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Fundamentals of Mechanical Upgrading of Athabasca Oil Sands: Mechanisms of Sand and Bitumen Separation

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Abstract

Sand and bitumen were separated mechanically from Athabasca oil sands using cold water in a plate mill. Sand extraction was found to be a function of the product of rotational frequency, oil sands charge weight, and the inverse fourth power of the distance between the rotating plate and the bottom of the mill. Ranges of testing were 20–150 rpm, 10–100 g, and 1.3–27 mm for rotational frequency, oil sand charge, and clearance, respectively. Sand extractions were primarily the result of particle–vessel collisions resulting in brittle failure of the bitumen layer. Extractions reached a limit for each set of experimental conditions after approximately 5 min. The maximum concentration of bitumen in the oil sand fraction was 27% by weight or 50% by volume. A dimensional analysis showed extraction to be a function of Reynolds number, volume fraction of oil sands, and the ratio of clearance to mill radius.

INTRODUCTION

The oil sands in the Athabasca region of Alberta constitute a total oil reserve of approximately 900 billion barrels, not all of which is easily recoverable. Current production is via open pit mining and the alkaline Clark hot water process, resulting in aqueous effluents which are difficult to handle. The latter problem provides an incentive for the development of alternative recovery processes. One possible alternative or partial alternative is to mechanically upgrade the oil sands in cold water; that is, to separate sand and bitumen from the oil sand agglomerate by physical forces. Such an alternative is attractive since the chemical state and purity

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of bitumen and sand is unaltered and, hopefully, the environmental impact may be minimized.

The complicated mechanisms underlying the mechanical separation of the sand from the bitumen of the oil sands have not been studied extensively before, previous research being concerned primarily with the efficiency of the separation in devices in which the shear cannot readily be quantified (*1*, *2*). Since the process involves rupturing the bitumen film and separating it from the sand particles, consideration of the fluid dynamics and surface properties of the system is important for an understanding of the mechanisms of mechanical upgrading. In the present work a plate mill was used to study the effects of rotational speed, amount of oil sand, clearance between the rotating plate and the bottom of the mill, and time of contact.

EXPERIMENTAL

Equipment and Materials

The plate mill was 20.3 cm in diameter, constructed from mild steel (Fig. 1) and powered by a 1/3 hp, 0–400 rpm variable speed motor. Clearances between the rotating plate and the bottom of the mill were adjusted with a built-in micrometer. Rotational speed was measured with a tachometer.

The composition of the Athabasca oil sands used was 81.3% solids, 12.5% bitumen, and 5.1% water, an "average" composition of this deposit. Pretreatment of the feed to remove heterogeneities and lumps consisted of mixing the oil sands by hand and subsequently passing them through a screen of 8.5 mm mesh in lots of approximately 500 g as required. The prepared oil sands were stored in covered aluminum pans. Slight oxidation and dehydration, or aging, was noted in the unscreened oil sands over a period of 2 weeks. The screened oil sands showed a tendency toward more rapid aging, possibly due to the increased exposed surface area. Although care was taken to ensure that aged oil sands were not used for the experiments, the results indicate slight aging effects.

Procedure

A preweighed charge of oil sands was spread across the diameter of the mill. The charge was then covered with water at room temperature and the bottom part of the mill raised to the rotating plate until the predetermined clearance was attained. The bottom surface of the rotating plate was submerged in water so that there was no air space present. The ranges of

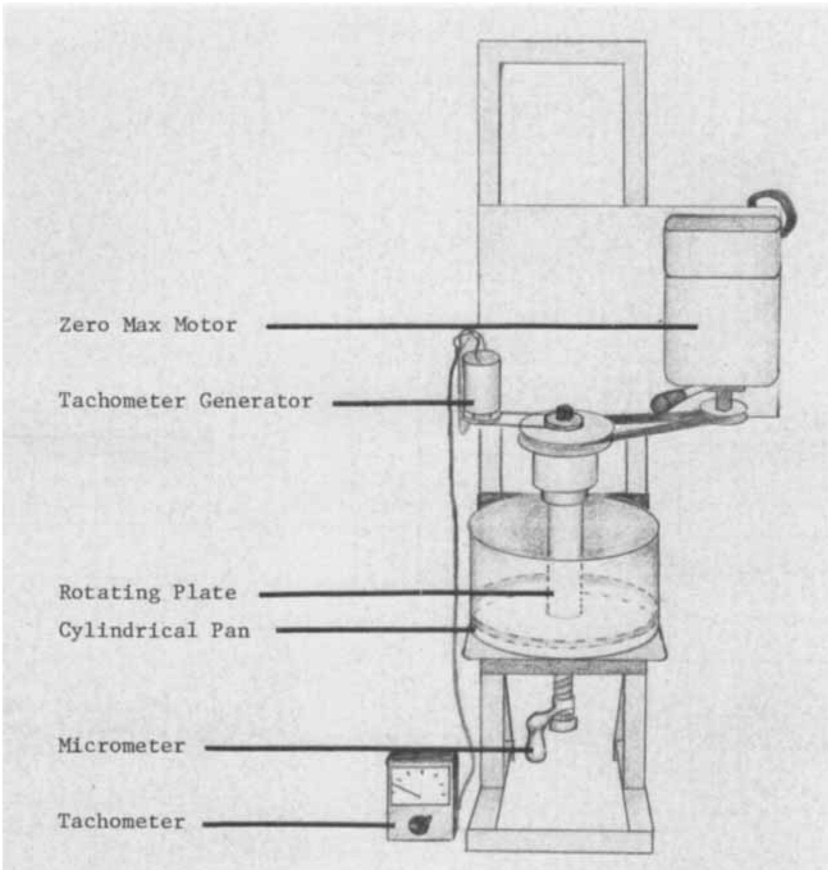

FIG. 1. Plate mill.

rotational frequency, time, clearance, and oil sand charge studied were 20 to 150 rpm, 0.5 to 60 min, 1.27 to 26.67 mm, and 10 to 100 g, respectively.

