



Factors Affecting Capillary Suction Time of Sludge Using Wet Front Distance and Filtrate Flow Rate Methods

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Authors' contributions

This work was carried out in collaboration among all authors. Author CO designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors JOA and CO managed the analyses of the study. Author VEA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Sludge generated during wastewater treatment is difficult to handle due to their high water content, hence a need for dewatering. The factors that affect the outcome of capillary suction time (CST) were studied using piggery and domestic sludge samples conditioned with ferric chloride. Effects of conditioner concentration, hydrostatic pressure and mixing time were investigated. Filtrate flow rate studies were also carried out as an alternative to wet front progression to determine CST. Ferric chloride was varied from 0.002 to 0.008 g/ml, hydrostatic height was varied from 20 to 40 mm while mixing time ranged from 0 to 120 sec. The optimum conditioner concentration was observed to be 0.0055 and 0.0035 g/ml for piggery sludge and domestic sludge respectively. At 5 % level of significance, hydrostatic height was observed to have no significant effect on the CST for the range of hydrostatic heights chosen. The optimum mixing time observed for 90 g/l and 30 g/l piggery sludge was 50 and 25 sec respectively. While the optimum mixing time for 28 g/l and 14 g/l domestic sludge was 10 and 5 sec respectively. Flow rate was discovered to have an inverse

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relationship with CST, with the optimum conditioner concentration corresponding to the peak flow rate and minimum CST for both test samples. Hence, in order to eliminate the difficulty presented by the anisotropic property of the capillary suction apparatus (CSA) filter paper, filtrate flow method can be used instead of wet front progression method.

Keywords: Sludge; capillary suction time; conditioner; hydrostatic pressure; filtrate flow rate.

1. INTRODUCTION

The capillary suction time (CST) apparatus was developed by Gale and Baskerville in 1967. It has long been established as a practical but empirical method for the determination of sludge dewaterability [1]. CST is cost effective, rapid and simple to execute, hence it has been used worldwide for sludge dewaterability studies [2,3,4]. However, the CST is a good index for sludge filterability if only the product of solid concentration and average SRF is of interest. On the other hand, the bound water content cannot be directly evaluated from the CST data. The CST apparatus involves the use of chromatography paper, which allows liquid when poured on it to spread out with a very smooth wet front enabling the wet front positions to be measured accurately.

A model to describe fluid flow in a capillary suction apparatus (CSA) using the piston like flow method was proposed [5]. The dewatering in CST apparatus consists of two consecutive processes, namely the filtration of sludge in the cylindrical tube and penetration of filtrate into the filter medium. It was also assumed that the structure of the filter medium is isotropic, hence the liquid front will be circular. Sawalha and Sholz [6] studied the fluid flow in CSA using the concept of diffusion. By assuming a power law dependence of diffusivity, the wet front radius versus time relation could be described by a cubic algebraic equation which contains no parameters that CSA used. It was shown that when pure liquid was used as the testing substance, the liquid saturation under the inner cylinder would be unity. But when cake is formed on the filter paper, the liquid saturation would first decrease and then approach a constant value which was less than unity. Arend et al. [7] investigated fluid flow through a porous media experimentally and theoretically and concluded that capillary suction time would increase when cake is formed in the CSA [8,9]. Though cylindrical capillary suction apparatus (CCSA) is very easy to use, there are several shortcomings. One among others is the anisotropic property of the machine made filter

paper which causes filtrate to move faster along the grain than across. The resulting wet area will be elliptical rather than circular. To overcome this difficulty, [10] proposed the concept of rectangular CSA (RCSA). The RCSA makes use of only one direction of the filter paper and leads to unidirectional flow field. [11] investigated experimentally and practically fluid flow and cake formation in a RCSA and concluded that RCSA is superior to the cylindrical CSA when treating liquids with small diffusivities or slurries with high solid concentration [12].

