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Physiochemical Treatment of Wastewater Utilizing Polyaluminum Chloride for Khartoum North Wastewater Effluent

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Abstract: This paper focuses on the possibility of applying physiochemical treatment for industrial wastewater combined with domestic wastewater that are currently treated by the conventional activated sludge process in Khartoum North Treatment plant at Haj Yousif (Wad Dafeah). A lab-scale experiment was carried out utilizing Poly aluminum chloride (PAC) as a coagulant for determining the optimum dose to reduce the turbidity of the wastewater sample to the lowest level. The results of the lab-scale model showed that a dose of 0.8 ml/l of the PAC achieved significant removal of turbidity (from turbidity >1000 NTU of raw sewage to turbidity level of 18 NTU of the treated effluent). This dose of 0.8ml/l obtained from the lab-scale experiment was applied in a pilot plant of capacity 30 m^3/d erected at the site of the treatment plant (Wad Dafeah). The process units utilized in the pilot plant were of minimum or negligible electrical power consumption. They include an inverted hydro cyclone for flash mixing of the coagulant, pipes arrangement to achieve hydraulic gentle mixing as flocculation process, vertical sedimentation tank to enhance efficient settling of particles and tertiary treatment using a rapid sand filter. Raw sewage of BOD5 = 5000 mg/l was introduced into the pilot plant and excellent quality of treated effluent was obtained. Removal efficiencies of both BOD5 and SS were high (97 % & 98% respectively).Treated effluent had BOD5 = 23 mg/l & SS = 22 mg/l. The high dose of PAC utilized for the treatment (0.8 ml/l= 1040 mg/l) can be reduced significantly if raw wastewater of lower BOD content such as domestic wastewater is treated. In a parallel study with the domestic sewage of BOD5 =350 mg/l, the PAC dose required was 0.1 ml/l (130 mg/l). Recycling of residual PAC in the sludge is recommended to decrease the cost of treatment. The approach & methodology followed in this study can be further adopted using other coagulant material such as ferric salts or other similar local product which can achieve high efficiency in reducing the load of organic substances in the wastewater with minimum cost.

Keywords: *Physiochemical; Poly aluminum chloride; inverted hydro cyclone; lab-scale model; pilot plant model.*

1. INTRODUCTION

Physiochemical treatment of wastewater focuses primarily on the separation of colloidal particles in wastewater. This is achieved through the addition of chemicals where the processes of coagulation, flocculation, sedimentation, filtration, and disinfection similar to that for treating turbid surface water are utilized. The colloids in wastewater change into a stable form of particles or flocs with settling properties whereas the treated effluent with quality conforming to the required standards can be reused for irrigation purposes or to be disposed of into water bodies.

The physiochemical method has been applied for over 100 years ago. However, in 1930, this method was replaced by biological processes due to the high costs incurred by the treatment of large quantities of sludge. Recently, the physiochemical processes have been reintroduced for various purposes as stated below [1]:

– Obtaining average quality treated effluent at a lower cost than the conventional biological treatment of wastewater. Power consumption is excessive in conventional treatment than physiochemical processes.
– Phosphorus can be eliminated and therefore physiochemical processes can be utilized for industrial wastewater treatment.
– Treated effluents can be utilized for irrigation and can be disposed of into water bodies.
– Physiochemical processes can be adopted in developing countries for small decentralized wastewater systems where sludge can be safely disposed of and effluents can be reused for irrigation purposes [2].

The aim of this study is to adopt a physiochemical process for treatment of industrial wastewater combined with domestic sewage utilizing the coagulant polyaluminum chloride. The study area is in Khartoum North Township in Sudan.

2. LITERATURE REVIEW

Vast secondary data as literature review from journals, textbooks, websites pertaining to physiochemical treatment for water & wastewater was investigated. Brief summary for utilizing of PAC as a flocculent material is also presented in this paper.

2.1. Case study No. 1: Tannery Wastewater

A recent paper in 2012 was published in the Journal of Science & research (Pakistan), focused on utilizing the physiochemical process for treating wastewater from a tannery. Combinations of chemicals including Aluminum sulfate were used as coagulants. A dose of 5g/l of the immobilized coagulants at pH = 7 was obtained as the optimum dose for reducing COD concentration in the wastewater of the tannery [3].

