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Recycling of Bag-House Dust from Foundry Sand

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Abstract

Non-metallic foundry waste is generally composed of spent green sand, core sand, and dust collected in the ventilation bag-house systems of the foundry facility. Currently, practices exist for the recovery of sand particles from green sand and core sand at the expense of the other constituents via combustion or degradation. However, new methods are necessary to extract values other than sand from the bag-house dust material. This is important, because the dust of composed of as much as 50 weight percent non-sand recoverable materials, such as coal and clay. This research evaluates the potential to beneficiate bag-house dust material by way of froth flotation. The coal constituent of the dust was extracted at grades near 60 weight percent and recoveries near 70 weight percent. The clay constituent was extracted at grades near 30 weight percent and recoveries near 40 weight percent.

Keywords: Froth flotation, green sand, coal, bentonite clay.

Introduction

Foundry green sand is composed of three basic components: a refractory material, a binder, and an oxidation inhibitor. Most commonly these components take the form of sand, clay, and coal. While green sand is reusable, its three main components are consumed or degraded with each use. This requires a continuous addition of fresh materials into a foundry's green sand system and the removal of used green sand. The removed green sand is typically discarded or used in some less critical application.

When one considers that new green sand may cost as much as 0.04 to 0.14 dollars (US) per kilogram to produce, and tens of dollars per ton to discard, there are serious economic motivations for recovering valuable materials from the used green sand[1].

Processes are currently in use to recover sand grains from used green sand by removing the coal and clay constituents from the sand particle surfaces by way of thermal degradation and surface abrasion[2]. The resultant sand particles, no longer encapsulated by the other constituents, may then be sorted by particle shape and size into more and less useful fractions, which may then be recycled or discarded. This style of recovery is very conducive to the recovery of sand from green sand, as green sand is primarily composed of sand grains with other materials present as minor fractions. However, this style of recovery is much less effective for the recovery of values from the dust fines generated in the bag-houses of foundry ventilation systems. Due to the nature of the dust and its very fine particle size, relative to green sand, the dust consists of a much larger proportion of coal and clay material. Also, the very fine and irregularly shaped sand particles present in the dust are not desirable for most green sand systems. In juxtaposition to used green sand recovery, dust recycling methods ought to focus on the extraction and recovery of coal and clay values while discarding the sand particles from the green sand system.

Material and Methods

Regarding flotation: Froth flotation has been selected as a means of beneficiation because it is already a commonly applied technique for extracting the targeted materials, coal and clay.

The basic practice of froth flotation is reliant upon physical and/or chemical differences in surface characteristics between the gangue material and the mineral, which will eventually result in the hydrophobicity of either the gangue material or mineral[3]. Froth flotation is conducted by mixing the feed material with water and bubbling air through the slurry. Hydrophobic materials attach to the bubbles and are carried to the slurry surface where the material may be collected in a froth. Some materials, like coal, maintain a naturally hydrophobic surface characteristic while other materials may require chemical reagents to modify their surface characteristics. For instance, cationic collector reagents make use of the negatively charged surfaces present on bentonite clay surfaces to physically adsorb a hydrophobic hydrocarbon chain to the particle surface. This is often referred to as "physisorption"[4].

It is known from research done by Oats[5] that the presence of clay hinders coal flotation, as bentonite clay masks the hydrophobic surface of coal. Bentonite, a commonly used clay in green sand, is the specific clay addition present in this investigated dust. It is hypothesized that this association and interaction may be used to extract both materials from the bag-house dust feed material.

Flotation practice: Experimentation for this work was conducted in a bench scale Denver batch mechanical flotation cell. The cell capacity is approximately 5 liters, agitates near 1400 rpm, and operates air sparging near 4 liters per minute.

Flotation was conducted by first filling the flotation cell with 4 liters of water before adding a known mass of dry feed material while the cell was agitating. Specified amounts of flotation reagents were then added by dropper and allowed to condition in the slurry for 3 minutes before initiating air sparging. The froth concentrate was collected by overflowing from the cell into a sequential series of collection pans. A small paddle was used to assist in froth collection. It is important to use consistent and shallow skimming strokes when using a paddle. The concentration tailings were collected upon the exhaustion of froth production. Collected slurries were then dried, measured, and analyzed.

Analysis: Analysis of the dust itself and products generated by experimentation were conducted by Qemscan, loss on ignition, clay leaching, and Microtrac particle size analysis.

Loss on ignition (LOI) was conducted based on ASTM International standard D7348-08 in which 1.0 grams of dry sample material is loaded into a dried crucible of known mass. The loaded crucible is then placed into a 100°C preheated furnace for one hour. The dried sample is weighed and replaced in the furnace at 450°C for one hour before increasing the temperature to 950°C for a three hour period. The furnace cooled sample is then measured for final mass.

Clay recoveries were measured using a leaching method based on a technique used by Zanetti[2] and Cruz[1]. After heating the sample material in air at 900°C for at least 30 minutes to remove any organic materials by combustion, a 6 gram sample was boiled in 50 milliliters of 6N hydrochloric acid for 1 hour. Upon filter paper filtration and washing with distilled water, the sample was then boiled in 60 milliliters of 4N sodium hydroxide solution for one hour. The leached sample material was then filtered and washed before drying and measuring a final mass to determine clay loss. Filter paper used during this analysis maintained a pore spacing of 2.5 micrometers.

Particle size measurements were conducted using Microtrac and Qemscan equipment. Microtrac equipment functions by measuring the scattering behavior of light passing through a slurry of sample material and water. Qemscan is essentially a scanning electron microscope (SEM) that has been optimized for mineral and particulate studies by the addition of extra X-ray detectors. This allows for the automatic scanning of prepared particulate samples in a greatly reduced period of time. The Qemscan also generates representative images of individual particles, conveying their size, shape, and composition[6].

Methylene blue titration (ASTM international standard C837-09), a common form of clay measurement, was not used in this work due to inconsistent results caused by the presence of organics, coal, in the sample material being measured.

Material characterization: Using the previously stated analysis methods, the dust material and green sand from the same foundry were characterized following proper sampling techniques utilizing a Jones riffle splitter. This data is presented in table 1. The remainders of the materials were composed of sand (silica).

