region, was extracted from the mined oil sands ore with toluene. The toluene-bitumen mixture was then filtered through Whatman 2 filter paper to remove solids, after which the bulk of toluene was removed from bitumen-toluene mixture by normal roto-evaporation technique under vacuum conditions at approximately 100 °C. Toluene content of the extracted bitumen was further reduced by gas stripping for another 6 h in a procedure that typically reduces the toluene content of bitumen to a value well under 0.1 wt%. The cleaned oil was then immediately poured into a stainless steel transfer cylinder from which air was promptly expelled.

To fulfil the fluids characterization objectives for the bitumen-IPC mixture, the focus was then shifted to the effect of presence of chemical on viscosity-temperature and density-temperature relationships for bitumen. To fulfill this objective, the bitumen phase (free of any residual solvent) was characterized to measure the weight fraction of saturates, aromatics, resins and asphaltenes (SARA), molecular weight, and alkane-equivalent carbon number distribution analysis through simulated distillation test.

The density and viscosity of the cleaned extracted bitumen were measured in a high-temperature PVT apparatus. About 482.50 g of the cleaned extracted bitumen was transferred into the PVT cell, and the remaining bitumen was transferred to a glass sample bottle and was stored in a freezer. The plan was to measure liquid parameters such as density and viscosity at three temperatures of 15, 100 and 200 °C (all below the thermal degradation temperature of IPC) and four elevated pressures of 1000, 4000, 7000 and 10,000 kPa. The bitumen compressibility and pressure coefficient of viscosity were also determined at these temperatures. All these measurements were repeated after addition of 0.5, 2 and 4 wt% of IPC at the same three temperatures to study the effect of chemical concentration on density and viscosity of bitumen-chemical mixture. The temperature was controlled within 0.1 °C or better by computer control of an air bath in which the primary thermocouples had been calibrated against a platinum resistance thermometer. Pressures were measured within 35 kPa accuracy with high-precision pressure transducers capable of operation to 34,500 kPa. The density was measured with an Anton-Paar densitometer capable of operation up to 200 °C, and viscosity was measured by measuring the pressure drop exhibited across a length of 0.306 cm O.D. tubing through which the bitumen was forced to flow at a constant rate. The capillary tube had been calibrated against a certified viscosity standard with a quoted accuracy of 0.4%. The pressure drop was measured at two different rates, with the higher rate normally being twice the lower one to test for any strong sensitivity to the shear rate which would indicate non-Newtonian behavior. The agreement at different shear rates was satisfactory, the maximum disagreement was 1.8% at 15 °C where experimental uncertainty was the largest, indicating that bitumen could be effectively treated as a Newtonian fluid over this temperature range. Once bitumen was charged into the PVT cell, pressure was fixed and the reference physical properties such as density and viscosity were measured at three temperatures through isobaric heating process.

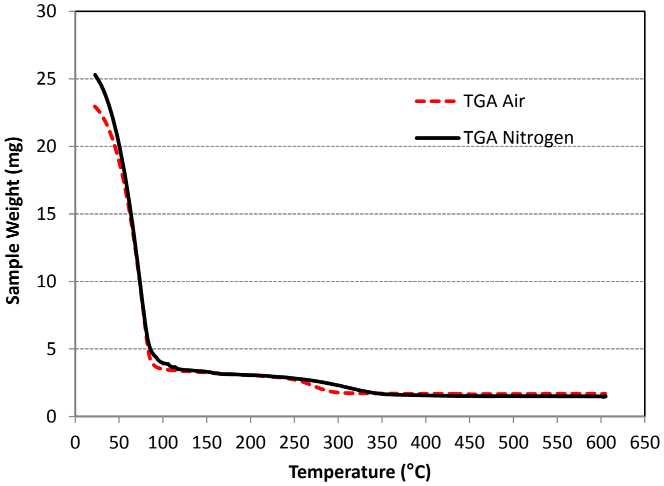

Fig. 1. TGA thermograms for IPC under air and nitrogen.

3. Results and discussion

3.1. Characterization and thermal stability of IPC

Density of IPC is similar to many oil reservoir brines at test temperatures. The dynamic viscosity of IPC is about 3–4 times that of water at similar test conditions. From the TGA thermograms (Fig. 1) and the time derivatives shown in Fig. 2, it was found that most of the chemical vaporized just below 100 °C, but the remaining portion was relatively stable at temperatures up to 250 °C. Focusing on the TGA under nitrogen, the mass of residue then dropped gradually and the maximum rate of loss of sample was obtained at about 310 °C. This maximum rate of loss was indicated at about 260–265 °C by the TGA test conducted under an air atmosphere, which is consistent with the temperature range of oxidation of paraffinic hydrocarbons. There are a few more inconsistencies between the rate of loss obtained under air and nitrogen atmospheres; for instance, oscillations observed around 100 and 150 °C for TGA nitrogen (which cannot be seen in TGA air signal) can be due to irregular vaporization, since they have not been reproduced when the test was conducted under air. The sample weight essentially remained unchanged at temperatures above 360 °C where only about 1.5 wt% of sample was left in the pan in the form of a white solid crystalline residue. To isolate the effect of non-aqueous components of IPC, one could subtract the thermograms obtained for carrier water from the ones belonged to IPC. This procedure enables indirect measurement of

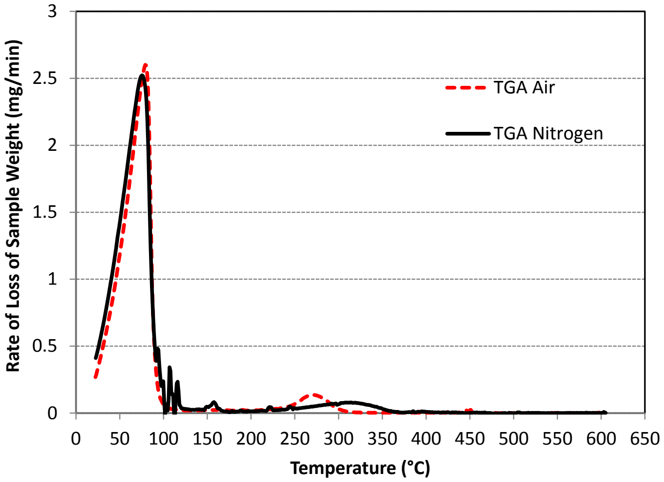

Fig. 2. Derivative of TGA signals for IPC under air and nitrogen.

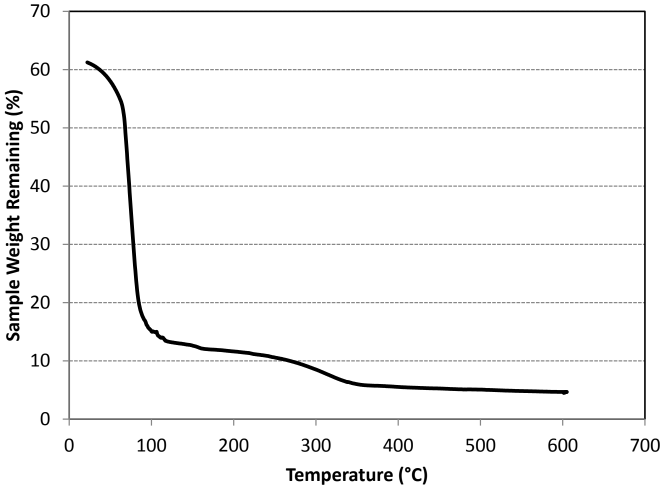

Fig. 3. TGA thermogram for IPC, corrected for carrier water, under nitrogen environment.

thermal stability of non-aqueous components of IPC (Fig. 3). It was found that a major portion of IPC that vaporized below 100 °C was not water.

The DSC tests were also performed with both air and nitrogen atmosphere blanket (Fig. 4). The results confirm that the process was endothermic at a temperature region just below 100 °C which agrees with the findings from the TGA tests. The endothermic behavior of the process is either due to the heat required for the phase change (i.e. evaporation of chemical) or simply due to the heat capacity of the materials being heated. In the DSC test with air atmosphere, there is an exothermic peak close to 300 °C which corresponds to the paraffinic oxidation peak observed in TGA test with air atmosphere (Figs. 1 and 2). To elucidate the status of thermal stability of non-aqueous components of IPC, the DSC test was performed for the carrier water which was used in preparation of IPC, and the curve was subtracted from that of IPC (Fig. 5). It was confirmed that a major portion of IPC that was lost because of the heating before reaching about 100 °C was not water as was shown before by the TGA tests. Based on the results of these thermal stability tests, it was concluded that any surface-active agent in IPC formulation will degrade at temperatures above 220 °C.

Amounts of IPC partitioned into the oil phase as a function of chemical ratios were measured in bench-top volumetric partitioning tests. Although IPC partitioned into the oleic phase for some of the mixing ratios, the tendency of IPC to partition correlated neither with the water/chemical volume ratio nor with the (oil + toluene) per chemical volume ratio used in these partitioning tests. The volumetric partitioning tests were inconclusive.

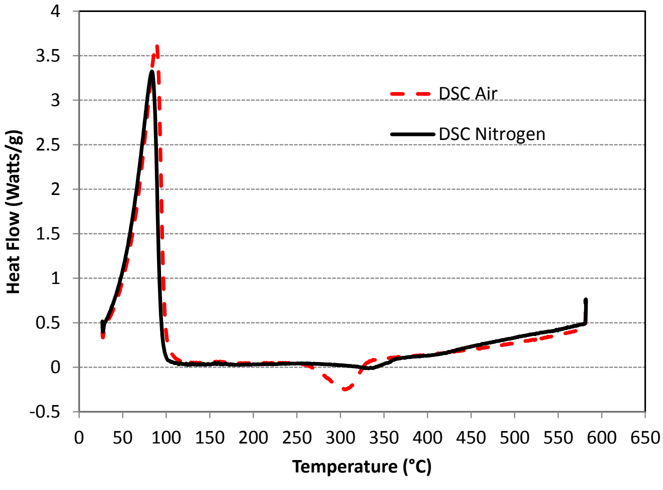

Fig. 4. DSC signal for IPC sample under air and nitrogen environments.

