

คณะวิศวกรรมศาสตร์
มหาวิทยาลัยสงขลานครินทร์

การสอบปลายภาคการศึกษาที่ 2

ปีการศึกษา 2547

วันอาทิตย์ที่ 27 กุมภาพันธ์ 2548

เวลา : 13.30-16.30 น.

วิชา : 235-322 : Mineral Processing II

ห้อง : A 201

คำชี้แจง

1. ข้อสอบมีทั้งหมด 6 ข้อ และข้อ 6 เป็นข้อโบนัสจะทำหรือไม่ก็ได้
คะแนนทั้งหมด 40 %
2. ห้ามนำเอกสารใดๆ เข้าห้องสอบ แต่สามารถนำเครื่องคิดเลขไม่จำกัด
รุ่นเข้าห้องสอบได้
3. ให้ตอบคำถามในกระดาษข้อสอบนี้

ชื่อ _____ รหัส _____

| ข้อ | คะแนนเต็ม | คะแนนที่ได้ |
|-----------|-----------|-------------|
| 1 | 15 | |
| 2 | 25 | |
| 3 | 25 | |
| 4 | 20 | |
| 5 | 25 | |
| 6 (โบนัส) | 15 | |
| รวม | 110 | |

ชื่อ _____ รหัส _____

1.3 การแต่งแร่ด้วยแบคทีเรีย

2. (25 คะแนน) จงอธิบายและยกตัวอย่างกระบวนการ

2.1 Coagulation และ Flocculation

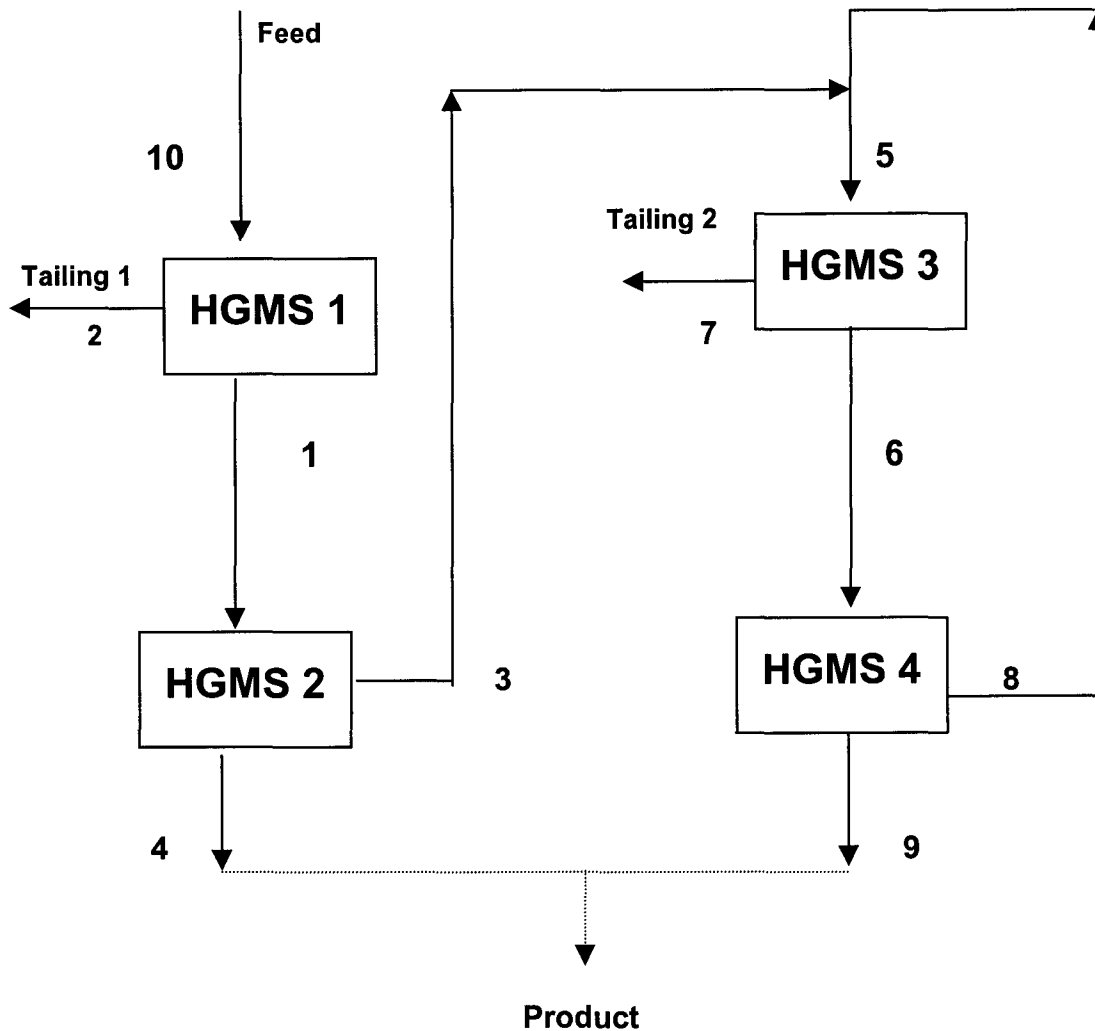
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2.2 จงอธิบายว่าทำไมอนุภาคเคลย์ (Clays) เมื่ออยู่ในสภาพ Slurry จึงเกิด Agglomeration และถ้าเติมโซเดียมซิลิเกต 0.2 % โดยน้ำหนัก หรือสารส้ม 0.01 % โดยน้ำหนักลงไปจะเกิดอะไรขึ้น

2.3 จงออกแบบการแต่งแร่ของสินแร่ที่ประกอบด้วยแร่ไพไรต์ 10 % ซิลิกา 10 % ดีบุก 15 % อิลมิไนต์ 35 % โมนาไซต์ 5 % เซอร์คอน 10 % รูไทล์ 10 % และการ์เนต 5 %

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3. (25 คะแนน) จาก Flowchart ของการแยกแร่ฟอสเฟตออกจากหิน Pyroxenite ด้วยเครื่องแยกแม่เหล็กชนิด H.G.M.S. ข้างล่างเพื่อแต่งแร่ให้ได้หัวแร่ P_2O_5 36.5 % เมื่ออัตราป้อนแร่เข้าสู่วงจรเท่ากับ 1,000 t/h ด้วยเกรด 7.2 % P_2O_5



| Streams | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|------------|------|-----|-----|------|-----|------|-----|-------------|------|
| % P_2O_5 | 13.1 | 1.3 | 9.5 | 36.5 | 9.5 | 14.8 | 1.6 | Not sampled | 36.5 |