Table-1
Loss on ignition and clay leaching results for the dust feed material in relation to green sand from the same facility

Feed Material	LOI Coal Grade (wt%)	Clay Grade (wt%)
Bag-House Dust	24	27
Green Sand	4	5

Results from table 1 demonstrate that the bag-house dust is enriched with coal and bentonite clay, relative to the green sand it had originated from. This is an expected outcome as the dust maintains a much finer and broader particle size distribution relative to the green sand. This is shown in figure 1 and figure 2. A finer particle size distribution means than the material will maintain greater surface area per mass and thus contain more surface encapsulating materials, such as coal and bentonite clay. In addition, clays simply have a smaller particle size and are thus more likely to be captured in a ventilation system. As particle size distribution is very important to the performance of a green sand mold, figure 1 and figure 2 give evidence supporting the need to extract valuable materials from the dust material rather than simply reintroducing sand grains from the dust back into the green sand system. The smaller, less round (as shown in figure 3) dust sand grains do not match the desired particle size distribution of the green sand. Addition of fine silica from the dust could negatively affect green sand properties by increasing effective mold density. This would reduce the ability of escaping gases to be transported through the green sand mold, require more binder material, and reduce 'flowability' of loose sand moving around the foundry's green sand system[7].

The encapsulation of sand grains is visually demonstrated by Qemscan imaging shown in figure 3 and figure 4. The dust sand grains are smaller, less round, and more heavily encapsulated in clays compared to green sand grains. Coal is not able to be measured using this analysis method.

Results and Discussion

Reagent selection: Amines were used as a cationic collector to adsorb to the negatively charged surfaces of the bentonite clay. It was hypothesized that targeting the clay would be most beneficial as the coal is naturally hydrophobic and will float on its own. Also, the interaction between bentonite and coal demonstrated by Oats[5] raised hopes that when the ability to collect clay was achieved, the coal would follow by association.

The amines selected for experimentation include Cytec's AEROMINE 3000C, AEROMINE 3000F, AEROMINE 3030C, and AEROMINE 3100C. The same frothing agent, AEROFROTH 70, a low molecular weight alcohol, was used throughout these experiments. This frothing agent was selected based on the recommendation from Cytec due to its compatibility with the amine collectors provided and its common usage in fine material, coal, and graphite flotation.

Following some preliminary scoping experiments, one of the four cationic amine collector reagents provided by Cytec was selected for continued research. However, all four of the reagents performed comparably. Table 2 compares the performance of the Cytec AEROMINE collectors to each other as well as to the collector absent condition. Each experiment was conducted with a slurry concentration of 6wt% dust solids, at natural pH (pH 9), using 320 grams per tonne of collector, and 600 grams per tonne frother. The reagent quantities used for these scoping experiments were based on recommendations from literature that approximately one pound of reagent per ton of dry material, or about 480 grams per tonne, are used industrially[8].

Table-2
Results for amine selection scoping experiments

Experiment	Coal Grade (wt%)	Coal Recovery (wt%)	Clay Grade (wt%)	Clay Recovery (wt%)
no collector	46	35	24	11
3000C	38	52	20	24
3000F	42	48	17	14
3030C	39	51	19	18
3100C	45	45	14	13

Based on results presented in table 2, AEROMINE 3000C was selected for further research and evaluation of other flotation variables, because it yielded greatest clay grade and recovery.

Attritioning: All extractive metallurgy and mineral processing maintains the fundamental basics of liberation and separation. Attrition scrubbing was selected as the preferred means of liberation; whereby the act of particle impingement serves to remove surface encapsulating materials from the particle surfaces. This was done in accordance with literature from O'Meara[9] which suggests that during silica recovery, foundry sand should be attrition scrubbed at very high water slurry solids content, about 70 weight percent solids, and at very high impeller speeds, about 1750 rpm. However, due to the very high concentration of clays in the dust material, the slurry solids content was reduced to near 50 weight percent solids for 5 to 15 minutes.

Figure 5 illustrates the liberation achieved by attrition scrubbing dust for 10 minutes, at 1725 rpm, and at a slurry density of 50 weight percent solids. It can be seen than the percentage of fine particles (near 10 micrometers) has increased at the expense of the largest particles. This is evidence that attrition scrubbing has a positive impact on the liberation of the encapsulating materials from the silica grains.

