Effect of Aggregants on Mineral Pastes and High Density Slurries

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ABSTRACT

In the vast majority, disposition of tailings from mineral processing operations is still based on subaqueous disposal in tailings dam basins. On the other hand, surface disposal of tailings as mineral pastes is increasingly being seen as an advantageous alternative to conventional subaqueous disposal for several reasons. The use of aggregants as polymeric flocculants and non-polymeric coagulants can improve solid-liquid separation techniques for mineral paste production. The objective of the current work is to present a comparative analysis of high density slurries and pastes, post the thickening process, obtained from Brazilian iron ore tailings through slump heights (consistency), rheological behaviour and settling behaviour. Results are presented from tests performed on a factorial 2^2 design array including as variables coagulant and flocculant addition rates, added to the already thickened material of high density being 70% and of paste being 75% solids by weight. The major findings of the current work are: a) the effect of the addition of a coagulant ($Al_2(SO_4)_3$) is more significant than that of adding a flocculant (SUPERFLOC N-100) in the conditions tested for slurry and paste regarding the settling rate; b) rheological behaviour was found best for blends containing 20g/t of coagulant, followed by those with 20g/t of flocculant and when both coagulant and flocculant were added together at 10g/t each the worst rheological results was attained; c) slump height differences were only encountered when the coagulant was added at 20g/t. In this latter situation, increased slump height would indicate easier pumping for the paste with the addition of $Al_2(SO_4)_3$ as a coagulant.

1 INTRODUCTION

A mineral paste can be defined as a homogenous system constituted by the mixture of liquid (generally water) and solids that are characterised by not presenting segregation of the solid particles and by not exhibiting significant water losses (exudation) when placed on a stable surface (Araujo et al., 2006). Generically speaking pastes can be produced on a wide size distribution range but should contain at least 15 to 20% of the total mass of solids of particles of size smaller than 20 µm (Johnson et al., 2005).

The presence of fine material in a mineral paste facilitates handling and transport tasks generally performed in pipes at low velocities with the help of positive displacement pumps or gravity. Consistency of the paste is frequently checked at plant site by employing ASTM slump test standard technique. In the laboratory a cone (or a cylinder) of 100 mm of height can be used for slump height determination.

The visual aspect of a mineral paste obtained as the underflow discharge of a paste thickener is shown in Figure 1a and Figure 1b depicts paste placed on an impervious surface. Both figures are taken from a paper by Vietti and Dunn (2002). Figure 1c shows laboratory version of a slump cylinder paste test, reported by Hernández et al., 2005.

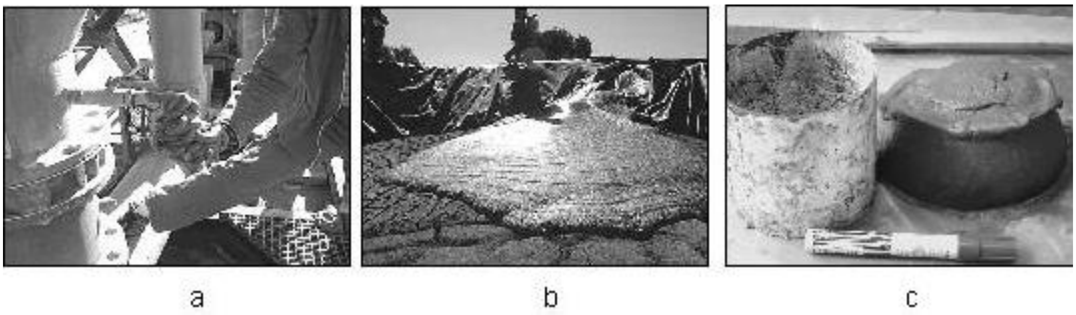

Figure 1 **a) discharge of paste thickener; b) surface disposal of an industrial mineral paste; c) laboratory slump cylinder**

Several application projects of mineral pastes for tailings disposal in Australia, Canada and Tanzania can be pinpointed as pioneers. Other examples of more recent applications are given by Slottee, 2003 as Kimberley CTP and Ekapa Mining in South Africa, Iscaycruz Pb-Zn project in Peru, and PPL Colstrip fly ash application in USA.

