# Tar sand pretreatment with diluent

## J. Hupka and J.D. Miller

**Abstract** — *Important aspects of kerosene penetration into tar sand have been investigated. The natural tar sand porosity was measured and used to analyze the performance of the hot water process. Subsequently, pretreatment experiments, using 20-kg tar sand samples (Asphalt Ridge and Whiterocks, Utah) and kerosene as a diluent were carried out at the expected summer temperature (26°C) and the expected winter temperature (-14°C). The natural tar sand porosity accessible by diluent has a crucial impact on the reduction of bitumen viscosity and influences the penetration time required for successful bitumen separation from tar sand by hot water processing. Thus, the tar sand porosity is a critical variable that determines appropriate operating conditions. Experimental results indicate that diluent penetration into the Asphalt Ridge tar sand (high porosity) is almost complete after 30 min, whereas for the Whiterocks tar sand (low porosity) the penetration process is much slower, being still incomplete after 15 hours regardless of the ambient temperature.*

## Introduction

As is true in most process engineering situations, operation of a hot water processing plant for the recovery of bitumen from tar sand strongly depends on the uniformity of the feed material. This becomes even more crucial when diluent is used prior to digestion in order to reduce bitumen viscosity (Hupka, Oblad and Miller, 1986; Hupka, Miller and Cortes, 1983). The critical bitumen viscosity below which a rapid increase in separation efficiency is observed was found to be 1.5 Pa•s (15 cP) (Hupka, Miller and Cortes, 1983). The amount of diluent (such as kerosene or naphtha) required to lower the digestion-separation temperature to 50°-55°C for most Utah tar sands is from 10 to 35 wt% with respect to bitumen content, and can be predicted from bitumen viscosity curves (Hupka, Oblad and Miller, 1986; Hupka, Miller and Cortes, 1983). Some organic solvents may exhibit greater dissolution power with respect to bitumen than kerosene or naphtha, however, due to cost and/or volatility, their commercial utility is limited (Yang, Bukka and Miller, 1989).

An industrial operation involving diluent spraying of crushed tar sand will require tight measures to prevent health and fire hazards and avoid air pollution. Because of the diluent vapor pressure, the system must be maintained below 40° to 50°C to prevent the ignition risk of hydrocarbon vapors. A rotating drum, which can easily be designed to provide sealed-off space for diluent spraying, was selected for tar sand mixing in our experiments. The importance of diluent pretreatment is discussed with respect to certain tar sand properties that impact the separation efficiency in hot water processing.

## Fundamental considerations

Two phenomena control diluent mixing into the bitumen phase during pretreatment of tar sand, namely capillary action and diffusion. The size of tar sand feed depends on tar sand origin, properties and the method of mining and handling of the mined material. Consolidated tar sand, such as the Whiterocks tar sand, requires crushing, which results in 1-cm to 3-cm aggregates. Unconsolidated tar sand, such as the Asphalt Ridge tar sand, can be processed as mined, but the feed size is distributed over a much larger range, e.g. from 0.5 cm to 30 cm. Lumps of unconsolidated tar sand break easily to smaller fragments when submitted to autogenous grinding. Diluent is sprayed on the surface of the feed tar sand, and the capillary action enables the diluent to penetrate and wet the bitumen contained therein. With respect to diluent pretreatment, the actual tar sand porosity, i.e. the pore volume of the bitumen impregnated sandstone, which is filled with gaseous hydrocarbons, air or water, is of critical importance for diluent mixing due to the capillary transport. The unoccupied-by-oil part of the pore volume will be termed here the natural porosity of tar sand. After penetration and wetting, diffusion finally leads to a uniform mixture of bitumen and diluent. The lower the tar sand porosity and the higher the bitumen viscosity, the longer the penetration time required for complete and uniform bitumen dilution. The wetting ability of the diluent is of pronounced importance, particularly when capillaries are filled with water. Diluent penetration will also depend on the ambient temperature (water may freeze in tar sand pores in the winter season).

