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Removal of methylene blue from wastewater using fly ash as an adsorbent by hydrocyclone

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Abstract

The excessive release of color into the environment is a major concern worldwide. Adsorption process is among the most effective techniques for color removal from wastewater and fly ash has been widely used as an adsorbent. Therefore, this study was carried out to understand the adsorption behavior of methylene blue from aqueous systems onto fly ash using the continuous mode. Continuous mode sorption experiments were carried out to remove methylene blue from its aqueous solutions in hydrocyclone equipment. The experiments were performed at constant temperature and dimensions of hydrocyclone with variation of flows through the equipment, concentrations of methylene blue solutions and fly ash concentration, respectively. A maximum removal of 58.24% was observed at adsorbent dosage of 900 mg/l at pH 6.75 for an initial methylene blue concentration of 65 mg/l.

Keywords: Color removal; Methylene blue; Fly ash; Hydrocyclone; Wastewater treatment

1. Introduction

Most industries use dyes and pigments to color their products. Today more than 9000 types of dyes have been incorporated in the color index and the biggest consumers of these dyes are textile, tannery, paper and pulp industry, cosmetic, plastics, coffee pulping, pharmaceuticals, food processing, electroplating and distilleries spew, perhaps these are the serious polluters of our environment as far as color pollution is concerned. Among these industries, the textile industry ranks first in usage of dyes for coloration of fiber [1]. The textile industry in India is one of the oldest and largest industries in the country. The textile mills required volumes of water of high purity and generate equally large volumes of wastewater, which is highly colored and complex in character. The total dye consumption of the textile industry worldwide is in excess of 10^7 kg/year, and an estimated 90% of this ends up on fabrics. Consequently, 1000 tonnes/year or more of dyes are discharged into waste streams by the textile industry worldwide [2].

Color can cause hazards to the environment due to the presence of a large number of contaminants like toxic organic residues, acids, bases and inorganic contaminants. Some of the dyes are carcinogenic and mutagenic because they were formerly made by hazardous chemicals such as benzidine, metals, etc. [3]. The discharge of colored wastes into the receiving water bodies not only affects their aesthetic nature but also interferes with the transmission of sunlight and therefore reduces the photosynthetic activity [4]. It may present an eco-toxic hazard and introduce the potential danger of bioaccumulation, which may eventually affect man through the food chain. Methylene blue is selected as a model compound in order to evaluate its capacity for the removal of methylene blue from its aqueous solutions. Methylene blue has wider applications, which include coloring paper, temporary hair colorant, dyeing cottons, wools, coating for paper stock, medical purpose, etc. Though methylene blue is not strongly hazardous, it can cause some harmful effects. Acute exposure to methylene blue will cause increased heart rate, vomiting, shock, Heinz body formation, cyanosis, jaundice, quadriplegia, and tissue necrosis in humans [5].

A range of conventional treatment technologies for dye removal have been investigated extensively, such as activated sludge, chemical coagulation, carbon adsorption, electrochemical treatment, reverse osmosis and hydrogen peroxide catalysis.

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However, most of the above methods suffer from one or more limitations and none of them were successful in completely removing the color from wastewater. The removal of dyes and organics in an economic way remains an important problem, although a number of systems have been developed with adsorption techniques. Adsorption has been found to be superior to other techniques for water re-use in terms of initial cost, simplicity of design, ease of operation and insensitivity to toxic substances [6]. The adsorption onto activated carbon has been found to be superior to other techniques in water re-use methodology because of its capability for adsorbing a broad range of different types of adsorbates efficiently, and simplicity of design. However, commercially available activated carbons are still considered expensive. Thus, many researchers researched for cheaper substitutes, which are relatively inexpensive, and are at the same time endowed with reasonable adsorptive capacity. These studies include the use of fly ash, bottom ash bagasse fly ash, starch, cellulose-based waste, rice husk, etc. [7–9].

Fly ash is a waste material originating in great amounts in combustion processes. At present, a number of thermal power plants fuelled with coal are in operation in many countries. In modern coal-firing power stations, pulverized coal is used, and fly ash is obtained as a waste product in large quantities. The fly ash collected in precipitators is generally disposed of in lagoons at the plant site or in landfills located in isolated areas. Indian coals have very high ash content. The ash content of coal used by thermal power plants in India varies between 25% and 45%. However, coal with an ash content of around 40% is predominantly used in India for thermal power generation. As a consequence, a huge amount of fly ash is generated in thermal power plants, causing several disposal-related problems. In spite of initiatives taken by the government, several non-governmental organizations and research and development organizations for fly ash utilization, the level of fly ash utilization in the country was estimated to be less than 10%. Globally, less than 25% of the total annual fly ash produced in the world is utilized [10]. Therefore, an inexpensive by-product management technology is needed for fly ash re-use. In India, more than 100 million tonnes/year of fly ash have been generated and disposal or utilization of this large amount of fly ash remains a problem. Although the disposal of fly ash using land filling is routinely practiced, increasing disposal costs and serious environmental concern over the leaching of latent toxic substance from the ash to soil, surface water and groundwater [11] are making the utilization of fly ash a more attractive alternative compared with direct disposal (land filling). Though fly ash is utilized effectively in brick and tile manufacturing, and other construction operations, it is unlikely that this will ever use all the fly ash generated [12]. Research is therefore needed to develop new alternative environmental friendly applications that can further exploit fly ash. In the present study fly ash has been used as adsorbent material for the treatment of dye-bearing wastewaters.

Adsorption of different type of dyes including methylene blue onto fly ash has been previously studied by many researchers [13,14]. Also, the adsorption of various dyes at solid–liquid interfaces has been studied extensively at equilibrium and various thermodynamic behaviors have been investigated. But very few studies were available explaining the actual dynamic and continuous mode during the sorption process.

The separation of dispersed solid particles from a suspension is an essential unit operation in many fields of mechanical separation technology. Typical apparatus used are filters, centrifuges and hydrocyclone. Whereas an enormous energy input is necessary using centrifuges at high rotational speed, hydrocyclones work more economically as the only amount of energy, which has to be supplied, is to overcome the pressure drop. A further advantage of hydrocyclone is their high operational reliability as they are simple in construction without any moving parts. In addition, in case of changing operational conditions, for example with unsteady flow, good separation efficiency can be achieved. Thus, hydrocyclones are widely used to separate particulates from liquid at high throughput because of their advantages like simple structure, low cost, large capacity and small volume, require little way of maintenance and support structure. Hydrocyclones belong to a class of fluid–solid classifying devices that separate dispersed material from a fluid stream [15].

