Coag-flocculation studies of *Moringa oleifera* coagulant (MOC) in brewery effluent: Nephelometric approach.

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ABSTRACT: The coag-flocculation behavior of MOC in respect of pH variation in brewery effluent has been investigated at room temperature using various dosages of unblended MOC. Coag-flocculation parameters such as order of reaction α, rate constants (K and K_s), coagulation period $\tau_{1/2}$ e.t.c were determined. Turbidity measurement was carried out using the single angle (90°) nephelometric standard jar test while MOC processing was based on work reported by Ghebremichael. Microsoft excel package was employed in the evaluation of simulated parameter K_s. The maximum MOC performance are recorded at K of 6.6667 x $10^{-4}m^3/kg.s$, dosage of $0.4kg/m^3$, pH of 4 and $\tau_{1/2}$ of 289.2614s while the minimum are recorded at K of 1.3333 x $10^{-4}m^3/kg.s$, dosage of $0.5kg/m^3$, pH of 2 and $\tau_{1/2}$of 1446.6419s. The least value of E (%) recorded after 30 minutes is > 78%, thus confirming MOC as effective coag-flocculant. In general, the parameter obtained lie within the range of previous works, confirming that the theory of perikinetics holds for coag-flocculation of brewery effluent using MOC at the conditions of the experiment.

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INTRODUCTION

The use of renewable resources of plant origin in local community for the removal of colloidal and non colloidal turbidity in waste water is not a new phenomenon. This phenomenon highlights the concept of coagulation / flocculation (cog-flocculation),a routine water treatment procedure that stimulate the formation of flocs arising from the destabilization of charged colloids(Ma et al,2001; Diterlizzi, 1994; Edzwald, 1987; O Melia, 1978). Among the factors that can influence the aggregation process are temperature, pH, effluent quality, stirring time e.t.c (Jin,2005).

Readily, coag-flocculation has been achieved via inorganic and organic synthetic substances such as alum, $FeCl_3$, polyamine e.t.c. However, the coag-flocculation performance of these aggregating agents are well researched and documented with inadequate attention especially in the aspect of kinetics given to the study of coag-flocculation behavior of the plant and animal derivatives. To this end, focus is hereby given to the study of coag-flocculation performance of plant origin, *Moringa oleifera* seed.

Moringa oleifera is a small, fast growing drought deciduous tree commonly found in the tropics such as Eastern Nigeria. The seed kernels of *Moringa olifera* contain significant quantities of positively charged water soluble protein which bind with the negatively charged particles in water to promote floc formation (Schwarz, 2000). *Moringa oleifera* are edible, non toxic, biodegradable and biocompatible substances. Previous results from its coagulation performance highlight prospects for renewable organic aggregating agent with extensive application in large scale water treatment technology.

Against this backdrop, this work embraces coag-flocculation kinetics and performance of MOC under varying pH of brewery effluent and MOC dosages, using single angle (90°) and simulated multi angle light scattering (nephelometry) techniques. Thus if well harnessed and developed, MOC can be an alternative to or be used in conjunction with the conventional coagulants. Ultimately, the post usage handling and health challenges posed by the inorganic coagulant can be reduced.

THEORETICAL PRINCIPLES AND MODEL DEVELOPMENT

For a uniformly coag-flocculating equilibrium phase with negligible influence of external force (Hunter, 1993):

$$\mu_i = \overline{G}_i = \left[\frac{\partial G}{\partial n_i}\right]_{P,T,n} = \text{a constant} \qquad \text{....1}$$

And

$$f_d = \frac{-K_B T}{C_i}\frac{dC_i}{dx} \qquad \text{...2}$$

Where G is the total Gibbs free energy

n_i is the number of moles of component i

μ_i *is* chemical potential

C_i is concentration

x is diffusion distance

f_d is viscous drag force.

But from Ficks law

$$D' = \frac{-f_d}{B}\frac{C}{\left(dC/dx\right)} \qquad \text{...3}$$

Where D' is diffusion coefficient

B is friction factor

Comparing equation 2 and 3 generates Einstein's equation:

$$D' = \frac{K_B T}{B} \qquad \text{...4}$$

For similar phase, the rate of successful collision between particles sizes i and j (mass concentration/Time) to form particle of size *k* is (Thomas et al, 1999):

$N_{ij} = \varepsilon_p\ \beta\ (i,j)\ n_i n_j$ ...5

where

ε_p = collision efficiency

β (i, j) = collision factor between particles of size i and j

$n_i n_j$ = particle concentration for particles of size i and j, respectively.

Assuming monodisperse, no break up and bi particle collision, the general model for perikinetic coag-flocculation is given as (Swift and Friedlander, 1964; Von Smoluchowski, 1917):

$$\frac{dn_k}{dt} = \frac{1}{2}\sum_{i+j=k}\beta(i,j)n_i n_j - \sum_{i=1}^{\infty}\beta(i,k)n_i n_k \qquad \text{...6}$$

where $\frac{dn_k}{dt}$ is the rate of change of concentration of particle of size k (concentration / time).

β is a function of the coag-flocculation transport mechanism.

The appropriate value of β for Brownian transport is given as(Von Smoluchowski,1917):

$$\beta_{BR} = \frac{8}{3}\varepsilon_p\frac{k_B T}{\eta} \qquad \text{...7}$$

Where K_B is Boltzmann's constant (J/K)

T is Absolute temperature (K)

The generic aggregation rate of particles (during coagulation / flocculation) can be derived by the combination of equations 6 and 7 to yield:

$$-\frac{dN_t}{dt} = KN_t^{\alpha} \qquad \text{...8}$$

Where N_t is total particle concentration at time t, $N_t = \sum n_k$ (mass / volume)

Meanwhile $K = \frac{1}{2}\beta_{BR}$ ...9

K is the menkonu coag-flocculation rate constant

α is the order of coag-flocculation process

Also, $\beta_{BR} = 2\varepsilon_p K_R$ …10

Combining equations 8, 9 and 10 produce:

$$-\frac{dN_t}{dt} = \varepsilon_p K_R N_t^{\alpha} \qquad ….11$$

Where K_R is the Von smoluchowski rate constant for rapid coagulation (Van Zanten, 1992)

However $K_R = 8\pi a D'$ ….12

$R_p = 2a$ ….13

Where a is particle radius.

From Einstein's equation: $D' = K_B \, T/B$

From Stoke's equation : $B = 6\pi\eta a$ ….14

where η is the viscosity of the coag-flocculating fluid

Combining equations 11 to14 gives:

$$-\frac{dN_t}{dt} = \frac{4}{3}\varepsilon_p \frac{K_B T}{\eta} N_t^{\alpha} \qquad …15$$

Comparing equations 8 and 15 show:

$$K = \frac{4}{3}\varepsilon_p \frac{K_B T}{\eta} \qquad ...16$$

For perikinetic aggregation, α theoretically equals 2 as would be shown below (Fridkhsberg,1984; Hunter,1993):

From Fick's law,

$$J_f = D' 4\pi R_p^{\,2} \frac{dN_t}{dR_p} \qquad ..17$$

Integrating equation 17 at initial conditions $N_t = 0$, $R = 2a$:

$$\frac{J_f}{D' 4\pi} \int_0^{R_p} \frac{dR_p}{R_p^{\,2}} = \int_{N_0}^{N_t} dN_t \qquad ...18$$

Thus $J_f = 8\pi D' a N_0$ …19

For central particle of same size undergoing Brownian motion, the initial rate of rapid coag-flocculation is:

$$-\frac{dN_t}{dt} = J_f \cdot \varepsilon_p \cdot N_0 \qquad …20$$

$$= \frac{4}{3}\varepsilon_p \frac{K_B T}{\eta} \cdot N_0^2 \qquad ...21$$

$$\equiv \frac{4}{3}\varepsilon_p \frac{K_B T}{\eta} N_t^2 \text{ at } t > 0$$

Hence, from equation 21, $\alpha = 2$

For $\alpha = 2$; equivalence of equation 8 yields:

$$\frac{dN}{dt} = -KN^2$$

Hence:

$$\int_{N_0}^{N} \frac{dN}{N^2} = -K\int_0^t dt \qquad …22$$

Thus $\frac{1}{N} = Kt + {}^{1}\!/\!_{N_0}$ ...23

Plot of $\left({}^{1}\!/\!_{N}\right)$ Vs t produces a slope of K and intercept of ${}^{1}\!/\!_{N_0}$.

