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Production of bio-waste granules and their evaluation as adsorbent for removal of hexavalent chromium and methylene blue dye

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Abstract

In this research, compost was used as raw materials in the production of biomass adsorbent granules using drum granulation technique. Different concentrations of aqueous sodium silicate solution were used as the binding agents. Chromium and Methylene Blue solutions were selected as model adsorbates for heavy metals and dyes, respectively. The results obtained showed that the concentration of sodium silicate used had a positive influence on the mechanical strength of the granules, increasing the concentration would increase the compressive strength of the granules. The adsorbent granules had sufficient strength to survive wet conditions they were subjected during the adsorption study. However, increasing the concentration has a negative influence on the adsorption properties of the compost granules for both Chromium and Methylene Blue.

Keywords

Sodium silicate; drum granulation; adsorbent; chromium; methylene blue; cationic dye; bio-waste

1. Introduction

Wet granulation is a size enlargement process that has received attention in several industries such as mineral processing, detergents, pharmaceuticals, chemical and fertiliser industries. During the wet granulation process, different kinds of equipment, such as fluidised bed, rolling discs, drum granulator and high shear granulators, are used to supply rolling, tumbling or shear forces to raw starting materials and finally form loose agglomerates (also called granules) with the addition of liquid binders. Recently, the wet granulation technique for biomass agglomeration has attracted worldwide attention to make different granular products such as fuel materials, soil conditioners or fertilisers [1-10].

To the best of our knowledge that there has been no study of the production of biomass granules as an adsorbent for heavy metal removal. Adsorption as a separation process is widely applied in the manufacturing economy and everyday life. Adsorption performance is strongly influenced by mass transfer of the species between the solution and the adsorbent surfaces and also the adsorption reaction rate. In carrying out adsorption studies, a good contact between adsorbent and the liquid solution which need to be treated is fundamental. Therefore, for adsorbent granules, the selection of the binder remains a crucial step as the binder has to be relatively stable and keep the shape of the adsorbent granules in aqueous solution at least for the duration of the adsorption process.

So far, different binders have been reported to make biomass granules. Using the starch - sodium alginate as a binder to make switchgrass granules was reported by Yandapalli and Mani [8]. Also, Bowden-Green and Briens used the hydroxypropyl methylcellulose solution as a liquid binder for granulation of biochar powders[11]. Furthermore, Ghasemi et al. produced the compost granules using sugar beet molasses as binders [1, 2]. Among these reports, organic binders are commonly used for biomass agglomeration. Recently, in our research group, Chen et al. produced the compost granules by using inorganic silicate-based binders and the produced granules had a good ability of water resistance[12]. It was reported that the silicate-based binders do offer higher performance in strength and water resistance of agglomerates [13], for the adsorption process, such water resistance ability can offer significant advantages over the other water-soluble binders.

Therefore, in this study, we focused on the investigation of (1) using different concentrations of inorganic silicate-based binders for the production of compost granules through a drum granulation process and also (2) evaluating the produced granules as potential adsorbents for removal of heavy

metals and dyes using chromium and methylene blue (a basic cationic dye) as model adsorbates, respectively.

2. Experimental method

2.1 Adsorbent granule production

Granules that were produced in our previous work were used in this study[12]. Briefly, the granules are produced from biomass material (using compost as model biomass) in a drum granulator with a length of 0.65m and an internal diameter of 0.38m. 300 grams of the biomass material was granulated with a sodium silicate solution as the binder. The biomass material was sieved through a 2.8 mm mesh sieve. The average size of the particles was about 1.4 mm. The liquid to solid ratio and rotational speed of the drum was kept constant at 0.77 and 37 rpm respectively whereas the concentration of sodium silicate was varied from 0 to 9% (w/w). The granulation time was also kept constant at 15 minutes. For more details please see reference [12]. The batches will be named using this nomenclature SX where X is percentage concentration of sodium silicate in the binder so for example for batch produced with a 3% sodium silicate binder the batch or sample ID will be S3 whereas if no sodium silicate was in the binder it will be referred to as S0. After granulation and drying of the granules, the granules were characterised in terms of size distribution, strength, and product yield and water resistance. More details on the analysis can be found in ref [12].