As a standard practice in industry (with exceptions) pastes are normally produced by paste thickeners, transported to the disposal area by a pumping system and disposed by spraying from vertical pipes (discharge towers) at the disposal site itself.

Several advantages can be listed when tailings are disposed in the form of pastes: increased water recovery allowing for an augmented recycling potential, smaller footprint of the disposal area, diminished environmental impacts and, in the case of backfill with pastes of underground stopes and chambers, increased ore recovery. A comparison of these two alternatives for tailings disposal on surface is shown in Figure 2 of Newman et al. (2001).

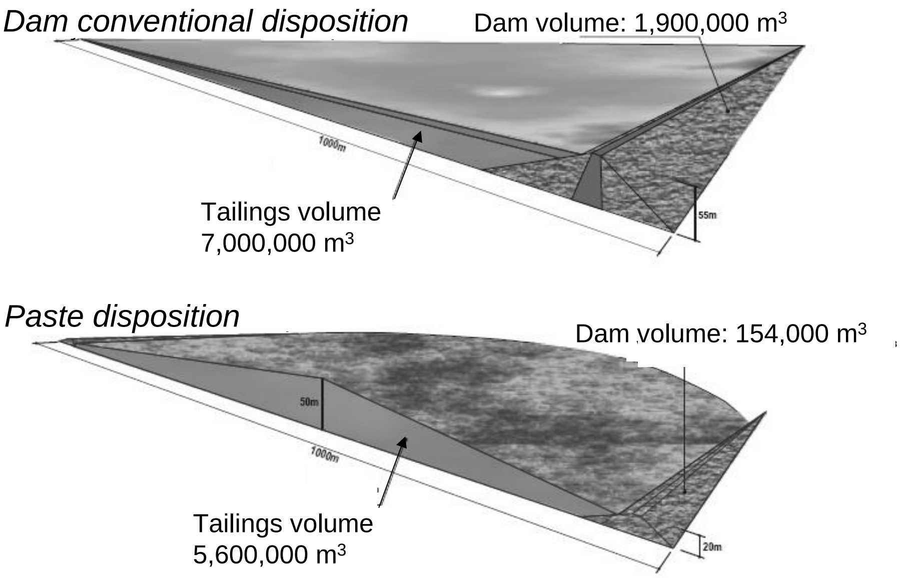

Figure 2 **Comparison between disposal systems for tailings on a conventional way and as a paste**

On the other hand, post thickening, the use once again of aggregants such as polymeric flocculants and coagulants can improve the solid-liquid separation processes, generating as beneficial effects on the production of pastes for instance enhancing paste characteristics such as viscosity, yield stress and fluidity.

Polymeric flocculants can affect the characteristics of paste in several ways. Figure 3 (Boger, 2003) shows the effect of the addition of different flocculants on the yield stress of pastes as a function of their content of solids. From this figure one can observe that the greater the addition of flocculant the greater the water content of the paste in order to obtain a significant increment of the rheologic response (yield stress).