In the present study, the effects of initial methylene blue concentration, fly ash doses on the removal of color in a hydrocyclone have been investigated. On the basis of available literature and from the point of view of advantages in terms of cost, space and power requirement, a hydrocyclone was chosen for the stated purpose. As powder particulate matter adsorbent have higher adsorption capacity compare to granular matter adsorbent, but again separation of adsorbent is a problem, so in our study hydrocyclone chosen to remove both color and adsorbent. Also some industries have particulate and color is a common pollutant, so this study is very useful for them. Commercial activated carbons are usually expensive, so that regeneration is essential, whereas fly ash is inexpensive, so regeneration is not necessary.

2. Experimental methods and technique

2.1. Adsorbate: methylene blue

Methylene blue is a basic dye, with the molecular formula $C_{16}H_{18}N_3ClS$ (molecular weight 373.91) with CAS No. 61-73-4, was chosen as adsorbate. The chemical structure of the dye is shown in Fig. 1. A stock solution of methylene blue was prepared (1000 mg/l) by dissolving required amount of methylene blue in distilled water. The stock solution was diluted with distilled water to obtain desired concentration. The concentration of methylene blue in each aqueous solution was measured on an ET99731 UV–vis spectrophotometer (Tintometer GmbH, Germany) by measuring absorbance at λ_{max} of 665 nm. A cali-

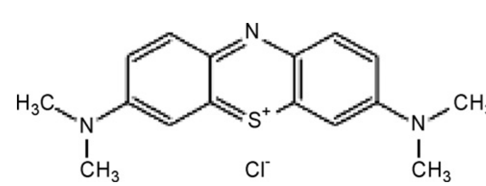

Fig. 1. Chemical structure of methylene blue dye.

bration plot was made in the concentration range of 10–100 mg/l for determination of the dye concentration.

2.2. Adsorbent: fly ash

The fly ash used in the present study was obtained from the Kolaghat thermal power plant, West Bengal, India. The collected materials were then washed with hot distilled water four to five times to remove the soluble organic matters that may be present in them. The washed materials were then dried in a hot air oven at 105 °C for 24 h. The dried materials were then stored in desiccators for use.

2.3. Reagents

All the chemicals used in the study were from Merck (India) Ltd. and Qualigens Glaxo (India) Ltd. analytical grade.

2.4. Pore structure characterization

The pore structure of the fly ash was analyzed using N_2 adsorption. The BET surface area, total pore volume and density functional theory (DFT) pore size distribution were determined from nitrogen adsorption/desorption isotherms measured at −194 °C (boiling point of nitrogen gas at atmospheric pressure) by a Quantachrome Autosorb-I. Density functional theory is a quantum mechanical theory used in chemistry to investigate the ground state of many-body systems, in particular atoms, molecules. The main objective of density functional theory is to replace the many-body electronic wave function with the electronic density as the basic quantity. Prior to gas adsorption measurements, the fly ash was degassed at 200 °C in a vacuum condition for a period at least 4 h. The BET surface area was determined by means of the standard BET equation applied in the relative pressure range from 0.05 to 0.3. The total pore volume was calculated at a relative pressure of approximately 0.98 and at this relative pressure all pores were completely filled with nitrogen gas. The DFT pore size distribution of fly-ash sample was obtained based on nitrogen adsorption isotherms, using Autosorb software package with medium regularization.

2.5. Method of experiment

The experimental setup as shown in Fig. 2 has been used for the studies of performance characteristic of hydrocyclone consisting of a vertical cylindrical portion and conical portion. The experimental setup mainly comprises a hydrocyclone, centrifugal pump and collection and supply tank. A conventional type hydrocyclone was designed according to optimum geometry for separation. The hydrocyclone is of transparent Perspex of cylindro-conical structure having a cyclone diameter of 100 mm. The length of the cylindrical portion is 77 mm and that of the conical portion is 110 mm. The cylindrical part is closed on top by a flat head through which the liquid overflow pipe known as vortex finder having a diameter of 50 mm protrudes some dis-

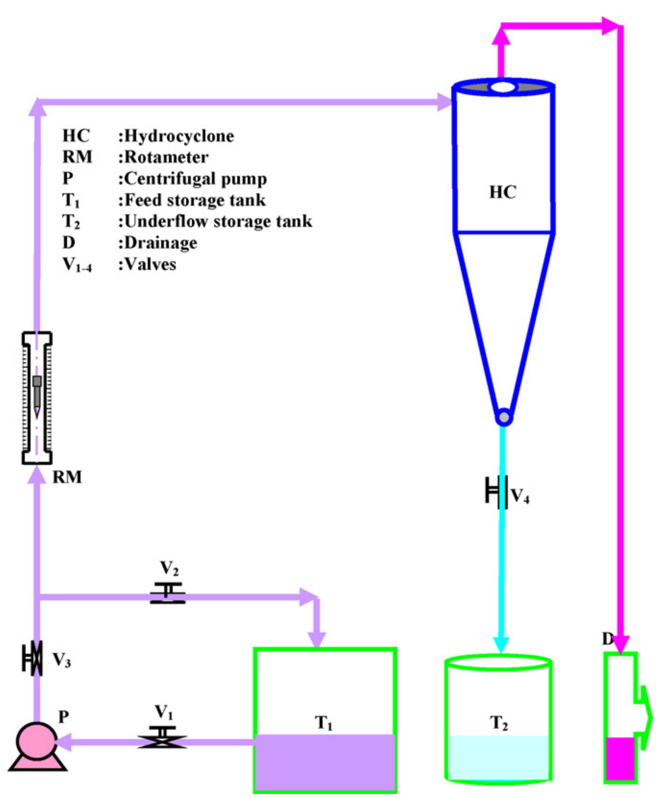

Fig. 2. Schematic diagram of experimental setup.

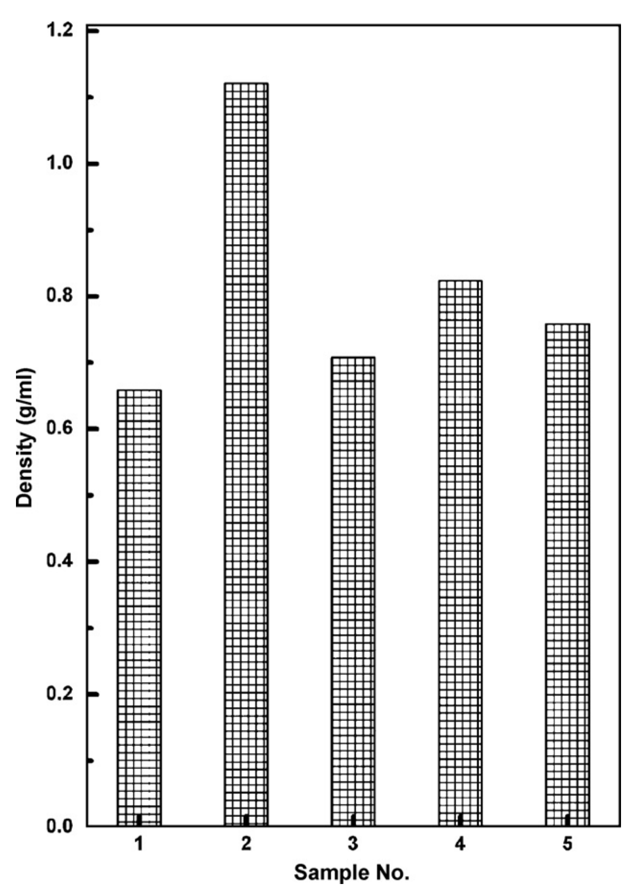

Fig. 3. Density of fly ash.