Several studies on the use of conditioners have been carried out. Lakshmanan and Rajarao [13] investigated the use of three flocculants which are magnetic iron oxide nanoparticles (MION), ferrous sulfate, and Moringa crude extract (protein) on sludge dewatering. Sludge water content was observed to reduce by 30% was treated with either ferrous sulphate or Moringa crude extract. Furthermore, MION resulted in a 95% reduction of the sludge water content. The effect of conditioners such as potassium was investigated in laboratory tests using simulated wastewater [3]. The dewatering property (CST) deteriorated beyond the concentration range of 0.25 – 0.5 meq/l, associated with an increase in soluble protein. Activated sludge was also subjected to ultrasound at 65 Watts to investigate the effect on CST [2]. CST was found to increase markedly with the shearing of flocs which depends on the intensity of the ultrasound. Inorganic sludge were conditioned with fly ash and polymer. The rheological characteristics of the conditioned sludge such as sludge viscosity, rheogram, CST and specific resistance to filtration (SRF) were determined [4]. Experimental results indicate that the sludge viscosity and rheogram peak can be used to assess inorganic sludge dewaterability, but not organic activated sludge. Additionally, the specific height of the rheogram peak is an alternative means to determine the best point of inorganic water sludge conditioned with polymer. This study focuses on the effects of cylinder diameter, hydrostatic pressure and shearing time on the outcome of a CST test. A modified CST procedure using optimized conditioner dosage is

further investigated. Filtrate flow rate studies were also carried out as an alternative to wet front progression to determine CST.

2. MATERIALS AND METHODS

2.1 Sludge Samples

Domestic and piggy sludge samples were used for this study. The domestic sludge was collected from the oxidation pond of University of Nigeria Nsukka while the piggy sludge was collected from Bora farms limited Enugu Ngwo in Enugu state. The waste samples were sieved with sieve number 0.6mm to remove the fibrous and coarse particles, and then the filtrate was allowed to settle for 24 hours to remove settleable particles. Then the mixture of water and unsettlable particle was collected with 5 litter plastic bottle as the test sludge sample. The piggery and domestic sludge samples had a total suspended solid (TSS) of 0.09 and 0.028 g/ml respectively and pH of 6.4 and 6.8 respectively.

2.2 Conditioning Chemical

Ferric chloride (FeCl_3) was used as the conditioning chemical for this study. A standard solution of the chemical of concentration 60 g/l was prepared from which different doses ranging from 0.002 to 0.008 g/ml used for the conditioning operations were obtained. The range of conditioner dose was selected to determine the effect of increasing conditioner dose on the dewatering process.

2.3 Apparatus

Standard CST apparatus was not available hence the apparatus was fabricated using locally available materials. These materials are perspex plates of size 150 mm × 200 mm × 5 mm, surgical syringe of internal and external diameter 12 mm and 13.5 mm respectively for the cylinder and Whatman number 1 filter paper with flow rate of 130mm/30min and 0.18 mm in thickness.

2.4 Mixing System

To mix the sludge and conditioner, a caframo RZR1 stirrer with a 5 mm three bladed, marine type impeller and speed range of between 400 – 2000 rpm was used. The experimental proceeding was first recorded with a camcorder, after which the readings were extracted.

2.5 Effect of Hydrostatic pressure on CST

3 ml of the piggery sludge sample was conditioned with 1 ml solution containing 0.003 g FeCl_3 and mixed for 60 sec at speed of 1000 rpm. Then using the 13.5 mm external diameter cylinder and with the conditioned sludge head in the capillary suction test apparatus cylinder varied from 20 mm, 30 mm to 40 mm respectively, the time for the wet front to advance to six different predetermined points on the filter paper was measured. The test was repeated using the domestic sludge sample and distilled water respectively.