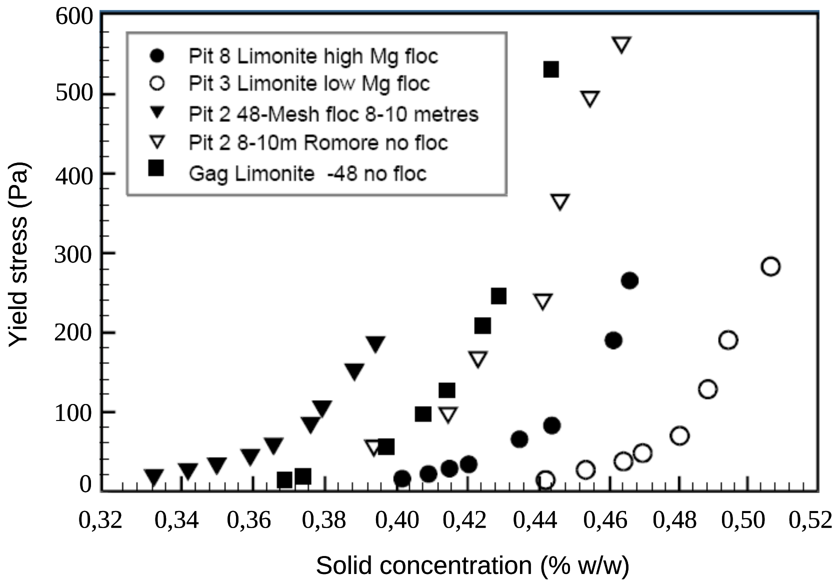

Figure 3 **Effect of flocculation on shear stress behaviour as a function of increased solids content**

2 METHODOLOGY

2.1 Materials

Mineral pastes were prepared using a sample that represents the tailings stream of an iron ore beneficiation plant from Urucum, operated by RDM-CVRD. The sample was taken at the underflow of an existing tailings thickener. Aggregants tested included a non-ionic flocculant, a polyacrylamide polymer (Superfloc SN-100, from CYTEC) and, as a coagulant, aluminium sulphate $Al_2\ (SO_4)_3$, obtained from Merck.

2.2 Methods and Equipment

Table 1 summarises the different techniques used currently for solid and paste characterisation.

2.2.1 Slump test

The slump behaviour of this material was investigated from 82% solids down to 71% without using aggregants. For a paste with 75% solids, consistency was also determined after the addition of aggregants. Figure 4 presents pictures of slump tests at laboratory scale (Clayton et al., 2003; Hernández, 2005) and the procedure employed, as recommended by Brazilian Standard NBR NM 76, 1998. Determination of the % of slump (%ABT) is given by equation (1), as follows:

$$\%ABT = s / H \times 100 \qquad (1)$$

where: “*s*” is the interval between the height of the cylinder and the height of the slump for the tested paste and “*H*” is the total height of the cylinder.

Table 1 Characterisation of solid and pastes

Property	Technique	Equipment
Specific gravity	Pycnometry	Gas and liquid pycnometers
Size distribution	Sieving, cyclosizing and laser diffraction	Standard vibrational sieving apparatus, Warmann Cyclosizer and Sympatec and Cilas Granulometers
Specific surface area	Air permeability	Blaine permeabilimeter
Chemical composition	XRF and EDS	Philips X-ray fluorescence and JEOL Scanning Electron Microscope with EDS capability
Mineralogical composition	XRD	Philips X-ray diffraction goniometer
Paste consistency	Slump height	PVC cylinder 100 mm x 100 mm
Paste fluidity	Flume test	Plexiglass apparatus 1000 mm x 200 mm x 200 mm
Paste viscosity	Viscosity	Rotational viscometer (Brookfield)
Settling rate	Sedimentation test	Graduate cylinder (1 litre)