At the completion of the experiment, five distinct phases were observed: bitumen-free clean sand, small free unattached drops of bitumen, oil sand agglomerates (i.e., sand with adhering bitumen), water, and, sometimes, clay fines in suspension. All sand and bitumen phases were distributed in a disklike formation about the center of the bottom of the plate mill.

Analysis of the products was conducted according to the scheme depicted in Fig. 2. The contents of the mill were rinsed into a preweighed pan and subsequently sifted through a 0.5-mm mesh screen into a second preweighed pan. The second pan was deep enough so that the screen could be submerged under the water surface while the clean sand was shaken

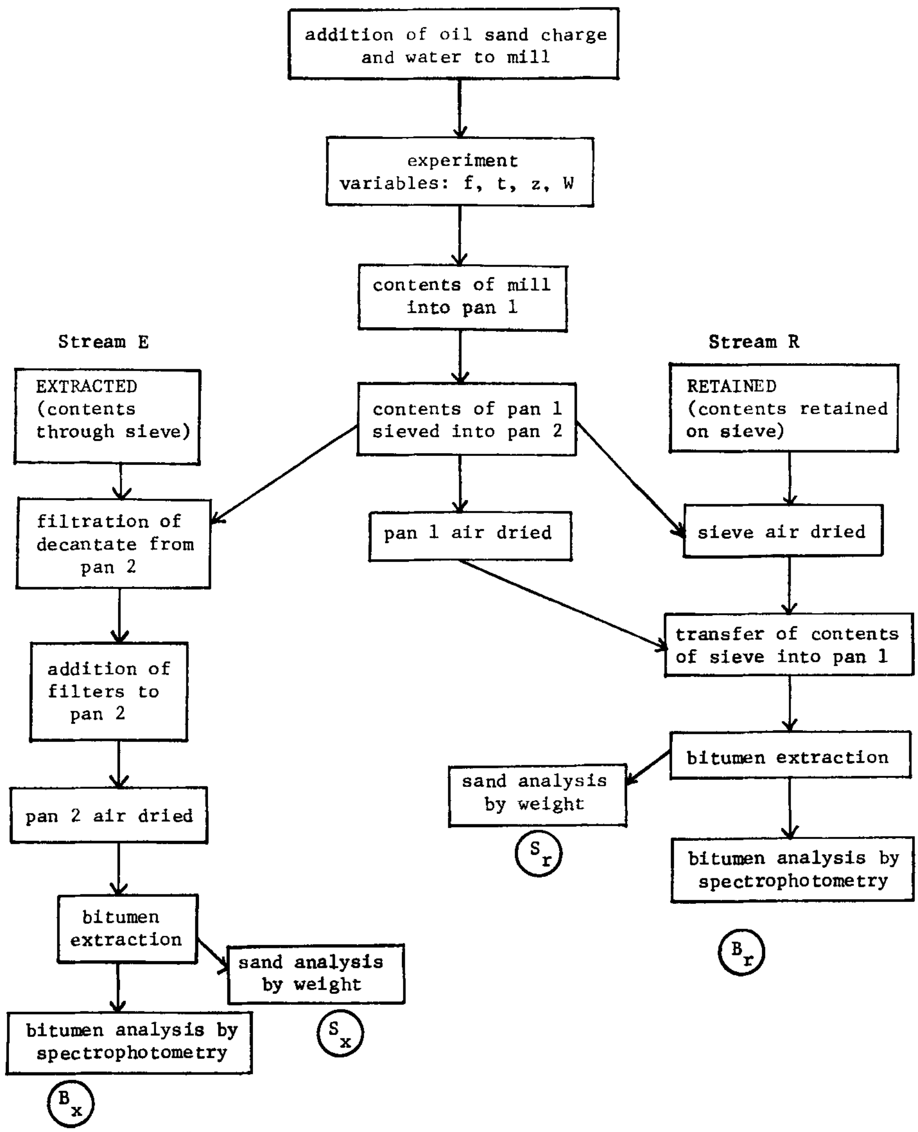

FIG. 2. Flow diagram of procedure.

through. Since the average sand particle diameter was measured to be slightly less than 0.5 mm, the screen mesh allowed only clean sand and unattached bitumen particles through. (The average diameter of the smallest sand agglomerate was greater than 0.5 mm since it contained at least two sand particles.) In this way original oil sands and any bitumen particles adhering to the oil sands were separated from free sand and bitumen particles.

After the screen and the first pan were air dried at approximately 120°C, the contents of the screen were scraped into the first pan and the screen rinsed with technical grade toluene into the same pan (Stream R in Fig. 2). Bitumen in this pan was then extracted with toluene until the washings were clear and colorless and diluted to 500 or 250 mL, as required, in a volumetric flask. This solution was further diluted by pipetting appropriate aliquots of bitumen solution and toluene, and then analyzed spectrophotometrically at 530 nm to determine the retained fraction of the total bitumen.