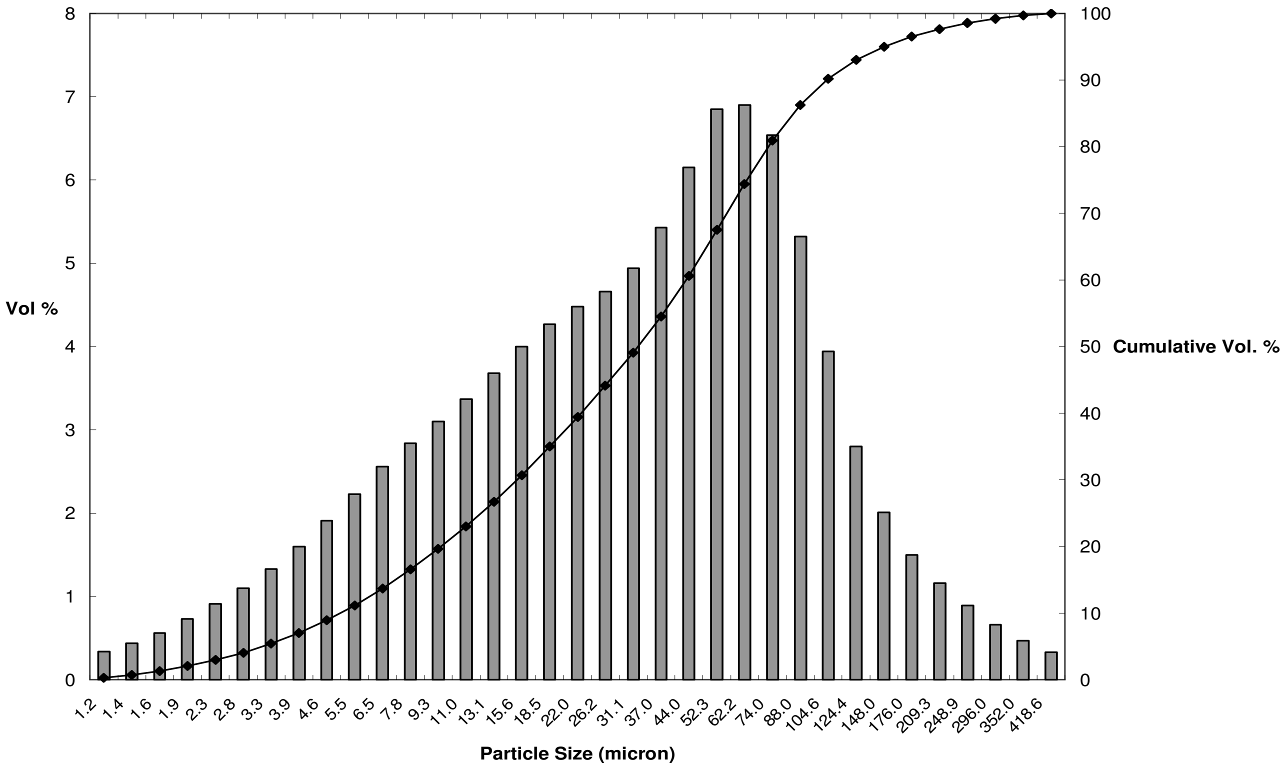

Figure-1
Bag-house dust particle size distribution generated by Microtrac showing a P_{80} near 74 microns and an AFS fineness number of 234 (metric sieve openings)

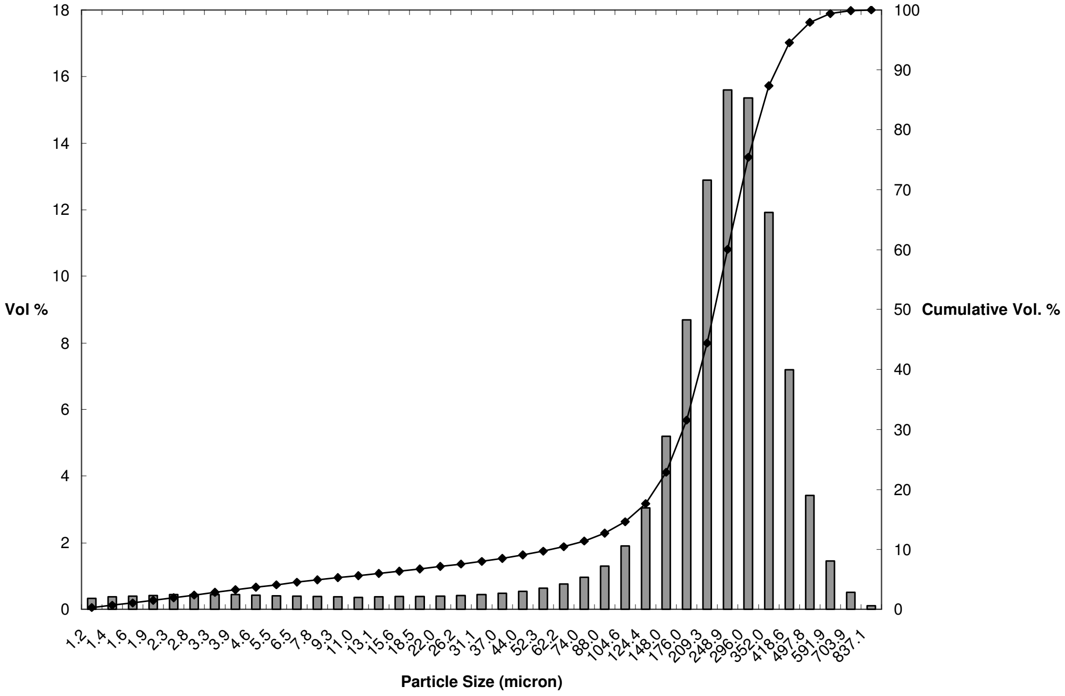

Figure-2
Green sand particle size distribution generated by Microtrac showing a P_{80} near 352 microns and an AFS fineness number of 80 (metric sieve openings)