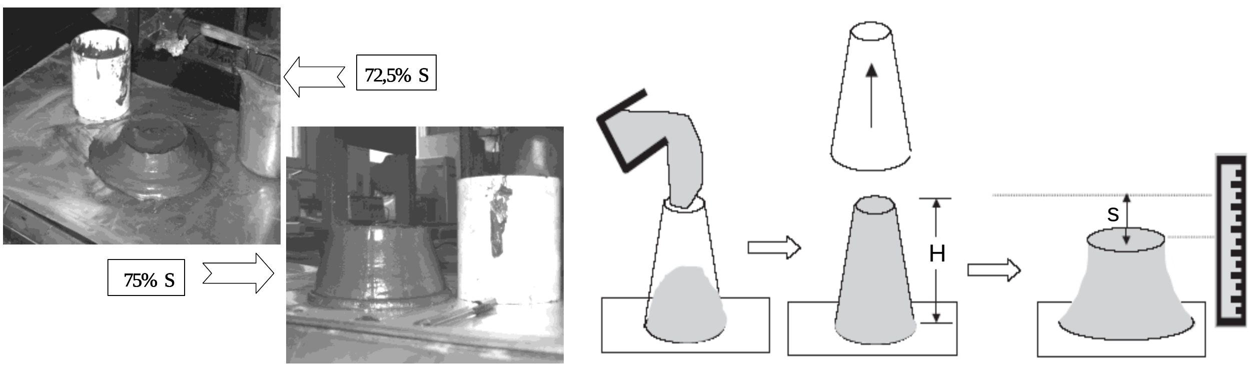

Figure 4 Photographs of laboratory slump apparatus and its procedure

2.2.2 Flume testing

Solid-liquid mixtures were prepared at 67% and 73% solids by wt (sheared samples). Slopes of the flume were adjusted at 0, 3 and 6% in relation to the horizontal surface. Figure 5 shows a picture of the apparatus (Araujo et al., 2006). Size and shape of the test flume were similar to those shown by Kwak et al. (2005). Equation 2 shows the way the repose angle of the paste (θ_R) can be calculated.

$$\theta_R = arctg\ [(h_1 - h_2) / L] \qquad (2)$$

Where: "h_1" is the height of the flume initial point; "h_2" is the height of the flume final point and "L" corresponds to the length of paste deposited on the flume after the paste sliding movement ends.

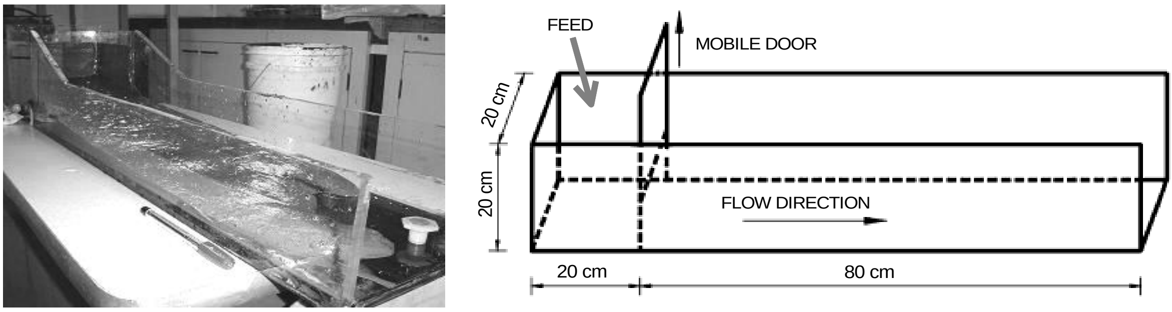

Figure 5 **Plexiglass flume picture and schematic procedure**

2.2.3 Rheology and settling

A Brookfield model DV-III viscometer was employed to evaluate the apparent viscosity of the pastes and high density slurries. The rheological cycle of 1-20-1 rpm was used to determine the rheological behaviour of these solid mixtures. A 2^2 factorial experiment (see Table 2) with high density slurry (70% solids) and mineral paste (75% solids) was planned. Both aggregants already mentioned were used. The experiment was performed taking into consideration as responses settling rate, apparent viscosity and rheological behaviour. The experiments at level (0) were carried out in duplicate for the error estimation.