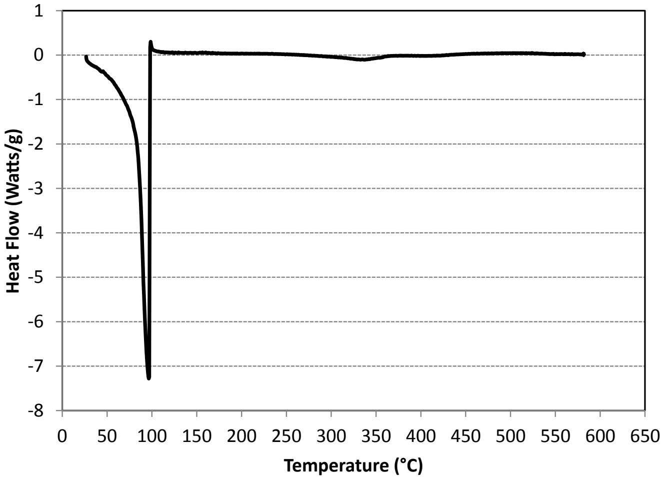

Fig. 5. DSC signal for IPC, corrected for carrier water, under nitrogen.

One of the objectives of this study was to obtain equilibrium solubility values for bitumen-IPC mixtures by taking vapor and liquid samples, conducting single-stage flash operation and measuring gas to oil ratio and compositions for the flashed oil and gas streams. Considering the difficulties experienced in terms of application of standard methods for measuring the concentration of active ingredients of IPC in liquid and gas phase, the attention was focused on measuring liquid mixture properties. Neglecting to measure vapor phase properties could adversely affect analysis of recovery process performance if there were major volatile surface-active agents in IPC which would evaporate at high temperatures associated with the steam-based recovery process. If the major dilution effects caused by IPC remains in the liquid phase, neglecting the properties measurement for the vapor phase will not discredit the investigation. The hypothesis for the phase behavior study of bitumen-IPC mixture was that major changes in fluid properties through the addition of IPC happens in the liquid phase, and that lack of data on vapor liquid equilibria (VLE) for such a system will not adversely affect the future fluid flow modelling of recovery process performance. The VLE characterization might not even be the most vital data to have to characterize the fluid system as well as to model the fluid flow performance when it comes to a solvent assisted thermal recovery process. There are other factors that influence recovery performance of such a process namely the interfacial tension between the oil phase and the chemical in formation water solution, the effect of chemical on rock surface wettability, its effect on oil and maybe brine viscosity, and perhaps its effect on oil density. Normally, VLE characterization becomes important for fluid systems with a volatile solvent that occurs in large volumes and has a major effect on oil phase viscosity. In such a system, it is essential to model the solvent partitioning between the vapor and liquid phases.

To test the hypothesis about accumulation of surface active agents of IPC in the liquid phase at elevated temperature and pressure conditions, a series of distillation tests were performed to examine volatility and stability of surface active constituents of IPC. Under the initial distillation conditions (100 °C and 67 kPa vacuum pressure), no visible distillation occurred, so the vacuum was increased to 74.5 kPa at which the chemical vigorously boiled. After phase separation, the densities of three distillate cuts of IPC (distillate, top and bottom liquid phases of the remainder) were measured (Table 1). The 2 wt% solutions of each of these cuts in 1 wt% NaCl brine were clear and homogeneous. The IFT values between these three solutions and the heavy oil sample, with properties shown in Table 2, are shown in Table 3, along with IFT values between the same heavy oil and fresh IPC in brine solution at the

Table 1
Densities of the distillation products.

Distillation cut	T °C	Density kg/m^3
Distillate	15	998.35
	25	996.19
	50	987.12
Top phase of the bottoms	15	1093.99
	25	1087.80
	50	1071.24
Bottom phase of the bottoms	15	1159.21
	25	1154.57
	50	1141.44

Table 2
Properties of Heavy Oil C used for IFT measurements with distillation products of IPC.

	Temperature (°C)	Heavy Oil C
Density (kg/m^3)	15	986.9
	20	983.7
	40	971.5
Viscosity (mPa.s)	15	22,800
	20	12,500
	40	1620
Acid number (mg KOH/g)		1.13

Table 3
IFT between Heavy Oil C and solutions of distillation products in 1 wt % NaCl brine.

Description of chemical added to brine	IPC added[a]	IFT,[b] mN/m
Nothing added (i.e. baseline)	0 wt%	58
Fresh IPC	2 wt%	0.141
Distillate	2 wt%	48
Top phase of the bottoms residue	2 wt%	0.681
Bottom phase of the bottoms residue	2 wt%	0.015

[a] All solutions were prepared in 1 wt% NaCl brine.
[b] IFT's measured at 20 °C.

Table 4
IFT between Heavy Oil C and solutions of 2 wt % IPC in 1 wt% NaCl, fresh and heated to 200 °C for 24 h.

IPC concentration, wt%	Description	IFT[a] mN/m
0	No chemical	58
2	Fresh chemical	0.141
2	Chemical solution heated to 200 °C for 24 h	0.174

[a] IFT's measured at 20 °C.

Table 5
Physical properties of bitumen sample.

Property	Measured value
Average molecular weight (g/gmol)	559.4
Vapor pressure at 200 °C (kPa)	255
SARA analysis	
Saturates	20.3
Aromatics	28.0
Resins	33.6
Asphaltenes[a]	18.1
Total recovery	100

[a] n-pentane insoluble.

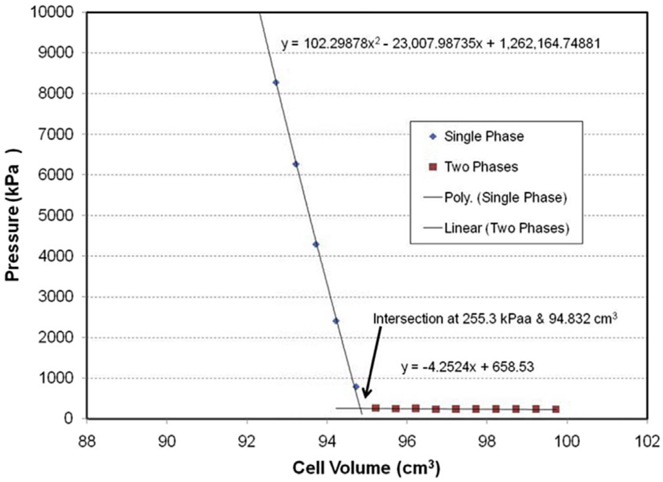

Fig. 6. Saturation pressure determination for bitumen at 200 °C.

Table 6
Calculated compressibility coefficient and pressure coefficients of viscosity for bitumen at different temperatures.

T (°C)	Compressibility $\left(=\frac{1}{V}\frac{\partial V}{\partial P}\right)$ (1/kPa)	Pressure coefficient for viscosity $\left(=\frac{1}{\mu}\frac{\partial \mu}{\partial P}\right)$ (1/kPa)
15	4.7×10^{-7}	6.06×10^{-5}
100	6.2×10^{-7}	2.76×10^{-5}
200	1.07×10^{-6}	1.57×10^{-5}

Table 7
Simulated distillation data for the bitumen sample.

% distilled	T (°C)
Initial boiling point	252
5	307
10	342
15	371
20	401
25	428
30	456
35	484
40	512
45	536
50	559
55	584
60	610
65	644
70	672
75	704
80	735

same operating conditions and brine salinity. The distillate cut did not show any surface activity, i.e. there was no (or very little) concentration of surface active agents in the distillate cut. In other words, the surface-active agents were not volatile enough or if they were, they were not thermally stable at 100 °C under 74.5 kPa of vacuum condition.

Another series of IFT measurements were conducted at 20 °C between the heated solution of chemical, obtained from the second distillation test, and Heavy Oil C (Table 4). The IFT of the chemical solution with Heavy Oil C was only deteriorated by about 23.5% when it was compared with the performance of fresh IPC in brine solution when all other parameters of temperature, chemical concentration and brine salinity were identical. Based on this test, the majority of surface active agents of IPC formulation remained thermally stable at temperature ranges associated with low pressure steam assisted gravity drainage (SAGD). Results of these distillation tests and the IFT measurements of different cuts associated with IPC distillation indicated that the majority of surface active agents of IPC formulation are retained in the distillation remaining phase (i.e. less volatile fractions) with little or no

Table 8
N-alkane equivalent carbon number distribution of the bitumen sample.

Component	Wt%	Cum. wt%	Mole%	Cum. mole%
Methane	0	0	0	0
Ethane	0	0	0	0
Propane	0	0	0	0
i-Butane	0	0	0	0
n-Butane	0	0	0	0
Other C4	0	0	0	0
i-Pentane	0	0	0	0
n-Pentane	0	0	0	0
Other C5	0	0	0	0
2-Hexane	0	0	0	0
1-Hexane	0	0	0	0
Other C6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0.08	0.08	0.23	0.23
15	1.38	1.47	3.52	3.75
16	1.20	2.67	2.87	6.62
17	1.62	4.29	3.64	10.26
18	2.00	6.29	4.25	14.51
19	2.05	8.33	4.12	18.63
20	2.00	10.33	3.83	22.46
21	2.42	12.75	4.41	26.87
22	1.61	14.36	2.80	29.67
23	2.14	16.50	3.56	33.23
24	1.83	18.33	2.93	36.16
25	1.83	20.17	2.81	38.97
26	1.87	22.03	2.75	41.72
27	1.79	23.82	2.54	44.26
28	1.85	25.67	2.53	46.79
29	1.73	27.40	2.29	49.08
30	1.50	28.90	1.92	51.00
31	1.64	30.54	2.03	53.03
32	1.63	32.17	1.95	54.98
33	1.10	33.27	1.28	56.26
34	1.15	34.42	1.30	57.56
35	1.51	35.93	1.66	59.22
36	1.47	37.40	1.56	60.78
37	1.02	38.42	1.06	61.84
38	0.96	39.38	0.97	62.81
39	1.62	41.00	1.60	64.41
40	1.60	42.60	1.54	65.95
41	1.03	43.63	0.96	66.91
42	0.96	44.58	0.87	67.78
43	1.58	46.16	1.41	69.19
44	1.52	47.68	1.32	70.51
45	0.91	48.58	0.77	71.28
46	0.84	49.42	0.70	71.98
47	1.00	50.42	0.82	72.80
48	1.00	51.42	0.80	73.60
49	0.90	52.32	0.71	74.31
50	0.88	53.20	0.68	74.99
51	0.89	54.09	0.67	75.66
52	0.89	54.98	0.66	76.32
53	0.84	55.82	0.61	76.93
54	0.82	56.64	0.58	77.51
55	0.78	57.42	0.55	78.06
56	0.71	58.13	0.48	78.54
57	0.71	58.83	0.48	79.02
58	0.77	59.60	0.51	79.53
59	0.70	60.30	0.46	79.99
60	0.70	61.00	0.45	80.44
C_{61+}	39.00	100.00	19.56	100.00

