DEVELOPMENT OF CRIETRIA FOR FORMING AND MAINTAINNING A SLUDGE BLANKET IN AN UPFLOW SLUDGE BLANKET CLARIFIER/ PULSATOR

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Degree of Doctor of Philosophy

Department of Civil Engineering

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Declaration

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The above candidate has carried out research for the Ph.D. thesis under our supervision.

Research Supervisors

Professor (Mrs.) Niranjanie Ratnayake Date: ………………..

Professor Jagath Manatunge Date: ………………..

Abstract
Forming and maintaining a sludge (floc) blanket

Keywords: Clarifier, floc blanket, particle structuring, sludge cohesion coefficient, settling velocity

Coagulation and flocculation is attained within a sludge (floc) blanket of an upward flow clarifier unit. In this study cohesivity of the floc blanket, measured by the indicator sludge cohesion coefficient (*SCC*) is used to explain the blanket characteristics and response of the blanket to variations of raw water turbidity (RWT), coagulant dose and ambient conditions.

The study found that *SCC* is an appropriate parameter to monitor floc blanket characteristics. A satisfactory floc blanket is established when *SCC* varies within 0.3 – 1.3 mm/sec and the sludge volume fraction of the blanket is between 0.2 and 0.25. At RWT occurrences > 450 NTU, the blanket cohesivity reduces. Increased coagulant dose leads to restabilization of particles by charge reversal leading to reduction of blanket cohesivity. It is recommended to introduce preliminary sedimentation (prior to clarifier) to effectively treat high turbidity raw water.

Beyond RWT 300 NTU optimum coagulant dose reported from *SCC* test is lower than that of Jar test. This will give savings in coagulants in the range of 6 - 25%. When RWT is > 300 NTU, the linear relationship established using the two parameters during the study can be used to find the optimum dose after carrying Jar test.

The study found that high inflow temperature reduces blanket cohesivity and particle settling efficiency. There is a significant linear relationship between the influent temperature and the effluent quality.

The particle structuring within the blanket is due to hydrodynamic forces between the particles counterbalanced by the cohesive forces. A steady floc blanket is formed when the individual particles are agglomerated and clusters are formed. Cluster formation/destruction is due to the cohesive/inertial forces between particles and/or particle clusters. With low *Re* (< 1) cohesive forces govern. Interstitial spaces between particles vary due to cluster formation/destruction, leading to the increase/decrease of blanket settling velocity.

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List of Abbreviations

Al - Aluminum
V - Apparent Volume
Vs - Blanket Settling (Sedimentation) Velocity
R^2 - Coefficient of Determination
ρ - Density of Fluid
D - Drafting
μ - Dynamic Viscosity
EFT - Effluent Turbidity
m - Empirical Exponent
Fe - Ferric
KMC - Kandy Municipal Council
K - Kissing
G -Mixing Intensity (Shear Rate)
NWS & DB - National Water Supply & Drainage Board
NTU - Nephelometric Turbidity Units
C - Particle Concentration
d - Particle Diameter
r - Pearson Correlation Coefficient
PACL - Poly Aluminum Chloride
pH - Potential of Hydrogen
RWT - Raw Water Turbidity
rpm - Revolutions Per Minute
Re - Reynolds Number
∞ - Significance Level
h_1 - Sludge/Clear
SCC (K) - Sludge Cohesion Coefficient
SCT - Sludge Cohesion Test
h - Sludge Height
SV (SVF) - Sludge Volume Fraction
SVT - Sludge Volume Test
Us - Superficial Velocity
Vt - Terminal Settling Velocity
t - Time
T - Tumbling
u - Upward Velocity
Φ - Void age
Vo - Volume at Zero Velocity

CHAPTER 1: INTRODUCTION

1.1 Background

The world’s water exists naturally in different forms and locations: in the air, on the surface, below the ground, and in the oceans. Surface water is available in streams, rivers, and lakes. Groundwater is found in shallow depths as well as in deep aquifers. With the population growth, available water resources face a host of serious threats, which are caused primarily by human activity. They include sedimentation, pollution, climate change, deforestation, landscape changes, and urban growth.

The necessity of water treatment has arisen in order to bring the naturally available water to a condition which is acceptable for human use. Treatment for drinking water production involves the removal of contaminants from raw water to produce water that is pure enough for human consumption without any short-term or long-term risk of any adverse health effect. Substances that are removed during the process of drinking water treatment include suspended solids, bacteria, algae, viruses, fungi, and minerals such as iron and manganese.

A combination, from the following processes is selected considering the quality of a specific raw water source, for municipal drinking water treatment:

- Pre-chlorination for algae control and arresting biological growth
- Aeration for removal of unwanted dissolved gasses and aeration along with pre-chlorination for removal of dissolved iron and manganese when present in small amounts
- Coagulation and flocculation followed with sedimentation. Coagulant aids, also known as polyelectrolytes to improve coagulation and for more robust floc formation
- Sedimentation for solids separation that is the removal of suspended solids trapped in the floc
- Filtration to remove particles from water either by passage through a sand bed that can be washed and reused or by passage through a purpose designed filter that may be washable.
- Disinfection for killing bacteria viruses and other pathogens.

Suspended impurities in water can be categorized into four main areas. They are dissolved matter, suspended matter and colloidal matter and microscopic matters.

These impurities vary in size. Up to a diameter of 10^{-4} m, particles can be categorized as settleable solids, 10^{-4} to 10^{-9} m suspended matter and colloids. Dissolved matter especially contributing to the colour of the water is of size range from 10^{-9} to 10^{-11} m.

1.2 Removal of particles from water

The removal of a considerable proportion of the particle in water is accomplished by sedimentation. The impurities too small to settle by gravitational forces alone have to be aggregated to make large settleable particles for successful separation by sedimentation. The process of aggregation of smaller particles into bigger particles is termed as coagulation.

Coagulation is the most widely used physico-chemical process used to treat water. The aggregation of colloidal particles involves two separate and distinct steps. They are particle transport to effect inter-particle contact and particle destabilization to allow attachment when in contact. Design of water treatment units for particle removal is based on particle transport mechanisms, flocculation and selection of type and dosage of coagulants in order to achieve particle destabilization.

Depending on the particle concentration and the interaction between particles, four types of settling can occur. They are settling of discrete particle whose size, shape and specific gravity do not change with time, Settling of flocculant particles, whose particle size shape and density changes with time, hindered settling, when a cloud of solid particles is settling in a quiescent liquid; the mass of particles settles as a unit with individual particles remaining in fix position with respect to each other. Fourth type of settling is compression settling where the concentration of particles is so high that sedimentation can only occur through compaction of the structure (AWWA, 2003). In a water treatment plant particle removal is achieved in a sedimentation/ clarification unit.

1.3 Upward flow clarification

The clarification process makes the water clear by removing all kinds of particles, sediments, oil, natural organic matter and color. Sludge blanket clarifiers are becoming popular worldwide due to their ability to withstand large variations in raw water quality within a short period, high loading capacity and high clarity effluent quality. National Water Supply & Drainage Board (NWSDB) as well as few Municipalities throughout Sri Lanka uses state of art solid contact clarification processes such as pulsator clarifers, super pulsator clarifiers, lamella settlers, tube settlers etc. in their water treatment plants and waste water treatment plants.

In upflow clarifiers, water flows up toward the effluent launders as the suspended solids settle, provide coagulation, flocculation, and sedimentation in a single unit. Mixing, internal solids recirculation, gentle flocculation and gravity sedimentation are all combined into the single unit. Upward flow through flocculation clarifiers forms a floc blanket which is a fluidized bed of aggregated suspended particles.

Various types of upflow clarifiers are developed. The Pulastor® uses a unique pulsating hydraulic system to maintain a homogeneous sludge layer in the floc blanket. Pulsation, carried out every 40 to 50 seconds maintains a uniform fluiduzed bed which enables particle agglomeration, and reduce the potential of short circuiting of the flow through the blanket (AWWA, 2003).

1.4 Justification for the study

Solid contact (flocculation) clarifiers have been widely used in clean water production since first being introduced in the 1930s. Owing to their more efficient flocculation and a better chance of making solid contacts, flocculation clarifiers can deal with a surface loading two to three times higher than conventional coagulation sedimentation basins (Kawamura, 1991; Masschelein, 1992; Stevenson, 1997; Edzwald et al., 1999).

Even though the fluidized bed (floc blanket) is a principal water treatment process, theoretically it is the least understood in terms of its operational behavior. Some fundamental studies on the operation of the blanket have been undertaken. However these have not been able to corroborate by experimental data at full-scale work. The theoretical models developed were based mostly on empirical studies done on the performance of pilot and full-scale units.

Gregory (1979) has done an extensive review on work carried out up to then on floc blanket clarifiers and concluded that though some qualitative work was presented, the theoretical work was limited and poor clarifier performance were mainly unproved. Almost all the theories explaining the floc blanket clarification process are based on the assumption that the settling velocity is dependent upon the particle concentration in the blanket. However, a comprehensive explanation on the behavior of a floc blanket satisfying all the conditions anticipated in a water treatment plant is yet to be established.

1.4.1 Factors affecting clarifier performance

The initial turbidity of water entering the clarifier, in other words, the particle number concentration is identified as a significant factor influencing clarifier performance. The raw water quality entering the clarifier differs throughout the year due to seasonal variations. High initial turbidity can occur in the case of heavy rain when surface run-off brings mud and particles to surface waters. Depending on the raw water quality the chemical requirement and subsequent floc formations will change. The initial turbidity of water will influence the coagulation performance. However, a clear understanding of the effects of initial turbidity on floc growth rate in the floc blanket of a upflow clarifier has not yet been well established (Xiao et al., 2010).

Formation of flocs, floc size and shape, and floc growth rate contributes to better effluent quality in a floc blanket. The coagulation process using hydrolysable metal salts enables floc formation. The type and dosage of coagulants, solution pH, and the mixing intensity and duration are operational parameters contributing to physiognomies of floc blankets. Studies done by Chen et al. (2003) at Ping Tsan Water Works of Taiwan reported that the blanket was rather unstable and complete washout was noticeable in the coagulation-flocculation treatment process when the PACl dose was insufficient. On the other hand, treatment of high turbidity raw water with combined treatment process; coagulating raw water and settling in a pre-sedimentation tank followed by coagulating again and clarifying in a clarifier resulted in a relatively stable floc blanket for shock load. Studies done by Su et al. (2003) using laboratory experiments with synthetic raw water and under-dosed, optimal and overdosed PACl suspensions concluded that change in coagulant dose would affect the blanket height and response time.

Another factor affecting floc formation and strength is the mixing intensity which is expressed by the velocity gradient. The influence of velocity gradient on flocs can be determined by jar test experiments. A study by Ching et al. (1994), found that slow mixing considerably affects the coagulation rate. Further, the variation of floc sizes as a function of slow mixing intensity can provide information about the floc strength

(Jarvis, 2006). Studies done by Xiao et al. (2010) showed that depending on the type of coagulant used (Al, Fe) average size of floc and floc growth rate will vary. Initial turbidity and slow mixing rate were able to increase the growth rate of both kinds of flocs. With increased mixing speed, floc size becomes smaller. However, the floc shape becomes more regular and rounder in shape. Flocculation before floc blanket formation significantly enhances the effluent quality through a floc blanket. Increasing energy dissipation rate in the flocculator could improve floc blanket performance (Hurst et al, 2010).

Upflow velocity is another important parameter affecting the floc blanket. Gould (1969) and Sung et al, (2005) identified upflow velocity as critical in determining floc blanket stability and performance using mass flux theory. The ability of particles to remain suspended in a floc blanket depends on the settling velocity of the flocculated particles counter-balanced by the upflow velocity (Gregory et al., 1996; Richard et al., 1997). At high upflow velocities a large portion of particles will be washed out making it difficult to establish a floc blanket, while at low upflow velocities, sedimentation can irreversibly change the nature of flocculated particles and the effectiveness of treatment (Arai et al., 2007). Optimal particle removal will be obtained at optimal upflow velocity. At higher than optimal velocities, the decreased hydraulic residence time in the floc blanket will result in poorer flocculation and filtration. At lower than optimal upflow velocities, channeling of the influent flow through the settled sludge will occur due to the settling of some particles (Hurst et al., 2010).

Ambient conditions such as temperature and wind also affect the stability of the floc blanket. Temperature variations in the uncovered clarifier tanks can occur due to meteorological conditions. Surface cooling in the winter season and influent of warm water to the tanks during the summer season is a common occurrence. Studies done by TeKippe and Cleasby (1968) using experimental investigations suggest a strong correlation between clarifier stability and temperature gradients in the tank.

McCorquodale (1993) observed that a density difference between the incoming and ambient mixture emerges from differences in temperature. Lau (1994) mentioned that temperature has a significant influence on the settling of cohesive sediments. Ekama et al. (1997) compared various energy inputs and showed that surface cooling and wind can be dominant factors affecting the overall hydrodynamics in secondary settling tanks. According to a study done by Wells and LaLiberte (1998), it is found that the degree of non-uniformity in a floc blanket is a complex function of inflow conditions (temperature, suspended solids, flow rate, tank geometry, and inlet baffle design) and meteorological conditions. Taebi-Harandy and Schroeder (2000) also reported the formation of temperature-driven currents in a clarifier.

1.4.2 Research Gaps

Different types of floc blanket clarifiers can be seen in many Sri Lankan water treatment plants; Ambatale, both new and old plants, Kandy South plant, Kantale plant and Kalutara plant of NWSDB and Getembe plant of Kandy Municipal Council (KMC) are few examples. Some of these plants are as old as forty years (KMC plant), whereas some others are constructed utilising latest developments of solid contact clarification process (Ambatale new plant and Kandy South plant).

Most important operational parameter in operating these plants is selecting the appropriate type and dose of coagulant. In Sri Lanka the widely used coagulants are Alum and Poly Aluminum Chloride (PACl). Due to pre-hydrolyzed elements present in PACl, it can be used in a wider pH range (5-8) compared with Alum (6-7) Bratby, 2016)

The optimum coagulant dose is the lowest (least cost) dose which will produce a readily settleable floc to remove turbidity efficiently in a reasonably short time, remove excess color from the water, and have suitable filterability properties. Standard laboratory flocculation test (Jar test), which simulates field operation, is used to find the appropriate coagulant dose when operating the clarifiers. The optimum pH, most suitable coagulants as well as optimum dosages to be used for particular raw water is established using Jar tester. The tests carried out at the temperature at which the full-scale treatment works operate, supposed to visualize the flocculation and its effects; time of formation, floc size, settleability, and, perhaps, filtration characteristics, in addition to determining the optimum coagulant dose.

Various parameters in existence in the raw water will have a contribution towards selection of type and dosage of coagulants to be used. Turbidity, because of its relationship with the colloidal particles or suspended material that affect the degree of transparency of the water; pH, since each coagulant has an optimal range of pH within which the action turns out to be more efficient; alkalinity, because if the water has a high degree of alkalinity the reaction of coagulant gets affected; Color, because of the contribution of color made by the colloidal particles; water conductivity, as an indirect measurement of ions or dissolved solids present in the water and temperature, since the lower the temperature the longer it takes for flocculation of particles to occur are some of these parameters (Wu and Lo, 2010).

However the raw water characteristics change continuously, affecting the effectiveness of this process. Each turbidity value may need a different coagulant dose. Therefore the flocculation tests are not sufficient to transpose the results to a full-scale level where a continuous change of raw water quality occurs due to seasonal as well as diurnal changes (Degremont, 2007).

Even though the output water quality of the clarifier units are within the permissible levels, whether the coagulant dose used is the most efficient and cost-effective dose in an upflow floc blanket clarifier is not clear. Therefore applicability of Jar test procedure to find the optimum coagulant dose in upflow solid contact clarifiers shall be further investigated in this study.

Temperature and wind are two ambient conditions which are identified as having an effect on the settling characteristics of a clarifier. A number of qualitative, quantitative and experimental research works were carried out on laboratory scale as well as on full-scale treatment plants to discusses the effect of temperature variations in a floc blanket.

Temperature differences will occur due to climatic conditions; top layers of the tank getting cooler during winter and due to difference in inflow temperature and tank contents; the inflow of warmer water into the tank. The outcome of the studies elucidates a number of reasons for the changes observed in the sludge blanket with temperature change; formation of temperature induced density currents between upper and lower layers making particles to be in suspension, influence on floc formation and breakage, decreasing of hydroxyl iron concentration leading to slower particle destabilization are some of the identified causes. It is concluded that temperature differences between the upper and lower layers of the tank will affect the quality of effluent. It is found that even a difference of 1 ^{o}C can cause considerable variation in effluent turbidity. (Ekma et al., 1997; Goula et al., 2008; Lau, 1994; McCorquodale and Zhou, 1993; Richard et al., 1997; TeKippe and Cleasby, 1968; Wells and LaLiberte, 1998)

Even though the outcome of the mathematical models as well as the experimental studies elucidate a number of reasons for the changes observed in the floc blanket with temperature variation, the influence of temperature changes for particle settling in a sludge blanket of a water treatment plant which is susceptible to changes in temperature is not clearly understood.