The second pan, which now contained only clean sand, was air dried at 120°C, cooled, and weighed to determine the weight of the retained sand fraction (Stream E in Fig. 2). Water in the second pan was decanted and filtered through two preweighed Whatman #1 filters which were subsequently added to the second pan and the total contents air dried at approximately 120°C. The extracted bitumen and sand fractions were found by the same methods used for the retained sand and bitumen fractions.

To calibrate the analytical procedure, the same method was also used for untreated oil sands using tapwater where required to aid in the screening. For untreated oil sands, free or extracted sand ranged from 1.5 to 20% of the total sand content. Oil sands that were dehydrated and oxidized tended to have a lower free sand content than fresh oil sands. For the untreated oil sands only, all of the sand and 93 to 97% of the bitumen were accounted for, errors being due to variations in the water and bitumen content of the oil sands.

RESULTS

Figure 3 illustrates a typical plot of extracted and retained sand fractions versus time for a fixed clearance and rotational frequency. The corresponding bitumen curves are illustrated in Fig. 4. In each case, extraction appears to be independent of time after an initial period. About 80% of the bitumen is accounted for.

All data are replotted against frequency for a given time to determine the effect of rotational speed. Sand extractions are approximately bounded

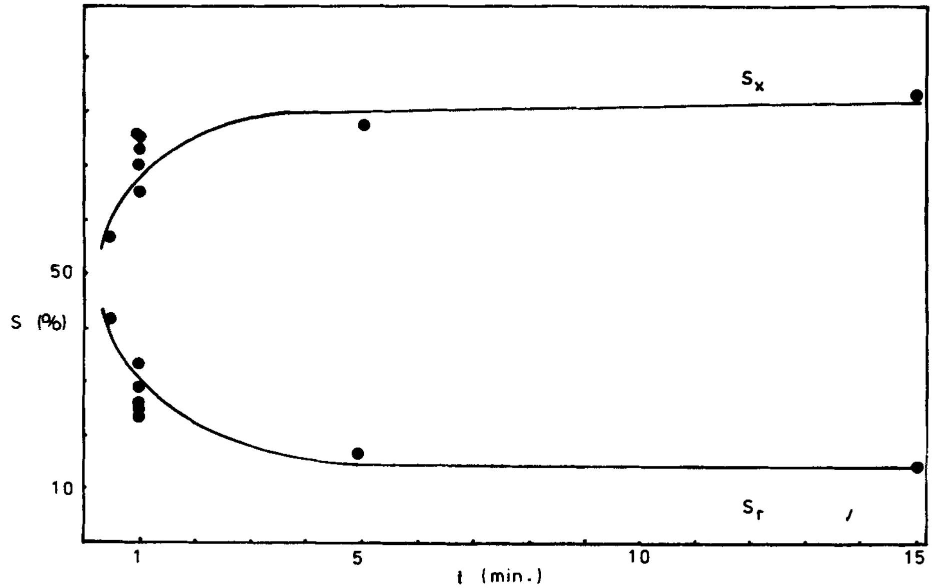

FIG. 3. Sand extraction, S_x, and sand retention, S_r, versus time for $f = 130$ rpm and $z = 2.54$ mm.

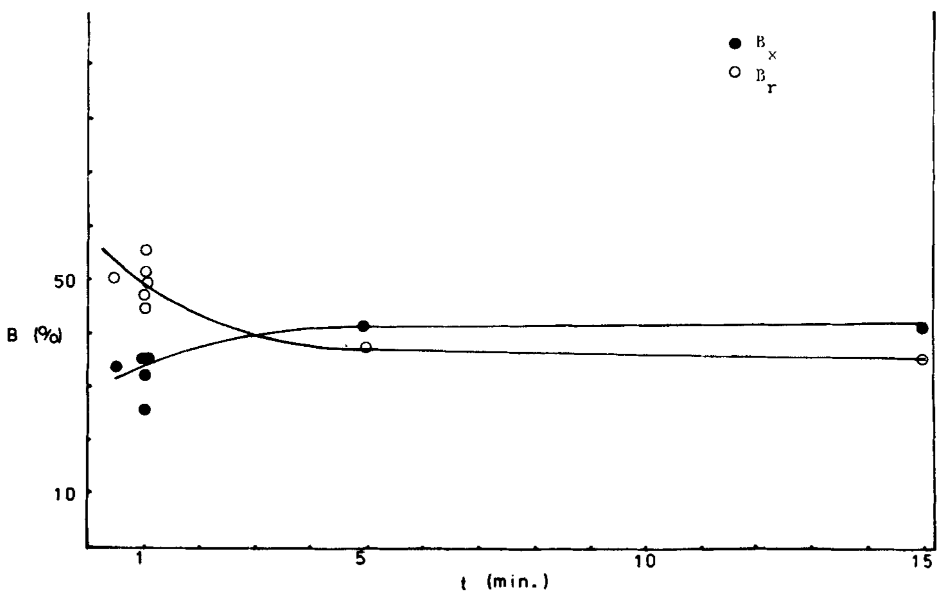

FIG. 4. Bitumen extraction, B_x, and bitumen retention, B_r, versus time for $f = 130$ rpm and $z = 2.54$ mm.