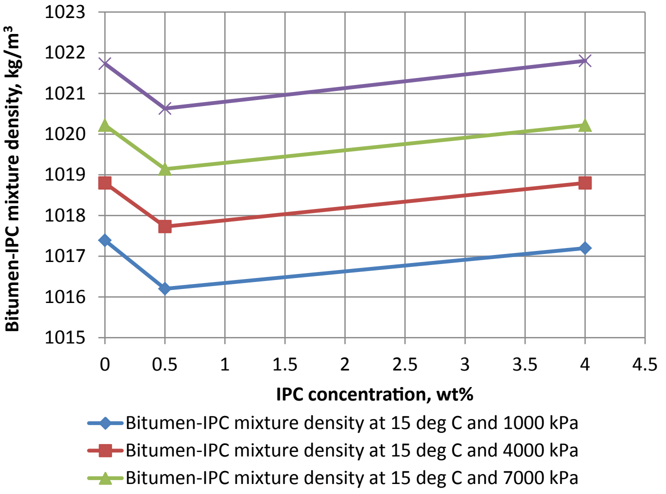

Fig. 7. Density of bitumen-IPC mixture at 15 °C.

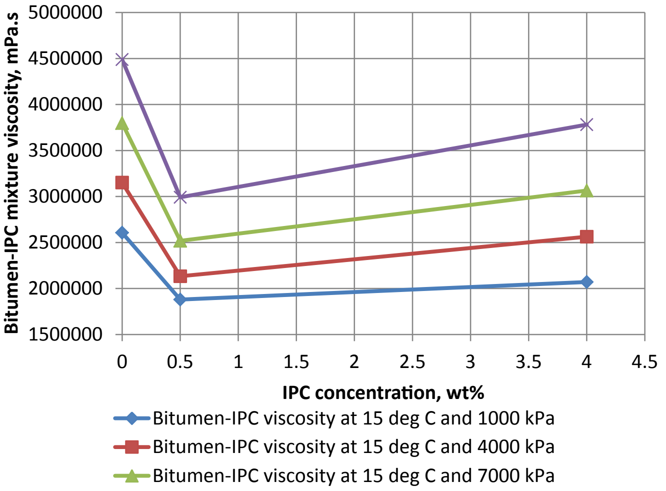

Fig. 8. Viscosity of bitumen-IPC mixture at 15 °C.

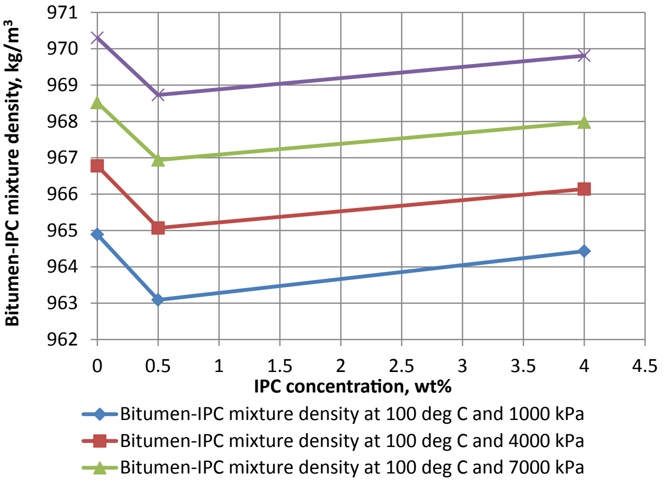

Fig. 9. Density of bitumen-IPC mixture at 100 °C.

transfer to the distillate phase, and that they are thermally stable. This important finding simplifies the fluid characterization tests for the oil-IPC fluid system and allows us to focus on brine-oil liquid-liquid partitioning of the IFT active ingredients as well as on the physical properties of the oil-IPC mixture as functions of temperature, pressure and chemical concentration.

3.2. Characterization of bitumen

The average molecular weight of bitumen was measured using the

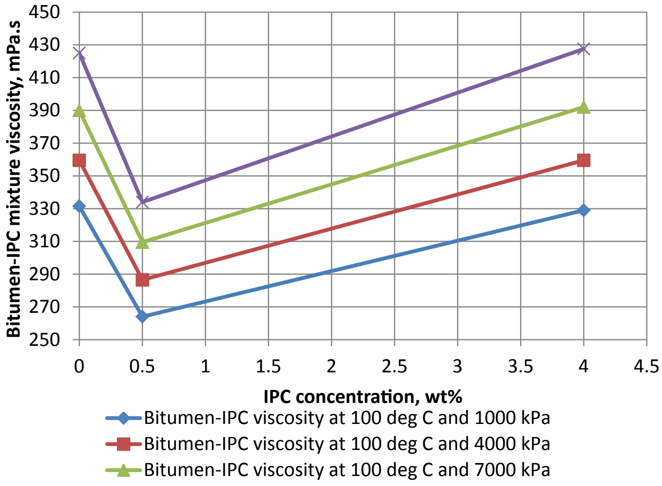

Fig. 10. Viscosity of bitumen-IPC mixture at 100 °C.

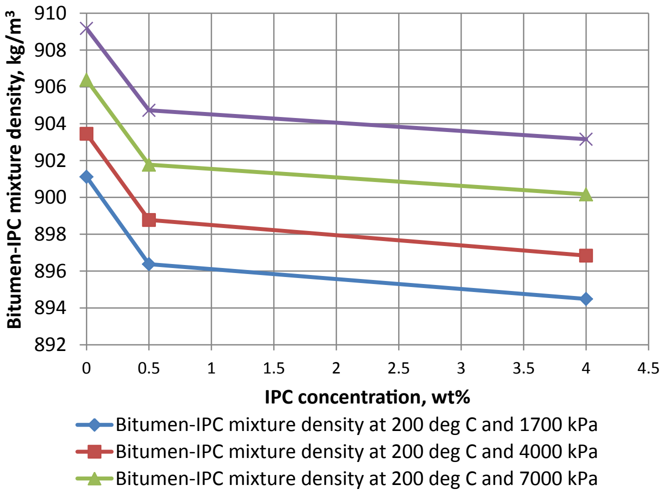

Fig. 11. Density of bitumen-IPC mixture at 200 °C.

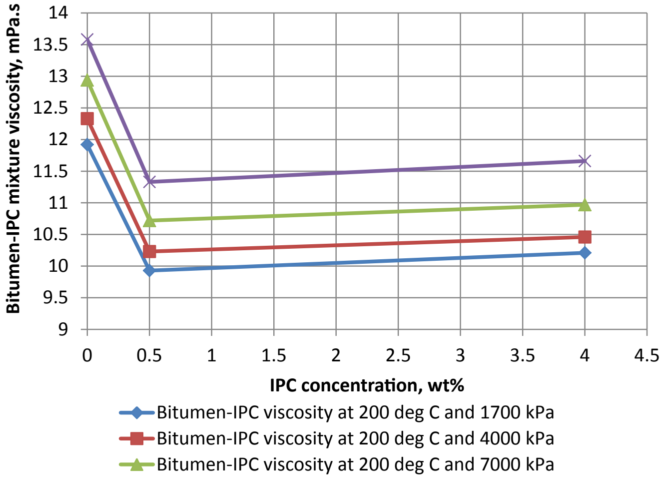

Fig. 12. Viscosity of bitumen-IPC mixture at 200 °C.

freezing point depression method. SARA analysis was conducted following the industry standard procedure of ASTM D 6560 – IP 143 method (Table 5). The procedure for saturation pressure determination is based on the pressure-volume history of bitumen using constant composition expansion (CCE) method (Fig. 6). Using the CCE data, the compressibility coefficient as well as pressure coefficient of viscosity for bitumen were calculated at different temperatures (Table 6).

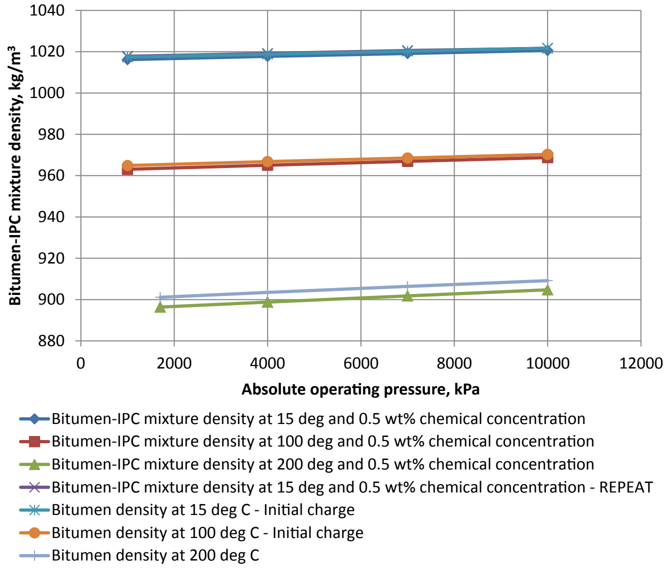

Fig. 13. Density of bitumen-IPC mixture at 0.5 wt% chemical concentration as a function of pressure at different temperatures.