Diluent imbibition of the tar sand can be modelled as an absorption process in a bundle of capillary tubes. Some tar sands may be partially saturated with water. In such cases, the diluent will have to displace capillary water. Assuming that the porosity is of an open type, a mathematical approach used to describe oil migration into a porous material (Leibovich, 1977) can be adopted for diluent penetration. The capillaries in the tar sand are considered to be sufficiently small that the influence of gravity can be neglected compared to the capillary pressure. The time (t, in seconds) required to fill the capillary can thus be derived from the Poiseuille and the Young-Laplace equations:

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$$t = 8\mu_d L^2/d\Delta s \qquad (1)$$

$$\Delta\sigma = \sigma_{ws} - \sigma_{ds} = \sigma_{dw}\cos\beta$$

Where:

$\mu_d$ = dynamic viscosity of diluent, Pa•s.
$L$ = capillary length, m.
$d$ = capillary diameter, m.
$\sigma_{ws}$ = water-solid (capillary wall material) interface tension; or gas-solid interface tension when no water is present, N/m.
$\sigma_{ds}$ = diluent-solid (capillary wall material) interface tension, N/m.
$\sigma_{dw}$ = diluent-water interface tension; or diluent-gas interface tension when no water is present, N/m.
$\beta$ = contact angle of the interface with the capilary wall measured through the most dense phase, deg.

It follows from Eq. (1) that the transport of diluent can be completed in a few minutes when the dimension of the tar sand aggregate is substituted for L. This is true even if the diluent is not sprayed uniformly, provided that the diluent preferably wets the tar sand ($\Delta\sigma\gg0$), and $\mu_d$ does not increase due to bitumen dissolution. In reality, however, the "diameter" of the pores change, and the pore length L may exceed the dimensions of the tar sand aggregate. Additionally, the diluent viscosity can increase significantly if the native bitumen viscosity is low. Also, it should be recognized that some tar sand capillaries are open on one side only which can contribute to an extended diluent penetration time. Of course, in order to maintain a large $\Delta\sigma$ the diluent should not be added during the tar sand digestion step (because $\sigma_{dw}$ drops in the alkaline environment) but in the pretreatment step prior to digestion. Finally, very limited driving force for diluent penetration is available in those aggregates of tar sand where sand grains are not completely covered with bitumen. In view of the foregoing, Eq, (1) probably represents the best case situation.

## Natural porosity of tar sand

Much faster diluent penetration into the bitumen can be expected if the natural pore volume is greater than the required amount of diluent. Otherwise, diluent penetration would be slow, and additional reduction in the size of tar sand aggregates would be required for effective diluent diffusion. Based on the literature, the porosity (including all fluid phases) of the tar sand host rock ranges from 15 to 40% (Anon, 1989), see Table 1. These values can be related to the original, almost unconsolidated sands and soft sandstone, ranging in texture from a fine silt to a coarse grit. Oil saturation usually represents 50% of the porosity.

Consolidated tar sands (i.e. tar sands in which sand grains are firmly bound by carbonates and/or silicates; e.g from the Sunnyside and Whiterocks deposits) require feed size reduction down to a few millimeters, unless a powerful shear force field is provided during digestion to facilitate disintegration of the tar sand aggregates down to the elemental sand grains. An extensive size reduction of the consolidated tar sand automatically leads to better bitumen exposure to the diluent. However, the feed size reduction (in addition to that obtained during the ore excavation) is usually not necessary for unconsolidated tar sands, such as the tar sands from the Asphalt Ridge and P.R. Spring deposits. In any case, the lack of sufficient pore volume available for diluent accommodation may seriously hinder the dilution rate, resulting in an extended penetration time or incom-

**Table 1 — Tar sand reservoir characteristics (from Anon., 1989)**

| Location | Grade % oil | Porosity % | Oil sat. % | Overburden ft. | Thickness ft. |
|---|---|---|---|---|---|
| Utah | 4-10 | 15 | 23-72 | 0-500 | 10-60 |
| Texas | — | 30 | 35-55 | 1500 | 15-300 |
| Kentucky | 6-10 | 15 | 20-70 | 0-200 | 10-50 |
| California | ≤30 | 30-40 | 50-75 | 0-3200 | 50-400 |
| Alabama | 1.5 | 6-24 | 4.56 | 0-1000 | 10-300 |

plete bitumen displacement from sand. The natural pore volume $V_p$ can be calculated by subtraction of the volume of bitumen and sand from the total volume $V_T$ of the tar sand:

$$V_T - V_p = m_b/\rho_b + m_s/\rho_s \qquad (2)$$

where:

$m_b, m_s$ = mass of bitumen and sand.
$\rho_b, \rho_s$ = density of bitumen and sand.

