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Characterisation of an attrition scrubber for the removal of high molecular weight contaminants in sand

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Abstract

According to a recent paper published in The Chemical Engineer, there is an estimated 200,000 ha of contaminated land in the U.K. [C. Cunningham, J. Philip, Partners in grime, Chem. Eng. 378/379 (2002) 34–36]. Due to the requirement to remediate this land to reduce the levels of toxins, there is a need for simple transportable remediation techniques. One possible technique is the attrition scrubber.

Investigations into the parameters that affect the efficiency of an attrition scrubber at removing high concentration, high molecular weight hydrocarbons from well defined silica sand medium are described.

Mineral oil (Catenex S341) and unrefined bees wax were used as the contaminants. A number of parameters including liquid–solid ratio, power input, contaminant type and concentration, were experimentally tested for their effects on contaminant removal efficiencies. Repeatable experimental results were successfully obtained for all parameters tested. Mixing vessel design, power input into the system, contaminant type and concentration all had significant effects on the removal of contaminants. Maximum removal efficiencies of 21.3 and 96.7% where achieved for bee's wax and S341 respectively. These results show that an attrition scrubber can be used to remediate contaminated silica media and that remediation of soils is possible. This is the focus of the future studies.

Keywords: Attrition; Remediation; Sand; Scrubbing

1. Introduction

There is considerable debate as to the volume of contaminated land currently in the U.K. For example Cunningham and Philip [1] state that there is approximately 200,000 ha of contaminated land in the U.K., whereas Cairney [2] quotes not the area of land that requires remediation, but the number of sites requiring remediation as 50,000–100,000. Even the U.K. Environment Agency [3] is unsure of the exact figure quoting 5000–20,000 contaminated sites in England and Wales. An undisputed fact however is that many of these sites will require some degree of remediation in the future.

One of the most common remediation processes to remediate contaminated land is soil washing (or flushing). These processes are predominately water and/or solvent-based processes. Soil washing processes rely on physical and chemical differences between the contaminants, solid phase, and the wash-water to remove the contaminants from the solid phase into the liquid. Further separation and treatment of the liquid phase can then be performed.

Usually soil washing processes are designed to separate out a course clean soil fraction from a fine dirty fraction as most of the contaminants are concentrated into this fine fraction. The fine fraction tends to concentrate the contaminants as a considerable fraction of the surface area available for contaminants to attach too is provided by the smaller soil particles. Stegmann et al. [4] states that up to 90% of all contaminants can be concentrated onto the fine fraction in soils. Thus removing the smaller soil particles will reduce the volume of soil to be remediated and concentrate the contaminants. An example of such a soil washing process is the attrition scrubber.

Attrition scrubbing is the physical impact and shearing action between contaminated particles themselves and either the liquid phase or the walls and impellers in the mixing

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vessel. The potential force that keeps the contaminant bonded to the surface of the particle consists of three forces:

(i) Possible chemical bonds that have occurred between the contaminants and the solid such as reactions with humic matter on the particle and the contaminants.
(ii) The hydrophobic/hydrophilic properties (solubility) of the contaminants.
(iii) Surface forces between contaminants and solid surface (van der Waals).

At the point of impact, contaminants on the surface of the contaminated particle are either dislodged from the surface of the particle, or the bonds between the particle surface and the contaminants is sufficiently weakened in some form so that the contaminant breaks under further impacts. There are a number of possible factors that influence the efficiency of attrition scrubbing such as residence time, and liquid/solid ratio.

1.1. *Residence time*

Strazisar and Seselj [8] conducted a series of attrition experiments with lead contaminated soils to investigate the effects of residence time on removal efficiencies. In this case natural and artificially contaminated soils (300 mg/kg of lead) with a particle size range from 0.1 to 1.25 mm were mixed in a 0.35 l vessel with a single axis six bladed impeller set at 570 rpm using water as the solvent with solid to liquid ratios of 70–80%. Strazisar and Seselj [8] found a direct link between the duration of attrition and removal efficiencies with 90% removal in 90 min for lead contaminated calcite samples. Additionally Strazisar and Seselj [8] found that the efficiency of removal of contaminates increased as the particle size range increased. In this case, a removal efficiency of 46% was found for a size range of 0.1–0.4 mm compared to the removal efficiency of 65% for larger particles in the size range of 0.8–1.25 mm. A limitation of the study conducted by Strazisar and Seselj [8] is the fact that only one contaminant was investigated (lead) and that there are no other publications on residence time effects in this type of attrition scrubber. This makes the findings of Strazisar and Seselj [8] of limited use when relating to the effects of residence time on an attrition scrubber when the solid media is contaminated with different contaminants especially contaminants such as organic hydrocarbons.