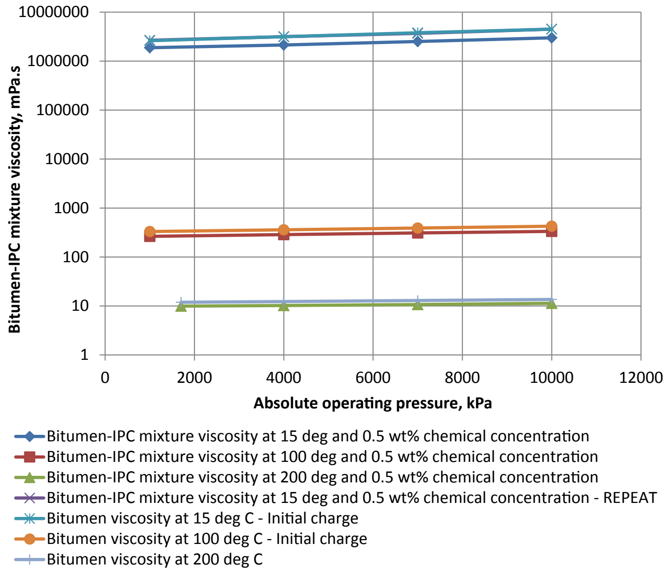

Fig. 14. Viscosity of bitumen-IPC mixture at 0.5 wt% chemical concentration as a function of pressure at different temperatures.

The simulated distillation (SD) data as well as the alkane-equivalent carbon number distribution of bitumen are presented in Tables 7 and 8. The initial normal boiling point of 252 °C, obtained from the SD test, corresponds to a carbon number fraction equivalent of C14 as displayed in Tables 7 and 8. This is significantly greater than the expected value based on the saturation pressure obtained from the CCE test, which has indicated a vapor pressure of about 255 kPa at an already lower temperature of 200 °C. The normal boiling point (i.e. saturation temperature at atmospheric pressure) obtained based on the SD analysis should have been significantly smaller than 200 °C which corresponds to the saturation pressure of 255 kPa which is more than twice the atmospheric pressure. Although the saturation pressure determination for bitumen is known to be subject to large uncertainties especially for cases in which the saturation pressures are only a few hundred kPa or less, the gap between these two values is too significant to attribute

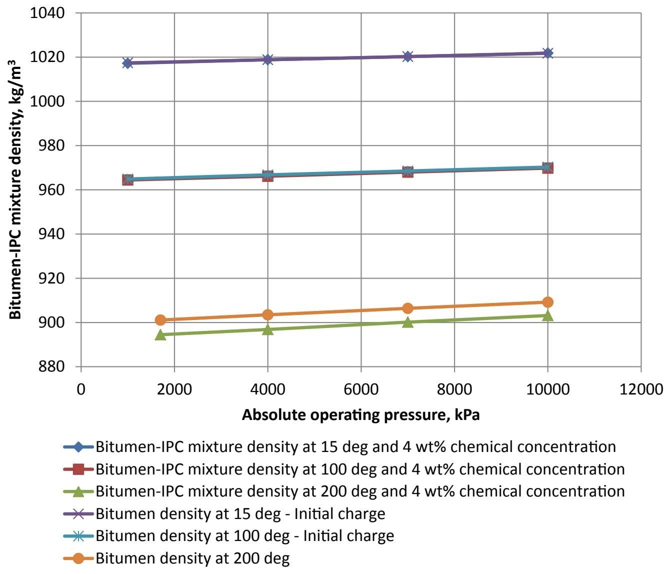

Fig. 15. Density of bitumen-IPC mixture at 4 wt% chemical concentration as a function of pressure at different temperatures.

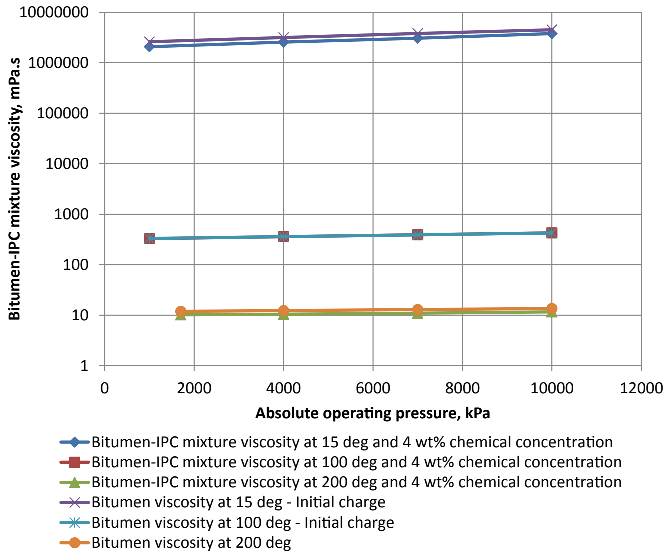

Fig. 16. Viscosity of bitumen-IPC mixture at 4 wt% chemical concentration as a function of pressure at different temperatures.

entirely to the experimental error.

The difference between the measured saturation pressure (from CCE) at the corresponding temperature and the normal boiling point condition obtained based on the SD data suggests that the bitumen phase under study contained some lighter components, lighter than the n-C_{14} equivalents which were identified as the lightest component in the carbon number distribution. Residual toluene, leftover from the bitumen extraction process, could have contributed to this difference in saturation temperature and/or pressure determination, but this factor by itself is not sufficient to be solely responsible because the concentration of toluene would have had to be more than an order of magnitude larger to account for the effect. The observed discrepancy was attributed to two other factors. First, the SD measurement was probably not sufficiently sensitive to detect the small amounts of lighter components, with carbon-equivalent numbers less than 14. Second, traces of air or nitrogen might have entered the bitumen phase during its transfer into the PVT cell, and small as these amounts might have been, they could still contribute slightly to the apparent vapor pressure.

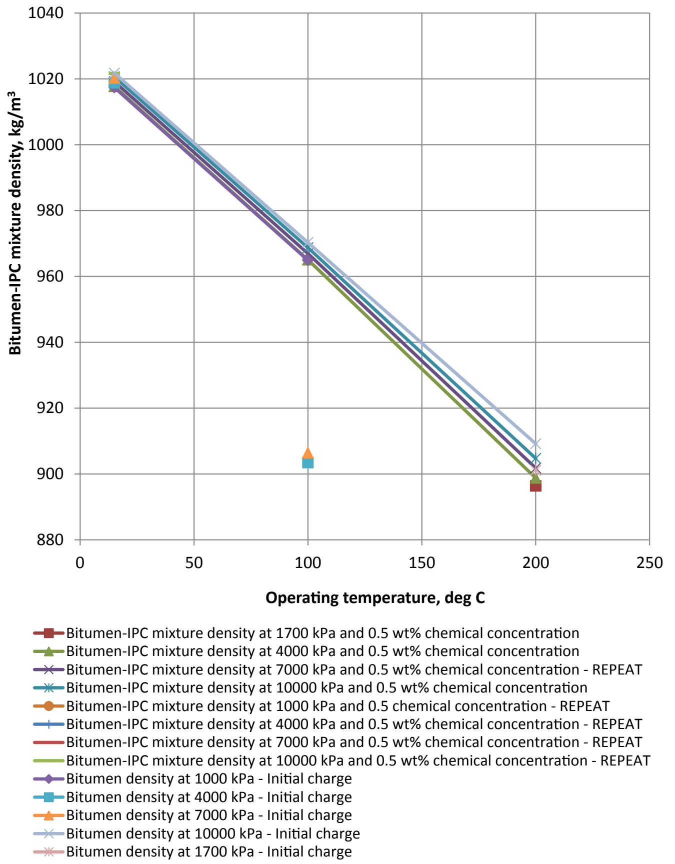

Fig. 17. Density of bitumen-IPC mixture at 0.5 wt% chemical concentration as a function of temperature at different pressures.

However, because of the care taken to minimize the contact between bitumen and air at the time of transfer, the latter effect is thought to be slight.

3.3. Characterization of bitumen-IPC mixtures

The original plan was to measure density and viscosity of the bitumen-IPC mixture at two concentrations of IPC (0.5 or 4 wt%), three temperatures (15, 100 or 200 °C) and four pressures of 1000, 4000, 7000 or 10000 kPa (Figs. 7–12).

As soon as the experimental data were analyzed, an unexpected trend was identified. Measured densities and viscosities of the bitumen-IPC mixture at 15 and 100 °C as well as mixture viscosity at 200 °C displayed a minimum in their plots when graphed versus the concentration of chemical instead of a monotonic decrease as had been expected. Changes in densities of the mixtures in all operating pressures were insignificant, to the maximum of 1 kg/m^3 in 15 °C and 2 kg/m^3 in 100 °C for both the chemical concentrations (Figs. 7 and 9, respectively). This change in mixture density is very close to the accuracy limit of the instrument. In contrast, IPC was influential in significantly reducing the mixture viscosity, especially at the lower operating temperature where the viscosity reduction due to operating at low temperature was minimal (Fig. 8). A less pronounced viscosity reduction due to the presence of chemical was observed at 100 °C (Fig. 10). However in both these cases, reduction of viscosity was anomalous such that a local minimum in viscosity was observed as the chemical concentration was increased. The decline in the density of bitumen-IPC mixture upon addition of chemical concentration follow the typical trend of such dilution (Fig. 11). For the viscosity of bitumen-IPC mixture at 200 °C, one might argue that viscosity of the mixture did not change significantly when IPC concentration increased from 0.5 to 4 wt

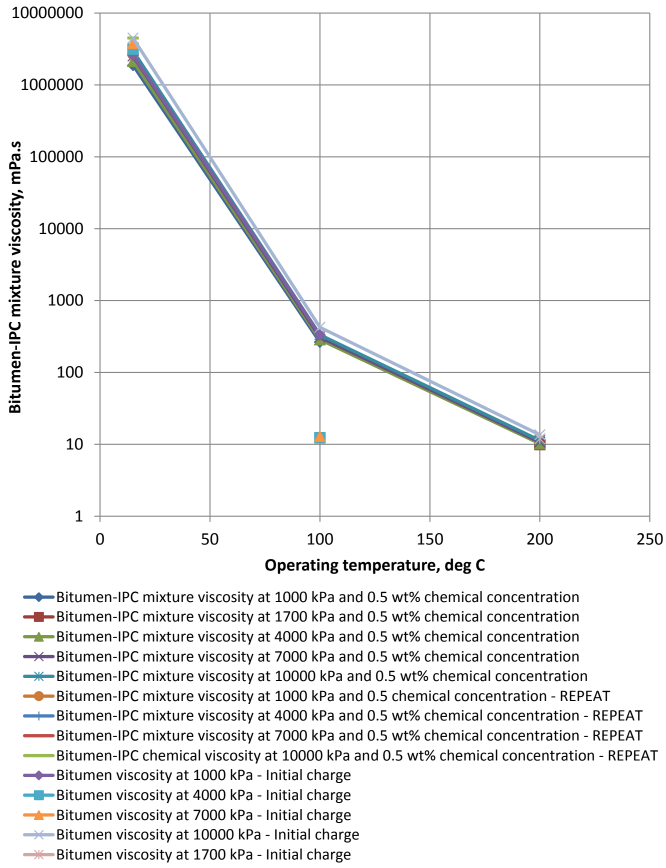

Fig. 18. Viscosity of bitumen-IPC mixture at 0.5 wt% chemical concentration as a function of temperature at different pressures.