By definition natural porosity $\varepsilon = V_p/V_T$ and the weight fraction of bitumen in the tar sand $x_b = m_b(m_b + m_s)$ allow us to eliminate $V_T$ and $m_s$ from Eq. (2):

$$V_p = m_b[1/\rho_b + (1-x_b)/\rho_s x_b]\,\varepsilon/(1-\varepsilon) \qquad (3)$$

Assuming complete filling of the natural pore volume by diluent (density $\rho_d$), the diluent mass $m_d = \rho_d \cdot V_p$. Thus the weight percent of diluent in bitumen that can be accommodated by the tar sand pores ($\alpha$) is:

$$\alpha = m_d/m_b = [1/\rho_b + (1-x_b)/\rho_s x_b]$$

$$[\varepsilon\rho_d/(1-\varepsilon)\,100\%] \qquad (4)$$

It is assumed that only the weight percent of diluent represented by the parameter $\alpha$ is readily available for bitumen dilution in the tar sand.

To estimate how amenable a particular tar sand may be to diluent pretreatment, the tar sand natural porosity was measured, the parameter $\alpha$ calculated from Equation (4), and the data compared with the required amount of diluent estimated from the viscosity curves (Hupka, Oblad and Miller, 1986; Hupka, Miller and Cortes, 1983).

*Porosity measurements*

The pore volume available for diluent was initially determined by submersion of tar sand samples in two liquids of differing ability to wet, and thus penetrate, the capillaries. These liquids were water and methyl alcohol. It was found that water did not migrate to any great extent into the capillaries of most tar sands, while methanol did. The difference in volume for the same tar sand sample immersed in water, and then in methanol, allows for the determination of the natural porosity. Methanol mixes well with water and does not dissolve the bitumen to any appreciable extent (thus the tar sand structure and bitumen distribution within the pores remains unaltered) which is crucial for the measurement. Volumetric measurements were supplemented by weighing each tar sand sample: prior to and after submersion in water, prior to and after submersion in alcohol, and after alcohol removal under vacuum at 25°C for 24 hours. Tar sand samples of 20 to 100 g were placed in water for a few minutes only, while soaking in methanol required at least 24 hours and frequent shaking to facilitate gas phase release from the pores. Each value of the natural porosity for a given tar sand

Table 2 — Natural porosity and diluent availability during pretreatment for several Utah tar sands and for a sample of Athabasca tar sand

| Tar sand Deposit | Nature* | Bitumen content wt. % | Bitumen viscosity at 50°C, Pa·s | Tar sand apparent density, kg/m³ | Natural porosity** range, % | Mean value, % | Amount of diluent Required† wt. % | Available†† wt. % |
|---|---|---|---|---|---|---|---|---|
| Athabasca | N | 14.4 | 5 | 1910-2060 | 10.5-15.2 | 12.0 | 5 | 36.8 |
| Asphalt Ridge | N | 12.5 | 80 | 1980-2050 | 3.2-5.7 | 5.0 | 14 | 16.0 |
| Hill Creek | C | 3.4 | — | 1890-1960 | 15.0-15.5 | 15.2 | — | 177.3 |
| P.R. Springs | N | 12.0 | 280 | 1870-2080 | 2.7-6.2 | 5.5 | 20 | 18.3 |
| Sunnyside | C | 9.5 | 1500 | 2030-2290 | 1.0-1.6 | 1.2 | 24 | 4.7 |
| Whiterocks | C | 7.5 | 110 | 2230-2240 | 1.9-2.2 | 2.0 | 17 | 9.7 |

* C – consolidated; N – not consolidated
** Pore volume in tar sand occupied by gas, air or water, and open for diluent penetration
† Based on viscosity curve for processing at 50° C (Hupka, Miller and Cortes, 1983)
†† Assuming complete filling of pore volumes with diluent

sample was obtained from at least five independent samples.

The original technique for porosity determination using methanol was supplemented by the extraction of the tar sand sample in an organic solvent and simultaneous volumetric determination of the gas phase released during extraction. The natural porosity data from both methods were identical, and the experimental error was reduced to ±5%. The greatest contribution to the experimental error arose from the determination of the tar sand sample volume. The data obtained also allowed for the calculation of the apparent density, which includes water present in the tar sand sample.

*Porosity results and discussion*

The original porosity of the host sandstone and the degree of saturation with bitumen determine the natural porosity. Higher natural porosity may also mean greater sensitivity of the mined tar sand to oxidation, which can alter processing efficiency. The range in experimental porosity was found to depend upon the location of the tar sand deposit, as reported in Table 2. With respect to hot water processing at 50°C, the data from Table 2 indicate that only for certain tar sands is the pore volume sufficient to contain all the kerosene necessary for bitumen dilution. In the case of the Hill Creek, Asphalt Ridge and Athabasca tar sands complete digestion and release of bitumen from sand is possible. For the other tar sands undigested particles are frequently found in the digested tar sand slurry. These undigested particles will report to the concentrate or will be found in the tailings, depending on their residual bitumen content, the degree of bitumen dilution, and the bitumen surface characteristics (Hupka, Lelinski and Miller, 1991).