For the evaluation of coagulation period ($\tau_{1/2}$), from Equation 23:

$$N = \frac{N_0}{\left[1 + \frac{t}{\left({}^{1}\!/\!_{N_0 K}\right)}\right]} \qquad ...24$$

Where $\tau = \left[{}^{1}\!/\!_{N_0 K}\right]$ …25

Hence:

$$N = \frac{N_0}{1 + (t/\tau)} \qquad …26$$

When $t = \tau$, equation 26 becomes

$$N = {}^{N_0}\!/\!_{2} \qquad …27$$

Therefore as $N_0 \rightarrow 0.5N_0 ; \tau \rightarrow \tau_{1/2}$

Hence $\tau_{1/2} = {}^{1}\!/\!_{(0.5N_0 K)}$ ...28

For Brownian (perikinetic) aggregation at early stages (t≤30 minutes), equation 6 can be solved exactly, resulting in the generic expression

$$\frac{N_{m(t)}}{N_0} = \frac{\left[{}^{t}\!/\!_{\tau'}\right]^{m-1}}{\left[1 + {}^{t}\!/\!_{\tau'}\right]^{m+1}} \qquad ...29$$

Where $\tau' = 2\tau$

Hence, for singlets *(m=1)*

$$N_1 = N_0 \left[\frac{1}{\left(1 + {}^{t}\!/\!_{\tau'}\right)^2}\right] \qquad ...30$$

For doublets *(m=2)*

$$N_2 = N_0 \left[\frac{\left({}^{t}\!/\!_{\tau'}\right)}{\left(1 + {}^{t}\!/\!_{\tau'}\right)^3}\right] \qquad ….31$$

For triplets *(m=3)*

$$N_3 = N_0 \left[\frac{\left({}^{t}\!/\!_{\tau'}\right)^2}{\left(1 + {}^{t}\!/\!_{\tau'}\right)^4}\right] \qquad ….32$$

Also for the coag-flocculating phase and multi angle nephelometry, the intensity of light scattered from suspension of monodispersed phase is described as (Van Zanten,1992):

$$I(q,\mathrm{T}) = I(q,0)\left[1 + 2\sum_{m=2}^{\infty} C_m(\mathrm{T}) A_m(q)\right] \qquad \text{....33}$$

Where I (q, T) is the intensity of light scattered by the initially unaggregated suspension ;

$T = t / \tau'$ (dimensionless time)

q is the scattering wave vector

$$q = \left(\frac{4\pi}{\lambda_0}\right) n_0 \sin(0.5\theta) \qquad \text{...34}$$

Where λ_0 is the wave length of the laser incident light in Vacuum, $(\lambda_0 = 2\pi a / 6)$

n_0 is the refractive index of the suspending medium

θ is the scattering angle

A_m is the form factor for an aggregate consisting of m primary particles.

a is radius of particles sphere.

If the coagulating medium obeys the Rayleigh-Gans-Debye (RGD) approximations, then

$$A_m(q) = \sum_{i}^{m} \sum_{j>1}^{m} \frac{\sin qr_i}{qr_{ij}} \qquad \text{...35}$$

Where r_{ij} is the centre-to-centre separation of primary particles i and j in the given m-fold aggregate. The summation accounts for all pairs of particle centers in the aggregate.

The expression for the scattered intensity in view of many possible configurations arising from larger aggregates is:

$$I(q,\mathrm{T}) = I(q,0)\left[1 + 2\frac{\sin qd_0}{qd_0}\frac{\mathrm{T}}{(1+\mathrm{T})^3} + 2\sum_{m=3}^{\infty} C_m(\mathrm{T}) A_m(q)\right] \qquad \text{...36}$$

The form factors are given by an average of all contributing structures where d_0 is hard core interaction diameter of singlets. Differentiating equation 36 as t→0 yields:

$$\frac{I}{I(q,0)}\left(\frac{dI(q,t)}{dt}\right)_{t\to 0} = \frac{d}{dt}\left[1 + 2\frac{\sin qd_0}{qd_0}\frac{\mathrm{T}}{(1+\mathrm{T})^3} + 2\sum_{m=3}^{\infty} C_m(\mathrm{T}) A_m(q)\right] \qquad \text{...37}$$

$$\frac{I}{I(q,0)}\left(\frac{dI(q,t)}{dt}\right)_{t\to 0} = \left[\beta_{BR} N_0 \frac{\sin qd_0}{qd_0}\right] \qquad \text{...38}$$

Using simulated version of equation 38, K_S (simulated K) can easily be determined at several scattering angles. A plot of $\frac{I}{I(q,0)}\left(\frac{dI(q,t)}{dt}\right)_{t\to 0} \; Vs \, \frac{\sin qd_0}{qd_0}$ gives a slope of $N_0\beta_{BR}$ from where $(K_S)_{t\to 0}$ could be determined.

MATERIALS AND METHOD

The sample of *Moringa olifera* seeds was sourced from Agulu Town, Anambra state Nigeria and processed to MOC based on the work reported by Ghebremichael (2004).

The jar test was conducted based on standard Bench scale Nephelometric method (single angle procedure) for the examination of water and waste water (WST,2005; AWWA,2005) using model WZS-185 MC Turbidimeter, APPNo 688644A Gulenhamp magnetic stirrer and mettler Toledo Delta 320 pH meter. For the simulation of multi angle nephelometry, excel package was used while d_0 = 0.8875μm and n_o were sourced from ENSWC (2008) and simple refractometric measurment respectively.

RESULTS AND DISCUSSION

Coag-flocculation parameters

The values of coag-flocculation parameters are presented in tables 1 to 6.At a general level, the values of R^2 for the results presented are quite satisfactory, confirming the theory of perikinetics that shown α=2 .Meanwhile, it is evident that α relates inversely with K.Thus, for a higher α to be obtained, a lower K is a necessary condition (Fridkhsberg, 1984). This is readily amplified in tables 1 to 5.For K $(=0.5\beta_{BR})$, there is no regular observed trend, as the pH increases from 2 to 10 for tables 1 to 5.However, it should be observed that the highest values if K are recorded at pH of 4.This explains why lowest $\tau_{1/2}$are also recorded at pH of 4.This is amply demonstrated in figs 5 to 9 where best coag-flocculation were recorded for pH of 4.Also,observations from tables 1 to 5 indicate that the values of K experiences minimal variation for $0.1kg/m^3$ to $0.5kg/m^3$ at a given pH. This clearly emphasizes that coag-flocculation is more sensitive to changes in pH than that of dosages. It can be argued that at given pH, a similar mechanism controls the process. This can account for the little variation in K at a given pH.

In theoretical bases, $\tau_{1/2}$,ε_p , and K_R are coagulation effectiveness factors, understood to be accounting for the coagulation efficiency, before flocculation sets in. In view of the particle distribution plots (Figs 17 and 18); the values of $\tau_{1/2}$ obtained are satisfactory, though millisecond has been reported in system where minimal Zeta potential exists (Hunter, 1993). For a case of minimal variation in K_R, ε_p relates directly to $2K=\beta_{BR}$. Hence ,high ε_p results in high kinetic energy to overcome the Zeta potential either by double layer compression or colloid destabilization.

Meanwhile, K_S, the simulated version of K for varying pH and dosages are presented in table 6.It is an attempt to assess the variation between K (from single angle) and K_S (from simulated multi angle) in view of the angular dependence of K_S .The agreement between K and K_S is satisfactory. Note that K and K_S were obtained from equations 23 and 38 respectively where the slope of equation 38 is $\beta_{BR}N_0$.Representative results are presented in (figs 1 and 2) and (Figs 3 and 4) for equation 23 and 38 respectively.

The discrepancies observed in the results presented in tables 1 to 6 are due to unattainable assumption that mixing of particles and MOC throughout the dispersion is 100% efficient before any aggregation occurs (Yates etal,2001). Another account is the interplay between Van der waal forces and the hydrodynamic interactions which alters the theoretically predicted parameter values by a factor ±2 .Other additional short range forces do also contribute (Holthof,etal,1997; Holthof, etal,1996).

SP (=N in kg/m^3) vs. time plots.

Plots of SP vs. time are presented in figs 5 to 9; with initial SP of $10.3691kg/m^3$ .Generally, for the plots, the SP decreases with time. This is expected because during coag-flocculation, particles aggregate into large flocs, settling under gravity and progressively decreasing the intensity of light scattered. The rapid settling of SP is very apparent in figs 5 to 9 in view of the initial value of SP. This is in consonance with the theory of rapid coag-flocculation. The best coag-flocculation was recorded at pH of 4 supporting lowest and highest values of $\tau_{1/2}$ and K respectively recorded in the study.

However, the least $\tau_{1/2}$ recorded is = 289.2614 at pH of 4.This is high in view that milliseconds have been recorded. This can be adduced to low initial SP present in the brew effluent. Secondly, the resulting flocs may be of less density such that there may exist disproportionality between the rate of coagulation and rate of settling of the flocs formed.

Efficiency E (%) vs. time

E (%) vs. time plots are presented in figs 10 to 14 .The E (%) indicates the effectiveness of ABC to remove SP from the effluent. The least E (%) recorded after 30 minutes of coag-flocculation is > 78% in spite of low value of initial SP .This confirms MOC as a plant derived aggregating agent. This collaborates with the general real life experience where in some cases, 90% particle removal are routinely achieved in minutes during water treatments. Observed that in general, the best efficiency is recorded at pH of 4.