2.2 Batch Adsorption Studies

All experiments for initial testing were carried out at room temperature (24 ± 2 °C) using 0.05 g of compost in a beaker containing 20 mL of Cr(VI) and 20 mL methylene blue solution with appropriate concentration. Depending on the particular experiment being studied, batch adsorptions were carried out at the desired pH value, contact time, and adsorbent dosage level. 1 mL of the chromium solution was taken and added to 9 mL of water. 6ml of the resultant solution was taken and added to 2 mL of a reagent (1 5-diphenylcarbazide). The solution was analysed using a U-V spectrophotometer at a wavelength of 540 nm. For methylene blue, the solution was analysed at a wavelength of 668nm. The absorbance values were used to determine the concentration of the solutions using the appropriate calibration constants. The amount of sorbed Cr (VI), q_e , was calculated in mg g^{-1} according to,

$$q_e = \frac{(C_o - C_e)}{m} * V \quad (5)$$

The removal percentage of Cr (VI) was calculated according to,

$$R = \frac{(C_o - C_e)}{C_o} * 100 \quad (6)$$

In equations (5) and (6) c_e , c_o , V and m are residual concentration in solution, c_o is initial concentration, mass of adsorbent and solution volume respectively.

Previous adsorption studies of chromium and MB show that the optimum pH are 2 and 10 respectively [14, 15]. For the isotherm studies, chromium solution of pH 2 was used and a mass of 0.05g of compost was weighed out and used in a beaker with 20ml of the chromium solution. Different concentrations of chromium were used for the test (25, 50, 75, 100 ppm). For the isotherm analysis of methylene blue, a pH solution of 10 was used and a mass of 0.05g of compost was weighed out and used in a beaker with 20 ml of the methylene blue solution of the methylene blue dye. 1 mL of the chromium solution was taken and 9 mL of water added. 6ml of the resultant solution was taken and added to 2 mL of a reagent (1 5-diphenylcarbazide). There was no need for a reagent for methylene blue, just the dilution factor of 10 was considered. The solution was analysed using a U-V spectrophotometer to calculate the absorbance and ultimately the concentration of chromium and methylene blue concentrations and the subsequent removal.

For the adsorption kinetics study, 100ml solutions of chromium and methylene blue were used and 0.25g of the compost material was used to test for the rate constant, the pH for each of the solutions was kept at 2 and 10 respectively, different temperatures were used from (25 to 60°C) and an agitation speed of 150rpm for 1 week were the conditions for the rate constant test. Samples were taken at different intervals and a dilution factor of 10 was used for both solutions. All granules used in the adsorption studies were in the size range 4.75 to 6.7 mm.

3. Results and discussion

3.1 Size Analysis

The granulation experiments were a success and granules produced were all spherical with size going up to 15mm. Figures 1(a) shows the size distributions of granules as the concentration of the sodium silicate binder increases, as can be seen from the plot the peak of the plots shift to the left as the amount of sodium silicate in the binders is increased, meaning the average size of the batches decreases with increasing binder concentration. The median size of each sample is given in Figure 1(b). It is clear from Figure 1 (b) that the granule median size decreases as the sodium silicate is introduced into the formulation for instance addition of just 1% of the silicate results in median size decreasing from 6.72 mm to ~ 5 mm, a further increase of the binder concentration to 5% results in a

reduction in granule median size a factor of 3. The yield of the granules decreased with increasing concentration of the sodium silicate in the binder. The viscosity of the binder increases as the concentration of sodium silicate increases as shown in Figure 2 (a). Whether the size of the granules decreases or increased with increasing binder concentration depends on the dominating growth mechanism under the given conditions. The observed decrease in the size of the granules with increasing binder concentration could be due to changes in the deformability of the granules as the concentration of the binder was changes as previously reported 1.4 mm [12]. Increasing the concentration of silicate in the binder increased with viscosity of the binder solutions which in turn reduced the mobility of the binder thereby limiting the amount of binder available at the nuclei surfaces. The reduction in the deformability limit granule growth by coalescence. Similar observations were made during the drum granulation of biochar powder with hydroxypropyl methylcellulose (HPMC) binder solution in recent work[11].

The yield of the granule in the desire size range was also negatively impacted by the introduction of sodium silicate into the formulation. As can be seen in Figure 2 (b) increasing the composition of sodium silicate result in a lower yield of granules for example batches where the binder concentration was 3% had product yield of about 60% compared to 50% for the 5% formulation and 90% when there is not sodium silicate in the binder solution.