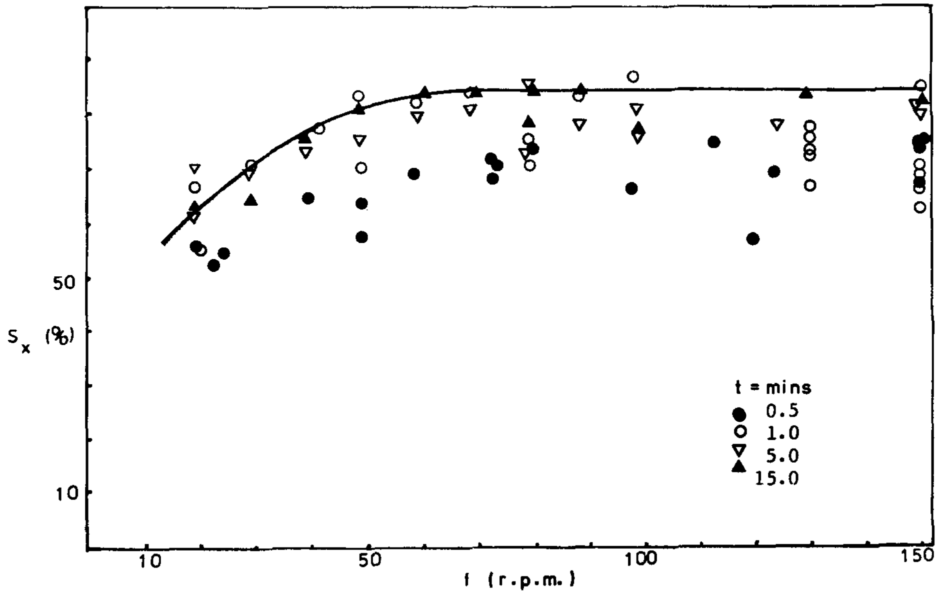

FIG. 5. Sand extraction, S_x, versus rotational frequency for $z = 2.54$ mm.

at the upper limit by the extractions at 15 min, as is demonstrated in Fig. 5. Sand extraction appears to be independent of rotational speed beyond 60 rpm. The retained sand fraction complements this trend, thus preserving the mass balance within the error of the experiment. A typical bitumen plot for $t = 15$ min is illustrated in Fig. 6. The retained bitumen fraction appears to be independent of rotational frequency beyond 50 rpm while the extracted fraction reaches a maximum at 50 rpm and decreases linearly with rotational frequency thereafter. This apparent inconsistency in the mass balance is explained by bitumen sticking to the apparatus but not included in the analysis because of the difficulty in determining whether or not the bitumen adhering to the vessel was initially free.

Sand extraction decreases rapidly from 93% at a clearance of 1.27 mm to 31% at a clearance of 8.89 mm as illustrated in Fig. 7. The extracted bitumen approaches a maximum of 36% at a clearance of approximately 3.8 mm, while the retained bitumen fraction approaches a limit of 84% at 8 mm as illustrated in Fig. 8. There is an apparent inconsistency in the mass balance for the reasons discussed previously.

Sand extraction is plotted against W/z in Fig. 9. In this way, the weight of oil sands per unit total active volume—termed herein the load—is conveniently represented since total volume is directly proportional to z in these experiments. In one curve, W/z varies by changing z at constant W, while in the other, W changes at constant z. That the curves are not

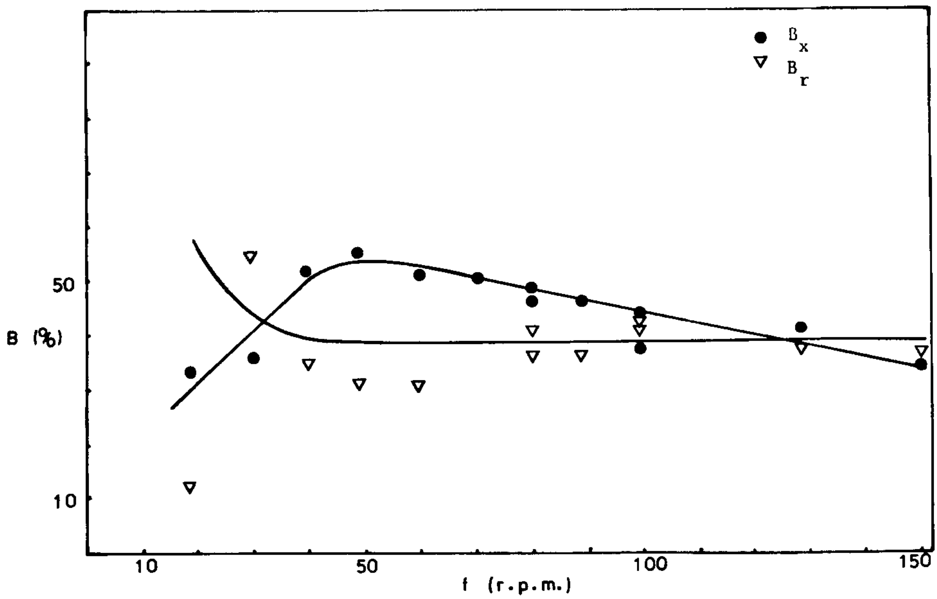

FIG. 6. Bitumen extraction, B_x, and bitumen retention, B_r, versus rotational frequency for t = 15 min and z = 2.54 mm.

