**DETERMINATION OF LIMIT DEPOSITION VELOCITY AND VISCOSITY IN
WASTE BRINES TRANSPORTED IN PIPELINES**

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ABSTRACT

The wastewater generated in the potash mines of the Bages region in Catalonia (Spain) was experimentally tested at Paterson & Cooke's Slurry Test Facility in Cape Town, South Africa, to determine the flow behaviour of various brine mixtures. The tests measured the limit deposition velocity, viscosity, and flow resistance of a range of brine mixtures at different concentrations of solid particles in suspension, and they are presented and discussed below. Tests were conducted on the slurries using both water (WT tests) and saturated brine (BT tests) as the medium for the solid sediment. In order to replicate the possible situations that could occur during their transport in the pipeline, the mixtures were generated with relatively low sediment concentrations, always less than 5% by volume. The test data showed that the limit deposition velocity at equivalent solid concentrations is higher for the WT than BT mixtures due to the differences in the kinematic viscosity of the medium. Finally, the kinematic viscosity obtained for both WT and BT mixtures trends moderately upwards as their volume concentration increases though viscosity in BT mixtures, presents some particularities that will be described below.

KEYWORDS: pipeline, brine transport, limit deposition velocity, dynamic viscosity, absolute roughness

1 INTRODUCTION

Previously, Sánchez-Juny et al. (2019) analyzed the hydraulic behaviour of a pipeline transporting waste brine generated in the Bages salt mines in Catalonia (Spain). The research stated that the mixtures transported by the potash Bages' pipeline contain very few insoluble fine particles. Although, in absolute numbers, the concentration of particles is less, they can modify the hydraulic behaviour of the brine dissolution inside the pipeline by depositing a significant stationary bed, which can affect the capacity of the pipeline.

When conveying slurries under pressurized conditions, liquid and solid phases should be distinguished. The liquid phase is assumed to be the transport vehicle and in the present work it consists of a dissolution of different compounds. The solid phase consists of particles of any size and concentration, which do not react with the liquid phase. The bulk density of the mixture (ρ_m) is a function of the density of the liquid phase (ρ_w), the solid phase (ρ_s) and the volume concentration of solid particles (C_V):

$$\rho_m = \rho_w + C_V \cdot (\rho_s - \rho_w) \quad (1)$$

Since the early investigations of (Coulson and Richardson (1955), Zandi and Govatos (1967) Govier and Aziz (1972), Wilson and Judge (1977) or Roco and Shook (1983). The transport of mixtures with sediments in pressurized pipelines can be classified according to the average flow velocity, which determines the distribution of the solid particles in the pipeline (Graf 1984; Moreno-Avalos 2012; Hu 2017). This distribution depends on the size of the particles, their density and volume concentration in the mixture, and the average mixture velocity. After Hu (2017), the following four types of flow regimes can be observed: homogeneous flow, heterogeneous flow, flow with a sliding bed, and flow with a stationary bed.

This article examines heterogeneous slurry flow, which is commonly characterized by sufficiently dense and large solid particles ($> 40 \mu\text{m}$) in a generally dilute state. The coarse particles settle in varying degrees so that they are no longer uniformly distributed in the flow, but the majority remain fully suspended (Hu, 2017), provided the average velocity in the pipeline is greater than the limit deposition velocity.

The majority of pipelines conveying coarse slurries operate in heterogeneous flow, and consequently researchers have focused on obtaining an equation to estimate the limit deposition velocity, defined as the maximum velocity at which the suspended solids deposit on the pipe invert and no longer move downstream.

61 The magnitude of the limit deposit velocity depends mainly on the size of the particles
62 transported, their density, the concentration, and the diameter of the pipe (Kaushal et al., 2002).
63 According to these factors, there are up to sixty different correlations, most of which are based
64 on Durand's Froude number (Durand 1952; Durand and Condolios 1952), F_L , and are limited
65 to a specific range of applicability.

66 Durand's Froude number is used to estimate the limit deposit velocity (v_D) in pipes of different
67 internal diameter (D) and for different solid relative densities (S). In the case of suspended
68 particle transport, this number is defined by the following expression:

$$F_L = \frac{v_D}{\sqrt{2 \cdot g \cdot D \cdot (S - 1)}} \quad (2)$$

69

$$S = \frac{\rho_s}{\rho_w} \quad (3)$$

70 Durand (1953) carried out a wide range of experimental measurements in horizontal and
71 straight pipelines with diameters ranging between 40 and 700 mm and particle volume
72 concentrations between 2% and 15%. The results are summarized in [Fig. 1](#) showing the
73 relationship between the mean particle size and the Froude number (F_L) as a function of the
74 volumetric solids concentration.

75
76 **Fig. 1.** Nomogram for obtaining the Durand's Froude number F_L , as a function of volume of
77 solids ratio and the average particle size obtained by Durand (1953) and also showed by Hu
78 (2017)

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In mining engineering, where particles are either large in size or very high in concentration, the most common method to determine the limit deposit velocity is Wilson's nomogram (Wilson and Judge 1977; Wilson 1979; Hu 2017). This determines the deposition velocity using the pipe diameter, grain size of the sediments transported, and the density of the solids relative to the liquid phase showed in relation (3).

