Purification of a dilute platinum group metals process stream using waste yeast biomass immobilized on plaster of Paris

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Synopsis

The removal of platinum group metals (PGMs) from a dilute industrial process stream using a packed bed column of ethanol-treated waste yeast biomass immobilized on plaster of Paris (POP) was investigated. The study also included the removal of base metals and other trace elements in dilute solution. The effects of feed flow rate and bed depth on the breakthrough characteristics of the adsorption system were determined. The results showed that removal was favoured by lower flow rates and higher bed depths. An increase in the bed depth with a decrease in flow rate increased the volume of effluent that could be treated effectively before breakthrough. The breakthrough curves for most of the elements do not resemble an ideal breakthrough curve, due to the complexity of the solution. The normalized concentration for most of the metals in solution remained high, even in the early stages of treatment when the sorbent material was most pristine. Generally, the affinity of the sorbent for the elements considered followed the order $Pd^{2+} > SO_4^{2-} > Te^{2+} > Pt^{2+} > Ir^{3+} > Ni^{2+} > Cl^- > .Ru^{3+} > Se^{2+} > Na^+$. The data from the column studies was fitted to Adam-Bohart and Thomas models. The Adam-Bohart model showed a superior prediction of the experimental data. COD analysis of the effluent was also carried out at different time intervals. The measured COD decreased from 200 mg/l to less than 68 mg/l after 30 minutes, which corresponds to the removal efficiency of about 66%.

Keywords
platinum group metals recovery, dilute process stream, biosorption, packed column, waste yeast biomass, immobilization.

Introduction

The recovery of metals from dilute platinum group metals (PGMs) process streams has a twofold advantage. Firstly, it minimizes contamination of the aquatic environment, and secondly, it recovers metals that have significant commercial value. Conventional methods for the removal of metals from wastewater have proven to be ineffective, especially in the case of very low metal concentrations. A satisfactory process would achieve the goal of metal recovery as well as wastewater purification at a relatively low cost, and without the generation of large amounts of residual solids. The search for new, effective and economical technologies for the removal of precious metals from waste streams has therefore shifted towards biosorption. Employing materials of biological origin allows existing knowledge to be applied to the development of technologies to treat metal- and organic-containing solutions. These bio-

sorbents possess metal –sequestering properties capable of quickly and efficiently decreasing the concentration of metals ions in dilute complex solution from parts per billion to parts per trillion (Wang and Cheng, 2006). For economic reasons, researchers have paid much attention to various byproducts from the fermentation industries because these are available in large quantities. One such waste from the food and beverage industry is brewery waste biomass, *Saccharomyces cerevisiae*. During fermentation, the yeast biomass increases three- to six-fold. However, this brewery waste material is largely used only as swine and ruminant feeds (Soares and Soares, 2012). The biosorbents can be treated by various chemical or physical processes to improve the effectiveness of their functional groups, thereby increasing the metal binding capacities.

The technical viability and biosorption capacity of the *Saccharomyces cerevisiae* waste biomass for the removal of PGMs from synthetic solution in a batch system has been investigated previously (Oke, Ndlovu, and Sibanda, 2014). However, for practical and large-scale operation, a packed column is preferred since a batch system is usually limited to the treatment of small quantities of wastewater. Free biomass has low mechanical strength and is not suitable for use in column applications (Rose and Townsley, 1986). Furthermore, high hydrostatic pressures are required to generate suitable flow rates in packed columns, and these high pressures can disintegrate the free biomass. These problems can be avoided by the use of immobilized biomass systems. In the biosorption processes for metal removal from wastes and dilute process streams, different immobilization

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materials have been used. However, no published work is available on the treatment of dilute industrial PGM streams using *Saccharomyces cerevisiae* immobilized on plaster of Paris (POP). Therefore, the aim of this work was to use waste yeast immobilized on POP as a biosorbent for the purification of a dilute industrial PGM process stream. POP was chosen as a support material because of its cost-effectiveness compared to other support materials mentioned in the literature.

Materials and methods

Biosorbent

Spent waste yeast biomass was obtained from a fermenter at South African Breweries in Johannesburg. The yeast cells were initially washed with distilled water and the biosorbent separated by centrifugation. The biosorbent was air-dried and stored for further use.