1.2. *Liquid/solid ratio*

Feng et al. [9] conducted a series of soil washing experiments to investigate the efficiencies of a variety of remediation technologies including an attrition scrubber. A range of sand particle size (0.1–0.5 mm), contaminated with diesel oil (at 5% by weight) with a range of liquid/solid ratios ranging from 0.18 to 0.43, using water as the solvent, was remediated using attrition scrubber. Feng et al. [9] found that the efficiency of removal increased as the liquid/solid ratio decreased from a residue of 1700 ppm of diesel oil at 75% solid concentration by weight, down to a residue of 1300 ppm of diesel oil for 80% solid concentration by weight. After this the efficiency decreased (residue diesel oil increased to roughly 2000 ppm at 85% solid matter) as the slurry became too dense and moved en masse, with little interparticle motion and therefore very little scrubbing action. Feng et al. [9] work focuses of the comparison between different remediation processes. Whilst the attrition scrubber compared favourably with other remediation technologies (Ultrasonic separation and the jet reactor) the results are largely based on limited experimental work and there is a lack of detail regarding the experimental conditions in order to be able to reproduce the results for different contaminants.

1.3. *Temperature*

For impact scrubbing to be successful the energy forced into the contaminant/solid interface at the point of impact must be greater than the potential energy that keeps the contaminants on the solid surface. Increasing the temperature reduces hydrophobic properties of hydrocarbon contaminants, therefore reducing the potential energy keeping the contaminants on the solid surface. The energy required to remove the contaminants from the solid surface has been decreased so there will be more incidences when there is sufficient energy to remove the contaminants from the solid surface.

This theory is supplemented by the experimental results published by Thorvaldsen and Wakefield [10] who showed by increasing the temperature in a jet pump scrubber to 55 °C, the final concentration of hydrocarbons with a carbon chain length of C_{29}–C_{36} decreased from 260 mg/kg to less than 20 mg/kg.

1.4. *Contaminant type and concentration*

On the laws of probability the greater the concentration of contaminants the greater the likely hood that when an impact takes place contaminants will be removed.

Therefore, greater volumes of contaminants should be removed from solid samples that have higher contaminant concentrations.

The type of contaminants could be as important as the concentration of those contaminants. The more hydrophobic the contaminant the harder it will be to remove from the solid matter. Therefore, hydrocarbons with a lower relative molecular mass (RMM) should be easer to remove than hydrocarbons with a higher RMM. The type of contaminant will also directly affect how it attaches onto the solid matter and therefore determine whether the contaminant seeps into the pores of the solid matter or attaches to the surface of the solid matter.

1.5. Power

The power inputted into the system directly affects the intensity of the scrubbing. The more energy imputed into the system the greater the removal of contaminants. The energy inputted into the system must be balanced with the amount of contaminant removed for the optimum efficiency to be achieved. The power inputted into the system is directly proportional to the speed of the impeller in the system.

1.6. Particle porosity/structural strength

The porosity of the solid phase will determine whether the contaminants are adsorbed onto the surface of the solid or into the solid. In general, solids that have a low porosity such as sands will be better suited to attrition scrubbing than solids with a high porosity such as limestone’s and sandstones. The structural strength of the solid phase is important as if the solid phase has a low structural strength then the solid particles may be broken up in the attrition process. This could be advantageous if the solid phase is very porous as surfaces that where inside the old particle are now outside surfaces of the new particles and therefore can be subjected to attrition scrubbing.

Therefore the literature that is available is largely empirical, equipment and contaminant specific which makes comparison and rigorous studies of the parameters that may affect the attrition scrubber efficiency to remediate contaminated media extremely difficult. Research that describes soil washing techniques tends to focus on soil reduction methods [5–7]. As a result very little research is concentrated on the ability of soil washing processes, such as attrition scrubbing, to separate contaminants from the solid media as a viable soil remediation process. Very little is known about the parameters which may affect this type of soil washing process.

The aim of this paper therefore is to understand and quantify these parameters. This paper will present and discuss the results achieved by experimentally determining the effects that the parameters of the residence time, L/S ratio, impeller speed, contaminant concentration and temperature have on the ability of an attrition scrubber to remove two high molecular weight contaminants from a solid media.

2. Materials and method

2.1. Sand

Clean silica sand was used, which had an organic content of less then 0.05%. This was determined by heating a 5 g sample to 750 °C for 60 min and measuring the weight loss using precisa 205 A swiss quality scales. The size range of the sand was measured using a mechanical shaker and a set of standard (BS410) sieves ranging from 200 μm up to 1 mm. The sand used had a size range of 300–709 μm. This range contained 97.5% (by weight) of all the sand in the sample and the mean and median size of the sand range was 606 and 679 μm respectively.

