An integrated mineral processing pilot plant practical programme designed for heavy mineral sands beneficiation

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The Western Cape Mineral Processing Facility (WCMPF) is a collaborative educational initiative between the Department of Process Engineering at the University of Stellenbosch and the Chemical Engineering Departments at the University of Cape Town and the Cape Peninsula University of Technology. The primary objective of the WCMPF is to facilitate the education, development and graduation of suitably qualified engineering graduates and diplomats for the mining and mineral processing industries.

In recent years the WCMPF has embarked on a number of initiatives aimed at improving the quality of mineral processing education which include, more importantly the introduction of novel ‘end to end’ or ‘integrated’ practicals. The practicals are developed around a specific mineral theme or route, which more than often includes the development of several new pilot plant practicals demonstrating key unit operations or processes in the selected mineral theme or route.

The most recent mineral processing pilot plant practical programme is developed around the beneficiation of heavy mineral sands. The programme consists of the following developed pilot plant practicals: the online electrostatic separation of free flowing mineral sands using a Roche Mining Carrara high-tension roll separator incorporating a Blue Cube Systems MQi in-line mineral quantifier; the production of titania-rich slag and pig iron from the smelting of ilmenite and anthracite in a 60 kW direct current (DC) plasma arc furnace as well as the mineralogical characterization of the feed and products; the continuous closed-circuit ball milling and screen classification of titania-rich slag. This paper illustrates the important role of a well-designed heavy mineral sands beneficiation pilot plant practical programme in facilitating the education and development of suitably qualified personnel for the mining and mineral processing industries.

Introduction

The integrated mineral processing pilot plant practical programme designed for heavy mineral sand beneficiation is managed under the auspices of the WCMPF, an initiative partly funded by the Mineral Education Trust Fund (METF). In order to achieve its objectives, the WCMPF aims to:

➤ Continuously improve academic programmes for the education of students in mineral processing, primarily through the development of practicals and practical facilities.
➤ Ensure the co-operation, mutual interaction and development among tertiary educational institutions teaching mineral processing in the Western Cape.
➤ Rationalize and make optimum use of equipment and manpower for the education of mineral processing students in the Western Cape.

The WCMPF consists of academics and technical officers at the collaborative educational institutions. The technical officers are usually metallurgists, with several years of industrial experience, whose main objective is to improve the practical education of mineral processing students by (Deglon, 2003):

➤ Organizing and managing mineral processing practicals, laboratories and equipment.

➤ Scheduling and demonstrating mineral processing practicals.
➤ Designing new mineral processing practicals based on industrial trends and needs.
➤ Implementing safety and operational procedures.
➤ Liaising between tertiary educational institutions teaching mineral processing in the Western Cape.

The WCMPF, as a consequence of collaboration, has now access to a collective pool of twenty-five mineral processing practicals, which facilitates the introduction of novel ‘end to end’ or ‘integrated’ practicals along a selected mineral theme or route.

Student learning

The first two years of the engineering curriculum cover the basic engineering and science skills and knowledge areas that are required in the third and fourth years. These include the foundation courses in engineering mathematics, chemistry, physics, material science, professional communication, mass and energy balances, fluid mechanics and classical thermodynamics, statistics, and an introduction to pilot plant laboratory experiments with associated report writing, presentation and data processing (Eksteen, 2006). From the third year onwards a focused
programme in process engineering or chemical engineering, which includes minerals processing and extractive metallurgy, is presented.

It is also found that active engagement in authentic practicals, which are relevant to industry, benefits student learning. Traditional teaching tends to be highly sequential, where theories are built up bit by bit, while many learners need to see the global picture at the start. Giving students an idea of how a practical fits into the ‘broader scheme of things’ is an important means of catering for global learners (Deglon, 2003).

**Student practical training**

Of paramount importance is to ensure that students acquire effective practical knowledge as the vast majority of engineering graduates and diplomats are expected to function in an industrial environment where many challenges are practical in nature. Towards this goal practicals are developed around a specific mineral theme or route, which more than often includes the development of several new pilot plant practicals demonstrating key unit operations or processes in the selected mineral theme or route. The most recent mineral processing pilot plant practical programme is developed around the beneficiation of heavy mineral sands.