3.2 Strength and water stability analysis

Even though the overall granule median size decreases with the increasing silicate concentration as discussed in the preceding sub-section, it is interesting to note that presence of the silicate in the formulation has a positive influence on the dry granule strength. Increasing the concentration of the sodium silicate increased strength of the granule exponentially as shown in Figure 3(a). This can be attributed to the silicate forming more strong solid bridges between the primary particles as it solidifies, the higher the binder concentration the more bonds are formed hence the greater the strength of the granules formed which is agreement previously reported in the literature [7, 16]. Since the granules are to be used for the adsorption under aqueous conditions it was also imperative to check their stability of in the water. The goal of this work was to produce granules that would not disintegrate in aqueous conditions. To this end, the granules were soaked in water and their strength analysed and the results are presented in Figure 3(b). As can be seen from Figure 3(b) there was a significant reduction in the strength of the granules after soaking them in water for a 24hour period, however, the granules remained intact as can be seen Figure 3 (a) and (b).

However, it was noted that there was a noticeable slight change in the colour of the water which may be attributed to leaching of some compounds for the granules and this was not pronounced for the S3 granules.

3.3 Adsorption Studies

Biomass granules as adsorbent of chromium (VI)

The results from the trial adsorption of chromium (VI) on to the four different types of granules are presented in Figure 5. As can be seen in Figure 5, the removal of chromium by the compost granules was successful, between 95 and 98 % removal achieved with 100 ppm solution using a dosage of 2.5 g/ L. The adsorption capacity of the granules ranged from 0.732 to 0.754 mmol Cr/ g. The highest removal was obtained when granules without sodium silicate (S0) was used. The granules with sodium silicate achieve slightly less removal ranging from 95 to 97% and a negative correlation between the sodium silicate concentration and the adsorption capacity and percentage removal of chromium. However, there was an insignificant difference between the removal capacity of S0 and S1 granules though further increase in concentration beyond 1% results in a marked decrease in the adsorption capacity of the granules. However, it is worth noting the adsorption capacity of the four samples of granules analysed here are comparable to those reported in the literature [7, 15, 17, 18].

3.4 Biomass granules as adsorbent of methylene blue dye.

Figure 5 (c) and (d) show results from adsorption of the model dye methylene blue. The results are based test done using methylene solution with an initial concentration 100 ppm solution with an adsorbent dosage of 2.5 g/L. As can be seen from Figure 5(c) the percentage removal ranged from about 69% to about 91%. Similar to results for chromium removal, the removal decreased with increasing concentration of sodium silicate in the granules and same applies to the adsorption capacity. However, the loss of adsorption capacity between the S0 and S5 samples was about 23% compared to 3% in the case capacity towards chromium removal. The adsorption capacity of the granule with respect of MB reported 39 mg/g is comparable to values reported in previous work [14, 15, 19-21].

The decrease in the adsorption capacity with increasing sodium concentration in the binder may be attributed to the coverage of the pores of the primary particles making up the composite granule as the silicate forms a glassy layer during the bond formation process. Besides the porosity of the granule results (See Figure 2(a)) was found to decrease with increasing sodium silicate concentration. This

makes the pores inaccessible to adsorbate molecules during the adsorption process thereby reducing the capacity of the granules. This effect is more pronounced when the adsorbate involved is a large molecule as is the case with methylene blue molecule. In the adsorption of MB, the presence of the silicate could also be altering the pH of the solution creating condition which are less conducive for adsorption of MB which favours alkaline conditions.

3.5 Isotherm Analysis

Adsorption isotherm studies are important to define the fraction of adsorbate molecules that are divided between solid and liquid phases at equilibrium. In the current study, the isotherm results were examined using the Langmuir and Freundlich isotherm models. The Langmuir isotherm model can be written as [15]:

$$q_e = \frac{q_m b C_e}{1 + b C_e} \quad (7)$$

Where q_m and b are the Langmuir constants related to maximum monolayer adsorption capacity and energy of adsorption, respectively. The values of q_m and b were calculated and presented in (Table 1).

The Freundlich isotherm is the other empirical model which is commonly used to describe adsorption data. The Freundlich isotherm is expressed by the following equation[15]:

$$q_e = k_f C_e^{\frac{1}{n}} \quad (8)$$

Where, k_f and n are the Freundlich adsorption constants.

Non-linear regression was used to obtained parameters of Langmuir and Freundlich models using a custom-built code written in MATLAB and these are presented in Table 1. For chromium, the Langmuir parameters whilst for methylene blue the Freundlich parameters are reported. It can be noticed from Table 1 that there is a general decrease in the Langmuir adsorption capacity for the chromium as the concentration of sodium silicate in the granules increases as observed in the preliminary adsorption studies. The data presented in Table 1 and Figure 6 show that the Langmuir model fit the chromium model best, whilst the Freundlich model fit the Methylene blue dye best.