Table 2 **Factorial design experiment 2^2 planned to investigate the effect of aggregants**

a) Factors and levels

Factors/Levels	**(–)**	**(0)**	**(+)**
Dosage of SN-100 (g/t) – x_1	0	10	20
Dosage of $Al_2(SO_4)_3$ (g/t) – x_2	0	10	20

b) Experiments

Experiment Nº	1	2	3	4	5	6
Factor x_1 SN-100	-	+	-	+	0	0
Factor x_2 $Al_2(SO_4)_3$	-	-	+	+	0	0

3 RESULTS

3.1 Solid Characterisation

The tested mineral sample presented an average specific gravity of 3,620 kg/m³ (3.62 g/cm³). After wet sieving the sample, 83% of the mass passed through an opening of 38 µm, was analysed by a Cyclosizer and by laser diffraction granulometers Sympatec and Cilas. The size analyses are shown in Figure 6. The results obtained are reasonably compatible and a d_{50} size is found from 4 to 10 µm.

Blaine permeabilimeter results showed an average surface area of 552.6 m²/kg (5.526 cm²/g). This high Blaine index is in accordance with the size distribution presented in Figure 6.

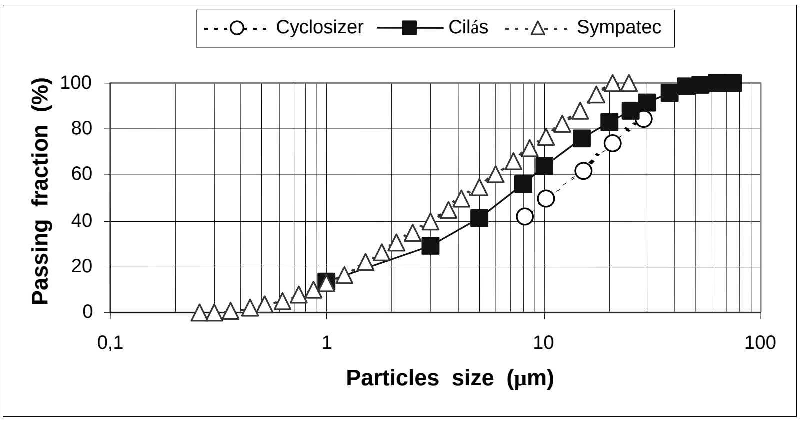

Figure 6 **Size distribution of the sample obtained with a Cyclosizer and two different granulometers (Sympatec and Cilás)**

Table 3 shows the chemical composition of the mineral sample used in this investigation.

Table 3 **Chemical analysis**

Component	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SiO_2	TiO_2	LOI
Grade (%)	8.3	0.08	60.7	0.14	0.25	0.14	< 0.1	0.38	28.2	0.36	3.46

LOI = loss on ignition

X-ray diffraction showed only quartz and hematite as clearly defined phases. SEM/EDS of particles of the sample also showed the presence of an aluminium bearing phase, likely gibbsite.

3.2 Paste Characterisation

Figure 7 shows the behaviour of mineral pastes between 21% and 29% moisture in terms of the slump tests. From this figure one can observe the most significant increase of the height of slump takes places from a value of 24% moisture for pastes without aggregants. With the addition of aggregants only for the paste with 75% solids were differences in slump observed, as shown in Table 4.

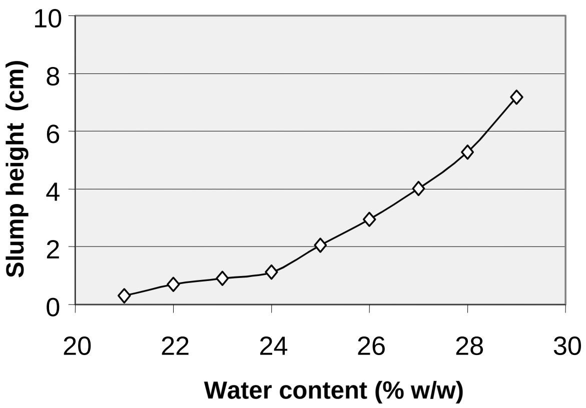

Figure 7 **Slump heights as a function of moisture content**

Figure 8 shows the behaviour of solid-liquid mixtures in the range of 67 to 73% solids. The largest repose angles are reached for the paste with 71% solids, above 10º for the flume without slope. For larger slopes of the flume the repose angle were decreased.