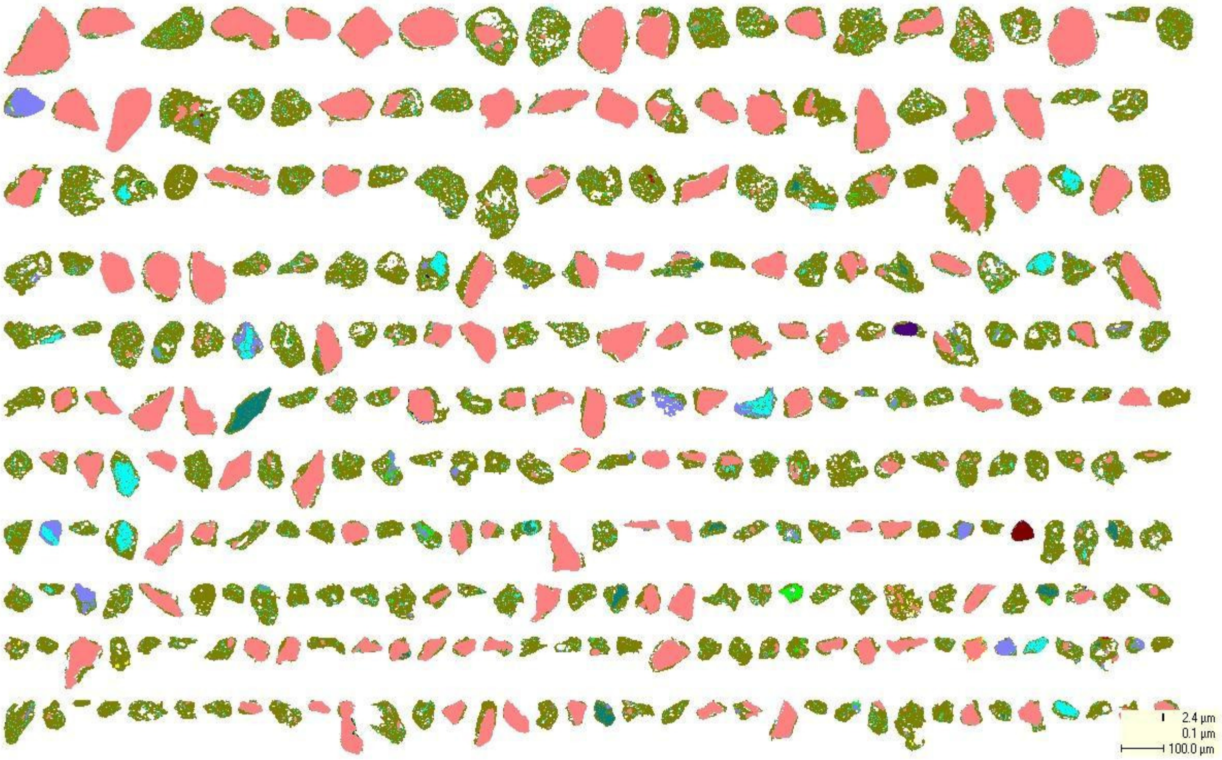

Figure-3
Composite Qemscan image of individual bag-house dust grains, in the color code used, Pink represents quarts, green represents bentonite clay, blues represents other clays, and black represents iron metal

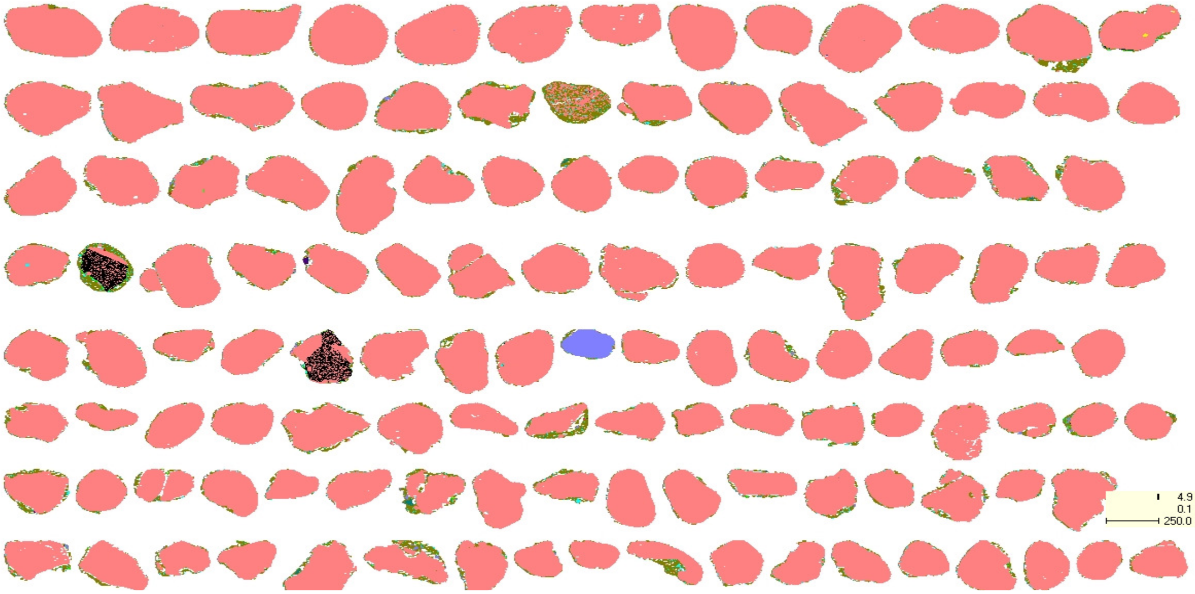

Figure-4
Composite Qemscan image of individual foundry green sand grains. In the color code used, Pink represents quarts, green represents bentonite clay, blues represents other clays, and black represents iron metal

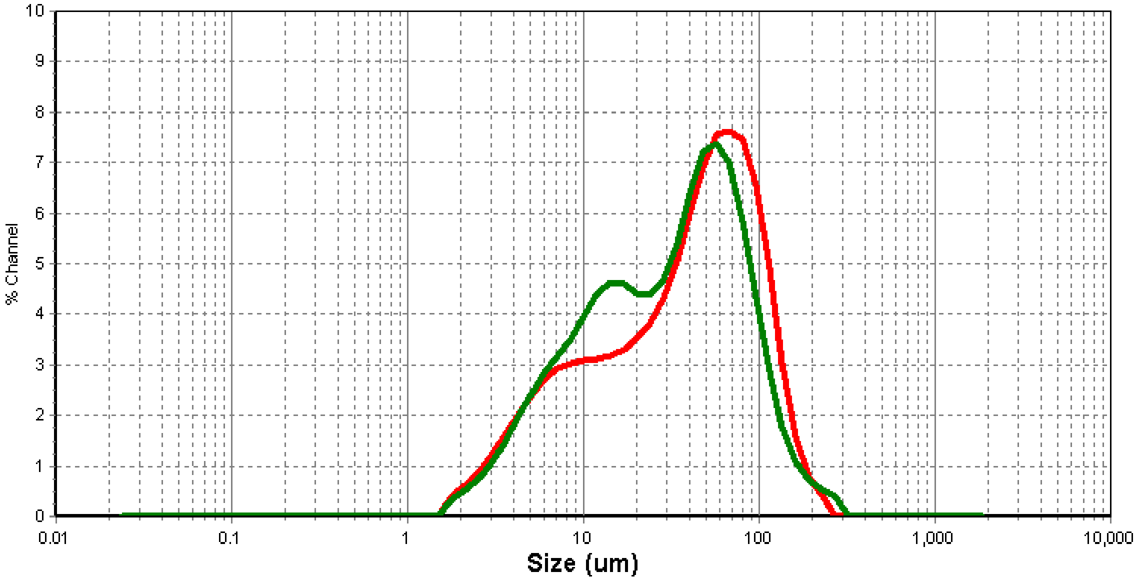

Figure-5
Microtrac particle size distribution of the bag-house dust, in red, compared to bag-house dust that has been attrition scrubbed, in green. The distribution is represented in volume percent and micrometers

Table 3 shows results of flotation scoping experimentation conducted with attritioned dust material in comparison to the previous scoping experiments as well as other scoping data used to define windows of operation in later experimentation. Table 3 suggests that attrition scrubbing is beneficial and that reagent surface saturation may have occurred when using quantities near 960 grams per tonne of collector reagent.