Chemical treatment of yeast cells

Ethanol-treated yeast cells were prepared by suspending 30 g of cells in 100 ml of 700 g/l ethanol solution for 20 minutes (Goksungur, Uren, and Guvenc, 2002). After treatment, the yeast cells were collected by centrifugation, washed several times with distilled water, and air-dried.

Dilute process solution

The industrial dilute process solution used was collected at the process outlet stream of a South African PGM refinery.

Plaster of Paris (POP)

The POP used in biomass immobilization was purchased at a local hardware shop.

Yeast immobilization on plaster of Paris

Immobilization of the yeast biomass was carried out with POP as support material using the method reported by Ghosh, (1988). The ethanol-treated yeast was suspended in water and plaster was added to form a thick dough. The final concentration of yeast was 20% (w/v). Beads (4.5–5.5 mm) were cast from the plaster dough and kept overnight at 26–28°C. The beads were then washed under running tap water

to remove any loosely adherent yeast and again kept overnight at 26–28°C. The immobilization procedure as reported by Ghosh (1988) was slightly modified: radiation killing of the yeast cells was avoided (radiation killing is a form of heat treatment using ultraviolet light), and the yeast cells were used as-is after immobilization for purification of the PGMs effluent.

Characterization the dilute industrial process stream

The dilute industrial solution was characterized for total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), pH, chloride, ammonia, sulphate, and salinity (conductivity). The PGM and base metals contents were analysed by inductively coupled plasma–mass spectrometry (ICP-MS) (Perkin Elmer Nexlon 300D). Table I gives the chemical composition of the PGM stream as received.

Chemical oxygen demand (COD) was determined with a Spectroquant Pharo 300 in accordance with the instructions of the manufacturer.

Column experiments

Column experiments were conducted in an acrylic glass tube of 25 cm inner diameter and 45 cm height packed with yeast immobilized on plaster of Paris. Glass beads were introduced at the top and the bottom of the packed column to prevent the adsorbent from floating. The dilute PGM process solution was conditioned to pH 3 (the optimum pH for adsorption obtained in the batch experiments (Oke, Ndlovu, and Sibanda, 2014) using 0.1 M NaOH and HCl solutions. The solution, with known concentration of solutes, was pumped through the column in an upflow direction using a peristaltic pump (Watson Marlow 5045) with variable speed adjustment. The upflow movement was chosen because it minimizes clogging and unintentional filtration. Samples were collected from the column at regular intervals and analysed by ICP-MS (Perkin Elmer Nexlon 300D). Figure 1 is a schematic of the experimental set-up for the column study.

The experimental conditions chosen for investigating the sorption performance of POP yeast in a fixed-bed column were as follows: bed depth 6.5, 8.5, and 13 cm; flow rate 0.9, 1.3, and 2.1 ml/s. All experiments were carried out for 180
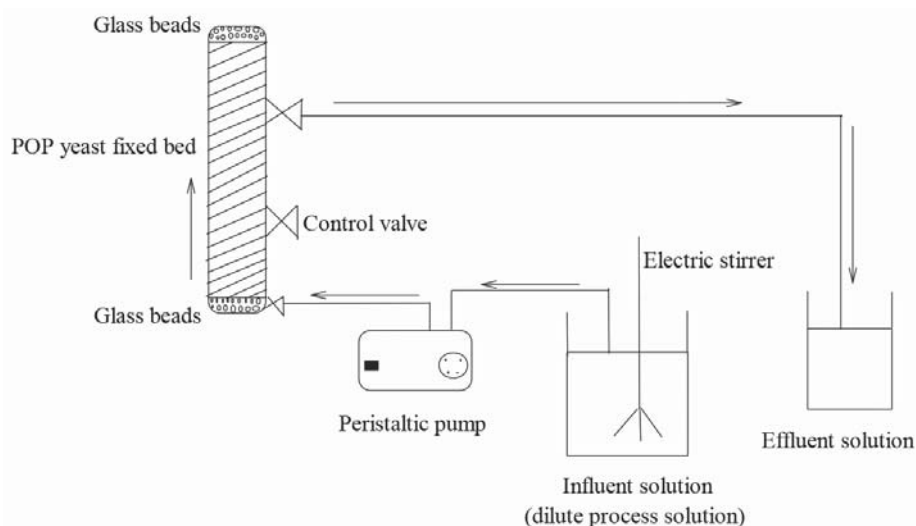

Figure 1—Experimental set-up for column study

minutes. The flow rates and bed depths were chosen based on information from the literature (Calero *et al.*, 2009; Danny, Porter, and McKay, 2000). The pH and the time used were based on the information gathered from the batch studies (Oke, Ndlovu, and Sibanda, 2014).