3.6 Adsorption Kinetics

The adsorption kinetics can be evaluated using pseudo 1st order kinetics equation which is written as[22]:

$$q(t) = q_e[1 - \exp(-k_1 t)] \quad (9)$$

where $q(t)$ is the amount of adsorbed solute at time t , q_e its value at equilibrium, and k_1 the pseudo-first-order rate constant.

According to Ho and McKay if the sorption process is 2nd order chemisorption, the sorption rate can be expressed by the equation[23]:

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \quad (10)$$

In Eq. (10) q_e and q_t are sorption capacity at equilibrium and at a time t respectively and k_2 is the rate constant of the pseudo order. Integrating the equation and using the boundary conditions of $q_t = 0$ at $t = 0$ and $q_t = q_t$ at $t = t$ will result in the following equation:

$$\frac{1}{(q_e - q_t)} = 1 + k_2 q_e t \quad (11)$$

It can be shown that Eq. (11) can be expressed as

$$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t} \quad (12)$$

The results from the kinetics study of the uptake of Cr(VI) and methylene blue dye onto the compost granules performed at different temperatures with different granule samples were evaluated by non-linear regression of Eq. (9) and (12) using a custom-built MATLAB program and the results are presented in Table 2. The removal kinetics for both chromium (VI) and methylene blue dye are presented in Figures 7 (a) and (b) and Figure 7 (c) and (b) respectively. The rate of removal chromium removal is higher at the beginning, this is largely due to the larger surface area of the compost being available at the beginning for the adsorption of metals. With time, the surface adsorption sites become exhausted where at this point, the uptake rate can be regarded to be controlled by the rate at which the adsorbate is transported from the exterior to the interior sites of the adsorbent particles. It can be

noticed from Figure 7 that increasing temperature has a significant effect on the amount of adsorbate uptake for both Cr(VI) and MB. For instance, after a contact time of 2 hours amount of Cr(VI) increases by 6 fold from 0.02 mmol/g to 0.12 mmol/g when system temperature is increased from 26°C to 60 °C. Also as observed in other studies the initial rate of adsorption is considerably increased by increasing the temperature[24]. The summary of the kinetics parameters obtained from non-linear regression is presented in Table 2. The data shows that both models can be applied to describe the kinetics of the removal of chromium (VI) and methylene blue as there is no significant difference in the goodness of fit.

3.7 Thermodynamic studies

The temperature dependency of adsorption can be described by the Arrhenius equation which is written as:

$$k = A * \exp\left(-\frac{E_a}{RT}\right) \quad (14)$$

where E_a is the activation energy (J/mol), k is the rate constant of adsorption, A is Arrhenius factor, which is the temperature-independent factor, R is the universal gas constant (J/K mol), and T is the solution temperature (K). Non-linear regression fit of equation 14 to the k versus T data is shown in Figure 8 and the obtained activation energies for adsorbent granules are reported in Table 3.

As can be seen from the plots presented in Figure 8 were as the adsorption kinetics of chromium is not significantly different for the two types of granules. However, that is not the case with the removal of methylene blue dye, the difference in the performance of the granules becomes more significant at higher temperatures in comparison to lower temperatures. The activation energy for the removal of MB dye is by the S0 granules is almost twice that of S3 granules. The activation energies of both the S0 and S3 adsorbent granules during removal of chromium are both higher than 40 kJ/mol (about 56 kJ/mol) which would suggest the removal is due to chemisorption as they are higher than the typical values for physisorption process which ranges between 6 and 16 kJ/mol [15, 25]. The difference in the activation energy for the binding of chromium and methylene blue ions does indicate that the ions are going through different processes in binding.

3.8 Thermodynamic parameters

To evaluate the nature and mechanism of biosorption MB and chromium on the granule surface, the biosorption data at different temperatures were used to calculate the thermodynamic parameters

namely change in enthalpy (ΔH), change in entropy (ΔS) and change in Gibbs free energy ΔG , using eq. (15), (16) and (17):

$$\Delta G = -RT \ln(55.5 \times K_d \times 1000) \quad (15)$$

$$\Delta G = \Delta H - T \Delta S \quad (16)$$

$$\ln(55.5 \times K_d \times 1000) = \frac{\Delta S}{R} - \frac{\Delta H}{RT} \quad (17)$$

where R is the universal gas constant (8.314 J/mol K). The term $55.55 \text{ (mol/dm}^3) \times k_d \text{ (dm}^3/\text{mmol}) \times 1000$ is dimensionless. $K_d = \frac{q_e}{c_e}$ where q_e and c_e are as defined previously.