Plots of E (%) vs. pH

This is presented in fig 15.it indicates the performance of various doses of MOC at varying pH. Maximum efficiency are recorded at pH of 4 followed by pH of 10.Low doses of $0.1kg/m^3$ and $0.2kg/m^3$ exhibit high E (%) at pH of 2 while high doses of $0.4kg/m^3$ and $0.5kg/m^3$ perform maximally at pH of 4 and 10.

Plot of E (%) vs. Dosages (kg/m^3)

This is presented in fig 16.The optimum dosages are recorded for pH of 4 at $0.4kg/m^3$ though performances for pH of 10 at $0.4kg/m^3$ are satisfactory. It confirms the earlier observation that pH of 4 provides optimum coag-flocculation properties for MOC .The minimum performance was recorded for pH of 2 at $0.5kg/m^3$ and $0.4kg/m^3$

Time evolution of the cluster size distribution

These are graphically presented in figs 17 and 18.They represent the time evolution for singlets , doublets and triplets obtained for $\tau_{1/2}$ = 289.2614s and $\tau_{1/2}$ = 1446.642s .Both figs 17 and 18 exhibit similar trend , an indication of a process controlled by similar mechanism. The curves represent a case in which the values of N_3 and $\sum N_i$ are close such that their variation with time is near same. Also, similar trend with respect to N_2 and N_1 is obtained .The curves indicate that there exists a wide margin of difference in concentration of SP between the pair of (N_3 and $\sum N_i$) and (N_2 and N_1).The implication is the existence of high shear force and resistance to collision .This is clearly demonstrated by the values of $\tau_{1/2}$ which are high. This is an indication of high Zeta potential associated with the process.

CONCLUSION

The potential of MOC as an effective natural organic coag-flocculants applicable in large scale water treatment has been confirmed. The conformity of the values of the obtained parameters with perikinetics theory in conjunction with the establishment of common parameter β_{BR} for both single (90°) and multi angle light scattering theories present a novelty in this work. These indicate a step further in what had already be developed in the coag-flocculation study.

The optimum dosage, pH and $\tau_{1/2}$ recorded are 0.4kg/m^3, 4 and 289.2614s respectively. The degree of agreement between K and K_S emphasizes that both single and multi angle light scattering techniques can be used to study coag-flocculation .This authenticates the validity of Von Smoluchowski theory. Overall, the results obtained are in line with previous works (Jin,2005; Van Zanten and Elimelech,1992;Holthof *et al*,1996;Menkiti *et al*,2009; Menkiti *et al*,2010).

NOMENCLATURE

K :α^{th} order coag-flocculation constant
β_{BR}: Collision factor for Brownian Transport
ε_p: Collision Efficiency
$\tau_{1/2}$: Coagulation Period / Half life
E: Coag-flocculation Efficiency
R^2: Coefficient of Determination
α: Coag-flocculation reaction order
$-r$: Coag-flocculation reaction rate
$(SP)_0^c$: Computed initial suspended particle (kg/m^3)
J_f:Flux
f_d: Drag force
K_S : K value obtained from simulation.
MOC: *Moringa olifera* coagulant
d_o : Hard core interaction diameter of the primary particle.
a: Radius of the primary particle

Table 1: Coag-flocculation Functional parameters for varying pH and constant dosage of 0.1kg/m^3 MOC

Parameter	pH=2	pH=4	pH=6	pH=8	pH=10
α	2	2	2	2	2
R^2	0.966	0.993	0.939	0.996	0.992
K (m^3/kg.s)	3.333×10^{-4}	5.001×10^{-4}	3.333×10^{-4}	1.667×10^{-4}	1.500×10^{-4}
β_{Br} (m^3/kg.s)	6.667×10^{-4}	1.000×10^{-3}	6.667×10^{-4}	3.333×10^{-4}	3.000×10^{-4}
K_R (m^3/s)	1.129×10^{-16}	1.698×10^{-16}	1.441×10^{-16}	1.698×10^{-16}	1.698×10^{-16}
ε_p (kg^{-1})	5.903×10^{12}	5.892×10^{12}	4.627×10^{12}	1.964×10^{12}	1.767×10^{12}
$\tau_{1/2}(s)$	578.648	385.762	578.648	1157.261	128.872
$(SP)_0^c$ (kg/m^3)	5	2.5	3.333	3.333	2.500
$(N_p)_0^c$ (m-^{3})	3.011×10^{27}	1.506×10^{27}	2.007×10^{27}	2.007×10^{27}	1.506×10^{27}
$-r$	$3.333\times10^{-4}\ c^2$	$5.001\times10^{-4}\ c^2$	$3.333\times10^{-4}\ c^2$	$1.667\times10^{-4}\ c^2$	$1.500\times10^{-4}\ c^2$

Table 2: Coag-flocculation Functional parameters for varying pH and constant dosage of 0.2kg/m^3 MOC

Parameter	pH=2	pH=4	pH=6	pH=8	pH=10
α	2	2	2	2	2
R^2	0.964	0.972	0.942	0.988	0.999
K (m^3/kg.s)	3.333×10^{-4}	6.667×10^{-4}	1.667×10^{-4}	3.333×10^{-4}	1.667×10^{-4}
β_{Br} (m^3/kg.s)	6.666×10^{-4}	1.333×10^{-3}	3.333×10^{-4}	6.667×10^{-4}	3.333×10^{-4}
K_R (m^3/s)	1.143×10^{-16}	1.625×10^{-16}	1.639×10^{-16}	1.626×10^{-16}	1.625×10^{-16}
ε_p (kg^{-1})	5.830×10^{12}	8.203×10^{12}	2.034×10^{12}	4.101×10^{12}	2.051×10^{12}
$\tau_{1/2}(s)$	578.648	289.320	1157.261	578.648	1157.261
$(SP)_0^c$ (kg/m^3)	3.333	10.00	2.500	3.333	2.500
$(N_p)_0^c$ (m-^{3})	2.007×10^{27}	6.022×10^{27}	1.506×10^{27}	2.007×10^{27}	2.007×10^{27}
$-r$	$3.333\times10^{-4}\ c^2$	$6.667\times10^{-4}c^2$	$1.667\times10^{-4}\ c^2$	$3.333\times10^{-4}\ c^2$	$1.667\times10^{-4}\ c^2$

Table3: Coag-flocculation Functional parameters for varying pH and constant dosage of 0.3kg/m^3 MOC

Parameter	pH=2	pH=4	pH=6	pH=8	pH=10
α	2	2	2	2	2
R^2	0.975	0.992	0.992	0.952	0.945
K (m^3/kg.s)	3.333 x 10^{-4}	5.001 x 10^{-4}	5.001 x 10^{-4}	3.333 x 10^{-4}	3.333 x 10^{-4}
β_{Br} (m^3/kg.s)	6.667 x 10^{-4}	1.000x10^{-3}	1.000x10^{-3}	6.667x10^{-4}	6.667x10^{-4}
K_R (m^3/s)	1.154x10^{-16}	1.315x10^{-16}	1.307x10^{-16}	1.333x10^{-16}	1.242x10^{-16}
ε_p (kg^{-1})	5.779x10^{12}	7.608x10^{12}	7.653x10^{12}	5.000x10^{12}	5.368x10^{12}
$\tau_{1/2}(s)$	578.648	385.762	385.762	578.648	578.648
$(SP)_0^c$ (kg/m^3)	5	3.333	3.333	2.500	2.00
$(N_p)_0^c$ (m-^{3})	3.011 x 10^{27}	2.007 x 10^{27}	2.007 x 10^{27}	1.506 x 10^{27}	1.204 x 10^{27}
$-r$	3.333x10^{-4} c^2	5.001x10^{-4} c^2	5.001x10^{-4} c^2	3.333x10^{-4} c^2	3.333x10^{-4} c^2

Table4: Coag-flocculation Functional parameters for varying pH and constant dosage of 0.4kg/m^3 MOC

Parameter	pH=2	pH=4	pH=6	pH=8	pH=10
α	2	2	2	2	2
R^2	0.986	0.857	0.952	0.895	0.998
K (m^3/kg.s)	1.667 x 10^{-4}	6.667 x 10^{-4}	6.667 x 10^{-4}	3.333 x 10^{-4}	6.667 x 10^{-4}
β_{Br} (m^3/kg.s)	3.333x10^{-4}	1.333x10^{-3}	1.333x10^{-3}	6.667x10^{-4}	1.333x10^{-3}
K_R (m^3/s)	1.165x10^{-16}	1.231x10^{-16}	1.260x10^{-16}	1.235x10^{-16}	1.242x10^{-16}
ε_p (kg^{-1})	2.862x10^{12}	1.083x10^{13}	1.059x10^{13}	5.399x10^{12}	1.073x10^{13}
$\tau_{1/2}(s)$	1157.261	289.320	289.320	578.648	289.320
$(SP)_0^c$ (kg/m^3)	5.000	10.00	5.000	2.000	3.333
$(N_p)_0^c$ (m-^{3})	3.011 x 10^{27}	6.022 x 10^{27}	3.011 x 10^{27}	1.204 x 10^{27}	2.007 x 10^{27}
$-r$	1.667x10^{-4}c^2	6.667x10^{-4}c^2	6.667x10^{-4} c^2	3.333x10^{-4} c^2	6.667x10^{-4} c^2