ชื่อ _____ รหัส _____

- 3.1 จงเขียนเป็น Simple node form และให้ Feed เป็น Stream สุดท้าย
- 3.2 จงเขียน connection matrix และคำนวณจำนวน Stream ที่น้อยที่สุดที่ต้องเก็บตัวอย่าง
- 3.3 จงเขียน material matrix และ Component matrix ทั้งหมดที่เป็นไปได้
- 3.4 จงเขียน Matrix รวมทั้งหมด
- 3.5 จงหาค่าอัตราการไหล (t/h) ของทุก Stream

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4. การวิเคราะห์ความเหมาะสมของวงจร

4.1 (10 คะแนน) จากการศึกษาการแยกแยะบอร์ดวงจรด้วยวิธีแม่เหล็กและไฟฟ้าสถิต (ตามเอกสารที่แนบด้านหลัง) จงวิเคราะห์กระบวนการและความเหมาะสมในวงจร สรุปผลที่ได้ให้ชัดเจน

ชื่อ _____ รหัส _____

4.2 (10 คะแนน) ในการผสมแร่เฟลด์สปาร์เพื่อเป็นวัตถุดิบของอุตสาหกรรมเซรามิก จงเขียนสมการ เชิงเส้นในการผสมเฟลด์สปาร์ 5 ชนิด โดยคำนวณปริมาณแร่แต่ละกองที่นำมาผสมกันให้ได้องค์ประกอบตามต้องการดังนี้

1. ปริมาณแร่ที่ต้องการ = 100 หน่วยน้ำหนัก
2. % Al_2O_3 = 25 %
3. % SiO_2 = 65 %
4. % Na_2O = 10 %
5. จุดประสงค์คือ ให้ราคาแร่รวมที่ได้ต่ำสุด (Minimization) ≤ 140 บาท/หน่วยน้ำหนัก

ผลวิเคราะห์ทางเคมีของแร่แต่ละกองเป็นดังนี้

| | กองที่ 1 | กองที่ 2 | กองที่ 3 | กองที่ 4 | กองที่ 5 |
|---------------------------|----------|----------|----------|----------|----------|
| % Al_2O_3 | 31 | 22 | 24 | 29 | 23 |
| % SiO_2 | 65 | 73 | 65 | 61 | 69 |
| % Na_2O | 4 | 5 | 11 | 12 | 8 |
| ราคาแร่ต่อหน่วยน้ำหนัก | 110 | 120 | 180 | 200 | 140 |

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5. (25 คะแนน) ในกระบวนการแต่งแร่แบบเปียก แร่ที่ไหลออกมาจากถังเกอร์อะมี % Solid 65 % จะต้องนำไปผ่านกระบวนการต่างๆ เพื่อให้แห้ง (ความชื้น < 10 %)
- 5.1 จงออกแบบกระบวนการเพื่อให้แร่แห้งตามวัตถุประสงค์ดังกล่าว โดยจะต้องระบุเครื่องมือที่ใช้ พร้อมอธิบายการทำงานมาให้เข้าใจ
- 5.2 กระบวนการที่เลือกในข้อ 5.1 มีแฟคเตอร์ที่ควบคุมการทำงานอะไรบ้าง มีข้อระมัดระวังเรื่องใดบ้าง
- 5.3 ท่านจะมีวิธีลดค่าใช้จ่ายของกระบวนการที่ท่านเลือกในข้อ 5.1 ให้น้อยที่สุดได้อย่างไร จงอธิบาย

