ELSEVIER

Int. J. Miner. Process. 52 (1998) 273–285

INTERNATIONAL JOURNAL OF MINERAL PROCESSING

High intensity conditioning and the carrier flotation of gold fine particles

L. Valderrama [a], J. Rubio [b,*]

[a] *Departamento de Metalurgia, Universidad de Atacama, Copiapó, Chile*

[b] *PPGEM-Departamento de Engenharia de Minas, Universidade Federal do Rio Grande do Sul, Av. Osvaldo Aranha 99, Porto Alegre, RS, Brazil*

Received 15 November 1996; revised 18 June 1997; accepted 15 July 1997

Abstract

The effect of high intensity conditioning (HIC) on carrier flotation of gold was studied at laboratory scale by keeping the degree of turbulence constant and by varying the energy transferred to the pulp. Best results were obtained after pulp HIC and showed a 24% increase in the recovery of gold, 50% in concentrate grade and higher flotation rates (at least 3–4 times faster). The fines adhere better to the surface of coarse particles (gold or pyrite) at low shear energy values, 0.5–2 $kW h/m^3$ pulp, and between 2 and 3 $kW h/m^3$ pulp they detach from the coarse ones due to the shear forces operating at the contact surface. At about 3–4 $kW h/m^3$ pulp they aggregate themselves, yielding more floatable species, and at 4 $kW h/m^3$ pulp inter-particle attrition rules again, and no aggregates are formed. Thus, gold fines recovery proceeds through carrier and/or autogenous carrier flotation. Differences in response are mainly due to the residence time of particles in the shear conditioning, particle size, hydrophobicity and size distribution of values. These phenomena are demonstrated by higher separation parameters (recovery–grade curves) and by the 'true' flotation values and their degree of entrainment. Alternatives for practical HIC, mechanisms involved and the effect of frothers are discussed. © 1998 Elsevier Science B.V.

Keywords: high intensity conditioning (HIC); carrier flotation; gold particles

1. Introduction

The problem of recovering fine (6–50 μm) and ultrafine (< 6 μm) mineral particles continues to be a challenge for researchers working in this area. Several studies have

* Corresponding author. Fax: +55-51-227 5715; E-mail: jrubio@vortex.ufrgs.br

PII S0301-7516(97)00068-9

been reported on in the past (Trahar and Warren, 1976; Fuerstenau et al., 1978, 1988; Kitchener, 1978; Fuerstenau, 1980; Trahar, 1981; Sivamohan, 1990) focusing on the problems posed by very fine particles during flotation, and several alternative processes have been suggested. Most of them are based on particle aggregation, namely shear flocculation, carrier/autogenous carrier flotation, oil agglomeration and selective flocculation (Rubio and Kitchener, 1977; Kitchener, 1978; Guerra et al., 1986; Rubio and Marabini, 1987; Subrahmanyan and Forssberg, 1989; Warren, 1991; Behl and Moudgil, 1993).

The shear flocculation process is based on the selective aggregation of hydrophobic particles in systems under high turbulence. Warren has reported several studies on shear flocculation (Warren, 1975a,b, 1991; Koh and Warren, 1979a,b) and concluded that formation of aggregates takes place within a short agitation range. Thus, at high stirring speed, the formed aggregates redisperse, due to attrition and/or high shear stress.

Autogenous carrier flotation (Hu et al., 1988) employs the same mineral particles which are being floated (but coarser) as carrier, and it is believed that this process proceeds like the shear flocculation with the fine particles floating attached to the larger particles (Chia and Somasundaram, 1983). Also, studies on 'induced' carrier flotation were carried out by Rubio and Hoberg (1993) to recover fine particles using hydrophobic polymeric spheres as carrier particles.

Dianzuo et al. (1988) refer to shear flocculation, carrier flotation and emulsion flotation as main examples of hydrophobic aggregation enhancing particle capture by bubbles.

The concept of shear flocculation has been extended to the conditioning stage ahead of flotation (Rubio, 1978; Bulatovic and Salter, 1989; Stassen, 1990, 1991; Rubio and de Brum, 1994). These authors claim that the energy transferred in the conditioning stage, often expressed as conditioning time at constant impeller speed or as impeller speed at constant time, has a pronounced effect on the concentrate recovery, grade and flotation rate. The high intensity conditioning process, HIC, as it has been named, enhanced the flotation recovery of the very fine particles of copper sulfides (Bulatovic and Salter, 1989), gold, uranium oxide and pyrite fines (Stassen, 1990, 1991) and oxidized copper ores and copper and molybdenum sulfides (Rubio, 1978; Rubio and de Brum, 1994). The fact that carrier or autogenous carrier flotation may be the responsible or be operating in the overall phenomena have not being recognized.