Table5: Coag-flocculation Functional parameters for varying pH and constant dosage of 0.5kg/m^3 MOC

Parameter	pH=2	pH=4	pH=6	pH=8	pH=10
α	2	2	2	2	2
R^2	0.975	0.981	0.955	0.897	0.866
K (m^3/kg.s)	1.333 x 10^{-4}	5.000 x 10^{-4}	3.333 x 10^{-4}	3.333 x 10^{-4}	3.333 x 10^{-4}
β_{Br} (m^3/kg.s)	2.667 x 10^{-4}	1.000x10^{-3}	6.667x10^{-4}	6.667x10^{-4}	6.667x10^{-4}
K_R (m^3/s)	1.107x10^{-16}	1.420x10^{-16}	1.542x10^{-16}	1.408x10^{-16}	1.461x10^{-16}
ε_p (kg^{-1})	2.409x10^{12}	7.042x10^{12}	4.323x10^{12}	4.735x10^{12}	4.564x10^{12}
$\tau_{1/2}(s)$	1446.642	385.762	578.648	578.648	578.648
$(SP)_0^c$ (kg/m^3)	5	5	2.500	2.00	2.00
$(N_p)_0^c$ (m-^{3})	3.011 x 10^{27}	3.011 x 10^{27}	1.506 x 10^{27}	1.204 x 10^{27}	1.204 x 10^{27}
$-r$	1.333x10^{-4} c^2	5.000x10^{-4} c^2	3.333x10^{-4} c^2	3.333x10^{-4} c^2	3.333x10^{-4} c^2

Table 6: Representative values of K (Experimental) and K_s (Simulated) at varying dosage and pH

pH	Dosage(kg/m^3)	N_0(Particles / m^3)	d_0(μm)	K($m^3/kg.s$)	K_S($m^3/kg.s$)
2	0.4	3.011×10^{27}	0.8875	1.667×10^{-4}	1.661×10^{-4}
4	0.4	2.007×10^{27}	0.8875	6.667×10^{-4}	6.642×10^{-4}
6	0.4	2.007×10^{27}	0.8875	6.667×10^{-4}	6.642×10^{-4}
8	0.4	1.506×10^{27}	0.8875	3.333×10^{-4}	3.321×10^{-4}
10	0.4	1.204×10^{27}	0.8875	6.667×10^{-4}	7.473×10^{-4}
4	0.1	1.506×10^{27}	0.8875	5.001×10^{-4}	6.642×10^{-4}
4	0.2	6.022×10^{27}	0.8875	6.667×10^{-4}	6.642×10^{-4}
4	0.3	2.007×10^{27}	0.8875	5.001×10^{-4}	4.982×10^{-4}
4	0.4	6.022×10^{27}	0.8875	6.667×10^{-4}	6.642×10^{-4}
4	0.5	3.011×10^{27}	0.8875	5.001×10^{-4}	4.982×10^{-4}