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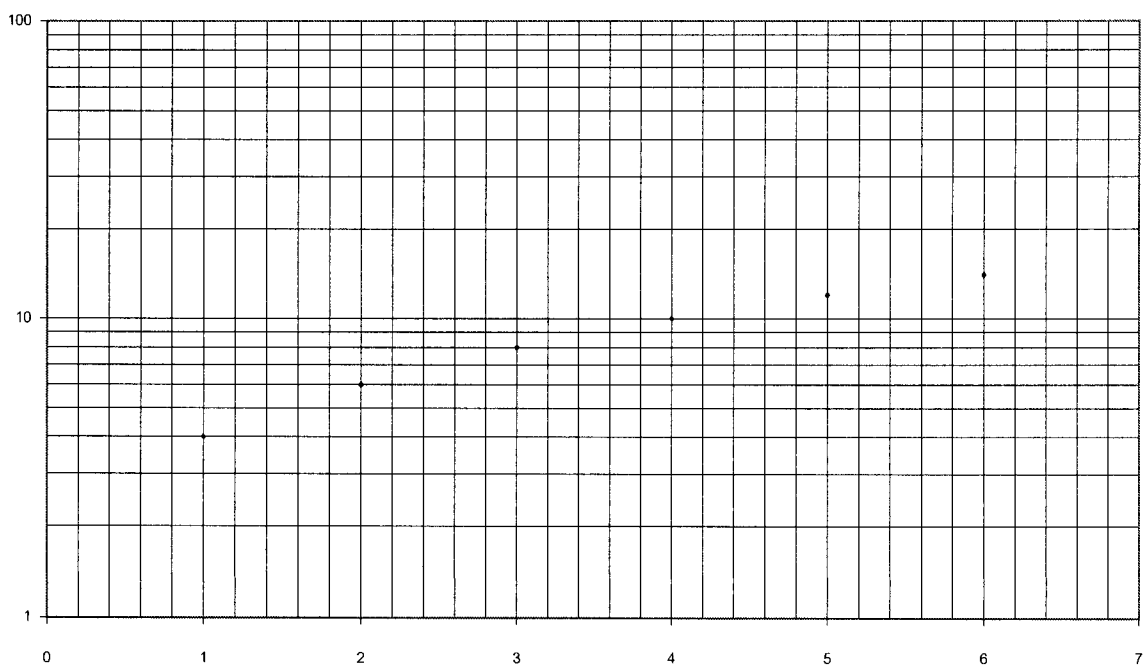
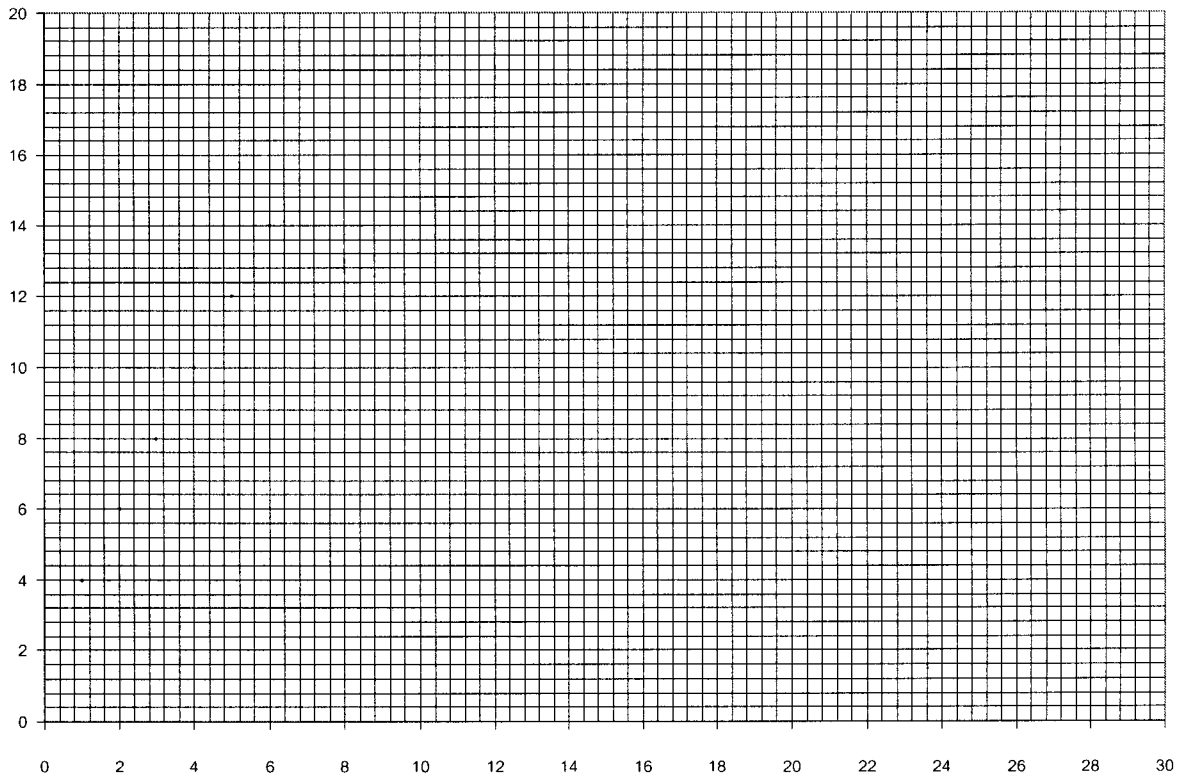
5.4 ในกระบวนการแต่งแร่ สฟาลอไรต์ ซึ่งเป็นกระบวนการเปียกในขั้นตอนสุดท้าย ต้องใช้วิธีการเกราะเพื่อแยกน้ำใสออกมา จึงได้มีการทดสอบการตกตัวได้ผลตามตารางที่ 5.4.1 สำหรับของผสมป้อนประกอบด้วยมวลของแข็ง 200 กรัม ใส่ในกระบอกตวง 1 ลิตร (สูง 40 ซม.) แล้วใส่น้ำให้ได้ปริมาตรทั้งหมดเป็น 1 ลิตร โดย ถ.พ. ของอนุภาค = 3.5 กรัม/ลบ.ซม.

ตารางที่ 5.4.1 แสดงข้อมูลการตกตัวของอนุภาคตัวอย่าง

| Time T (Hrs) | Height of Interphase H, Cms | | | | | | | | |
|--------------|-----------------------------|--|--|--|--|--|--|--|--|
| 0 | 40 | | | | | | | | |
| 0.2 | 35 | | | | | | | | |
| 0.4 | 29 | | | | | | | | |
| 0.6 | 24 | | | | | | | | |
| 1.0 | 16 | | | | | | | | |
| 1.4 | 12 | | | | | | | | |
| 2.0 | 9 | | | | | | | | |
| 3.0 | 7 | | | | | | | | |
| 4.0 | 6.5 | | | | | | | | |
| 5.0 | 5.8 | | | | | | | | |
| 5.5 | 5.7 | | | | | | | | |
| 6.0 | 5.6 | | | | | | | | |
| H_{∞} | 5.5 | | | | | | | | |

- 5.4.1 จงหาความเข้มข้นของของผสมเริ่มต้นในกระบอกตวง เป็นหน่วยกรัม/ลิตร และ % Solids โดยน้ำหนัก
- 5.4.2 คำนวณพื้นที่ของถังเกราะจากข้อมูลในตารางที่ 5.4.1 โดยวิธีของ Kynch เมื่อของผสมถูกเกราะจนให้ได้ 70 % Solids โดยน้ำหนัก ถ้าปริมาณแร่ที่ต้องเกราะในแต่ละวัน = 60 ตัน
- 5.4.3 คำนวณความลึกของ Compression zone
- 5.4.4 จงอธิบายการเกราะดินขาวให้เร็วขึ้นโดยใช้สารส้ม

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6. ข้อโบนัส (15 คะแนน)