% since the viscosity reduction impact of heat at that operating temperature was dominant.

The trends of bitumen-IPC mixture density and viscosity versus pressure at various levels of chemical concentration and operating temperatures were plotted (Figs. 13–16). The observed trends were all expected, i.e. with an increase in test pressure at constant ratio of bitumen to chemical and temperature, density values of the single-phase liquid have a monotonously increasing trend because of weak dependency of liquid density to pressure. Clearly, addition of 0.5 wt% IPC formulation to bitumen did not change the mixture density but the impact was more pronounced at greater concentrations of IPC (Figs. 13 and 15, respectively). The mixture viscosity-pressure trends observed (Figs. 14 and 16) were expected. There was a non-significant direct dependency between liquid viscosity and pressure. The impact is more noticeable at lower operating temperatures but diminishes at 200 °C. Addition of 0.5 wt% IPC chemical to bitumen at higher operating temperatures slightly decreased the mixture viscosity to less than that of bitumen at each particular pressure.

The bitumen-IPC mixture density and viscosity values changed versus temperature, respectively, at constant levels of IPC concentration and measurement pressure (Figs. 17–20). As observed in these four figures, an increase in measurement temperature at constant concentrations of IPC and operating pressure results in a monotonously decrease in density of single phase liquid as well as a decrease in viscosity of the mixture. The changes are modest, the largest is about a one-third reduction in viscosity at 15 °C. At 200 °C, there is much less difference between the measurements at 0.5 and 4 wt% IPC concentration. In fact at this maximum operating temperature, the density continues to decrease a little with concentration, but not nearly as much as had been anticipated. With the unusual trend observed for behavior of density and viscosity values versus IPC concentration at 15 and 100 °C, it was decided to re-examine the underlying assumptions.

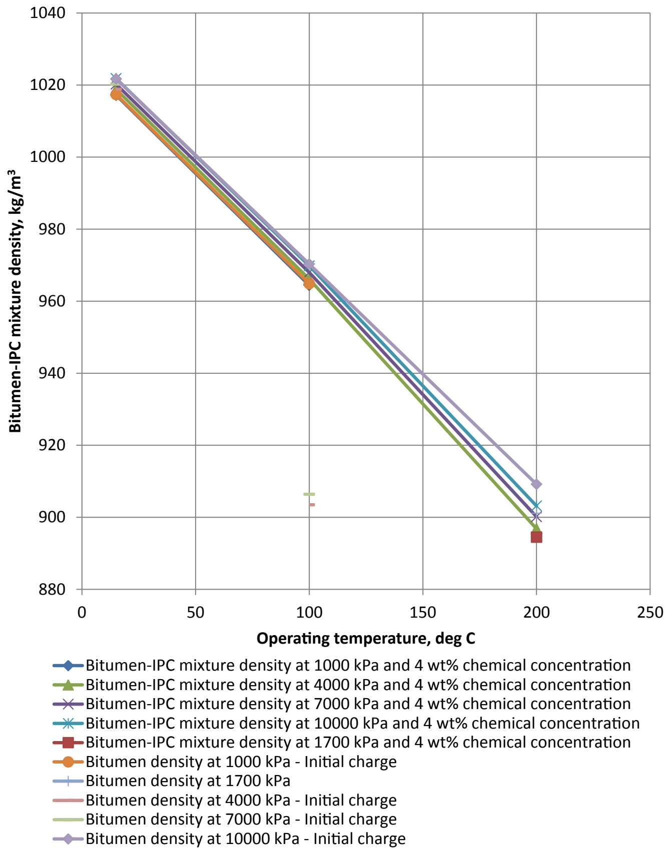

Fig. 19. Density of bitumen-IPC mixture at 4 wt% chemical concentration as a function of temperature at different pressures.

The most plausible cause postulated to explain this unusual trend is that a small amount of chemical had possibly dissolved in oil at a chemical concentration of 0.5 wt%, thereby reducing viscosity and density as expected. However, as additional chemical was added at greater IPC concentrations, it reached its solubility limits and any excess IPC became dispersed throughout the oil phase as an emulsion. The overall apparent bulk density of the oil would therefore increase because of the emulsification, because it would be the volume-weighted average of the slightly changed-in-density original bitumen and the denser portion of the chemical that would have not been dissolved in the oil phase. The presence of emulsion droplets would also interfere with and lengthen the smooth, laminar flow lines within the oil phase, thereby increasing its apparent viscosity. Another unverified assumption was found to revolve around the sequence and procedure in which the initial data had been collected. To avoid the long mixing times that would have been needed at 15 °C at which the bitumen viscosity was very high, IPC chemical was always added to bitumen and initially mixed at 100 °C at which the first measurements were taken. The apparatus was then cooled to 15 °C for the next set of measurements, and finally heated to 200 °C for the measurements at the final target temperature. If exposure of the chemical to the 100 °C temperature promoted some chemical reactions or decomposition within one or more of its major constituents, then the subsequent solubility of the chemical in, or even its interfacial tension with, the oil phase could have negatively changed. The data that had been collected at the lowest temperature of 15 °C, near those found in heavy oil and bitumen reservoirs, could therefore have been affected by the preliminary mixing at the intermediate level of temperature. To test the underlying assumptions and validate the initial data collected for mixture density and viscosity, a second phase of fluid characterization experimentation was design and executed.

3.4. Verification of hypotheses for the unusual trend in mixture density and viscosity

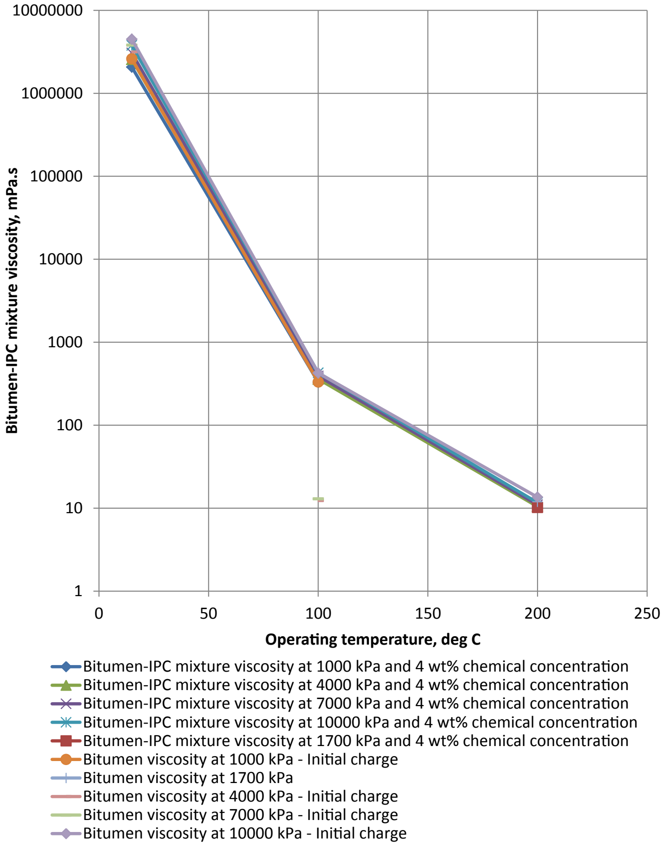

Fig. 20. Viscosity of bitumen-IPC mixture at 4 wt% chemical concentration as a function of temperature at different pressures.

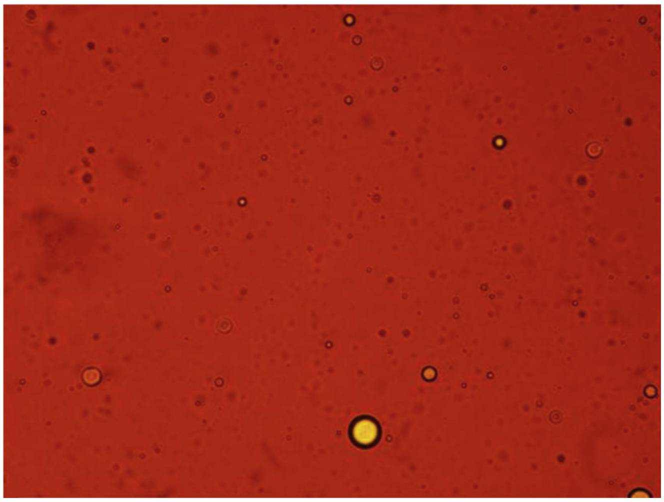

Fig. 21. Microscopic photograph of the bitumen-IPC mixture (at 4 wt% chemical concentration) shortly after sampling.

A sample of the oil phase that had been in the apparatus at the end, and had been mixed with 4 wt% of IPC concentration, was removed and promptly examined under a microscope. A photomicrograph captured shortly after the oil sample was collected demonstrates this effect (Fig. 21). It revealed that a second phase had indeed appeared and was dispersed throughout the oil phase as emulsified liquid droplets with a large range of sizes, some apparently in the form of oil-in-water droplets within the continuous oil phase. When the sample was observed after it had been on the glass slide and exposed to air for an extra day, crystals had appeared in some of the droplets (Fig. 22). The question of the significance of the appearance of solids was raised, but was subsequently dismissed as irrelevant because it could be explained very simply by the evaporation of water or other bonding solvents from the chemical mixture, which would naturally lead to the less volatile constituents becoming saturated and dropping out of the solution.