By limiting the amount of diluent available to the bitumen, the natural tar sand porosity can be a decisive factor in determining the lower limit of the processing temperature. For example, the porosity of the P.R. Spring tar sand is 5.5% which allows for only 18.3% diluent (with respect to bitumen) while 20% diluent is required at 50°C to secure bitumen viscosity below 1.5 Pa·s. The extra diluent will not be able to fill the capillaries and hence will not effectively penetrate the tar sand in the few hours of pretreatment time that would be available in a commercial operation. In this case, a diminished bitumen recovery would be expected.

The impact of the natural porosity can be better illustrated with the Sunnyside and the Whiterocks tar sands. For example, hot water processing of the Sunnyside tar sand yields bitumen concentrates of at least 30% lower grade and tailings containing twice as much residual bitumen when compared to the bitumen concentrate and tailings from the Asphalt Ridge tar sand, despite

proper diluent application in the pretreatment step preceding digestion (Hupka, Miller and Cortes, 1983; Yang, Bukka and Miller, 1989; Misra and Miller, 1980; Hupka and Miller, 1991). The poor separation was previously attributed to compositional and, eventually, chemical heterogeneity. Our porosity data provides new evidence that the lower separation efficiency for bitumen recovery from these tar sands can also be related to porosity and inadequate viscosity control during pretreatment.

The apparent density, which is given in the fifth column in Table 2, does not always correlate with the measured tar sand porosity, because some pores are closed to diluent penetration. It was observed, that porosity determined from several smaller pieces of tar sand was greater than the porosity determined from one larger tar sand fragment, which may support the existence of the inaccessible void space within the tar sand.

## Tar sand pretreatment with diluent

The bitumen from almost all US deposits is more viscous than that from the Athabasca tar sands, therefore, a moderate processing temperature for the US tar sands requires significant bitumen dilution with an organic solvent during the tar sand pretreatment step (Hupka, Miller and Cortes, 1983). The pretreatment step involves diluent spraying on the "dry" tar sand feed prior to digestion. Considering the bitumen concentrate clean-up, which is one of the final operations for the hot water process, the more diluted the bitumen prior to digestion the more favorable are the subsequent dissolution kinetics of the bitumen concentrate in the organic solvent (kerosene) (Chakraborti, et al., 1993).

*Experimental procedure*

To select proper pretreatment conditions and to provide design information for pretreatment, diluent penetration experiments have been completed. Two tar sand samples of comparable bitumen viscosity, namely samples from the Asphalt Ridge and the Whiterocks deposits, were selected. The Asphalt Ridge tar sand was used as received without additional crushing, thus, fragments up to 30 cm were present. The Whiterocks tar sand had to be crushed and screened. The resulting product of up to 2 cm in size was easy to handle, because it did not undergo secondary consolidation.

The experiments and procedure involved both a short time for mixing and a longer time for penetration after diluent addition. The experiments were carried out in a cement mixer (33 rpm, max. load 50 kg, max. internal dia. 60 cm) using 20-kg feed samples. The tar sand was placed in the rotating cement

Table 3 — Tar sand pretreatment with diluent.

**Processing conditions**

| | |
|---|---|
| Weight of tar sand sample ................................................................................... | 20 kg |
| Diluent ................................................................................................................. | kerosene |
| Amount of diluent added (with respect to the bitumen content in tar sand) ........... | 13% |
| Diluent application time ...................................................................................... | 40 sec |
| Mixing device ....................................................................................................... | rotating drum with lifters, 33 rpm (42" diam. cement mixer) |

| | Experiment | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Description | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Tar sand deposit* | W.R. | W.R. | W.R. | W.R. | W.R. | A.R. | A.R. | A.R.** | A.R. | A.R. |
| Bitumen content, wt. % | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| Temperature, °C | 14 | −14 | 24 | 26 | 25 | −13 | −14 | 26 | 23 | 23 |
| Mixing time, min. | 2 | 5 | — | 2 | 5 | 2 | 5 | — | 2 | 5 |
| Maximum size of tar sand fragments, cm | <2.5 | <2.5 | <1.5 | <1.5 | <1.5 | 15 | 10 | <8 | <5 | <5 |