Because of that and because mechanisms involved are not very clear and data reported on the effect of HIC are still insufficient, the aim of this work is to report results on the characterization of the effect of HIC on flotation of gold fines. The effect of HIC was monitored by measurements of the 'true' flotation of gold fine particles, concentrate grade and recovery, degree of entrainment of values and flotation kinetics. The study has been conducted with gold fines from North Chile (Atacama), where gold is usually found in a finely dispersed form and, thus, fine grind is required in order to achieve particle liberation to enhance flotation recovery. This results in significant losses in the flotation of the ultrafine particle fractions.

2. Experimental

2.1. Materials

A representative ore sample of a copper/gold ore from Atacama (46 kg) was crushed to less than 10 mesh. Grinding was carried out in a stainless-steel ball mill (17.2 cm diameter and 22 cm length) with 55% solids by weight during 21.5 min to yield a material which was almost 65% under 400 mesh fraction (90% < 200 mesh). The mineralogical analysis showed that the ore consisted mainly of quartz, limonite, hematite, pyrite and chalcopyrite, and that gold liberation in the 200 mesh fraction was about 82%. The sample analyzed 3.7 g/t Au, 4.5 g/t Ag, 1.36% Cu, 14.15% Fe and 59.24% SiO_2.

Table 1 and Fig. 1 show the gold and particle size distribution in feed. Results show that about 64% of total gold is found below 38 μm.

2.2. Methods

Conditioning of a gold flotation feed (22% w/w), before HIC, was first conducted in a 3-l Denver cell, during 3 min to allow collector and frother adsorption. Then the same cell was endowed with four acrylic baffles to produce the HIC under a turbulent regime. Results, expressed in kW h/m^3 pulp, were obtained by stirring at a constant 1500 rpm, the pulp volume at 2 l with conditioning time varying in the range of 25–100 s to yield 0.5 to 4 kW h/m^3 pulp inputs. The energy transferred was monitored using a voltmeter and an amperimeter. The HIC was performed in the presence of 120 g/t amylxanthate as collector and the frothers (72 g/t) studied were: pine oil, MIBC and DF-250. The medium pH varied between pH 7.5 and 7.8.

'Blank' experiments were standardized tests with pulps conditioned at the same 2 l for 1.5 min at 1000 rpm (no turbulence), at pH 7.5 and with 22% solids content. Flotation tests were carried out maintaining pulp level constant by adding water and monitoring water content in each concentrate to calculate the true flotation values and the degree of entrainment following the method reported by Warren (1985). Thus true flotation was measured from a plot having gold flotation recovery in the ordinate and the cumulative water flotation recovery in the abscissa. The intercept value at the ordinate

Table 1
Gold and particle size distribution in feed

Size (μm)	Mass (g)	Mass retained (%)	Gold grade (g/t)	Gold (%)
150	3.50	0.53	10.00	1.57
106	16.40	2.47	5.00	3.69
75	48.50	7.32	3.50	7.63
63	52.30	7.89	3.80	8.93
53	36.20	5.46	3.50	5.70
45	47.20	7.12	2.51	5.33
38	29.20	4.40	2.60	3.41
< 38	429.70	64.81	3.30	63.74

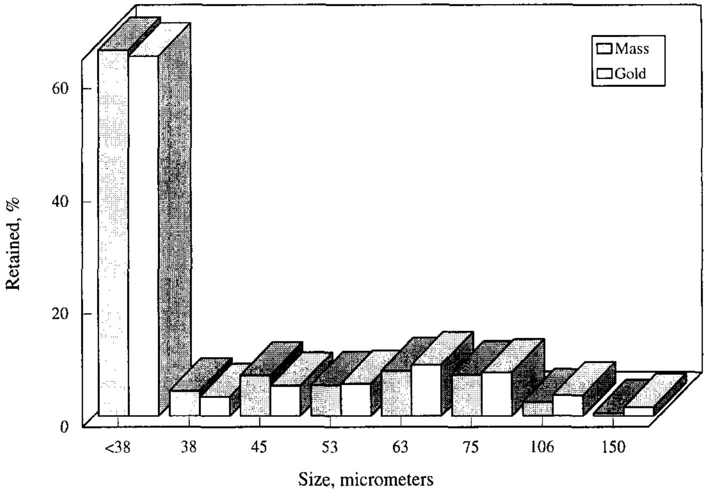

Fig. 1. Gold and particle size distribution in feed.

for 0% water recovery yields the true flotation value. The slope of the same figure yields the degree of entrainment of values.