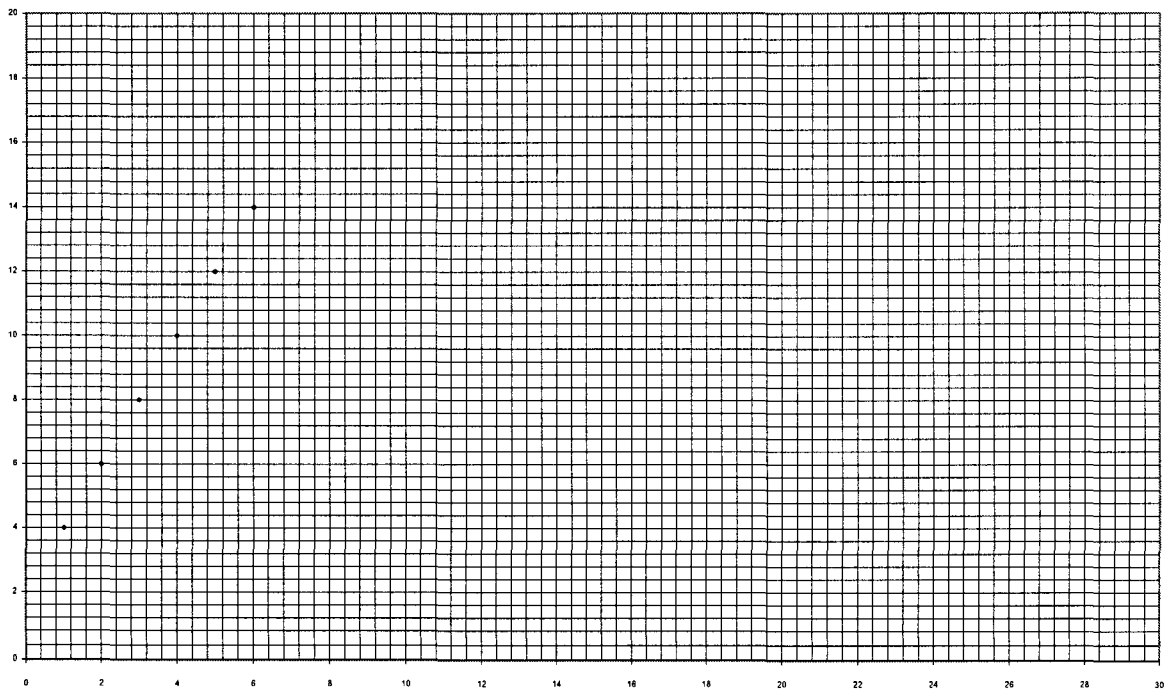
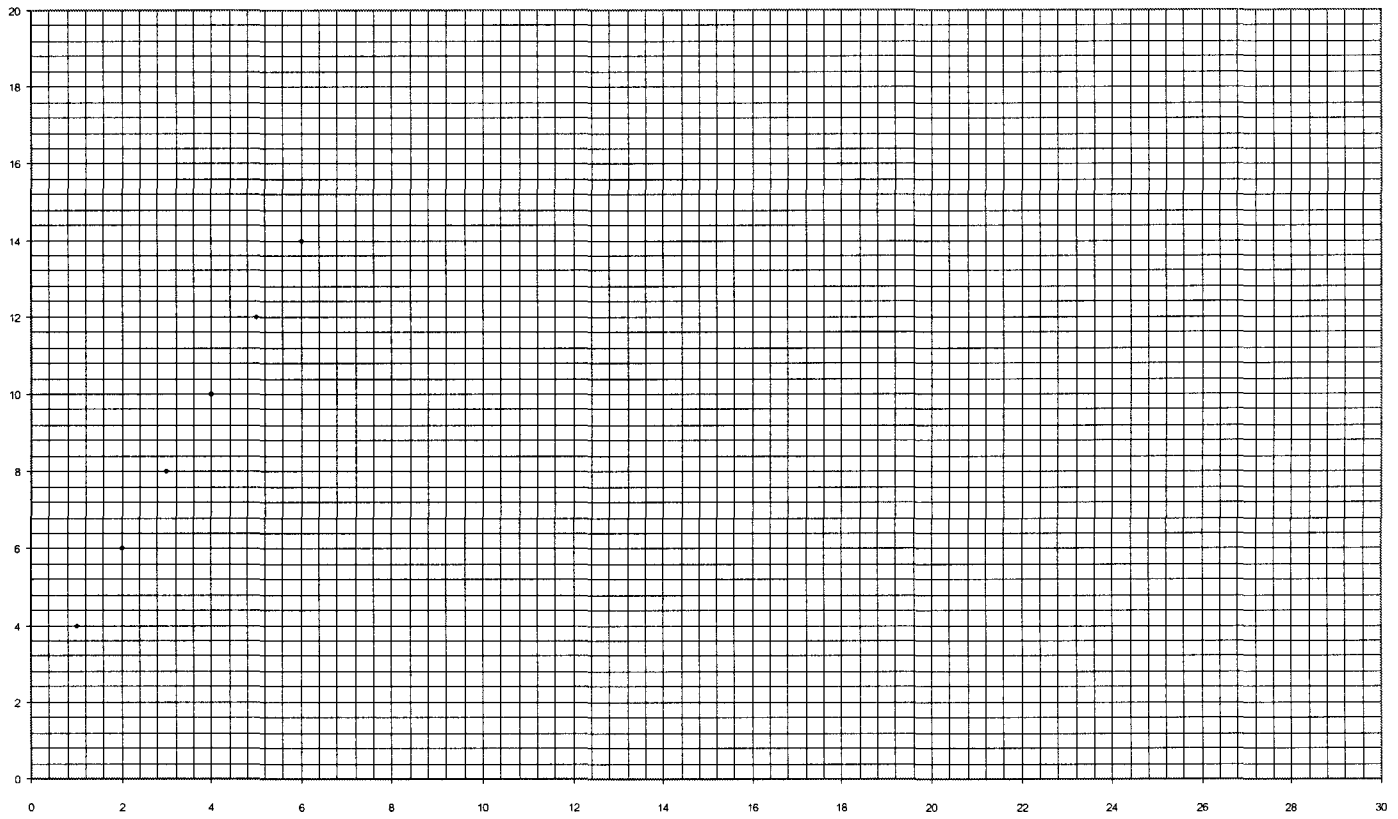
จากข้อมูลการทดสอบการกรองโดยใช้ความดัน 3 ค่า แล้ววัดปริมาณน้ำที่เทียบกับเวลา ดังตาราง

| $\Delta P_1 = 1.8 \times 10^5 \text{ N/m}^2$ | | $\Delta P_2 = 2.2 \times 10^5 \text{ N/m}^2$ | | $\Delta P_3 = 2.5 \text{ N/m}^2$ | |
|--|-----------------|--|-----------------|----------------------------------|-----------------|
| $V (x10^{-6}), \text{ m}^3$ | $t \text{ (s)}$ | $V (x10^{-6}), \text{ m}^3$ | $t \text{ (s)}$ | $V (x10^{-6}), \text{ m}^3$ | $t \text{ (s)}$ |
| 400 | 50 | 400 | 40 | 400 | 30 |
| 800 | 54 | 800 | 45 | 800 | 36 |
| 1200 | 59 | 1200 | 51 | 1200 | 43 |
| 1600 | 65 | 1600 | 58 | 1600 | 51 |
| 2000 | 72 | 2000 | 66 | 2000 | 60 |
| $C_1 = 1710 \text{ kg/m}^3$ | | $C_2 = 1650 \text{ kg/m}^3$ | | $C_3 = 1600 \text{ kg/m}^3$ | |