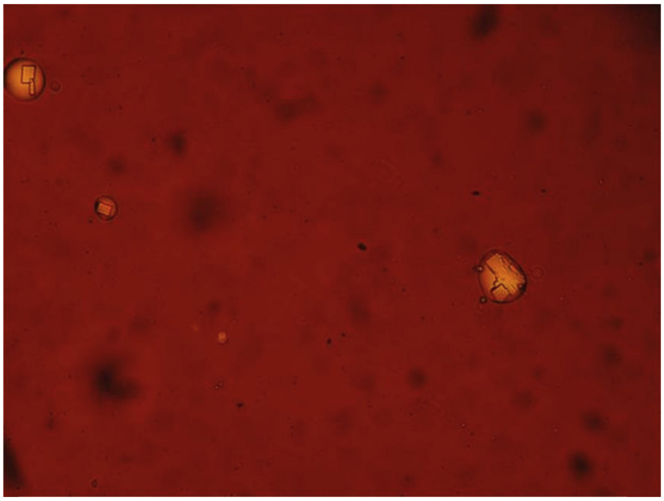

Fig. 22. Microscopic photograph of the bitumen-IPC mixture (at 4 wt% chemical concentration) after one day ageing on a slide at lab conditions.

It was then decided to test the effect of exposure temperature by cleaning out the old system and recharging the apparatus with the remainder of the cleaned bitumen, and then repeating the measurements at 15 °C after first mixing the chemical and bitumen at a much lower temperature. Because of the extremely high viscosity of bitumen at 15 °C, some increase in temperature was needed to accomplish the mixing in a permissible time period, and 40 °C was chosen as the mixing temperature. Bitumen was added first so that its density and viscosity could be re-measured to test whether either the bitumen properties or the apparatus's calibration had changed significantly. This was done at both 15 and 100 °C. Comparison with the initial measurements showed that the results were almost identical. The density values were different by 0.01–0.12 kg/m^3, and the viscosity values matched within 4%; they were now slightly greater at 15 °C, a change that was consistent and actually a little smaller than that which often accompanies storage and additional handling of viscous oil samples. All the measurements that were conducted on pure bitumen, both initial and the second phase of experiments, are provided (Table 9).

To obtain a nominal 0.5 wt% mixture, IPC was subsequently added to the system while it was still at room temperature. The concentration calculated on the mass basis of chemical and oil that was introduced into the apparatus was 0.525 wt%, which was very close to the earlier value of 0.521 wt%. Bitumen and IPC were initially forced to intermingle by pumping them back and forth between the two pump cylinders at ambient temperature. The system was then cooled and held within the range of 14.98–15.00 °C, at which a set of density and viscosity measurements was made. It appeared that there had not been any significant change in the oil properties compared to the pure bitumen, and therefore a small oil sample was removed from the cell and examined under the microscope. Emulsified droplets were observed in the continuum of oil, which indicated that at least some contact/agitation occurred between the chemical and the oil phase. However, viscosity and density of the mixture had not been reduced because of the addition of chemical as had been observed when the first mixture

Table 9
Bitumen density and viscosity as a function of pressure and temperature.

Temperature (°C)	Absolute Pressure (kPa)	Density (kg/m^3)	Viscosity (mPa.s)	% relative error with respect to initial measurement	
				Density	Viscosity
15 (Initial measurement)	1000	1017.39	2,607,000.00	N/A	N/A
	4000	1018.80	3,152,000.00	N/A	N/A
	7000	1020.22	3,799,000.00	N/A	N/A
	10,000	1021.73	4,489,000.00	N/A	N/A
15 (2nd charge of bitumen)	4000	1018.89	3,276,000.00	0.0088	3.9340
	7000	1020.34	3,927,000.00	0.0118	3.3693
100 (Initial measurement)	1000	964.89	331.50	N/A	N/A
	4000	966.78	359.50	N/A	N/A
	7000	968.52	390.00	N/A	N/A
	10,000	970.30	425.00	N/A	N/A
100 (2nd charge of bitumen)	4000	966.79	365.10	0.0010	1.5577
	7000	968.51	387.30	−0.0010	−0.6923
200	1700	901.12	11.92	N/A	N/A
	4000	903.46	12.33	N/A	N/A
	7000	906.39	12.94	N/A	N/A
	10,000	909.18	13.58	N/A	N/A

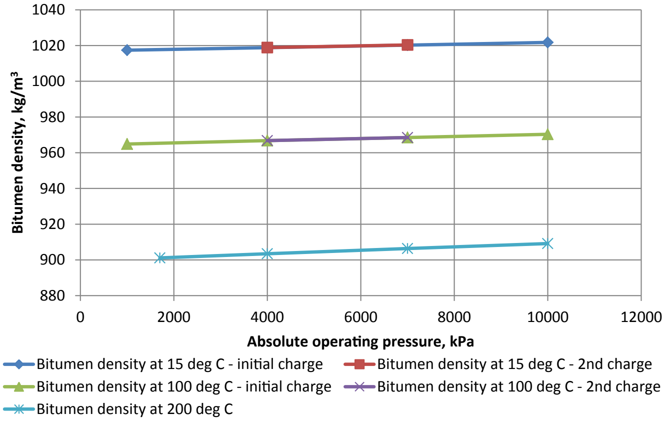

Fig. 23. Bitumen density versus pressure at different operating temperatures – All measured datasets.

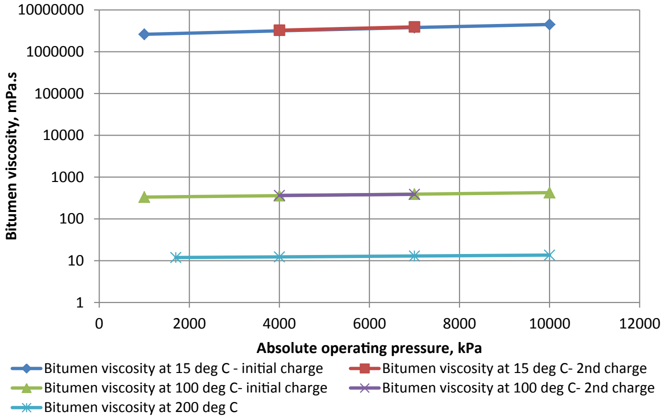

Fig. 24. Bitumen viscosity versus pressure at different operating temperatures – All measured datasets.

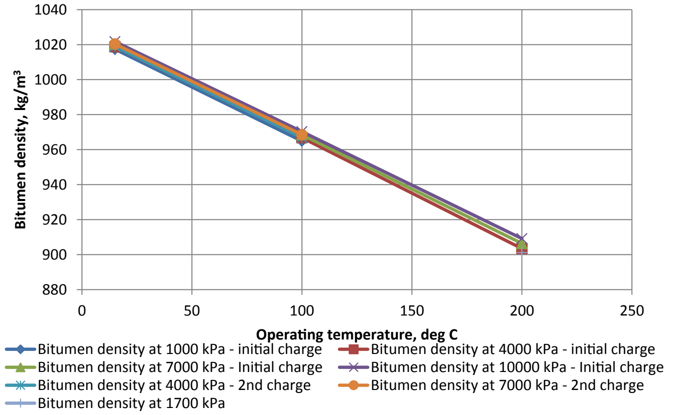

Fig. 25. Bitumen density versus temperature at different operating pressures – All measured datasets.

had been prepared on the same concentration of chemical. The new results disagreed with the initial interpretation of the data, and it was therefore assumed that the contents of the apparatus had simply not yet been mixed effectively. To ensure continued contact, the contents were heated to 40 °C and were subjected to another 100 mixing cycles. During this time, the apparent mixture density at 40 °C did not change from the observed value of around 1004.79 kg/m^3, and the measured viscosity reduced only slightly from 61,250 to 57,500 mPa s. Mixing was resumed for four more days, after which essentially the same value of viscosity (57,800 mPa s) was observed. The system was then cooled to 15 °C, at which the density and viscosity were measured at 4000 kPa. The results were indistinguishable from those previously obtained at this condition.

At this point, it was postulated that some small volume of the chemical that had been added to the system had somehow become lodged/sequestered in some tiny dead volumes within the pumps and tubing of the PVT system. To resolve the issue encountered (Figs. 7–10 and 12) in which density and viscosity both exhibited a local minimum at some chemical concentration, it was decided to increase the chemical concentration to the intermediate value of 2 wt%, and also to repeat the procedure by mixing at successively greater temperatures to see whether initial exposure to high temperature caused a measurable change. It is not apparent at what exact concentration this local minimum would happen, or even whether this minimum occurred sharply or gradually (Figs. 7–10 and 12). One of the pump cylinders was opened, and a weighed amount of IPC was added, which resulted in a bulk average concentration of about 2 wt%. The contents were mixed at 40 °C for several days, after which the system was again cooled to 15 °C, and a set of measurements was conducted between 4 and 10 MPa. The system was subsequently heated to 100 °C and held within 0.01 °C of that value while another set of measurements was performed. Once again, the temperature was lowered to 15 °C and the same measurements were taken. These results showed that the apparent densities and viscosities fluctuated slightly around those values taken earlier at this

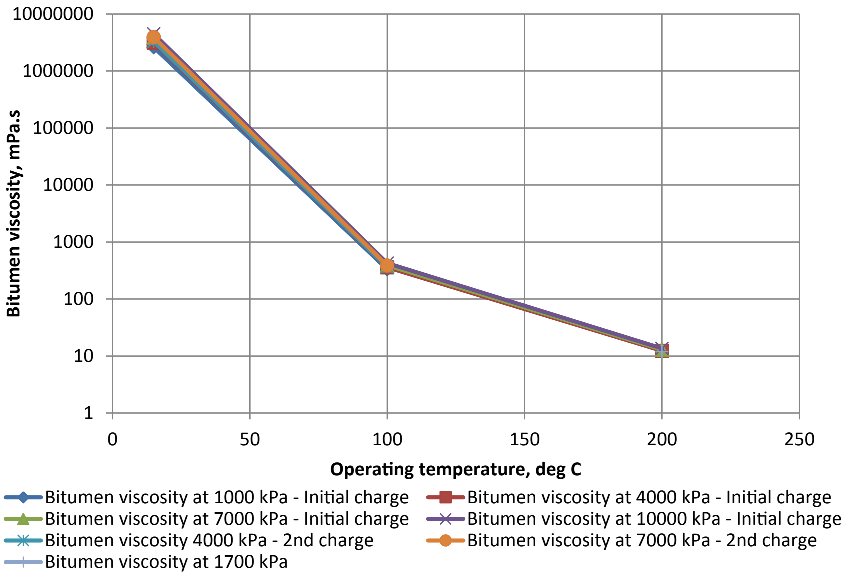

Fig. 26. Bitumen viscosity versus temperature at different operating pressures – All measured datasets.