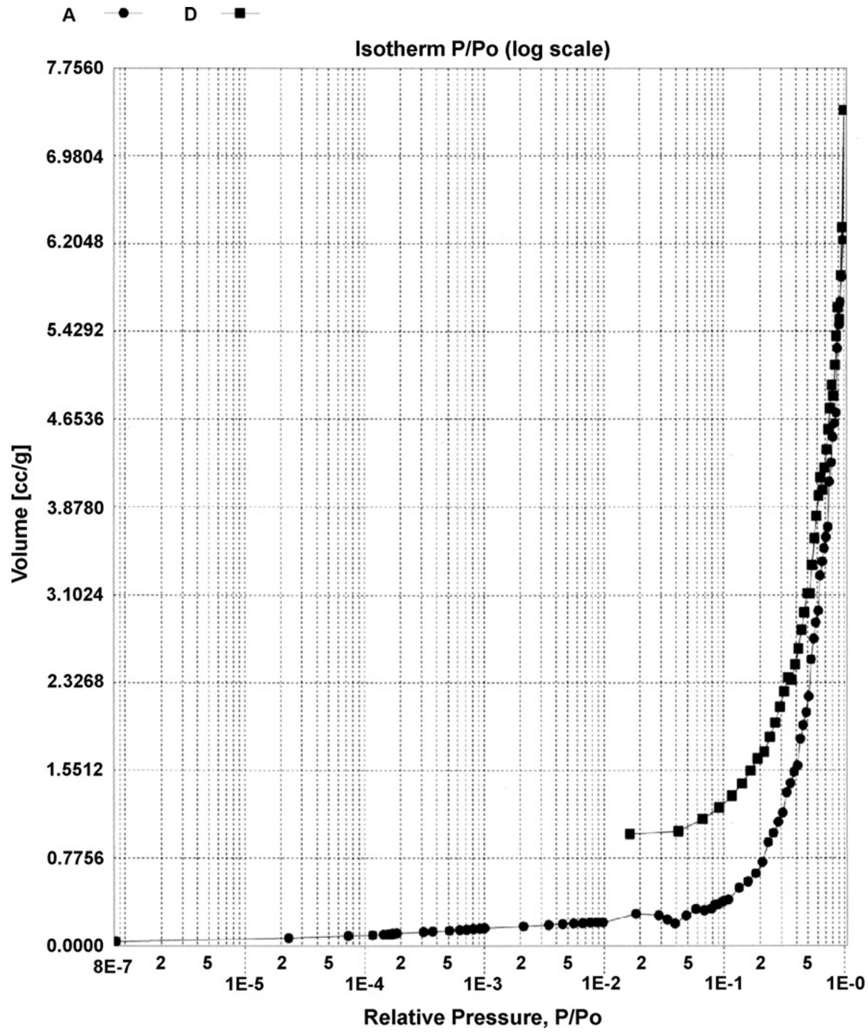

Fig. 4. N_2 adsorption/desorption isotherm of fly ash.

tance into the cyclone body. At the bottom of the conical section apex pipe having a diameter of 50 mm has been fitted through coarser particles will move. The liquid is injected tangentially by an inlet pipe of diameter 30 mm fitted tangentially to the cylindrical portion of the hydrocyclone. The dimensions of the hydrocyclone have been presented in Table 1.

A tank having a storage capacity of 1000 l has been placed as shown in the figure (T_1). A small storage tank having capacity 500 l (T_2) is provided at bottom section to collect underflow liquid. The overflow is passed to drainage (D) as unwanted material coming through it. The liquid is pumped to the cyclone by a centrifugal pump (P). There is a gate valve (V_1) between the tank and the centrifugal pump. The volumetric flow rate of feed slurry can be maintained by regulating the flow through a gate valve (V_1) between tank (T_1) and centrifugal pump (P) and by regulating the gate valve (V_2) through the bypass line. The flow through apex and split chamber can be controlled by valve (V_3) and valve (V_4). Rotameter (RM) is installed to measure total inlet volumetric flow rate to the hydrocyclone (HC). The separation action of a hydrocyclone treating particulate slurry is a consequence of the swirling flow that produces a centrifugal force on the fluid and suspended particles. The feed slurry is injected tangentially into the hydrocyclone at high velocity to produce a large centrifugal force field. The feed moves down the wall rapidly and generates a helical vortex, which extends beyond the lower end of the vortex finder. This swirling flow is highly turbulent and three-dimensional. In the centrifugal field, the particles move relative to the fluid with respect to the balance of centrifugal and drag forces acting upon particles in the radial direction, such that classification occurs. The coarser or heavier particles move toward the wall and are swept downward to the apex of the cone. The fluid phase, which carries the smaller or lighter particles, approaches the apex and reverses

Table 1
Specification of hydrocyclone used for experimental purpose

Parameters	Values
Diameter of hydrocyclone (mm)	100
Length of cylindrical portion of hydrocyclone (mm)	77
Length of conical portion of hydrocyclone (mm)	110
Internal diameter of feed inlet pipe (mm)	30
Internal diameter of vortex finder pipe (mm)	50
Internal diameter of apex pipe (mm)	50
Apex angle (°)	15.6