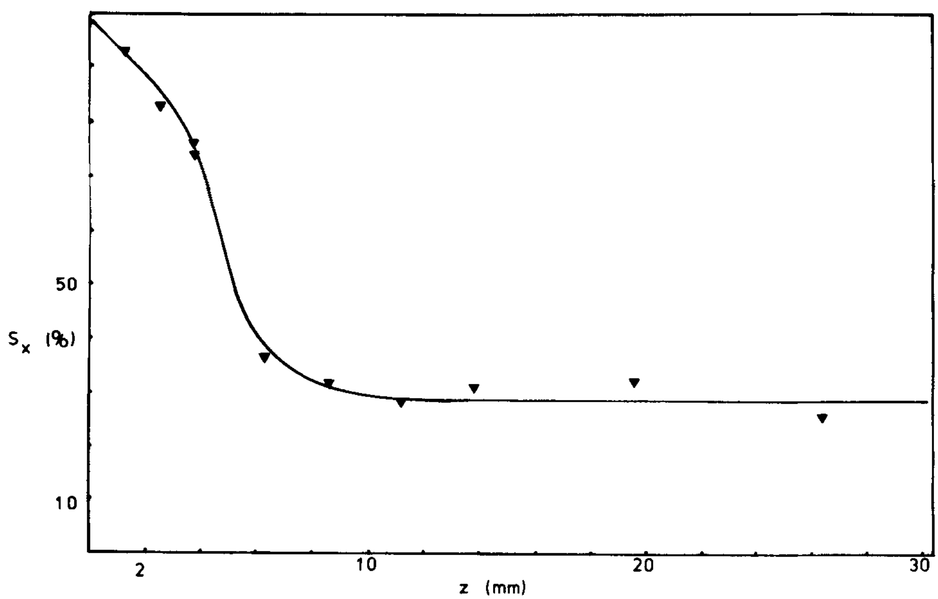

FIG. 7. Limit of sand extraction, S_x, versus clearance at f = 150 rpm.

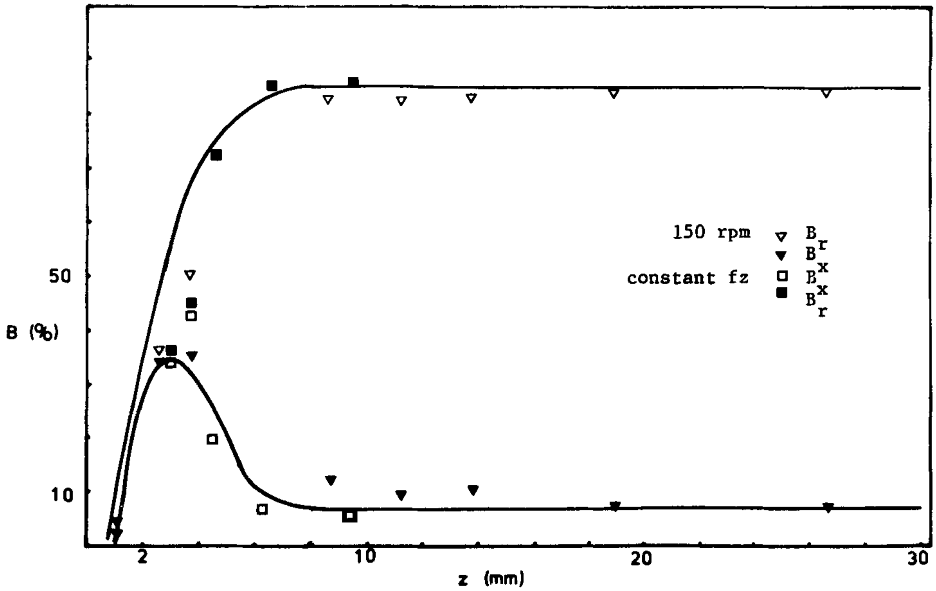

FIG. 8. Limits of bitumen extraction, B_x, and bitumen retention, B_r, versus clearance.

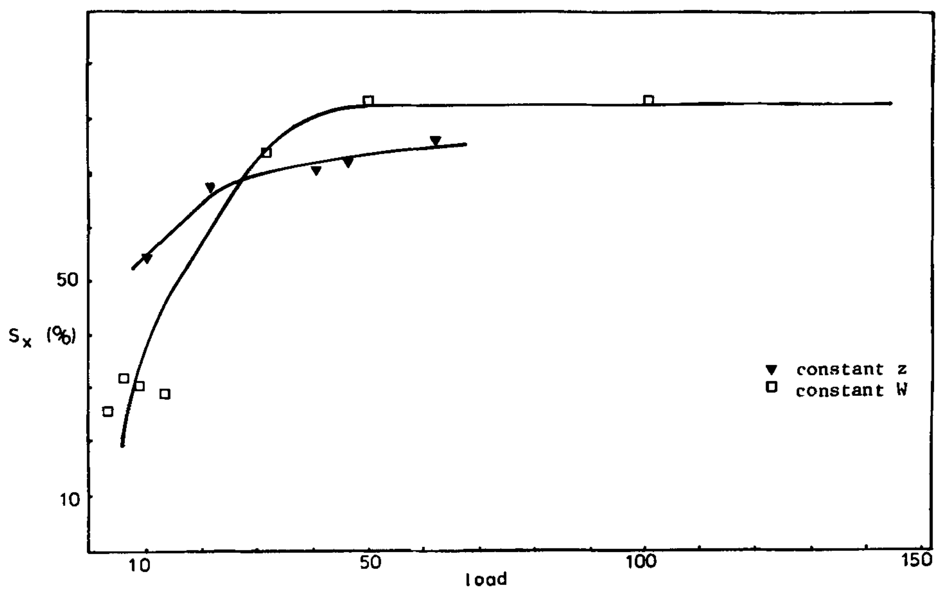

FIG. 9. Limit of sand extraction, S_x, versus load, W/z.