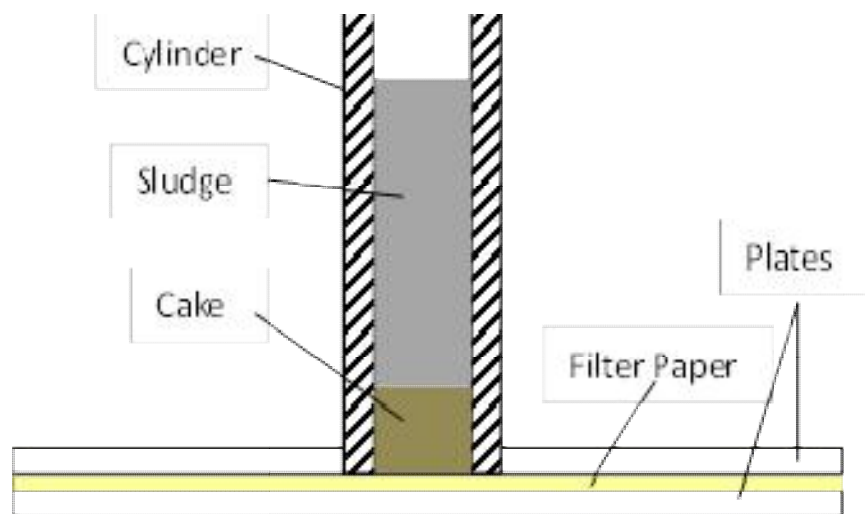


Fig. 1. Schematic of capillary suction test apparatus

2.6 Effect of Mixing Time on CST

The two sludge samples with two different concentrations were tested. 6 ml of the piggery sludge sample (TSS) 0.09 g/ml was conditioned with 1 ml solution of 0.003 g/ml $FeCl_3$ and mixed for a predetermined time with the stirring speed set at 800 rpm then the CST was measured using the 12 mm internal diameter cylinder. The shearing time was varied by repeating the test for different mixing times. Mixing times of 0, 5, 10, 15, 20, 30, 40, 60, 90 and 120 sec were used for the test. The same test was repeated for 0.03 g/ml piggery sludge sample, 0.028 g/ml and 0.014 g/ml domestic sludge sample to evaluate the effect of dilution on mixing time.

2.7 Filtrate Flow Rate Measurement

CST was measured as a function of the filtrate flow rate. The time for the conditioned sludge sample to lose a predetermined volume of filtrate was progressively determined. The 12 mm internal diameter cylinder was used for this test with each calibration on the test cylinder equal to 0.2 ml. 3 ml of the sludge sample was conditioned with 1 ml solution of ferric chloride and mixed. The mixture was poured into the cylinder of the assembled capillary suction apparatus. Standard CST was measured as the time for the wet front to advance between points 5 mm and 15 mm (wet front distance) from the external diameter of the test cylinder. The filtration process was allowed to progress until the filter paper is completely saturated. The time

it took for the filter paper to absorb 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6 and 1.8 ml of the filtrate was recorded. The test was conducted for the two sludge samples using varying doses of ferric chloride.

3. RESULTS AND DISCUSSION

The effects of hydrostatic pressure on CST are shown as Figs. 2 – 4. As seen in Fig. 2, varying the hydrostatic height does not affect the CST of distilled water as can be seen in the uniformity of slope at different heights. However, when the test liquid was changed to flocculated sludge, the CST increased with decrease in hydrostatic pressure this is shown by increase in the slopes of Figs. 3 and 4 as hydrostatic height decreases. This could possibly explain the variation in the pressure gradient across the sludge cake. An increase in sludge height will lead to increase in the pressure gradient, this increases the flow rate across the cake and hence decreases the CST.

To test the significance of the results obtained, one way analysis of variance (ANOVA) was done. Based on the results obtained, two hypotheses were put forward, they are;

H_0 (null hypothesis) = Hydrostatic height of sludge has no significant effect on wet front progression.

H_1 (Alternate hypothesis) = Hydrostatic height of sludge has significant impact on wet front progression.