Control experiments

Control experiments were performed with only the POP beads without yeast to ascertain the adsorption characteristics of POP itself (if any).

Results and discussion

Characterization of dilute PGM solution

Table I gives a summary of the physico-chemical characteristics of the PGMS effluent stream. Most of the values are above the permissible limit set by the US Environmental Protection Agency (USEPA, 2010) as well as the Department of Water Affairs and Forestry, South Africa (DWAF, 1996).

The high concentration of sulphate, sodium, and chloride ions causes the solution to have a very high ionic strength. The ionic strength and the pH strongly influence metal speciation and the type of metal ion complexes in industrial wastewater. The solubility of most metals decreases as the ionic strength of the medium increases. According to the

DWAF guidelines (shown alongside the dilute process stream characteristics in the table), the wastewater is not suitable for re-use in industrial processes. The pH, chloride, and sulphate levels are likely to lead to problems such as corrosion and scaling of process equipment.

Chemical oxygen demand (COD)

The chemical oxygen demand (COD) test is commonly used to indirectly measure the amount of organic compounds in water. During the adsorption process, the COD of the effluent was measured at different time intervals. The COD decreased from 200 mg/l to less than 68 mg/l after 30 minutes, which corresponds to a removal efficiency of about 66%. Beyond this time, there was no significant change in the COD level.

Column experiments

Continuous-mode sorption studies play an important role in evaluating the technical feasibility of a treatment process for industrial application (Akar and Divriklioglu, 2010). This work focused on the removal of metal species with high concentrations or those species found to be above their discharge limit (in the case of base metals and the anions) or with concentrations above 0.1 mg/l in the case of PGMs. The species of interest include sulphates, chlorides, Na, Ni, Se, Ru, Pd, Pt, and Ir. For the test work, the dilute process stream was conditioned to pH 3 (the optimum pH for PGM adsorption in the batch studies (Oke, Ndlovu, and Sibanda, 2014).

Control experiments

The results from the control experiments showed that the adsorption of the species of interest was due to the functional groups on the biomass, as reported by Oke, Ndlovu, and Sibanda, (2014), and not affected in any way by the POP.

Effect of flow rate

The effect of flow rate on the biosorption of the metals of interest was studied by varying the flow rate from 0.9 to 2.1 ml/s while the bed height was held constant at 13 cm. The breakthrough curves were constructed as C/C_0 (where C is the effluent concentration at time t, and C_0 is the initial concentration of the influent stream) *versus* time, as presented in Figures 2–4. Breakthrough is considered to have occurred when there is a sharp increase in the outlet concentration. The breakthrough time is arbitrarily inferred to occur at $C/C_0 = 0.05$ according to Oliviera *et al.* (2011). However, the breakthrough in this study is based on the allowable discharge limits of various metal of interest as outlined by USEPA (2010), as well as by DWAF (1996), as given in Table II. In addition, saturation was assumed to have occurred when the effluent concentration was generally at 90–95% of the influent concentration (Oliviera *et al.*, 2011). However, from examination of Figures 2–4, it can be concluded that saturation of the bed, by the above definition, was not reached. In addition, the steepness of most of the graphs shows that frequent and accurate monitoring of the effluent quality is needed to ensure that a high concentration of the contaminant is not allowed to exit the column before the run is terminated (Benjamin and Lawler, 2013). The steepness of the breakthrough curve determines the extent to which the capacity of an adsorbent bed can be utilized.