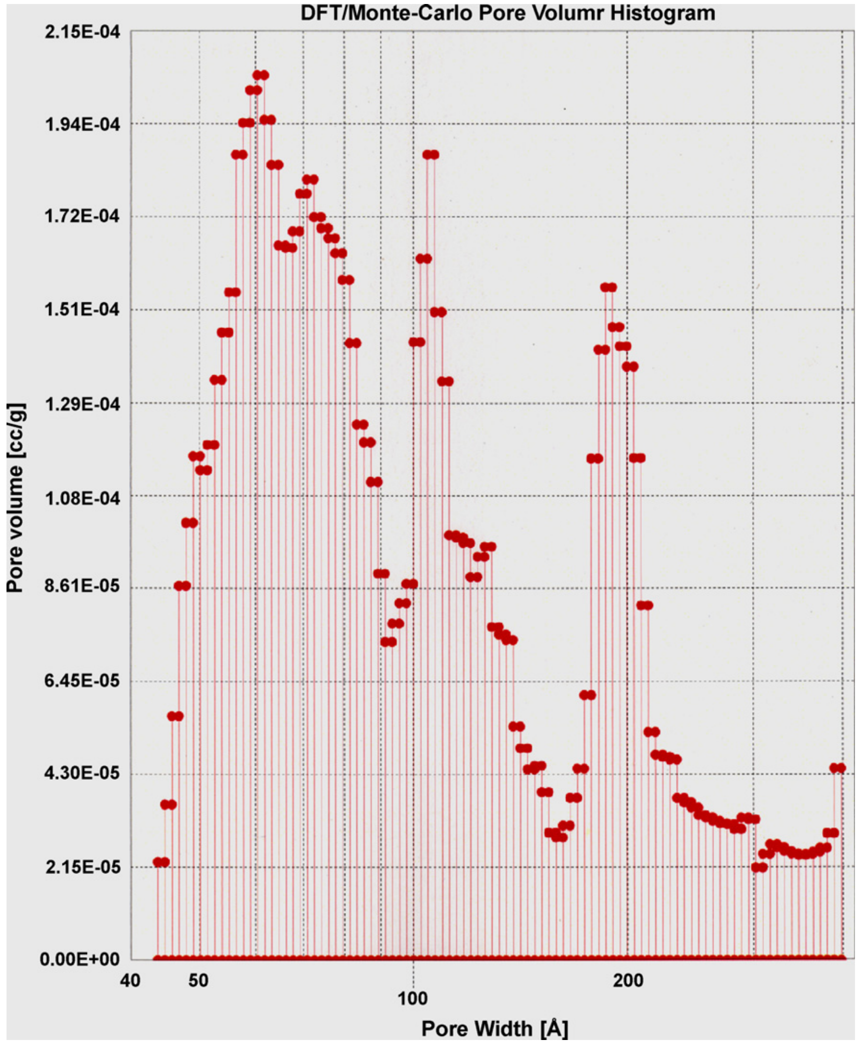

Fig. 5. Determination of pore size distribution of fly ash using DFT.

in the axial direction spiraling upward and leaving the hydrocyclone through the vortex finder. Along the axis, an area of low pressure is created by the very high angular momentum. This may cause the formation of a rotating free liquid surface at the center. If the hydrocyclone is open to the atmosphere, air is inhaled through the apex and forms an air core. In that case, the pressure at the air–liquid interface is equivalent to atmosphere pressure (neglecting both the surface tension and viscous forces).

Prepared particles and water as liquid medium is used for experiment. Storage tank with sufficient amount of water is filled so that continuous flow of liquid takes place inside the hydrocyclone. Flow from overflow is passed to drainage and underflow is kept in the small storage tank. By knowing the particle size at inlet and overflow, the efficiency of separation of each particle by hydrocyclone can be calculated by using the following equation for efficiency of separation of particle:

$$\eta_{PM} = \frac{C_{PM,inlet} - C_{PM,overflow}}{C_{PM,inlet}} \times 100 \quad (1)$$

where η_{PM} is the collection efficiency of the particulates, $C_{PM,inlet}$ the concentration of particulates at inlet (kg/m^3), and $C_{PM,overflow}$ is the concentration of particulates at overflow (kg/m^3).

Similarly prepared methylene blue, fly ash and water as liquid medium is used for experiment. Storage tank with sufficient amount of water is filled so that continuous flow of liquid takes place inside the hydrocyclone. Flow from overflow is passed to drainage and underflow is kept in the small storage tank. The overflow of hydrocyclone is first sedimented and then discharged to drains to avoid downstream chocking or generation of secondary pollutants. By knowing the methylene blue dye concentration at inlet and overflow, the efficiency of separation of methylene blue dye by hydrocyclone can be calculated by using the following equation for efficiency of separation of methylene blue dye:

$$\eta_{MB} = \frac{C_{MB,inlet} - C_{MB,overflow}}{C_{MB,inlet}} \times 100 \quad (2)$$

where η_{MB} is the collection efficiency of the methylene blue dye, $C_{MB,inlet}$ the concentration of methylene blue dye at inlet (mg/l), and $C_{MB,overflow}$ is the concentration of methylene blue dye at overflow (mg/l).

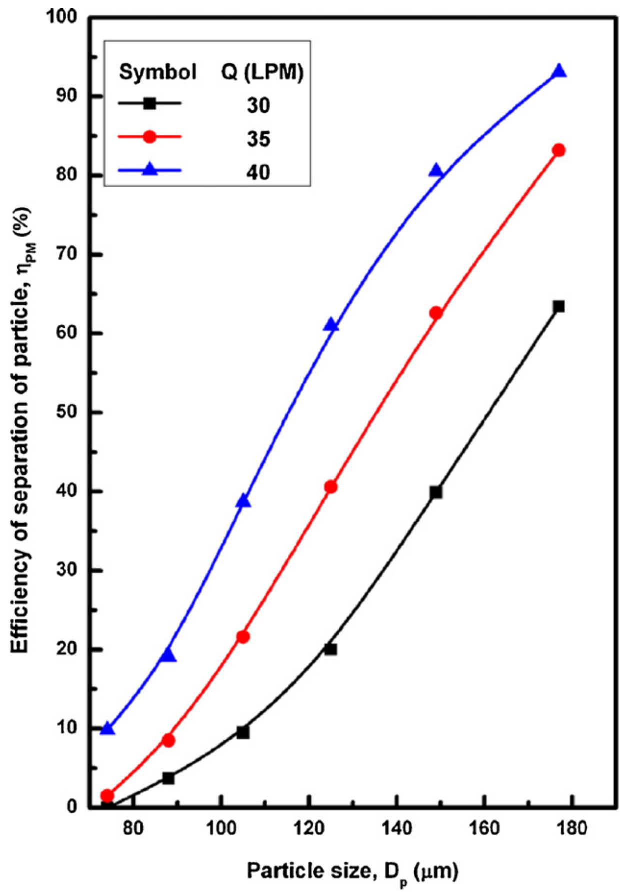

Fig. 6. Effect of particle size on efficiency of separation at different inlet flow rate.