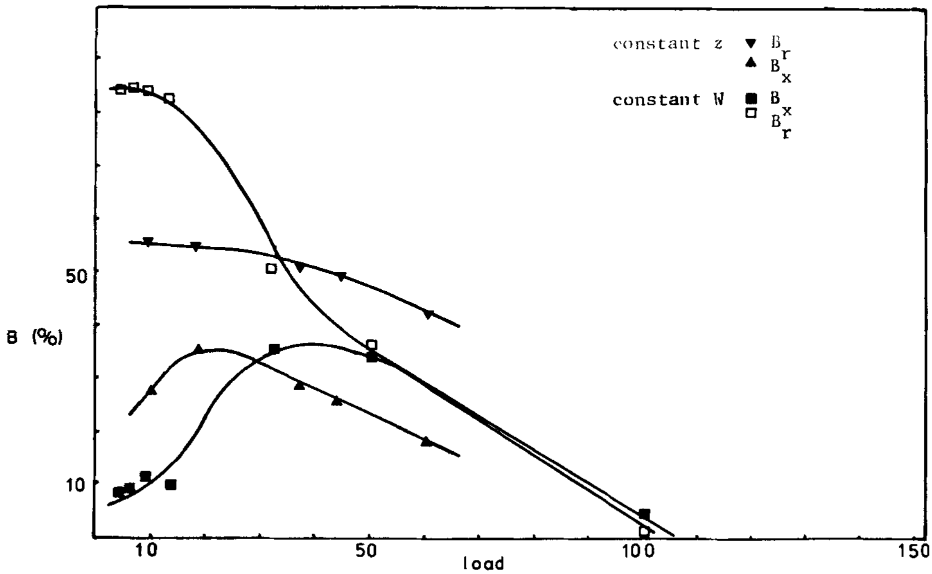

FIG. 10. Limit of bitumen extraction, B_x, and bitumen retention, B_r, versus load, W/z.

identical illustrates that sand extraction is not uniquely determined by W/z. The extracted and retained bitumen fractions are plotted against W/z in Fig. 10. The extracted bitumen fraction approaches a maximum of approximately 36% at $W/z=26.7$ and decreases from about 83 to 1% over the entire range tested.

DISCUSSION

Fluid Dynamics in the Plate Mill

The primary flow imparted to the fluid by the rotating plate has only an angular component of velocity (*3*). The velocity is zero at the center line and wall of the apparatus, decaying roughly exponentially with distance away from the plate. The superimposed secondary flow is toroidal. The Reynolds number is defined as $R^2\ 2\pi f/v$ (*4*); that is, a function of the radius of the plate rather than of z.

A factor complicating the flow of oil sands in the plate mill is that the oil sand and sand particles are much denser than the suspending medium, water, so that sedimentation of particles occurs. Also, the average diameter of the sand particle is slightly less than 0.5 mm, much larger than the average particle size of the suspensions used in viscometric studies in the literature.

Surface Energies

The surface tension of bitumen/water is 30 ± 5 ergs/cm^2; of the aggregate/water zero because the sand surface is approximately a free water surface; and of the bitumen/aggregate 17 ± 3 ergs/cm^2 (*5*). The actual value of the surface tension of a particular sample is highly dependent upon composition and aging, but these figures give a rough estimate. The change in free energy occurring during detachment of bitumen from the aggregate is then -47 ergs/cm, indicating that stripping of bitumen from the oil sands into water is a spontaneous process.

Mechanisms

A dimensional analysis of the experimental variables f, W, z, and R, and viscosity term μ to account for shear forces yields the relation for separation of free sand S_x:

$$S_x = F[(fW/\mu z)(R/z)^3] \tag{1}$$

A plot of the maximum free sand extracted for a given set of experimental conditions against fW/z^4 (Fig. 11) results in a reasonable fit of all data onto one line. The data are more scattered when plotted against fW/z^3 and fW/z^5.

The oil sand charge W can be represented as

$$W = \rho_{os}\pi R^2 z\varepsilon \tag{2}$$

Therefore, the group fW/z^4 can be represented as

$$fW/z^4 = f\rho_{os}\pi R^2\varepsilon/z^3 \tag{3}$$

Substitution of this group into (1) gives, neglecting constants,

$$S_x = F[(f\rho_{os}R^2\varepsilon/\mu)(R/z)^3] \tag{4}$$

The term $f\rho_{os}R^2/\mu$ is the Reynolds number while the term $z/R = Z$ is the dimensionless clearance as defined by Hill (*4*), so that

$$S_x = F[\mathrm{Re}\varepsilon Z^{-3}] \tag{5}$$

where ε is a concentration factor.