2.2. Case study No. 2: Tertiary Treatment

A study was conducted in Greece in 2007 investigated the tertiary physiochemical treatment of the secondary effluent from the Chania Wastewater Treatment Plant (WTP). Laboratory experiments were carried out with the aim of studying coagulation efficiency regarding the reduction of turbidity, soluble COD & Phosphorus both in a Conventional Coagulation – Settling scheme as well as by means of Contact Filtration. The results showed that high doses of coagulants (0.5 mmole me^{+3} per liter or higher) are required to achieve significant removals of turbidity after settling. At these high doses, soluble COD can be removed by about 50%, while soluble Phosphorous by 80—95 %. Ferric Chloride demonstrated slightly better removal ability compared to Alum [4].

2.3. PAC characteristics and applications

Poly aluminum chloride is increasingly used for water treatment. It shows distinct advantages against the conventional use of aluminum sulfate (alum). Poly aluminum chlorides are synthetic polymers dissolved in water [5]. They react to form insoluble aluminum poly-hydroxides which precipitate in big volumetric flocs. The flocs absorb suspended impurities or pollutants in water which are precipitated with the PAC & can together be easily removed. PAC can be used as a flocculent for all types of water treatment, drinking water, industrial wastewater, urban wastewater & in the paper industry.

The possible slightly higher unit price of PAC is compensated by [5]:

- Lower dosage requirement
- No requirement for any neutralizing agent (soda or lime).
- Shorter flocculation time
- Small amount of sludge
- Reduced number of backwashing steps
- High quality of the treated water

There are two types of PAC in industry:

2.3.1. Poly aluminum Chloride 9% AL_2O_3

PAC 9% AL_2O_3 high basicity is mostly used for drinking water treatment. Properties of PAC are summarized below:

Table 1. Characterization of PAC type 1

Appearance	liquid with yellow color
AL_2O_3 content	8.8-9.2 %
CL	9.8-11 %
Basicity	62-68 %
Specific Weight @ 20 ^{0}C	1.18 -1.22 g/ml
Solidification point	- 10 ^{0}C

2.3.2. Poly aluminum Chloride 18% AL_2 O_3

PAC 18% AL_2O_3 can be used for most applications.

Table 2. Characterization of PAC type 2

Appearance	liquid with yellow color
AL_2O_3 content	17-19 %
CL	21-22 %
Basicity	36 -42 %
Specific Weight @ 20 ^{0}C	1.36-1.39 g/ml
Solidification point	- 10 ^{0}C

3. MATERIALS AND METHODS

- A literature review was cited for utilizing of PAC as a coagulant material for water and wastewater. Previous studies in physiochemical treatment for industrial wastes were also cited as explained earlier in section 2.
- A lab-scale bench model (Jar-test) was prepared and utilized for determining the optimum dose of the coagulant material (PAC) to decrease the turbidity and organic matter in samples of raw sewage.
- The experiments were conducted considering various adjusted pH values.
- A field-scale pilot plant was constructed for determining the effectiveness of the flocculent material (PAC) in treating combined industrial and domestic sewage entering the existing anaerobic ponds in Khartoum North wastewater treatment plant (Haj-Yousif, Wad Dafeah ponds) as illustrated in **Fig. 1.** The optimum dose of PAC that was obtained in the lab-scale model was used. The components of the pilot plant were: rapid mixing equipment (utilizing inverted hydro-cyclone), slow hydraulic mixing in a piping arrangement (flocculation), vertical settling tank & rapid sand filtration as a tertiary treatment. The quality of the treated effluent is expected to conform to the standard quality of reuse for irrigation purposes.