Flotation was carried out with no baffles, at 1000 rpm. Samples were collected every 6 s and results reported are the average of three different experiments. These concentrates were analyzed for the content of Au, solids and water.

3. Results and Discussion

Fig. 2 shows that without high intensity conditioning, gold recovery was about 53% (curve 1) with 53 g/t Au (curve 5). The microscopic analysis of concentrates showed that, in this case, the larger gold particles were the first to be collected; then the medium size and finally a very small fraction of the fine particles. Because of the solution pH value, chalcopyrite flotation was very poor but not the pyrite.

Fig. 3 shows, as a function of the energy transferred during HIC, two optimal recovery values, as a result of aggregation of small particles onto coarse or medium size particles or among themselves.

The first peak with increasing the intensity of conditioning corresponds to gold fines adhering to pyrite and medium size gold particles (as revealed by microphotographs), and the second to gold fines adhering to each other (also observed microscopically).

In the first case, an assemblage of coarse and small particles appeared in the first minutes of flotation. Thus, separation proceeded by carrier flotation (gold–pyrite aggregates) and by autogenous carrier flotation (mid-size and fine gold particles).

In the second peak, the gold recovery proceeds mainly by autogenous carrier flotation of the gold fine aggregates (see Fig. 4). The fact that the second peak yields higher flotation rates, recoveries (66%) and grades (80 g/t Au) compared to the first one is

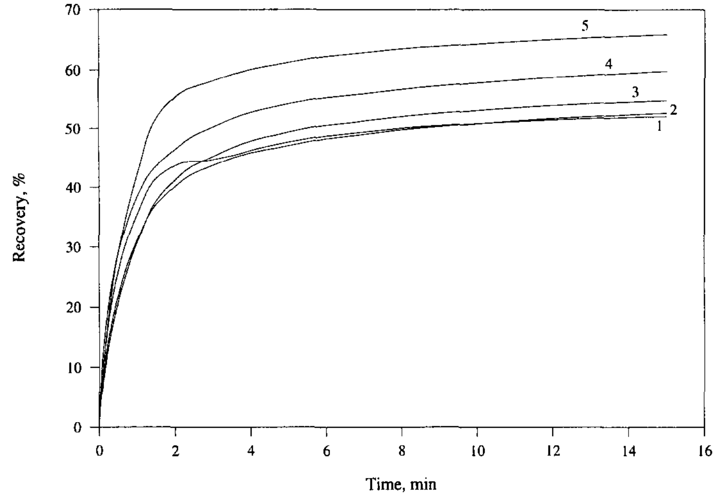

Fig. 2. Flotation kinetics of gold particles as a function of the energy transferred during HIC. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector. *1* = 0; *2* = 4; *3* = 1; *4* = 0.5 and *5* = 3 kWh/m^3 pulp.

explained by the high proportion of gold fine particles in the feed (Fig. 1) and by the amount of entrained gangue particles, in the first peak.

Warren (1975a) reported that the adhesion of fine particles onto coarse is about 1000–10000 times more probable than between the fine particles themselves. This probability is modified under HIC and the magnitude of the effect depends much on

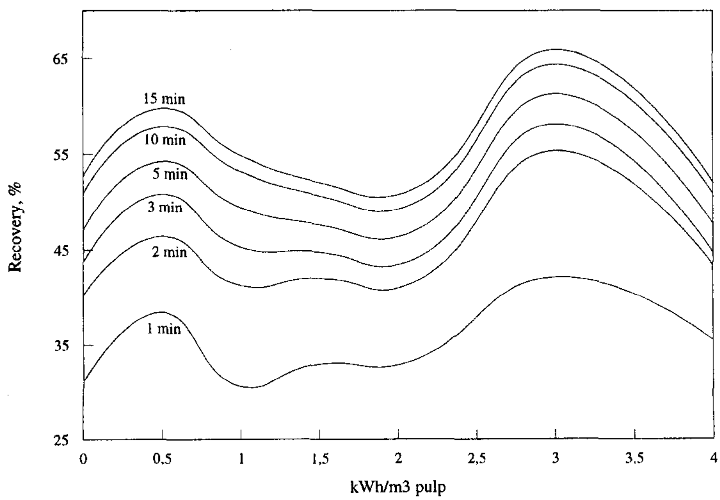

Fig. 3. Gold flotation recovery as a function of time and shear energy transferred in the conditioning stage. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector.