Plant operators in both the old and new plants have reported sudden disturbances in the floc blankets during some hours of the day. The sludge blanket disturbance is more frequently observed on sunny days with high ambient temperature. When considering diurnal temperature variation, it can be seen that the particles are moving upward and entering the clear water zone between 10 am to 3 pm. Also thinning of upper layers of sludge blanket is observed during this time. The blanket is gradually resettled in the evening.

Particle structuring within a floc blanket and settling velocity are major factors which can be used to interpret the blanket behavior and the effluent quality. The process of flocculation involves both floc growth and floc break-up. The floc properties such as size, shape, density and structural strength define the quality of floc. Settling of particles in the blanket depends on the quality of floc formation. There is a range of floc sizes in the floc blanket under an equilibrium condition. The floc size and shape, as well as the floc concentration, density, viscosity and Reynolds number (Re) of a floc blanket, varies depending on the raw water characteristics, the characteristics and the dosages of the coagulant and other chemicals used and the ambient conditions (e.g., temperature and wind) (Gregory, 1979). These parameters are subject to seasonal and diurnal variations.

Various theories have been proposed for the particle structuring mechanisms within the blanket (Bhatty, 1986; Ham and Homsy, 1988; Gudipaty et al., 2011; Lee et al., 2015; Zaidi et al., 2015; Cocco et al., 2017). Blanket settling depends on the characteristics of the particle and the fluid medium (Davies, 1968; Gould, 1974; Concha and Almendra, 1979a, 1979b; Lee, 1989). Several empirical methods have been developed to determine the blanket settling velocity. (Steinour, 1944; Richardson and Zaki, 1954; Concha and Almendra, 1979a, 1979b).

However, it is not possible to interpret the blanket settling velocity (V_s) and particle settling mechanisms of a floc blanket in an operational context using the available mathematical or empirical models.

1.3 Objective of the research

NWSDB is using fluidized bed upflow clarification in many of its treatment plants. However currently forming and maintining of a floc blanket in a clarifier is solely based on knowledge and experience of plant operators.

Taking in to consideration the uncertaininties faced by the plant operators when operating the fluidized bed clarifiers and the research gaps, the objective of this study was to comprehend the formation of a floc blanket in an upflow clarifier. Mechanisms of blanket formation were established using which the response of the blanket to varying raw water quality, operating conditions, and ambient conditions were explained. Recommendations were formulated for improved plant operations.

The study was carried out in three steps;

Step 1: Effect of raw water quality on floc blanket formation. Effect of raw water turbidity on the floc blanket formation will be studied and recommendations will be made for establishment of optimum conditions.

Step 2: Effect of operating conditions on the floc blanket. Effect of coagulant dose on the floc blanket will be analysed and recommendations will be made on the optimum coagulant dose to be used.

Step 3: Effect of ambient conditions on the formation and operation of floc blanket. Effect of inflow temperature variations will be analysed and recommendations will be made for operating the clarifier during temperature variations.

Firstly, the study will aim at finding a suitable parameter to describe the clarifier sludge blanket characteristic. Using the parameter established, laboratory tests, field tests, and anlaysis will be made on the blanket behavior, particle settling mechanism using which, recommendations will be given for effective handling of a floc blanket clarifier.

CHAPTER 2: LITERATURE REVIEW

2.1 Raw water turbidity and coagulation

In order to produce quality effluent, the flow dynamics, as well as type and correct application of coagulants, is an important parameter for the design and operation of clarifiers (Yang et al., 2010). Different mechanisms are used to achieve particle removal in clarifiers. The clarifiers having a mixing zone and a clarification zone is one type. Particle contact and floc formation are achieved in the mixing zone, and flocculated particles are settled in the clarification zone. The mixing zone is designed with a conical shape, where the upward flow of raw water will have a decreasing mixing intensity (G) enabling hydraulic flocculation. In some other clarifiers, flocculation is achieved using mechanical mixing devices in the mixing zone.

Pulsators® is another type of clarifiers where the coagulated water in an inlet chamber is subjected to a periodic up and down motion (pulse) by the action of a vacuum pump. Water flows through a perforated pipe system out of the inlet chamber to the Pulsator® tank. A motion opposite to the inlet chamber occurs in the Pulsator® tank. A floc blanket is formed in the tank, which enables the required flocculation and solids contact. Suspended particles contained in the raw water are agglomerated in the sludge blanket (Binnie et al., 2002).

In all the clarifier types, the hydrodynamic treatment stage controls floc layer stability and coagulation, the chemistry-based treatment stage, controls the characteristics of the generated floc layer. The existence of a consistent floc blanket in clarifiers depends upon the upward flow and settling characteristics of particles and type and dosage of coagulants applied. The type and dose of coagulants to be used in clarifiers depend on the raw water quality and the ambient conditions. The optimum coagulant dose is the lowest (least cost) dose which will produce a readily settleable floc to remove turbidity efficiently in a reasonably short time, remove excess color from the water, and have suitable filterability properties. Thus finding the optimum coagulant dose is yet another important parameter in establishing the floc blanket especially at the initial blanket formation phase.

Studies have been done by Head et al. (1997) for developing a mathematical model for simulating the floc blanket, concluded that the concentration of the blanket rises and falls due to changes in throughput and the solids loading in the clarifier and the temperature.

For high turbidity water, some investigators have recommended that the majority of the turbidity should be removed in a pre-sedimentation tank with a suggested residence time of 90 minutes (Chen et al., 2003). For high turbidity source waters (200 NTU), Su et al. (2004) reported that treatment was feasible with the addition of a pre-sedimentation tank. In contrast, Sung et al. (2005) reported a stable floc blanket could be formed from 450 NTU source water without the need for a pre-sedimentation tank or two-stage clarifier. At very low turbidities (5 NTU) floc blankets have been reported to be easily washed out (Chen et al., 2003). Chen et al. (2002) observed stable floc blanket formation from raw waters with turbidity between 4 and 10 NTU in full-scale clarifiers, but during a low turbidity period (2–3 NTU), floc blankets gradually lost solids until no floc blanket remained.

When the influent turbidity is very low the formation of floc blanket will not be up to the requirements. El-Nahas (2009) experimentally demonstrated the possibility of turbidity removal enhancement by increasing the contact mass by adding a sludge dosage during the flocculation process. The attractive forces should prevail for colloids removal to form large flocs, while it should be minimized keeping each particle discreet during sludge hydro transport.

Commonly used coagulants are alum and poly aluminum chloride (PACl). Matsui et al. (1998) studying the coagulation kinetics of both the coagulants showed that the increase in alum dosage reduce the time required for particle destabilization and increase the rate at which the number of primary particles was destabilized. This happens due to increased collision attachment efficiency and increased particulate volume. The rate was faster with PACl than with alum. Hence it is concluded that PACl more effectively coagulates finer particles than alum.

Chen et al. (2003), by treating high-turbidity water using full-scale floc blanket clarifiers showed that given a step-change in coagulant (Polyaluminum Chloride, PACl) dosage the blankets in the clarifiers were easily washed out using the conventional coagulation-clarification process (the “single-stage process”), seriously threatening drinking water quality. Consequently, a pre-treatment stage was introduced. The performance of treating high-turbidity stormwater with the two-stage process achieved stable blanket, and good quality clarified water that was insensitive to variation in raw water turbidity or PACl dose. Pilot tests done to reveal the performance difference between single stage and two stage processes in dealing with high turbid water found that the blanket was easily washed out in single stage process when the coagulant dose was step reduced. Also, reestablishment of the blanket was very slow when the coagulant dose was increased to its original value. The blanket yielded by the two-stage process was more robust and recovered more easily when coagulant supply was increased. They concluded that applying the two-stage process to achieve the same effluent quality from the single-stage process could significantly reduce total PACl dosage.

The work carried out by Chen et al. (2006) on charge reversal effect on a blanket in full-scale floc blanket clarifier showed that, even when the raw water is sufficiently alkaline, the blanket responded anomalously to the increased coagulant dose of polyaluminum chloride (PACl). Rather than being stabilized, the blanket was destabilized by the high dose of PACl. This “anomalous” behavior of the blanket is explained to be caused by a temporary drop in local pH at the injection port at the bottom of the blanket, which is caused by poor PACl dispersion, and the subsequent charge reversal of the constituent particles and the decline in the blanket stability. It is mentioned that a step increase in PACl dose may result in complete blanket loss.

The response time and the optimal operating condition of the blanket that produces the lowest effluent turbidity corresponds to the optimal coagulant dose determined by the jar test. Hurst et al. (2010) studying the variables affecting the performance of a floc blanket using a laboratory scale reactor showed that depending on the raw water turbidity, an optimum coagulant (alum) dose can be found. For the range of doses tested in the experiment, they have shown that under-dosing of alum could decrease the size and the amount of flocculated particles entering the floc blanket, whereas overdosing showed little effect on the floc blanket performance.

The settling velocity of the coagulated flocs and the upward flow velocity control the stability of the blanket. Stringent operational control is required to prevent sludge carryover (Gregory et al., 1996; Head et al., 1997). Chen et al. (2003) have reported that when the changes in solid concentration, zeta potential, floc size and capillary suction time were monitored, a relatively stable blanket to the shock load in raw water turbidity was observed when the turbidity was high (> 100 NTU). When the raw water turbidity was low (< 10 NTU), the blanket was rather unstable. With varying raw water quality, appropriate coagulant dose shall be used to get the desired effluent quality. The researchers had reported complete washout when the PACl dose was insufficient.

The settling velocity of flocculated particles depends on the size and type of flocculent particles. The solid flux in a blanket has been defined as the settling velocity of particles x particle concentration. The solids flux depends on the coagulant used. Su et al. (2003) proposed that solids flux in the blanket contribute to the effluent quality. Using a simplified one-dimensional wave equation to model the dynamic characteristics of a floc blanket, the researches confirmed solids fraction would evolve along the characteristic velocity determined by the difference between upflow and downward solids fluxes.

Experiments with synthetic raw water using poly aluminum chloride (PACl) as coagulant confirmed the model predictions that the blanket would first converge to a uniform distribution at a lower solids concentration, then it would compact itself to a new, uniform distribution at a higher solids fraction. The minimum effluent turbidity is found to be obtained at the optimal coagulant dose.

Accordingly, a good control of coagulants in the clarifier is essential. The control of coagulants in a clarifier unit is based on an analysis of raw water, treated water, jar test results and condition of the sludge blanket (Pulsator®). (Degremont, 2007).

Previous studies have shown the importance of finding the appropriate coagulant dose to operate a clarifier. As explained above, the laboratory flocculation test; Jar test is the most commonly used method to find the optimum coagulant dose to be used, be it plain sedimentation, clarifiers with hydraulic mixing or clarifiers with mechanical mixing or Pulsators®. However, the flocculation tests are not sufficient to transpose the results to a full-scale level where continuous changes to raw water quality occur due to seasonal as well as diurnal changes.

2.2 Formation of particle structures within the blanket and settling velocity

Gravitational settling is commonly used to separate particles in an aqueous suspension. The settling velocity of particles is affected by the concentration of suspension. Singular particles or particles in very low-concentration suspensions settle freely through a fluid unaffected by hydrodynamic influences of other particles. Hindered settling occurs when the settling rate of a particle in the liquid suspension is affected by the presence of particles nearby (Allen and Baudet, 1977). The transition from free settling to hindered settling occurs as the concentration of solids in the suspension increases. In hindered settling, the distance between particles reduces sufficiently such that the drag force created by the settling particles will affect the movement of nearby particles (Oliver, 1961; Mirza and Richardson, 1977). However, if the concentration of solids in the suspension is too high, entrapment and misplacement of particles will dominate, thereby increasing en-masse settling, which is independent of particle size and density (Davies, 1968). At the onset of hindered settling particles in a suspension will settle at a constant rate irrespective of their individual sizes.

Particle clustering within a floc blanket was studied in detail to understand the blanket settling. Factors affecting the growth of clusters are found to be flow rate and suspension concentration (measured by void ratio). The growth rate of clusters is increasing with increasing flow rate and decreases with decreasing void fraction. The decrease of the particle void fraction by a factor of 10, leads to reduce the cluster area by a factor of 2.

Gudipaty et al. (2011) studying the formation and growth of clusters in a dilute suspension suggested that cluster formation/ growth is possibly due to one or all of the following mechanisms;

1. Particle-particle interactions
2. Particle-cluster interactions
3. Cluster-cluster interactions

A uniformly diffused return flow of fluid occurs through the evenly dispersed cloud of particles. Cluster growth initially proceeds through the recruitment of individual particles (particle-particle interactions). Small particles having higher specific surfaces have a higher degree of clustering. The cluster formation with a pair of particles is the most prominent clustering mechanism, especially when the particle diameter is bigger. These clusters are more stable. Smaller particles will make clusters with ~2–7 particles in a cluster. In clusters with fewer particles, the stability is higher (Bhatty, 1986).

Particle-cluster interactions are the dominant growth mechanism at the early stages of the cluster growth. The growth rate of the particle during this period is almost linear with time. After some time, cluster-cluster interactions such as cluster collision and merging become prevalent, and the growth rate becomes non-linear. Aggregation of clusters was observed for particle void fractions (volume of suspended particles/total suspension volume = *SV*) as low as 0.001 (Bhatty, 1986).

Clustering is assumed to be due to inelastic deformation or cohesion where bonds formed between particles by short-ranged cohesive forces, including Van der Waals forces or capillary forces. Turbocharging of particles generates large amounts of net negative or positive charges on individual particles resulting in long-range electrostatic forces. In turbocharging larger particles will be positively charged, whereas smaller particles will be negatively charged. Lee et al. (2015) showed initiation of clustering due to the aggregation of these charged particles via multiple bounces. Clusters can form by the collision of two particles or collision of a single particle with a cluster. Translational kinetic energy will be lost when two particles collide. However, the amount of energy lost will be less (High Coefficient of restitution ~ 1). When single particles collide with clusters of particles the coefficient of restitution is significantly less than unity probably due to the dissipation of energy via intra-cluster rearrangements. Three possible outcomes are identified in particle cluster collisions. Capture; the particle is embraced and stick with the cluster, Escape; particles bounces and leave the cluster, and fragmentation; One or more particles in the cluster disengaged from the cluster due to the collision. The clustering due to long-ranged electrostatic forces can occur at velocities much higher than needed for sticking at a head-on collision.

Two modes of cluster-cluster interactions are identified; constructive and destructive. Constructive mode is merging of nearby clusters when the gap between them is filled by independent growth of each cluster. When the hydrodynamic force overcomes, the adhesion force cluster will be dislodged and carried away in the destructive mode. The degree of turbulence in a fluid medium is estimated using the Reynolds Number; *Re*. The clusters are more stable, and laminar flow is considered to occur with *Re* up to 0.6. When *Re* > 0.6 more destruction of clusters is expected due to turbulent flow conditions. However,, the clusters yet survived/ appearing in this region, in a suspension forms due to inter-particle forces which are strong enough to resist the moments applied to them by turbulent flow Kaye and Boradman (1962).

Particle clustering appears to be a two-step process; short-ranged attraction by cohesive forces and long ranged attraction between oppositely charged particles. The first step will be an aggregation of particles surrounding a highly charged particle by long-ranged electrostatic interactions, where particles become charged by transfer of electrons or ions during contact. Secondly, particles will then cluster due to the short-ranged cohesive forces. The cohesion was proposed to be due to van der Waals forces or capillary type interactions from molecularly thin layers of water absorbed on the particle surface (Cocco et al., 2017).

Floc size and structure is found to be strongly dependent on how the shear rate (G) is varied during flocculation before reaching a steady state (He et al., 2012). The higher the shear rate in a flocculation process, the growth in floc size is faster due to increased rate of floc aggregation with increasing energy dissipation. At low shear rates (3-7 s^{-1}), flocs formed with open and porous structures permits great quantities of flow through them, and attain high settling velocities. The increase in floc size is proportion to the shear rate. But further growth of floc size is limited by low particle collision rates. At high shear rates (11–16 s^{-1}), significant floc breakage and reformation occurs. The study describing the development of floc size and structure in low shear flow using a fractal growth model concluded that fragmentation followed by reformation is more effective in forming larger and more compact aggregates than the restructuring process due to erosion and reformation.

Study on the temporal evolution of floc size and structure during flocculation showed that floc generation is fractal; self-similar and scale invariant. As per Monroe et al. (2010) fractal geometry explains the changes in floc density and sedimentation velocity as a function of floc size. Fractal dimension is a function of the size ratio of the colliding flocs. Based on floc measurements, the fractal dimension of flocs is found to be approximately 2.3. The relative velocity between flocs is set by viscous shear because their separation distance is less than the inner viscous scale. The time required per collision is a function of the relative velocity between flocs, the average separation distance between flocs, and the floc size. Tangent and rotational velocities cause shear and unzipping of bonds between particles of different sizes. Tangent velocity is proportional to the sum of the diameters of the particles. Flocs reach a terminal size based on a balance of the adhesive force of the bonds and the shear force that tends to tear them apart. Once a floc has reached its terminal size any further collisions are unsuccessful. Very few small particles get close enough to a big floc to collide. Viscosity is shown to be significant for the early stage of flocculation, and turbulent eddies are shown to be significant for the final stage of flocculation.