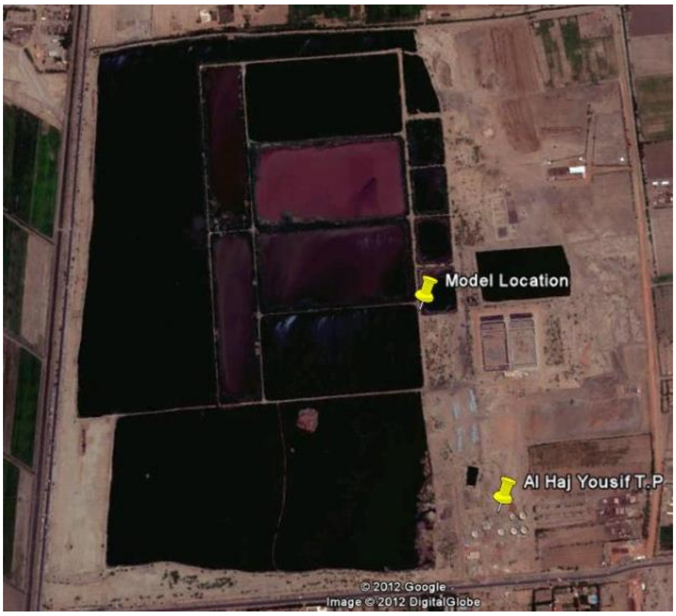

Fig. 1. Study Area: Haj Yousif, Wad Dafeah Ponds

4. EXPERIMENTAL & FIELD WORK

Before constructing the pilot plant model, laboratory tests were carried out to select the optimum dose of the coagulant (PAC). Jar tests were carried out for three samples of wastewater from the existing ponds In Haj-Yousif Wad Dafeah ponds.

4.1. Lab-scale tests by Jar-test

A. Sample NO. 1

Properties of the sample (raw wastewater):
- pH=7.10
- Turbidity=616 N.T.U
- Raw wastewater BOD =5000 mg/l

Table 3. Results of sample 1 after Jar test

No.	PAC Dose (mg/l)	pH	Turbidity (NTU)
1	260	7.14	39
2	520	7.10	35
3	780	7.16	27
4	1040	7.20	13
5	1300	7.14	35

B. Sample NO. 2

The sample was taken from the facultative pond.

Properties of the sample before jar test:
- PH=9.90.
- S.S=284 mg/l (Turbidity > 1000 NTU)

Properties of the sample after jar test:
- PH=9.30.
- S.S = 222 mg/l (Turbidity > 1000 NTU)

The PAC has no effect on this sample because pH is more than 8.5 (algae). (PAC pH range from 5.0-8.50).

C. Sample No. 3

The sample was taken from the anaerobic pond where an intake floating (Panton) was erected for abstracting wastewater to the pilot plant.

Properties of the sample before jar test:
- S.S=378 mg/l. (Turbidity > 1000 NTU)

Properties of sample after jar test for dose of PAC = 0.8 ml/l:
- S.S =7 mg/l. (Turbidity = 18 NTU)

Table 4. Results of sample 3 after Jar test

No.	PAC Dose (mg/l)	pH	Turbidity (NTU)
1	1040	7.12	18.2
2	1820	6.95	24
3	650	7.25	32

Therefore, the optimum dose of PAC obtained to reduce the turbidity to a value of about 18 NTU from turbidity of greater than 1000 NTU of raw wastewater was 1040 mg/l. This dose is utilized in the pilot plant.

4.2. Pilot plant model and experimental tests

The pilot plant capacity was 1.2 m^3/hr and the main components of the pilot plant were:
- Flash mixing unit adopting inverted hydro cyclone
- Slow hydraulic mixing using piping system
- Sedimentation using Vertical tank
- Tertiary treatment using rapid sand filter

The following is a description of the above treatment units:

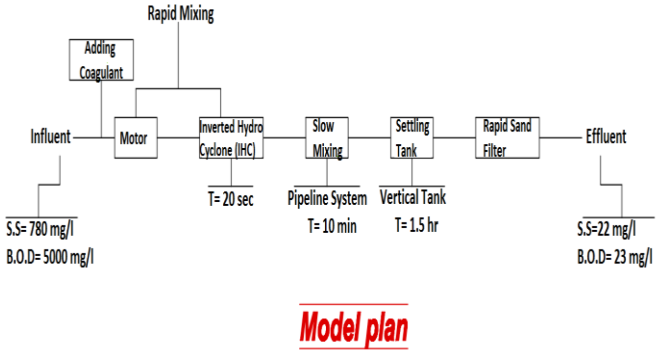

Fig.2. Scheme describing the layout of the pilot plant

4.2.1. Inverted Hydro Cyclone (Flash Mixing): (Fig. 3.)

Hydro-cyclone is used usually as a separator of grits (sand) from water but in this project, it is used as a rapid mixer for the coagulant agent (PAC). Wastewater passes through the inverted hydro cyclone tangentially by pressure and high velocity which leads to the occurrence of adequate vortices initiating rapid mixing for the added dose of the coagulant (PAC).This technology is equivalent to the procedure used in the centrifugal pump. The high loss (drop in pressure) is occurring due to vortices. The following criteria were satisfied [6], [7], [8], [9], [10] and [11]:

- Retention time=volume/flow=20 sec; Range (15-60)sec
- Tangential velocity = 0.658 m/s >0.5235 m/s (lab)
- Velocity gradient = 500 s^{-1}, Range (500-100)s^{-1}
- Drop in pressure= 5m

A dose of PAC of value 1040mg/l was injected into the pilot plant through the inverted hydro cyclone which is considered as a flash mixing system. The capacity of the pilot plant was 1.2m^3/hr.

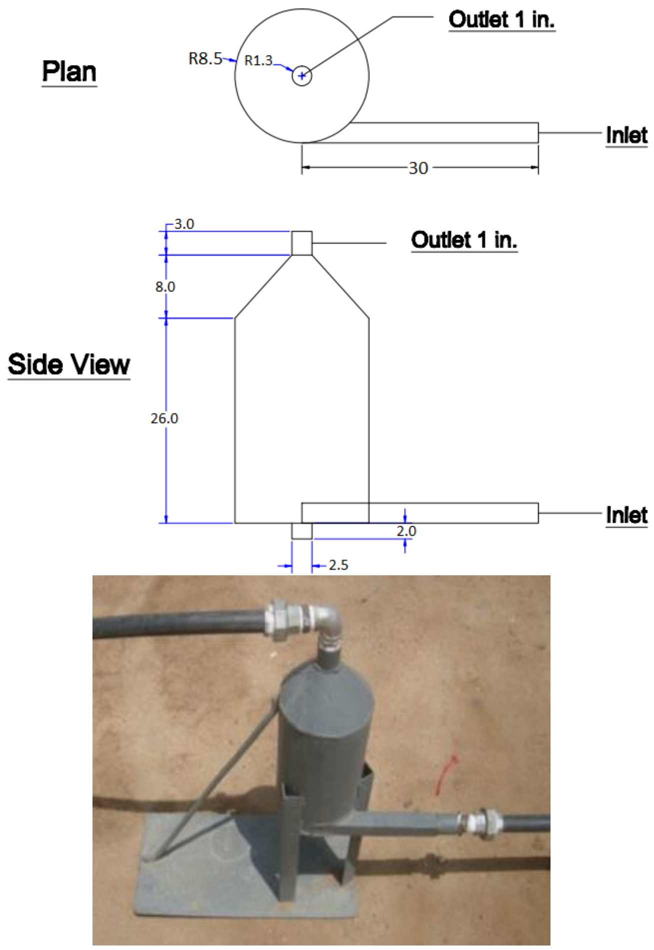

Fig. 3. Inverted Hydro Cyclone Design (dimensions in cm)

4.2.2. Slow Mixing (Pipeline System) Using Hydraulic Mixing: (Fig. 4.)

Four criteria should be satisfied [8], [9], [10] and [11]:

- Velocity in pipe=16.5 cm/sec; Range (15-45)cm/sec (Two dimeters were used: 2 and 4 inch)
- Retention time =10 minutes; Range (10-30)minutes
- Velocity gradient= 7 s^{-1}; Range (20-70) s^{-1} , not sufficient, but the following criteria was satisfied
- pipes of equivalent hydraulic length of at least 20 times the diameter were used (i.e., diameter = 4 inch = 0.1 m, length= 20*0.1= 2.0 m)

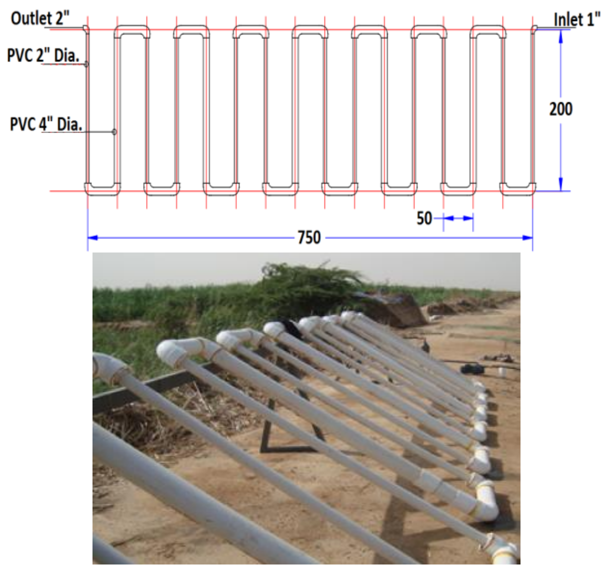

Fig. 4. Design of Mixing (Pipeline System) Using Hydraulic Mixing (dimensions in cm)