Graphs and material behavior: A large experimental matrix was performed evaluating the relationships between clay and coal grades and recoveries produced as input variables fluctuated. The variables evaluated were collector reagent quantity added (0.16 to 0.48 grams per kilogram of dry feed material), attrition scrubbing time (5 to 15 minutes), and weight percent solids in the flotation slurry (4 to 8 weight percent). Other, non-specified, parameters were maintained the same as in the scoping experiments. The most significant relationships are presented in the following figures.

Table-3
AEROMINE 3000C flotation variable scoping data

Experiment	Coal Grade (wt%)	Coal Recovery (wt%)	Clay Grade (wt%)	Clay Recovery (wt%)
320 g/t 3000C	38	52	20	24
960 g/t 3000C	43	47	18	15
320g/t 3000C, Attritioned	45	51	24	16
320 g/t 3000C, Attritioned, 12 wt% solids	32	54	24	39

Overall, clay grades and recoveries generated by experimentation produced disappointing results. Feed grade remained the upper limit of the flotation capabilities. Figure 6 illustrates the clay grade and recovery results and shows a direct relationship with one another. This suggests that they are both following mass pull. As more material is recovered more clay is being recovered, but without actually beneficiating the material. This indicates that either the feed material is not liberated before flotation and/or selectivity is not being achieved by the reagent and flotation parameters during flotation. This statement is further supported by figure 7 which shows a positive relationship between grade and the increasing of both input variables. Figure 7 also shows a stronger relationship between grade and slurry solids concentration than other input variables. A strong relationship was not observed between attrition time variance and clay beneficiation.

The coal grades and recoveries generated by the same set of experiments produced results which illustrate an inverse relationship between grade and recovery. This is a classic trade off scenario in which enrichment is obtained at the expense of recovery. Figure 8 depicts this relationship. However, unlike clay this shows that the coal can be beneficiated well above feed grade while maintaining moderate recovery.

Figure 9 and figure 10 are surfaces used to reveal the optimum conditions at which to conduct the separation. Based on these surfaces it can be deduced that one way to obtain the maximum coal grade product is to collect the least amount of material. Figure 9 shows the maximum coal grade being obtained with the minimum amount of collector and solids addition. Minimizing attrition duration also improves grade as seen in figure 10. Due to its inverse relationship, grade is likewise minimized by maximizing recovery via high collector addition, high solids concentration, and long attrition duration.

pH modification: All of the experiments presented thus far have been conducted at the natural pH of the material slurry, pH 9. The respective isoelectric points of the three dust constituents: silica, bentonite, and coal are located at pH 2, 3, and 7. So, at the natural pH the surfaces of all three constituents maintain a negative zeta potential. This serves to reduce the selectivity of any cationic collector. It is no surprise that separating these constituents using a cationic collector is an arduous task. However, it was hypothesized that the bentonite constituent would be more sensitive to a cationic collector than the silica gangue material due to characteristics inherent to bentonite such as small particles size, large surface area, and high cation exchange capacity. Also, at the natural pH the bentonite constituent should maintain a slightly more negative zeta potential of -30 millivolts (mV) to -50 millivolts compared to a zeta potential of -25mV to -35mV for silica[10]. Results in the previous sections suggest that these differences between bentonite and silica are not enough to distinguish the two constituents in the eyes of the collector.

One approach that may be used to generate zeta potential contrast between the constituents would be through pH modification. In one scenario the pH may be lowered to below 2. This pH is located below the isoelectric points of all three constituents. With a positive zeta potential the silica constituent should not be collected by cationic collectors. Bentonite on the other hand, while being at a pH below the isoelectric point, will maintain permanently negatively charged basal plane surfaces which represent the majority of the total charge of the bentonite particle[10]. Also, the coal constituent, with a now positive zeta potential, should still be collected to some degree due to natural hydrophobicity.

These experiments were conducted at a pH of 1.75 using sulfuric acid as the pH modifier, a slurry solids concentration of 6 weight percent, 10 minute attrition duration, and a 320 gram per tonne AEROMINE 3000C collector reagent concentration. It should also be noted that a new polyglycol frother reagent, Cytec's Oreprep F-549, was required to generate a useful froth at this pH as the alcohol frother reagent proved ineffective at such low pH levels, generating a very thin froth which was unable to carry significant quantities of solids. The same mass concentration of Oreprep F-549 was used as when using AEROFROTH 70.

The results are shown in table 4 in comparison to previous experiments. These results are very disappointing, indicating that pH modification was ineffective at greatly improving clay grades and recoveries.

Table-4
Grade and recovery data from pH modified experiments

Condition	Coal Grade (wt%)	Coal Recovery (wt%)	Clay Grade (wt%)	Clay Recovery (wt%)
Attritioned pH 2	54	15	24	12
Unattritioned pH 9	38	52	20	24
Attritioned pH 9	45	51	24	16

Even the best results using this approach may not be useful for the overall objective of this work: to re-introduce the flotation products into the foundry sand system. The lowered pH of the flotation products may have a negative impact on mold characteristics. Also, the introduction of a pH modifier will add a whole new element to the waste streams generated at a foundry.

Multiple stage flotation: Several industrial flotation operations use multiple stages of flotation to sequentially collect individual components from the feed material. Data conveyed previously indicates that it is much easier to collect coal than clay from the dust feed using one stage flotation. In light of this, an approach was attempted in which the dust material was floated in a series of stages with the intent of removing the coal material in the early stages and then targeting the clay constituent in later stages. This would be similar to a rougher and scavenger flotation system.

It was hypothesized that the collector reagent would be more effective in collecting clay in the subsequent stage in the absence of coal. The inputs for this experiment were selected with the intent of maximizing coal grade in the first stage. The experiment was conducted using a 6 weight percent slurry solids concentration, normal pH (pH9), 160 grams per tonne of the AEROMINE 3000C collector reagent, 600 grams per tonne AEROFROTH 70 frother reagent, and a very low attritioning time of zero minutes. Upon the completion of a flotation stage an amount of additional collector and frother reagents equal to the original input were added to the flotation slurry. This increased the effective reagent quantity in each continuing stage as the slurry mass decreases with each stage. This should be favorable for clay recovery in later flotation stages as indicated in by figure 7. Data produced from this experiment is shown in figure 11 and table 5.