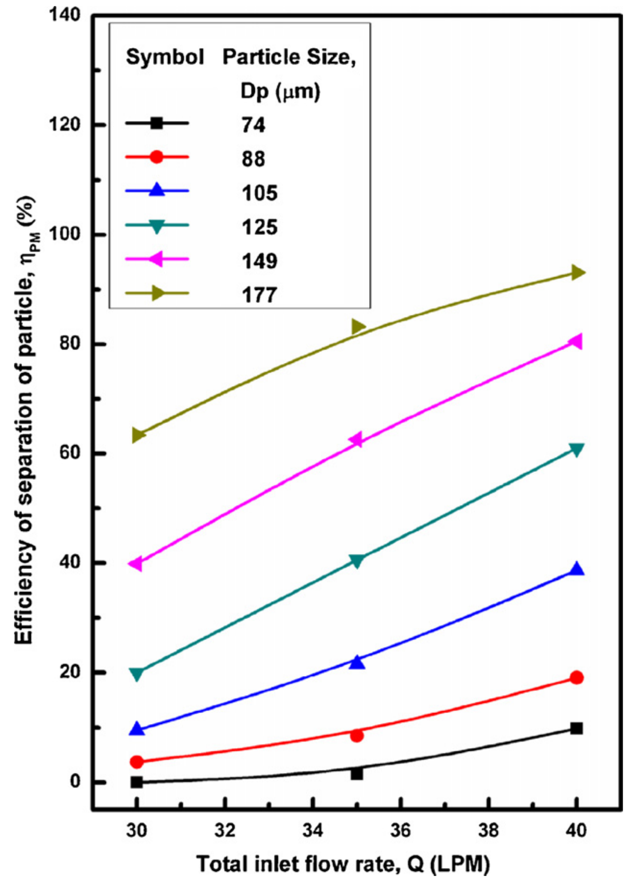

Fig. 7. Effect of total inlet flow rate on efficiency of separation at different particle size.

3. Results and discussions

3.1. Physical and chemical characterization of the adsorbent

3.1.1. Chemical properties

Adsorbent pH may influence the removal efficiency. Distinctly acidic adsorbent may react with the material to be removed and may hamper the surface properties of the adsorbent. The pH of fly ash was measured by using the method recommended by Al-Ghouti et al. [16] as follows: 3 g of fly ash was mixed with 30 ml of distilled water and agitated for 24 h. Then the pH value of the mixture was recorded with a pH meter. For our experiment the pH of fly ash was 6.75. The fly ash consists mainly of minerals such as silica, aluminum, iron, magnesium and calcium. Major oxide of fly ash was analyzed by X-ray florescence (XRF) technique. The chemical properties of the fly ash used are shown in Table 2.

3.1.2. Physical properties

Particle size distribution analysis was done manually. Initial sample of weight 400 g was taken for analysis. This sample was passed through different sieves and amount of fine and coarse were measured by screen analysis. Based on the mass fraction retained was shown in Table 3. Density is particularly important in removal. If two adsorbent differing in bulk density are used at the same weight per liter, the adsorbent having higher bulk density will be able to remove more efficiently. Average bulk density can be calculated by water displacement method. In this method, volume of water displaced is observed by a particular amount of fly ash. The data were obtained for this experiment is shown in Fig. 3. The average bulk density is 0.8138 g/ml.

Table 2
Chemical composition of fly ash

Component	% Elemental composition	% Oxide composition
Si	47.71	54.17
Al	26.61	30.08
Fe	7.07	4.57
K	3.43	2.50
Ti	3.06	2.12
Ca	2.73	1.11
Rb	2.35	1.20
Na	2.15	1.02
Mg	1.87	0.91
Ba	1.35	0.65
S	0.49	0.52
Others	0.08	0.05
Loss on ignition	1.10	1.10

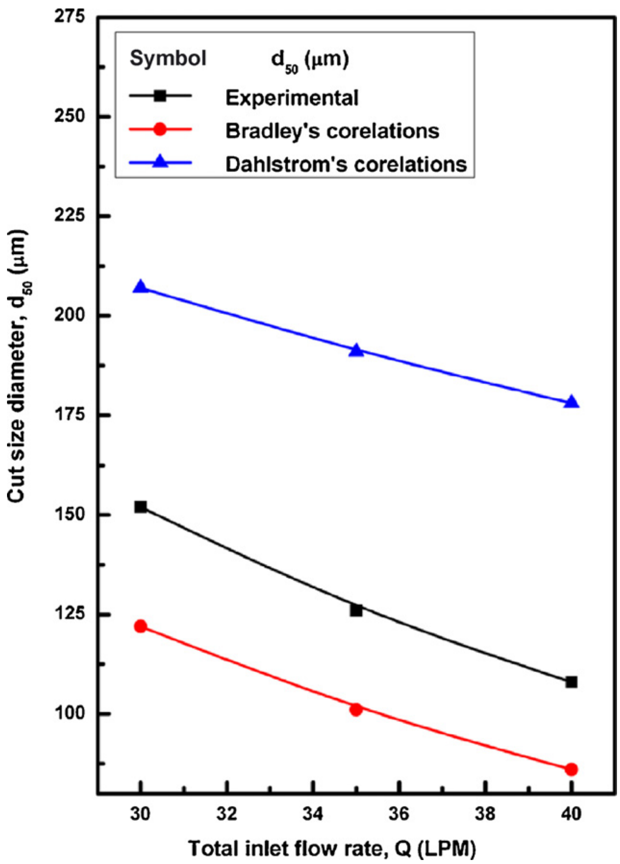

Fig. 8. Effect of total inlet flow rate on cut size, d_{50} for fly ash.

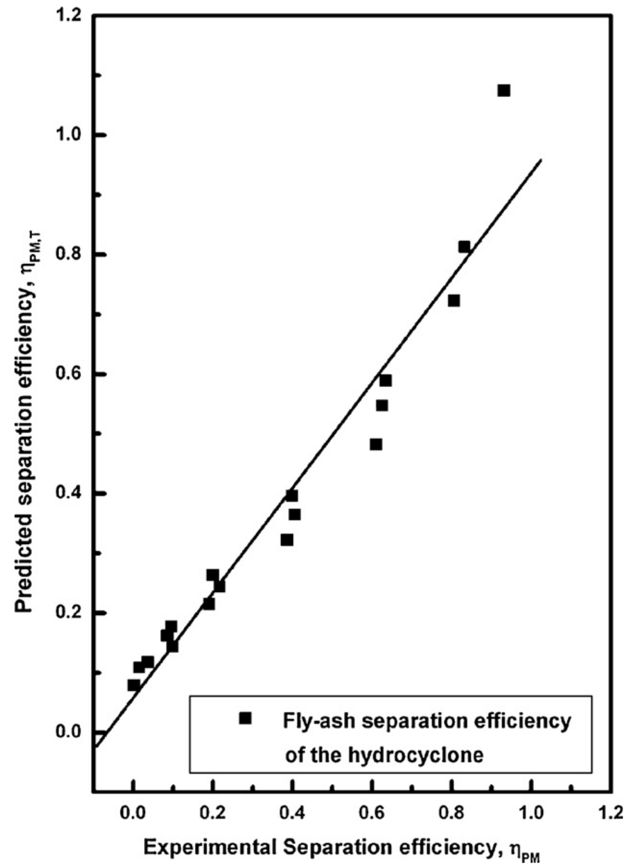

Fig. 9. Comparison of theoretical and experimental values of particle separation efficiency.