Figures 2–4 show the breakthrough curves of some of the elements studied at different flow rates. The choice of

Table I

Physico-chemical characterization of the dilute PGMs solution

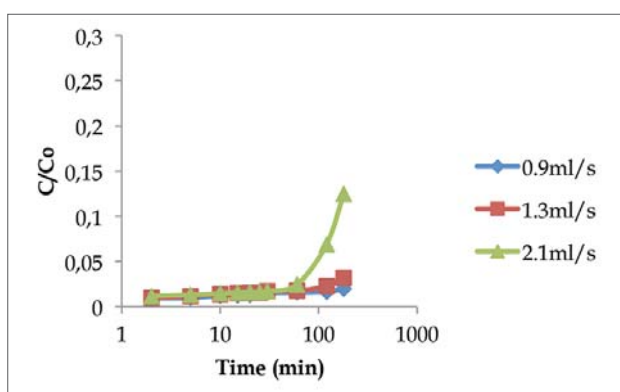| Characteristic	Measured value	USEPA limits	DWAF guideline for industrial disposal
pH	1.8	n/a	5-10
Total conductivity (mS/m)	12,644	n/a	n/a
Colour	Brown	n/a	n/a
COD (mg/l)	200	5	0-75
TSS (mg/l)	1080	4	0-25
TDS (mg/l)	220	50	n/a
TS (mg/l)	1300	n/a	0-1600
Chloride (mg/l)	3497	n/a	0-500
Sulphate (SO$_4$) (mg/l)	10,947	5	0-500
t (NH$_3$) (total ammonia) (mg/l)	79.1	0.01	n/a
Ag (mg/l)	0.004	n/a	n/a
Au (mg/l)	0.015	0.005	n/a
Pd (mg/l)	0.248	0.02	n/a
Pt (mg/l)	1.88	0.1	n/a
Rh (mg/l)	0.065	0.02	n/a
Ir (mg/l)	8.25	0.02	n/a
Ru (mg/l)	0.937	0.1	n/a
Co (mg/l)	0.026	0.005	n/a
Cu (mg/l)	0.275	0.005	0.006
Zn (mg/l)	0.077	0.0002	0.05
Te (mg/l)	1.24	0.02	n/a
Se (mg/l)	416	0.01	0.05
Fe (mg/l)	1.17	0.005	0.0–10.0
Na (mg/l)	45100	0.1	n/a
Ni (mg/l)	2.08	0.005	n/a

Figure 2—Breakthrough curves for palladium adsorption at different flow rates (C_o = 0.248 mg/l, bed height = 13 cm, T = 25°C)

Figure 3—Breakthrough curve for sulphate adsorption at different flow rates (C_o = 10,947 mg/l, flow rate = 0.9 ml/s, T = 25°C)

Figure 4—Breakthrough curve for tellurium adsorption at different flow rates (C_o = 1.24 mg/l, flow rate = 0.9 ml/s, T = 25°C)

elements was not based on any criteria, but is intended as a representation of the whole study, as due to space limitations the breakthrough curves for all the elements studied cannot be included in this manuscript. Figure 2 shows the effect of flow rate on the adsorption of palladium at an inlet metal concentration of 0.248 mg/l. The results show that if the maximum allowable limit for palladium is 0.02 mg/l (Table III), then the breakthrough time occurred at 180 minutes for a flow rate of 0.9 ml/s, 120 minutes for 1.3 ml/s, and 60 minutes for 2.1 ml/s. For a sharp breakthrough to occur at the lower flow rates, and for the bed to be saturated with palladium ions, the adsorption time must be prolonged beyond 180 minutes. Since a longer breakthrough time implies better adsorption capacity, when operating at lower flow rates it would take much longer for the adsorbent to be completely saturated with the adsorbate. It can be inferred from Figure 2 that despite the very low concentration of palladium in the influent, the sorbent has high affinity for palladium.

Figure 3 shows the effect of solution flow rate on the adsorption of sulphate ions at an inlet concentration of 10 947 mg/l .The figure shows that as the flow rate increased, the breakthrough time decreased from 30 minutes to 10 minutes. In addition, despite the high concentration of sulphate ions in solution, saturation of the column could not be achieved, unlike other ions with high concentrations in solution such as Se^{2+}, and Na^+ (data not shown). This may be explained by using the point of zero charge (pHzc) of the yeast. The pHzc of the yeast is 6.31; at pH values lower than this, the surface of the sorbent will be positively charged and will thus attract negatively charged ions. This may be the reason why sulphate ions and metals such as platinum and palladium, which form negative complexes such as chloroanionic complex in solution, were easily adsorbed from the solution regardless of their concentration.