| Penetration time, min*** | Average bitumen content based on six samples, wt. % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 7.26 | 7.23 | 7.22 | 7.23 | 7.20 | 12.57 | 12.51 | 12.56 | 12.68 | 12.61 |
| 10 | 7.30 | 7.30 | 7.27 | 7.31 | 7.25 | 12.59 | 12.51 | 12.49 | 12.71 | 12.65 |
| 20 | 7.22 | 7.29 | 7.22 | 7.26 | 7.28 | 12.73 | 12.70 | 12.53 | 12.70 | 12.54 |
| 60 | 7.28 | 7.26 | 7.20 | 7.26 | 7.25 | 12.64 | 12.76 | 12.50 | 12.57 | 12.53 |
| 180 | 7.23 | 7.28 | 7.30 | 7.24 | 7.33 | 12.66 | 12.89 | 12.47 | 12.54 | 12.50 |
| 960 | 7.25 | 7.23 | — | 7.27 | 7.30 | 12.62 | 12.65 | — | 12.40 | 12.49 |

\* W.R. - Whiterocks (southwest); A.R. – Asphalt Ridge.
\** No kerosene was used in these experiments.
\*** Penetration time which elapsed when samples were taken varied slightly from one experiment to the next; exact values were used in Figs. 1–6.

mixer for preliminary mixing of three minutes for each load. During this time the Asphalt Ridge tar sand feed underwent extensive autogenous size reduction, which was further enhanced after diluent addition in the subsequent operation. This next operation involved kerosene spraying (13 wt% with respect to bitumen) for 40 seconds. The drum was then allowed to rotate for an additional two or five minutes (mixing time). When mixing was complete, the tar sand was discharged to a polyethylene tray and a layer of approximately 42 x 38 x 8 cm was formed. Because of mixing, the tar sand feed now contained a broad size distribution of particles, beginning from almost elemental sand grains. The tar sand layer was covered with a loose polyethylene (PE) sheet between sampling periods. Depending on conditions water condensation on the PE was observed. Six 50- to 60-g cylindrical samples of the tar sand from different locations throughout the entire layer were taken after a certain penetration time (usually after three, ten and 20 minutes and one, three and 16 hours) and were then analyzed in the Dean-Stark apparatus. The Dean-Stark analysis involved tar sand extraction with toluene and provided the content of water, the organic phase (bitumen+kerosene) and solids. Diluent spraying was done at both summer (26°C) and winter (-14°C) temperatures. Frozen tar sand samples were taken with a sharp-edged metal sampler, which was forced through the layer with a hammer. The experimental conditions are given in detail in the upper part of Table 3.

An important point is revealed in the lower part of Table 3, which comprises the average bitumen content based on six samples related to a given penetration time. The average bitumen content was obtained by subtraction of the known kerosene addition, which amounted to 13% of the bitumen content. The average bitumen content remains relatively constant throughout the entire experiment, indicating insignificant kerosene loss due to evaporation, and demonstrating the reliability of the experimental technique. On the other hand, the standard deviation of bitumen+kerosene content changes significantly with the penetration time, as discussed in the next paragraph.

*Pretreatment results and discussion*

The effectiveness of diluent migration into the tar sand was evaluated by simple statistical analysis of the data pertaining to the organic phase (bitumen+diluent) content. The standard deviation (s) for each set of the six tar sand samples was calculated:

$$s = \pm[E(f_1^2 + f_2^2 + \ldots + f_N^2) / (N-1)]^{1/2} \quad (5)$$

where:

f = deviation of particular measurement from the mean ($\bar{x}$).
N = number of measurements; N = 6.

To better compare tar sands of different bitumen content, the relative standard deviation (RSD), also known as the coefficient of variation or the relative error, was used:

$$RSD = \frac{s}{\bar{x}} \cdot 100\% \quad (6)$$

and plotted versus time that had elapsed after diluent addition to the tar sand (Figs. 1 to 4). It was anticipated that the kerosene distribution would become increasingly more uniform due to the capillary action. Additionally, because of the dissolution in the diluent, the bitumen should also be more evenly distributed throughout the tar sand. Therefore, after a certain time, the RSD should reach a plateau, which would indicate the end of the capillary transport of the diluent, and would simultaneously determine the minimal penetration time necessary for the tar sand pretreatment step.