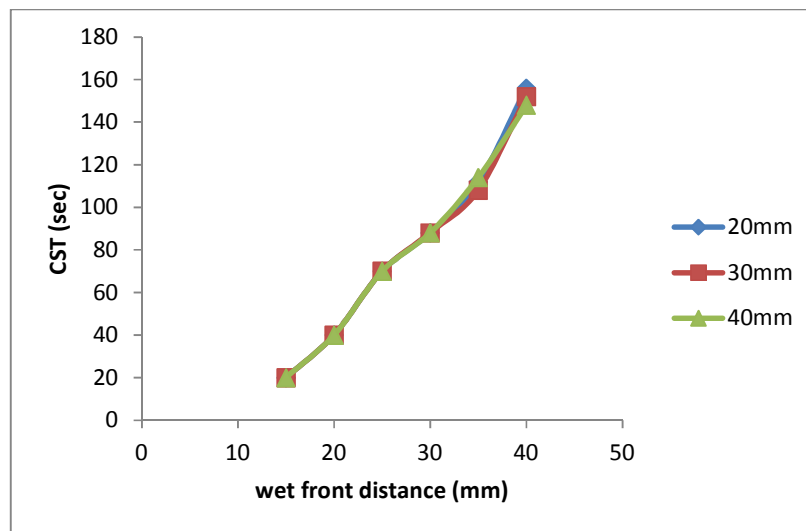


Fig. 2. CST of distilled water at different hydrostatic pressure

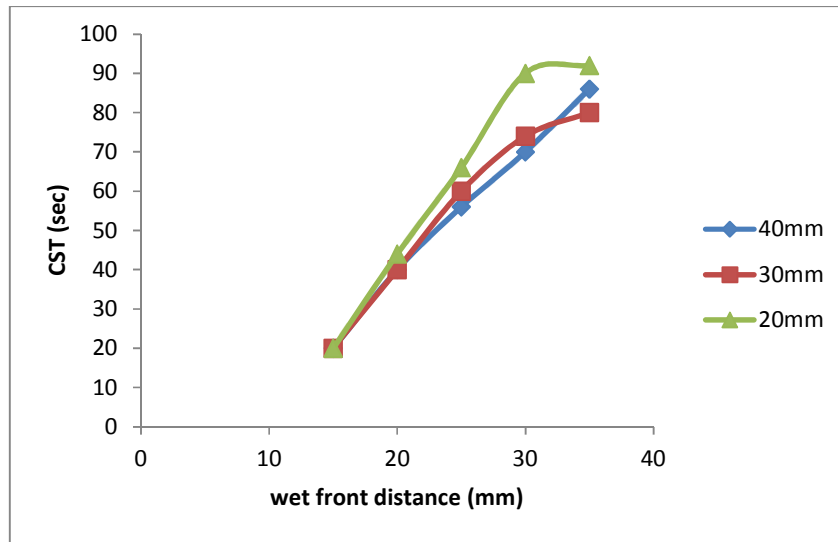


Fig. 3. CST of conditioned piggery sludge at different hydrostatic pressure

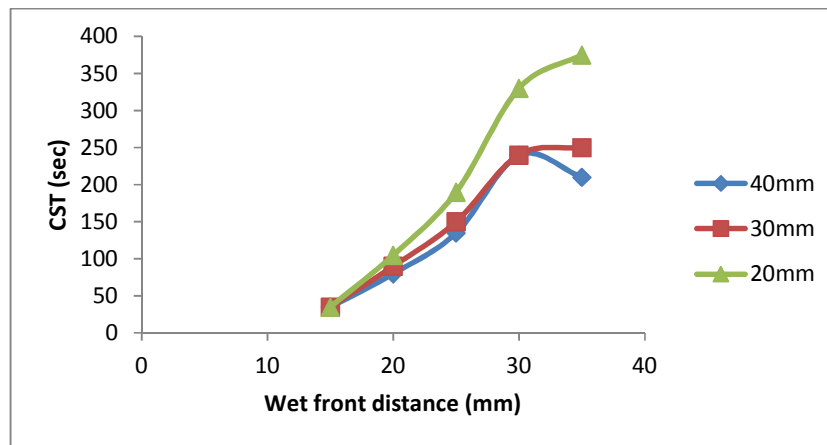


Fig. 4. CST of conditioned domestic sludge at different hydrostatic pressure

Table 1. Analysis of variance of different hydrostatic heights of distilled water