The focus of the pilot plant practical programme is the development of practical hands-on engineering skills, where engineering intuition plays an important role and where it is required of the students to observe not only measurements, but also many operational and qualitative aspects of the heavy mineral sands beneficiation process. It is preferred to work with imperfect systems, where statistical uncertainty plays an important role, where mass balances do not close unless they are reconciled, where the correct sampling of particulate matter is addressed, and where safety aspects are paramount to the operational procedures (Eksteen, 2006). The interaction between the heavy mineral sands beneficiation route, theoretical courses and the skill acquired are diagrammatically outlined in Figure 1 below.

Prior to the commencement of the practical programme, students are also required to investigate and report on the overall process and broader macro-environment, which include the geology and mineralogy, raw materials and resources, routes to titanium metal production, properties-applications-markets and environmental impact, toxicology and safety and health aspects. It is the view within the WCMPF that students improve their technical knowledge through group work, therefore it is essential for students to complete the integrated practicals in groups that are multiracial, multicultural and interinstitutional. This arrangement generates healthy competition between and within groups that motivates students to perform. Often part of the practical programme would include a one-day visit to a heavy mineral sands operation in the region, such as Namakwa Sands. This allows students to experience their specific process theme in an industrial context.

**The pilot plant laboratory course**

The most recent pilot plant laboratory course is a third year second semester course where students from the Universities of Stellenbosch and Cape Town, working together in mixed groups, perform integrated practicals developed around the beneficiation of heavy mineral sands. The programme consists of the following developed pilot plant practicals: the online electrostatic separation of free flowing mineral sands using a Roche Mining Carrara high tension roll separator incorporating a Blue Cube Systems MQi in-line mineral quantifier; the production of titania-rich slag and pig iron from the smelting of ilmenite and anthracite in a 60 kW direct current (DC) plasma arc furnace, as well as the mineralogical characterization of the feed and products; and the continuous closed-circuit ball milling and screen classification of titania-rich slag.

![Figure 1. Heavy mineral sands process theme in relation to course content and skills acquired](image-url)
The practicals were developed along the following guidelines (Deglon, 2003):

➤ The practical must illustrate a scientific principle using a common industrial unit operation or process.
➤ The practical must force students to physically operate equipment.
➤ The theory must be reconciled with the practical using a suitable mathematical model or correlation.
➤ Findings must be reported in written and oral form, both individually and in groups.
➤ Emphasis must be placed on teamwork, both within and between groups.

The online electrostatic separation of free-flowing mineral sands using a HTRS

Operational, engineering and safety factors influencing the electrostatic separation of minerals sands are investigated by students in a pilot plant-scale Roche Mining Carrara high tension roll separator, as shown in Figure 2. Measurements of the non-conductor stream are collected online by means of a Blue Cube Systems MQi in-line mineral quantifier using diffused reflectance spectroscopy to determine the mineralogical composition. The operating variables in Table I are investigated.

The separator is fitted with a feed chute with electrical heating elements to allow the adjustment of the temperature of the feed. The speed of both feed and main roller drive motors, as well as the setting of the high tension voltage is digitally controlled and adjusted by the students. The position of the corona wire, high tension plate and splitter flaps on the discharge are all manually adjustable and also done by the students. The main objectives of the practical are:

➤ The practical operation of the HTRS.
➤ The practical operation of the Blue Cube Systems MQi in-line mineral quantifier.
➤ Determination of grade-recovery curve diagrams.
➤ To prepare a set of recommendations that identifies the optimum operating conditions for the HTRS.
➤ A statistical analysis (ANOVA) based on 2N factorial design.
➤ To give a complete and accurate account on issues relating to safety and health, reliability and maintenance, interfaces with other equipment, measurement, analyses, sampling, and sample preparation.

The results thus far have indicated that the roll speed and potential were the dominant variables affecting separation and that the feed rate, temperature and position of the plate has little effect. The effect of the ambient relative humidity could not be assessed conclusively at this point.