Table-5
Overall cumulative results for the three stage flotation experiment

Coal Grade (wt%)	Coal Recovery (wt%)	Clay Grade (wt%)	Clay Recovery (wt%)	Mass Recovery (wt%)
38	59	23	25	30

Figure 11 shows a relatively high coal grade and recovery being achieved in the first (rougher) flotation stage. The efficiency of coal flotation is reduced significantly following the rougher stage showing that most of the easy to float coal has been removed. An inverse trend is observed for the clay constituent. A typical clay grade and recovery are achieved in the initial stage, but clay grade improves with subsequent stages. This supports the hypothesis that clay flotation would improve in the absence of some of the coal material that is also consuming flotation reagents. However this improved grade is more likely due to the absence of coal in the flotation product rather than improved flotation of clays. Unfortunately, the slight improvement in clay grade was also countered by a drastic decline in clay recovery in the later (scavenger) stages. Table 5 showing the overall coal and clay data does not portray any results that greatly exceed the single stage flotation performance.

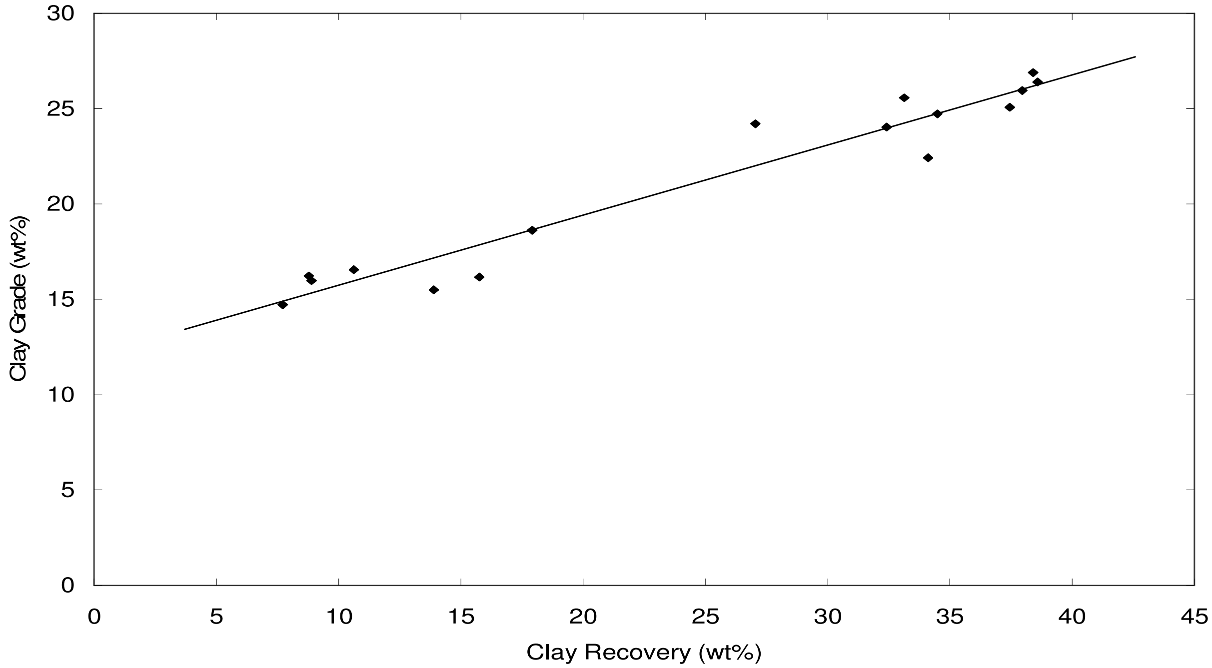

Figure-6
Graph of experimental matrix results for clay grade versus clay recovery

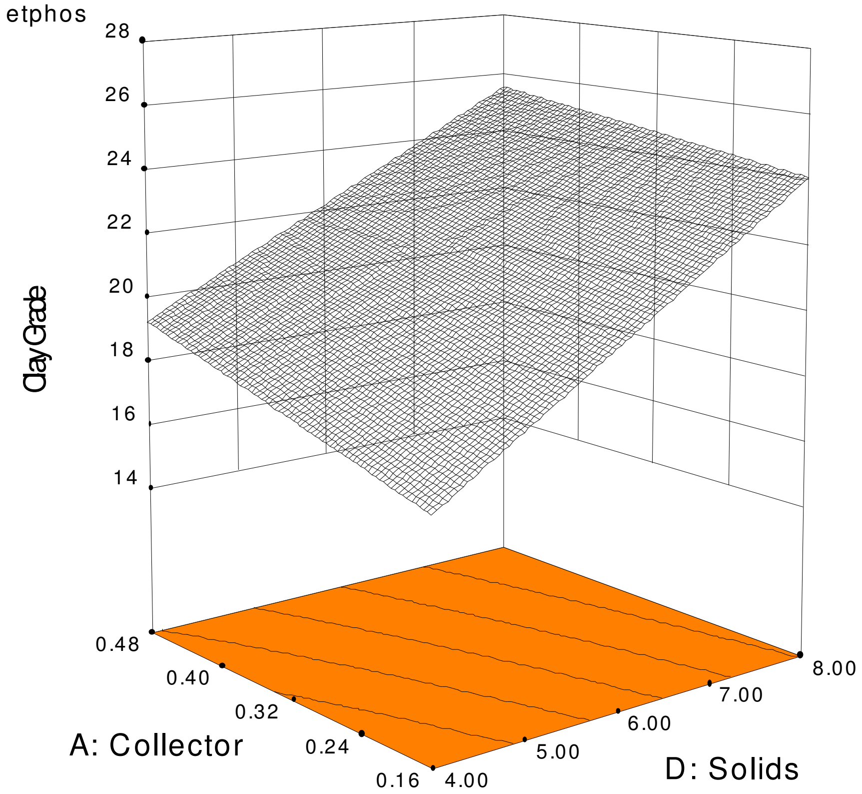

Figure-7
Surface graphic depicting clay grade (wt%) as a function of collector input (g/kg dry feed) and slurry solids concentration (wt%). This data is generated using a calculated attrition time of 10 minutes