Turian et al. (1987) obtained five different empirical correlations based on a collection of 864 experimental deposition limit velocity data with pipe diameters up to 0.5 m and particle sizes up to 19 mm. Their correlations are

$$v_D = \sqrt{2 \cdot g \cdot D \cdot (S - 1)} \cdot \chi_1 \cdot C_v^{\chi_2} \cdot (1 - C_v)^{\chi_3} \cdot \left(\frac{D \cdot \rho_w \cdot \sqrt{g \cdot D \cdot (S - 1)}}{\mu_w} \right)^{\chi_4} \cdot \left(\frac{d_p}{D} \right)^{\chi_5} \quad (4)$$

All these correlations proposed in previous research works present a quite broad disparity. So, Durand's nomogram (Fig. 1) provides high values (conservative) for v_D related to slurries containing mixtures of particles with different sizes and slurries with significant proportions of particles finer than 10 μm (Hu, 2017). Wilson's nomogram is concerned fundamentally about sliding bed flow and can be applied to a wide range of fluid densities, particle size and pipe diameter (Hu, 2017). On the other hand, Turian's correlation shows a dependence of v_D nearly equal to $D^{1/2}$, it is also valid for slurries comprised of large non-colloidal particles, for which v_D is almost independent of particle size, and shows a maximum value of the limit deposition velocity for concentrations between 0.25 and 0.30 (Turian, Hsu, and Ma et al. 1987).

And the corresponding values of the fitted constants are shown in Table 1.

$$\%D = 100 \times \frac{1}{N} \sum \left| \frac{v_{D(calc)} - v_{D(exp)}}{v_{D(exp)}} \right| \quad (5)$$

$$RMS = \sqrt{\frac{1}{N} \cdot \sum (v_{D(calc)} - v_{D(exp)})^2} \quad (6)$$

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101 In the case of a pipeline with a positive slope, the deposition velocity can increase up to 40%
102 and make it difficult to drag solid particles, whereas for pipes with a negative slope this rate
103 decreases (Wilson and Tse 1984).

104 On the other hand, when the solid particles transported through a pipe deposit due to a stoppage
105 in the flow, the velocity required to re-suspend them increases with the duration of the stopping.
106 According to Goosen (2015), in just a 15-minute stoppage, the resuspension velocity can exceed
107 the limit deposit velocity by 25% due to consolidation of the settled bed.

108 The present article examines the transportation of the brine from the potash mines of Bages in
109 Catalonia (Spain). The results from the test work were used to analyze the effect of varying
110 concentrations of insoluble particles on the behaviour of different brine mixtures at a constant
111 salt concentration. The experiment was conducted at the slurry test laboratory of Paterson &
112 Cooke Consulting Engineers Pty Ltd. in Cape Town, South Africa. The scope of this paper is

- 113 - To determine, in each case, the limit deposition velocity of the insoluble solid particles
114 present in the tested mixtures.
- 115 - To determine the viscosity of various brine mixtures, depending on the concentration of
116 solid particles in suspension.
- 117 - To analyze the variation in the flow resistance of a mixture based on its fluid medium
118 and the concentration of particles it transports for volume concentrations below 5%.

119 **2 FACILITIES AND METHODS**

120 **2.1 Experimental setup**

121 The schematic layout of the pipeline system in this study is shown in Fig. 2. It consisted of a
122 closed loop about 20 m long, made of metal pipes, except for a 2 m stretch of transparent PVC
123 pipe. The test loop comprises a 62.4 mm inner diameter pipeline connected to a 30 kW
124 centrifugal slurry pump fitted with a variable speed drive so that the flow rate can be changed.
125 Next to the pump is a small intermediate conical tank that allows sediment to be added without
126 stopping the circulation.

127

Fig. 2. Schematic layout of the experimental facility (EF) at Paterson & Cooke's Slurry Test Laboratory. The transparent pipe is used to visually observe the particles settling on the pipe invert at low velocities

Downstream of the pump, a Coriolis mass flow meter measures the flow rate, density, and temperature of the slurry. The flow rate measurement interval depends on the mass flow rate and ranges from 0 to 70,000 kg/h, and its uncertainty is $\pm 0.10\%$ of the range. For example, if the liquid is water with a density of 1000 kg/m^3 , the measurement range is between 0 and 19.4 l/s. The higher the density, the lower the range of measurement of the flow rate. The average fluid velocity is determined from the flow rate and internal diameter of the pipeline. The flowmeter is also capable of measuring densities ranging between 0 and 5000 kg/m^3 with an accuracy of $\pm 0.0005 \text{ kg/m}^3$. Finally, it includes a thermometer for measuring the temperature of the liquid ranging between $-50 \text{ }^\circ\text{C}$ and $150 \text{ }^\circ\text{C}$ with an accuracy of $\pm 0.5 \text{ }^\circ\text{C}$.

Fig. 3. On the left, a view of the centrifugal slurry pump with 30kW motor, the mass flow meter, and the inlet conical sump. On the right, a general view of the test pipeline installed at Paterson & Cooke's Slurry Test Laboratory

Downstream, on a horizontal section of pipeline, there is a differential pressure gauge (ENDRESS+HAUSER, model Deltabar S, PMD75) capable of measuring the difference in pressure between two points, in this case 2 meters apart, ranging between 0 and 160 kPa, and its uncertainty is $\pm 0.035 \%$ of the total range. The differential pressure gauge is calibrated before each test.

154 **Fig. 4.** View of the differential pressure gauge in the upper pipeline located between the two
155 pressure tapplings. Each pressure tapping in the pipeline is connected with water filled tubes to
156 the differential pressure gauge, and the tubes are flushed to remove air
157

158 **2.2 Properties of the tested brines**

159 The saturated solution is made up of water as a solvent and, as a solute, the soluble components
160 of sylvinit from the Bages deposits. This solution was generated in a large bin and the insoluble
161 solid particles were decanted to obtain a pure saturated solution without suspended particles.
162 These particles are removed to control the characteristics of the solid phase to ensure that they
163 are similar for the water and the saturated solution mixes.