The enthalpy ΔH and entropy ΔS associated with adsorption are obtained from the slope and the linear plot of $\ln K_d$ versus $1/T$.

The estimated thermodynamics parameters; change in free Gibbs energy (ΔG), change in enthalpy (ΔH) and change in entropy (ΔS) for the removal of Cr(VI) and MB by S0 and S3 adsorbent granules are presented in Table 3. As can be seen from the table the change in enthalpy values are all positive for both the removal of Cr(VI) and MB by the adsorbent granules which imply endothermic removal processes. The relatively high enthalpy values for the removal of MB by the adsorbent granules are indicative of strong bond formation between the MB molecules and the functional groups on the compost granules. Similar endothermic sorption of methylene blue on palm kernel fibre[26], date pit [27], and neem leaf powder[28] have been reported in the literature. The small positive ΔS values suggested an increase in the randomness at the solid/solution interface for both the adsorption of Cr(VI) and MB on the S0 and S3 adsorbent granules. For the removal of Cr(VI), the Gibbs free energy values decrease with increasing temperature suggesting that the spontaneity of the process increases with increasing temperature which is a similar trend observed in literature in a study of the biosorption removal of Cr(VI) by chemical modified date pit [27]. For the biosorption of Cr(VI), the free energy values are negative at higher temperatures indicating thermodynamically feasible and spontaneous nature of the adsorption process. At the same temperature, the S3 granules the ΔG values are slightly lower than the corresponding values for S0 granules.

3.9 Comparison with other materials

Comparison of the chromium removal capacity of the compost granules with other different adsorbent materials reported in the literature[7, 17, 18, 24, 27, 29-32] is presented in Table 4. In the same table list of other materials used for removal of methylene blue dye is also provided [26, 28, 33-35]. It can be noted that the compost granules have comparable removal capacity for both Cr(VI) and MB.

4. Conclusion

This work investigated the feasibility of using granules produced from compost by drum granulation as adsorbent material for removal of heavy metals and dyes via adsorption. It can be concluded that compost granules have great potential for use as an adsorbent material and have adsorption capacity that is comparable to other adsorbent material. The results show that the addition of sodium silicate enhances the strength of the granules however will reduce the adsorption capacity the granules. If the composite granules are to be used as an adsorbent for chromium or methylene, it is recommended the concentration of the sodium silicate should be limited to 1% as adding anything more than 1% will reduce the performance of the granule. The kinetic studies denoted that the adsorption of chromium and methylene blue ions onto compost material followed the pseudo-second-order model and the equilibrium data fitted well with Freundlich isotherm model for methylene blue and Langmuir isotherm model for chromium. The thermodynamics results showed that the adsorption of chromium and methylene blue ions onto compost material was spontaneous and the reaction was endothermic. Currently, desorption of the ions from the material to be reused for adsorption is being studied and further analysis would be provided in the future.

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Table1: Langmuir and Freundlich adsorption isotherm constants for adsorption of chromium (VI) and methylene blue on compost granules with different sodium silicate content.

Sample	Chromium (VI)			Methylene blue dye		
	Langmuir constants			Freundlich constants		
	Q_{max} (mg g ⁻¹)	b (L mg ⁻¹)	R^2	$1/n$	k_f	R^2
s0	73.37	0.61	0.81	1.36E-03	4.60	0.97
s1	65.43	0.53	0.80	3.46E-09	9.73	0.98
s3	53.70	0.61	0.75	7.43E-02	1.82	0.99
s5	64.09	0.32	0.87	7.31E-02	1.69	0.90

Table 2 Kinetic parameters for Chromium and Methylene blue adsorption by s0 and s3 compost material.