Table 1
Properties of mineral oil S341

Density (kg/m^3) (at 15 °C)	884
Kinematic viscosity (mm/s^2) (at 20 °C)	330
Initial boiling point (°C)	415
Final boiling point (°C)	627

2.2. Contaminants

Two different contaminants were used. The first contaminant was a refined mineral oil called S341 (Shell U.K. Oil Products Limited). S341 comprises of two substances identified by The European Chemicals Bureau in EINECS (http://ecb.jrc.it/), as EINECS numbers 265-169-7 and 265-166-0 both of which are de-waxed petroleum based hydrocarbons with a carbon count between C_{20} and C_{50}. The properties of the mineral oil are outlined in Table 1.

The second contaminant was unrefined bee’s wax. Bee’s wax is solid at room temperature and pressure, and is a complex mixture of hydrocarbons, esters, hydroxyl esters, and free acids. The basic composition of unrefined bee’s wax was defined by Tulloch [11] and is given in Table 2.

2.3. Method development

2.3.1. Mixer and mixing vessel

The glass mixing vessels with a total volume of 150 ml were used for all experiments. A mechanical overhead stirrer, which was attached to a simple two bladed impeller, was used in all attrition experiments. The impeller height in the mixing vessel was fixed such that the impeller blade where just above the bottom of the mixing vessel.

2.3.2. Contamination of solid media

Sand was contaminated by addition of a defined volume of Catenex S341 such that the final mass of sand and Catenex S341 equalled 1 kg. The mixture was then manually mixed for 5 min or until a homogenous sample was visually achieved.

Table 2
Composition of unrefined bee’s wax

Component	Percentage by weight
Hydrocarbons	14.0
Monoesters	34.7
Diesters	13.7
Trimesters	3.3
Hydroxy monoesters	3.6
Hydroxy polyesters	7.7
Free acids	11.9
Acid monoesters	0.8
Acid polyesters	1.7
Recovered from column (unidentified)	2.1
Not recovered by column (unidentified)	6.5

Fig. 1. (A) Clean sand; (B) bee's wax 10% contamination; (C) S341, 10% contamination.

Sand to be contaminated with bees wax was heated to 70 °C in a Carbolite oven. A defined amount of bee's wax was melted at 70 °C and the hot sand added to the bees wax (so the final mass equalled 1 kg). The mixture was then manually mixed for 5 min or until a homogenous sample was visually achieved. Examples of the clean sand, and sand contaminated with 10% bee's wax and Catenex S341 are shown in Fig. 1.

2.3.3. *Experimental design*

To test the possible influence of factors on the efficiency of attrition, as previously discussed, experiments were conducted over a range of residence times, L/S ratios, impeller speeds, and contaminant concentrations for both S341 and bees wax contaminated samples and two different temperatures for S341 contaminated sand.

The experimental procedure that was used for all experiments generally involved the following steps. First a predetermined amount of sample with a known contaminant concentration was weighed and added to a mixing vessel. Then a predetermined volume of water was added so the total mass of the sample equalled 50 g. This mass allowed sufficient headspace in the mixing vessel so that no matter was lost under vigorous mixing. The impeller was then lowered into the sample and the impeller speed set. The mixer was then switched on after a predetermined time of agitation, the experiment was stopped, the impeller removed. To aid separation of contaminants removed by the attrition 80 ml of water was added to the sample and the sample was left to stand for 2 h. The contamination removed by the attrition was then separated from the mixing vessel and sample by a gravimetric method (see Section 2.3.4). The remaining water in the mixing vessel was removed from the sample via a combination of pipetting and oven drying (oven drying at 110 °C for 24 h). The sample was then cooled and weighed again. In the experiments that required elevated temperatures the mixing vessels were partially submerged in to a water bath. Table 3 details all the parameter changes in the attrition experiments conducted.

2.3.4. *Analysis and error calculation*

Experimental results where determined by a mass balance method. The amount of contamination removed by attrition in one experiment can be calculated from the equation below

$$\begin{aligned}&\text{Matter removed due to attrition}\\&\quad=(\text{initial mass of sample})\\&\qquad-(\text{mass of sample after 24 h drying}\\&\qquad+\text{mass of contaminant lost due to oven drying})\qquad(1)\end{aligned}$$

For each sample the initial mass and final mass (after 24 h drying) was weighed. Therefore all that is required to calculate the mass of contaminant removed from the sample by attrition, is to determine the mass of contaminant that is lost due to volatilization in the oven over 24 h. This was experimental calculated by measuring the loss of mass of predetermined volumes of contaminant, contaminant/sand, contaminant/water, contaminant/sand/water samples under the same conditions as the experimental sample. Using these values and Eq. (1) the amount of contaminant removed by attrition could be calculated.