In the plate mill, two types of interaction are possible, particle–particle and particle–vessel. For the former mechanism, the abrasion rate/unit

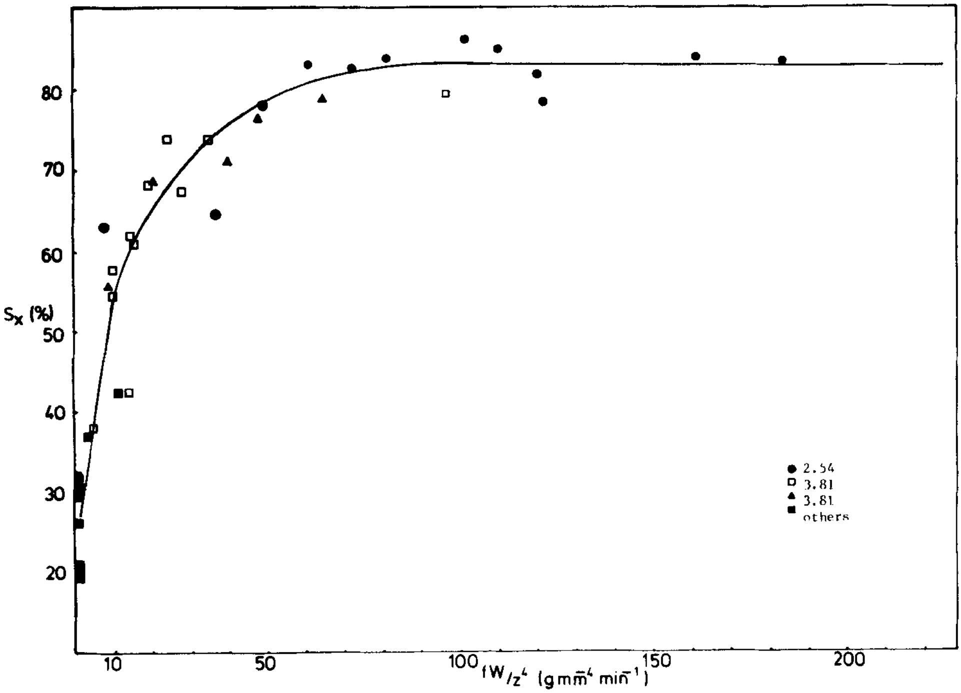

FIG. 11. Limit of sand extraction versus fW/z^4.

volume of fluid J is given by (*6*)

$$J \propto \bar{E}C_s^{\,2} \qquad (6)$$

while for the latter mechanism (*6*):

$$J \propto \bar{E}C_s \qquad (7)$$

It appears, therefore, that the separation of free sand and bitumen particles from the oil sands occurs by particle–vessel interactions. Observation of bitumen adhering to the sides of the apparatus at higher values of fW/z^4 lends further credibility to this hypothesis.

Even though the flow of water is mainly angular with toroidal superposition, the centrifugal forces exerted on the oil sands would cause collisions between the particles and the vessel. The net force experienced by the particle would also depend on the net viscosity of the slurry. Therefore the success of the collisions in breaking the sand/bitumen bond would be dependent on the Reynolds number.

To gain further insight into the mechanisms of sand removal by mechanical upgrading, the percent bitumen concentration of each fraction is

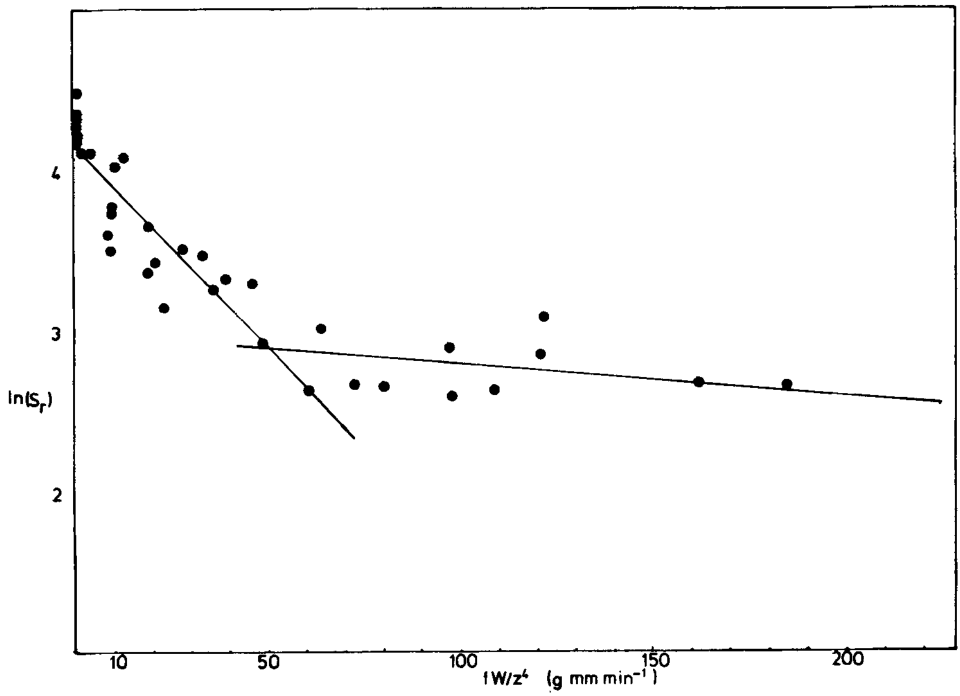

FIG. 12. Percent bitumen in extracted and retained fractions versus fW/z^4.

plotted against fW/z^4 (Fig. 12). The weight fraction of bitumen in the oil sand phase appears to approach a limit of 27%. Assuming a bitumen density of 1.01 g/cm^3 (*7*), a sand density of 2.65 g/cm^3, and neglecting the water content, this corresponds to a volume fraction of 50%. It would be reasonable to assume that at this volume concentration all of the sand particles in the oil sand agglomerate are covered with a thick layer of bitumen.