164 The percentages of sodium, potassium, chlorides and insoluble residues in the sylvinit are
165 presented in [Table 2](#). From these data it is possible to calculate approximately the NaCl and
166 KCl content of the soluble particles, which corresponds to 75% and 21% by mass respectively.
167 These percentages have been calculated over the total soluble particles, since the insoluble ones
168 are not part of the transport fluid. So, the potassium chloride content of the one used in the
169 following tests is quite high. Finally, the mass fraction of the total dissolved solids in the
170 saturated solution is 27% (kg of solids/kg of mixture × 100).

Table 3 and Table 4 present relevant characteristics of all the mixtures used for the tests. For four mixtures, the solvent is clear water (WT prefix), while the remainder use saturated solution (BT prefix). In order to replicate the possible scenarios during conveyance, the mixtures were generated with relatively low sediment concentrations, always less than 5% by volume.

The sediments in the mixtures were chosen to ensure that their representative diameter and granulometric distribution were as similar as possible to that of the insoluble solid particles of the mixtures generated in Sánchez-Juny et al. (2019), where the d_{50} was around 140 μm . So, for the present tests, a fine grained non-cohesive silica sand was chosen, and all particles larger than 500 μm were filtered to obtain a 158.2 μm value for d_{50} with a density of 2650 kg/m^3 and a similar granulometric curve. Fig. 5 shows the granulometric distribution of the original sand and that obtained after sieving. It also shows the curve obtained in the analysis of the sediment sample used in Sánchez-Juny et al. (2019), which, as can be seen, has a great similarity with that of the sand used in the present study.

Fig. 5. Graphs (in %) of passing (solid lines) and retained material (dashed line) versus sieve size. The d_{50} grain size is 158.2 μm . The blue and black solid lines correspond to the “Test Sand” before and after sifting of particles above 500 μm , respectively. Finally, the grey solid line represents the curve for the sediments in the Bages area tested by tested by Sánchez-Juny et al. (2019)

2.3 Tests methodology

First, the differential pressure probe was statistically calibrated. Later, the procedure used to perform the tests is as follows:

1. The circulation of the water, or the brine, reaches flow equilibrium at a constant flow rate, and any air bubbles that can form along the pipeline are completely removed.
2. The differential pressure loss measurements are recorded for different recirculating flow rates causing different velocities, at 0.5 m/s intervals, from the highest velocity (4 m/s) down to zero. Each recorded data point corresponds to the average of 15 measurements performed at a frequency of one second and is done twice to ensure that steady state has been reached. If both measurements are within ± 0.05 kPa/m of each other (± 0.03 % of the total range), they are considered valid; if not, they are discarded and the process is repeated.
3. Next, the flow rate is established at a rate high enough to keep all the particles suspended, and then the velocity is slowly reduced until the deposition of the first grain of sand is observed at the bottom of the clear viewing section pipe. This velocity corresponds to the sediment deposition limit velocity in this pipeline. This is observed by naked eye in the transparent section of the pipeline (Fig. 2 and Fig. 6 left).
4. Continuing the flow, sediment is added to the mixture (Fig. 2 and Fig. 6 right) through the intermediate conical tank, and the steps 2 and 3 are repeated. In the case of clear water as a transport fluid, sediment addition was performed three times (WT tests); and four in the case of saturated dissolution (BT tests).

It should be noted that before performing the tests, a water and sand mixture was circulated to remove solid particles that may have adhered to the pipe wall during previous tests. This is important because the other tests contained solid particles, and if the pipe was not clean enough, the hydraulic roughness could vary during the tests. However, it was not always possible to remove 100% of the particles and a very small fraction remained, so tests completely free of sediment could not be performed.

It can also be appreciated that temperature increased during each test, because the friction of the flow with the pipe causes a very rapid heating of the mixture. However, it remained in the range of 16.6 °C to 23.7 °C.

The density of the mixtures was measured during the tests, and a sample was taken of each mixture to check the accuracy of the Coriolis flow meter readings. In the case of tests performed with clear water as a transport liquid, the densities measured by the Coriolis flowmeter

223 corresponded to the calculated density based on the volume of the loop and the mass of material
224 added.

225
226 **Fig. 6.** *Experimental determination of the deposition limit velocity, in the transparent pipe*
227 *section of the pipe (left). Sediment addition to the pipeline, through the intermediate conical*
228 *tank (right)*

230 2.4 Pipeline calibration

231 Differential pressure sensor readings were taken in a 2-meter straight and horizontal section of
232 the pipeline, and therefore the local head losses in this section are negligible. The pipeline
233 calibration is based on the WT00 mixture, whose solvent is clear water with an insoluble
234 particle volume concentration of 1.12%. Since the sediment concentration in the mixture is
235 small, Eq. (7) was used by Einstein (Einstein, 1906) to calculate the viscosity. This equation is
236 only valid for highly diluted suspensions, $C_v < 2\%$ (Rutgers, 1962) as is the case. As the test
237 was performed at 18 °C and the dynamic viscosity of water at this temperature is $1.060 \cdot$
238 $10^{-3} \text{ N}\cdot\text{s}/\text{m}^2$ (ISO/TC28 1998), the viscosity of the WT00 mixture is obtained as $1.089 \cdot$
239 $10^{-3} \text{ N}\cdot\text{s}/\text{m}^2$.

240 Once the viscosity is determined for WT00, the absolute roughness of the pipeline can be
241 estimated using a least squares method adjustment on the pressure gradient and velocity values
242 recorded in the WT00 test. This adjustment was performed using the Darcy-Weisbach equation
243 and the formula of Swamee and Jain (1976), as is shown in Fig. 7. The value of the absolute
244 roughness obtained was 0.014 mm, with $\pm 10\%$ of error for a 95% confidence, and a correlation
245 coefficient (R^2) of 0.999. The obtained value is within the usual range for smooth metal tubes
246 (Lencastre 1998).