Table 3
Experimental conditions investigated for attrition experiments

Bees wax and S341 experiment	Residence time (min)				
	5	30	60	120	240
Liquid–solid ratio: at 10% contamination, and 1200 rpm					
80/20	√	√	√	√	√
70/30	√	√	√	√	√
60/40	√	√	√	√	√
50/50	√	√	√	√	√
Contaminant concentrations: at 80/20 liquid/solid ratio, and 1200 rpm					
5%	√	√	√	√	√
10%	√	√	√	√	√
15%	√	√	√	√	√
Impeller speeds (RPM): 80/20 solid/liquid ratio and 10% contamination					
300	√[a]	√[a]	√[a]	√[a]	√[a]
600	√	√	√	√	√
1200	√	√	√	√	√
1800	√	√	√	√	√
2400	√[a]	√[a]	√[a]	√[a]	√[a]
Temperature: 20/80 solid/liquid ratio, 10% contamination, and 1200 rpm.					
20 °C (room temperature)	√[b]	√[b]	√[b]	√[b]	√[b]
55 °C	√[b]	√[b]	√[b]	√[b]	√[b]

[a] Not performed with contaminant S341.
[b] Not performed with contaminant Bee's wax.

Table 4
Error percentage breakdown for bee's wax and S341 experimental results

Error type	Error value (g)	
	Bee's wax	S341
Error incurred due to scales	±0.011	±0.011
Average suspended matter in S341 samples, residence time 5 min	–	±0.087
Average suspended matter in S341 samples, residence times other than 5 min	–	±0.029
Total error		
Sample with residence time 5 min	±0.011	±0.098
Sample with residence times other than 5 min	±0.011	±0.04

The accuracy of the analysis method described depends on the ability to accurately measure the weight of the samples concerned. This is important as the amount of contaminants removed in some experimental runs samples have been weighed to 1×10^{-4} g. Weighing samples to this accuracy can be difficult and errors are induced into the results. All error bars have been calculated by weighing a range of predetermined weights on the scales used in the experiments and collecting up to 200 individual readings. From these readings an average weighing error has been calculated. Further errors have been calculated for all samples contaminated with S341. In all cases where S341 was removed by attrition the mineral oil contained small amounts of sand particles in suspension. To calculate this error the oil from each of these samples was filtered to separate the sand from the oil. The sand was then dried in an oven for 4 h at 550 °C to drive off all oil attached. The sand was then weighed and these values were added to the individual error bar value for that sample. Table 4 summarises the calculated errors.

The average mass of contaminants lost due to vaporisation in the oven at 105 °C over a 24 h period was 0.54 ± 0.4% for bee's wax and 1.65 ± 0.34% for S341 samples. As expected the amount of bee's wax lost in the oven is considerably less than that of the S341, due to the difference in boiling points of bee's wax and S341.

3. Results and discussion

3.1. Effects of residence time and L/S ratio

The amount of contaminant removed for varying agitation times and L/S ratios for both bee's wax and S341 are shown in Figs. 2 and 3, respectively. In all case the impeller speed was set at 1200 rpm and the contaminant concentration was 10% by weight. All attrition experiments with residence times of 5, 30, and 60 min duplicates samples were performed. Due to time considerations no duplicates were run for residence time 120 and 240 min.

For all results shown in Figs. 2 and 3 both bees wax and Catenex S341 contaminated samples, increasing the liquid/solid (L/S) ratio increases the total mass of contaminants removed. This is because there is more material in the system therefore there is a much greater chance of contaminated particles colliding and removal of contaminants from the particle surfaces occurring. No results where obtained for bee's wax contaminated samples with an L/S ratio of 60/40, for a residence time of 240 min. Similarly no results were achieved for L/S ratio 50/50 for residence times of 60, 120 and 240 min. The reason for this is that solid clumps formed (see Fig. 4)

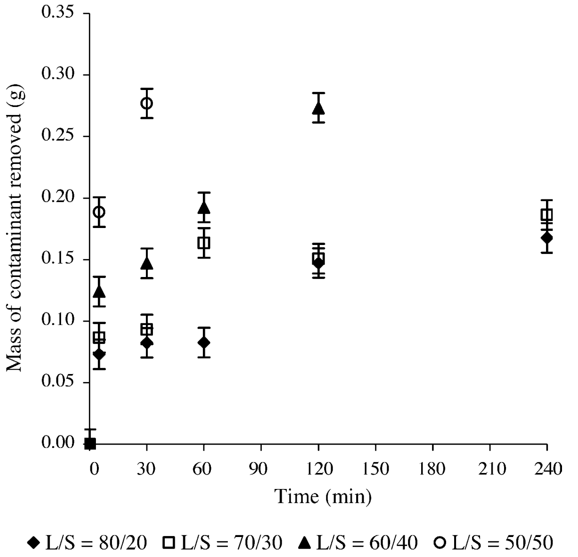

Fig. 2. Effect of residence time and L/S ratio on 10% bees wax contaminated samples at impeller speed of 1200 rpm.