4.2.3. Vertical Settling Tank: (Fig. 5.)

Five criteria must be satisfied [8], [9], [10] and [12]:

- Surface loading=20m^3/m^2/day; Range= (15-35)m^3/m^2/day
- Retention time=1.5 hours; Range=(1.5-2.5) hours
- Weir loading range (100-200) m^3/m^2/day; use 12 V notch weirs, 3 weirs in each side.
- Hopper angle=60 degree from X axis
- Out let pipe =2 inch; velocity range (20-60) cm/sec

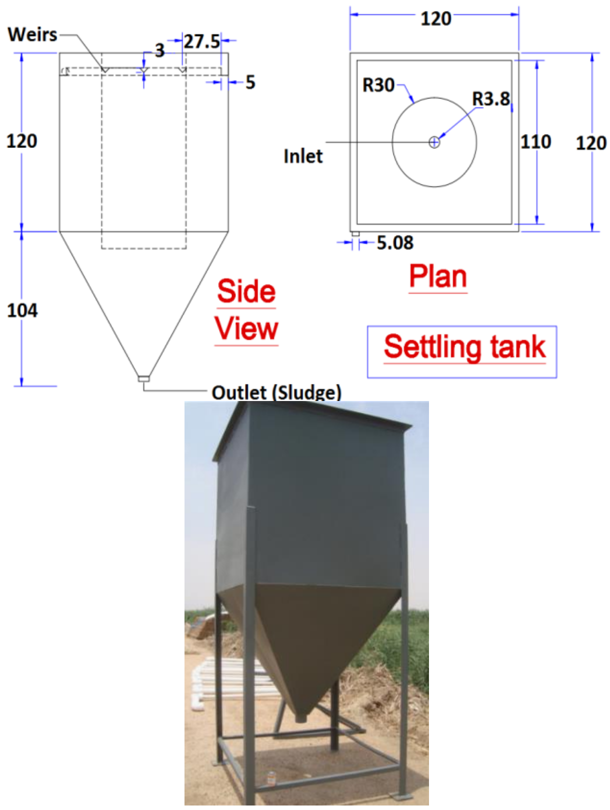

Fig. 5. Design of Vertical Settling Tank (dimensions in cm)

4.2.4. Rapid Sand Filter: (Fig. 6.)

Design criteria [8], [9], [10] and [11]:

(i) Filtration rate (120-240) m^3/m^2/day. Take (60) m^3/m^2/day (low filtration rate was adopted in the model in order to design a filter with a larger cross-section area. The filter run of this pilot was larger (few days) than that the standards filter with higher filtration rate (filter run for rapid sand filter 1-4 days). Therefore, cross-section area= 30/60= 0.5 m^2, L= 1 m, B= 0.5 m. (L/B=2). L/B ratio range from (1-3).

Table 5. Layers of the filter

Layer	Type	*Size (mm)	Depth (cm)	Porosity (*f*)	Shape factor (ψ)
1	Sand	0.9	50	0.40	0.9
2	Sandy gravel	(2-4)	10	0.41	0.85
3	Gravely sand	(5-7)	10	0.42	0.85
4	Gravel	(10-15)	20	0.43	0.85

*Effective Size (ES, d10= 10th percentile media grain size, mm) &Uniformity Coefficient (UC = d60/d10) should be determined for the filter media by sieve analysis. In general, a low UC (1.3-1.7) is an important factor in the design of rapid sand filters

(ii) Capacity of storage tank for backwash water:

– Q backwash range (500-600) l/m^2 of filter area/min, Take = 500l/m^2/min
– Flow= 500*0.5= 250 l/min, volume=2.5 m^3, T=10 minutes, range (5-15) min
– Pump head=15 m