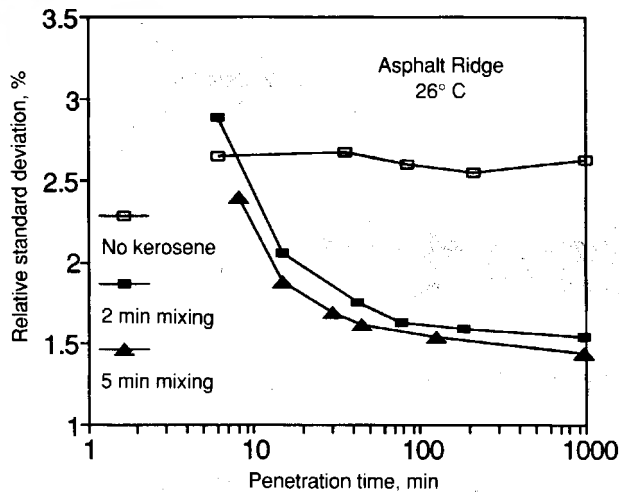The experimental results for the Asphalt Ridge tar sand

Fig. 1 — Relative standard deviation of bitumen+kerosene content for Asphalt Ridge tar sand after pretreatment in rotating drum and storage in 8-cm-thick layer at 26°C; 13 wt% kerosene with respect to bitumen.
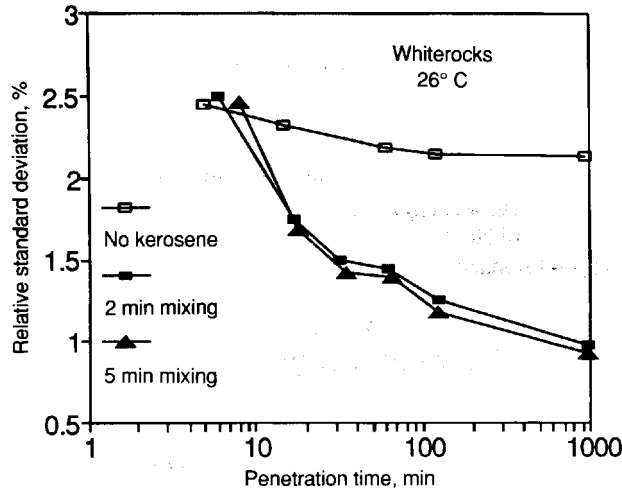
Fig. 3 — Relative standard deviation of bitumen+kerosene content for Asphalt Ridge tar sand after preteatment in rotating drum and storage in 8-cm-thick layer at -14°C; 13 wt% kerosene with respect to bitumen.

Fig. 2 — Relative standard deviation of bitumen+kerosene content for Whiterocks tar sand after preteatment in rotating drum and storage in 8-cm-thick layer at 26°C; 13 wt% kerosene with respect to bitumen.

Fig. 4 — Relative standard deviation of bitumen+kerosene content for Whiterocks tar sand after pretreatment in rotating drum and storage in 8-cm-thick layer at -14°C; 13 wt% kerosene with respect to bitumen.

sample at 26°C ambient temperature are presented in Fig. 1. Each curve in this plot represents one of three different experimental conditions: five minutes tar sand mixing after diluent spraying, two minutes tar sand mixing after diluent spraying, and a blank experiment in which no diluent was used (the tar sand was formed into a layer after three minutes of preliminary mixing, see experimental procedure). The RSD diminishes rapidly for the first 10-20 minutes and seems to approach a plateau after 60-80 minutes of diluent penetration. The RSD of the bitumen content, when diluent was not used, remained unchanged and relatively high (approximately 2.7%) indicating local compositional heterogeneity of the 20 kg tar sand sample being examined. Prolonged mixing times had little effect on the diluent penetration rate at 26°C.