Production of titania-rich slag and molten iron from the smelting of ilmenite and anthracite in a 60kW DC plasma arc furnace

In the ilmenite smelting practical performed by students, the raw material is upgraded by decreasing the iron content of the oxide. This is achieved by using carbon (anthracite) as reductant to convert some of the iron oxide in the ilmenite to metallic iron. The reactions occur in a molten slag with temperature of 1650 to 1750°C. The process yields two products, namely a titania-rich slag and molten iron. A 60 kW direct current plasma arc furnace provides the required energy for smelting, as shown in Figure 3.

A 1 kg mixture of ilmenite (obtained from Namakwa Sands) and milled anthracite are prepared for and fed using a vibratory feeder for each furnace run. Anthracite is added in a ratio of 127 kg per ton ilmenite (the same ratio used by...
Namakwa Sands) to ensure a carbon excess for maximum reduction. The off-gas is cooled, ventilated and the dust is captured. Arc-length, current and the reductant to ilmenite ratio is varied and their impacts on titania-rich slag and pig iron yields and chemistries are determined. The students are required to reconcile the material balance across the furnace. An infrared pyrometer is used to estimate the temperatures of the slag in a graphite crucible.

Mineralogical characterization of the feed used and product materials produced is performed using XRF for total elements, proximate analysis for anthracite, SEM-EDS for pig iron (see Figure 4) and LECO for carbon.

The aim of the mineralogical characterization is to expose the students to different characterization methods and the metallurgical information they can provide. The ilmenite smelting conditions, in particular the effect of changes in temperature and reductant-to-ilmenite ratios, are simulated using FactSage®, to evaluate the effect on the amounts and types of phases formed, and the composition of the phases.

The main objectives of the practical are:

➤ The practical preparation and operation of the 60 kW DC plasma arc furnace.
➤ To obtain a better understanding of the thermodynamics and chemistry of the ilmenite smelting process.
➤ To obtain a better understanding of mineral characterization and the appropriate analytical techniques.
➤ To integrate the practical with the appropriate simulation tools.
➤ To give a complete and accurate account on issues relating also to safety and health, reliability and maintenance, interfaces with other equipment, measurement, analyses, sampling and sample preparation.

The continuous closed-circuit ball milling and screen classification of titania-rich slag

This part of the experiential learning phase is designed to introduce students to the process of fine wet grinding as a basic mineral liberation activity in mineral processing. Fine grinding is presented as part of the broader fundamental activity of comminution, which encompasses blasting of rock at the mining stage and the subsequent crushing of coarse ore through various stages to produce suitably sized feed material for the fine grinding stage. Apart from the primary objective of liberating valuable minerals from ore, fine grinding is contextualized as an influential precursor to the efficient operation of other value-adding mineral processing activities downstream such as leaching, flotation, thickening and filtration.

Commonly used comminution models are introduced as helpful tools for designing and evaluating milling plant performance. Material breakage is modelled using first order kinetics, i.e. the rate of disappearance of mass in a size fraction, $i$, is proportional to the mass in that fraction:

$$\frac{dM_i(t)}{dt} = -S_i M_i(t) \tag{1}$$

where $S_i$ is a proportionality constant called the rate of breakage (min$^{-1}$) for mass fraction $i$. A mass balance on each of selected size fractions takes cognizance of the fact that mass from size fractions larger than $i$ report to this fraction and the following equation represents this occurrence:

Accumulation = −Disappearance + Appearance \tag{2}

This model can be presented in matrix form, which takes into account various size fractions that may be considered at any instance. Thus this becomes:

$$\Delta M = -M_{\text{disappearance}} + M_{\text{appearance}} = -S M A t + B_{ij} S M A t \tag{3}$$

where $B_{ij}$ is called the breakage distribution function. Although fundamentally correct, the above equation is tedious and requires a lot of computation time when applying it to a whole range of narrow size fractions. A simpler model proposed by Rajamani and Herbst (1991) uses only two size fractions, oversize and undersize, and considers material disappearing from the oversize fraction. The second term in the above equation disappears and only the rate of breakage is considered. A mass balance around the circuit based on the simple model is performed on material above a selected critical size according to the following relationship (Rajamani and Herbst, 1991):