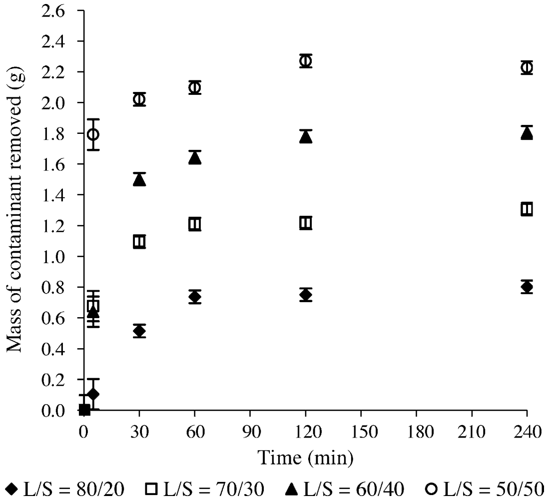

Fig. 3. Effect of residence time and L/S ratio on 10% S341 contaminated samples at impeller speed of 1200 rpm.

Fig. 4. Clumps of bees wax/sand from solid/liquid ratio 50/50 residence time 120 min.

consisting mostly of bees wax with a small percentage of sand.

The formation of bee's wax clumps in the sample with an L/S ratio of 60/40 was between 140 and 180 min of attrition. For samples with an L/S ratio of 50/50 the clumps started to form between 50 and 70 min of attrition. From this the conclusion can be made that the formation of these clumps is directly linked to the decrease in L/S ratio. Therefore the clump formation is directly linked to the total volume of contaminant in the samples. The greater the total amount of contaminant in the sample the quicker these clumps form.

From visual inspection of all experiments where clumps were formed, sand that was not entrapped in these clumps had a considerably reduced amount of residue bee's wax. Effective reduction in the final contaminant concentration in the bulk of the sample had been achieved however the amount removed was not measurable using the mass balance analysis method as it was impossible to determine the composition of the bee's wax/sand clumps.

As can be seen from Figs. 2 and 3 generally increasing the residence time increase the amount of contaminants removed which agreed with the findings of Strazisar and Seselj [8]. Therefore efficiency of removal of contaminants increases with an increase in the residence time. However for higher L/S ratios (80/20 and 70/30) for the bees wax samples and for all S341 samples increasing the residence time from 60 to 240 min had very little effect on the total removal of contaminants. Due to the fact that in both cases after 60 min residence time most of the easily removable contaminants had been separated and further mixing had little effect on the removal of more contaminants. This trend is very similar to that found by Strazisar and Seselj [8] for the lead contaminated attrition experiments.

3.2. *Effect of contaminant type*

Comparison of Figs. 2 and 3, shows that the removal efficiency for the S 341 samples is much higher than that of the bee's wax samples for all liquid/solid ratios (mass removed from a bees wax contaminated sample after a residence time of 240 min, impeller speed of 1200 rpm, and an L/S ratio of 80/20 = 16.8% compared to 80.2% for S341 sample with the same L/S ratio, residence time, and impeller speed). This is expected due to the physical characteristics of the two contaminants where one is a solid and the other a liquid at room temperature and pressure. This difference in removal efficiencies highlights the great effect that the physical state the contaminant has, on the ease at which that contaminant can be removed from the contaminated media.

However the efficiency of removal of contaminants can be improved by further optimisation of the key parameters in the experiments. For example the maximum efficiency achieved for bees wax contaminated samples was found to be 21.3% for an L/S ratio of 80/20, impeller speed 1200 rpm and contaminant concentration of 5%, and residence time of 240 min. Similarly S341 the highest removal efficiency achieved was 96.7% for L/S ratio of 80/20, impeller speed 1800 rpm and contaminant concentration of 10% and residence time of 240 min.

3.3. *Effects of residence time and contaminant concentration*

The amount of contaminant removed for varying agitation times and contaminant concentrations for bee's wax and S341 are shown in Figs. 5 and 6, respectively. In all cases the impeller speed was set at 1200 rpm with L/S ratios of 80/20.