Settling velocity of particles is a governing factor for efficient removal of suspended particles in a water treatment process. The particle structuring within the blanket and cluster formation will govern the particle settling within the blanket as well as blanket settling velocity.

Particle settling within a sludge blanket is described by Zaidi et al, (2015) using direct numerical simulation. In fluidized beds with low sludge volume fraction (SV) ≤ 0.2, increase in Re adversely affects particle clustering. It is observed that in dilute suspensions and a moderate range of Re ($Re > 0.1$), average settling velocity deviates from the (Richardson and Zaki, 1954) equation. With high SV (> 0.3), the effect of Re is found to be negligible.

These behaviors are explained to be due to inter-particle wake interactions. At high Re due to reduced drag created by the wake of the leading particle, the downstream particle will move faster. The above authors named it as the 'Drafting' mechanism. Drafting (D) will occur until it touched the leading particle and was called 'Kissing' (K). Once the two particles are contacted they will become horizontally separated due to unbalance and 'Tumbling' (T) will occur. Hence D, K, and T have a large effect on particle settling. They concluded that for liquid-solid suspensions of $\mathrm{Re} \leq 0.2$, no D, K or T is perceived; for suspensions of $0.2 \leq \mathrm{Re} \leq 1$ only D and K are observed; whereas when $\mathrm{Re} > 1$, frequent D, K and T occur. In a sludge blanket, hydrodynamic interactions between particles are the principal forces due to which particles develop structures that affect settling characteristics.

Study of cluster formation during sedimentation of dilute suspensions by Bhatty (1986), established Stokes' Law is applicable for solid concentrations below 0.83%. Up to a solid concentration of 4.5% and an average distance between particles equivalent to 2.2 particle diameter, the settling velocity of clusters will be 1.58 times the settling velocity obtained from Stokes' Law. At this range, flocculent settling will occur. Particle clusters 3 or 4 particles which have some associated immobile fluid incorporated in them is found to be falling unaffected by the presence of other particles. Beyond this hindered settling will occur. Experiments under this study show the volume concentration of the particular blanket to be around ~41% at the onset of hindered settling.

Also, particles in a cluster carry a layer of immobile liquid around it. A large cluster with a great interstitial area will carry more liquid. The settling velocity of these clusters can be obtained using Stokes law, using the radius and density corresponding to the cluster surrounded by a sphere and applying Stokes' Law. For well-developed hindered settling, the liquid volume fraction of suspension is reported to be 0.90 (Kaye and Boradman, 1962).

Smaller clusters will break into individual particles whereas larger clusters break into sub-clusters. Larger clusters will break due to its high settling velocity and turbulence during settling (Bhatty, 1986),

The average velocity of hindered settling is a function of particle concentration, and hydrodynamic dispersion occurs in a quiescent sedimenting suspension with a particle concentration of 2.5 - 10% under creeping flow and in the absence of Brownian motion. In addition, the hydrodynamic dispersion of suspended particles is found to be the result of viscous interactions between the particles (Ham and Homsy, 1988).

Most notable works on hindered settling include the studies by Steinour (1944) and Richardson and Zaki (1954). The equation developed by Steinour (1944) proposed a relationship between effective fluid density and viscosity, which was used to calculate the hindered settling velocity by applying an empirical factor to the free settling velocity. This equation was fitted only within a range when the Reynolds Number (*Re*) was less than 0.00025.

Richardson and Zaki (1954) described a method for calculating the sedimentation velocity (blanket settling velocity or fluidization velocity in a liquid-solid system) as a function of the free-falling velocity of a single particle and the concentration of particles based on the Reynolds Number of the solution. (Ref. Section 2.5)

Concha and Almendra (1979a, 1979b) derived an equation for the free-settling velocity of an individual spherical particle that relates solid volume concentration and hindered-settling for low (Re → 0) and high (Re → ∞) Re. The hindered-settling equation developed by Lee (1989) has been found to be valid for all flow regions (laminar, intermediate and turbulent) covering any value of Re. However, according to Zimmels (1985), it could not be verified to interpret hindered settling of multi-density, multi-particle size distributions.

Knowledge and understanding of particle settling mechanisms and sedimentation velocity (V_s) in a floc blanket are important to design and operate sludge blanket clarifiers used in water treatment. The available mathematical models for computation of sedimentation velocity of a floc blanket, as explained above are based on Reynolds number, terminal settling velocity of particles, particle concentration and a number of other parameters such as fluid density, viscosity, etc. The particle size and shape and the Re of a particular sludge blanket depending on the raw water characteristics, the characteristics and dosages of coagulant and other chemicals used as well as the ambient conditions (e.g., temperature and wind). All these parameters are subject to seasonal and diurnal variations. Thus, using the available mathematical or empirical models to interpret the Vs and particle settling mechanisms of a sludge blanket to an operational context is impracticable.

2.3 Effect of Temperature variation

Temperature variations in the water in uncovered clarifier tanks occur due to changes in ambient meteorological conditions. Disturbance to the sludge blanket of uncovered clarifiers is observed when the ambient temperature is high. The temperature has a significant influence on the settling of cohesive sediments (Lau, 1994). Surface cooling in the winter season and influent of warm water to the tanks during the summer season is a common occurrence. Surface cooling and the wind could be dominant factors affecting the overall hydrodynamics in secondary settling tanks (Ekama et al., 1997). Studies done by TeKippe and Cleasby (1968) in midnineties using experimental investigations suggest a strong correlation between clarifier stability and temperature gradients in the tank.

Richard et al. (1997) aimed at developing a mathematical model for simulating the sludge blanket, concluded that the concentration of the blanket rises and falls due to changes in throughput and the solids loading in the clarifier and the temperature. The model predicted, when the temperature is low in winter, the blanket can easily be washed out at upward velocities which produced good quality treated water in summer.

The studies done thereafter on the effect of temperature variations found that a vertical convective current originates within the clarifiers due to the difference in temperature between the upper layers and the bottom layers of a floc blanket. This difference takes place when the surface layers get cool/ warm due to environmental conditions when the temperature of inflow water is significantly different from the temperature inside the tanks etc. A density difference will occur by the change of viscosity of water due to the change in temperature. Vertical convective currents will be generated due to this density difference, which will, in turn, affect the stability of the blanket leading to higher solids concentration in the effluent.

Wells and LaLiberte (1998) performing a field study on three uncovered circular tanks subject to significant winter cooling, during periods of low flow observed temperature induced vertical convective currents in the tanks due to surface cooling. Temperature differences of the only 1^{o}C between surface and bottom were sufficient to induce a density current with vertical velocities of about 2 orders of magnitude greater than tank overflow rates. These density currents had the potential to keep the particles in suspension and hinder the settling of suspended solids. When the temperature decreases, the rate of settling becomes slower.

McCorquodale and Zhou (1993) observed that a density difference between the incoming and ambient mixture emerges from differences in the temperature. The depth of the temperature driven currents was inversely related to the difference between temperatures of the influent and the tank contents Taebi-Harandy and Schroeder (2000) also reported the formation of temperature-driven currents in a clarifier. Temperature differences as low as 0.2 ^{o}C was sufficient to induce density currents. The depth of the temperature driven currents was inversely related to the difference between temperatures of the influent and tank contents. Moreover, the formation of this temperature driven current was independent of the amount of suspended solids in the entering suspension, and the current type, surface or bottom, was dependent on whether the influent was warmer or cooler than the tank.

By evaluating water mixing characteristics of storage tanks in a distribution system, Mahmood et al. (2005) also confirmed that differences in temperature between the bulk tank water and the inflow significantly affect the mixing characteristics and may result in density gradients inside the tank that cause stratification and poor mixing.

Goula et al. (2008) used CFD modelling with particle conservation equations for each particle size class to understand the effect of a change in temperature to the efficiency of solid removal in a clarifier of a potable water treatment plant. The model is adjusted using the observations made at a full-scale treatment plant. The study reconfirmed the findings of Wells and LaLiberte (1998). A temperature difference of only 1^{o}C between influent and tank content was found to be sufficient to induce density currents and produce a considerable variation in the effluent turbidity comparable to the diurnal temperature variation. When the influent temperature rises, the tank exhibited a rising buoyant plume that changes the direction of the main circular current. This process kept the particles in suspension and led to a higher effluent suspended solids concentration, thus, worse settling. Non-uniform distribution of solids and short-circuiting through tank resulted in a reduction of detention time and solid removal efficiency of the tank.

As the warmer water kept coming in, the temperature difference decreased, and the current started going back to its original position, thus, decreasing the suspended solids concentration. It was noted that increased effluent turbidity is associated with large positive slopes (with time) of the influent temperature. On the contrary, constant temperature (zero slopes) or negative temperature slopes seem to lead to rather constant turbidity.

Winkler et al. (2012) reported that smaller and lighter granules settled slower than bigger and denser granules in a secondary clarifier of a wastewater treatment plant. Results of their study revealed a two-fold difference in settling velocity for the same granule at 5 ^{o}C and 40 ^{o}C. Further, the study showed that ionic strength dependent density and viscosity changes of water have great impact on settling velocity of granular sludge. They suggested that the corresponding slow settling of small granules at decreased water viscosities and increased water densities as caused by a lower temperature can be an important reason for the reported troublesome start-up of granular sludge reactors.

Laboratory experiments done by Fitzpatrick et al. (2004) to assess the effect of temperature on floc formation, breakage, and reformation, found that floc formation is slower at lower temperatures for all coagulants. Increasing the shear rate results in floc breakage in all cases and the flocs never reform to their original size. This effect is most notable for temperatures around 15°C. Breakage, in terms of floc size reduction, is greater at higher temperatures, suggesting a weaker floc. Recovery after increased shear is greater at lower temperatures implying that floc break-up is more reversible for lower temperatures.

Joudah (2014), in his studies “Effect of Temperature on Floc Formation Process Efficiency and Subsequent Removal in Sedimentation Process”, found that the rate of particle destabilization, reduction of destabilized primary particles and agglomeration varied with mixing intensity and temperature. At constant pH, the hydroxyl ion concentration decreased with lowering of temperature leading to slower particle destabilization rates. A constant G value which will offset the increasing viscosity resulting from cold water will maintain constant flocculation rate.

Further, he showed that increased shear stress of the floc particles due to higher water viscosity at low temperature leads to prolonged flocculation time. This will impair the floc strength and virtually floc formation efficiency. Prolonged flocculation would break the big formed flocs into smaller ones.

The results also showed that the effect of temperature on the best flocculation time required for efficient sedimentation became less when temperature increased and reached 25 ^{o}C. Little difference in flocculation times was observed at a temperature range from 10 to 25 ^{o}C, while much higher differences were observed at temperatures less than 10 ^{o}C. However, PACl was less sensitive to reduction of hydroxyl ion concentration and performs better than alum in cold water.

The outcome of the mathematical models as well as the experimental studies elucidates a number of reasons for the changes observed in the floc blanket with temperature variation. However, the influence of temperature changes for particle settling in a sludge blanket of a water treatment plant which is susceptible to changes in temperature is not clearly understood.

2.4 Sludge Cohesion Coefficient

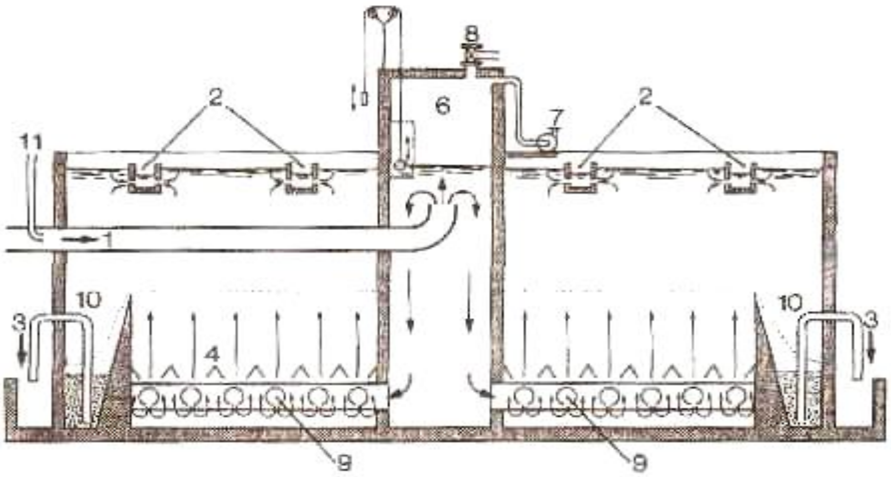
Pulsator® technology, where the sludge blanket is formed by an inlet of water through pulsation created using a vacuum chamber is used all over the world, with the first patent having been registered in 1954 (Figure 2.1). Pulsator® has extremely efficient functioning, whatever be the source or temperature of water. In a pulsed sludge blanket clarifier, coagulation and flocculation are carried out simultaneously.

The sludge formed during flocculation is made up of an expansion mass. Water, that has coagulated beforehand, arrives from the bottom of the device and flows through this sludge blanket to emerge clarified at the top of the settling tank. The sludge bed is kept in expansion with the help of pulsating operation created using vacuuming. The inflow pipe is located in a chamber. The air in the chamber is de-pressurized by pumping out the air that it contains, resulting in a gradual rise in inlet water level until a height of 0.6 to 1 m above the water level in the Pulsator® tank is reached. During this phase, the sludge bed settles down with the effect of gravity.

When the high level is reached in the air chamber, at flushing, decompression the vacuum-breaking valve opens; the water then flows at great speed through the manifolds into the Pulsator® tank creating a flushing effect. The sludge bed is decompressed. The excess sludge (water impurities and reagents) flows into the concentrators at the top level of the sludge blanket where it is extracted at regular intervals (Degremont 2007).

Optimized with laminar modules on the upper part and/or plates in the sludge bed, in the Pulsatube® TM and Ultra-pulsator versions, the Pulsator® clarifier can double its operating speeds and adapt itself to water at extremely cold temperatures. Also, it optimizes the contact of powdered activated carbon to eliminate pesticides and organic matter more effectively due to the sludge bed functioning.

Degremont (2007) recommends three tests for producing and maintaining a floc blanket in a Pulsator® unit. Laboratory jar tests are conducted at first to determine the optimum coagulant dose. Secondly a settling column test will be carried out using sludge samples drawn from the top and bottom of the sludge blanket, which will give settling velocities of the particles, based on which regulation of pulse can be made.



1.Raw water inlet
2.Clarified water outlet
3.Sludge discharge
4.Stilling plates
6.Vacuum chamber
7.Vacuum pump
8. Automatic vacuum-breaker
9. Raw water perforated distribution piping
10. Sludge concentrator
11. Reagent inlet

Figure 2.1 *- Schematic Pulsator Clarifier*
Source: http://www.thewatertreatments.com/

Thirdly it is recommended to carry out sludge cohesion test which will indicate the blanket condition and serves as a check for optimum coagulant and polyelectrolyte doses and pulse operation.

The cohesion has been defined as a parameter which characterizes the sludge blanket. A sludge layer submitted to upward water current expands and occupies an apparent volume roughly proportional to the upward velocity of the water entering the blanket, according to a ratio that characterizes the cohesion of the sludge blanket**.** The Sludge Cohesion Coefficient (*SCC*) is an indicator of blanket condition and serves as a check for optimum coagulant dose.

The curve representing the variation in velocity according to the volume of expanding sludge is a straight line (Figure 2.2):

$$u = SCC\left(\frac{V}{V0} - 1\right) \qquad \text{--- 2.1}$$

u: upward velocity in the cylinder necessary to obtain volume *V*

V: apparent volume of sludge in the expansion

V_0: volume of settled sludge corresponding to a zero velocity

SCC (K): sludge cohesion coefficient

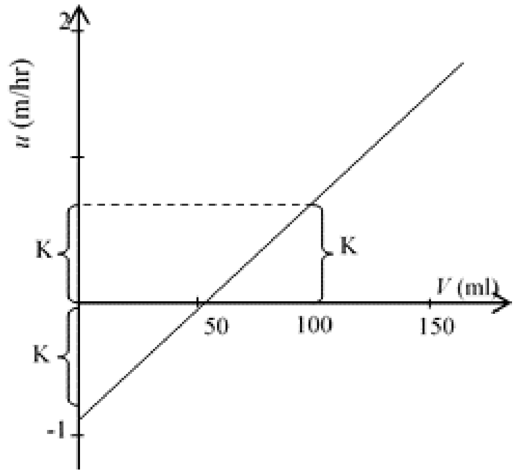


***Figure 2.2** - Sludge cohesion coefficient*

The coefficient is the characteristic of the cohesion of the sludge and is known as the "Sludge Cohesion Coefficient." It depends on the temperature. For quickly settled consistent sludge, the value of *SCC* can reach 0.8 to 1.2. For sludge composed of a flocculate that is fragile, light and rich in water, value of the *SCC* might not exceed 0.3. Measuring *SCC* will enable to learn the behavior of precipitates in a solids contact clarifier and to determine the influence of flocculent aids. (Degremont, 2007)

For optimum Pulsator® operation a figure within the range 0.8 to 1.0 is desirable (Harper and Bullock, 1981).