In very thin films, bitumen binders fail in a brittle manner with the fracture plane located in the adhesive layer. In very thick films, failure is by necking and in a ductile manner (*5*). Thus, as the percentage of bitumen in the oil sands increases, the mechanism changes from brittle fracture to ductile necking. Since the plate mill is conducive only to brittle fracture, a limit in sand extraction would be expected as was shown earlier.

Effect of Time on Extraction

The ratio of the retained sand fraction to the maximum retained sand fraction for a given set of experimental variables is shown as a function of

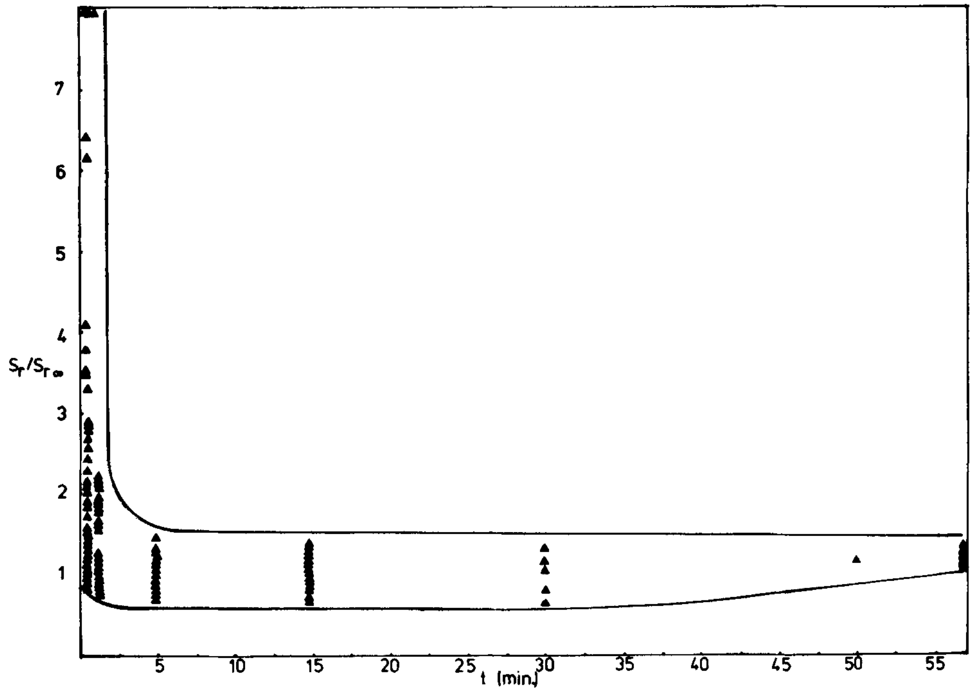

FIG. 13. Ratio of sand retention to ultimate relation, $S_r/S_{r\infty}$, versus time. Lines represent the upper and lower bounds of normalized experimental data.

time in Fig. 13. The envelope shown bounds the upper and lower limits of all data. The upper limit, which defines the highest retained sand data, is very high at $t = 0.5$ min but decreases rapidly to 1.4 at about $t = 5.0$ min and remains at that level. Reproducibility suffers severely if experimental times are short. The lower limit is constant at about 0.6 to $t = 30$ min and appears to increase to a value of 1 at $t = 60$ min. The time frame in which the experiments were conducted was too long to conclude anything about the rate of sand extraction, except that it happens within 5 min.

CONCLUSIONS

Separation of clean sand from oil sands in the plate mill is a function of frequency of rotation, oil sands charge, and clearance. The mechanism of sand extraction by mechanical upgrading appears to be predominantly particle–vessel interaction resulting in brittle failure. Concentration of bitumen in the oil sand fraction approaches a limit of approximately

50% by volume or 27% by weight. At this concentration of bitumen it is speculated that the mechanism changes to separation by ductile necking, controlled by bitumen viscosity.

The effect of scale-up was not investigated, but for processes involving a thicker layer of oil sands and a larger diameter of mill, gravitational forces may need to be taken into account.

Acknowledgments

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SYMBOLS

B_x	bitumen fraction passing through 0.5 mm screen; fraction consisting of free bitumen particles
B_r	bitumen fraction adhering to oil sands
C_s	initial concentration of particles (kg/m^3)
$\bar{E}$	mean energy dissipation rate/unit volume of fluid (W/m^3)
f	rotational frequency (rpm)
J	number of abrasion fragments produced per unit volume of fluid per unit time (m^{-3}/s)
R	radius of plate mill (mm)
S_x	sand fraction passing through 0.5 mm screen; fraction consisting of free sand particles
S_r	sand fraction adhering to oil sands
t	time (min)
W	oil sand charge (g)
z	clearance between rotating plate and bottom of mill (mm)
Z	dimensionless clearance (z/R)

Greek Letters

ε	ratio of oil sands volume to total volume
ρ_{os}	density of oil sands (g^{-3})
μ	viscosity (Nsm^{-2})

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