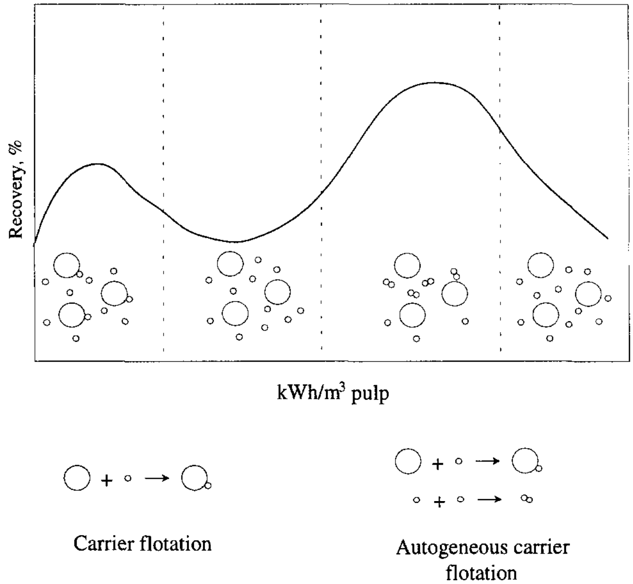

Fig. 4. Particle aggregation phenomena during the conditioning stage and mechanisms of flotation.

values of particle size distribution, their surface hydrophobicity and the energy being transferred (amount and mode) (Warren, 1975a; Chia and Somasundaram, 1983; Dianzuo et al., 1988; Hu et al., 1988; Bulatovic and Salter, 1989; Smith and Warren, 1989; Subrahmanyan and Forssberg, 1990; Rubio and Hoberg, 1993).

As in the bubble–particle interaction, adhesion among particles may be explained in terms of probabilities of attachment and detachment. Coarse particles collide with sufficient energy to cause particles attachment. The very fine particles, because of their higher surface area and energy, adhere better to the surface of coarse particles during a short period of HIC. This occurs similarly to the slime coating phenomenon with the coarse particles acting as carrier.

At longer times of HIC, fines attached to coarse particles begin to detach due to the high shear forces operating at the contact surface, but they begin to form aggregates themselves yielding again more floatable species (Warren, 1975a, 1991). Finally, and after a while (highest transferred energy), inter-particle detachment, due to attrition, takes place again (Warren, 1975a) levelling off flotation of gold particles.

The mineralogical composition of the carrier defines the type of flotation, whether carrier or autogenous carrier flotation. Fig. 4 depicts mechanisms proposed for the particle aggregation phenomena and type of flotation involved after high intensity conditioning (HIC) of the pulp.

These mechanisms are supported by the following facts:

- Higher flotation rates (Fig. 1) specially when gold fines aggregated themselves and autogenous carrier flotation proceeds (second peak).
- Typical grade–recovery curves (Fig. 5).

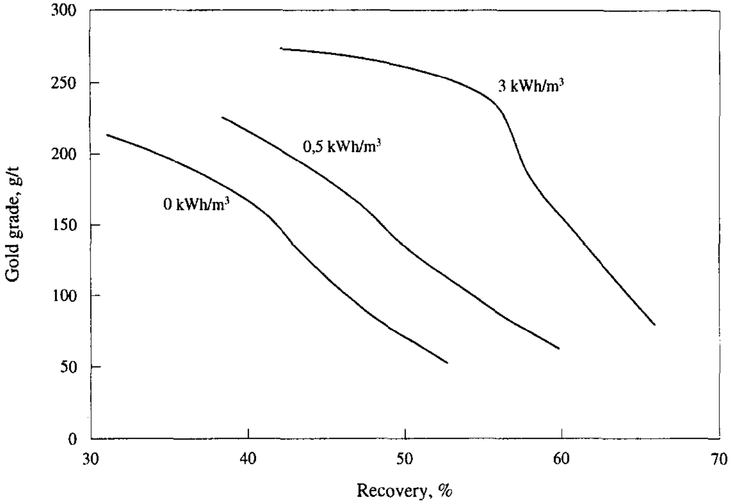

Fig. 5. Grade–recovery flotation curves with and without HIC. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector.

- High true flotation values (recovery without entrainment) which follow the same trend as the total gold recovery, with two clear peaks (Fig. 6); Again, the second peak was substantially higher.
- Higher concentrate grades, showing also two peaks with higher values in the second peak (Fig. 7).
- Lower degree of entrainment of values when the very fine gold particles aggregate (second peak) and float selectively (Fig. 8).