6.1 สมมติเส้นผ่านศูนย์กลางของกระดาษกรอง 40 cm และ $\mu = 1$ จงหา R_m และ α

6.2 จงหาสัมประสิทธิ์ความอัดแน่น, S

ชื่อ _____ รหัส _____



สูตรที่มีประโยชน์

$$\frac{dt}{dv} = \frac{\mu \alpha^2}{A^2 (\Delta P)} V + \frac{\mu R m}{A (\Delta P)}$$

$$\alpha = \alpha_0 (\Delta P)^S$$

$$A = m / H_0 C_0$$

$$d = t (\bar{x} + 1) / 24 A \bar{\rho}$$

$$\text{Dilution ratio} = \frac{\text{มวลของเหลว}}{\text{มวลของแข็ง}}$$



Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap

H.M. Veit^{a,*}, T.R. Diehl^a, A.P. Salami^a, J.S. Rodrigues^a, A.M. Bernardes^a,
J.A.S. Tenório^b

^a LACOR-PPGEM, Universidade Federal do Rio Grande do Sul, Brasil Av. Osvaldo Aranha 99/706, 90035-190 Porto Alegre - RS, Brazil

^b PMT-EPUSP, Universidade de São Paulo, Brasil Av. Prof. Mello Moraes, 2463, 05508-900 São Paulo - SP, Brazil

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1. Introduction

The quantity of electro/electronic equipment produced nowadays is very high and it has been constantly increasing due to the growth in the consumption of these goods by the population as well as the relatively short lifetime of this equipment.

On the basis of its high electrical conductivity, copper is the one of the basic materials of electrical engineering technology.

Bertram et al. (2002) studied the waste management system, especially the copper cycle in Europe, and they affirm that wastes from electrical and electronic equipment (WEEE) are the fastest growing waste category; this finding emphasizes the need for efficient WEEE recycling strategies.

In western Europe, 6 million ton of electric and electronic waste were generated in 1998. The amount of this waste is expected to increase by at least 3–5% per annum (Forssberg and Cui, 2003). According to Bertram et al. (2002), the generation of WEEE is around 7 kg per capita per year in Europe. In the USA, a recent study predicted that over 315 million computers would be at the end of their life by the year 2004 (Forssberg and Cui, 2003).

In Taiwan, in terms of industries producing post consumer wastes, the top three are electronics and electrical engineering industries, with 630.000 ton (43%), chemicals with 450.000 ton (31%) and metal industries with 200.000 ton (14%) (Wei, 2000).

The recycling of this scrap is still quite limited due to the heterogeneity of the materials present on the product and the complexity of the production of this equipment.

Printed circuit boards are part of this equipment and their composition is quite varied, containing polymers,

* Corresponding author. Tel./fax: +55 51 33163349.

E-mail address: hugomarcelo@zipmail.com.br (H.M. Veit).

ceramics and metals. The metal content is around 28% (copper: 10–20%, lead: 1–5%, nickel: 1–3%). The content of the most important materials remaining is: plastics 19%, bromine (especially as flame-retardant) 4%, glass and ceramics 49% (Ludwig et al., 2003). In addition, there are also considerable quantities of toxicologically relevant substances, such as the flame-retarding “synergist” antimony trioxide, which is suspected to be carcinogenic, as well as precious metals (in decreasing order: silver, platinum metals like palladium, gold, to a total of ≈ 0.3 –0.4%).

Aside from the special case of precious metals, copper in circuit boards is economically the most interesting metal for recovery and use as a secondary raw material because of its relatively high content compared to the corresponding content in explorable ores and its economic value. Copper recovery is also of ecological importance because of the relatively high copper content in comparison to the earth’s crust composition and the corresponding low acceptable concentration limits, concerning leachate from landfills (Ludwig et al., 2003). Nevertheless, the contents of some chemical elements are much higher than in earth’s crust, especially of some harmful chemical elements like bromine, antimony, cadmium and lead.

In addition to these inorganic elements, the following important organic compounds are found in circuit boards: isocyanates and phosgene from polyurethanes, acrylic and phenolic resins, epoxides and phenols, such as chip glues (Ludwig et al., 2003). Therefore, the circuit boards cannot be considered inert materials and are not suited for direct disposal in landfills.

The existing processes of recycling printed circuit boards use pyrometallurgical (Felix and Riet, 1994; Schichang et al., 1994; Bernardes et al., 1997; Szczygiel et al., 1998) or hydrometallurgical methods (Gloe et al., 1990; Pozzo et al., 1991; Hoffmann, 1992; Shibata and Matsumoto, 1999; Marca et al., 2002), which generate atmospheric pollution through the release of dioxins and furans (Menad et al., 1998) or high volumes of effluents.

Some authors are using mechanical processing (Zhang and Forssberg, 1997; Tenório et al., 1997; Noakes, 1999; Veit et al., 2002a) as an alternative to concentrate the metals in a fraction and the polymers and ceramics in another. The metal concentrate fraction can be sent to electrochemistry processes (Brown, 1992; Scott et al., 1997; Fornari and Abbruzzese, 1999; Kékesi et al., 2000; Brandon et al., 2002; Ubaldini et al., 2003) in order to separate the metals among themselves.

This work intends to study magnetic and electrostatic separation processes in order to obtain fractions with higher metals concentration, especially copper, from printed circuit boards scrap, previously comminuted and separated by size.

2. Experimental

In this work, mechanical processing was used as an alternative to processes that are usually used (thermal and hydrometallurgical processes) to the recycling of copper. This was done in order to concentrate metals in a fraction and polymeric and ceramic materials in another, without great amount of energy consumption and atmospheric pollution generation, case of thermal processes, or great amount of effluents generation, case of hydrometallurgical processes.