247 For tests in which the transport liquid is a saturated solution, it is necessary to empty the circuit
248 and refill it with this solution. To ensure that the pipeline roughness coefficient has not changed

during the first series of tests, a water calibration test with a minimum percentage of suspended particles is performed again, before filling the circuit with brine, with a similar result.

Fig. 7. Fitted curve by the least squares method ($R^2 = 0.999$), using the Darcy-Weisbach expression to the points obtained from the experimental laboratory data, in order to determine the value of the absolute roughness of the pipeline (test WT00)

2.5 Results Analysis

The measured data are analyzed as follows:

- For the test performed with WT00 mixture, for different flow rates:
 - a. Estimation of the viscosity of the mixture using the expressions ~~(7)~~ proposed by Einstein (1906) and, based on the measured pressure and the mixture velocity, the calculation of ~~linear-distributed~~ energy losses and finally, using the Darcy-Weisbach formula, the associated friction coefficients.

$$\frac{\mu_m}{\mu_w} = 1 + 2.5 \cdot C_v \quad (7)$$

- b. Calculation of the absolute roughness (k) of the pipe from the ~~linear~~-head loss values obtained in the previous point, by means of the Darcy-Weisbach relation and Swamee and Jain (1976) formula, and a least squares fitting as explained in the section on pipeline calibration. The Swamee and Jain formula ~~(8)~~ is valid for $5000 < Re < 10^7$ and $4 \cdot 10^{-5} < \frac{k}{D} < 5 \cdot 10^{-2}$. [The errors involved in the determination of the friction](#)

factor by means of expression (8) are well within $\pm 1.0\%$ in comparison with those obtained by classical Colebrook and White Equation (Swamee and Jain, 1976) (Turgut, Asker, and Çoban et al., 2014). Particularly, this expression is useful because it is a non-iterative friction factor correlations for the calculation of pressure drop in pipes:

$$f = \frac{0.25}{\left[\log_{10} \left(\frac{k}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}} \right) \right]^2} \quad (8)$$

- For the tests performed with the other mixtures, for different flow rates:
 - a. Calculation of the linear distributed-energy losses using the recorded pressures and flow velocities and, by means of the Darcy-Weisbach formula, calculation of the associated friction coefficients.
 - b. Estimation of the viscosity of each mixture from the obtained linear-head losses in the previous step, using the Darcy-Weisbach ratio and the Swamee and Jain formula, and a least squares fitting.

3 RESULTS AND DISCUSSION

3.1 Friction factor determination

The friction factor for each brine test was obtained from Darcy-Weisbach's expression, which relates to the friction loss, the mean velocity, and the diameter of the pipe.

Records of tests performed for velocities lower than the limit deposition were excluded from the calculation process as their sedimentation at the bottom of the pipe varied the conditions of the flow as the sediment bed causes a change in absolute roughness and in the effective cross section of the pipe. In the case of WT00 and BT00 mixtures, the deposition velocity was approximated by extrapolating the data obtained by the other mixtures, depending on the volume concentration of the sand particles (Fig. 13Fig. 13).

The values of the friction factor are plotted as a function of the corresponding Reynolds number in the Moody diagram in Fig. 8Fig. 8. As can be seen, flow is in the intermediate turbulent regime zone in all cases so that the Swamee and Jain (1976) formula used in the previous calculations is applicable. Likewise, it shows that the scattered data is close to the smooth wall turbulent curve, which is consistent with the type of pipe used in these tests.

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298 The values obtained for WT tests are very close to each other and tend to follow closely the
 299 curves in the Moody's diagram. However, for lower Reynolds numbers this accuracy decreases
 300 and variability increases; the sensitivity analysis given below shows that the error associated
 301 with the estimated friction factor increases as the flow velocity decreases. In the case of BT
 302 mixtures, the obtained friction factor also follows the tendency curves in the diagram, around
 303 the imposed relative roughness curve, with $k/D = 0.00022$. The accuracy obtained in the
 304 calculations is considered acceptable taking into account that the studied variables are very
 305 sensitive to the smallest error in the measurements (Sánchez-Juny et al. 2019).

306
 307 **Fig. 8.** Darcy – Weisbach friction factor values corresponding to the tests carried out with the
 308 mixtures whose transport liquid is clear water and those whose transport liquid is a saturated
 309 solution on a Moody's graph

311 3.2 Sensitivity analysis related to friction factor determination

312 The accuracy of the calculated values of the friction factor relative to each test is analyzed.
 313 These are calculated using the Darcy-Weisbach equation. Each of these parameters has its
 314 associated accuracy error: in the case of the inner diameter ± 0.1 mm and the length of the tube
 315 ± 1 mm. The flow velocity has been estimated from the flow rate measurements of the Coriolis

flowmeter, whose accuracy error is $\pm 0.1\%$ of its measuring range which is variable depending on the mixture density. The ~~linear~~-distributed head losses (local losses are considered negligible), have been calculated directly from the energy balance equation, in which only the pressure difference between the inlet and outlet of the test section is considered. Therefore, in this case the measurement error associated with the differential pressure sensor, which is $\pm 0.035\%$ of its range, has been considered.

The propagation of uncertainty has been carried out by means of a Monte Carlo simulation of one thousand repetitions, and it is shown in ~~Fig. 9~~Fig-9. This figure shows the relative error (%) associated with calculation of the friction factor as a function of the Reynolds number for each mixture tested. The error rate increases for smaller Reynolds numbers, especially in the case of the WT00 mixture. However, in this case, the accuracy in the calculation of the friction coefficient is high enough, below 1% in almost all tests.