Figure 4 shows the effect of solution flow rate on the adsorption of tellurium at an inlet concentration of 1.24 mg/l. The results show that the breakthrough time decreased from 30 minutes to 10 minutes as the flow rate increased from 0.9 to 2.1 ml/s. In addition, it can be seen that the allowable limit (0.02 mg/l) for tellurium was achievable only at a flow rate of 0.9 ml/s.

Table II summarizes the breakthrough times at different flow rates for the different metals. The overall results show that as the flow rate increased, the breakthrough time decreased.
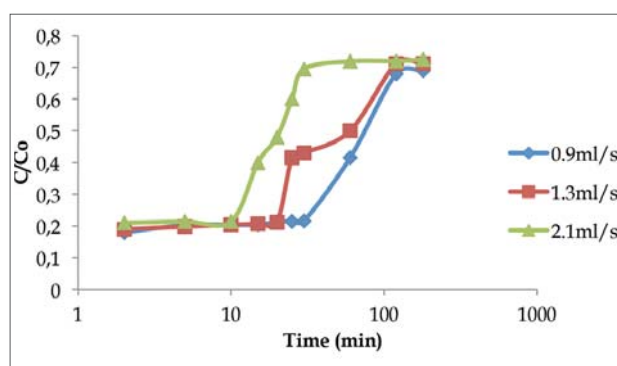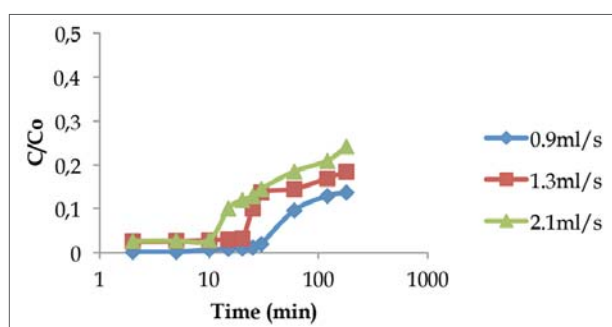
With increased flow rate, the bed utilization, as well as the bed adsorption capacity, will be reduced. This is due to insufficient residence time of the solute in the column, leading to insufficient diffusion of the solute into the pores of the adsorbent. The solute therefore leaves the column before equilibrium is established. These results are in agreement with findings in the literature for systems of biosorption in columns for different metals using different sorbent materials (Calero *et al.*, 2009; Danny, Porter, and McKay, 2000; Khan, Bury, and Hogstrand, 2011). For most of the platinum group metals present in the solution under study, a prolonged residence time, typically more than 180 minutes, is required to reach column saturation, regardless of the flow rate used. The significant difference in breakthrough time for palladium compared with the other PGMs is due to the fact that the sorbent has high affinity for palladium, which is in agreement with the results obtained in the batch studies.

The experimental results indicate that a flow rate of 0.9 ml/s produces a classic breakthrough curve to work with compared to the higher flow rates tested, since a longer breakthrough time indicates higher efficiency of the

Table II

Breakthrough times (minutes) at different flow rates

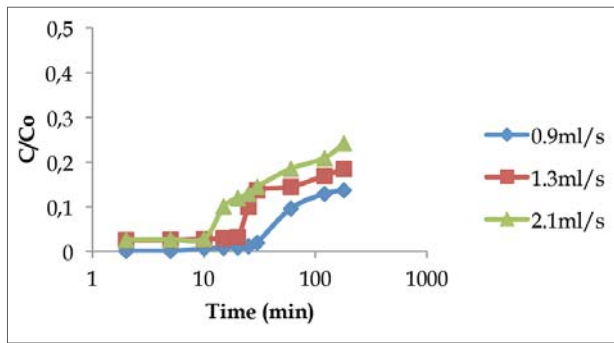| Flow rate	Pt	Pd	Ir	Ru	Se	Te	Ni	Na	SO$_4$	Cl
0.9 ml/s	25	180	25	10	10	30	25	5	30	25
1.3 ml/s	10	120	10	5	2	20	15	2	20	15
2.1 ml/s	5	60	5	2	2	10	10	2	10	5

Figure 5—Breakthrough curve for palladium at different bed depth (C_o = 0.248 mg/l, flow rate = 0.9 ml/s, T = 25°C)

Figure 7—Breakthrough curves for tellurium adsorption at different bed depths (C_o = 1.24 mg/l, flow rate = 0.9 ml/s, T = 25°C)

adsorbent. Therefore, the subsequent experiments were carried out at a flow rate of 0.9 ml/s.