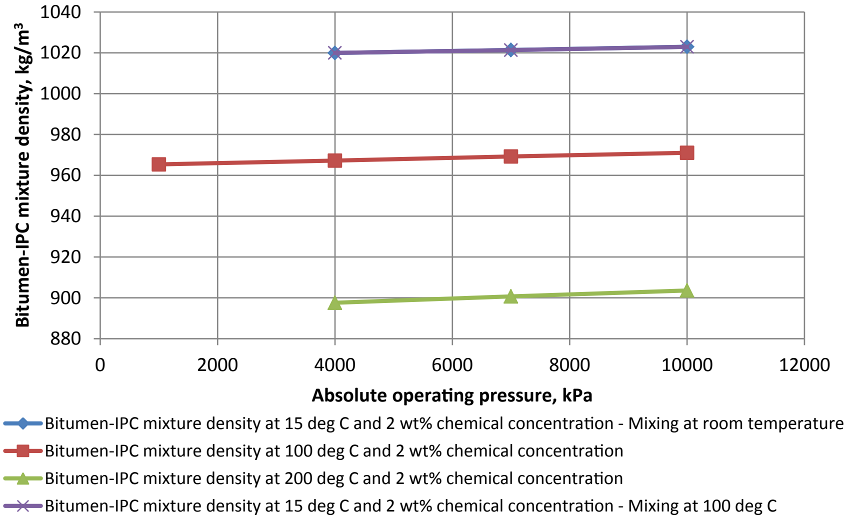

Fig. 27. Bitumen-IPC mixture density versus measurement pressure at different operating/mixing temperatures – All measured datasets.

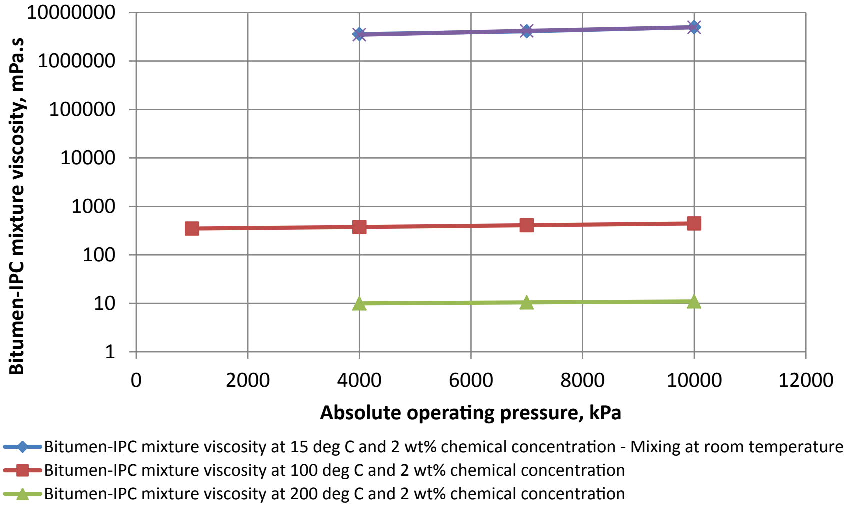

Fig. 28. Bitumen-IPC mixture viscosity versus measurement pressure at different operating/mixing temperatures – All measured datasets.

Table 10
Measured density and viscosity values for bitumen-IPC mixtures.

Temperature (°C)	Absolute Pressure (kPa)	Density (kg/m^3)	Viscosity (mPa.s)
	IPC concentration: 0.5 wt%		
15	1000	1016.20	1,880,000.00
	1,000*	1017.78	2,662,000.00
	4000	1017.73	2,133,000.00
	4,000*	1019.14	3,157,000.00
	7000	1019.14	2,518,000.00
	7,000*	1020.56	3,691,000.00
	10,000	1020.63	2,992,000.00
	10,000*	1021.63	4,482,000.00
100	1000	963.09	264.00
	4000	965.07	286.50
	7000	966.94	309.50
	10,000	968.73	334.00
200	1700	896.38	9.93
	4000	898.78	10.23
	7000	901.78	10.72
	10,000	904.73	11.33
	IPC concentration: 4 wt%		
15	1000	1017.20	2,071,000.00
	4000	1018.80	2,563,000.00
	7000	1020.22	3,065,000.00
	10,000	1021.80	3,781,000.00
100	1000	964.43	329.00
	4000	966.14	359.50
	7000	967.98	392.00
	10,000	969.81	427.50
200	1700	894.49	10.21
	4000	896.84	10.46
	7000	900.17	10.97
	10,000	903.16	11.66
	IPC concentration: 2 wt%		
15	4,000**	1019.93	3,587,000.00
	4,000***	1019.98	3,498,000.00
	7,000**	1021.40	4,112,000.00
	7,000***	1021.36	4,186,000.00
	10,000**	1022.98	4,992,000.00
	10,000***	1022.92	4,948,000.00
100	1000	965.34	349.00
	4000	967.22	376.00
	7000	969.21	408.00
	10,000	971.05	445.00
200	4000	897.57	9.95
	7000	900.72	10.46
	10,000	903.59	10.99

*: replicate test.
**: measurement was done after mixing at room temperature.
***: measurement was done after mixing at 100 °C.

same concentration, and as a result, it was concluded that the mixing temperature had no effect on the results. Finally, the temperature of the 2 wt% mixture was increased to 200 °C ± 0.01 °C, and the last set of density and viscosity measurements was collected.

3.5. Additional data gathered for mixture density and viscosity

It was observed that change in density and viscosity of bitumen versus pressure at constant temperature (Figs. 23 and 24) as well as change in density and viscosity of bitumen with respect to temperature at constant pressures (Figs. 25 and 26) are consistent, reproducible, and follow typical trends as expected.

As was described earlier, an intermediate concentration of 2 wt% IPC was selected to resolve the uncertainty observed regarding mixture density and viscosity at lesser chemical concentrations. Density and viscosity of mixture at 2 wt% IPC are plotted versus pressure at different

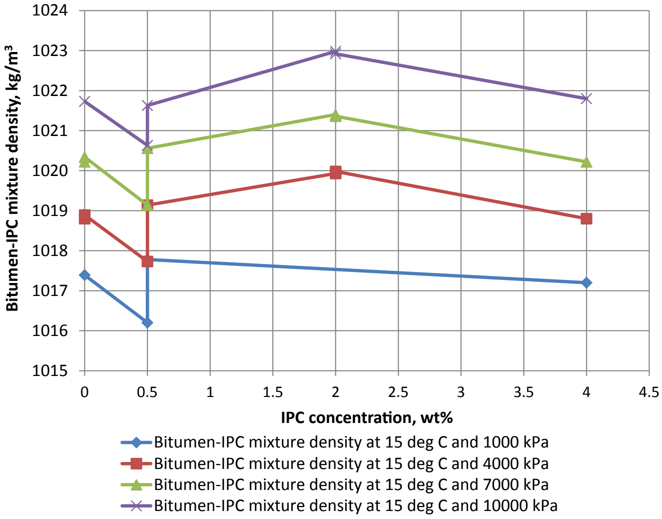

Fig. 29. Bitumen-IPC mixture density versus IPC concentration at 15 °C.

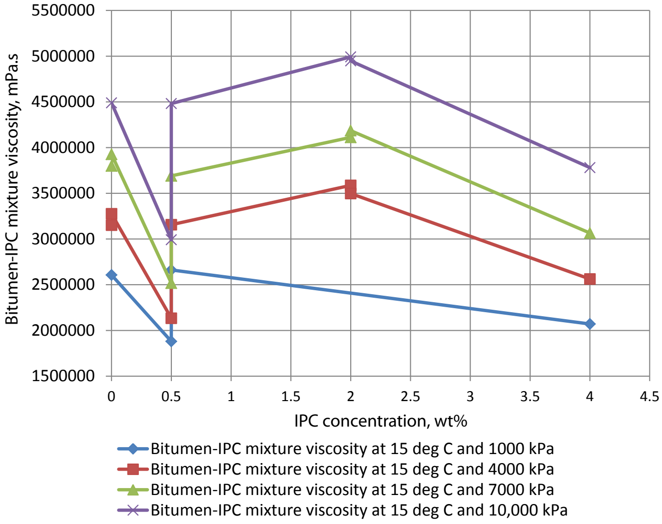

Fig. 30. Bitumen-IPC mixture viscosity versus IPC concentration at 15 °C.

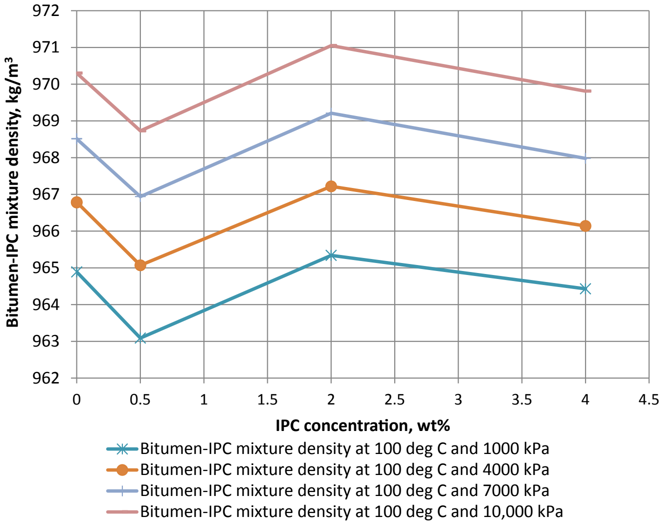

Fig. 31. Bitumen-IPC mixture density versus IPC concentration at 100 °C.