Above literature suggests that the performance of the solids contact clarifier depends on the cohesivity of the sludge blanket through which the majority of the suspended particle removal takes place.

As the *SCC* is a parameter that can be conveniently measured, evaluating the relationships between *SCC*, V_s, and particle settling mechanisms can enable water treatment plant operators to understand the operational conditions of the floc blanket (Illangasinghe et al., 2016).

Efficiency of a floc blanket clarifier depends on the ability of the blanket to respond to the varying raw water quality, ambient conditions and operational parameters. Even though the current research work based on several numerical models as well as experimental studies elucidate number of reasons for the changes observed in the floc blanket and propose design, operation and maintenance techniques, development of criteria for forming and maintaining a sludge blanket in an upflow clarifier is yet to be developed.

2.5 Fluidization Theory

When a cloud of solid particles is settling in a quiescent liquid, additional hindering effects influence its settling velocity. These are the increased drag caused by the proximity of particles within the cloud and the upflow of liquid as it is displaced by the descending particles. The hindering effects are strongly dependent on the volumetric concentration of solids in the cloud, SV. The relationship between particle settling velocity and the sludge volume is established by Richardson & Zaki, 1954;.

$$V_s = V_t(1 - SV)^m \qquad \text{--- } 2.2$$

Where V_s is the hindered settling velocity of solid particle, V_t is the terminal settling velocity, m - empirical exponent related to the particle, SV – solid volume fraction of the blanket and Re_p the Reynolds number.

Table 1.1: Values for the Richarson-Zaki index m :

Reynolds No. $(\frac{V_t d}{V_f})$	m	
$Re_p \leq 0.2$	4.6	Stoke's law region
$Re_p < 0.2 < 1$	$4.4Re_p^{-0.03}$	Stoke's law region
$1 < Re_p < 500$	$4.4Re_p^{-0.1}$	Intermediate region
$500 \leq Re_p$	2.4	Newton's law region

Theoretically, the validity of the Richardson & Zaki equation is limited by the maximum solids concentration that permits solids particle settling in a particulate cloud. This maximum concentration corresponds with the concentration in an incipient fluidized bed (C_v of about 0.57). Practically, the equation was experimentally verified for concentrations not far above 0.30.

Studies done by Zaidi et al, with suspension of Reynolds number in the range of 0.1-50 and solid volume fraction in the range from single sphere to 0.4 observed that the average settling velocity of particles deviate from R&Z relation for dilute suspension and higher range of Reynolds number.

CHAPTER 3: MATERIALS AND METHODS

3.0 Sampling locations

Raw water extracted from the Mahaweli River or synthetic raw water was used to prepare sludge samples for laboratory testing. Water samples were collected form three water intake locations belong to NWSDB (Figure 3.1). All three intakes were located downstream of Kotmale Dam. The intake of Gampola Water Supply Scheme is situated in Atabage Oya, which is a tributary to Mahaweli River. The intake of Kandy South Water Supply scheme at Meewatura and intake of Katugastota Water Supply scheme at Katugastota are extracting water directly from the Mahaweli River.

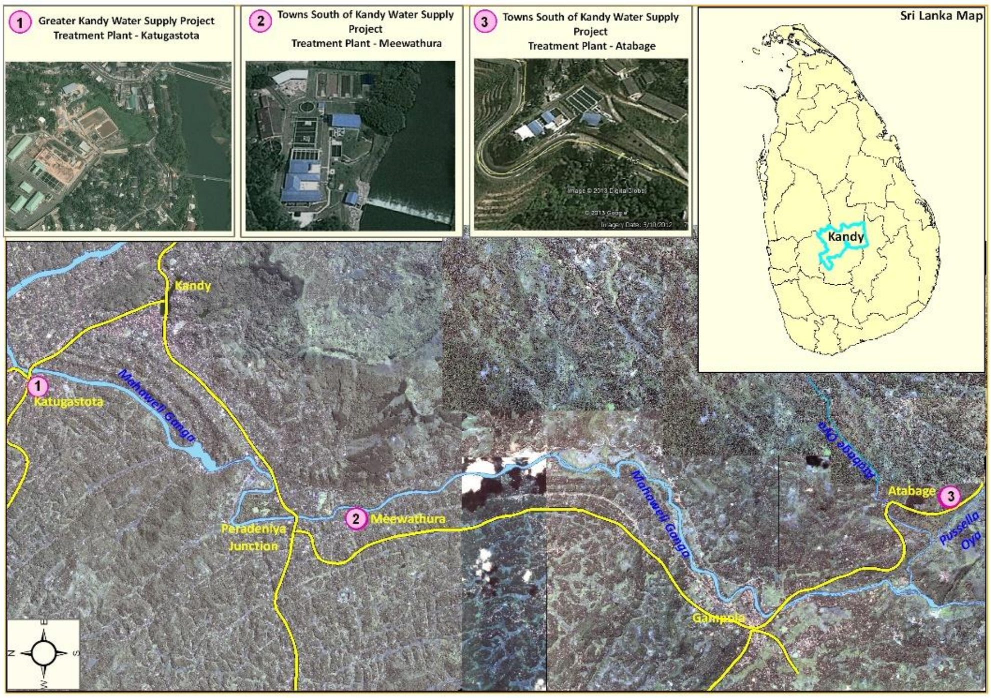


Figure 3.1 - Raw water extraction locations; Mahaweli River

3.0.1 Characteristics of raw water – Mahaweli River at Meewatura intake

The seasonal variation of raw water quality due to climate change, other environmental factors and activities in the watershed was established using data from Meewatura intake. The daily average, maximum and minimum raw water turbidity values during 2010 April 20th to 2011 April 10th were plotted in Figure 3.2. Figure 3.3 shows the variation of pH within the same period.

The daily average turbidity was changing in the range 10–500 NTU throughout the year due to seasonal environmental changes and other activities in the watershed. Raw water turbidity as high as 908 NTU also has been recorded. However, this was not a typical value for the rivers in the Kandy district. The pH of the raw water varied within the range 6.6-7.5 with an average of 6.6.

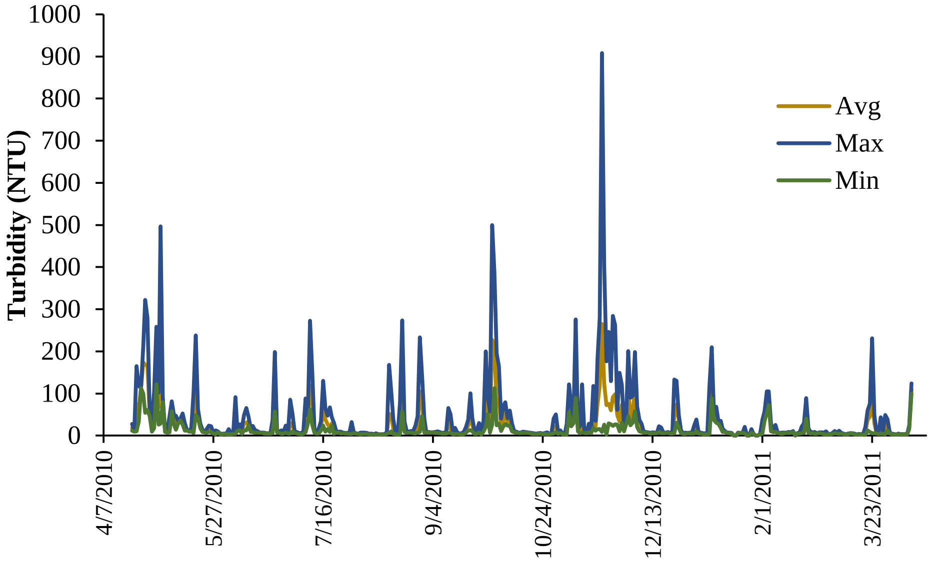


Figure 3.2 - Variation of raw water turbidity at Meewatura intake, Mahaweli River (April 2010 to April 2011)

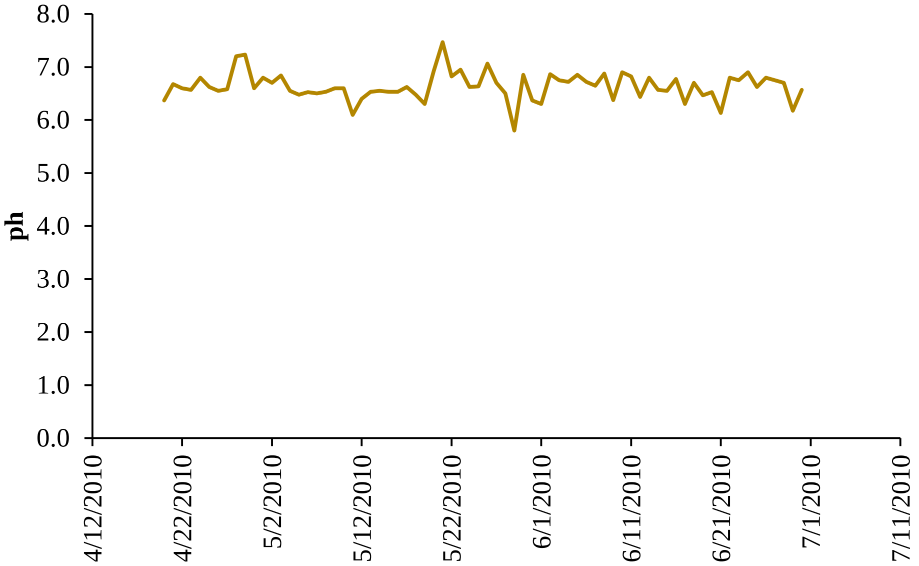


Figure 3.3 - Variation of pH at Meewatura intake, Mahaweli River (April 2010 to June 2011*)*

The Kandy South water treatment plant uses upward flow floc blanket clarification. Two Pulsator® (Degrémont) units with a capacity of 16,000 m^3 each, operate as the clarifier unit. In addition to the sludge samples prepared at the laboratory using river water, sludge samples extracted directly from the sludge blanket of Pulsator® unit at Kandy South Water Supply Scheme also were used for laboratory testing. Field testings were carried out at the Pulsator® unit of Kandy South Water Supply Scheme.

3.1 Sample preparation

3.1.1 Preparation of synthetic raw water

Stock solution for the synthetic raw water sample was prepared by adding 10 g of commercially available Bentonite clay powder into 1 L of tap water. The suspension was well stirred in order to ensure uniform mixing of Bentonite particles. The solution was left for 24 hours to allow complete hydration of particles. The synthetic turbid stock solution was diluted immediately with tap water to get the desired raw water turbidity values which were decided based on the River water turbidity variation observed in section 3.0.1, Figure 3.2.

3.1.2 Preparation of sludge samples

The raw water extracted from the river or synthetic raw water prepared at the laboratory was subjected to the laboratory flocculation test (Jar Test). Jar test is conducted with initial rapid mixing at 150 rpm for 2 minutes followed by slow mixing at 30 rpm for 20 minutes. The samples were then allowed to settle for 20 minutes after which the sludge at the bottom of the beaker and the supernatant were carefully separated.

3.1.3 Equipment

Jar tester, turbidity meter, pH meter and temperature meter are the main equipment used in the laboratory and field testing. The relevant specifications are given below;

1. Armfield W1MkII **Flocculation test unit** (Jar Tester), 0-200 rpm, 6 numbers 1l beakers
2. HACH **turbidity meter** 2100Q01, range 0-100 NTU, accuracy ±2%
3. HACH Sension+PH3 **pH meter**, range -1 – 16 pH, accuracy 0.02 pH, T**emperature** range -20–150 °C, accuracy $\leq$ 0.2

3.2 Parameter to describe sludge blanket characteristics

Following parameters related to the sludge blanket are considered;

a. Sludge Volume Fraction v/v
b. Sludge Cohesion Coefficient
c. Settling velocity

The Sludge Cohesion Coefficient (*SCC*) depicting the cohesivity of the sludge blanket is selected as the main parameter to describe the sludge blanket characteristics and continue this study.

3.2.1 Sludge Cohesion Test (SCT)

The sludge sample, separated from supernatant after a Jar test, was poured into a 250 ml measuring cylinder and allowed to rest for 10 minutes. Apparent sludge volume in the cylinder was made to be 50 ml after the ten minutes by siphoning off the excess sludge. A small funnel of which the stem was extended by a glass tube, the end of which was located about 10mm above the bottom of the cylinder was introduced into the cylinder, as shown in the experimental set up (Figure 3.2).

100 ml of the supernatant from the jar test was collected and poured lightly into the cylinder through the funnel making sure no air bubbles were drawn along. Water was introduced in a discontinuous manner by small quantities, and the excess liquid was allowed to run off by overflow from the top of the cylinder. The supernatant of the beakers after flocculation (Jar test) was used for the *SCC* test to ensure no variation in pH or temperature between the contents of the cylinder and the water introduced through the funnel.

The expanded height of the sludge column and time taken were recorded for each pour of 100 ml. The sludge blanket was observed carefully while adding water to avoid contraction of the sludge blanket. A divider funnel was introduced to the test setup, mounted above the small funnel as shown in Figure 3.2, replacing the hand pouring of water. The rate of flow was varied if the sludge blanket was observed to be dormant or tended to contract.

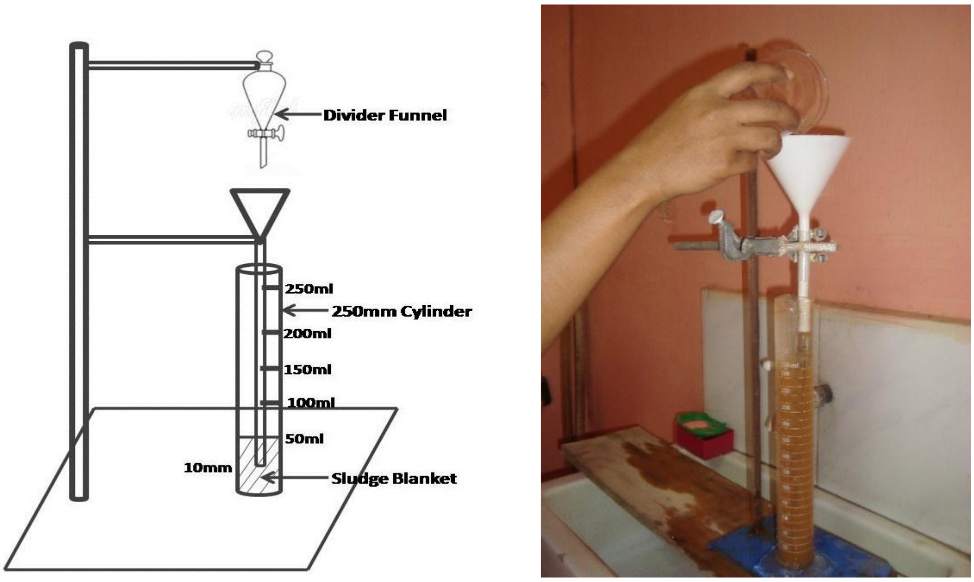


Figure 3.4 - Experimental Setup of Sludge Cohesion Test

3.3 Effect of raw water quality on floc blanket formation

3.3.1 Floc blanket prepared with raw water

The *SCC* of floc blanket prepared using raw water extracted from the three sampling locations of Mahaweli River and its tributary was investigated under this section. The characteristics of each sample were recorded with the following parameters; Turbidity, pH, temperature.

Table 3.1 gives the dates and number of samples collected from each source.

Table 3.1 - Sampling details; effect of raw water quality

	Intake location	Water source	Sampling Dates	No. of samples collected
1	Meewatura Intake Kandy South WSS	Mahaweli River	2013.05.18 2013.06.01	5
2	Paradeka Intake Gampola WSS	Paradeka Oya	2013.06.12	2
3	Gohagoda Intake Katugastota WSS	Mahaweli River	2013.05.16 2013.05.17	2

The raw water samples were subjected to Jar Test to find the optimum PACl dose. Sludge collected in the jar tester using optimum PACl dose is then used to conduct the sludge cohesion test.

3.3.2 Pulsator® floc blanket

Obtaining an idea of the sludge cohesion coefficient in a clarifier floc blanket would be useful to formulate test plan for the understanding formation and to maintain the blanket. A series of sludge cohesion tests was performed using sludge withdrawn from the floc blanket of Kandy South water treatment plant for this purpose. Table 3.2 gives the details of sampling at Pulsator® unit.