Effect of bed depth

The retention of metal ions in a fixed-bed column depends, among other factors, on the quantity of solid sorbent used or on the bed depth of the column (Calero *et al*., 2009). The sorption performance of plaster of Paris-immobilized yeast was assessed using bed depths of 6.5 cm, 8.5 cm, and 13 cm at flow rate of 0.9 ml/s. Figure 5 shows the effect of bed depth on the sorption of palladium. As the bed height decreased from 13 cm to 6.5 cm, the breakthrough time decreased from 180 minutes to 30 minutes. This is because at lower bed depth there are fewer binding sites, which are quickly taken up by the adsorbing ions.

Figure 6 shows the effect of bed depth on the sorption of sulphate ions. The results similarly show that the breakthrough time increased from 10 minutes to 30 minutes when the bed depth increased from 65 mm to 130 mm.

Figure 7 shows the effect of bed depth on the sorption of tellurium. The breakthrough time increased from 10 minutes to 30 minutes as the bed depth increased from 6.5 cm to 13 cm. The results demonstrate that the adsorbent has a high affinity for tellurium compared to platinum, ruthenium, and nickel, which were also present in lower concentration in the solution.

Table III summarizes the breakthrough times for different metals at different bed depths. Generally, the breakthrough time increased as the bed depth increased from 6.5 cm to 13 cm. Similarly, the time necessary for saturation of the column is higher as the bed depth is increased; in some cases a
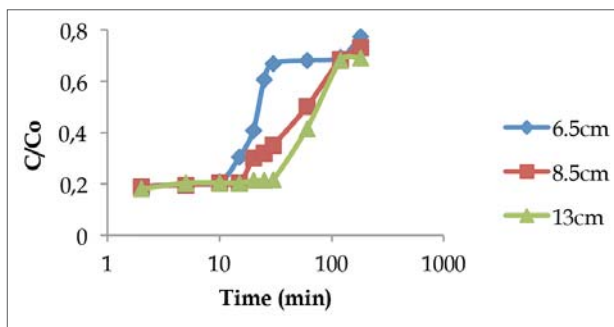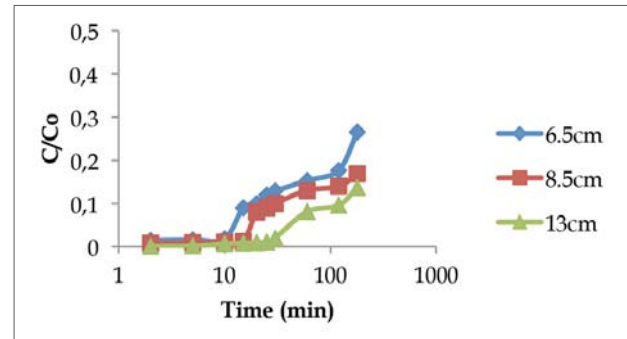
contact time longer than 180 minutes was necessary. Although an increase in bed depth increased the breakthrough time, a very deep bed is not practical for a single column; instead, multiple columns should be designed (Netpradit, Thiravetyan, and Towprayoon, 2004). This is because when the bed height (the adsorbent dosage) increases to a certain level, the adsorption density (the amount adsorbed per unit mass) decreases.

Based on the information in Tables II and III, it is evident from the breakthrough times (t_b values at 0.9 ml/s and 13 cm) that the binding affinity for the PGMs in the solution under study on POP-immobilized yeast follows the order $Pd^{2+}>Pt^{2+}>Ir^{3+}>Ru^{3+}$, while the binding affinity for other elements in the solution follows the order $Te^{2+}>SO_4^{2-}>Ni^{2+}>Se^{2+}>Cl^->Na^+$. Generally, the binding affinity for all the elements follows the order $Pd2+> SO42->Te^{2+}>Pt^{2+}>Ir^{2+}>Ni^{2+}>Cl->Ru^{2+}>Se^{2+}> Na^+$.

Table IV gives the allowable discharge limits of various elements (USEPA, 2010) and the metal concentration at breakthrough point (flow rate 0.9 ml/s and 13 cm bed depth). Most of the elements in the solution did not reach their allowable discharge limit even before breakthrough was achieved, except Pd and Te. Therefore a multiple column is recommended for practical purposes in treating effluents of this nature.