The RSD change for the Whiterocks tar sand (at the expected summer temperature) followed the same trend as that obtained for the Asphalt Ridge tar sand. Nevertheless, the scatter of the organic phase content, as given by the magnitude of the RSD, was slightly smaller than that for the Asphalt Ridge tar sand, which can be attributed to the more uniform saturation of the tar sand with bitumen. This feature may also have resulted from the smaller size and narrower size distribution of the feed material. The migration of the diluent was slower, with the RSD reaching a plateau after 15 hours. The prolonged diluent-bitumen contact resulted in mutual dissolution of both organic phases, which
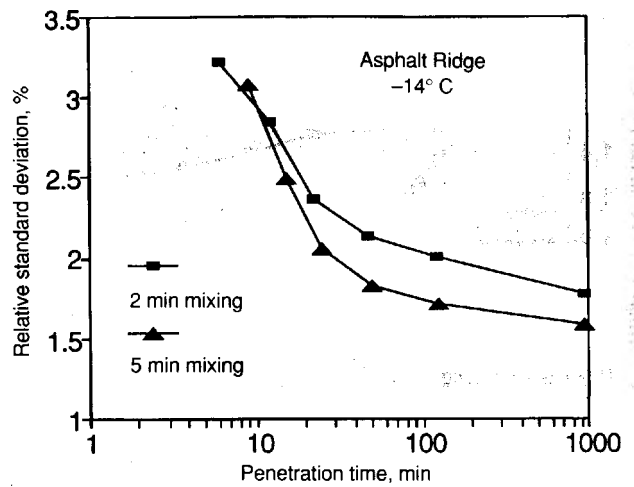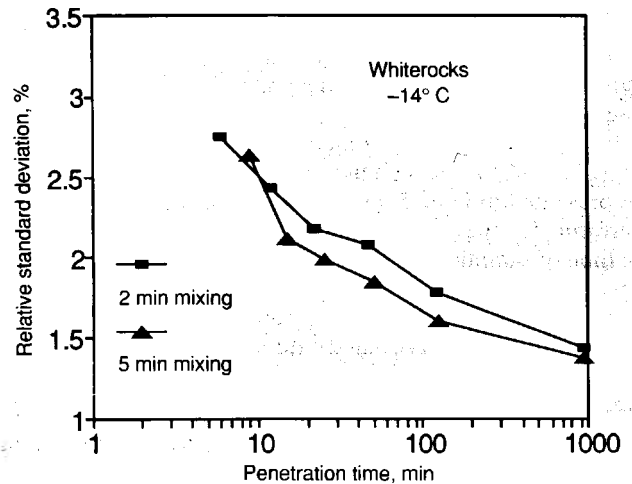
resulted in an extended penetration time. In the case of the Whiterocks tar sand, the diluent penetration could also be enhanced from macropores formed by the well-crushed feed material. However, these void spaces are of much greater size when compared to natural capillaries, and under these circumstances diluent transport may no longer be dependent on capillary forces.

Another set of experiments was carried out during the winter season, when the outside temperature dropped to -14°C. The results are presented in Fig. 3 and 4. For both cases, the penetration rate did not change when compared to the summer temperature (26°C). The lack of significant difference in the penetration rate for the summer and winter temperatures is somewhat surprising. According to Eq. (1), the time for penetration should be dependent on the temperature sensitive viscosity term. Hence, a lower temperature should lead to higher diluent viscosity and a longer penetration time. Such is not the case, and it seems that other factors must be taken into consideration. For example, the viscosity of the diluent in the summer may be higher than expected due to bitumen dissolution into the diluent. Also, it can be imagined that the higher summer temperatures may seal off pores and thus make penetration more difficult.

Some beneficial effect of the extended mixing can, however, be noticed. Frozen Asphalt Ridge feed fragments did not break so easily during the preliminary preparation of tar sand prior to
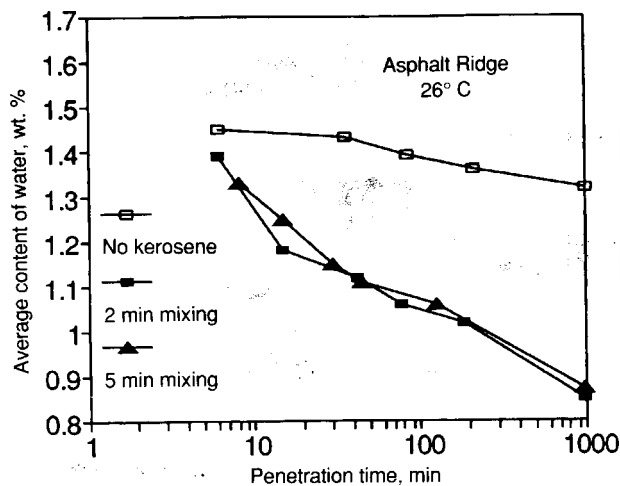
Fig. 5 — Average water content for Asphalt Ridge tar sand after preteatment in rotating drum and storage in 8-cm-thick layer at 26°C; 13 wt% kerosene with respect to bitumen.
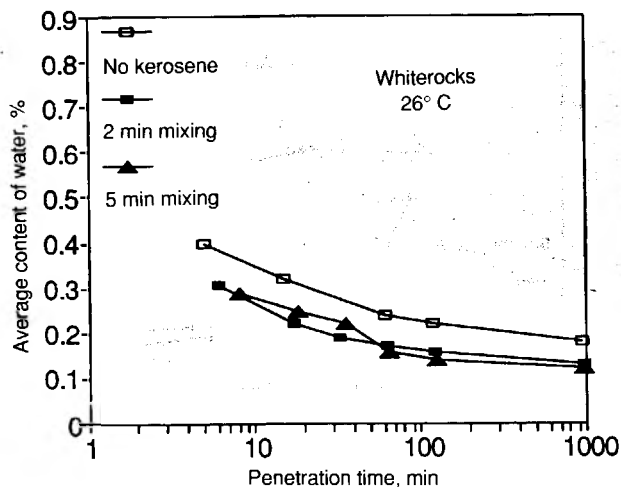


Fig. 6—Average water content for Whiterocks tar sand after preteatment in rotating drum and storage in 8-cm-thick layer at 26°C; 13 wt% kerosene with respect to bitumen.

diluent addition. In this case, a less uniform kerosene distribution is obtained; higher and more varied RSD values were observed.