(iii) Pipes:

– from settling to filter d=5cm, v = (20-60) cm/sec
– filtrated water pipe d=2.5cm, v =(90-180)cm/sec
– back wash inlet pipe d=5cm, v= (150-300)cm/sec
– back wash outlet pipe d= 5cm, v =(100-200)cm/sec

(iv) Design of gutter to collect the dirty backwash water:
For rectangular trough with free flow, adopt $Q = Cwh^{1.5}$
Where Q backwash= flow rate = 0.00042m^3/s
w= trough width, m
h= water depth in trough, m
c= 1.71
w= 10 cm, h= 8.5 cm, H= 10 cm (including free Board)

(v) Design under drainage system to collect filtrated water or to pass water during backwashing:

– Size of one hole= 0.2 inch = 5 mm, range (0.2-0.7) inch
– All holes area=0.002*filter area , range (0.0015-0.005)*filter area
– Number (N) =48 holes with a diameter of 5 mm each.

(vi) Branch pipes in under drainage system:

– Spacing (3-12) inch ,take=6.0 inch=15.5 cm
– Number (N)=12 pipes, 6 pipes in each side
– 4 holes in each pipe (staggered)
– Branch pipe area= 3*area of perforations in one branch pipe, diameter= 0.75 inch= 1.9 cm.

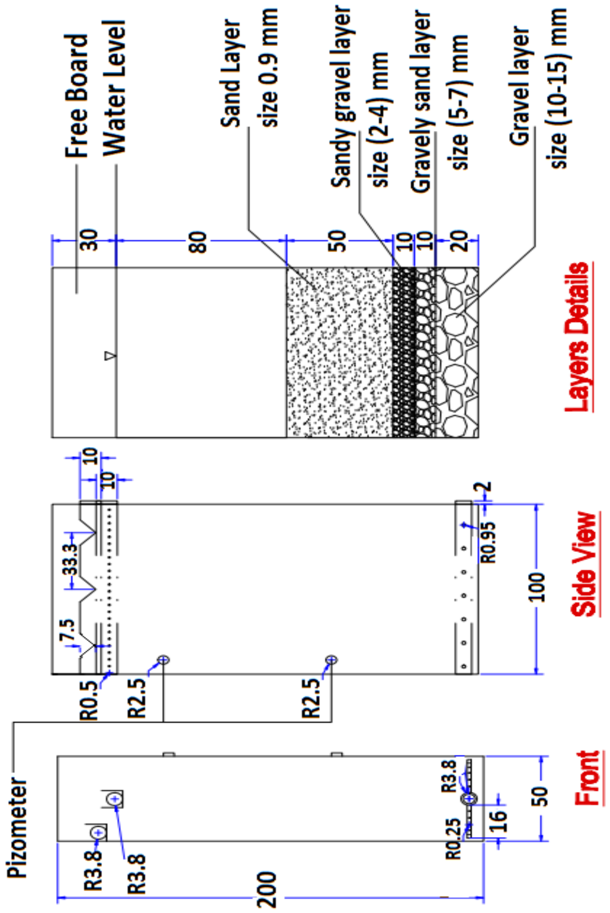

Fig. 6. Rapid Sand Filter (dimensions in cm)

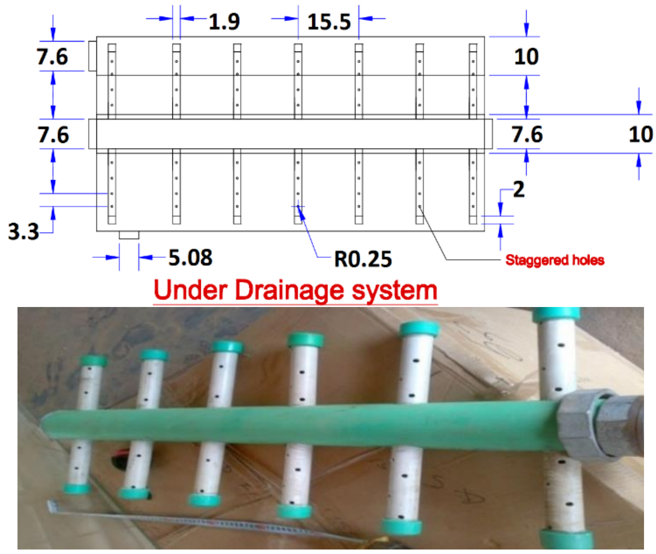

Fig. 7. Design of under-drainage system (dimensions in cm)