The steps of mechanical processing used in this work were comminution, size separation, magnetic separation and electrostatic separation.

All experiments were conducted at least two times and the analysis show an experimental error always smaller than 5%.

2.1. Preparation, comminution and size separation

Particle size, shape and liberation degree play crucial roles in mechanical recycling processes. Almost all mechanical recycling processes have a certain effective size range (Forssberg and Cui, 2003).

Printed circuit board scrap used in this work originated from damaged or obsolete personal computers. About 3 kg of whole printed circuit boards as well as 4 kg of electronic components were used. By previous experiences, we accepted these as a representative sample to this study, since there are no great differences in copper content between printed circuit boards in new and older personal computers (Angerer et al., 1993; Veit et al., 2002a,b). Each motherboard of personal computers weighs 500 g on average. With 3 kg of printed circuit boards, we are working with scrap of six personal computers. The average metal composition found in printed circuit boards was previously studied (Veit et al., 2002a). The copper content of this scrap is on average 12.5%. Besides this scrap contains 4.0% tin and 2.7% lead.

The electronic components used in this work were removed from the substrata, to which they were welded, by heating the printed circuit boards and consequently melting the Pb–Sn weld. This way we obtained two types of samples:

- Entire printed circuit boards (containing also electronic components) (PCB): ± 3 kg.
- Electronic components (just the electronic components) (EC): ± 4 kg.

These two types of samples were used in order to evaluate two different possibilities of obtaining the scrap. The first one occurs with post consumer (defective or obsolete) personal computers. The second sample could be generated with residues of the production line,

when defects are detected or some project changes are necessary.

Both types of samples were comminuted separately in a cutting mill until the fractions reached particle sizes smaller than 1 mm. The scrap was comminuted below 1 mm to warrant an excellent grade of release from metals (Zhang and Forssberg, 1997).

The samples were separated by particle size into three different fractions: F1 < 0.25 mm; 0.25 < F2 < 0.50 mm and 0.50 < F3 < 1.00 mm.

The chemical composition of the scrap studied is presented in Table 1 (for the entire printed circuit boards) and in Table 2 (for the electronic components). From the data in the tables, it is possible to say that copper is the main element present in printed circuit board scrap, reaching 24% in F3 of whole printed circuit board and 30% in F3 of electronic components.

Lead, tin and aluminum also have significant concentrations: 3.2% lead in electronic components, 4.9% tin in electronic components and 3.0% aluminum in whole printed circuit board.

2.2. Magnetic separation

When a magnetisable particle is placed in a magnetic field, it is acted upon by a magnetic force. Various classification schemes of magnetic separators have been introduced and probably the most practical and logical one is that which classifies separators as either dry or wet.

The equipment used was a dry magnetic separator, with a maximum magnetic field of 6500 G. A dry separator was chosen since for this type of residue the operation is easier; in addition the scrap was hydrophobic and would therefore, make the use of a wet separator more difficult.

A dry magnetic separation process was applied to each fraction of each sample, using, on average, a magnetic field from 6000 to 6500 G. A magnetic field close to the maximum capacity of the equipment was chosen to guarantee that all magnetic material was separated, since due to the small amount (in terms of mass) the

Table 1
Chemical composition of complete printed circuit boards after comminution and particle size separation (Veit et al., 2002b)

| Chemical composition (%) | F1 | F2 | F3 |
|--------------------------|------|-------|-------|
| Copper | 6.28 | 23.53 | 24.34 |
| Iron | 0.13 | 0.13 | 0.18 |
| Aluminum | 3.01 | 1.55 | 1.56 |
| Nickel | 0.05 | 0.20 | 0.20 |
| Lead | 0.35 | 0.95 | 1.35 |
| Tin | 2.51 | 2.50 | 2.51 |

F1 < 0.25mm; 0.25 < F2 < 0.50 mm; 0.50 < F3 < 1.00 mm.

Table 2
Chemical composition for electronic components after comminution and particle size separation (Veit et al., 2002b)

| Chemical composition (%) | F1 | F2 | F3 |
|--------------------------|------|-------|-------|
| Copper | 9.68 | 17.25 | 30.15 |
| Iron | 0.28 | 0.10 | 0.80 |
| Aluminum | 2.06 | 1.62 | 0.92 |
| Nickel | 0.40 | 0.31 | 0.60 |
| Lead | 2.34 | 3.18 | 2.78 |
| Tin | 3.83 | 4.78 | 4.92 |

F1 < 0.25mm; 0.25 < F2 < 0.50 mm; 0.50 < F3 < 1.00 mm.

magnetic material could be dragged with other non-magnetic materials present in the scrap.

The main application of dry magnetic separators is either the removal of tramp iron and strongly magnetic impurities or the concentration of a strongly magnetic valuable component (Svoboda and Fujita, 2003).

In this stage, we obtained a magnetic fraction and a non-magnetic fraction. The non-magnetic fraction was transported to an electrostatic separator that would separate conducting from non-conducting materials.

2.3. Electrostatic separation

The electrostatic separators were initially developed to recover non-ferrous metals from shredded automobile scrap or for the treatment of municipal solid waste, but are now widely used for other purposes including foundry casting sand, polyester polyethylene terephthalate (PET), electronic scrap, glass cullet, shredder fluff, and spent potliner.

The electrostatic separator segregates conducting of non-conducting materials. The equipment includes two electrodes of continuous current, one of induction and another of attraction. The extreme difference in the electrical conductivity or specific electrical resistance between metals and non-metals provides an excellent condition for the successful implementation of a corona electrostatic separation in waste recycling. This separation has been mainly utilized for the recovery of copper or aluminum from chopped electric wires and cables, and the recovery of copper and precious metals from printed circuit board scrap.

The electrostatic separator used was the Model ES 1010 produced by Equimag. Fig. 1 shows schematically the operation of the electrostatic separator.

In this work, the electrostatic separator was controlled as follows:

- Ionizing electrode: distance of rotor = 25 cm and angle = 80°.
- Static electrode: distance of rotor = 25 cm and angle = 52.5°.
- Rotation of the rotor: 85 rpm.
- Source of high tension: 45–46 kV.