In addition to bitumen content, the water content was also determined. Only the summer ambient temperature results are presented in Figs. 5 and 6. During winter experiments (performed in the open air), a slight precipitation of snow at the time of sampling distorted the water balance. Considering water content change in the tar sand, there is clear evidence, comparing water loss from the tar sand to which kerosene was not added, that the diluent stimulates evaporation due to water displacement from the capillaries. This effect is more pronounced for the Asphalt Ridge tar sand (which contains larger pore volume and apparently wider capillaries), and does not depend on the mixing time after diluent addition. The water liberated during diluent penetration tests apparently can be classified as the free water, contrary to well bound intrinsic water as discussed in detail by Audeh (Audeh, 1989).

## Conclusions and comments

• The natural porosity of tar sand accessible by diluent has a crucial impact on the reduction of bitumen viscosity, and influences the penetration time required for successful bitumen separation from tar sand. Thus, the tar sand porosity can control the lowest processing temperature applicable, unless crushing to almost elemental grains is provided prior diluent pretreatment.

• The change of the relative standard deviation of the tar sand grade indicates that diluent penetration into the Asphalt Ridge tar sand was almost complete in about 30 minutes, whereas for the Whiterocks tar sand the penetration process was slower, and still not complete after 15 hours regardless of the ambient temperature.

• After diluent pretreatment, the bitumen is more uniformly distributed within the tar sand. Diluted tar sand does not undergo secondary consolidation and is easier to handle when compared to the as received feed. Diluent application in the pretreatment step is recommended only when the feed

has a proper size as established by the natural porosity of the tar sand.

• A rotating drum seems to be adequate for tar sand pretreatment. Since mixing time after diluent spraying had little impact on the penetration kinetics, the drum used for pretreatment should have only two sections: the inlet section serving for preliminary size reduction of tar sand lumps (this section is necessary only for nonconsolidated tar sands), and the diluent spraying section.

## Acknowledgements

## References

Anon., 1989, US Production of Liquid Transportation Fuels: Costs, Issues, and Research and Development Directions, National Academy Press, Washington, D.C., p. 4-23.

Audeh, C.A., 1989, "Tar Sands and Their Water Content," Proceedings of the 1989 Eastern Oil Shale Symposium, Nov. 15-17, 1989, Lexington KY, pp 119-123.

Chakraborti, N., et al., 1992, "A Dimensional Analysis of Cleanup of Bitumen Concentrate Derived from Utah Tar Sand," AOSTRA J. Res., 1993.

Hupka, J., and Miller, J.D., 1991, "Electrophoretic Characterization and Processing of Asphalt Ridge and Sunnyside Tar Sands," International Journal of Mineral Processing, vol. 31, pp. 217-231.

Hupka, J., Lelinski, D., and Miller, J.D., 1991, "Air Bubble Filming during Bitumen Flotation from Digested Tar Sand Slurry," Abstract Proceedings of The 22nd Annual Meeting of the Fine Particle Society, July 29-August 2, 1991, San Jose, CA, pp. 83-84.

Hupka, J., Miller, J.D., and Cortes, A., 1983, "Importance of Bitumen Viscosity in the Hot Water Processing of Domestic Tar Sands," Mining Engineering, vol. 35, no. 12, pp. 1635-1641.

Hupka, J., Oblad, A.G, and Miller, J.D., 1986, "Diluent-Assisted Hot-Water Processing of Tar Sands," AOSTRA J.Res., vol. 3, pp. 95-102.

Leibovich, S., 1977, "Hydrodynamical Problems in Oil-Spill Control and Removal," Journal of Petroleum Technology, March, pp. 311-324.

Misra, M., and Miller, J.D., 1980, "The Effect of Feed Source in the Hot Water Processing of Utah Tar Sand," Mining Engineering, vol. 32, no. 3, pp. 302-311.

Yang, Y.J., Bukka, K., and Miller, J.D., 1989, "Selection and Evaluation of Diluents in the Modified Hot Water Process," Energy Processing Canada, vol. 82, no. 1, pp. 14-21.