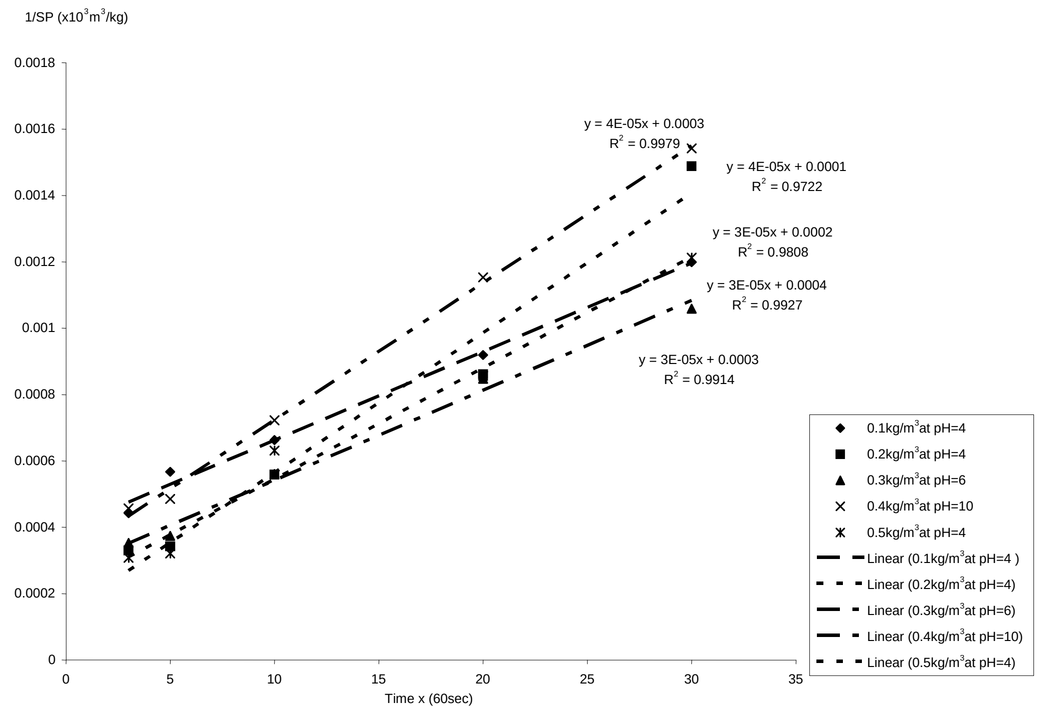

Fig1: Selected representative plot of 1/SP vs. time based on minimum half life

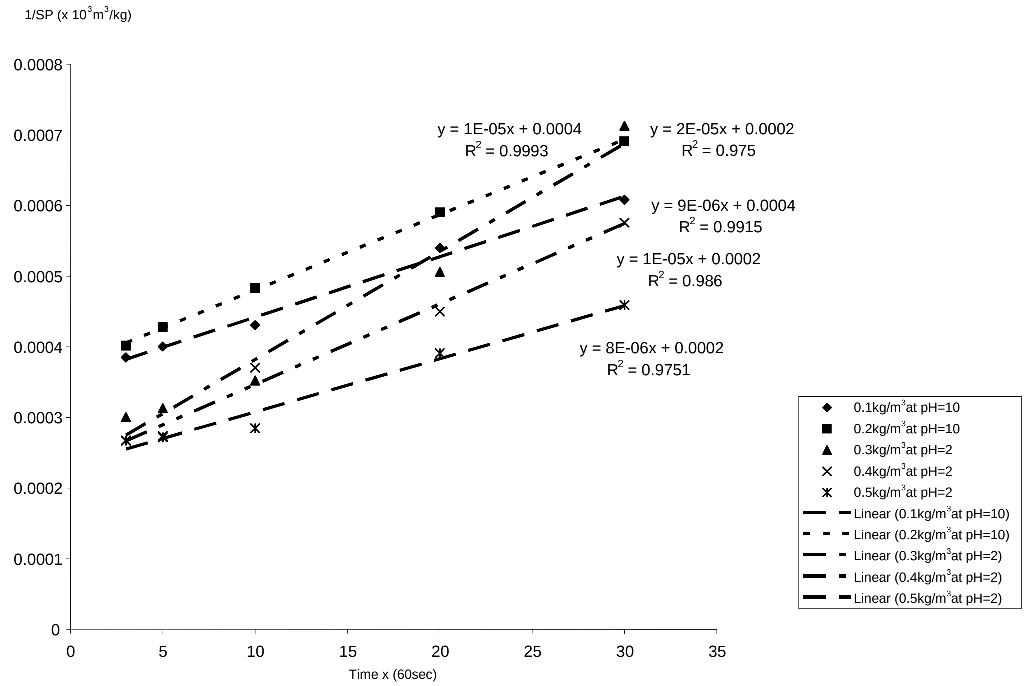

Fig 2: Selected representative plot of 1/SP vs. time based on maximum half life

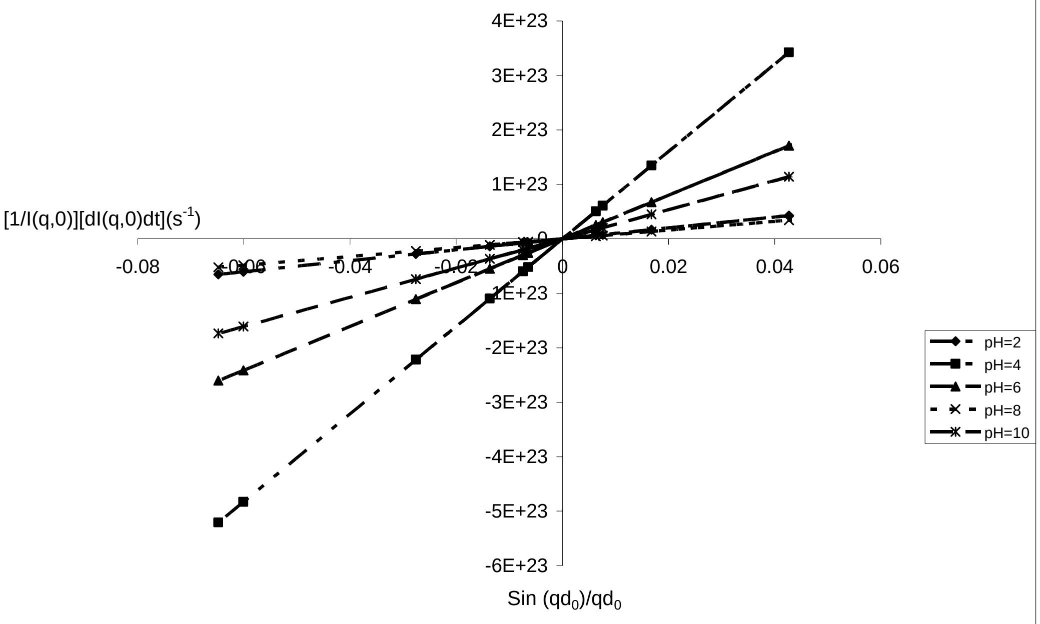

Fig 3:Initial Intensity changes vs. interference factor at 0.3kg/m^3 MOC

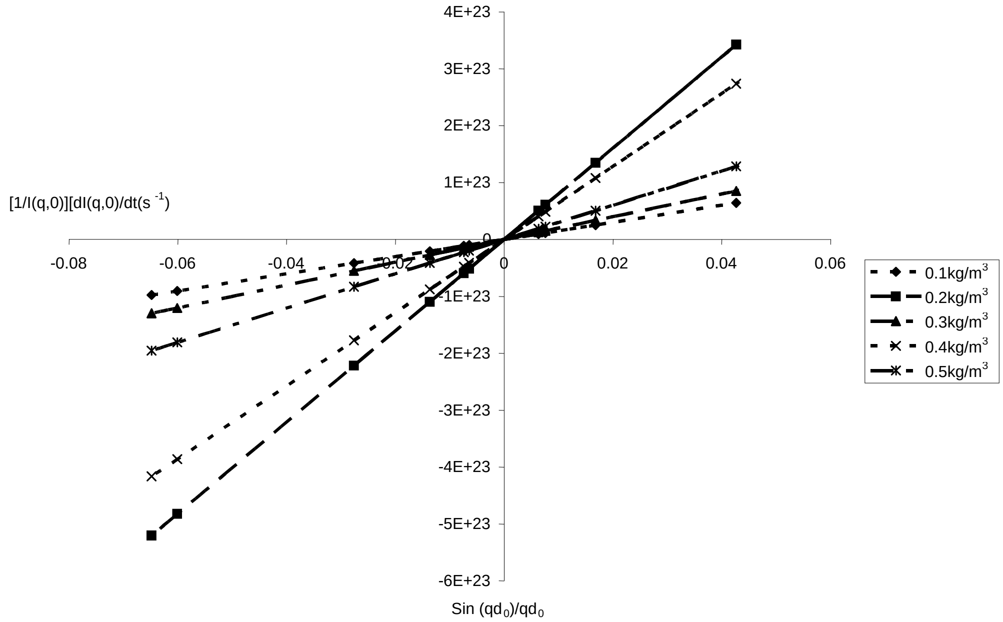

Fig 4:Initial Intensity changes vs. interference factor for MOC at pH=4

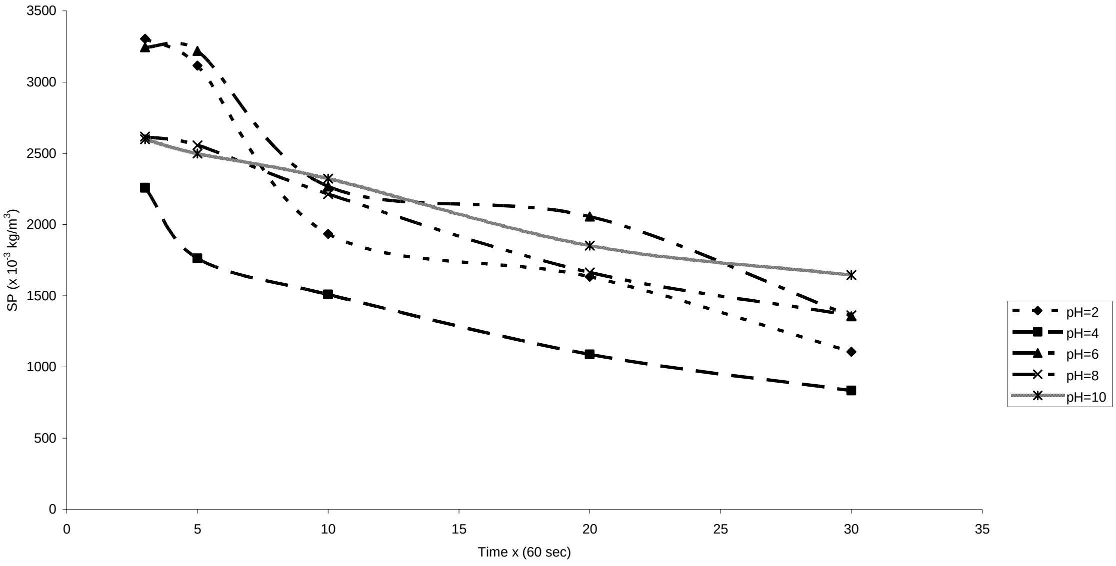

Fig 5:Plot of SP vs. coag-flocculation time for 0.1kg/m^3 MOC at varying pH