Fig. 9. Relative error (%) related to the Darcy-Weisbach friction factor determination

3.3 Dynamic viscosity determination

On the other hand, the viscosity of the tested brines is needed to estimate the Reynolds number of each test since these are in the transition zone. The viscosity of the mixtures used during the laboratory testing has been obtained from the relationship between the pressure gradients recorded and the associated flow velocities. For each tested mixture, a nonlinear regression was performed on the experimentally obtained points, using the Darcy-Weisbach equation and the friction factor expression by Swamee and Jain (1976). Since the value of the absolute roughness of the pipe is already known, as it has been previously calibrated with the WT00 mixture, the

only unknown parameter that remains is the viscosity of the mixture. As in the previous calculation of the Darcy-Weisbach friction factor, in this case, the records of the tests carried out at velocities below the deposition limit velocity of the suspended particles have also been removed from the calculation process.

[Fig. 10](#) shows the test data and curves fitted to the WT mixtures (left) and the BT mixtures (right) and it is seen that the pressure gradient increases with increasing solids concentration.

Fig. 10. Comparison of the slope of energy line computed from experimental data with the one obtained from the measured pipe roughness and estimated viscosity (WT mixtures – left, BT mixtures - right)

As it can also be seen in [Table 5](#), the tests were performed for different temperatures, between 16.6 °C and 23.7 °C. This makes it difficult to compare the results obtained, because they correspond to different volume concentrations of insoluble particles and different temperatures. Despite this fact, [Fig. 11](#) depicts the kinematic viscosity values calculated from the experimental data, based on the volume concentration of the suspended solids. On one hand, the values obtained for the WT mixtures follow a moderate upward trend as their volume concentration increases. On the other hand, the kinematic viscosity of the BT mixtures increases rapidly to the BT03 ($C_V = 3.1\%$), but at this point the growth stops suddenly since the BT04 has a viscosity very similar to BT03. This unexpected value of the BT04 mixture viscosity could be due to an error during the data collection, but it is unlikely because all records were duplicated and checked in real-time, the similarity between measurements taken for the same flow velocity. It can be seen that there are no problems with the adjustment made on these data to obtain the viscosity of the mixture ([Fig. 10](#)).

364 It should be noted that the solute of this saturated solution consists of 96% in mass of sodium
 365 chloride (75%) and potassium chloride (21%). Zhang and Han (1996) studied the viscosity of
 366 this type of solution and found that it varies depending on the ratio of moles between one solute
 367 and another, the concentration of salts, and the temperature of the mixture. Knowing the density
 368 of the saturated solution (1234 kg/m^3) and the concentration of dissolved solids, of 27% in
 369 mass, it is determined that the molar relation between these is of 4.52 mol NaCl/mol KCl,
 370 whereas the molality of the solution is 5.22 mol solute/kg water. Considering the data, the tables
 371 of viscosity published by Zhang and Han (1996) allow for the estimation of the viscosity of the
 372 solution. Despite this, the maximum molar ratio presented by these authors is 3 mol NaCl/mol
 373 KCl, and all values were obtained at 25 °C temperature. Extrapolating at a molar ratio of 4.52
 374 mol NaCl/mol KCl, the viscosity obtained would become $1.23 \cdot 10^{-6} \text{ m}^2/\text{s}$. Since the viscosity
 375 to be obtained corresponds to 20 °C and it increases when the temperature decreases, a value
 376 of $1.25 \cdot 10^{-6} \text{ m}^2/\text{s}$ is estimated. This viscosity could still increase if the remaining 4% in mass
 377 of solutes were formed by MgCl_2 , which is unknown; the presence of this salt in sodium
 378 chloride solutions also affects its rheological properties (Qiblawey and Abu-Jdayil 2010).
 379 However, it is considered a reasonable value given the results obtained during the tests.

380

381

Fig. 11. Relative kinematic viscosity values over the viscosity of the saturated dissolution as a function of volume concentration of insoluble particles, including associated errors with 95% confidence. The whole graph is normalized with the theoretical kinematic viscosity of water at 20 °C. ~~is shown~~

In ~~Fig. 11~~Fig. 14, the values of the kinematic viscosity and associated error bars as a function of the volume concentration of insoluble particles are shown. The comparison with the proposed curves of some other authors is also presented. The curves of tests using clear water as transport liquid are compared with the curves proposed by Einstein (1906), Kunitz (1926) and Chong et al. (1971) for a maximum volume concentration of solid particles $C_{Vmax} = 0.2$ at 20°C. As expected, the curve by Einstein showed the worst fitting because this was obtained for more dilute mixtures. On the other hand, the curve by Chong et al. (1971) is the one with the best fit although other authors (Konijn et al. 2014) use it for higher C_{Vmax} values between 0.5 and 0.8. Likewise, the tests using a saturated dissolution as transport liquid are compared with the curves by Kunitz (1926) and Chong et al. (1971) for $C_{Vmax} = 0.1$ at 20 °C. In that case, the fitting is better for the curve by Chong et al. but more experimental data would be required to further analyze the real tendencies. Nevertheless, viscosity is more variable in the case of BT than WT tests.

3.4 Influence of absolute roughness on the viscosity determination

The calculation of the relative viscosity of the mixtures was preceded by the calibration of the pipeline to obtain the value of its absolute roughness. For this purpose, an adjustment was made to the experimental data using the least squares method by which the value of k could be determined with an associated error of $\pm 10\%$. To know the influence of this possible error on the calculation of the viscosity, the process has been repeated, assuming a deviation of $\pm 10\%$ on the value of the absolute roughness. The results are shown in ~~Table 6~~Table 6 and plotted in ~~Fig. 12~~Fig. 12 based on the concentration of suspended solid particles by volume. From those results, it can be appreciated that the lower the volume concentration the higher the deviation in viscosity.