(vii) Main pipe (manifold) in the under-drainage system to collect filtrated water from branch pipes, or to pass water to branch pipes during backwashing :

- Area of the main pipe= 2*area of total branch areas
- Diameter=3 inch= 7.6 cm

(viii) Initial Head losses in the filter after every backwash:

- Method 1: Carman-Kozeny equation

$$\frac{h}{L} = \frac{E(1-f)V_s^2}{f^3 dg\psi}$$

$$E = 150\frac{(1-f)}{Re} + 1.75$$

$$Re = {}^{\psi d\rho V_s}/_{\mu}$$

Where
L: depth of filter bed (m),
h: Head loss (m),
f: Bed Porosity,
V_s: superficial Filtration velocity (m/sec),
μ: Viscosity (0.001 N.s/m^2),
ψ: Particle shape factor,
d: average grain size diameter (m),
E: friction factor,
Re: Reynold number,
ρ= water density= 1000 kg/m^3,
g= acceleration due to gravity= 9.81m/s^2.

Theoretical total head losses for the four layers= 0.0086+0.02+0.082+4.42= 4.53cm

- Method 2: Rose equation:

$$\frac{h}{l} = 1.067 C_D \frac{v^2}{gd\psi}\frac{1}{f^4}$$

Where
f = bed porosity = volume of voids/total volume,
d = average characteristic diameter of bed particle,
ψ = particle shape factor and
C_D= $Newton's\ drag\ coefficient = \left({}^{24}/_{R}\right) + \left({}^{3}/_{\sqrt{R}}\right) + 0.34$

Theoretical total head losses for the four layers= 0.013+0.0275+0.11+5.7= 5.85cm

Both values of the two methods almost similar to that have been noticed in the real operation, (5.5 cm).The filter should be washed (cleaned) when the head losses reach 60-75 cm.

(ix) Expansion of the filter sand bed while backwashing

$$ {}^{L_2}/_{L_1} = {}^{(1-e_1)}/_{(1-e_2)}$$

$$e_2 = \left({}^{V}/_{V_s}\right)^{0.22}$$

When Re< 2, (Stokes Law) used to calculate V_s:

$$V_s = \frac{g(s_g - 1)\rho d^2}{18\mu}$$

When Re> 2 (Trial and error method) using:

$$V_s = \left(\frac{4g(s_g-1)\rho d}{3CD}\right)^{0.5}$$

Where
L_2: depth of expanded sand bed (m),
L_1: depth of unexpanded sand bed (m),
e_1: porosity of unexpanded sand bed,
e_2: porosity of expanded sand bed,
V= up-flow velocity of backwash flow (m/sec),
V_s: settling velocity of sand particle (m/sec),
s_g: Specific gravity of sand=2.65

L_2=0.63 m, Expansion depth= 13 cm= 26% of sand layer (50 cm) which is in the range (25-50) %. Therefore, the weirs and gutter that meant to collect the dirty backwash water, is located 1 m (>>13 cm) above the top level of the sand layer to ensure that there is no any loss in the sand during backwashing.

(x) Determine the drop in pressure while back washing:

$h=L_2*(s_g-1)*(1-e_2) =0.63*(2.65-1)*(1-0.52) =0.5m$

The quality of effluent obtained after running the test in the pilot plant for raw sewage of BOD5 of 5000 mg/l and S.S of 780 mg/l utilizing PAC dose of 1040mg/l is as follows:

BOD_5= 23 mg/l
SS= 22 mg/l

This quality of effluent conforms to the irrigation water quality requirements reuse for restricted agricultural irrigation.

5. RESULTS AND DISCUSSION

The main feature of the treatment units used in the pilot plant for the physiochemical treatment of wastewater is to adopt units with minimum power consumption. The inverted hydro cyclone is used as a flash mixing unit where the small pump is utilized to create centrifugal forces which induce flash mixing for the coagulant (PAC). For gentle agitation or flocculation, hydraulic mixing in a set of the piping system is adopted. For sedimentation process, a vertical tank with hopper bottom to collect the settled sludge, and collection weirs are utilized to collect the effluent to be conveyed to the tertiary treatment. A rapid sand filter is used as a tertiary treatment for the effluent. It is obvious from the above processes that electrical power consumed is minimum or almost negligible.