As the concentration of chloride was one of the highest among the contaminating anions, the chloride concentration was also monitored. The chloride concentration decreased in the early stage of treatment (at 0.9 ml/s and 13 cm bed depth), indicating that the column did adsorb chloride ions. Within 20 minutes, the chloride concentration had reached 2098 mg/l, equivalent to 40% removal. It is therefore expected that the use of more columns will inevitably continue to decrease the concentration of anions and other elements in solution, but a decision must be made regarding how many columns would be economically feasible.

Figure 6—Breakthrough curve for sulphate adsorption at different bed depth (C_o = 10,947 mg/l, flow rate = 0.9 ml/s, T = 25°C)

Table III

Breakthrough times (minutes) at different bed depths

Flow rate	Pt	Pd	Ir	Ru	Se	Te	Ni	Na	SO$_4$	Cl
6.5 cm	10	30	10	2	2	10	10	2	10	10
8.5 cm	10	60	15	5	5	15	15	2	15	15
13 cm	25	180	25	10	10	30	25	5	30	25

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Discharge limits (USEPA, 2010) for tested elements in wastewater and breakthrough concentrations

Component	Pt	Pd	Se	Te	Ir	Ru	Na	SO$_4$	Ni	Cl
Limit (mg/l)	0.1	0.02	0.01	0.02	0.02	0.1	0.1	5	0.005	500
Concentration (C$_b$) at breakthrough(mg/l)	0.58	0.005	208	0.025	2.64	0.38	18 085	2 364	0.29	2 098

Once the breakthrough time had been determined, the breakthrough capacity Q_B (the column adsorption capacity at breakthrough point) of the adsorbent was calculated as (Goel *et al.*, 2005):

$$Q_B = \left(\frac{t_b Q_w C_o}{m} \right) \qquad [1]$$

where t_b is the breakthrough time (minutes), Q_w is the flow rate of the influent wastewater (l/min), C_o is the inlet concentration (mg/l), and m is the mass (g) of the adsorbent. In addition, the volume of effluent treated (V_{ef}) at breakthrough was calculated as:

$$V_{ef} = Qt_B \qquad [2]$$

The results presented in Tables V and VI show that, the bed adsorption capacity (Q_b) increases as the flow rate decreases and the bed height increases. However, a slightly

Table V

Adsorption breakthrough data at different flow rates

Metal ion	Q (ml/s)	Q$_b$ (mg/g)	V$_{ef}$ (ml)
Platinum	0.9	0.058	1 350
	1.3	0.034	780
	2.1	0.027	630
Palladium	0.9	0.056	9 720
	1.3	0.053	9 360
	2.1	0.043	7 560
Iridium	0.9	0.258	1 350
	1.3	0.149	780
	2.1	0.12	630
Ruthenium	0.9	0.012	540
	1.3	0.008	390
	2.1	0.005	252
Nickel	0.9	0.065	1 350
	1.3	0.056	11 790
	2.1	0.060	1 260
Selenium	0.9	5.212	540
	1.3	1.500	156
	2.1	2.432	252
Tellurium	0.9	0.046	1 620
	1.3	0.044	1 560
	2.1	0.036	1 260
Sodium	0.9	282.500	270
	1.3	163.230	156
	2.1	263.690	252
Sulphate	0.9	411.460	1 620
	1.3	396.220	1 560
	2.1	320.020	1 260
Chloride	0.9	109.535	1 350
	1.3	94.930	1 170
	2.1	51.112	630

different trend was observed for selenium and sodium with regard to the value of Q_b at different flow rates. The results indicated that the adsorption capacities (Q_b) for selenium and sodium at 2.1ml/s are higher than at 1.3ml/s. This may be a result of the low affinity of the adsorbent for these ions, which results in the same breakthrough value at the two flow rates.