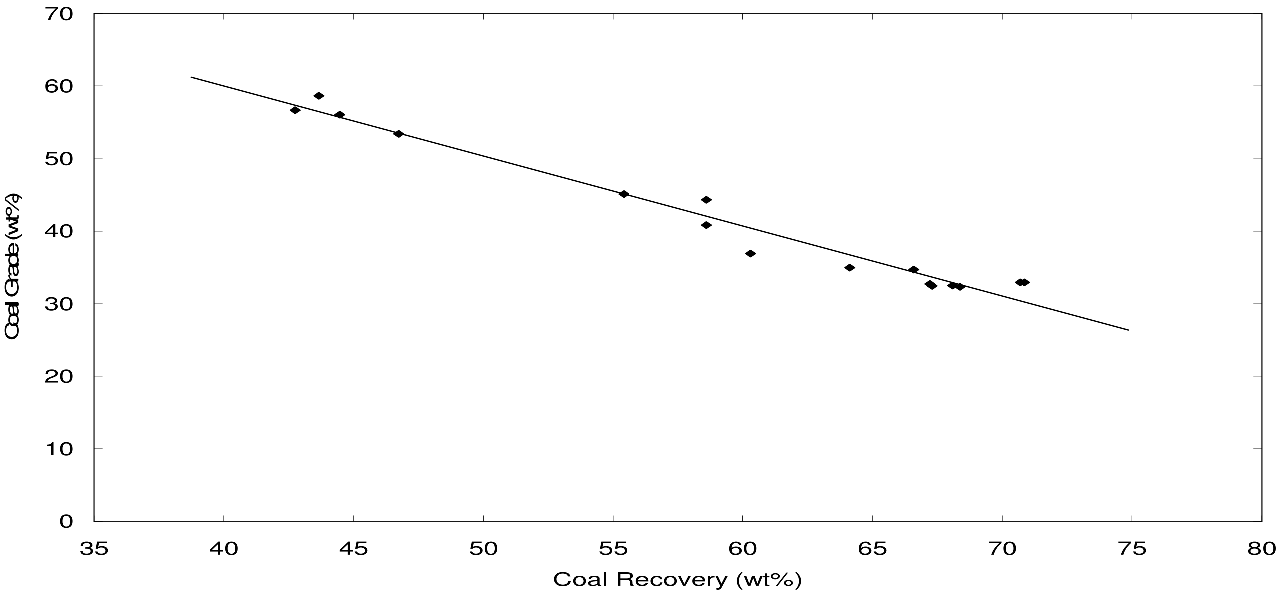

Figure-8
Graph of experimental matrix results for coal grade versus coal recovery

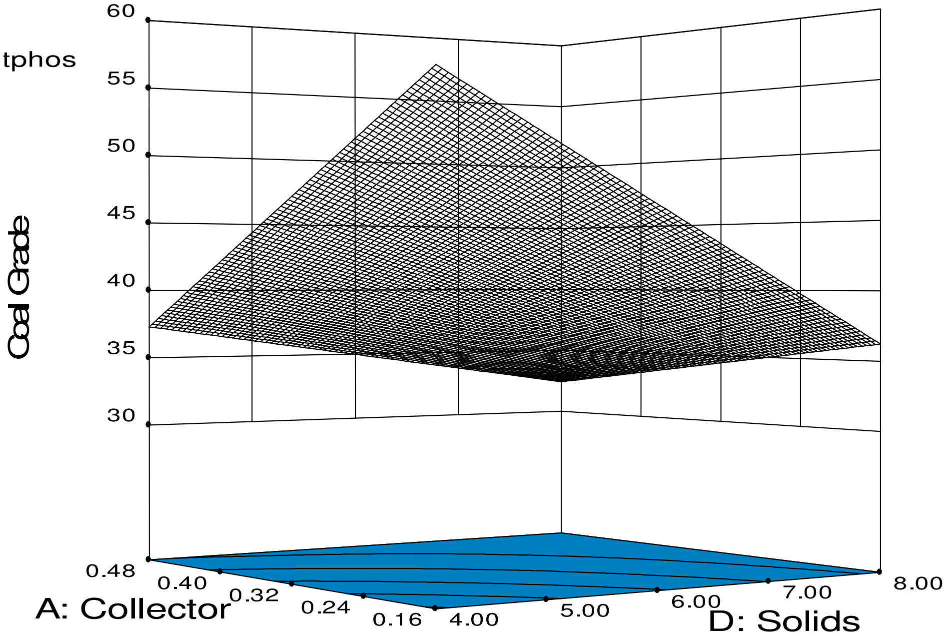

Figure-9
Surface graphic depicting coal grade (wt%) as a function of collector input (g/kg dry feed) and slurry solids concentration (wt%). This data is generated using a calculated attrition time of 10 minutes