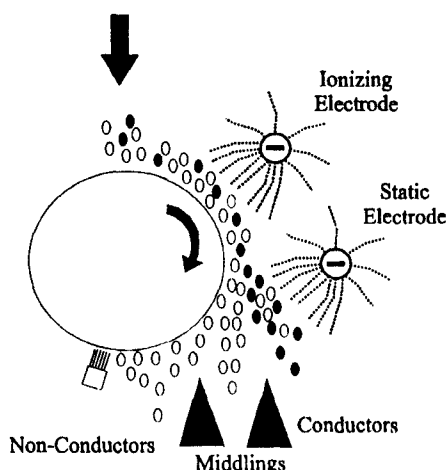


Fig. 1. Operation of an electrostatic separator.

The initial parameters were chosen according to studies by Zhang and Forsberg (1998). Some adjustments were done in order to achieve better results, what was observed by practical experiments.

A conductive fraction and a non-conductive one resulted from the electrostatic separation. The flow chart (Fig. 2) shows schematically all of the experimental steps of this work.

The magnetic, conductive and non-conductive samples were dissolved with aqua regia and after were chemically analyzed by means of atomic absorption spectrometry (AAS).

3. Results

3.1. Magnetic separation

The results are presented in Fig. 2, which shows quantities (mass) of magnetic material and non-magnetic material in each fraction after magnetic separation for whole printed circuit board and electronic components. Fig. 3 presents the contents of Fe, Ni, Cu and Pb after chemical analysis. The metals that should be analyzed were chosen as follows: in Fe

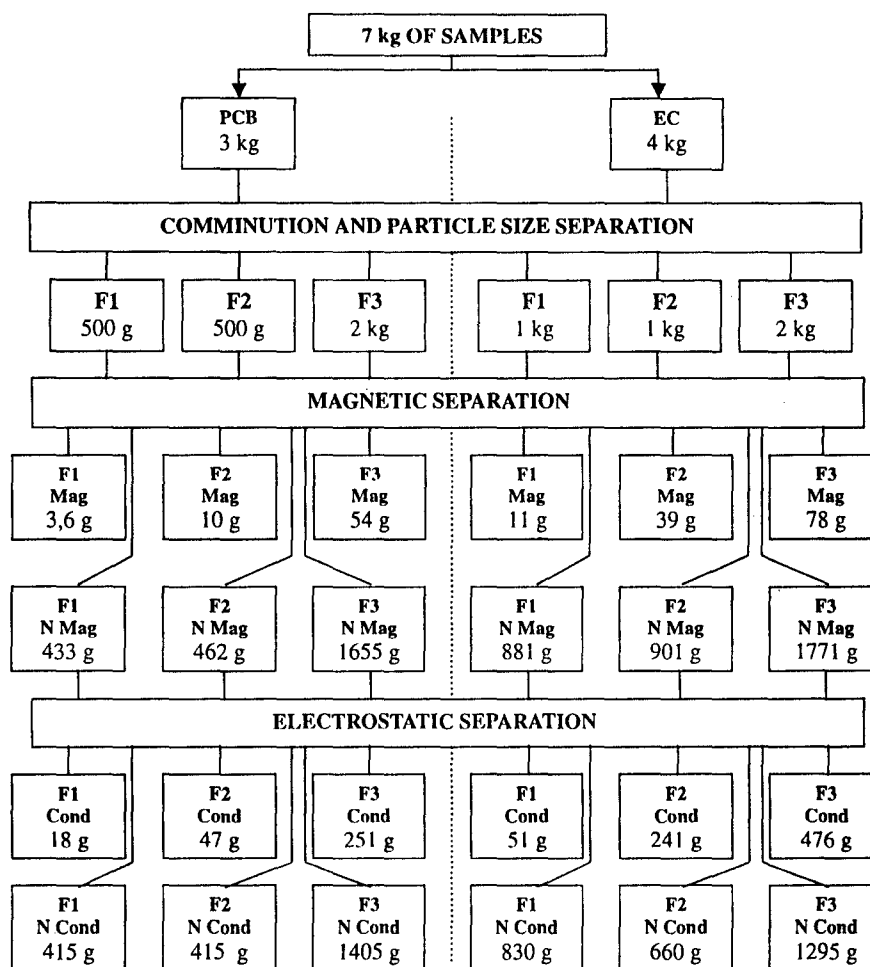


Fig. 2. Flowchart of the printed circuit board scraps recycling process. Mag, magnetic; N Mag, non-magnetic; Cond, conductive; N Cond, Non-conductive; PCB, printed circuit board; EC, electronic components; F1, $f < 0.25$ mm; F2, $0.25 < f < 0.50$ mm; F3, $0.50 < f < 1.0$ mm.

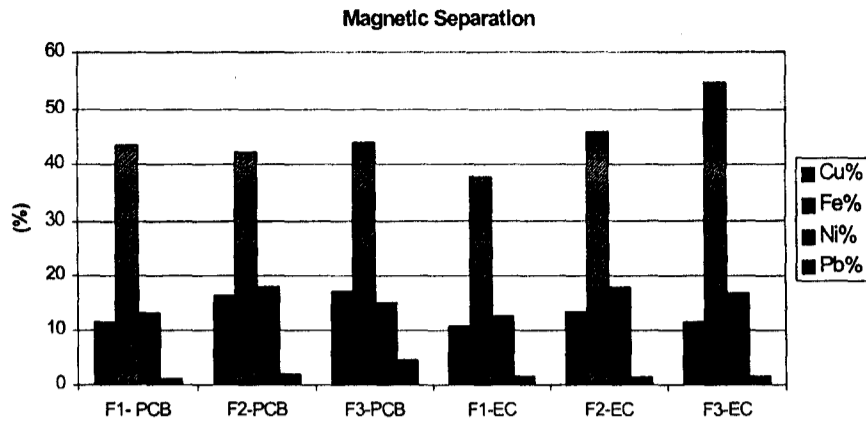


Fig. 3. Chemical analysis of the magnetic fractions after magnetic separation.

and Ni cases, because they are ferromagnetic, they should be present after a magnetic separation; in the case of Cu, since this is the most commonly present element in printed circuit boards and the main metal studied in this work; in the case of Pb, because it could turn the waste of our recycling process into a hazardous waste.