Figure 3. Assembly of the DC plasma arc furnace

Figure 4. Group SEM image of pig iron sample (dark phase: Fe, light phase: Ti)
$\frac{dM(t)}{dt} = Ff + Rr - (R + M)m - kHm$ \hspace{1cm} [4]

(Non-steady state operation)

$0 = Ff + Rr - (R + M)m - kHm$ \hspace{1cm} [5]

(Steady state operation)

where:

$H$ = hold-up of solids in the mill,
$F, R, M$ = solids flow rates of the mill feed, classifier coarse return and mill product respectively
$f, r, m$ = mass fraction of material above the selected critical size $i$ in the above mentioned respective streams.

This simple model requires only the solving of the rate of breakage constant ($k$).

The performance of the classifier is evaluated using the commonly known partition curve. As should be expected with this method, the recovery into the oversize product should be low for the small sizes and should increase to almost 100% for the largest particle sizes in the classifier feed. The expected cut size for this evaluation is taken as the screen aperture for the screen used for classification in this practical.

The pilot plant consists of a grate discharge Buhrg ball mill which is 1.040 m long with an internal diameter of 0.420 m (see Figure 5). The ball charge sizes range from 20 mm to 60 mm. The mill is operated in closed circuit with a screen classifier with 250 $\mu$m aperture size. Ancillary units include product and screen classifier pumps for slurry transport. The entire pilot plant is mounted on a trailer for convenient cartage between locations (see Figure 6). A calibrated dry ore feeder and regulated top-up water feed system completes the circuit equipment inventory.

Flow rates of the slurry streams are determined by weighing entire stream flows directed into sampling containers for given time periods. The same samples collected are used to determine the particle size distribution for each stream. The students are required to pay particular attention to the critical roles of correct sampling and accurate measurement in obtaining good data (accurate and unbiased) as the success of the practical hinges on these important skills.

Apart from introducing the students to the use of performance determination tools in a typical mineral processing plant setting, the practical also aims to acquaint students with hands-on operation of a typical plant by adjusting operating parameters such as pulp density, mill speed, and residence time, and observing the effect of these changes on product size distribution. The main objectives of the practical are:

➤ To perform a mass balance around the circuit.
➤ Calculate important mill parameters such as critical speed, aspect ratio, recycle ratio, etc.
➤ Use simplified first order kinetic models to estimate the breakage constants for selected critical ore sizes.
➤ Use simplified screen models to estimate the efficiency of the classifier.

Titanium-rich slag with a nominal top size of 10 mm is currently used as a raw material. A jaw crusher and a cone crusher (see Figures 7 and 8) with power draw indication are used to prepare the raw slag as received from the smelter. Observation of power consumption during feed preparation is considered critical as it provides an indication of the relative amount of energy consumed at this stage.

Safety remains a priority at all times while the plant is in operation. Safety hazards arising from noise (mill and screen operation), presence of high tension power supply cables, spillage, and moving machinery parts are assessed by the students prior to performing the practical and measures (which include the wearing of appropriate personal protective equipment) are taken to mitigate potential incidents.
Conclusions

It is the view of the WCMPF that the integrated nature of the pilot plant practical programme developed around the beneficiation of heavy mineral sands provides students with the opportunity to understand the interrelationships between the various stages of mineral and metal extraction. The students get to work with the actual mineral and metal containing process streams where correct measurements, sampling, analysis and the identification of the associated errors are viewed as important. The students are taught practical mineralogical, chemical and physical characterization techniques for materials, normally not covered in any other courses. Safety and environmental issues are paramount due to the real-life aspects of the programme. The programme also provides context and support to the theoretical courses taught in the third and fourth years. The WCMPF considers the introduction of the heavy minerals process route as a key activity in providing a quality learning environment for the practical training of suitably qualified engineering graduates and diplomats for the mining and mineral process industries.

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