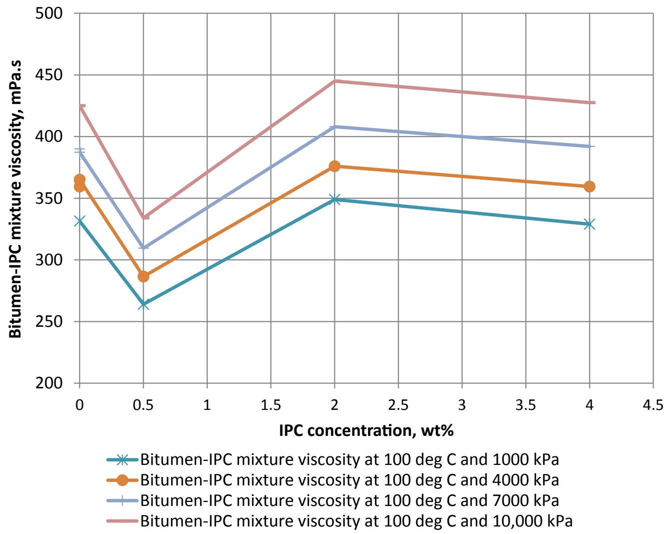

Fig. 32. Bitumen-IPC mixture viscosity versus IPC concentration at 100 °C.

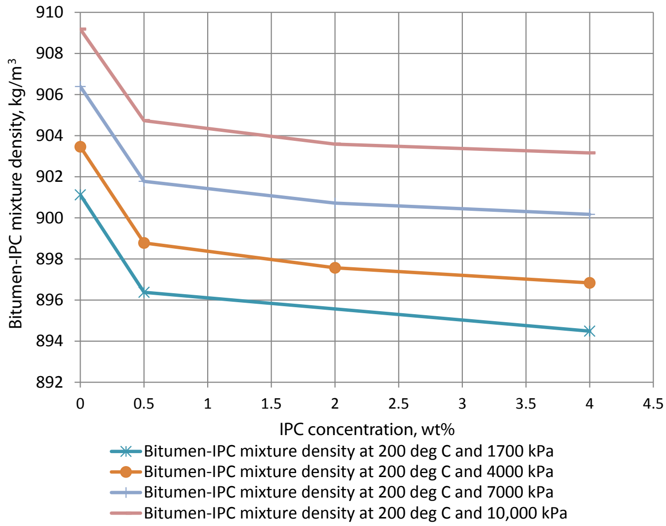

Fig. 33. Bitumen-IPC mixture density versus IPC concentration at 200 °C.

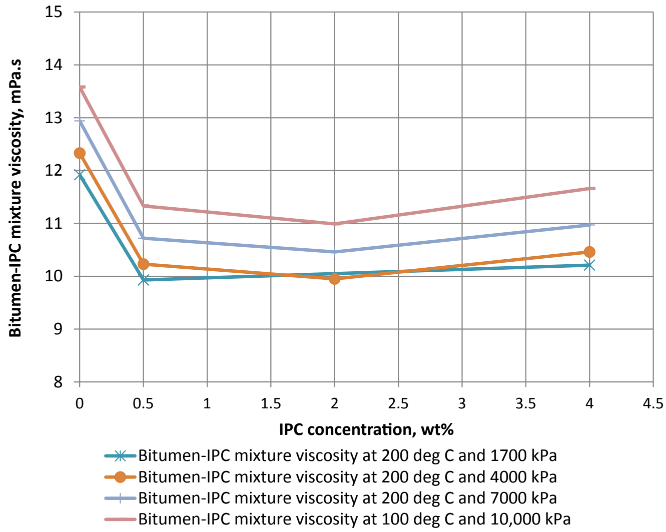

Fig. 34. Bitumen-IPC mixture viscosity versus IPC concentration at 200 °C.

target temperatures (Figs. 27 and 28). No matter what was the mixing temperature of chemical and bitumen, typical meaningful trends are observed for density and viscosity versus target pressure at different operating temperature. However, the inconsistencies are being noticed when all the density and viscosity values for bitumen-IPC mixtures at different concentrations of IPC, temperature and pressure were compared (Tables 9 and 10, Figs. 29–34). When the additional data were compiled and compared against the initial measured density and viscosity values, it was concluded that the results initially obtained at 0.5 wt% IPC were inconsistent with the others, hence were finally regarded as potentially less trustworthy. Another inconsistency was observed in density and viscosity values of the intermediate IPC concentration, i.e. 2 wt%.

The bitumen-IPC mixture density and viscosity measurements at 15 °C and different operating pressures (Figs. 29 and 30, respectively), were inconclusive. The typical viscosity and density trends at this temperature should be a monotonous decline for both properties with an increase in chemical concentration with the assumptions that: a) there has been a complete mixing of bitumen and chemical to the extent of having a homogeneous mixture; and, b) the chemical concentrations used (from 0.5 to 4 wt%) are enough to impose such density and viscosity reductions. Not fulfilling either of these two assumptions can originate such inconclusive results. These results also showed that the temperature at which bitumen and IPC were mixed did not really affect the viscosity and density measurements. The same anomalies, with lesser variation range, were also found in density and viscosity values of the bitumen-IPC mixture at 100 °C when plotted versus chemical concentration (Figs. 31 and 32, respectively). However at 200 °C, the bitumen-IPC mixture density and viscosity values behave as expected (i.e. monotonous decline) when plotted versus IPC concentration (Figs. 33 and 34, respectively).

No causes for the anomalous behavior of the 0.5 wt% mixture, especially at the two lower temperatures of 15 and 100 °C where the differences were most prominent, were identified. However at 200 °C, it was no longer immediately apparent that there was any discrepancy. In other words, the initially measured values at 0.5 wt% chemical concentration, although possible low, are not necessarily inconsistent with the data at other chemical concentration values. It is noteworthy to mention that at temperatures of 150 °C or greater, it has been reported by Glandt and Chapman (1992) that water solubility in oils can be sufficient to significantly affect the viscosity of the oil phase. The IPC formulation contains a significant amount of water; therefore, the observed modest decreases in oil viscosity at 200 °C may have been partially a result of water solubility in the oil phase. Overall, both the true density and viscosity of bitumen appear to have been affected only minimally by any of the chemical constituents of IPC dissolving into the oil phase. Through the use of measurements done in this study, it was not possible to distinguish between the effects of dissolution from those due to emulsification. The explanations that can be offered for the differences and unexpected trends observed in the lower temperature measurements are as follows:

- Emulsified IPC might have had very different droplet sizes and size distributions for the two sets of tests (i.e. initial measurements and the replicate trials for mixture density and viscosity values). In the end, the overall behavior could still be explained as a combination of a small solubility of some of the chemical constituents in the oil, thereby truly lowering density and viscosity of mixture by a small amount, combined with increases in these apparent mixture density and viscosity values because of the appearance of a dispersed phase. However, this explanation by itself is not fully satisfactory, i.e. it can explain the changes in mixture viscosity, but not the differences seen in density values at the duplicated conditions.
- Some volumes of added chemical might have entered some of the small dead volumes in the fittings or in the bottom of the pump cylinders, and remained there during the mixing process. Even

though mixing was proven by the existence of emulsions, the volumes of chemical involved in this study were small, usually only several cubic centimeters, and the accidental sequestration of even a small volume portion of chemical in one of these locations could have significantly affected the apparent bulk density and viscosity of mixtures.

- It is possible that some mechanical malfunction, or operational or data logging error might have encountered. However in this case, the consistency with which both the density and viscosity changed eliminates malfunctions of equipment in either the density and viscosity measurement modules. Furthermore, the accuracy with which pure bitumen measurements were repeated shows that the equipment calibrations were unaffected over the course of the experiments. The possibility that the temperature readings could have been in error for a period of time was also considered. The temperatures would have needed to be high by 2.0–4.4 °C to account for the anomalies at the two lower isotherms. However, the temperature readouts for this equipment have otherwise appeared to be consistent to within a few hundredths of a degree, making this an incredibly large error.

The use of a liquid-liquid equilibrium expression became superfluous with the discovery that the solubility of IPC ingredients into the bitumen phase was too small (less than the least concentration used in these tests, 0.5 wt%). In view of the strong surfactant quality of IPC (Mohammadzadeh et al., 2015b), any changes to the bitumen viscosity or density, as obtained through this study, are expected to be insignificant in comparison with the other effects that the chemical has on emulsification as well as on rock-fluid interfacial properties.

Through the course of these measurements, bitumen can be characterized as a single pseudo-component phase whose density and viscosity vary with pressure (Table 6). This bitumen also showed a viscosity-temperature relationship in the form of the Antoine Equation (Equation (1)), which for viscosities adjusted to a pressure of 1000 kPa, is as follows:

$$\mu = 1.198 \times 10^{8}\, e\left[\frac{1539.166}{T+70.529}\right] \tag{1}$$

where “μ” is the bitumen viscosity in mPa.s and “T” is temperature in °C.

The above equation provides reasonably accurate viscosities in the range of 15–200 °C, but will be subject to increasingly large errors outside this range. The calculated average thermal expansion coefficient for the bitumen phase between 15 and 200 °C is $6.54 \times 10^{-4}\,C^{-1}$.

4. Conclusions

A series of viscosity and density measurements were conducted for several mixtures of bitumen and IPC formulation. To characterize the mixture properties, several tests were performed to independently measure the properties of bitumen and IPC formulation. The following conclusions can be drawn from this study:

1 The solubility of IPC in bitumen was small, and its effects on the oil phase viscosity and density values could not be separated from its effects on bulk properties caused by dispersed emulsified droplets of the chemical. The solubility of IPC in bitumen at 15 °C was less than 0.5 wt%.

2 The emulsion formed as a result of contact between bitumen and IPC formulation in the laboratory PVT apparatus was fairly complex. A wide range of droplet sizes was qualitatively observed, and some apparently aqueous droplets themselves contained oil droplets within them in the form of oil in water in oil (i.e. o/w/o) double emulsions.

3 Up to the measurement temperature of 100 °C, the temperature at which IPC was subjected to and mixed with bitumen, it had no measurable effect on the density of bitumen-IPC mixture. However, its impact on viscosity of the mixture started to be quantifiable at operating temperature of 100 °C.

4 The bitumen phase can be treated as a single pseudo-component for most reservoir simulation purposes, unless pressures are low enough to potentially involve the appearance of a vapor phase. In the latter case, a small portion of the lightest components would need to be segregated as a separate pseudo-component, and its volatility to be adjusted to approximate the observed saturation pressure of pure bitumen at 200 °C. Considering this assumption, the bitumen phase used in this study was treated as a single pseudo-component, its density and viscosity were represented by the observed values at the reference temperature of 15 °C, plus the temperature dependence of viscosity, the observed oil compressibility, and the pressure coefficient of oil viscosity.

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