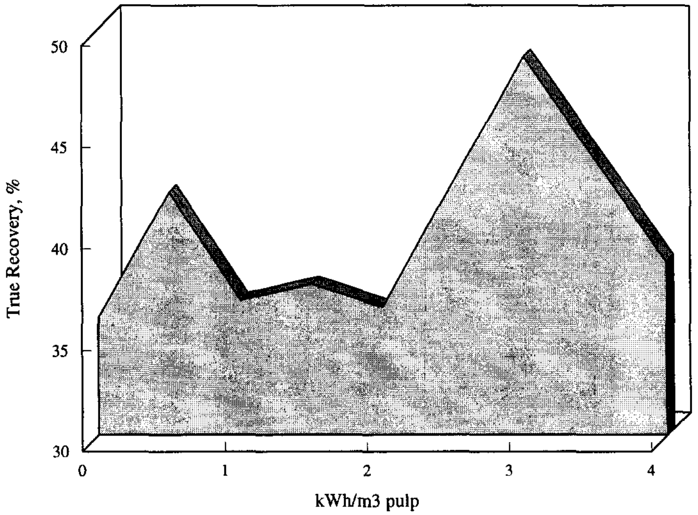

Fig. 6. Effect of HIC on gold true flotation recovery. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector.

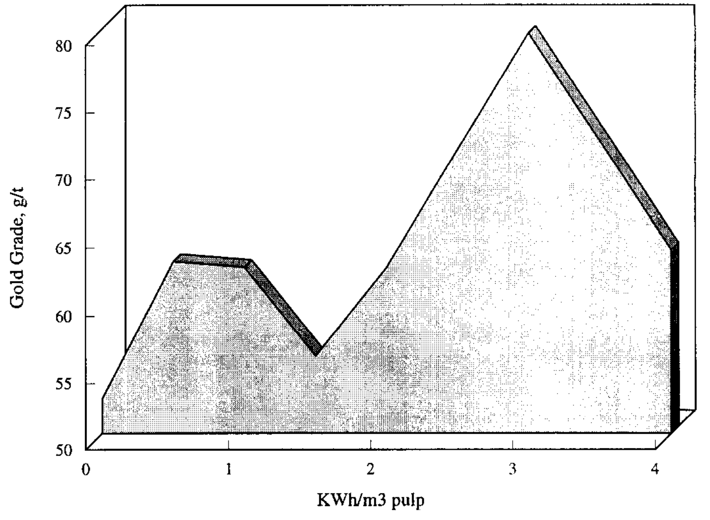

Fig. 7. Effect of HIC on concentrate gold grade. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector.

At the first peak, the aggregates floating carried, as entrained material, more gangue particles because of their higher volume and more voids. This yielded poorer concentrate gold grade.

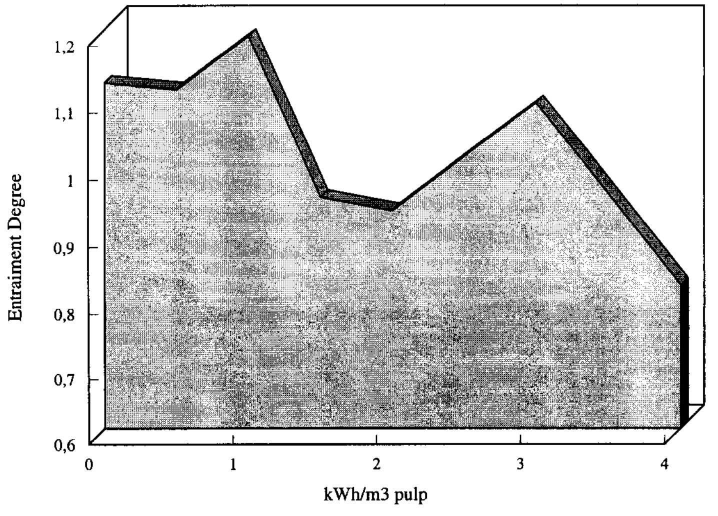

Fig. 8. Effect of HIC on the degree of gold values entrainment. Pine oil, 72 g/t as frother and 120 g/t amyl xanthate as collector.