3.1.3. Pore structure characterization

The N_2 adsorption isotherm shows in Fig. 4. The fly-ash exhibit type I isotherm. Type I isotherm corresponds to essentially microporous fly ash. The isotherm has characteristics; at low pressure region significant uptake of nitrogen occurred. This means that nitrogen molecules are adsorbed in the microporous structure. The adsorption in micropores was interpreted according to the pore filling mechanism, thus result in highly adsorbed volume. Surface area and total pore volume of fly ash is also obtained from N_2 adsorption isotherm. The surface area and total pores volume for the fly ash is found to be 5.184 m^2/g and 0.0094 cm^3/g, respectively. The DFT result is given in Fig. 5 shows that the fly ash consists mainly of micropores of pore width up to 200 Å.

Table 3
The particle size distribution (based on % mass fraction retained)

Mesh	% Mass fraction
+325	0.0058
−325 +270	0.0119
−270 +200	0.2035
−200 +170	0.5022
−170 +100	0.0710
−100 +60	0.1237
−60	0.0819

3.2. Performance of hydrocyclone for fly ash removal

3.2.1. Effect of particle diameter on separation efficiency

Experiments have been conducted for different size of fly ash particles to characterize the performance of a hydrocyclone. The slurry volumetric flow rate used for experimental studies was in the range of 30–40 LPM (30, 35, 40 LPM). From Fig. 6 it can be seen that with increasing particle size, the efficiency of separation increases almost exponentially. It can also be seen from plot that at low flow rate i.e. 30 LPM, the cut size, the 50% efficiency of separation is 152 μm; at 35 LPM, the 50% efficiency of separation of particles is 126 μm and at 40 LPM, the 50% efficiency of separation of particles is 108 μm. It is interesting to note that at 40 LPM, the efficiency of separation is almost 93% for particles above 177 μm. It is quite obvious that with increasing flow rate of the cyclonic motion, the larger particles are removed easily. So, with increase in particle size, at a particular inlet flow rate, the efficiency of separation increases. As shown in Fig. 7 with increasing inlet flow rate the efficiency of separation of each particle size range also increases. At high inlet flow rate, the particles separate more efficiently.

3.2.2. Effect of inlet flow rate on cut size particle diameter

For different inlet flow rate Q of slurry across the hydrocyclone, d_{50} values were calculated for fly ash. The d_{50} value was also calculated using Bradley's [17] correlation as given in

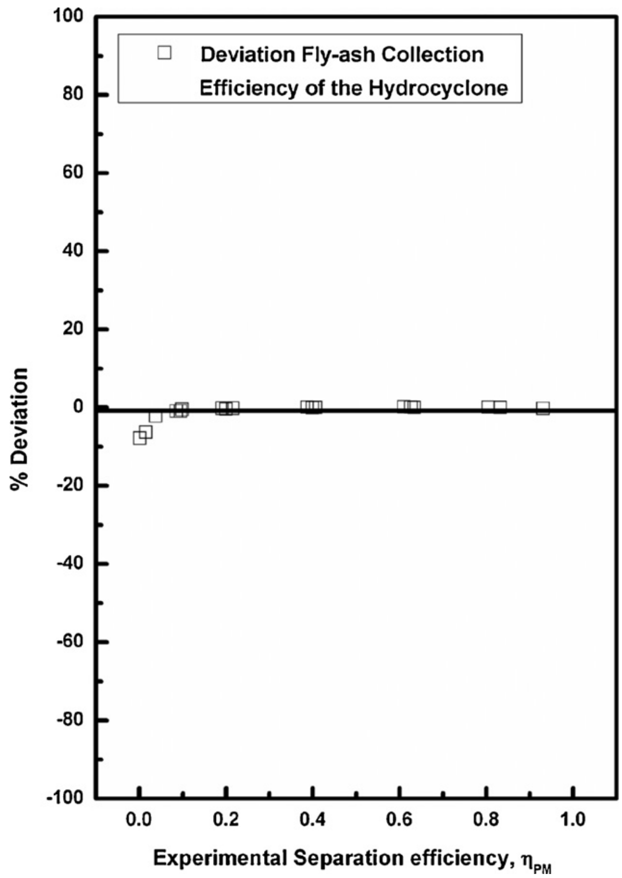

Fig. 10. Deviation between experimental and predicted values of separation efficiency.

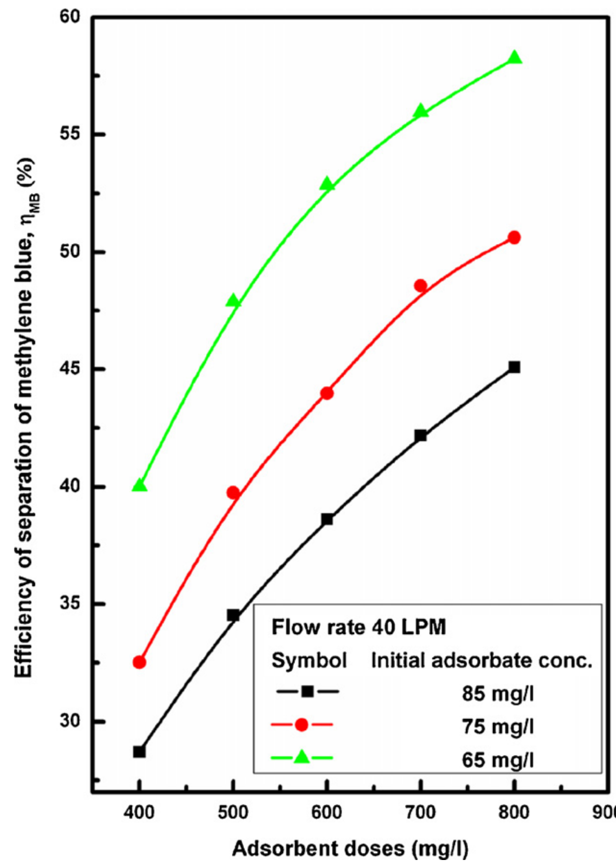

Fig. 11. Effect of adsorbent doses on methylene blue separation.

Eq. (3) and Dahlstrom's [18] correlation given in Eq. (4) below and compared with the experimental findings of the present system:

$$d_{50} = \frac{D_c^3 \mu}{Q^{1.2}(\rho_s - \rho_l)} \tag{3}$$

$$d_{50} = \frac{2248.5(D_i D_c)^{0.68}}{Q^{0.53}} \left[\frac{1.73}{\rho_s - \rho_l}\right]^{0.5} \tag{4}$$

where d_{50} is the cut size diameter (μm), the 50% efficiency of separation, D_c is the diameter of hydrocyclone (mm), D_i is the diameter of feed inlet pipe (mm), Q is the total inlet flow rate (LPM), μ is the water viscosity (g/ms), ρ_s is the density of fly ash (g/ml), ρ_l is the density of water (g/ml).