Table 3.2 - Sampling details; Pulsator®, Kandy South Water Treatment Plant

	Sampling Date	Time	No. of samples collected
1	2013.05.18	9.00 am	1
2	2013.05.23	9.00 am	1
3	2013.06.01	9.00 am, 2.30 pm, 3.30 pm	2
4	2013.06.07	1.30 pm, 2.45 pm, 3.50 pm	3

After obtaining an overview of *SCC* in different sludge samples, the testing related to the Segment 2, the effect of operating conditions on floc blanket was planned.

3.4 Effect of operating conditions on floc blanket and settling velocity

3.4.1 Tests using synthetic raw water

The coagulant dose is the most prominent operating parameter which affects the physiognomies of the blanket. Therefore, it is planned to identify the behavior of the floc blanket with varying coagulant doses. Due to a large number of variables involved with the field samples; ambient conditions, raw water characteristics, and plant operating conditions, this series of tests were planned to be done using synthetic raw water at the laboratory level, using sludge blanket prepared with synthetic raw water.

The samples were subjected to Jar test at first. The sludge produced at Jar test was then used to conduct *SCC* test.

3.4.2 Preparation of coagulant dose

Based on the seasonal variations of Mahaweli River water quality (3.0.1), tests pertaining to this segment were carried out using floc blankets prepared with raw water turbidity in the range of 20 to 550 NTU. The pH was within the range 6.5 to 7.5. The coagulant commonly used in the water treatment plants is Poly Aluminum Chloride (PACl). PACl can perform in a wider range as it is already hydrolyzed. Therefore it was decided to use PACl as the coagulant in the experiments.

1% stock PACl solution was prepared by dissolving 1 g of PACl in 100 g (ml) of distilled water. The required PACl dose for testing was obtained by pouring measured quantities of the above stock solution into 1 L beakers filled with raw water. Coagulant (PACl) dose was planned to vary between 5–100 mg/l depending on the Jar test outcome.

3.4.3 Trial tests

At first, a set of tests were made using sludge blanket prepared with synthetic raw water to understand the nature of synthetic sludge blanket and resemblance to the actual blanket (Pulsator floc blanket @ Kandy South). Tests were performed with samples of raw water turbidity $250 \pm 1\%$ and $400 \pm 1\%$. The two values were selected considering the average and maximum raw water turbidities observed at Mahaweli River during tests under Section 3.3.1 and River water quality during a year (Figure 3.2). Sludge samples were prepared using a range of coagulant doses 5 – 25 mg/l. The range of coagulant dose was selected based on the coagulant doses used in the Pulsator® during previous year operation.

Table 3.3 gives the test plan.

Table 3.3 - Trial tests on synthetic sludge for *SCC*

	Date	Raw water turbidity (NTU)	PACl doses (mg/l)	No. of samples tested
1	2012.08.02	397	5, 15, 20	3
2	2012.08.17	396	5, 10, 25	3
3	2013.07.27	252	10	1
4	2013.12.21	252	5, 15, 20, 25	4

At the same time of studying cohesivity of the sludge blanket using *SCC* during the trial tests some of the samples were subjected to the settling test in order to find the settling velocity of the blanket (Table 3.4).

Table 3.4 – Trial tests on synthetic sludge for settling velocity

No	Date	Raw water turbidity (NTU)	PACl dose mg/l	No. of tests
1	2013.07.27	252	10	1
2	2013.07.27	396	10	1
3	2013.08.02	397	5, 15, 20	3
4	2013.08.17	396	5,10	2

After completing the trial tests with sludge prepared using synthetic raw water, a series of tests were planned to find the effect of coagulant dose on the floc blanket.

3.4.4 Test Series

Two test series (1 and 2) were conducted to cover the turbidity range 20 – 550 NTU. The ranges handles in each series were 20 – 200 NTU, 250 – 550 NTU respectively. Table 3.5 and Table 3.6 give the test plan.

In addition to the *SCC* test, each sample was subjected to the laboratory flocculation test (Jar Test). Jar test is conducted with initial rapid mixing at 150 rpm for 2 minutes followed by slow mixing at 30 rpm for 20 minutes. The samples were then allowed to settle for 20 minutes after which the supernatant turbidity of each sample were recorded.

Table 3.5 – Raw water turbidity 20-200 NTU, Test Series 1

	Date	Raw water turbidity (NTU)	PACl doses mg/l	No. of samples tested
1	2015.05.16	100	5,7,9,11,13	5
2	2015.03.07	150	3,6,9,12,15	5
3	2014.02.22	200	5,10,15,20,30	5
4	2015.03.07	200	7,10,10,13,15	5
5	2015.05.06	200	5,7,9,11,13	5

Producing sufficient sludge to carry out the test was not possible with low raw water turbidity samples.

Table 3.6 – Raw water turbidity 250-500 NTU, Test Series 2

	Date	Raw water turbidity (NTU)	PACl doses mg/l	No. of samples tested
1	2013.07.27/08.02/08.17	396	5, 10, 15, 20, 25	5
2	2013.12.21	250	5, 10, 15, 20, 25	5
3	2014.02.22	200	5, 10, 15, 20, 30	5
4	2014.02.22	500	15, 20, 25, 30, 40, 50, 60, 70	8
5	2014.02.27	500	30, 40, 50, 60, 70	5
6	2014.04.02	445	20, 30, 40, 50, 60, 70	6
7	2014.04.02	550	20, 30, 40, 50, 60, 70	6
8	2014.04.26	300	10, 15, 20, 25, 30,	5
9	2014.04.26	340	10, 20, 30, 40, 50	5
10	2014.04.26	409	10, 20, 30, 40, 50	5
11	2014.05.01	200	10, 20, 30, 40, 50	5
12	2014.05.01	250	5, 10, 20, 30, 40	5
13	2014.05.02	300	10, 30, 40, 50, 60, 70, 80, 90, 100	9

The necessary sampling was possible beyond 100 NTU only. Therefore testing for raw water turbidity less than 100 NTU was not done. Repeat tests also not envisaged due to the difficulties in producing sufficient amount of sludge. The results obtained from the test series 2 were reconfirmed by a series of repeat tests within the identical range. Table 3.7 gives the test plan of the repeat.

Table 3.7 – Raw water turbidity 250-500 NTU Test Series 2 (Repeat)

	Date	Raw water turbidity (NTU)	PACl doses mg/l	No. of samples
1	2014.07.29	305	10, 15, 20, 25, 30	5
2	2014.07.29	453	20, 30, 40, 50, 60	5
3	2014.07.29	501	20, 30, 40, 50, 60	5
4	2014.08.22	402	10, 20, 30, 40, 50	5
5	2014.12.13	250	5, 10, 15, 20, 25	5
6	2014.12.13	550	30, 40, 50, 60, 70	5
7	2015.03.07	150	3, 6, 9, 12, 15	5
8	2015.03.07	200	7, 10, 11, 13, 15	5
9	2015.05.16	100	5, 7, 9, 11, 13	5
10	2015.05.16	200	5, 7, 9, 11	4

Altogether 123 sludge cohesion tests were conducted under the second testing programme carried out within a one year period from 2014 April 26th to 2015 May 16th. The raw water turbidity values as well as the coagulant dose selection had to be adjusted with the experiences gathered during the tests.

3.4.5 Settling velocity

A one liter graduated measuring cylinder is filled with the sludge sample. The sludge in the cylinder is shaken well to ensure sludge was completely mixed. Starting from immediately after the sludge is left to settle in the cylinder, the height of the sludge/clear water separation line (h_1) was plotted over time (t) (Figure 3.5).

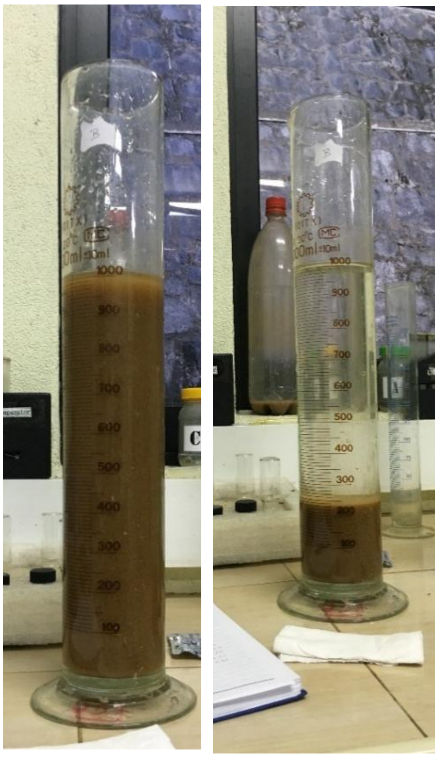


Figure 3.5 - Settling Test
(a) At t=0, (b) At t=20 minutes

The gradient of the graph gives the settling velocity (V_s) of the particular sludge. (Figure 3.6)

$$V_s = h_1/t \qquad \text{--- 3.1}$$

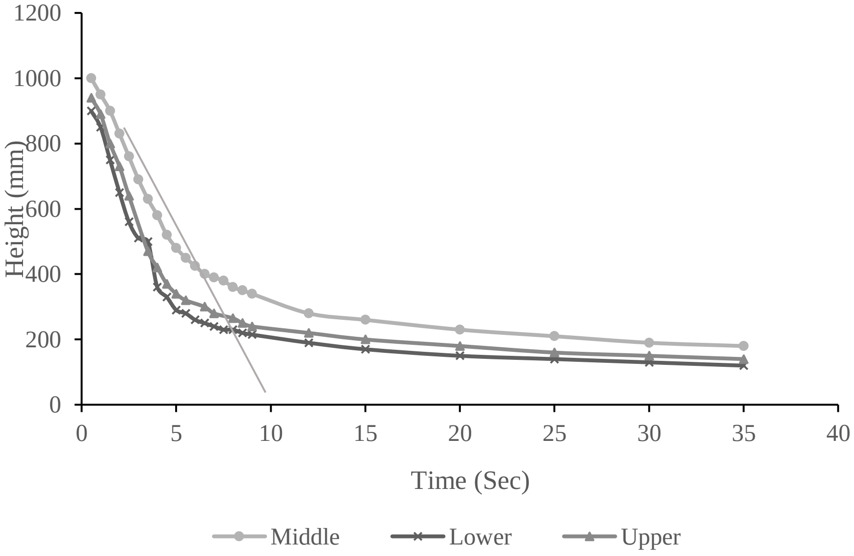


Figure 3.6 - Settling Curve

3.4.6 Testing at full scale using Pulsator® unit, Kandy South WTP

After establishing the *SCC* and settling velocity of the particles, the effect of raw water quality and coagulant dosage on the blanket performance at the laboratory, a series of tests were conducted to find the blanket behavior at full scale.

The floc blanket of the Pulsator® unit at Kandy South water treatment plant is used for the field testing. In order to determine the blanket characteristics number of parameters relating to the blanket were measured directly or established by laboratory testing. Table 3.8A gives the measured or tested parameters.

Table 3.8A - Parameters measured/ tested

No	Description	Parameters
1	Raw water	Turbidity, pH, conductivity, temperature
2	Pulsator® floc blanket	pH, temperature, effluent turbidity, *SCC*, settling velocity (V_s), Sludge volume (*SV*)

Sludge samples were collected during different times of the day and at different depths within the blanket. Figure 3.7 gives the cross section of the Pulsator® including sampling points. Grab sampler was used to collect samples at depths 2 and 2.5 m (Figure 3.8) whereas mid sampling tap was used to extract the sample at the middle of the blanket (Figure 3.7). Table 3.8B gives the test plan.

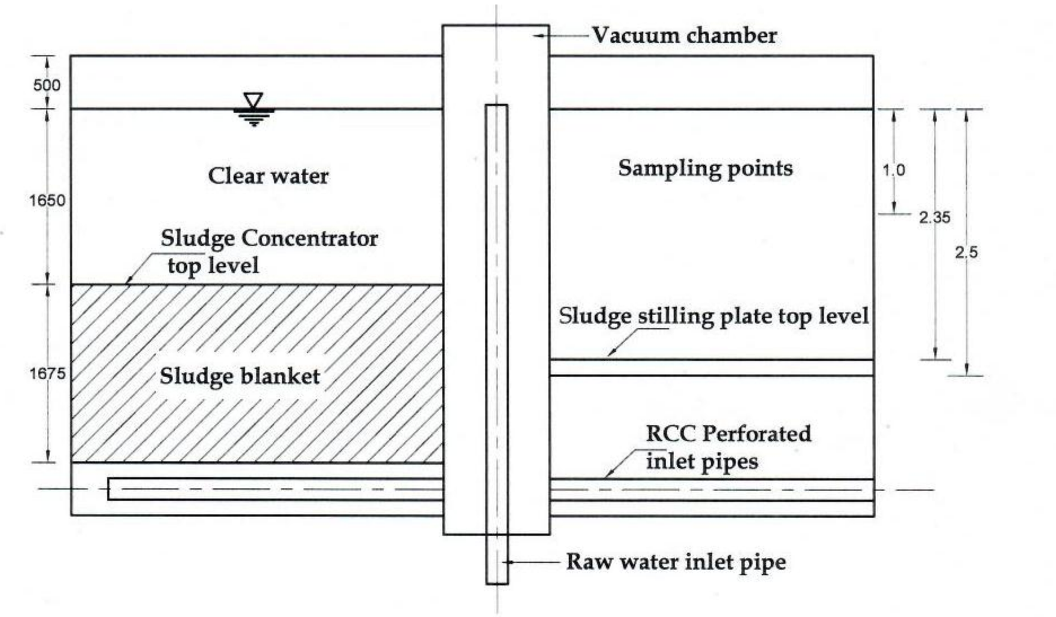


Figure 3.7 – Pulsator® sectional view

Table 3.8B - Test plan at the Pulsator® sludge blanket

No	Date	Sampling time	Sampling depth m	No. of samples tested
1 - 3	2013.07.27	09:30, 13:25, 15:54	Mid point	3
4 - 6	2013.08.02	10:00	2, 2.5, midpoint	3
7 - 12	2013.08.17	09:00, 10:00, 11:00, 12:00, 13:00, 14:00	Mid sampling point	6
13 - 33	2013.08.19	08:15, 09:20, 11:00, 12:00, 13:00, 14:00, 15:00	1, 2, 2.5	21
	2015.12.25	8:30 to 15:00 at every half hour	Bottom mid and top sampling points	14

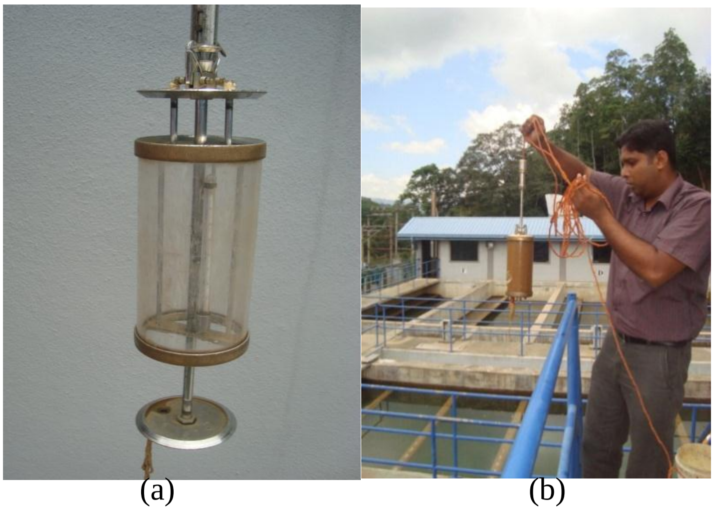

(a) (b)

Figure 3.8

(a) Grab sampler
(b) Sampling

3.5 Formation of floc blanket and effect of temperature on the blanket

In order to establish formation of floc blanket and effect of inflow temperature variation, laboratory tests were performed using a test setup and synthetic raw water. Subsequently blanket formation was observed in field using the Kandy South Pusator® unit. The raw water (inflow) temperature and the blanket temperature were recorded.

3.5.1 Laboratory tests using synthetic sludge samples

3.5.1.1 Experimental setup

The test setup was designed and assembled using two acrylic columns 1300 mm long with diameter 100 mm (inner cylinder) and 250 mm (outer cylinder) mounted on a metal stand approximately 300 mm height. A glass tube (diameter:10 mm) with a funnel on top was mounted above the two cylinders using a steel frame. An inverted funnel (diameter: 95 mm) was fixed at the bottom of the glass tube. The lower funnel was held approximately 25 mm above the bottom of the inner cylinder. Two taps were fitted at the bottom of the two cylinders to facilitate the draining of the cylinder content. An outlet pipe was fitted at the top of the inner cylinder to collect effluent samples.