Sample	Temp. °C	Chromium VI						Methylene Blue					
		Pseudo 1 st order			Pseudo 2 nd order			Pseudo 1 st order			Pseudo 2 nd order		
		k ₁ x 10 ⁻⁴ (min ⁻¹)	<i>R</i> ²	Q _{max} (mmol/g)	k ₁ x10 ⁻⁶ (g/mmol min)	<i>R</i> ²	Q _{max} (mmol/g)	k ₁ x 10 ⁻⁴ (min ⁻¹)	<i>R</i> ²	Q _{max} (mmol/g)	k ₂ x10 ⁻⁶ (g/mmol min)	<i>R</i> ²	Q _{max} (mmol/g)
S0	25	1.10	0.99	1.13	0.66	0.99	1.91	2.02	0.98	0.121	3.05	0.98	0.169
	30	1.52	0.99	0.99	1.40	0.99	1.58	3.85	0.98	0.112	8.39	0.98	0.141
	40	7.23	0.97	0.78	19.40	0.97	0.89	7.66	0.97	0.104	25.80	0.98	0.118
	60	1.79	0.99	0.78	44.90	0.98	0.86	28.60	0.98	0.112	82.90	0.98	0.122
S3	25	1.03	0.99	1.19	0.59	0.99	2.02	3.27	0.99	0.092	7.69	0.99	0.120
	30	1.62	0.99	0.97	1.36	0.99	1.51	4.08	0.99	0.092	10.70	0.99	0.116
	40	7.14	0.97	0.78	18.90	0.97	0.89	6.13	0.97	0.096	18.80	0.98	0.114
	60	17.8	0.99	0.78	44.30	0.97	0.86	17.60	0.97	0.111	47.20	0.98	0.125

Table 3 : Thermodynamic parameters for the biosorption of of Cr(VI) and MB onto S0 and S3 granules.

Material	Adsorbate	Activation energy [kJ/mol]	$\Delta H(\text{kJ/mol})$	$\Delta S(\text{kJ/mol K})$	$\Delta G(\text{kJ/mol K})$			
					25 °C	30 °C	40 °C	60 °C
S0 Granules	Cr(VI)	56.2	95.0	0.3	1.79	1.29	-6.11	-8.37
	MB	40.6	43.4	0.1	8.03	6.67	5.35	3.61
S3 Granules	Cr(VI)	57.4	97.8	0.3	0.76	0.076	-4.28	-10.2
	MB	21.8	44.4	0.1	7.00	6.70	5.28	2.75

Table 4 Review of literature for adsorption of chromium for various industrial wastes.

Adsorbent material	Adsorbate		Reference
	Cr(VI) [mg/g]	MB[mg/g]	
Composite granules	64-73	29-36	Current study
Tannery waste	177	-	[30]
Clarified sludge	26.31	-	
Chemical modified pit	53.31	-	[28]
Dolochar from sponge iron industry	5.21	-	[25]
Teawaste	107.8	-	[33]
Date pits	96.02	-	[22]
Neem leaf powder	-	3.67 - 19.61	[29]
Teawaste & Dolomite	-	150.4	[15]
Magnetic graphene- carbon nonotube composite	-	65.79	[36]
Activated lignin-chitosan composite extrudates	-	36.3	[14]
functionalized activated carbon from date palm	-	34.70	[35]

(a)

(b)

Figure 1: (a) Granule size distribution of granules with different concentration of sodium silicate in the binder (b) granule mean diameter as a function of concentration of sodium silicate in the binder.

(a)

(b)

Figure 2:(a)Binder viscosity and granule porosity as a function of concentration of sodium silicate. (b) Percentage yield of granules in the desired size range as a function of concentration of sodium silicate in the binder. The desired size range is 4.75 to 14 mm .

(a)

(b)

Figure 3: (a) Effect of sodium silicate concentration on granule strength (b) Granule strength after 24 hr soaking in water

Figure 4: Images of compost granules after immersion in water (a) 1 min and (b) 24 hours

(a)

(b)

(c)

(d)

Figure 5: (a) and (b) effect of sodium silicate binder concentration of removal efficiency of chromium (VI) and its adsorption capacity (multiplied by 100). (c) and (d) effect of sodium silicate binder concentration of removal efficiency of Methylene Blue and its adsorption capacity..

(a)

(b)

Figure 6: Isotherms for adsorption of Cr(VI) (a) and methylene blue dye (b) onto granules with different concentrations of sodium silicate binder. The continuous and dashed lines in (a) and (b) are non-linear regression fits of the Langmuir and Freundlich isotherms respectively.

Figure 7 : Kinetics of Chromium removal by (a) s0 compost granules. (b) s3 compost granules at different temperatures. (c) and (d) show the removal kinetics of MB by S0 and S3 granules respectively. The continuous and the dashed lines in the plot represent the Pseudo 1st order model represents the Pseudo 2nd order fits.

Figure 8: adsorption rate constant as function of temperature (a) removal of Cr(VI) (b) removal of Methylene blue dye with biomass granules.