The predicted values and d_{50} data obtained from experimental results have been calculated for fly ash. The effect of slurry flow rate on cut size particle diameter, d_{50} has been presented in Fig. 8 for fly ash. It can be seen from this figure that with increase in flow rate the cut size decreases.

3.2.3. Development of correlation for predicting removal efficiency of fly ash

In order to quantify the performances of the hydrocyclone, we tried to develop an empirical model, by dimensional analysis, in order to predict the removal efficiency from directly measurable parameters. The experimental result show, that the conceivable variables which could possibly affect the collection efficiency of the particulates, η_{PM}.

As the motion of particle and fluid inside a hydrocyclone is very complex, the possibility of using any one of the proposed models or empirical correlations, with a degree of accuracy, was therefore found difficult for the present system. Hence, the experimental separation efficiency has been analyzed on the basis of dimensionless analysis to predict the removal efficiency of the hydrocyclone. Conceivable variables on which the efficiency of separation of particles in the hydrocyclone may depend are: flow properties and fluid flow rate Q; physical properties namely diameter of suspended particle D_p, density of suspended particle ρ_s, density of fluid ρ_l, viscosity of fluid μ; geometric properties: hydrocyclone diameter D_c, diameter of eductor D_e, and inlet diameter $D_i = f(D_c; D_u)$. The large numbers of possible variables on which the efficiency of separation depend have been reduced to a pertinent few, since many of these variables are interrelated or are maintained constant. A theoretical relation exists between the efficiency of separation $\eta_{PM,T}$, and the physical characteristic, and the fluid variable of the system. Then $\eta_{PM,T}$ may be written in the following form:

$$\eta_{PM,T} = f(\rho_s, \rho_l, Q, D_p, D_i, \mu) \tag{5}$$

The variables in the above equation can be grouped into dimensionless groupings by employing the Buckingham's π-

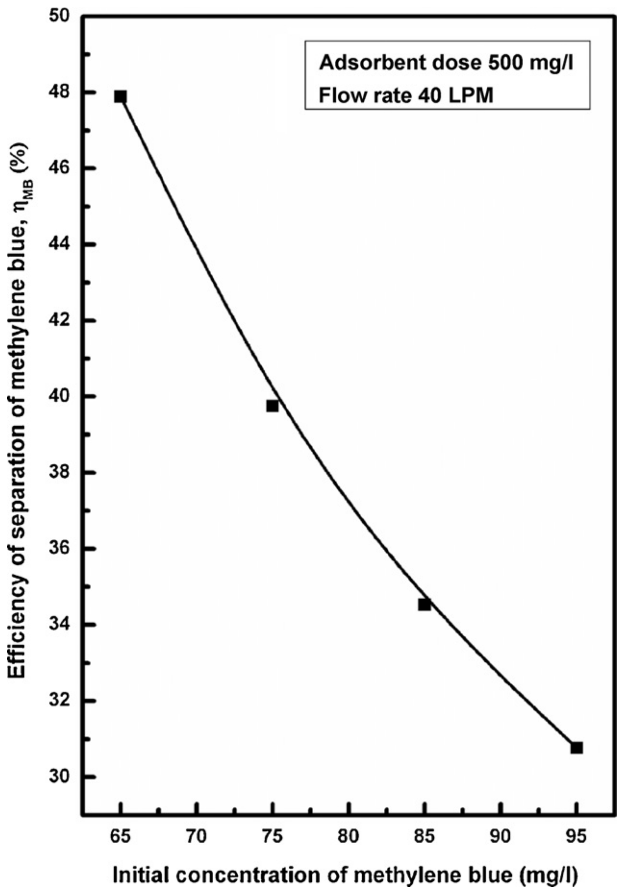

Fig. 12. Effect of initial adsorbate concentration on methylene blue separation.

Theorem, and the equation can be reduced to

$$\eta_{PM,T} = f_2\left(\frac{\rho_s Q}{\mu D_i}\right)^a \left(\frac{D_p}{D_i}\right)^b \left(\frac{\rho_l}{\rho_s}\right)^c \tag{6}$$

The form of the equation can be rearranged to give the retention of the particles in the hydrocyclone are a measure of efficiency of separation, given as

$$RP = 1.0 - \eta_{PM,T} = 1.0 - Z\left(\frac{\rho_s Q}{\mu D_i}\right)^a \left(\frac{D_p}{D_i}\right)^b \left(\frac{\rho_l}{\rho_s}\right)^c \tag{7}$$

The dimensionless analysis presented earlier indicates that the percentage separation efficiency of particles presented in Eq. (6), may be simplified to

$$\eta_{PM,T} = S\left(\frac{\rho_s Q}{\mu D_i}\right)^a \left(\frac{D_p}{D_i}\right)^b \left(\frac{\rho_l}{\rho_s}\right)^c \tag{8}$$

In order to establish the fundamental relationship between the separation efficiency $\eta_{PM,T}$ and the various dimensionless groupings, a multiple linear regression analysis has been carried out to evaluate the constant and coefficients of the equation. The optimum equation which yield's minimum percentage of error and minimum standard deviation, gives the best possible correlation of fractional efficiency as

$$\eta_{PM,T} = 12.43\left(\frac{\rho_s Q}{\mu D_i}\right)^{2.1} \left(\frac{D_p}{D_i}\right)^{2.3} \left(\frac{\rho_l}{\rho_s}\right)^{16.1} \tag{9}$$

Eq. (9) actually describes the particle penetration within the hydrocyclone, which is an important parameter for assessing the performance of the hydrocyclone.

The values of the parameter can be expressed as

$$RP{=}1 - \eta_{PM,T}{=}1 - \left[12.43\left(\frac{\rho_s Q}{\mu D_i}\right)^{2.1} \left(\frac{D_p}{D_i}\right)^{2.3} \left(\frac{\rho_l}{\rho_s}\right)^{16.1}\right] \tag{10}$$

The values of percentage removal of fly ash, $\eta_{PM,T}$ predicted by Eq. (9) have been plotted against the experimental values of percentage removal of fly ash, η_{PM} in Fig. 9. The percentage deviation between the experimental data and those of predicted by Eq. (5) has been plotted in Fig. 10. It is seen from this figure that the percentage deviation is quite low (within ±8%).