Tables 4 and 5 present the results of twice repeated tests of the responses settling rate, consistency (% slump) and class of rheological behaviour as determined by the rheological cycle for a slurry containing 70% solids and a paste containing 75% solids, respectively. Settling tests employed 1l graduate cylinders and temperature was kept at 25º C.

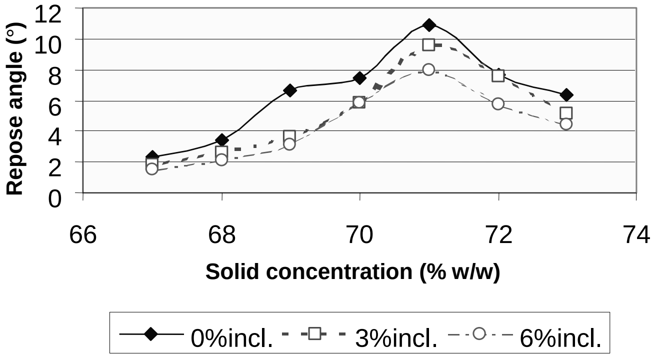

Figure 8 **Graph of repose angle as a function of the solids content**

Table 4 **Effect of aggregants on the settling rate and rheological behaviour of a high density slurry at 70% solids**

Test	**Aggregation condition**	**Settling rate $\times 10^3$ (cm/min)**	**Rheological behaviour on an 1 – 20 – 1 rpm cycle**
1	Blank test	4.5 - 4.7	Double (mostly rheotropic)
2	Addition of 20 g/t of coagulant (C)	13.0 - 13.6	Double (mostly thixotropic and with smaller viscosities)
3	Addition of 20 g/t of flocculant (F)	5.4 - 5.8	Double (mostly thixotropic and with smaller viscosities)
4	Addition of 20 g/t of (C) and 20 g/t of (F)	5.4 - 5.6	Almost Newtonian (viscosities very close)
5	Addition of 10 g/t of (C) and 10 g/t of (F)	4.7 - 4.9	Double (mostly rheotropic with increased viscosity)
6	Addition of 10 g/t of (C) and 10 g/t of (F)	4.9 - 5.1	Double (mostly rheotropic with increased viscosity)

From Table 4 it can be observed that the best aggregation condition corresponds to the addition of 20 g/t of coagulant $Al_2(SO_4)_3$ when settling rate and rheological behaviour (smaller viscosities and a trend to thixotropic behaviour) are taken into account. On the other hand, the combined addition of 10 g/t of each aggregant represents the worst condition as the settling rate increased only 10% and the trend in rheological behaviour was found to be towards rheotropic fluid. Transport of a rheotropic fluid is a much more complicated issue in comparison to a thixotropic one. In this case, the consistency of slurries (90% of slump) was the same for all conditions.

Table 5 **Effect of aggregants on the settling rate and rheological behaviour at 75% solids**

Test	Aggregation condition	Settling rate $\times 10^4$ (cm/min)	Consistency (% slump)	Rheological behaviour on an 1 – 20 – 1 rpm cycle
1	Blank	1.70 - 1.78	35 - 33	Thixotropic
2	Addition of 20 g/t of coagulant (C)	4.30 - 4.52	60 - 60	Thixotropic
3	Addition of 20 g/t of flocculant (F)	3.46 - 3.00	44 - 42.5	Double (mostly thixotropic and less rheotropic)
4	Addition of 20 g/t of (C) and 20 g/t of (F)	3.70 - 4.00	60 - 62	Thixotropic
5	Addition of 10 g/t of (C) and 10 g/t of (F)	2.59 - 2.82	48 - 49	Double (mostly thixotropic)
6	Addition of 10 g/t of (C) and 10 g/t of (F)	2.60 - 2.70	51 - 49	Double (mostly thixotropic)

From Table 5 one can observe that the best aggregation condition is that corresponding to the addition of 20 g/t of coagulant if one takes into account the settling rate, consistency and rheological behaviour (decreased viscosity and the maintenance of the thixotropic behaviour obtained for the blank test). One should re-state that the combined addition of aggregants as well as the addition of flocculant alone corresponded to less favourable conditions regarding settling rate, consistency and rheological behaviour of the pastes (trend towards rheotropic fluid behaviour). Figure 9 shows the results of settling rate in a graph relating flocculant dosage as a function of coagulant dosage. Figure 10 shows the values of the responses settling rate (a) and % slump (b) for the paste with 75% solids for the dosages of flocculant and coagulant.