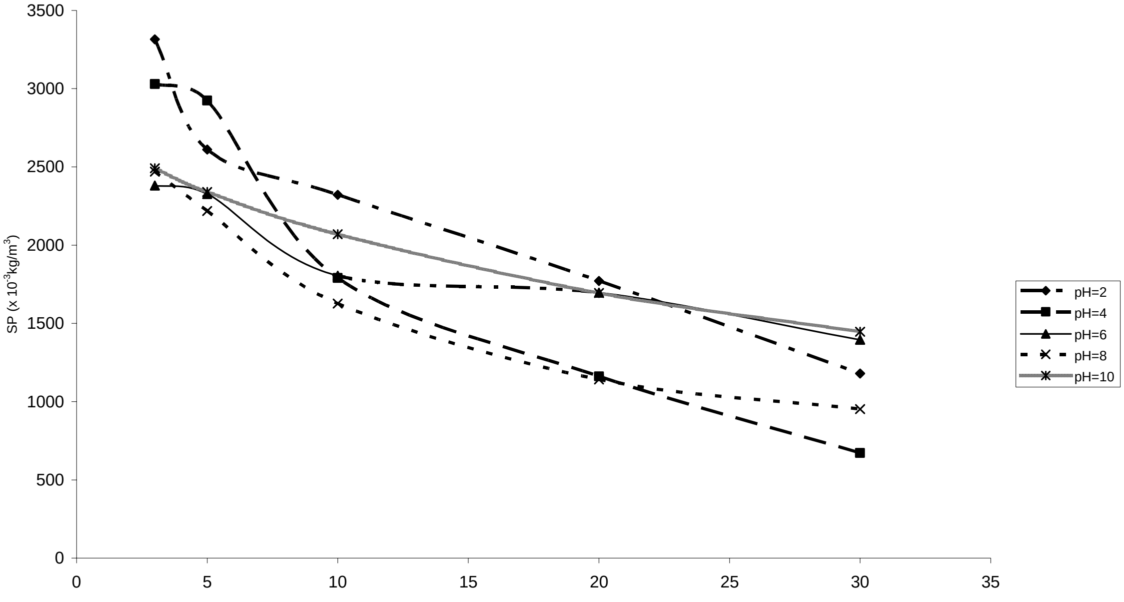

Fig 6:Plot of SP vs. coag-flocculation time for 0.2kg/m^3 MOC at varying pH

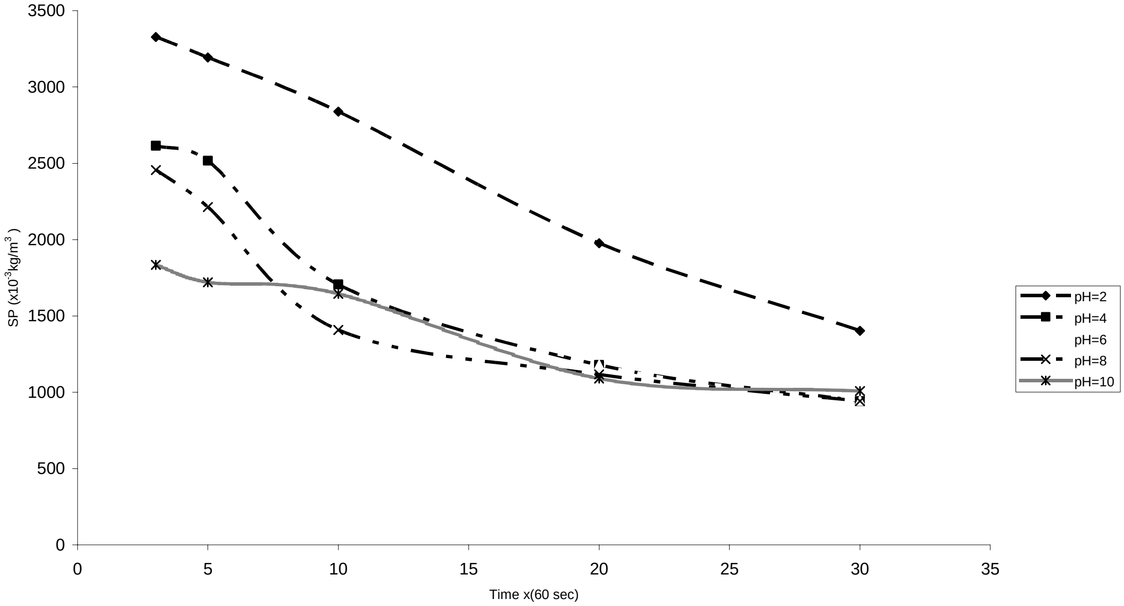

Fig 7:Plot of SP vs. coag-flocculation time for 0.3kg/m^3 MOC at varying pH

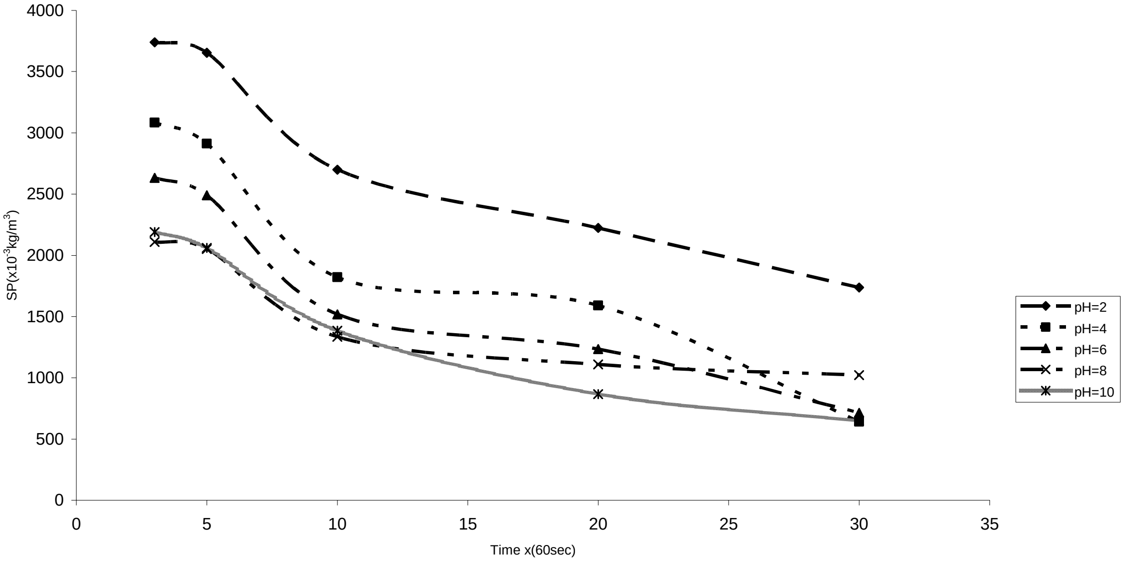

Fig 8:plot of Sp vs. coag-flocculation time for 0.4kg//m^3 MOC at varyinf pH

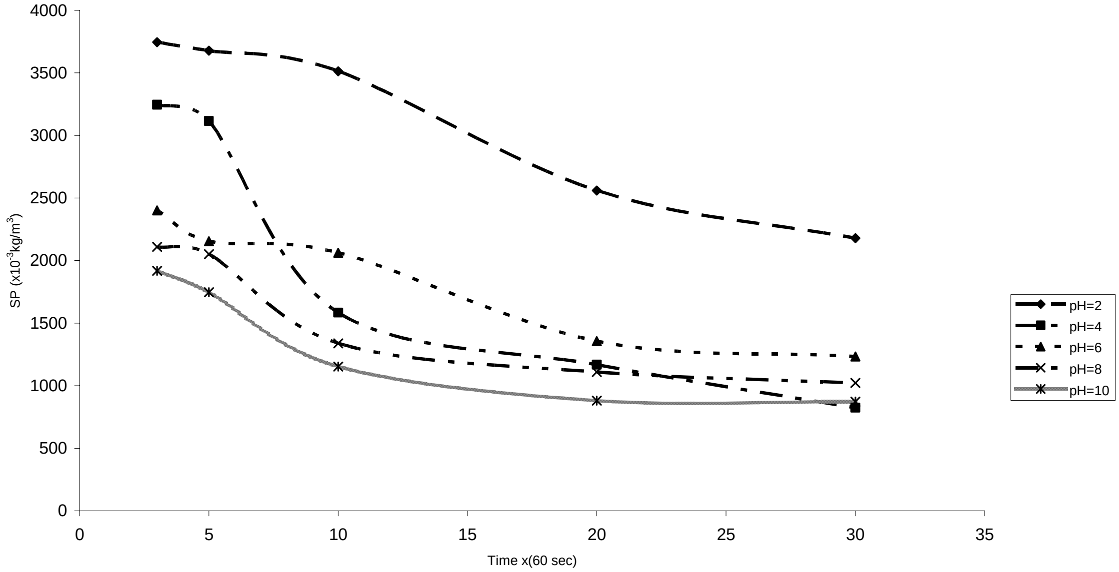

Fig 9:Plot of SP vs. coag-flocculation time for 0.5kg/m^3 MOC at varying pH

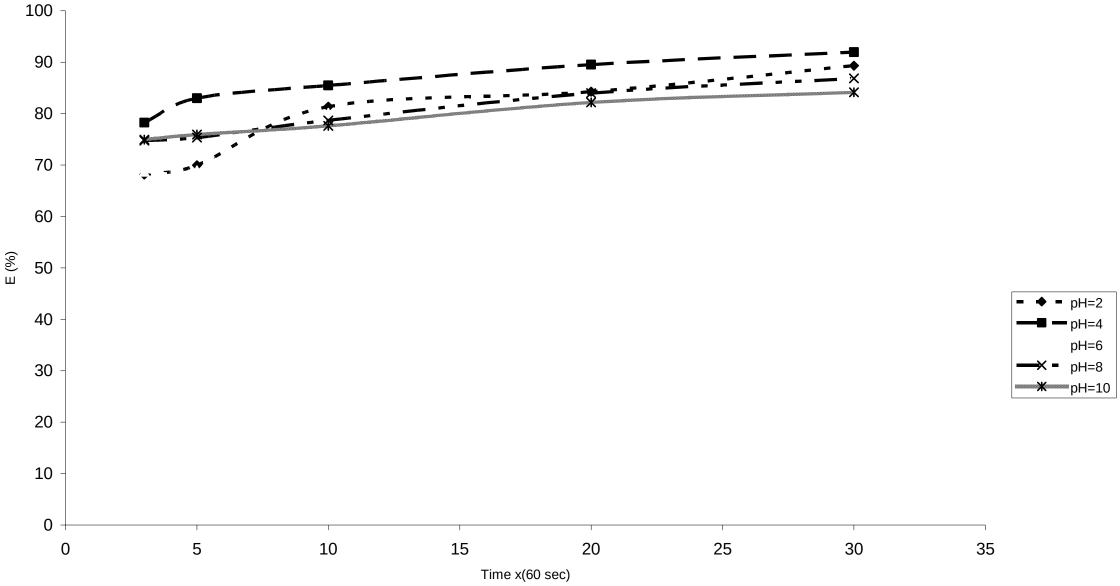

Fig 10:Plot of E vs. coag-flocculation time at varying pH and constant dosage of 0.1kg/m^3