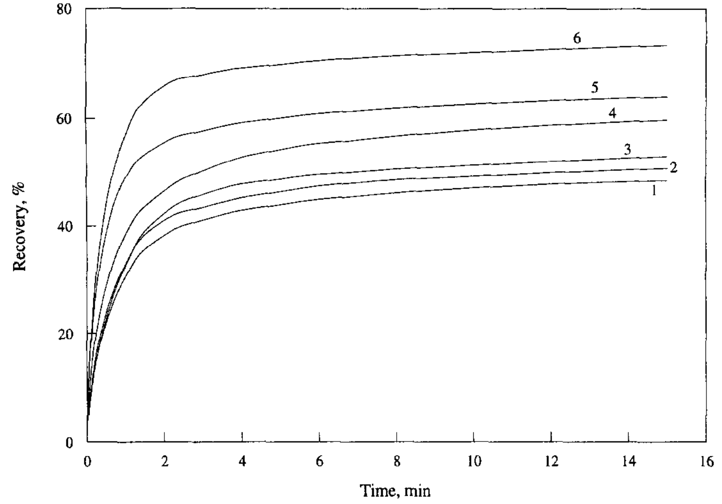

Fig. 9. Effect of frother type on flotation kinetics of gold particles as a function of shear energy in the conditioning stage. 120 g/t amyl xanthate as collector and 72 g/t the frother concentration. *1* = MIBC: 2 kWh/m^3 pulp; *2* = pine oil: 2 kWh/m^3 pulp; *3* = MIBC: 0.5 kWh/m^3 pulp; *4* = pine oil: 0.5 kWh/m^3 pulp; *5* = Dowfroth 1012: 0.5 kWh/m^3 pulp and *6* = Dowfroth 1012: 2 kWh/m^3 pulp.

3.1. Effect of frothers

Figs. 9–12 show the effect of frothers type (at constant concentration, 72 g/t) on flotation kinetics (Fig. 9), grade–recovery curves (Fig. 10), true flotation recovery (Fig.

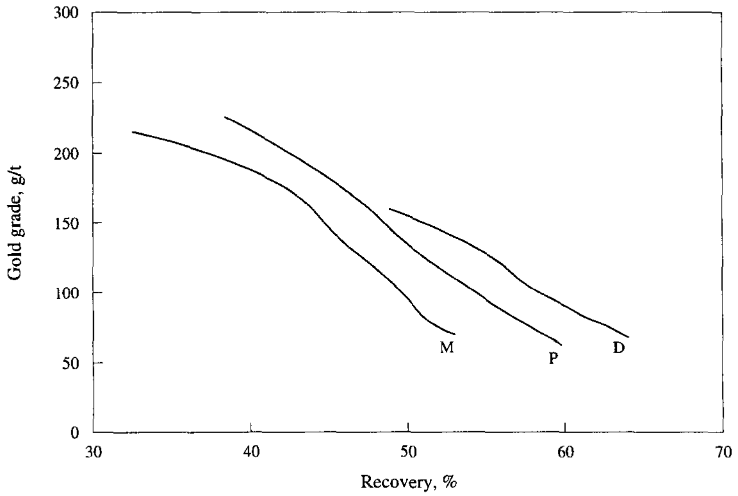

Fig. 10. Grade–recovery flotation curves for different frothers. HIC = 0.5 kWh/m^3 pulp; 120 g/t amyl xanthate as collector and 72 g/t the frother concentration. *D* = Dowfroth 1012; *P* = pine oil and *M* = MIBC.

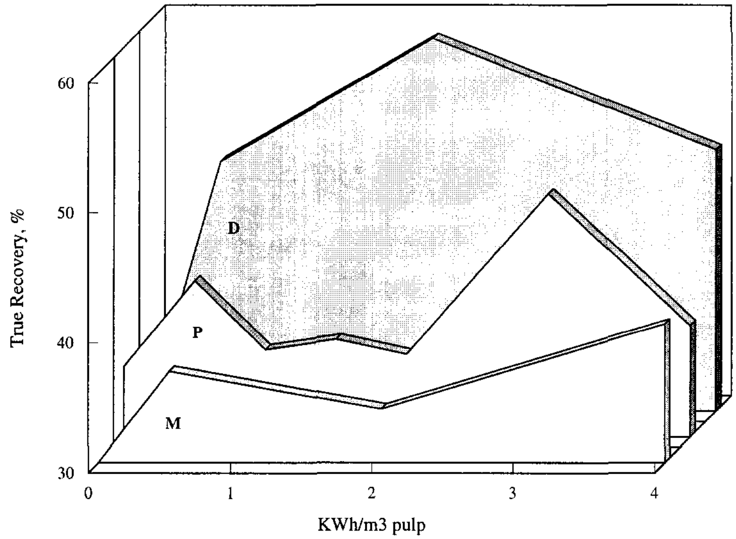

Fig. 11. Effect of HIC on true gold recovery values for different frothers. 120 g/t amyl xanthate as collector and 72 g/t the frother concentration. D = Dowfroth 1012; P = pine oil and M = MIBC.

11) and concentrate grade (Fig. 12). Fig. 9 shows higher kinetic values for Dowfroth 1012 (D) followed by pine oil (P) and MIBC (M), even with a less intense conditioning, 2 kW h/m^3 pulp. Other results showed that a similar trend occurred also at other frother concentrations (but 72 g/t).