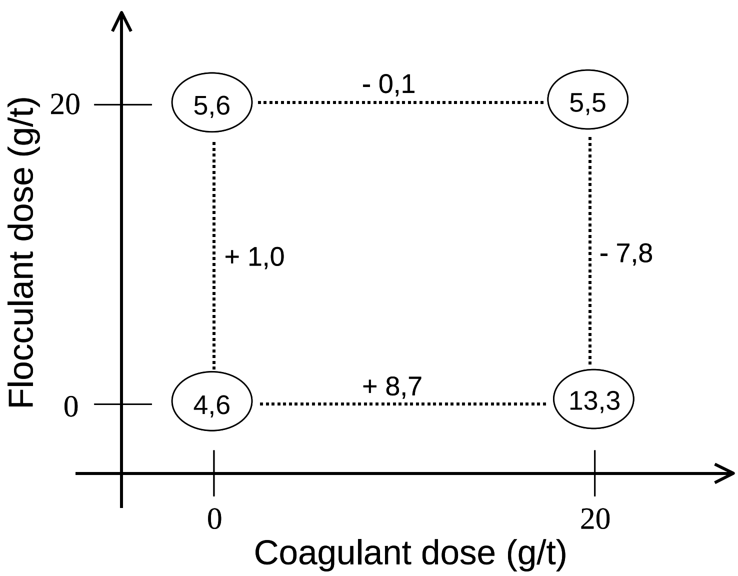

Figure 9 **Settling rate graph ($\times 10^3$ cm/min) obtained in different conditions of the addition of aggregants for the slurry with 70% solids**

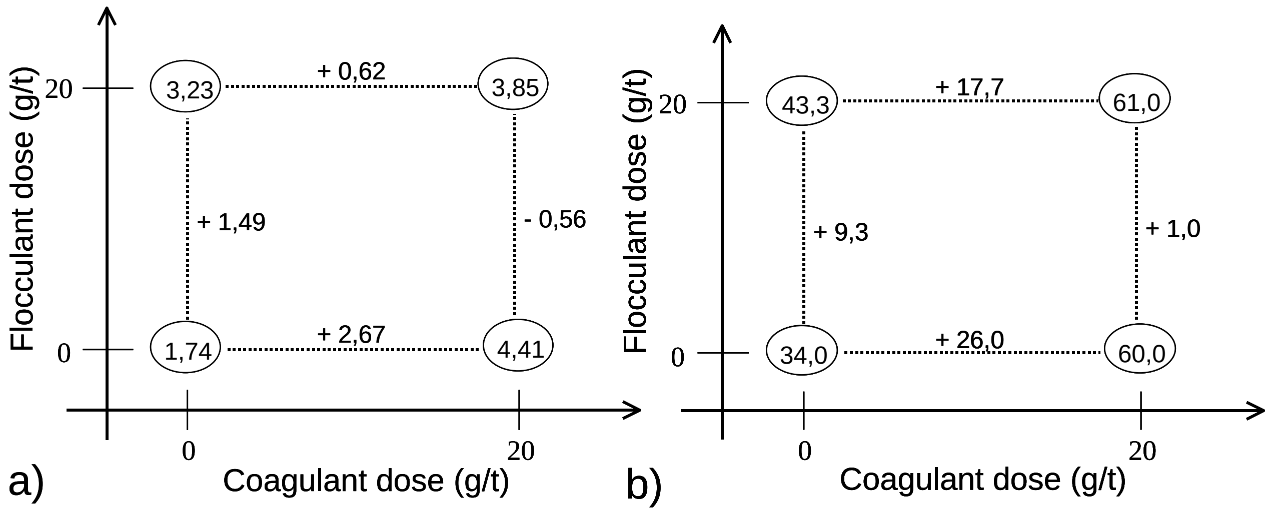

Figure 10 **Graphical representation of: a) settling rate (× 10^4 cm/min) and b) % of slump obtained under different conditions of aggregation for a paste with 75% solids**