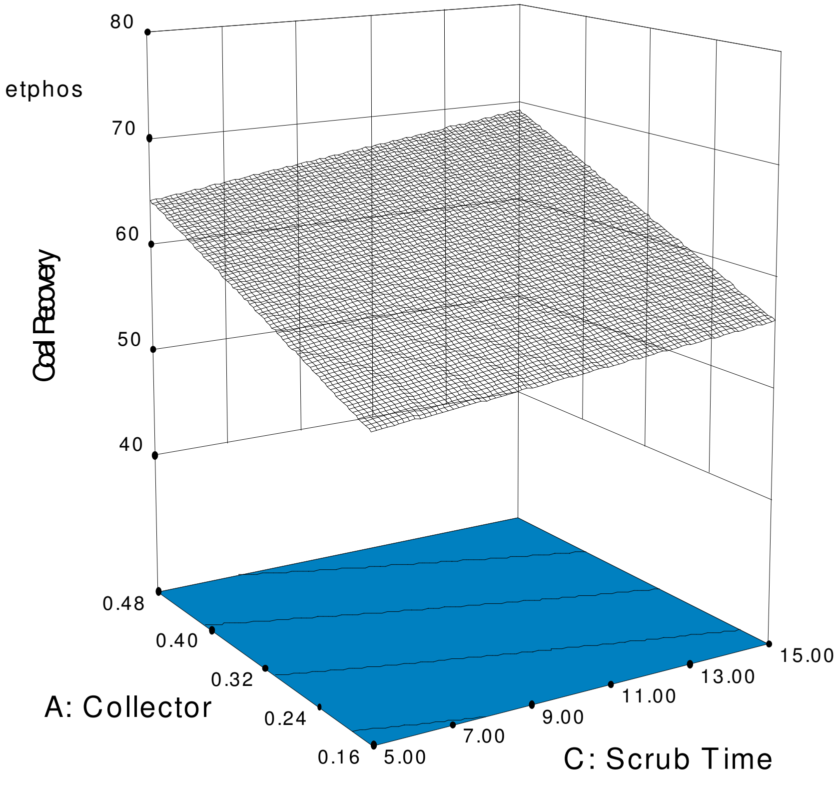

Figure-10
Surface graphic depicting coal recovery (wt%) as a function of collector input (g/kg dry feed) and attrition duration (minutes). This data is generated using a calculated 6wt% solids concentration

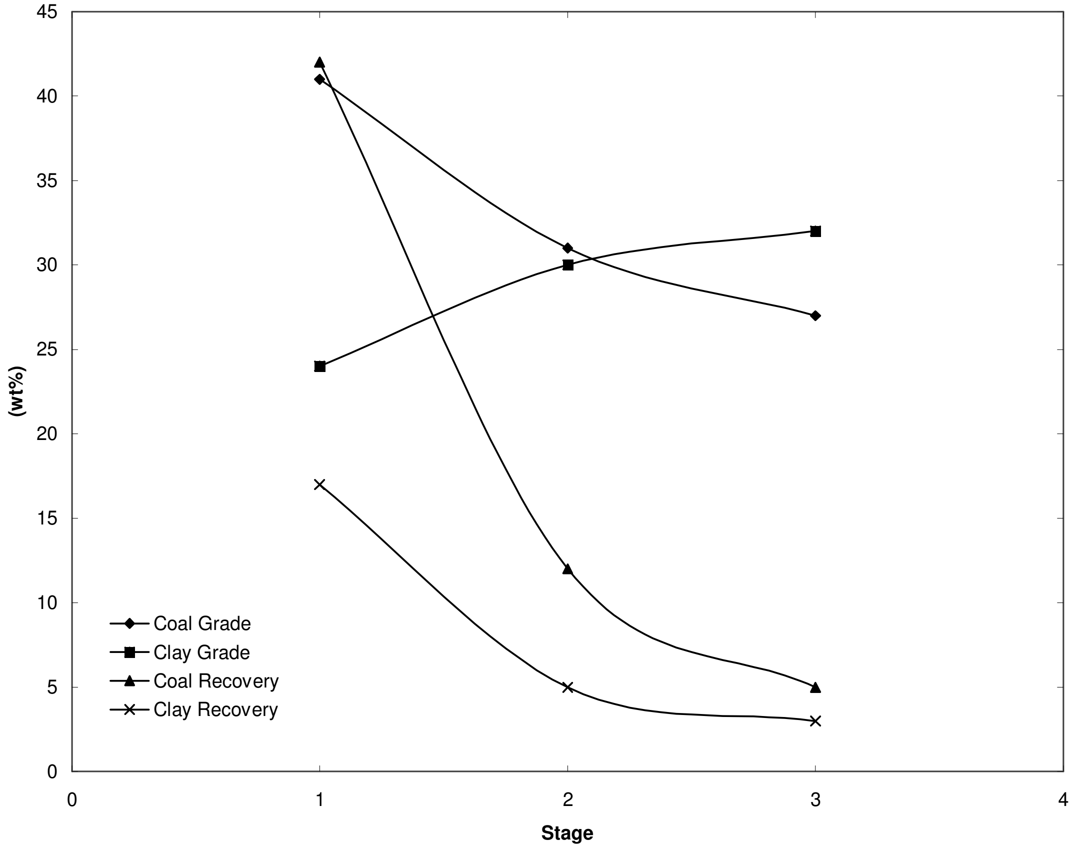

Figure-11
Multiple stage flotation grade and recovery results by stage

Conclusion

The overall goal of this project was to recycle foundry dust back into the foundry green sand inputs. It was hoped that high selectivity between constituents could be achieved by using a collector reagent to target specific constituents within the material system. However, the very fine nature of the material provided a challenge for flotation techniques. It is for this reason that industrial coal flotation operations typically de-slime their feed material before conducting flotation. Unfortunately, in this case de-sliming was not an option as the slimes were composed of the desired materials.

The experiments conducted in this research show that is it very difficult to beneficiate the clay constituent via froth flotation. The hydrophilic nature and small particle size of the clay combined with its similarity to the silica gangue material greatly impair the selectivity of the flotation regime. It was hypothesized that the clay's constantly negative surface potential and high cation exchange capacity would make it a suitable candidate for cationic physical adsorption flotation, but most experimental techniques did not achieve clay grades in excess of the feed grade. It is hypothesized that the reason for clay's poor flotability is due to the lack of selectivity of the collector reagent, inherent slime characteristics, and the inability to fully liberate the material constituents.

Low slurry density and collector addition proved to improve clay grades by recovering only readily floating materials, but as mass recovery increased with increased collector and slurry density, selectivity was lost. Even multiple stage flotation did not improve the relationship between grade and recovery. The barrier here, as with industrial coal flotation from primary sources, appears to be the fine silica 'slime' material which becomes entrained in the flotation froth and contaminates the final product

Beneficiation of the dust's coal constituent proved to be relatively successful. Grades above 60wt% coal have been achieved along with recoveries above 70wt% coal. Unfortunately these results never occurred together in the same experiment.

The primary outcome from this research is that the clay and coal constituents can be collected and independently separated from one another. However, an efficient method must still be identified which is suitable for this very fine particulate material.

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