3.2. Electrostatic separation

Fig. 2 presents quantities (mass) of conductive and non-conductive materials in each fraction after an electrostatic separation for whole printed circuit board and electronic components. The following figures present the percentages of conductive materials in each

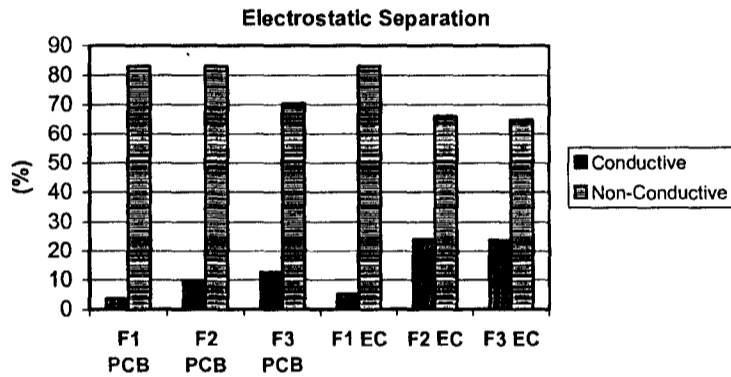


Fig. 4. Percentage of conductive and non-conductive materials after electrostatic separation.

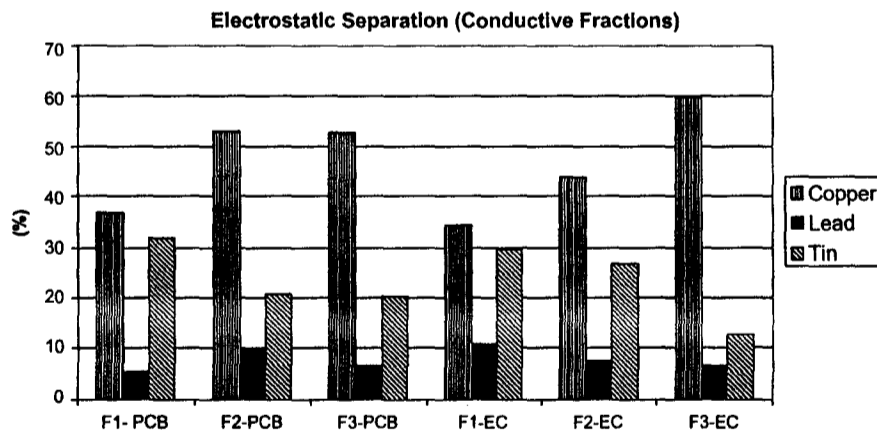


Fig. 5. Chemical analysis of the conductive fractions after electrostatic separation.

lysis of non-conductive fractions.

The concentration of iron in the magnetic fractions were, on average, 43% for whole printed circuit boards.

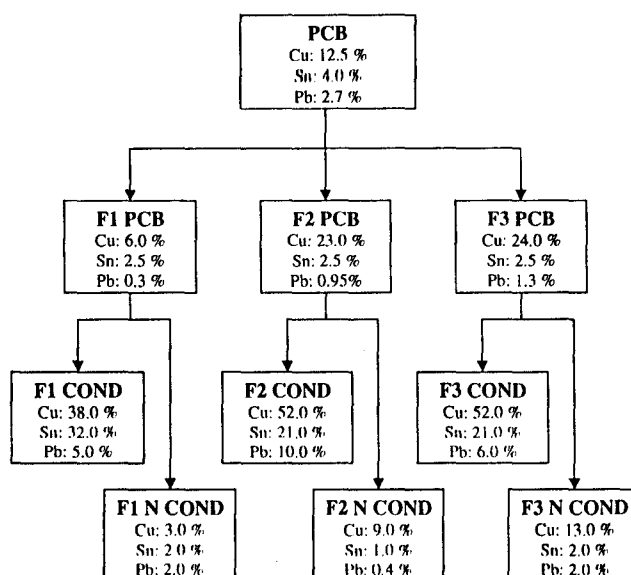


Fig. 6. Flowchart of enrichment/depletion of copper, tin and lead in the fractions as compared to the input.

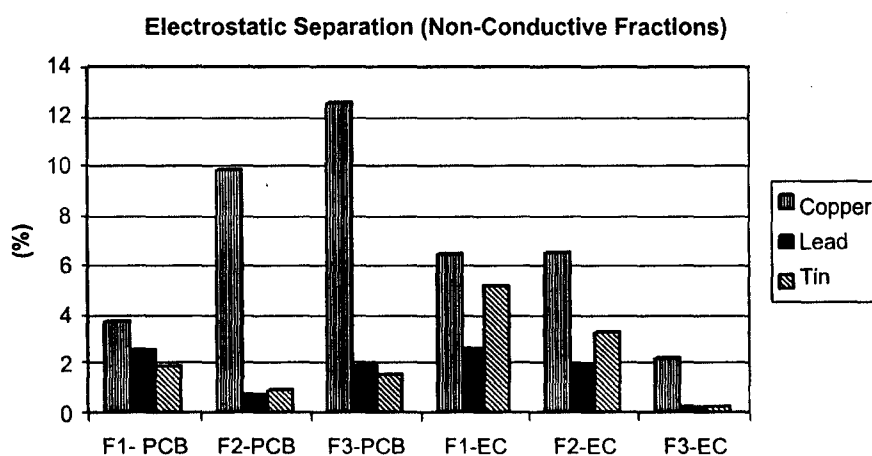


Fig. 7. Chemical analysis of the non-conductive fractions after electrostatic separation.

fraction (Fig. 4) and the contents of metals obtained after electrostatic separation (Figs. 5 and 6). The metals to be analyzed were chosen because they are good conductors and also because they are the metals with the highest content found in the printed circuit boards (compare Tables 1 and 2).

Fig. 5 presents the contents of Cu, Pb and Sn on the conductive fractions and Fig. 6 shows the chemical analysis of non-conductive fractions.

Although the amount of magnetic material present in printed circuit boards is small, it is interesting to separate it previously, in order to obtain conductive fractions with higher copper content. The largest amount of magnetic material in whole printed circuit boards was obtained for the fraction F3: 54 g in 2 kg of samples. In electronic components 78 g in 2 kg was obtained for the fraction F3 (Fig. 2).

The concentration of iron in the magnetic fractions were, on average, 42% for whole printed circuit boards.