3.3. Performance of hydrocyclone for methylene blue removal

3.3.1. Effect of adsorbent dose

The effect of fly ash mass on the amount of methylene blue removed was obtained at total inlet flow rate 40 LMP of slurry of methylene blue concentration 65, 75 and 85 mg/l in a hydrocyclone at room temperature (30 °C). The samples were then collected at inlet and over flow sampling points and analyzed for left out concentration, as said before. The effect of adsorbent dosage on the percentage removal of methylene blue has been shown in Fig. 11. It can be seen from the figure that initially the percentage removal increases very sharply with the increase in adsorbent dosage (400–900 mg/l) but beyond a certain value, the percentage removal reaches almost a constant value. This trend is expected because as the adsorbent dose increases the number adsorbent particles increases and thus more methylene blue is attached to their surfaces. In another word, increase in percent removal with increase in absorbent dosage is due to the increase in absorbent surface area. A maximum removal of 58.24% was observed at adsorbent dosage of 900 mg/l at pH 6.75 for an initial methylene blue concentration of 65 mg/l. The adsorption is both chemisorption and physical adsorption as it contains some metal ions.

3.3.2. Effect of initial adsorbate concentration

Several experiments were undertaken to study the effect of varying the initial methylene blue concentration on the efficiency of dye removal from solution at total inlet flow rate 40 LPM in a hydrocyclone at room temperature (30 °C). The effect of methylene blue concentration in the solution on the adsorption has been shown in Fig. 12. It can be seen from the figure that with increased methylene blue initial concentration, there was decrease in percentage of removal efficiency of methylene blue in the hydrocyclone. The percent dye removal decreased from 47.89% to 30.77% for methylene blue as the dye concentration was increased from 65 to 95 mg/l. The effect of initial adsorbate concentration was investigated and found that the increase in initial concentration of methylene blue enhances the interaction between methylene blue and fly ash. Methylene blue concentration is a driving force to overcome the resistances to the mass transfer of dye between the solution and the adsorbent surface. The adsorption capacity beyond methylene blue concentration 95 mg/l did not increase, that the fly ash reached its maximum adsorption capacity. It is clear that the removal of methylene blue depends on the concentration of the dyes. The removal curves are single, smooth and continuous leading to saturation.

4. Conclusions

The objective of this work was to study the performance of hydrocyclone for removal of methylene blue by using fly ash as an absorbent in a continuous mode. Conclusions from the present study are as follows:

(I) Characterization has shown a clear demarcation in the physico-chemical properties of the adsorbent.
(II) The performance of the hydrocyclone was evaluated for fly ash removal; it shows that in the separation of particulate size the efficiency increases with the increase in particle diameter. Also the cut size of the hydrocyclone increases with decreases in the flow rate.
(III) The experimental values were compared with the values obtained by empirical and it shows close agreement between the experimental points and empirical curves.
(IV) Methylene blue adsorption onto fly ash shows that for the same concentration of adsorbent particles the efficiency decreases with increase in the adsorbate concentration in the feed solution. Also for the same feed dye concentration, the efficiency increases with increase in the adsorbent particles.

Similar work is in progress for investigating the efficacy of fly ash for other colors and heavy metal. Initial results imply that fly ash has good adsorption capacity for methylene blue in a hydrocyclone and hence it can be used for wastewater applications in multicomponent system due to its universality and easy availability.

References

[1] V.K. Garg, R. Gupta, A.B. Yadav, R. Kumar, Dye removal from aqueous solution by adsorption on treated sawdust, Bioresour. Technol. 89 (2) (2003) 121–124.
[2] R. Marc, Asian textile dye makers are a growing power in changing market, C EN Northeast News Bureau 73 (1996) 10–12.
[3] M. O¨zacar, I.A. Sengil, Adsorption of reactive dyes on calcined alunite from aqueous solutions, J. Hazard. Mater. 98 (2003) 211–224.
[4] C. Namasivayam, R. Radhika, S. Suba, Uptake of dyes by a promising locally available agricultural solid waste: coir pith, Waste Manage. 21 (2001) 381–387.
[5] K. Vasanth Kumar, V. Ramamurthi, S. Sivanesan, Modeling the mechanism involved during the sorption of methylene blue onto fly ash, J. Colloid Interface Sci. 284 (2005) 14–21.
[6] V. Meshko, L. Markovska, M. Mincheva, A.E. Rodrigues, Adsorption of basic dyes on granular activated carbon and natural zeolite, Water Res. 35 (14) (2001) 3357–3366.
[7] S. Xu, J. Wang, R. Wu, H. Li, Adsorption behaviors of acid and basic dyes on crosslinked amphoteric starch, Chem. Eng. J. 117 (2006) 161–167.
[8] G. Annadurai, R.-S. Juang, D.-J. Lee, Use of cellulose-based wastes for adsorption of dyes from aqueous solutions, J. Hazard. Mater. B92 (2002) 263–274.
[9] K. Mohanty, J.T. Naidu, B.C. Meikap, M.N. Biswas, Removal of crystal violet from wastewater by activated carbons prepared from rice husk, Ind. Eng. Chem. Res. 45 (14) (2006) 5165–5171.
[10] R.S. Iyer, J.A. Scott, Power station fly ash—a review of value-added utilization outside of the construction industry, Resour. Conserv. Recycl. 31 (2001) 217–228.
[11] J. Wang, H. Ban, X. Teng, H. Wang, K. Ladwig, Impact of pH and ammonia on the leaching of Cu(II) and Cd(II) from coal fly ash, Chemosphere 64 (2006) 1892–1898.
[12] F.X. Wang, B. Han, Mechanism and application of fly ash inwaste treatment, China Resour. Compr. Utiliz. 3 (2002) 19–22.
[13] P. Janos, H. Buchtova, M. Ryznarova, Sorption of dyes from aqueous solutions onto fly ash, Water Res. 37 (2003) 4938–4944.
[14] L. Li, S. Wang, Z. Zhu, Geopolymeric adsorbents from fly ash for dye removal from aqueous solution, J. Colloid Interface Sci. 300 (1) (2006) 52–59.
[15] R. Sripriya, M.D. Kaulaskar, S. Chakraborty, B.C. Meikap, Studies on the performance of a hydrocyclone and modeling for flow characterization in presence and absence of air core, Chem. Eng. Sci. 62 (2007) 6391–6402.
[16] M. Al-Ghouti, M.A.M. Khraisheh, S. Allen, M.N.M. Ahmad, The removal of dyes from textile wastewater: a study of the physical characteristics and adsorption mechanisms of diatomaceous earth, J. Environ. Manage. 69 (2003) 229–238.
[17] D. Bradley, D.J. Pulling, Flow patterns in the hydraulic cyclone and their interpretation in terms of performance, Trans. Inst. Chem. Eng. 37 (1959) 34–45.
[18] D.A. Dahlstrom, Fundamentals and applications of the liquid cyclone, in: Chemical Engineering Progress Symposium Series No. 15, vol. 50, Mineral Engineering Techniques, 1951, pp. 41–56.