Source of Variation	SS	DF	MS	F	P-value	F crit
Between Groups	5.78	2	2.89	0.0013	0.999	3.68
Within Groups	34633.33	15	2308.89			
Total	34639.11	17				

SS = Sum of squares; df = Degrees of freedom; MS = Mean squares; F = F-statistic

Table 2. Analysis of variance of different hydrostatic heights of piggery sludge

Source of Variation	SS	DF	MS	F	P-value	F crit
Between Groups	203.2	2	101.6	0.14	0.87	3.89
Within Groups	8883.2	12	740.27			
Total	9086.4	14				

SS = Sum of squares; df = Degrees of freedom; MS = Mean squares; F = F-statistic

Table 3. Analysis of variance of different hydrostatic heights of domestic wastewater

Source of Variation	SS	DF	MS	F	P-value	F crit
Between Groups	12623.33	2	6311.67	0.51	0.61	3.89
Within Groups	148060	12	12338.33			
Total	160683.3	14				

SS = Sum of squares; df = Degrees of freedom; MS = Mean squares; F = F-statistic

The test was carried out at 5% level of significance and the results shown as Tables 1 to 3. It is observed that *P* value ranged from 0.61 to 0.999 which is greater than alpha value of *P* = .05. Therefore, we accept the null hypothesis and conclude that varying the hydrostatic height will have no significant effect on the CST. This agrees with [7, 12, 14, 15] who showed that capillary pressure in CST filter paper is far higher than hydrostatic pressure, hence many researchers ignore the effect of hydrostatic pressure.

It was observed that at different concentrations of conditioning chemical and sludge samples, the CST decreased with increase in mixing time and after sometime started to increase with further increase in the mixing time. The optimum mixing time for 90 g/l and 30 g/l piggery sludge was 50 and 25 sec respectively. While the optimum mixing time for 28 g/l and 14 g/l domestic sludge was 10 and 5 sec respectively. These results are shown as Figs. 5 and 6. The initial decrease in CST can be attributed to improved distribution of the conditioning chemical on the sludge particle surface due to better mixing of the chemical with the sludge. This leads to improved floc formation and hence reduction in the sludge cake resistance and CST. After the point of least cake resistance, further mixing of the mixture lead to shearing of the sludge flocs into tiny particles. These particles settled into and blocked the

pores of the filter septum thereby increasing its resistance to flow leading to increased CST. When the mixing time after the optimum point is prolonged, tiny particles are generated to block the pores hence the progressive increase in CST. Therefore, mixing the conditioned sludge beyond the optimum mixing time limit is detrimental to the CST operation. The degree of concentration of the sludge sample affects the optimum mixing time. The more concentrated the sample, the longer time it will take for the conditioning chemical to be properly mixed for any given concentration of the conditioner.

From Figs. 7 and 8, the filtrate flow rate in the filter paper increased progressively with filtration time up to a point referred to as point of maximum flow rate (PMF) after which it decreased with further increase in filtration time. This trend was followed for the different doses of the conditioner used to condition the tested samples. The initial increase in flow rate with time is as a result of increase in the rate at which the liquid trapped within the sludge structure is being released occasioned by formation of flocs as the filtration progressed. At this stage, the effect of flocculation is so dominant that it diminished the effect of sedimentation within which 20 to 25 % of the total sludge liquid is lost. However, after the PMF, effect of sedimentation dominates leading to reduction in flow rate with increase in filtration time.