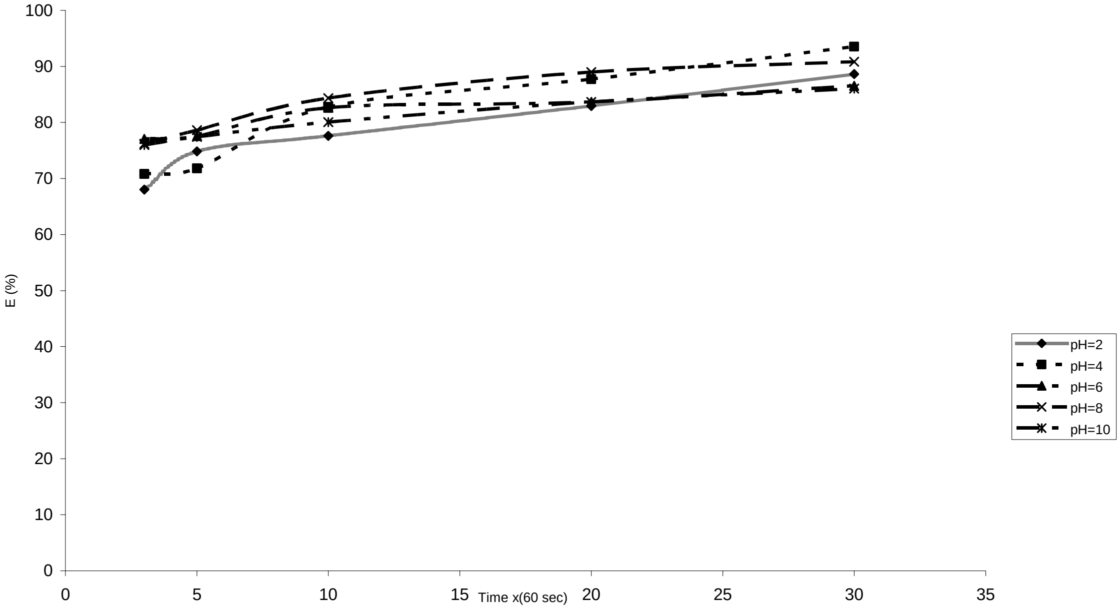

Fig 11:Plot of E vs. coag-flocculation time at varying pH and constant dosage of 0.2kg/m^3

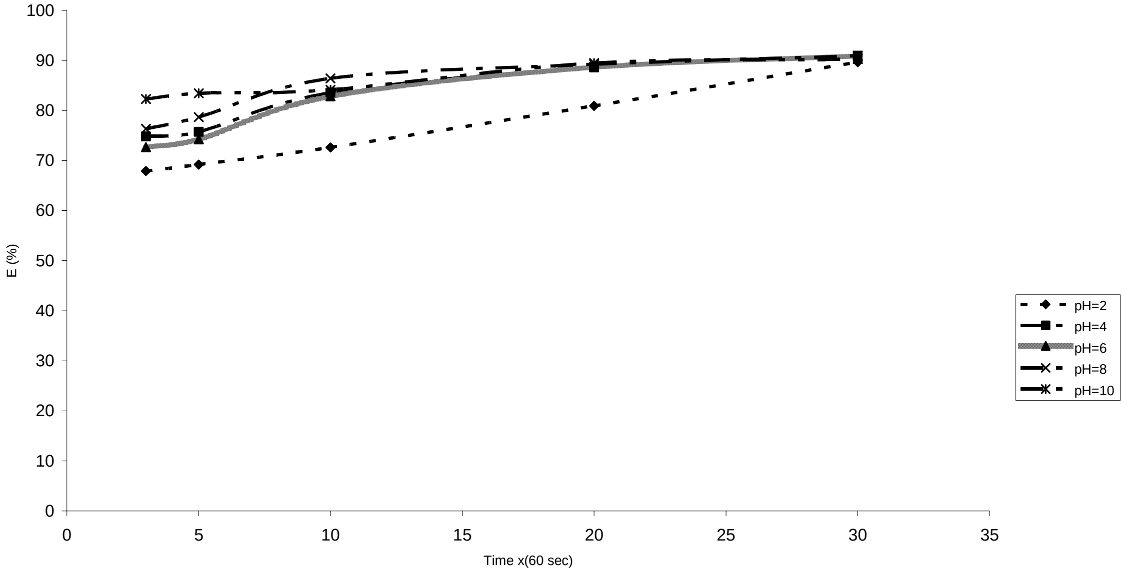

Fig 12: plot of E vs. coag-flocculation time at varying pH and constant dosage of 0.3kg/m^3

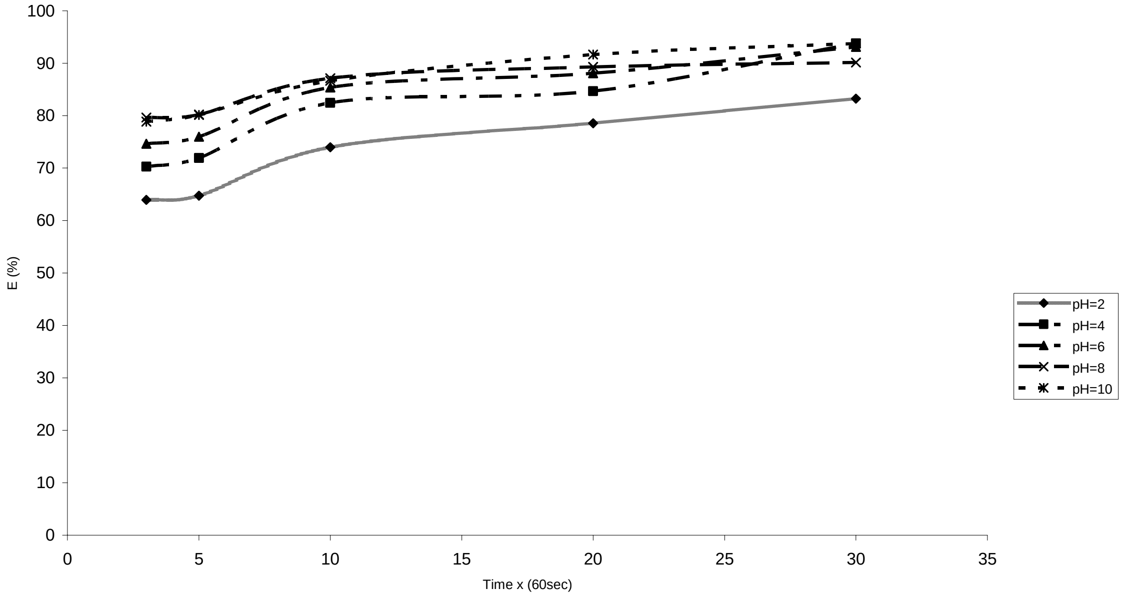

Fig 13: Plot of E vs. coag-flocculation time at varying pH and constant dosage of 0.4kg/m^3

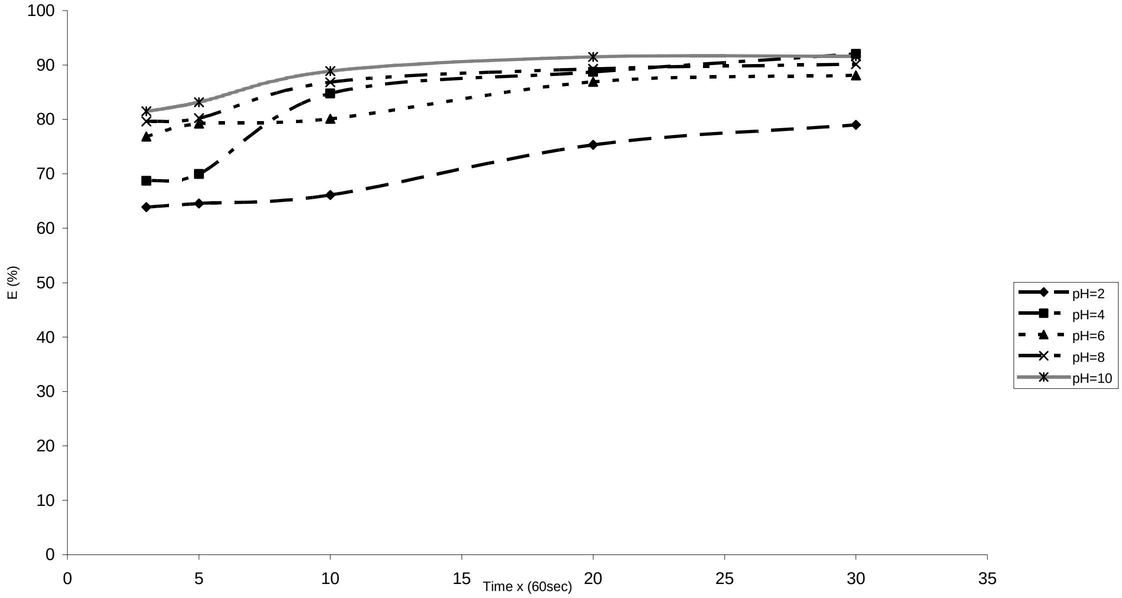

Fig 14:plot of E vs. coag-floccualtion time at varying pH and constant dosage of 0.5kg/m^3