The apparatus supported on the sturdy metal frame was conveniently placed on a laboratory bench close to a water supply and a drain. (Figure 3.9)

3.5.1.2 Sample preparation

Synthetic raw water was prepared as explained in Section 3.1.1. With the understanding gathered on the characteristics of the sludge prepared using different raw water turbidities in Section 3.4.1, it was decided to use synthetic raw water with higher turbidity for this test in order to ensure the sludge blanket prepared will be consistent and sufficiently dense to facilitate better observation of blanket characteristics during the experiment. Raw water was flocculated using the jar test apparatus with a suitable coagulant dose.

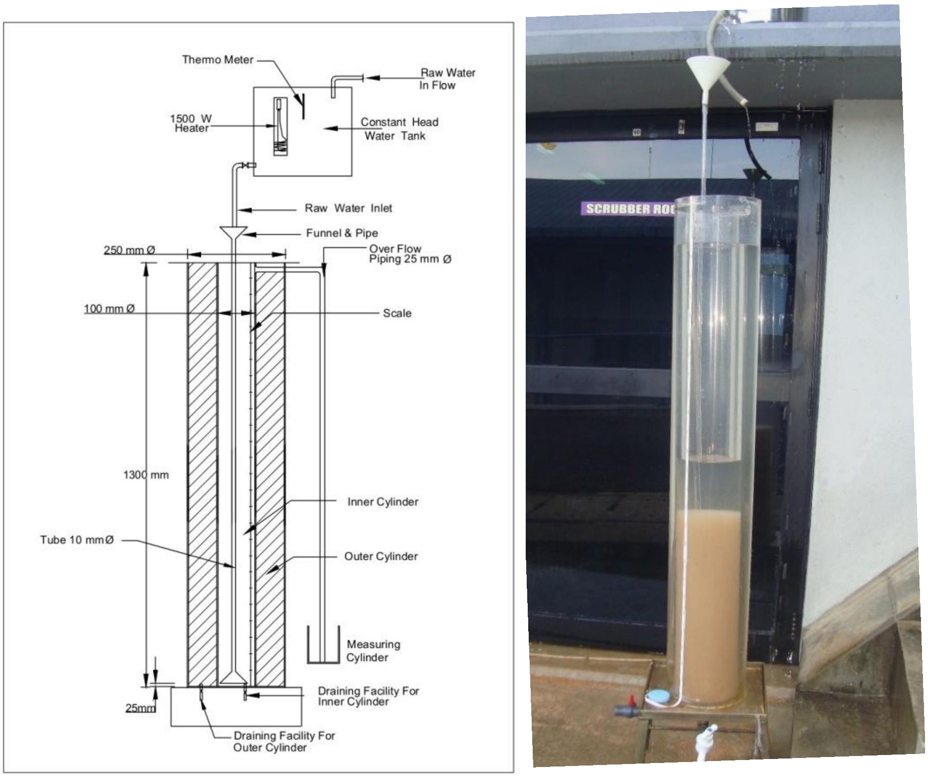


Figure 3.9 - Experimental setup for blanket formation and effect of temperature variation

A raw water turbidity of 800 NTU is used for the experiments. The pH was in the range of 5.5 to 6.5. Coagulant dose of 90 mg/l was introduced to all the beakers and jar test was conducted with the rapid mix at 150 rpm for 2 minutes and a slow mix at 30 rpm for 30 minutes. Four experiments were conducted using synthetic sludge. First, two experiments established the formation of floc blanket and effluent quality. The last two experiments investigated the effect of inflow temperature variation on the floc blanket and effluent quality.

The overall test plan is given Table 3.9

Table 3.9 gives the summary of a test plan for the formation of floc blanket and effect of temperature variation on the blanket (Raw water turbidity 768- 800 NTU, Ph 5.5-6.5, PACl dose 60-90 mg/l)

Table 3.9 - Summary of test series

Test No.	Initial blanket height (mm), h	Up flow velocity (mm/sec)	Time to reach outlet (min)	Parameters Measured	Test period (min)
1	330	2.63	57	h, e	72
2	200	1.15, 3.4 , 7.9	52	h_1, h_2, e	100
3	350	2.94	41	h_1, e, t_1	127
4	470	4.25	28	h_1, e, t_1, t_2	127

- Initial blanket height after 15 minutes settling - h,
- Varying blanket height with influent- h_1 (top), h_2 (bottom),
- Effluent quality (NTU) - e
- Inflow temperature (^{o}C) - t_1
- Effluent temperature (^{o}C) - t_2

Water temperature in the constant head tank has been increased using the electric heater placed within the constant head tank.

3.5.1.3 Methodology - Experiment 1

This experiment was conducted to establish blanket formation. The prepared sludge samples were carefully poured into the inner cylinder of the test apparatus, taking care not to break the flocs, and were left for 10 minutes to establish a sludge blanket. The outer cylinder was filled with clear water to ensure enhanced visibility. Water was added to the upper funnel using a constant head tank at a constant velocity. The water leaving the inverted lower funnel flowed upward through the sludge blanket.

The variation of blanket height with time after introduction of an upward flow of 2.63 mm/sec (which was determined during preliminary experiments) was recorded. During this test, blanket stabilization occurred before the effluent reached the outlet. Therefore, it was not possible to capture the effluent for quality testing at blanket stabilization.

3.5.1.4 Methodology - Experiment 2

This experiment was designed to capture the effluent quality at blanket stabilization. Using a similar sample as above, this experiment was carried out while incrementally changing the inflow velocity. The inflow velocity was increased in three steps of 1.15 mm/sec, 3.4 mm/sec and 7.9 mm/sec within 40 minutes, after which the velocity was kept constant (at 7.9 mm/sec) (Figure 3.10). Upon introducing inflow, the sludge blanket raised and stabilized at a constant level. Effluent reached the outlet level after 52 minutes and measuring of effluent quality started after that.

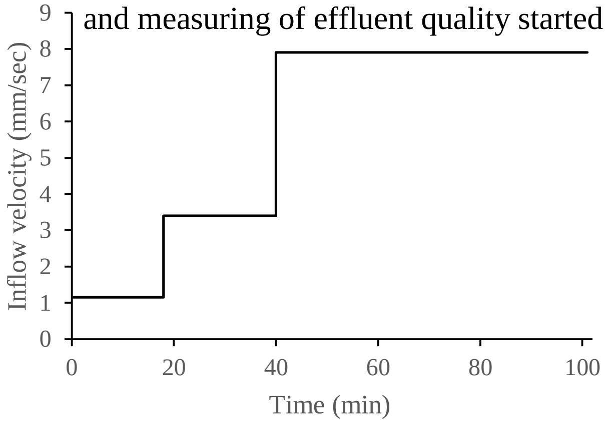


Figure 3.10 - Variation of inflow velocity with time (Experiment 2)

3.5.1.5 Methodology - Experiment 3

During Experiment 3, water was added to the upper funnel at an upflow rate of 2.94 mm/sec, using a constant head tank. Water leaving the inverted lower funnel flowed upward through the sludge blanket. Variation of the blanket height, effluent turbidity and temperature of inflow were recorded with time.

The blanket was first stabilized at an average total height of 58 cm. After stabilization of the blanket the heater in the inflow water tank was switched on at the 66th minute allowing inlet water temperature to rise. After the heater was switched on, the blanket was stable with a slight increase in depth to 59 cm for about 10 minutes after which it started rising steadily. Blanket rose up to 102 cm, the outlet level, in 43 minutes, while inflow temperature increased up to 52 °C. Then the heater was switched off and inflow temperature was allowed to decrease and the readings were continued for another 18 minutes. During the temperature recession phase, the blanket stabilized at an average height of 100 cm.

3.5.1.6 Methodology - Experiment 4

Having established the blanket behavior with the introduction of the warm upward flow, the experiment 4 was conducted to verify the results of the experiment 3. Inflow velocity was set to 4.25 mm/sec. The blanket was allowed to stabilize at room temperature after which the temperature of inflow was increased. The temperature variation, blanket behavior and effluent turbidity were recorded. The temperature of the effluent was also recorded during this experiment.

The stabilization of the blanket at room temperature occurred after 48 minutes at a blanket height of 100 cm. The heater was switched on and temperature at the constant head tank increased steadily up to 44 ^{o}C after which the heater was switched off. Readings were continued for another 30 minutes until the effluent reached the ambient temperature.

3.5.2 Testing at full scale Pulsator® floc blanket at Kandy South WTP

After establishing effect of temperature variation on floc blanket using laboratory scale experiment, observations were made in the full scale, Pulsator® unit at the Kandy South WTP to find out the behavior of floc blanket with ambient temperature changes. The volumetric concentration of particles in the floc blanket, measured using sludge volume test is used to understand the characteristics of the floc blanket.

Data collected during a period of eight hours from 8.30 am to 3.00 pm on 25th December 2016 (Table 3.8A and 3.8B) were used.

3.5.2.1 Sludge Volume Test

The sludge volume (*SV*) is a measure of the volumetric concentration of particles in a sludge blanket. The *SV* helps determine the health of the floc and severity of poor settling (bulking) episodes in a blanket. Sludge samples extracted from the three sampling points were poured into 250-mL measuring cylinders and left to settle for

10 minutes, after which the sludge height (h) was measured. The SV fraction was calculated using Equation 3.2.

$$SV = h/250 \qquad \text{--- 3.2}$$

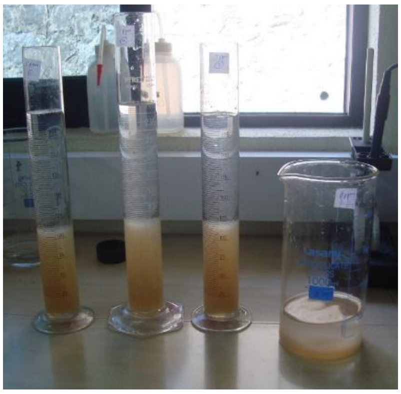


Figure 3.11 - Sludge Volume Test

3.6 Pulsator® startup - Kandy South water treatment plant

A series of tests were planned to monitor the formation of the sludge blanket during Pulsator® startup. Before the test, one Pulsator® out of the two 16,000 m^3/day pulsator units was taken out of operation. After proper cleaning, the Pulsator® was refilled with raw water mixed with the coagulant (PACl) and put back into operation.

The Pulsator® startup will enable understanding of the parameters affecting the formation of the blanket as well as verifying the conclusions arrived at, based on the experiments up to now. During the laboratory tests, the effect on the sludge blanket due to individual parameters; raw water quality, coagulant dose, and temperature were anlaysed independently. However, these parameters are acting upon the Pulsator® sludge blanket simultaneously. Thus the experiments and observations done under this section will enable to establish the behavior of sludge blanket with natural occurrence and verify the test results obtained under Sections 3.3, 3.4 and 3.5.

Continuous recordings of the input water quantity and turbidity, coagulant dose, suction height, suction and flushing times and the turbidity of Pulsator® effluent water were carried out. Hourly readings were taken for a period of 8 hours from 8.30 am to 3.30 pm during a day. After the sludge blanket had satisfactorily formed from the bottom to the top layer, tests were conducted three times a day to measure the sludge volume (*SV)*, V_s and *SCC* (details of these parameters are described below) of samples extracted from the three sampling points at different heights of the blanket (1, 2 and 2.36 m). (Figure 3.7)

3.6.1 Test plan

Refilling of the Pulsator® started at an inflow rate of 600 m^3/hr. After 27 hours the Pulsator® was completely filled. The pulsation rate was adjusted by varying the pulsation height, flush time and suction time and the sludge volume fraction of bottom, middle and top of the sludge blanket was monitored continuously in order to comprehend the formation of the blanket.

At each testing time following parameters were measured or tests were performed. Raw water turbidity, flush height, flush time and suction time and effluent turbidity were measured. The sludge volume fraction of all three test depths (Figure 3.7) were tested at the laboratory. After the sludge blanket was formed (Figure 3.12), the *SCC* and V_s at each layer were measured. However until the sludge blanket has established, it was not possible to carry out SVT without sludge being available. The turbidity value at each test depth was recorded prior to the establishment of the blanket.

Figure 3.12 Pulsator® floc blanket

Table 3.10 - The Testing programme of the Pulsator® startup

No.	Dates	Days	Sludge Blanket	Measured/ Tested
1	2015.11.25 - 2015.12.01	1 to 7	Not available	RWT, EFT, turbidity at each layer
2	2015.12.02 - 2015.12.06	8 to 12	Not available in the middle and top layers	RWT, EFT, SVF (mid), turbidity at mid & top
3	2015.12.07 - 2015.12.11	13 to 17	Available in all layers	RWT, EFT, SVF, SCC, and Vs in all three layers

In addition to the parameters indicated in the Column 5 of Table 3.11, the inflow rate, flush height, flush time and suction height were recorded at each testing time.

The sludge cohesion coefficient (*SCC*) is a parameter used to describe the cohesivity of a floc blanket and is determined by Equation (2.1) (Refer Section 2.4, Figure 2.2 and Equation 2.1) (Degrémont, 2007). The experimental setup is given in Figure 3.4.

Experiments were conducted in the laboratory to obtain the relationship between u and V, where u is the upward velocity, V is the corresponding apparent volume of the expanding sludge, and V_0 is the volume of settled sludge corresponding to a zero velocity and is determined from the graph of u vs. V (Figure 2.2).

$$u = SCC\ (V/V_0 - 1) \qquad \text{--- 2.1}$$

Particle movement in a suspension is due to hydrodynamic forces counteracted by the viscous forces. As reported by Kotlyar et al. (1998), particle movement in a liquid-solid suspension is due to the dissipation of energy by viscous or turbulent conditions. The *Re* indicates at what scale this viscous dissipation occurs. Dwivedi (1997) defined the *Re* for a liquid fluidized bed system with particle diameter d, voidage $ø$, superficial velocity v_s, density of fluid ρ, and dynamic viscosity of the fluid μ as:

$$Re = \rho v_s d/\mu(1 - ø) \qquad \text{--- 3.3}$$

Equation 3.3 can be reformulated to obtain *Vs* as follows;

$$V_s = Re.\mu.SV/\rho.d \qquad \text{--- 3.4}$$

The equation developed by Richardson and Zaki (1954) based on their experimental results calculates the settling velocity (V_s) of a suspension with respect to the fractional volumetric concentration of particles and the *Re* of the medium. (Ref. Section 2.5)

$$V_s = V_t(1 - SV)^m \qquad \text{--- 2.2}$$

Where, V_s is the hindered settling velocity, V_t is the terminal settling velocity of particles, *SV* is sludge volume fraction and *m* is an empirical value that depends on the *Re*:

For $Re < 0.2$ $m = 4.65$

$0.2 < Re < 1$ $m = 4.4Re^{-0.03}$

$1 < Re < 500$ $m = 4.4Re^{-0.1}$

$Re > 500$ $m = 2.4$

In a floc blanket, the size and shape of the particles constantly changes due to agglomeration. The terminal settling velocity (V_t) of the particles and the *Re* must be determined based on Stokes' Law or by experimental methods.

CHAPTER 4: RESULTS AND OBSERVATIONS

4.1 Effect of raw water quality on sludge blanket formation:

4.1.1 Floc blanket prepared with river water

Table 4.1 gives the date of testing, raw water characteristics; turbidity, pH, temperature, the coagulant dose used and the results of the *SCC* test.

Table 4.1 *- Raw water characteristics, coagulant dose, and* SCC

Location	**Date**	**Raw water NTU**	**pH**	**Water temp ^oC**	**PACl mg/l**	***SCC* (K) m/hr**	**Pearson r**
Katugasthota	2013.05.17	88	7.5	27.5	7	3.09	0.83
Meewatura	2013.05.18	166	6.2	27	10	2.55	0.82
Meewatura	2013.06.01	54.4	6.6	23.3	8	2.53	0.94
Meewatura	2013.06.01	52.7	6.8	23.3	8	2.39	0.94
Meewatura	2013.06.01	49.5	6.8	23.3	10	3.39	0.94
Gampola	2013.06.12	328	6.71	22.5	20	4.53	0.97
Gampola	2013.06.12	383	6.71	22.5	10	4.67	0.99

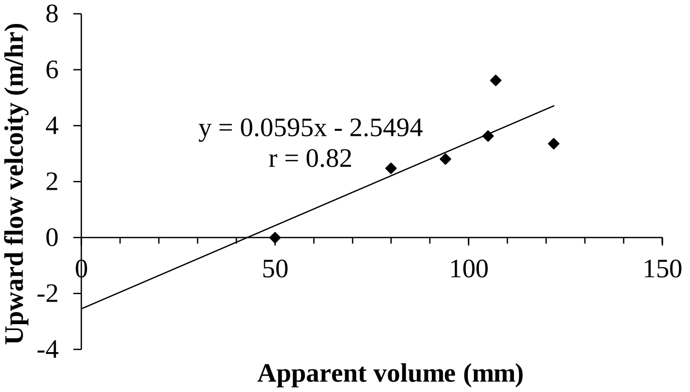


Figure 4.1 *- Upward flow velocity Vs apparent volume (Raw water extracted at Meewatura 2013.05.18)*

Figure 4.1 gives the SCT results of one sample. A significant positive linear relationship exists between the upflow velocity and the apparent volume expansion of the floc blanket with a Pearson r of 0.82 and p value < 0.05. Interceptor of the graph gives the *SCC*.