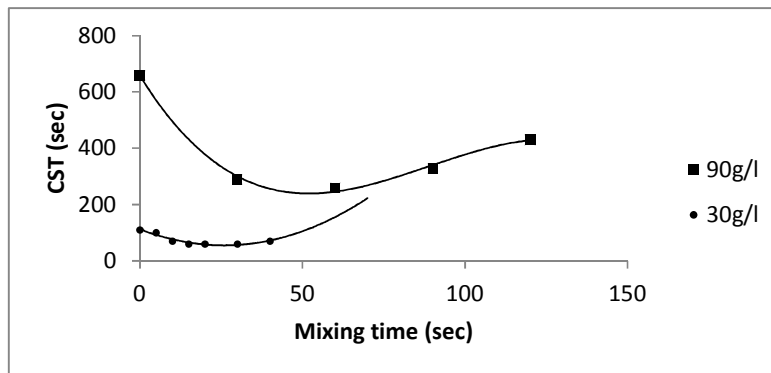


Fig. 5. CST of piggery sludge at different mixing time

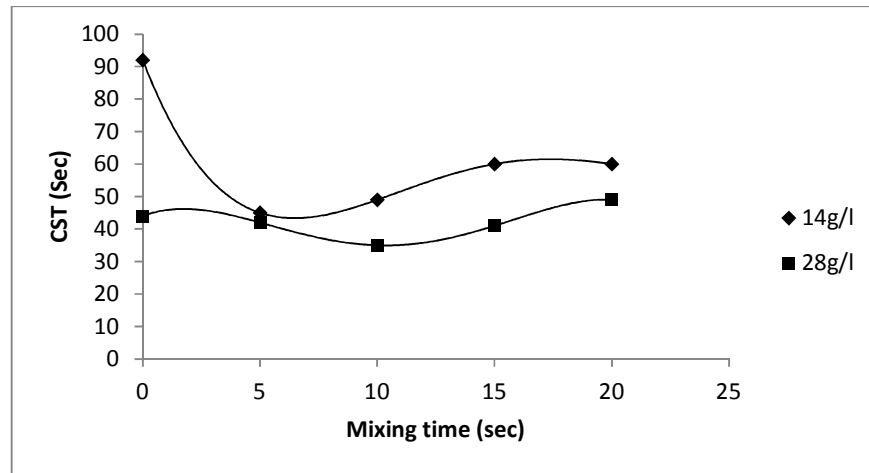


Fig. 6. CST of domestic sludge at different mixing time

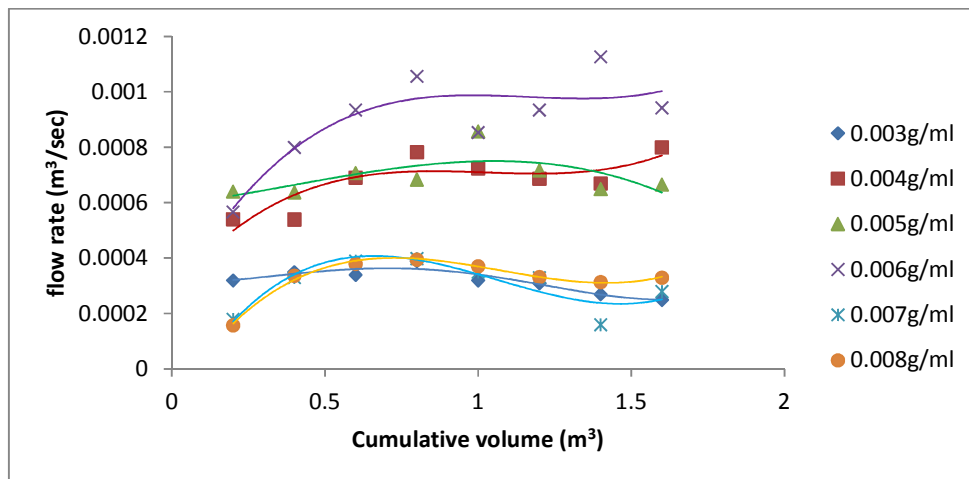


Fig. 7. Flow rate at varying doses of FeCl₃ for piggery sludge

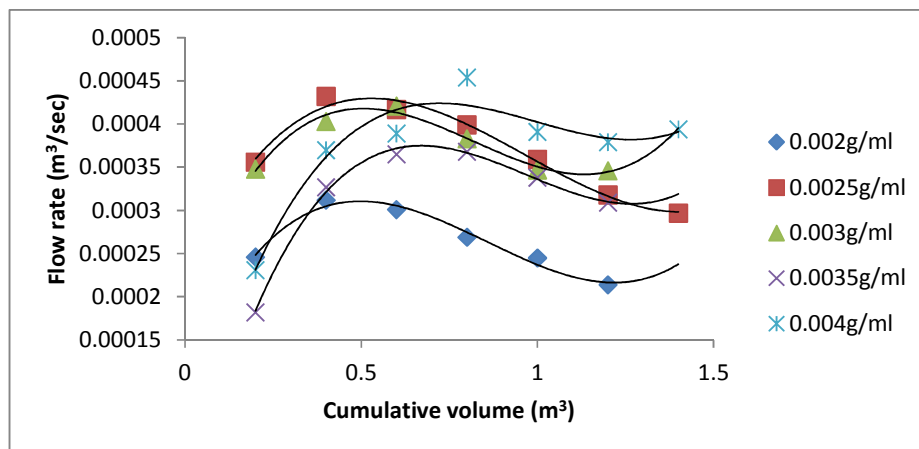


Fig. 8. Flow rate at varying doses of FeCl₃ for domestic sludge

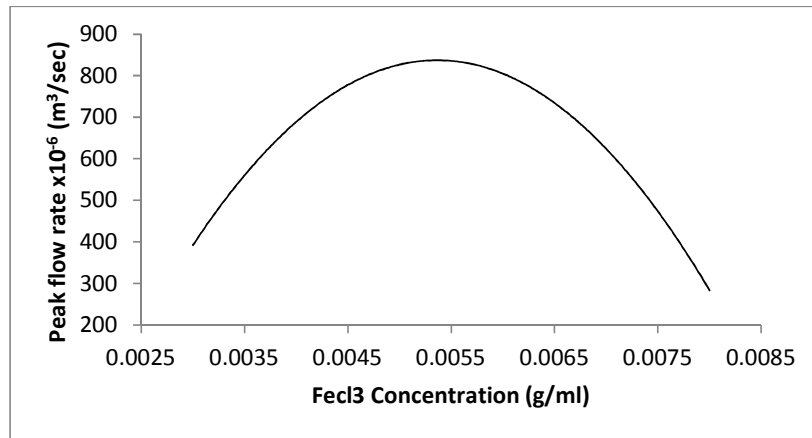


Fig. 9. Peak flow rate at different conditioner dosage for piggery sludge

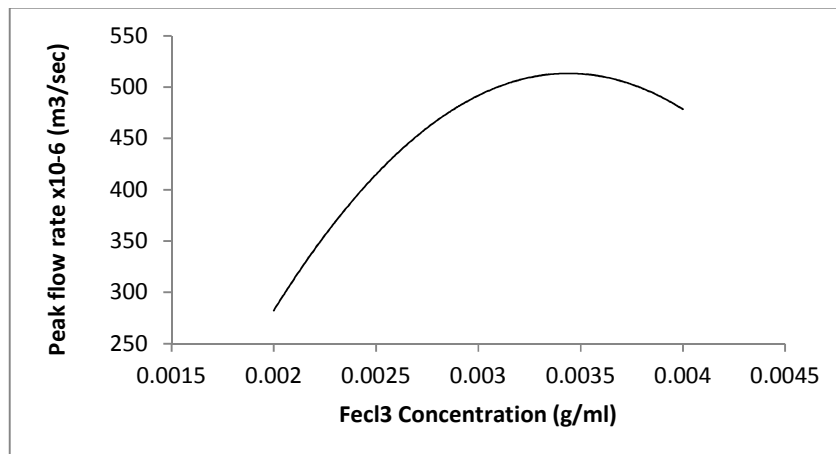


Fig. 10. Peak flow rate at different conditioner dosage for domestic sludge

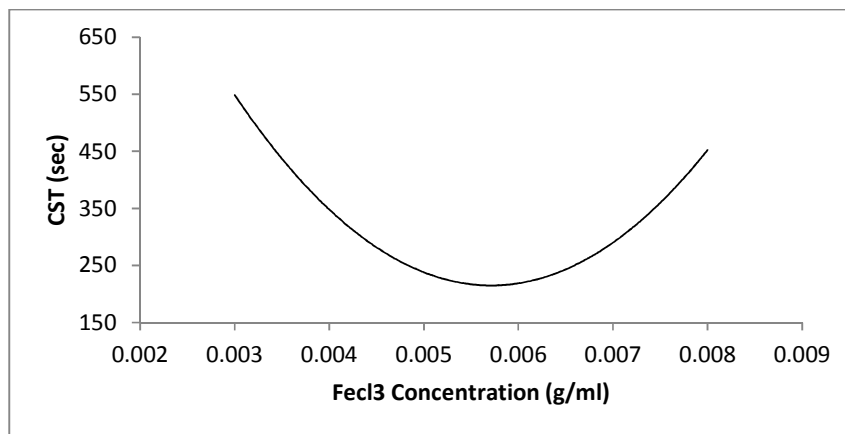


Fig. 11. CST at different conditioner dosage for piggery sludge

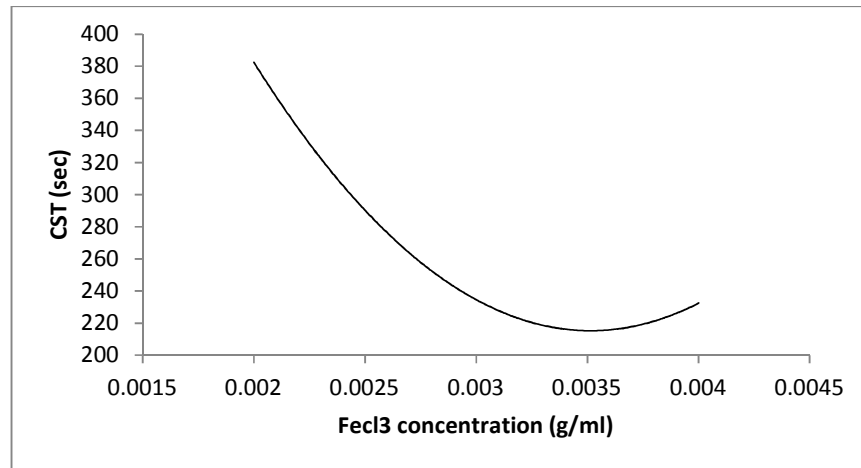