The increase in the bed adsorption capacity (Q_b) with increasing bed depth (Table VI) is due to the increase in the specific surface of the adsorbent, which supplies more fixation binding sites (Taty-Costodes *et al.*, 2005). Furthermore, the results show that an increase in the bed depth with a decrease in flow rate increased the volume of effluent that could be treated effectively before breakthrough. Since industrial effluents contain more than one metal ion in solution, calculating the volume of effluent treated at breakthrough point will give an indication of the volume of solution that can be treated in order for each metal to reach its allowable limit, *i.e.* if the breakthrough time for each metal in the effluent is known, then the volume of effluent that can be treated effectively can be determined. However, a slightly different trend was observed for sodium with regard to the value of Q_b at different bed depths. The adsorption capacity (Q_b) for sodium is higher at 6.5 cm bed depth than at 8.5 cm. This is a result of the close values of the breakthrough times at these bed depths.

Evaluation of kinetic models

The fundamental equations for a fixed-bed column depend on the mechanism responsible for the process (mass transfer from the liquid to the surface of the solid, diffusion and/or reaction on the surface of the solid), and include mass balances between the solid and the fluid and for the sorbed solute, rate of the process, *etc*. The equations derived to model the system with theoretical rigor are differential in nature and their solution usually requires complex numerical methods (Calero *et al.*, 2009; Danny, Porter, and McKay, 2000). Because of this, various simple mathematical models such as Adam-Bohart (Bohart and Adams, 1920), Thomas (Thomas, 1944), Thomas, and Yoon and Nelson (Yoon and Nelson, 1984) have been developed to predict the dynamic behaviour of a column and allow some kinetic coefficients to be estimated. The Adam-Bohart and Thomas models were used in this study to analyse the behavior of the packed column.

The column data fitted better with the Adam–Bohart model than with the Thomas model for all the conditions tested. The results from the model indicated that the greater the bed height, the higher the adsorption capacity, No, of the adsorbent and the lower the mass transfer coefficient, KAB.

Conclusions

The removal of PGMs, as well as base metals and other trace elements, from a dilute industrial PGM solution was

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Table VI

Adsorption breakthrough data at different bed depths

Metal ion	Z (cm)	Q_b (mg/g)	V_{ef} (ml)
Platinum	6.5	0.037	540
	8.5	0.045	540
	13.0	0.058	1 350
Palladium	6.5	0.018	1 620
	8.5	0.029	3 240
	13.0	0.056	9 720
Iridium	6.5	0.198	540
	8.5	0.245	810
	13.0	0.258	1 350
Ruthenium	6.5	0.004	108
	8.5	0.009	270
	13.0	0.012	540
Nickel	6.5	0.050	540
	8.5	0.061	810
	13.0	0.065	1 350
Selenium	6.5	2.000	108
	8.5	4.120	270
	13.0	5.212	540
Tellurium	6.5	0.029	540
	8.5	0.037	810
	13.0	0.046	1 620
Sodium	6.5	217.350	108
	8.5	178.650	108
	13.0	282.530	270
Sulphate	6.5	263.780	540
	8.5	325.240	810
	13.0	411.460	1 620
Chloride	6.5	84.265	540
	8.5	103.898	810
	13.0	109.535	1 350

investigated using *Saccharomyces cerevisiae* waste yeast immobilized on plaster of Paris support material in a packed column. Dynamic adsorption conditions such as bed height (Z), and solution flow rate (Q) were tested to establish their influence on the purification process. The packed bed column was found to perform better with lower influent rate and greater bed depth. In addition, it was found that for the bed to reach saturation for most of the metals, an adsorption time greater than 180 minutes was necessary. Successful selective binding and recovery of metal from the mixed metal solutions depended on the binding affinity of the metals, which followed the order $Pd^{2+}>SO_4^{2-}>Te^{2+}>Pt^{2+}>Ir^{2+}>Ni^{2+}>Cl^->Ru^{3+}>Se^{2+}> Na^+$.

The study showed that if multiple fixed-bed columns are used, all the valuable metals can be recovered, and the concentration of other contaminants like sulphate, chloride, and sodium reduced to meet the Department of Water Affairs and Forestry (1996) guidelines for industrial water re-use. The purified stream could be used for dust suppression, firefighting, ash quenching, and irrigation *etc*. In light of continued population growth, ongoing contamination of both ground and surface waters, uneven distribution of water resources, and periodic droughts, consideration must be given to purifying industrial water. The recycling of the purified waste stream within the refinery would constitute a considerable saving in terms of water required from surrounding municipalities, which are already struggling to provide enough water.

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