Similar graphs were established for SCT tests done on all the samples and the *SCC* obtained. The Pearson r for all the samples were within 0.82-0.99 with p value < 0.05

indicating a strong correlation between the up-flow velocity and the apparent volume of the floc blanket.

4.1.2 Pulsator® floc blanket

Table 4.2 gives the results of SCT carried out using the samples obtained from the floc blanket of the Pulsator® unit at the Kandy South water treatment plant.

Table 4.2 *- Sludge cohesion of samples taken at pulsator® floc blanket*

Number	**Date**	**Sampling time (hr)**	**pH**	**Water temp ºC**	**Plant PaCL mg/l**	***SCC* m/hr**	**Pearson r**
1	2013.05.18	09.30	6.2	27	7	3.37	0.99
2	2013.05.23	09.30	6.5	28.1	8	3.65	0.97
3	2013.06.01	09.30	6.8	23.3	8	3.02	0.95
4	2013.06.01	03.30	NA	NA	8	2.97	0.99
5	2013.06.07	09.30	6.3	24.4	6	4.06	0.94
6	2013.06.07	11.00	6.1	24.7	6	3.28	0.99
7	2013.06.07	13.00	6.1	24.4	6	3.56	0.96

Figure 4.2 shows the SCT results of one sample drawn out form the Pulsator®.

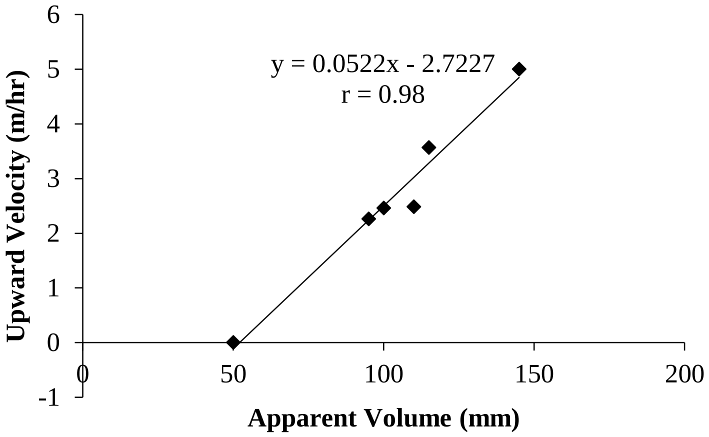


Figure 4.2 *- Upward flow velocity vs apparent volume (Raw water extracted from Pulsator®, Meewatura)*

A significant positive linear relationship exists between the upflow velocity and the apparent volume expansion of the floc blanket with a Pearson r of 0.98 and p value < 0.5. The Pearson r values of all the samples were within the range of 0.94 to 0.99 indicating a good correlation between the upflow velocity and the apparent volume of the sludge blanket. The turbidity of the samples could not be recorded due to the turbidity values were in excess of the maximum reading of the turbidity meter used.

4.2 Effect of operating conditions on the floc blanket and settling velocity

A series of laboratory tests were performed using floc blanket made with sludge obtained from varying synthetic raw water and coagulant dose combinations to determine the effect of coagulant dose on the floc blanket.

4.2.1 Trial tests using synthetic raw water

Table 4.3 gives the results of trial tests on sludge blanket prepared using synthetic raw water. Figure 4.3 shows the outcome of SCT for a sludge sample prepared using synthetic raw water.

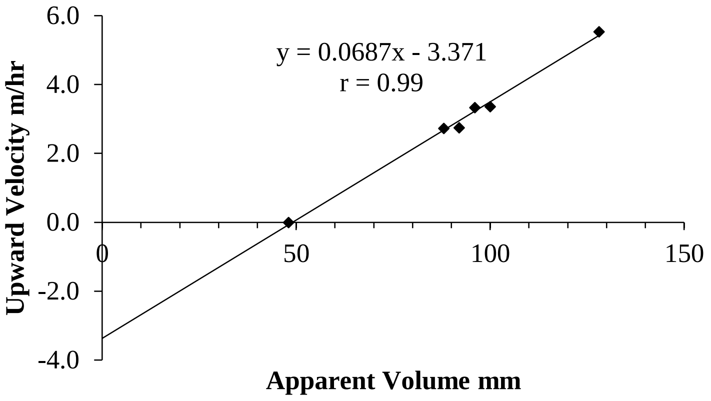


Figure 4.3 *- Upward flow velocity vs apparent volume (Synthetic raw water; 397 NTU, PACl 10 ppm)*

As evident in the sludge samples prepared with river water as well as Pulsator® sludge samples, synthetic sample also shows a significant positive linear relationship between the upflow velocity and the apparent volume expansion of the floc blanket with a Pearson r of 0.99 and p-value < 0.5.

The SCC values reported in the trial tests are within the range 0.91- 3.25 mm/hr (0.25 – 0.9 mm/sec). The range corresponds to recommended range for a consistent and well established sludge blanket (Degremont, 2007).

Table 4.3 *- Results of trial tests (SCC in m/hr)*

Number	Date	RWT	ph	PACl	*SCC1*	*SCC2*	*SCC3*	Average *SCC*
1	2012.08.02	397	7.7	5	3.39	3.18	3.19	3.25
2	2012.08.02	397	7.7	15	3.22	3.13	2.86	3.07
3	2012.08.02	397	7.7	20	2.93	1.22	1.81	1.99
4	2012.08.17	396	6.2	5	1.79	1.46	2.33	1.86
5	2012.08.17	396	6.2	10	2.05	2.87	2.61	2.51
6	2012.08.17	396	6.2	25	2.08	2.55	2.18	2.27
7	2013.07.27	252	6.9	10	2.83	2.52	3.22	2.86
8	2013.12.21	251	6.6	5	4.38	2.82	2.72	3.31
9	2013.12.21	251	6.6	15	2.59	3.00	2.26	2.62
10	2013.12.21	251	6.6	20	3.36	2.55	3.22	3.04
11	2013.12.21	251	6.6	25	0.91	-	-	0.91

4.2.3 Test Series using synthetic raw water

4.2.3.1 Series 1- Raw water turbidity 20 NTU to 200 NTU

Producing sufficient sludge to carry out the test was not possible with low raw water turbidity samples. The necessary sampling was possible beyond 100 NTU only. Jar test and *SCC* test were conducted with 30 samples; raw water turbidity 100, 150, 200 NTU and PACl dose in the range of 5-50 ppm.

The results are given in Table 4.4.

Table 4.4*-Supernatant turbidity (Jar test) & sludge cohesion coefficient SCC (m/hr)*

	PACl dose (mg/l)													
	3	**6**	**5**	**7**	**9**	**10**	**11**	**12**	**13**	**15**	**20**	**30**	**40**	**50**
NTU														
100	-	-	8.95	13.6	15.2	-	16.1	-	27.5	-	-	-	-	-
150	22	22	-	-	-	-	-	10	-	16	-	-	-	-
200-1	-	-	66.7	-	51.3	-	14.1	-	3.4	-	-	-	-	-
200-2	-	-	-	-	-	10.1	-	-	-	-	1.15	1.03	1.51	1.48
200-3	-	-	38	-	-	44	-	-	-	12	6	5	-	-
SCC														
100	-	-	1.44	2	0.5	-	1.39	-	4.02	-	-	-	-	-
150	1.32	2.08	-	-	2.86	-	-	2.97	-	0.90	-	-	-	-
200-1	-	-	0.76	0.85	1.62	-	0.84	-	3.3	-	-	-	-	-
200-2	-	-	-	-	-	0.14	-	-	-	-	1.36	1.21	1.83	1.33
200-3	-	-	0.55	-	-	0.38	-	-	-	0.63	0.95	0.88	-	-

For the raw water turbidity range 100 – 200 NTU, Optimum PACl dose (Jar test) varied within the range 7 – 13 mg/l. The highest *SCC* was within the range 0.95 to 1.8 m/hr (0.25-0.5 mm/sec).

4.2.3.2 Series 2 – Turbidity 250 – 550 NTU

For each raw water turbidity the coagulant dose was varied between 5-50 NTU. For few samples coagulant dose had to be increased up to 70 and 100 NTU to get the optimum coagulant dose. Altogether 64 samples were tested. For each turbidity/coagulant dose combination, 3 *SCC* tests were conducted and average SCC was calculated.

Table 4.5 *- Supernatant turbidity after jar test and average* SCC *(m/hr)*

	PACl dose mg/l												
	5	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
NTU													
250	3.24	1.34	11.5	47.2	61.3	-	-	-	-	-	-	-	-
250	30.9	13	-	2.78	-	4.41	5.59	-	-	-	-	-	-
300	-	35	-	-	-	4.21	2.83	2.71	1.87	1.83	1.93	2.19	
300	41.5	15.4	7.63	2.66	1.89	1.54	-	-	-	-	-	-	-
339	-	53	-	7.11	-	1.86	1.79	1.49	-	-	-	-	-
397	NA	NA	NA	NA	NA	-	-	-	-	-	-	-	-
409	-	76.4	-	22.4	-	4.55	1.49	1.19	-	-	-	-	-
445	-	-	-	89.1	-	18.2	6.19	5.91	6.27	14.5	-	-	-
500	-	-	135	102	52.1	27.7	8.38	4.68	6.21	2.54	-	-	-
500	-	-	-	-	-	58.6	17.3	5.7	2.4	3.3	-	-	-
550	-	164	-	113	-	42.5	9.16	3.13	6.14	10.28	-	-	-
SCC													
250	3.31	2.81	2.59	3.05	0.91	-	-	-	-	-	-	-	-
250	0.98	1.63	-	2.18	-	2.18	2.83	-	-	-	-	-	-
300	NA	0.43	-	-	-	1.54	1.74	2.43	1.04	1.44	1.65	1.80	2.22
300	-	1.22	1.40	1.72	1.81	0.98	-	-	-	-	-	-	-
339	-	2.22	-	1.46	-	1.06	2.0	3.48	-	-	-	-	-
397	2.56	2.66	3.07	1.99	2.27	-	-	-	-	-	-	-	-
409	-	1.85	-	2.28	-	2.4	2.69	2.56	-	-	-	-	-
445	-	-	-	0.72	-	2.76	3.15	1.88	0.59	2.31	-	-	-
500	-	-	1.34	1.15	1.75	2.14	2.22	1.53	1.83	2.32	-	-	-
500	-	-	-	-	-	1.82	2.22	1.53	1.83	2.32	-	-	-
550	-	-	2.05	-	-	2.38	2.39	2.33	1.63	2.03	-	-	-

For the raw water turbidity range 250 – 550 NTU, Optimum PACl dose (Jar test) varied within the range 10 – 50 mg/l. The highest *SCC* was within the range 1.81 to 3.48 m/hr (0.5-0.96 mm/sec).

4.2.3.3 Series 2 – Turbidity 250 – 550 NTU (Repeat)

In order to verify the results obtained in the Test Series 2, another test series were conducted within the same turbidity range. Altogether 30 samples were tested. For each turbidity/coagulant dose combination, 3 *SCC* tests were conducted and average SCC was calculated. The outcome is given in table 4.6.

For the repeat test of raw water turbidity range 250 – 550 NTU, Optimum PACl dose varied within the range 25 – 70 mg/l. The highest *SCC* was within the range 1.85 to 4.56 m/hr (0.5 to 1.27 mm/sec).

Table 4.6 *- Supernatant turbidity after Jar Test and Sludge Cohesion Coefficient (m/hr) - Repeat test*

	PACl dose mg/l												
	5	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
NTU													
250	88	67	25	7	4	-	-	-	-	-	-	-	-
305	-	80.6	22.1	10.1	9.8	5.5	-	-	-	-	-	-	-
402	-	61	-	20	-	5	2	2	-	-	-	-	-
450	-	-	-	85	-	68	5	3	3	-	-	-	-
500	-	-	-	106	-	59	3.9	2.3	7.9	-	-	-	-
550	-	-	-	-	-	103	55	16	8	5	-	-	-
											-	-	-
SCC											-	-	-
250	NA	1.82	1.47	2.44	2.07	-	-	-	-	-	-	-	-
305	-	1.75	1.84	1.26	1.85	2.6	-	-	-	-	-	-	-
402	-	1.0	-	2.61	-	2.85	1.81	2.75	-	-	-	-	-
450	-	-	-	1.97	-	2.48	2.23	2.93	2.03	-	-	-	-
500	-	-	-	0.98	-	1.53	3.11	2.14	2.23	-	-	-	-
550	-	-	-	-	-	2.01	1.48	2.32	4.56	1.66	-	-	-

At the same time observations were made of formation and behaviour of sludge blanket with each coagulant dose during the test series. These observations gave a good understanding of the characteristics of sludge blanket with respect to raw water turbidity and coagulant dose used.

At low raw water turbidity, the amount of sludge formed was less, and the sludge was light and fragile. With higher raw water turbidity sufficient amount of sludge was formed. However, it is noted that depending on the PACl dose the characteristics of the sludge varies. Sludge formed with PACl dose closer to optimum (PACl dose at lowest supernatant turbidity @ Jar test) was consistent, and the raising and lowering of the sludge blanket was easy to distinguish. Sludge formed with other PACl doses was light and fragile compared with the sludge at the optimum PACl dose.

4.2.4 Trial tests for settling velocity

The outcome of the settling velocity tests was tabulated in Table 4.7. (Section 3.4.5, Table 3.4)

Table 4.7 - *Settling velocity of particles*

Number	Raw water turbidity NTU	PACl dose mg/l	Settling velocity mm/sec
1	252	10	1.6
2	396	10	0.95
3	397	5	0.49
4	397	10	0.6
5	397	15	0.53
6	396	5	0.35
7	396	10	1.72

The settling velocity of the sludge blanket is within the range 0.35 to 1.72 mm/sec.

4.2.5 Results- testing at full scale using Pulsator$^{®}$ unit Kandy South WTP

After establishing the *SCC* and settling velocity (V_S) of the particles, the effect of raw water quality and coagulant dose on the blanket performance were tested at the laboratory using sludge blanket formed with synthetic raw water, a series of tests were conducted to find the blanket behavior at full scale. The Pulsator$^{®}$ at Kandy South water treatment plant was used for these testing. (Section 3.4.6)

Table 4.8 - *Field testing at Kandy South Pulsator$^{®}$ (SCC m/hr,* V_s *mm/sec)*

No.	Time	Raw water			Depth m	Pulsator$^{®}$ sludge				
		RWT	pH	Temp		pH	Temp	Eff. T	*SCC*	V_s
1	09.30	5.89	6.3	NA	2.35	NA	NA	NA	2.56	1.54
2	13.25	NA	6.1	26.5	2.35	7	23.2	1.81	3.73	1.395
3	15.54	5.33	NA	NA	2.35	4.7	23.3	1.09	2.44	0.79
4	10.00	5.5	6.1	24.9	2.0	6.4	23.4	3.07	2.33	1.17
5	10.00	NA	NA	NA	2.35	NA	NA	3.07	2.65	-
6	10.00	NA	NA	NA	2.5	6.3	23.1	3.07	1.93	0.96
7	09.00	8.77	6.7	24	2.35	6.5	23.2	0.06	2.57	1.58
8	10.00	NA	NA	NA	2.35	6.4	22.8	NA	2.47	7.58
9	11.00	NA	NA	NA	2.35	6.8	23.2	NA	3.23	1.14
10	12.00	NA	NA	NA	2.35	6.6	23.7	NA	2.65	1.53
11	13.00	NA	NA	NA	2.35	6.4	23.4	NA	2.16	1.03
12	14.00	NA	NA	NA	2.35	6.1	23.4	NA	2.58	1.27
13	08.15	7.38	6.2	24.2	1	6.7	23.2	NA	-	-
14					2	6.9	23		2.9	2.05
15					2.5	6.6	22.7		2.2	1.09
16	09.20	6.8	5.2	25.1	1	6.2	23.4	NA		
17					2	5.3	23.2		2.36	2.19
18					2.5	5.3	23.1		2.54	1.11
19	11.00	7	5.3	25.2	1	5.4	23.9	NA		
20					2	5.3	23.6		2.91	1.8
21					2.5	5.3	23.4		2.38	1.53

No.	Time	Raw water			Depth m	Pulsator® sludge				
		RWT	pH	Temp		pH	Temp	Eff. T	*SCC*	V_s
22	12.00	6.4	5.3	26	1	5.5	23.9	NA	-	-
23					2	5.3	23.6		3.11	3.88
24					2.5	5.3	23.4		2.8	0.78
25	13.00	NA	NA	NA	1	5.5	23.9	NA	-	-
26					2	5.4	23.7		2.0	1.6
27					2.5	5.5	23.6		2.86	1.72
28	14.00	NA	5.4	23.1	1	5.6	23.8	NA	-	-
29					2	5.5	23.6		2.26	2.47
30					2.5				2.33	0.96
31	15.00	6.04	5.6	27.2	1	5.8	24		-	-
32					2	5.8	23.8		0.04	2.01
33					2.5	5.7	23.6		0.047	1.25

Some parameters; RWT, effluent turbidity, pH and temperature were not recorded during some hours of the day. At depth 1 m no sludge were available in the blanket. Therefore *SCC* and V_s tests could not be consducted.