Fig. 12. CST at different conditioner dosage for domestic sludge

Figs. 9 and 10 show that the peak flow rate increases with increase in conditioner dosage up to an optimum dose of 0.0055 g/ml and 0.0035 g/ml for piggery and domestic sludge respectively and then decreased with further increase in the conditioner dosage. Figs. 11 and 12 show that the CST decreases with increase in the conditioner dose to an optimum conditioner dosage of 200 sec and 220 sec for piggery and domestic sludge respectively and then increases with further increase in conditioner dosage. CST is seen to have an inverse relationship with flow rate.

4. CONCLUSION

When the test liquid contains settleable particles, CST will decrease with increase in hydrostatic pressure. However, capillary pressure in CST filter paper is far higher than hydrostatic pressure, hence many researchers ignore the effect of hydrostatic pressure. If ferric chloride conditioner is to be used, it was shown that there exists an optimum mixing time of 50 and 10 seconds for piggery and domestic sludge respectively, beyond which finer particles are produced leading to increased CST. This means that mixing time must be optimized when dealing with different sludge samples. The optimum conditioner dosage is seen to correspond to the peak flow rate and minimum CST for both the piggery and domestic sludge. Hence, in other to eliminate the difficulty presented by the anisotropic property of the CSA filter paper, filtrate flow method can be used.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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