Fig. 12. Kinematic viscosity deviation produced by a reduction (-10%) and increment ($+10\%$) of absolute roughness k

3.5 Theoretical deposition limit velocity estimation

The deposition limit velocity of the sediments in the mixtures has been obtained by using Durand and Condolios' (1952) methodology as it is the one that best fits the small particle diameters and low concentrations used in this work. As it was already mentioned in the introduction section, Durand and Condolios (1952) do not consider volume concentrations lower than 2%; in those cases, an extrapolation has been done. The expression proposed by those authors depends on the transport liquid density (ρ_w), solid density (ρ_s), their volume concentration over the total volume of the mixture (C_v), the representative solid particles diameter (usually referred as d_{50}), and the diameter of the pipeline (D).

Fig. 13. Limit deposit velocity (v_D) obtained through the method of using Durand and Condolios (1952) and the Turian et al. (1987) correlations, depending on the volume concentration of insoluble solid particles and if the mixture solvent liquid is clean water or the saturated solution. These values are associated to a pipe diameter of 62.4 mm, solid density of 2650 kg/m³, and a d_{50} of 158.2 μ m

The correlations by Turian et al. (1987), depicted in the dimensionless Eq. (4)(4) and Table 1Table 1, allow the user to select the parameters on which the limit deposition velocity depends. Thus, particularly, correlation 1 states the relation of the Durand's Froude number (Eq. (2)(2)) with the volume concentration over the total volume of the mixture (C_v), a Reynolds number which introduces the dependence on the dynamic viscosity of the transport liquid (μ_w), and the ratio between the particle diameter (d_p) and the internal diameter of the pipe (D). On the other hand, correlation 2 and 3, do not depend on ratio between the particle and pipeline diameters and that Reynolds number, respectively. Correlation 4 does not depend simultaneously on the last two parameters and, finally, the correlation 5 only depends on the Durand's Froude number and the volume concentration over the total volume of the mixture (C_v).

In Fig. 13Fig. 13, the obtained deposition limit velocity depending on the sediment volume concentration and the transporting liquid (clear water or saturated mixture) is shown. The deposition rate of the suspended particles decreases as the density of the transport liquid

increases because a denser liquid shows more ability to drag the same particles. Therefore, sedimentation should occur at a slower rate in the case of mixtures transported by the saturated solution than those transported by clear water.

3.6 Observed deposition limit velocity

[Table 7](#) summarizes the deposition limit velocities observed in the tests performed with each of the mixtures (except WT00 and BT00), and [Fig. 13](#) compares those results with the prediction made above using the expression by Durand and Condolios (1952) and the five correlations by Turian et al. (1987). As expected, the limit velocities obtained in the case of mixtures in which the transport liquid is clear water are higher than in mixtures formed by saturated dissolution due to the higher density and viscosity of the latter.

The overall absolute average percent deviations and the root mean square deviation have been obtained for each one of the correlations analyzed, and the results obtained are shown in [Table 8](#).

In the case of Durand and Condolios' (1952) estimation, [Fig. 13](#) clearly shows that the prediction overestimates the measured velocities in all cases so that the transport fluid has a greater drag capacity than expected, especially in the case of mixtures generated with the saturated solution. The whole set of observations, however, shows a tendency to reach those velocities calculated for higher sediment concentrations.

Turian et al. (1987) correlations 1 and 4, for WT tests, show an overall absolute average percent deviation with observed data of the same order as those showed in [Table 1](#). Nevertheless, in the case of BT tests, a better fitting is needed.

A new expression [\(9\)](#) to fit the observed limit deposition velocities for both WT and BT set of tests is proposed. It is based in the dimensionless correlation proposal showed in Turian et al. (1987). This expression will be valid for $d_p/D \approx 0.0025$ and a regression of 94.3% is achieved. Its overall absolute average percent deviation and root mean square deviation are presented in [Table 8](#).

$$\frac{v_D}{\sqrt{2 \cdot g \cdot D \cdot (S - 1)}} = 0.130 \cdot C_v^{0.885} \cdot \left(\frac{D \cdot \rho_w \cdot \sqrt{2g \cdot D \cdot (S - 1)}}{\mu_w} \right)^{0.442} \quad (9)$$

4 CONCLUSIONS

From the experiments carried out at Paterson & Cooke's test facility in Cape Town, South Africa, using different sets of brine mixtures generated with relatively low sediment concentrations (less than 5%v) to determine the limit deposition velocity, viscosity and flow resistance, the followings conclusions are arrived at:

- The limit deposition velocity observed in the case of mixtures in which the transport liquid is water are higher than those of the mixtures formed by the saturated solution, due to the higher density of the latter. The prediction using the method of Durand and Condolios (1952) overestimates the measured limit deposition velocity, especially for the more viscous brine mixtures, which shows that the effect of increasing viscosity as solids concentration increases reduces the deposition velocity when compared to similar solid concentration mixtures using water as a carrier. The set of observations, however, shows a clear tendency to converge towards the calculated velocities at higher sediment concentrations.
- The values of the friction coefficient obtained for all the mixtures tend to follow the curve of relative roughness of the Moody chart corresponding to $k/D = 0.00022$. Nevertheless, the error rate increases for smaller Reynolds numbers, especially in the case of the WT00 test (mixture transported by clear water and a minimum concentration). However, in this case the accuracy in the calculation of the friction coefficient is high enough, below 1% error in almost all tests (Fig. 9).
- The kinematic viscosity obtained for mixtures having water as a transport liquid (WT tests) follows a moderate upward trend as their volume concentration increases. On the other hand, those for mixtures in which the transport liquid is the saturated solution (BT tests) increases until the mixture BT03, with a $C_V = 3.1\%$, but at this point the growth stops suddenly, since the mixture BT04 presents a viscosity very similar to that of BT03.
- The relative viscosity curve that best fits the values obtained for WT mixtures is the one by Chong et al. (Chong, Christiansen, and Baer 1971) for $C_{Vmax} = 0.2\%$. In the case of BT mixtures, there is no curve that fits the values obtained, that of Chong et al. for $C_{Vmax} = 0.1\%$ being the closest. The viscosity shows much more variation in the case where the transport liquid is a saturated solution (BT tests) than in the case of WT tests.
- In all the tests, the variation in linear head losses is small, but is higher for BT mixtures. For velocities lower than the limit deposition ones, the dispersion of the obtained results increases due to the variation in the pipe characteristics (absolute roughness and effective diameter of the tube) when forming a bed of sediments in the pipe.