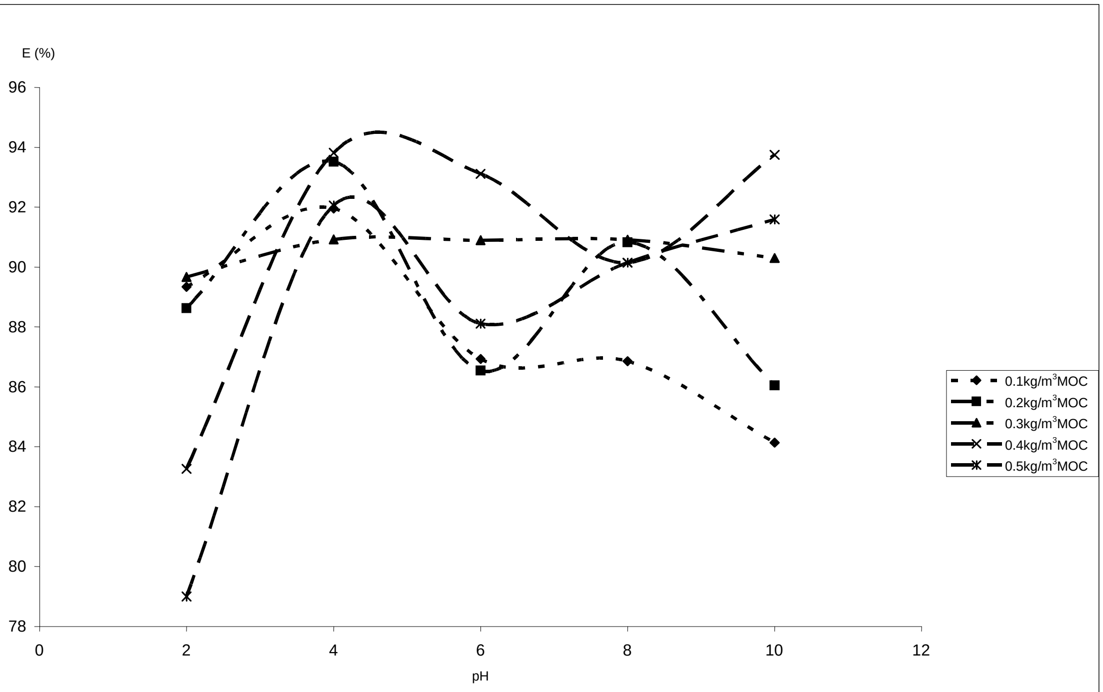

Fig15: Plot of E vs. pH at 30 mins for varying dosages

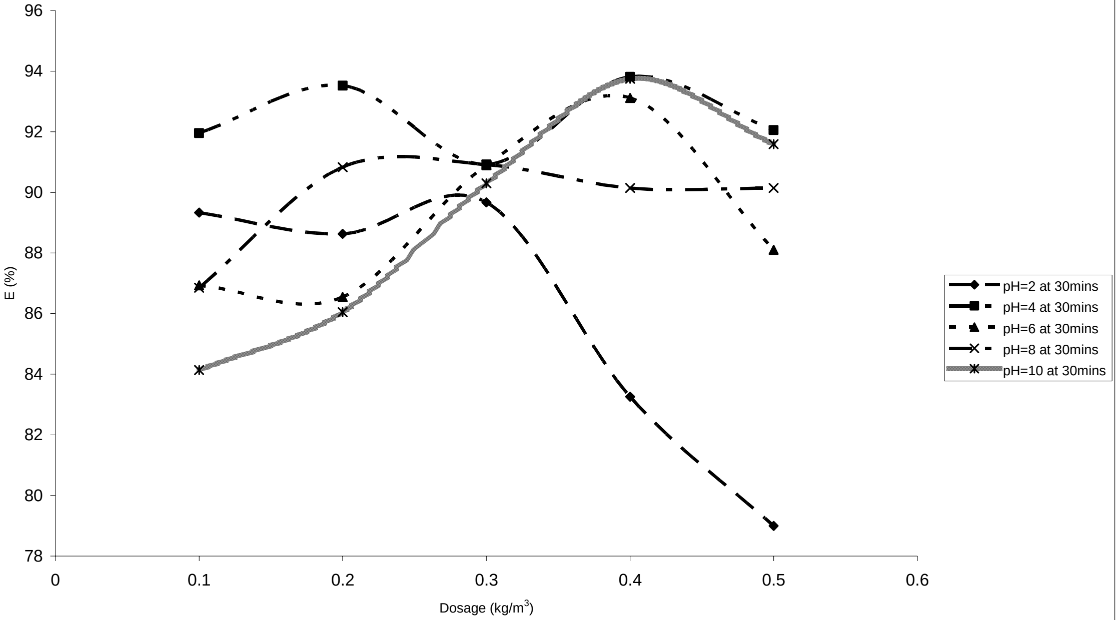

Fig16:Plot of E vs. Dosage at varying pH and constant time

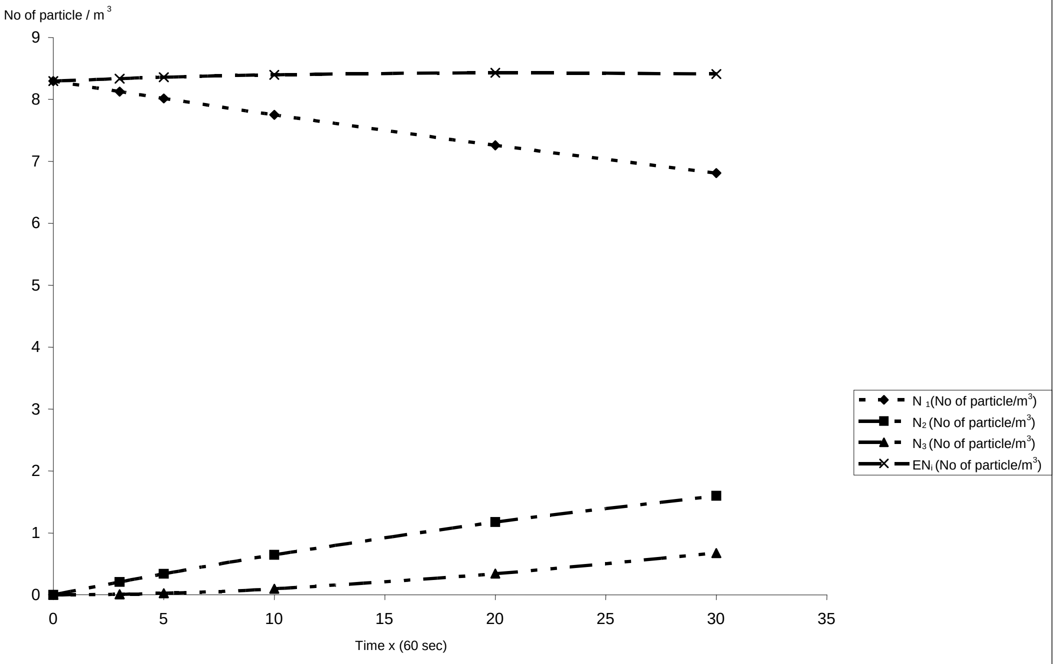

Fig 17: Time evolution of the cluster size distribution for half life of 289.261s

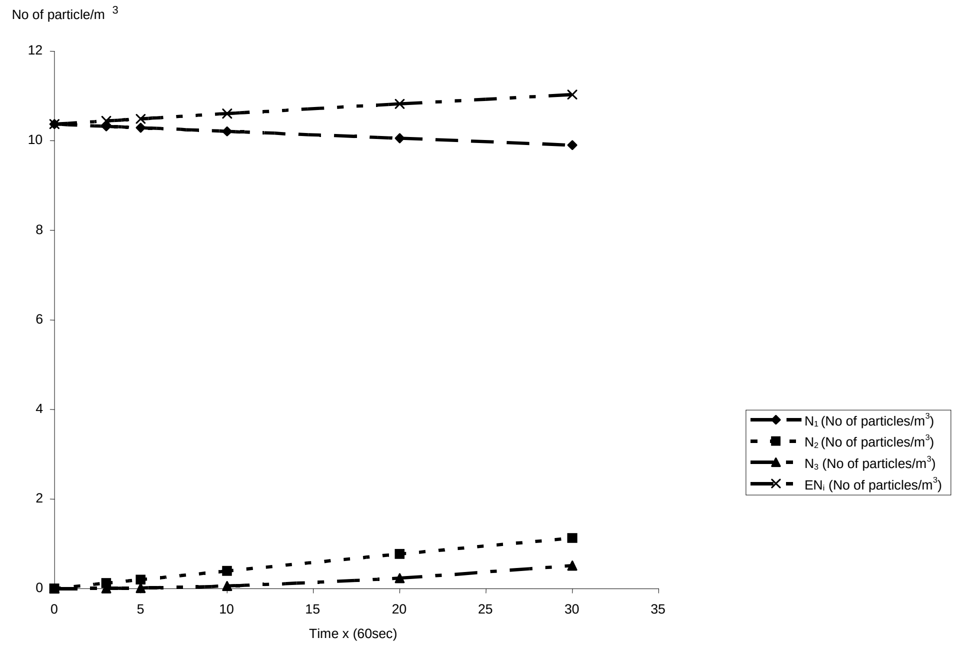

Fig 18: Time evolution of the cluster size distribution for half life of 1446.642s

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