Calculating the major effects of each factor considered and the interaction between the factors, one can establish the following linear models that allow the prediction of values of the response variables settling rate and % slump. These models are shown in equations 3, 4 and 5.

For a slurry with 70% solids:

$$Y = V_S = 6.467{\times}10^{-3} - 3.4{\times}10^{-3}{\times}X_1 + 4.3{\times}10^{-3}{\times}X_2 - 4.4{\times}10^{-3}{\times}X_1{\times}X_2 \quad (3)$$

Where: $X_1 = (x - 10) / 20$; $X_2 = (y - 10) / 20$; “x” and “y” are the dosages of flocculant and coagulant, respectively.

For the paste with 75% solids:

$$Y = V_S = 3.098{\times}10^{-4} + 0.47{\times}10^{-4}{\times}X_1 + 1.65{\times}10^{-4}{\times}X_2 - 1.03{\times}10^{-4}{\times}X_1{\times}X_2 \quad (4)$$

$$Z = \%ABT = 49.467 + 5.15{\times}X_1 + 21.85{\times}X_2 - 4.15{\times}X_1{\times}X_2 \quad (5)$$

The error associated with these models, based on replicated tests, would be 3.28%, 5.29% and 2.03%, respectively for the response settling rate of the slurry, settling rate of the paste and % slump of the paste. The range of validity of these models is within the limit of dosages from 0 to 20 g/t of aggregant.

In a general way, from analysing Equations 3, 4 and 5 one can observe that on the response settling rate an important effect of the interaction x_1x_2. On the other hand this interaction is not very significant when the response consistency of the paste is considered. It can also be seen that with the addition of 20 g/t of coagulant the highest values for the responses settling rate and consistency are reached which would make easier solid-liquid separation and transport processes for the mineral paste.

One possible explanation for the result obtained with the coagulant would be the state of aggregation of the slurry and of the paste at the natural pH of 6.25 for a temperature of 25ºC. This natural pH value is relatively close to the average isoelectric point (pH 6.98) determined by the Mular and Roberts’s technique (1966). Hence, the coagulation action would be more efficient than flocculation and the combination of flocculation and coagulation due to the mechanism being based mostly in electrostatic attraction of the particles in the sample (heterocoagulation) combined with the action of the trivalent cation and its hydroxy-complexes cations and the pH conditions of natural stability for the sample tested.

4 CONCLUSIONS

The major conclusions of the present work were as follows: a) the mineral sample used, a thickened iron ore tailings, shows very fine particle size distribution, high specific surface area and is composed chiefly by quartz and hematite; b) slump and flume tests are simple techniques adequate to characterise consistency and fluidity of mineral pastes; c) the effect of adding aggregants was only perceived on settling rate measurements and on the % slump for the paste at 75% solids; d) settling rate increases by a factor of almost three-fold after adding 20 g/t of coagulant to the high density slurry and a more favourable thixotropic rheological behaviour is reached on the 1-20-1 rpm rheological cycle at 70% of solids; e) for a paste of 75% solids the increment in settling rate is of 250% caused by the addition of coagulant and this condition is also the best to reach % slump of 60% while maintaining the condition of thixotropic behaviour for the paste; f) the most significant interaction from the factorial design experiment is the response on the settling rate as the % slump shows a small effect as it is compared to the dosage of coagulant which is seen as the most significant factor.

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