According to the results in Figs. 5 and 6 the net mass of contaminant removed is directly linked to the initial concentration of the contaminant in the samples for both bees wax and S341 contaminated samples. When considering the percentage removal (the amount removed divided by the initial amount of contaminant) there are differences between the S341 and bee's wax contaminated samples. In the case of the S341 contaminated samples the percentage removal of contaminants does increase with the increase of initial contaminant concentration removal and also the rate of removal (see Table 5). In the case of the bees wax contaminated sam-

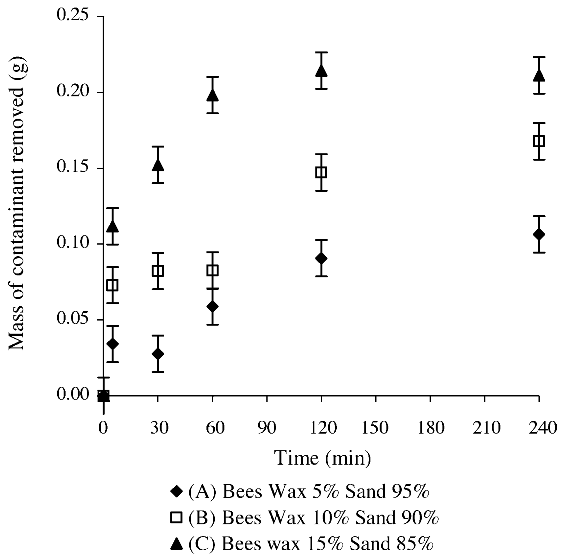

Fig. 5. Effect of residence time and contaminant concentration on bees wax contaminated samples at impeller speed of 1200 rpm and L/S ratio 80/20.

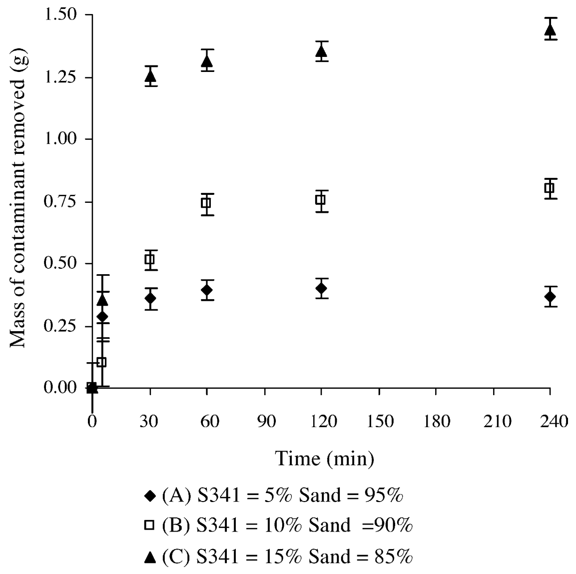

Fig. 6. Effect of residence time and contaminant concentration on S 341 contaminated samples at impeller speed of 1200 rpm and L/S ratio 80/20.

ples however there is a decrease in the percentage removal of contaminants as the initial concentration of contaminants increases. This could be due to the fact that at higher contaminant concentrations the bee's wax is conglomerating when particles impact with each other rather than separating off from the particle like in the S341 contaminated samples.

For all three concentration levels for the bee's wax contaminated samples, increasing the residence time from 0 to 120 min had a positive effect on the final removal of the contaminant. However increasing the residence time further to 240 min did not increase the final amount of contaminant removed by any significant amount. This may be due to that all the remaining bees wax could be tightly sequestered onto the sand particles.

The main difference between the bee's wax and S341 contaminated media is the point at which further residence time does not significantly improve removal efficiency. In the bee's wax contaminated cases the rate change was roughly after 120 min agitation compared to 60 min in the S341 contaminated media.

3.4. *Effects of residence time and impeller speeds*

Figs. 7 and 8 represent the results of the experiments designed to calculate the effects of impeller speed on the removal of contaminants. In all cases the contaminant concentration was set at 10% by weight, with an L/S ratio of 80/20.