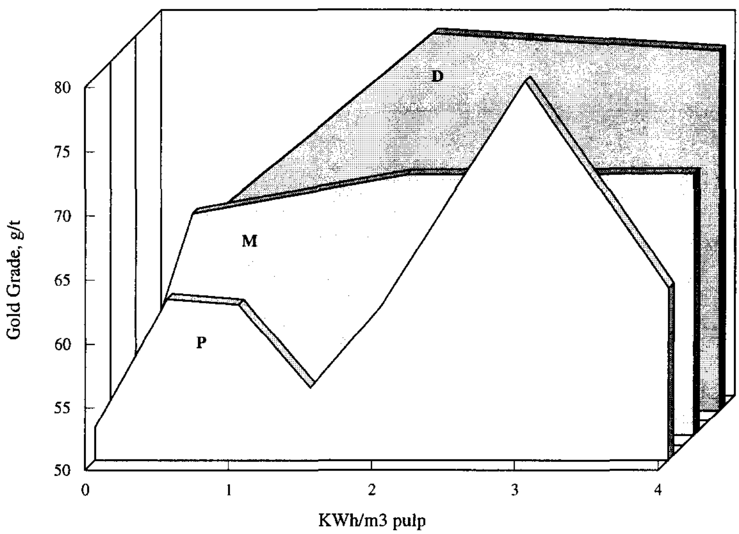

Fig. 12. Effect of HIC on concentrate gold grade for different frothers. 120 g/t amyl xanthate as collector and 72 g/t the frother concentration. D = Dowfroth 1012; P = pine oil and M = MIBC.

Figs. 10 and 11 presents grade–recovery curves and the effect of HIC on true flotation values for the three frothers used. There are better results with Dowfroth 1012. These results are accompanied by higher concentrate grades (Fig. 12) and are due to the fact that with Dowfroth 1012, the froth formed was more stable, smoother and well structured.

Thus, HIC allows the formation of aggregates between small, non-floatable particles and carrier (medium size particles), and themselves enhancing all separation parameters.

These results (and others already published), strongly suggest that is time to go back to 'conditioners' and we should not merely use pulp distributors. Various alternatives to provide the shearing needed, at low costs, have to be found for each individual mineral system, either by changing the degree of turbulence in the pulp transport system, modifying the design of present conditioners or simply by changing drastically the concept of pulp conditioning for froth flotation.

The use, for example, of static mixers or the recirculation of the 'first' concentrates serving as 'seeds' for aggregates formation, should be explored. Staged flotation has already been reported upon and may lead to a good means of fines flotation (Fuerstenau et al., 1988). However, of course, economical considerations based on energy costs versus production gains must be taken into account. A striking problem will be to find the proper shear energy values which will depend on feed grade and size distribution. However, it appears that 2–3 kWh/m^3 is not an uneconomical value to attain and is comparable with the energy transferred in old conditioners!

4. Conclusions

Results found in this work allow the following conclusions:

(1) High intensity conditioning, as a pulp pre-treatment step enhanced flotation recoveries of gold fines by about 24%, flotation rates were at least 2–3 times faster and the gold concentrate grade increased 50%.

(2) Results obtained are explained by the increase in the concentration of floatable particles as a result of the aggregation of gold fines followed by carrier and/or autogenous carrier flotation. This was demonstrated by the enhancement in the true flotation values, grade–recovery curves and a low entrainment of the values.

(3) The need for new conditioners appears to be the key to improve fines particle recovery by froth flotation and practical shear conditioners have to be invented.

Acknowledgements

The authors thank to all the institutions that support research in Chile and Brazil. Special thanks to Professor R.W. Smith from University of Nevada, Fabiana Tessele and Jailton J. da Rosa (UFRGS-Brazil) for their contribution in the discussion and preparation of the text format.

References

Behl, S., Moudgil, B.M., 1993. Control of active sites in selective flocculation. Part I and II. J. Colloid Interface Sci. 161, 414–429.

Bulatovic, S.M., Salter, R.S.H., 1989. High intensity conditioning: a new approach to improve flotation of mineral slimes. In: Conference of Metallurgists, Halifax, Canada, Proceedings, pp. 182–197.

Chia, Y.H., Somasundaram, P.A., 1983. Theoretical approach to flocculation in carrier flotation for beneficiation of clay. Colloids Surf. 8, 187–202.

Dianzuo, W., Guanzhou, Q., Weibal, H., 1988. The effect of carrier-promoting aggregation of coarse particles. In: Fine Particle Flotation. Can. Inst. Mining Metall., pp. 309–316.

Fuerstenau, D.W., 1980. Fine particle flotation. In: Somasundaram, P. (Ed.), Fine Particles Processing. AIME, vol. 1, pp. 669–705.