505 - A new expression ~~(9)~~(9) is proposed to estimate the limit deposition velocity valid for values
506 d_p/D around 0.0025.

508 **5 DATA AVAILABILITY STATEMENT**

509 Some or all data, models, or code that support the findings of this study are available from the
510 corresponding author upon reasonable request.

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519 **7 NOTATION LIST**

520 BT = tests with mixtures generated with saturated brine

521 C_V = volume concentration of solid particles

522 D = inside diameter of the pipeline, m

523 %D = per cent deviation for each data point

524 d_p = diameter of solid particle, μm

525 d_{50} = value of the particle diameter at 50% in the cumulative distribution, μm

526 F_L = Durand's Froude number

527 f = Darcy-Weisbach friction factor

528 g = gravity, m/s^2

529 k = absolute roughness, mm

530 N = Number of data points

531 PVC = Polyvinyl chloride
532 Re = Reynolds number
533 RMS = root mean square deviation
534 S = solid to liquid density ratio
535 v_D = limit deposition velocity, m/s
536 $v_{D(calc)}$ = calculated limit deposition velocity, m/s
537 $v_{D(exp)}$ = experimental limit deposition velocity, m/s
538 WT = tests with mixtures generated with water
539 ρ_m = bulk density of the mixture, kg/m³
540 ρ_s = density of the solid phase, kg/m³
541 ρ_w = density of the liquid phase, kg/m³
542 χ_i = constants ($i = 1, 2, \dots, 5$)
543 μ_w = dynamic density of liquid phase, Pa·s
544 μ_m = dynamic density of the mixture, Pa·s
545

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FIGURE CAPTIONS

Fig. 1. Nomogram for obtaining the Durand's Froude number F_L , as a function of volume of solids ratio and the average particle size obtained by Durand (1953) and also showed by Hu (2017)

Fig. 2. Schematic layout of the experimental facility (EF) at Paterson & Cooke's Slurry Test Laboratory. The transparent pipe is used to visually observe the particles settling on the pipe invert at low velocities

Fig. 3. On the left, a view of the centrifugal slurry pump with 30kW motor, the mass flow meter, and the inlet conical sump. On the right, a general view of the test pipeline installed at Paterson & Cooke's Slurry Test Laboratory

Fig. 4. View of the differential pressure gauge in the upper pipeline located between the two pressure tapings. Each pressure tapping in the pipeline is connected with water filled tubes to the differential pressure gauge, and the tubes are flushed to remove air

Fig. 5. Graphs (in %) of passing (solid lines) and retained material (dashed line) versus sieve size. The d_{50} grain size is $158.2 \mu\text{m}$. The blue and black solid lines correspond to the "Test Sand" before and after sifting of particles above $500 \mu\text{m}$, respectively. Finally, the grey solid line represents the curve for the sediments in the Bages area tested by tested by Sánchez-Juny et al. (2019)

Fig. 6. Experimental determination of the deposition limit velocity, in the transparent pipe section of the pipe (left). Sediment addition to the pipeline, through the intermediate conical tank (right)

Fig. 7. Fitted curve by the least squares method ($R^2 = 0.999$), using the Darcy-Weisbach expression to the points obtained from the experimental laboratory data, in order to determine the value of the absolute roughness of the pipeline (test WT00)

Fig. 8. Darcy – Weisbach friction factor values corresponding to the tests carried out with the mixtures whose transport liquid is clear water and those whose transport liquid is a saturated solution on a Moody's graph

Fig. 9. Relative error (%) related to the Darcy-Weisbach friction factor determination

Fig. 10. Comparison of the slope of energy line computed from experimental data with the one obtained from the measured pipe roughness and estimated viscosity (WT mixtures – left, BT mixtures - right)

Fig. 11. Relative kinematic viscosity values over the viscosity of the saturated dissolution as a function of volume concentration of insoluble particles, including associated errors with 95% confidence. The theoretical kinematic viscosity of water at 20 °C is shown

Fig. 12. Kinematic viscosity deviation produced by a reduction (–10%) and increment (+10%) of absolute roughness k

Fig. 13. Limit deposit velocity (v_D) obtained through the method of using Durand and Condolios (1952) and the Turian et al. (1987) correlations, depending on the volume concentration of insoluble solid particles and if the mixture solvent liquid is clean water or the saturated solution. These values are associated to a pipe diameter of 62.4 mm, solid density of 2650 kg/m³, and a d_{50} of 158.2 μ m

677 **TABLES**

678 *Table 1. Parameter values of Eq. ~~(4)~~(4) for the five correlations by Turian et al. (1987)*

	χ_1	χ_2	χ_3	χ_4	χ_5	$\%D^a$	RMS^a
1	1.7951	0.1087	0.2501	0.00179	0.06623	20.53	0.3416
2	1.08471	0.1126	0.03421	-0.03093	0	21.54	0.3447
3	1.8176	0.1086	0.2525	0	0.06486	20.57	0.3412
4	1.3213	0.1182	0.3293	0	0	21.04	0.3552
5	1.1228	0.07367	0	0	0	21.35	0.3559

679 ^a $\%D$ is the overall absolute average percent deviation (Eq. ~~(5)~~(5)) and RMS is the root mean
680 square deviation (Eq. ~~(6)~~(6)).