Table 5
Contaminant removal percentage change after 240 min attrition compared to initial concentration percentage

Initial contaminant percentage concentration	Percentage removal	
	Bees wax	S341
5	21	73
10	17	80
15	14	96

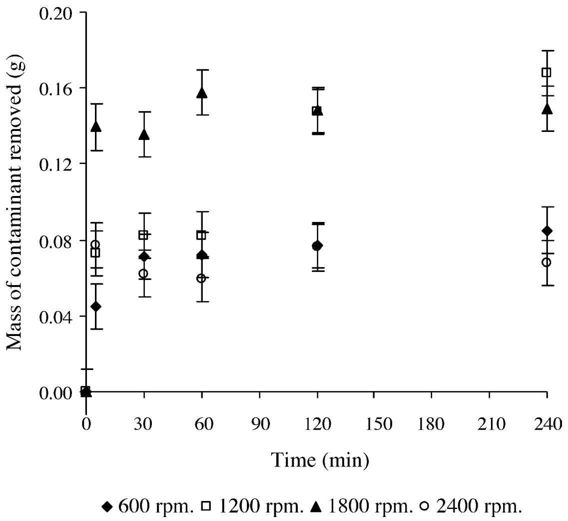

Fig. 7. Effect of residence time and impeller speed on 10% bees wax contaminated samples at L/S ratio 80/20.

For bees wax contaminated samples impeller speeds of 300, 600, 1200, 1800, and 2400 rpm were used in the experiments. The results for the experiments carried out for bee's wax at impeller speeds of 300 rpm are identical to those of acquired from the experiments carried out at impeller speeds of 600 rpm. Therefore to make Fig. 7 clearer the results of the 300 rpm experiments have not been included. As the impeller speed is increased from 600 to 1800 revolutions per minute (rpm) the amount of bees wax removed increases. This is due to the fact that as the impeller speed increases the rate and the intensity of the collisions between particles also increases and therefore there is a greater removal of contaminants.

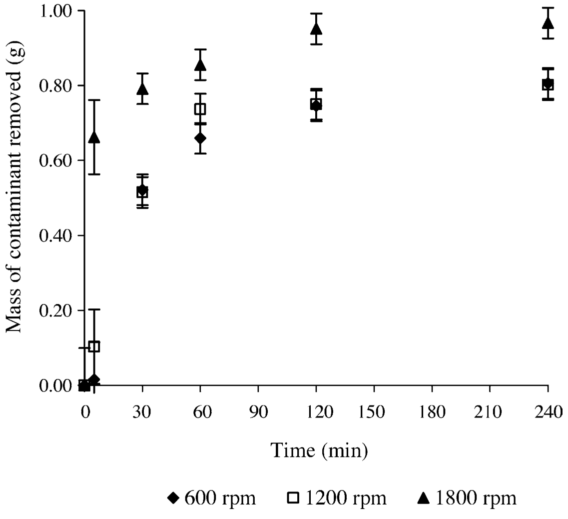

Fig. 8. Effect of residence time and impeller speed on 10% S341 contaminated samples at L/S ratio 80/20.

However at impeller speeds of 2400 rpm there is a greatly reduced removal of contaminants. From visual inspection of the samples undergoing agitation, the fluid and particles looked as if they where moving around en masse. This means that the relative velocity between particles may not be sufficiently different and therefore the rate and intensity of the collisions is reduced. This phenomenon can be over come if baffles are installed in the mixing vessel. These would then stop the fluid moving en masse and increase turbulence and hence removal of contaminants. This suggests that the design and shape of the mixing vessel is crucial to the mixing characteristic and therefore the amount of contaminants removed. The greatest contribution increasing the impeller speed has made is the rate at which contaminants are removed. At 1800 rpm nearly all the removable contaminants have been separated from the sand in 30–60 min compared to that of 60–120 min for impeller speeds of 1200 rpm.With consideration of the results from the bee's wax impeller speed experiments the impeller speed range for the S341 experiments was reduced to only include experiments with the impeller speeds of 600, 1200, and 1800 rpm. The results of these experiments can be found in Fig. 8. There is no increase in the amount of contaminant removed when in increasing the impeller speed from 600 to 1200 rpm for the S341 contaminated samples. However increasing the impeller speed further to 1800 rpm does increase the volume of contaminant removed. This suggests that there is a threshold energy value somewhere between impeller speed of 1200 and 1800 rpm. Below this threshold value increasing the impeller speed up to the threshold has little effect on the amount of contaminants removed. Increasing the impeller speed above the threshold value then further removal of contaminants is possible.

Fig. 8 also suggests that there are at least two forms of attachment for the contaminant on the solid media. Considering that the contamination levels are high (10% by weight) there are two possible contaminant situations. The first type of contamination is when the contaminants cover and bond with the entire surface of the solid particle. The second is when the rest of the contaminants then attach to layer of contaminants that is attached to the surface of the particle. Contaminants only attach to the surface of a particle if the resultant situation is energetically favourable. Therefore the bonding of the contaminants to the surface of the particle must be more energetically favourable than forming bonds with more contaminant. This means that the layer bonded to the particle will be more tightly sequestered than the outer layer of contaminants that is only bonded to the inner layer of contaminants. This would explain why there is a threshold impeller speed, bellow this threshold the outer layer of contaminants is removed and above this threshold the inner layer of contaminants also starts to be removed.