Fuerstenau, D.W., Chander, S., Abouzeid, A.M., 1978. The recovery of fine particles by physical separation methods. In: Somasundaram, N., Arbiter, P. (Eds.), Beneficiation of Mineral Fines: Problems and Research Needs. Nat. Sci. Found. Workshop Report, chap. 1, pp. 3–59.

Fuerstenau, D.W., Li, C., Hanson, J.S., 1988. Shear–flocculation and carrier flotation of fine hematite. In: Plumpton, (Ed.), Symp. on the Production and Processing of Fine Particles. Can. Inst. Mining Metall., pp. 329–335.

Guerra, E., Solari, J., Rubio, J., 1986. A comparative study of oil based beneficiation processes of ultrafine Brazilian coals. In: International Coal Preparation Congress, 10., Edmonton, Proceedings. AIME, New York, vol. 1, pp. 105–121.

Hu, W.B., Wang, D.Z., Qu, G.Z., 1988. Autogenous carrier flotation. In: 16th Int. Miner. Process. Cong., Stockholm. Proceedings. Elsevier, Amsterdam, vol. 10A, pp. 329–335.

Kitchener, J.A., 1978. Flocculation in mineral processing. In: Ives, K.J. (Ed.), Scientific Basis of Flocculation, NATO Advanced Study Institute Series. Sijthoff and Noordhoff, The Hague, pp. 283–328.

Koh, P.T.L., Warren, L.J., 1979. Flotation of an ultrafine scheelite ore and the effect of shear flocculation. In: Proceedings 13th Int. Miner. Process Cong., Warsaw, pp. 263-293.

Koh, P.T.L., Warren, L.J., 1979b. Flotation of flocs of ultrafine scheelite. Trans. Inst. Min. Metall. C 86, 94–95.

Rubio, J., 1978. Conditioning effects on flotation of a finely divided non sulphide copper ore. Trans. Metall. C, 87–107.

Rubio, J., de Brum, I., 1994. The conditioning effect on the flotation of copper/moly mineral particles. In: Castro, S., Alvarez, J. (Eds.), IV Southern Hemisphere Meeting on Mineral Technology, Concepción-Chile, vol. II, pp. 295–308.

Rubio, J., Hoberg, H., 1993. The process of separation of fine mineral particles by flotation with hydrophobic polymeric carrier. Int. J. Miner. Process. 37, 109–122.

Rubio, J., Kitchener, J.A., 1977. New basis for selective flocculation of mineral slimes. Trans. Inst. Min. Metall. C, 86–97.

Rubio, J., Marabini, A.M., 1987. Factors affecting the selective flocculation of hydroxyapatite from a quartz/calcite system. Int. J. Miner. Process. 20, 59–71.

Sivamohan, R., 1990. The problem of recovering very fine particles in mineral processing: a review. Int. J. Miner. Process. 28, 247–288.

Smith, P.G., Warren, L.J., 1989. Entrainment of Particles into Flotation Froths. In: Laskowski, J.S. (Ed.), Frothing in Flotation. Gordon and Breach, pp. 123–146.

Stassen, F.J.N., 1990. Conditioning for flotation of gold, uranium oxide and pyrite. M. Ing. Thesis, University of Pretoria.

Stassen, F.J.N., 1991. Conditioning in the flotation of gold, uranium oxide and pyrite. J. S. Afr. Inst. Min. Metall. 91, 169–174.

Subrahmanyan, T.V., Forssberg, K.S.E., 1989. Carrier Flotation of Galena. In: Konferens i Mineralteknik, Hogskolan i Lulea, Proceedings, Lulea, pp. 61–73.

Subrahmanyan, T.V., Forssberg, E.F.S., 1990. Fine particle processing: shear flocculation and carrier flotation – a review. Int. J. Miner. Process. 30, 265–286.

Trahar, W.J., 1981. A rational interpretation of role of particle size in flotation. Int. J. Miner. Process. II, 289–327.

Trahar, W.J., Warren, L.J., 1976. The floatability of very fine particles. A review. Int. J. Miner. Process. 3, 103–131.

Warren, L.J., 1975a. Shear flocculation of ultrafine scheelite in sodium oleate solutions. J. Colloid Interface Sci. 50, 307–318.

Warren, L.J., 1975b. Slime coating and shear–flocculation in the scheelite– sodium oleate system. Trans. Inst. Min. Metall., C 84, 99–104.

Warren, L.J., 1985. Determination of the contribution of true flotation and entrainment in batch flotation tests. Int. J. Miner. Process. 14, 33–44.

Warren, L.J., 1991. Shear flocculation. In: Laskowski, J.S., Ralston, J. (Eds.), Colloid Chemistry in Mineral Processing. Elsevier, Amsterdam.