From the lab-scale model, the optimum dose of PAC obtained to treat the high concentration of organic wastewater sample (B.O.D_5= 5000 mg/l) is 0.8 ml/l. This dose of PAC is equivalent to 1040 mg/l because the density of PAC is considered as 1300 kg/m^3. When this dose was used in the pilot plant the treated effluent quality is B.O.D_5= 23 mg/l and S.S= 22 mg/l. This is an excellent effluent quality which conforms to water quality requirements for restricted agricultural irrigation water. Although the dose of PAC utilized in the pilot plant is rather high (1040 mg/l), yet it is possible to recycle the sludge in order to utilize the residual

PAC in a further batch of the influent wastewater. In a parallel study where domestic wastewater (B.O.D_5= 350 mg/l) was used the optimum dose utilized was 0.1 ml/l which is equivalent to 130 mg/l of PAC.

The sludge production in the physiochemical process is relatively small than the sludge produced by the conventional biological process. The cost for treatment of sludge is generally very high and it accounts for about 30% of the cost of the wastewater treatment plant [13].

From the lab-scale model, the dose of the coagulant the PAC seems to be very sensitive to pH value in the range of 7.1 to 7.4. For wastewater with high pH value in the alkaline side (8.5 to 9.5), it is necessary to add acid to control the pH to a lower value to give an optimum dose of PAC.

The approximate cost of the PAC during this study in 2013 is about 1.5 U.S. $ per liter [14]. Therefore, cost comparison can be made by the physiochemical process utilizing the PAC and the conventional biological process considering also the sludge production and treatment in both systems. For the optimum dose of PAC (1040 mg/l) to treat industrial wastewater of BOD content of 5000 mg/l, the cost of removing one Kg BOD is about 0.225 U.S $ according to the above stated PAC price in 2013 (1.5 U.S. $ per liter).

6. CONCLUSIONS

The following conclusions are drawn:

- When adopting physiochemical processes for treatment of wastewater, it is essential to carry out a lab-scale model for a representative sample of the waste under control pH value to determine the optimum dose of the coagulant. Optimum pH range in this study is 7.1 to 7.4.
- The dose of the coagulant is directly proportional to the concentration of the organic load in the wastewater. Therefore, after determining the optimum dose of the coagulant for a particular waste, the cost estimate should be adopted and comparison should be made between the cost of chemical utilized and the cost of power consumption if conventional biological treatment is adopted. Cost of PAC in 2013 is equal to 1.5 U.S. $/l.
- The unit processes utilized in the pilot plant for the physiochemical treatment have a minimum or negligible power consumption.
- The coagulant utilized (PAC) has a density of 1300 kg/m^3. Being a liquid, the dose of the PAC in the unit of ml/l can be converted to mg/l unit (0.8 ml/l= 1040 mg/l).
- The quality of the treated effluent after the tertiary treatment has B.O.D_5= 23 mg/l and S.S= 22 mg/l. This is excellent effluent quality to be reused for restricted agricultural irrigation purposes. The cost of removing one Kg BOD of industrial waste of BOD content 5000 mg/l by adopting PAC dose of 1040 mg/l was about 0.225 U.S. $ according to PAC price in 2013 (1.5 U.S. $ per liter).

7. RECOMMENDATIONS FOR FUTURE STUDIES

- To adopt a suitable procedure for recycling of the wastewater (sludge) which has a high concentration of residual PAC from the bottom of settling tank to the inverted Hydro Cyclone in order to enhance the floc formation. This process will decrease the dose of PAC substantially.
- Further study is recommended in this field by comparing the efficiencies of removal of B.O.D5 and suspended solids by the physiochemical treatment method and the activated sludge process and to compare the cost incurred between the two methods
- To carry out further studies for the quantity and quality of the sludge generated by the physiochemical process.
- Lab-scale tests to be carried out utilizing other coagulants such as ferric salts or Aluminum sulfate and to compare the efficiency of organic load removal.
- Further study is recommended for the quality of the treated effluent in order to ensure its suitability for irrigation purposes and whether further treatment is required.

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