Further evidence for this two-layer contamination theory can be found from Fig. 3 where the impeller speed is below the threshold level (1200 rpm). The average level of contamination left on the sand after 240 min of attrition is 0.21 ± 0.03 g for all samples even though the liquid/solid ratio changes from 80/20 to 50/50 in these samples.

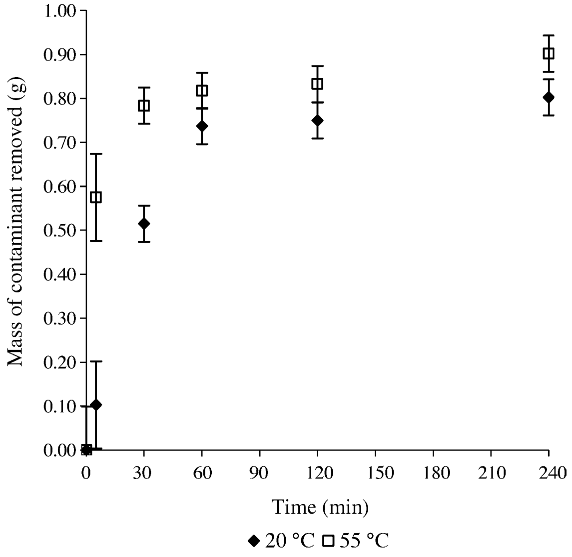

Fig. 9. Effect of residence time and temperature on 10% S341 contaminated samples at L/S ratio 80/20 and 1200 rpm.

3.5. Effects of residence time and temperature

Fig. 9 displays the results of the experiments designed to calculate the effects of temperature on the removal of contaminants. All samples where contaminated to a concentration of 10% by weight and had an L/S ratio of 80/20 and the experiment was carried out with an impeller speed of 1200 rpm.

Increasing the temperature from 20 to 55 °C did increase the total volume of contaminant removed. This increase in removal of contaminants improved the removal efficiency from 80% at 20 °C up to 90% at 55 °C however this increase of contaminant removal is not as great as that found by Thorvaldsen and Wakefield [10]. This can be explained by the fact that there are many differences between this experiment and those carried out by Thorvaldsen and Wakefield [10] also used a jet pump scrubber and undefined crude oils. Increasing the temperature also increased the rate, at which the contaminants are removed. These findings correspond well with the theory that increasing the temperature will reduced the strength of the bonding of the contaminants to the sand particles, and therefore increasing the ability of the attrition scrubber to remove contaminants from the particle surfaces.

No temperature experiments have been conducted for bee's wax contaminated samples. This because the boiling point of bee's wax is between 64 and 70 °C, as a sample of bee's wax increases in temperature the wax become increasingly sticky. Due to this effect experiment run at elevated temperatures with samples contaminated with bee's wax become prone to formation of clumps as described in Section 3.1.

4. Conclusions

A set of experimental attrition tests have been completed. There results indicate the importance of a number of factors that influence the efficiency of removal of contaminants from a controlled silica media. These results can be summarised as follows:

- Very little pervious work has been conducted on the attrition scrubber, and much of this work is not complete or is very specific to one type of contaminant or parameter.
- The amount of contaminants removed for both the bee's wax and S341 is directly proportional to the liquid–solid ratio and initial concentration of contaminants. For S341 and bee's wax experiments increasing the residence time above a certain value had very little effect on the total amount of contaminants removed.
- The properties of the contaminants are of critical importance in defining what removal efficiency can be achieved. In the case of the two types of contaminants use in these experiments removal efficiencies for S341 were seven times greater that those for bees wax contaminated sample.
- Increasing the impeller speed and therefore the power inputted into the system increased the rate of removal of both contaminants. In the case of S341 increasing the impeller speed above a threshold value also increased the total amount of contaminant removed.
- The design of the mixing vessel is of great importance to the mixing characteristic and therefore the amount of contaminants that can be removed.
- In the case of S341 contaminated media there appears to be a two-tier contamination system. Where an inner layer of contaminants is more tightly sequestered to the media than the outer layer of contaminants that is sequestered to the inner layer.
- Increasing the temperature from 20 to 55 °C had a direct positive effect on the amount of S341 removed from contaminated samples. In the case of bee's wax contaminated samples no results where measurable due to sand clumps forming in the samples.
- The attrition scrubber is a suitable remediation process for contaminated sands. The ability for the scrubber to remediate contaminated soils rather than sand however needs further experimentation.

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