682 *Table 2. Mass percentage of the components in a sample of the sylvinite used to generate the*
683 *saturated solution*

Component	Mass %
Sodium (Na)	28.1
Potassium (K)	10.6
Chloride (Cl)	54.9
Insoluble	2.4
Other	3.98

684
685 *Table 3. Density and volume concentration of the mixtures using clear water and their average*
686 *temperature during the tests (solvent density 999 kg/m³)*

Mixture	Mixture density (kg/m ³)	C_v (%)	Average temperature (°C)
WT00	1017	1.12	18.2
WT01	1034	2.13	19.3
WT02	1051	3.20	19.6
WT03	1067	4.12	20.1

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688

Table 4. Density and volume concentration of the mixtures using saturated solution and their average temperature during the tests (solvent density 1234 kg/m³)

Brine Mixture	Mixture density	C_V (%)	Average temperature (°C)
Saturated dissolution	1234	-	-
BT00	1251	1.20	16.6
BT01	1267	2.33	19.6
BT02	1272	2.68	22.1
BT03	1278	3.11	23.1
BT04	1301	4.73	23.7

Table 5. Kinematic and relative viscosity values (using the transport liquid viscosity at 20 °C) of the mixtures at the measured temperature, obtained by the nonlinear regressions performed for each mixture

Mixture	C_V (%)	Kinematic viscosity (m ² /s)	Relative viscosity (μ_m/μ_w)	Adjustment relative error for 95% confidence (%)	Average temperature (°C)
WT01	2.13%	1.23E-06	1.26	8.79%	19.3
WT02	3.20%	1.23E-06	1.28	11.89%	19.6
WT03	4.12%	1.43E-06	1.51	13.93%	20.1
BT00	1.20%	1.32E-06	1.07	19.22%	16.6
BT01	2.33%	1.73E-06	1.42	7.39%	19.6
BT02	2.68%	2.50E-06	2.06	6.63%	22.1
BT03	3.11%	2.96E-06	2.45	3.52%	23.1
BT04	4.73%	2.98E-06	2.51	5.38%	23.7

Table 6. Kinematic viscosity deviation produced by a reduction (−10%) and increment (+10%) of absolute roughness k

Brine Mixture	C_V (%)	Viscosity deviation related to a reduction of 10% in k	Viscosity deviation related to an increment of 10% in k
WT01	2.13	4.15%	−4.07%
WT02	3.20	4.15%	−4.15%
WT03	1.20	3.57%	−3.64%
BT00	1.20	4.48%	−4.64%
BT01	2.33	3.58%	−3.52%
BT02	2.68	2.40%	−2.44%
BT03	3.11	2.00%	−2.00%
BT04	4.73	2.15%	−2.12%

Table 7. Observed and expected deposition limit velocity (v_D), obtained though the methods of Durand and Condolios (1952) and Turian et al. (1987). The solid density considered $\rho_s = 2650 \text{ kg/m}^3$, pipe diameter $D = 0.0624 \text{ m}$

			WT00	WT01	WT02	WT03	BT00	BT01	BT02	BT03	BT04
ρ_w (kg/m ³)			1017	1034	1051	1067	1251	1267	1272	1278	1301
μ_w (10 ⁻³ Pa.s)			1.02	1.27	1.29	1.53	1.65	2.19	3.18	3.78	3.88
C_V (%)			1.11	2.14	3.17	4.14	1.20	2.33	2.68	3.11	4.73
$v_{D(exp)}$ (m/s)			0.67	1.00	1.17	1.26	0.28	0.46	0.56	0.67	0.87
$v_{D(calc)}$ (m/s)	Durand and Condolios (1952)		1.09	1.15	1.20	1.248	0.917	0.968	0.984	1.00	1.07
	Turian, et al. (1987)	Case 1	1.06	1.12	1.15	1.16	0.888	0.940	0.949	0.959	0.982
		Case 2	0.651	0.696	0.718	0.734	0.556	0.597	0.611	0.622	0.641
		Case 3	0.835	0.857	0.863	0.863	0.700	0.719	0.722	0.724	0.725
		Case 4	1.009	1.15	1.19	1.21	0.913	0.972	0.983	0.995	1.02
		Case 5	1.130	1.17	1.19	1.20	0.948	0.984	0.991	0.997	1.01
	Eq. (9)(9)		0.525	0.838	1.16	1.35	0.382	0.599	0.574	0.602	0.849

708 *Table 8. Overall absolute average percent deviation and root mean square deviation, of the*
709 *estimations of limit deposition velocity by Durand and Condolios (1952) and the five*
710 *correlations by Turian et al. (1987).*

	Durand and Condolios (1952)	Corr. 1	Corr. 2	Corr. 3	Corr. 4	Corr. 5	Eq. (9) (9)
%D WT tests	20.4	19.8	28.4	24.2	20.7	23.1	11.4
%D BT tests	97.4	89.4	34.2	52.0	95.8	98.9	16.3
RMS WT tests	0.224	0.208	0.379	0.274	0.223	0.248	0.118
RMS BT tests	0.446	0.412	0.175	0.242	0.441	0.455	0.084

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