4.3 Formation of floc blanket and effect of temperature on the blanket

4.3.1 Laboratory testing using synthetic sludge samples

Formation of the floc blanket after introducing the upflow was studied as described in Chapter 3, Section 3.5.1. The first two experiments were conducted to investigate the blanket behaviour and effluent quality. Results of Experiment 1 and 2 are given in Table 4.9A and Table 4.9B.

4.3.1.1 Results of Experiment 1

***Table 4.9A** - Experiment 1 Variation of floc blanket height and effluent turbidity until the water reached outflow level (Up flow velocity 2.63 mm/sec)*

t min	h cm	t min	h cm	t min	H cm
0	33	16	44.6	32	49.4
1	32.8	17	45	33	49.6
2	33.2	18	45.8	34	49.6
3	34.4	19	46.6	35	49.6
4	35.8	20	47.4	36	49.6
5	36.6	21	47.6	38	49.6
6	37.6	22	47.8	39	49.6
7	38.4	23	48.2	40	49
8	39.2	24	48.4	42	48.6
9	39.8	25	48.6	47	48
10	40.6	26	48.6	52	46
11	42	27	48.6	57	43.4
12	42.4	28	48.6	60	41.8
13	43.2	29	48.8	63	42.2

t min	h cm	t min	h cm	t min	H cm
14	43.8	30	49	67	36.8
15	44	31	49.4	72	33

During Experiment 1, capturing the effluent quality at formation of the floc blanket was not possible due to the effluent not reaching the outlet level of the experimental setup (Fig. 3.9). Through the stepwise increment of inflow velocity during Experiment 2, effluent quality at the formation of the sludge blanket was captured.

4.3.1.2 Results of Experiment 2

***Table 4.9B** - Experiment 2 Variation of inflow velocity, floc blanket height and effluent turbidity*

Time min	Inflow velocity mm/sec	Floc Blanket height (cm)		Eff turbidity
		FB Top	FB Bottom	
0	1.15	20	0	NA
13	1.15	-	0	NA
18	3.4	15.5	0	NA
37	3.4	26	4	NA
40	7.9	-	4	NA
42	7.9	-	4	NA
49	7.9	47	4	NA
52	7.9	53	4	82
68	7.9	87	8	-
73	7.9	92	13	41.5
83	7.9	107	17	33.2
93	7.9	116	22	33.5
101	7.9	122	17	31

Floc blanket top could not be clearly distinguished at some instances where it was not possible to capture the readings.

The effluent reached the outlet level after 52 minutes of starting the experiment. Until that effluent turbidity measurements were not possible. The effluent turbidity could be measured afterwards.

Table 4.9C and 4.9D gives the test results of the next two experiments, which were conducted to study the effect of temperature variation on the floc blanket.

4.3.1.3 Results of Experiment 3

Table 4.9C *- Experiment 3, Variation of inflow temperature, sludge blanket height and effluent turbidity (Upward flow velocity 2.94 mm/sec)*

Time min	Inflow temp °C	Height cm	Effluent turbidity NTU
0	24	-	-
41	24	57	4.72
43	24	57.6	4.3
48	24	58	4.87
53	24	58.4	4.45
58	24	58.6	3.94
63	24	58.6	3.89
69	29	59.4	3.64
70	35	59.4	3.43
71	36	59.6	3.33
72	38	59.6	3.54
73	40	59.6	3.56
74	44	59.6	3.46
75	46	59.6	3.92
76	46	59.6	4.26
77	47	59.6	4.08
78	51	60	4.93
79	53	60.6	3.92
80	53.5	60.8	4.7
81	54	60.8	-
82	55	61	-
83	56	61.2	-
84	57		-
85	58	61.6	-
86	59	61.8	-
87	60	62.2	-
89	61	62.2	-
90	61	62.6	-
91	61.5	63.2	-
93	63	64.6	-
94	61	63.4	-
95	64	64	-
96	63.8	64.2	6.29
103	54	74	-
105	51	81	-
107	50	92	-
109	51	102	43.5

Time min	Inflow temp °C	Height cm	Effluent turbidity NTU
110	52	103	-
111	51	101	-
112	50.5	100.8	48.8
113	50	100.8	-
114	50	100.6	-
115	49.5	100.8	-
116	49	100.8	40.8
117	49	100.6	24.8
118	48.5	100.6	23.7
119		100.6	14.4
121	47.5	101	13.1
123	46	100.2	13.2
125	45		9.7
127		100	-

With the temperature increase in a more rapid rate, collection of effluent water for each and every temperature-blanket height reading was impracticable which lead to the non-availability of some effluent turbidity readings.

During the fourth experiment, repeatability of the behavior of floc blanket with inflow temperature increase was tested. In addition readings were continued in the temperature decreasing phase. Temperature at the effluent outlet level also measured.

4.3.1.4 Results of Experiment 4

***Table 4.9D** - Experiment 4, Variation of inflow temperature, sludge blanket height and effluent turbidity (Upward flow velocity 4.25 mm/sec)*

Time min	Temperature °C	Height cm	Effluent Temperature °C	Effluent turbidity NTU
Heat On	23			8.6
1	23	100.2	24	12.2
2	28.5	100.6	24.5	13
3	30	100.6	24.5	15.5
5	32	100.8	24.5	18.4
6	36	101.6	24.5	26.6
7	36.8	101.2	24.5	35.6
9	38.5	103	24.5	48.6
10	40	103.4	24.5	55.3
11	41	104.4	24.6	47.6
12	42.5	106.8	24.6	55
14	44	127.4	24.7	73.2

Time min	Temperature ^{o}C	Height cm	Effluent Temperature ^{o}C	Effluent turbidity NTU
Heat Off				
0	44	127.4		-
2	41	127.2	25	-
4	40	127.2	26.5	-
6	40		27	99.2
8	39	128.2	27	-
10	37	129.6	27	94.6
12	36.5	129.2	27.5	87.3
14	35.5	129.4	27.6	89.1
16	34	129.4	27.8	81.2
18	33	128.6	28	70.6
20	32	128.6	28	-
22	31	128	28.5	63.1
26	30	127.8	28.5	61.3
28	29.5	127.2	28.5	51.7
30	29	127	28.5	60.3
32	28.5	127	28.5	45.1

With the temperature decrease in a rapid rate, collection of effluent water for each and every temperature-blanket height reading was impracticable which lead to non-availability of some effluent turbidity readings.

4.3.2 Testing at full-scale Pulsator® floc blanket at Kandy South WTP

After establishing the effect of temperature variation on sludge blanket in the laboratory scale experiment, observations were made in full scale, the Pulsator® unit at the Kandy South treatment plant.

Table 4.10 gives the data collected during eight hours from 8.30 am to 3.00 pm on 25th December 2015. (Tables 3.8A and 3.8B)

Table 4.10 *- Variation of inflow and Sludge blanket characteristics*

Time	**Influent NTU**	**RWT Tem**	**pH**	**Tem. Bottom**	**SV Bottom**	**Temp Mid**	**SV Mid**	**Temp Top**	**SV Top**	**Pul Out NTU**
8.30	5.37		7.33	23	0.22	23	0.24	23	0.11	6.6
9.00	3.9		7.35	23	0.17	23	0.16	23	0.22	3.49
9.30	4.83		7.38	23.5	0.04	23	0.17	23	0.22	5.32
10.00		23.8	8.84	23	0.076	23.5	0.02	23.5	0.11	
10.30	3.58	24.9	7.24	24	0.24	24	0.25	24	0.08	2.88
11.00	4.04	24.8	6.82	23.5	0.22	23	0.09	23.8	0.05	2.53
11.30	4.11	24.3	7.05	23.5	0.072	24	0.22	24	0.09	1.76

Time	Influent NTU	RWT Tem	pH	Tem. Bottom	SV Bottom	Temp Mid	SV Mid	Temp Top	SV Top	Pul Out NTU
12.00		24.8	7.25	23.5	0.2	23.5	0.17	24	0.05	2.23
12.30	3.04	24	7.35	23.5	0.2	23.5	0.19	24	0.04	2.36
13.00	3.72	24.3	7.48	23.5	0.25	23.5	0.16	23.5	0.1	2.24
13.30	5.25	24.3	7.51	23.5	0.072	23.5	0.23	23.5	0.06	2.3
14.00	3.67	25.9	7.53	23.5	0.11	24	0.19	24	0.13	3.61
14.30	3.06	26	7.16	23.5	0.22	24	0.07	24	0.14	2.99
15.00	3.03	25.8	7.06	24	0.26	23.5	0.1	24	0.09	2.9

Note: Temperature ^{o}C, SV sludge volume fraction, Turbidity in NTU

4.4 Formation of the sludge blanket at pulsator startup, Kandy South WTP

One Pulsator® unit at Kandy South treatment plant was taken out of operation. After emptying the Pulsator® tank, all internal pipes, stilling plates, and other fixtures were cleaned and repaired, and startup was carried out. Tables below give the observations made during 16 days period starting from the date at which inflow started until Pulsator® sludge blanket is satisfactorily formed.

The inflow rate, pH and turbidity of raw water, Pulsator® and treated water were obtained daily or two to three times a day. The pulsation characteristic; pulsation rate, pulsation height, flush time and suction time were also recorded.

The formation of the floc blanket was visualized by obtaining sludge volume percentage. It is planned to measure sludge volume fraction of top, middle and bottom layers of the blanket. However, during the first six days of startup, no floc blanket has formed. Turbidity readings of each layer were recorded instead. From 7th day onwards floc blanket was appearing in the bottom layer. The sludge volume fraction could be recorded only in the bottom layer until the 12th day after Pulsator® startup. The floc blanket was formed in all three layers after the 12th day.

The SVT, SCT, and V_s of the particles within the blanket were tested three times a day in the top, mid and bottom layers of the blanket after formation of the blanket from 12th day until the 16th day. Tables 4.11, 4.12 and 4.13 summarize the RWT, EFT, inflow rate, pulsation rate, and turbidity, *SV*, *SCC* and V_s. The last three parameters were tested after formation of floc blanket.

Table 4.11 *- Pulsator® startup at Kandy South water treatment plant; RWT & EFT data*

Time	RWT	EFT	Time	RWT	EFT	Time	RWT	EFT	Time	RWT	EFT	Time	RWT	EFT
0	14	1.4	66	-	-	143	357	5.1	216	15	4.6	298	10	2.5
1	14.6	1.2	68	-	-	146	367	8.1	218	13.8	4.2	300	10.1	2.9
2	16.2	1.5	70	-	-	148	353	9.18	220	12.9	3.6	302	11.4	4
3	15.5	1.6	72	-	-	150	205	8.41	222	13.5	3.5	304	10.8	4.3
4	15.9	1.5	74	-	-	152	181	7	224	13.2	4	306	10	4.3
5	15.3	1.3	76	-	-	154	186	7	226	13	4.3	308	9.6	4.1
6	13.4	1.6	78	-	-	156	180	6.8	228	12.9	3.4	310	10.4	3.8
7	13	1.5	80.5	5.3	4	156.5	184	18	230	10.8	2.7	312	10.6	3.6
8	13.2	1.2	82	4.8	2.55	158	172	39.4	232	12.1	2.9	314	9.3	3.2
9	12.6	1	84	3.2	1.4	160	144	19.6	234	9.47	3.58	316	9.4	2.8
10	12.3	1.1	86	4	1.68	161	160.1	16.5	236	34.2	3.5	318	8.28	2.6
11	16.1	2.4	88	4.08	2	162	227	14	238	90.7	3.4	320	-	-
12	17.4	3.8	90	4.8	1.88	164	259	19	240	88.2	2.7	322	13	4.2
14	12.6	1.3	92	5.3	2.1	166	210	13.4	242	70.1	2.2	324	-	-
16	14.1	3.8	94	6.9	3	168	194	10.4	244	56.4	2.3	326	12.9	2.9
18	13.4	3.6	96	6.8	2.8	170	134	15.4	246	40	1.6	328	11.4	2.8
20	12.7	2.8	98	7	2.4	172	86.7	9.7	248	28.6	3.7	330	33.4	2.6
22	11.7	2.25	100	6.93	2.6	174	65.4	8.6	250	24.4	2.8	332	148	2.9
24	10.3	3	102	7.19	2.41	176	49.3	11.7	252	27.1	3	334	196	2.7
26	9.6	3.1	104	6.6	4.1	177	57.3	11.4	254	34.6	2.4	336	164	3.1
28	9.3	2.96	106	5.2	2.2	178.5	46.1	16.3	256	22	2.5	337.3	142	2.8
30	7.5	2.4	111	5.3	2.5	180	43.4	8.81	258	18.7	3	340.3	93.1	2.7
32	6.6	2.7	110	5.8	2.7	182	36.7	7.2	260	17.4	3.1	342	88.1	3
34	13.9	6	112	4.6	2.1	183.5	33.1	6.3	262	20.1	3.2	344	75.9	3
36	8.9	2.8	114	4.4	2.3	184	27.1	4.4	264	48.6	2.8	346	63.4	2.96
38	6.6	2.8	116	12.4	2.7	186	20.2	3.2	266	50.6	3	348	57.2	2.8
39	6.8	2	118	18.3	3.1	188	-	-	268	51	2.9	350	54.9	2.97
40	7.2	2.1	120	32.4	3.4	190	-	-	270	51.8	2.7	352	33.7	3.1
42	5.9	2.4	122	57.8	2.9	191	28.1	2.9	272	44.6	2.8	354	27.1	2.8
44	7.4	2.8	124	52.6	5	192	33.4	2.9	274	33.2	3.1	356	33.4	2.4
46	7.9	3.1	126	53.8	8.6	194	40.2	2.9	276	46.5	2.6	358	42.3	2.6
48	7.3	2.9	128	79.2	4.7	196	33.1	2.7	278	30.6	3.2	360	48.4	2.7
49	6.9	2.4	129	68.9		198	21.2	3.1	280	24.2	2.7	362	59.4	2.3
50	7.6	2.4	130	55.3	10	200	15.6	7.2	282	13.2	2.3	364	58.6	2.6

Time	**RWT**	**EFT**	**Time**	**RWT**	**EFT**	**Time**	**RWT**	**EFT**	**Time**	**RWT**	**EFT**	**Time**	**RWT**	**EFT**
			.3											
52	7.1	1.9	132	48.4	9.71	202	21.3	4	284	12.1	2.8	366	57	2
54	6.3	2.1	134	42.1	6.1	204			286	14.2	2.9	368	61	2.4
56	5.1	2.7	136	57.1	3.14	206	15.6	3.7	288	13.1	2.6	370	41	2.7
58	-	-	138	57.9	3	208	14.3	6.4	290	10.4	2.3	372	48	2.5
60	-	-	140	256	2.96	210	13.3	3.8	292	9.2	2.5	374	45.6	2.5
62	5.1	1.85	142	-	-	212	13.6	5.3	294	9.6	2.8	376	53.1	2.8
64.5	-	-	-	-	-	214	12.8	4.8	296	9.7	2.7	378	27.1	2.73
380	12.4	2.8	390	11	2.1	400	12.6	2.4	410	8.7	1.9	420	10.2	1.3
382	13.1	2.6	392	12.3	2.7	402	10.2	1.9	412	9.3	2	422	8.6	2.2
384	13	2.3	394	13.4	2.9	404	10.6	1.8	414	9.8	2.1	424	9.11	2.4
386.45	11.25	2	396	10.8	1.8	406	11.2	1.8	416.3	13.5	1.5	426	8.9	2
388	11.54	2	398	14.7	2.1	408	11.5	1.9	418	12.4	1.4	428	7.68	2.2

Few readings were not available.

Table 4.12 - *Pulsator® startup at Kandy South water treatment plant (1-6 days), RWT, Flow, Pulsation, and turbidity at three layers (prior to the formation of the blanket)*

Day	Hour	RWT	Pul B Flow m^3/hr	Pulsation rate m/hr	Turbidity NTU		
					Bottom	Middle	Top
0	13.50						
1	10.50	13.9	265	4.35	25.0	19.2	19.1
1	14.00	6.6	265	4.35	22.0	18.1	18.0
2	8.5	5.1	265	4.35	25.1	14.2	13.3
2	10	5.0	265	4.35	51.2	12.5	9.7
3	15.5	3.49	265	4.35	79.1	11.4	9.9
5	8.5	68.9	265	4.35	180.0	41.0	40.0
6	10.5	181.0	400	4.86	71.4	44.3	49.0
6	11	-	415	4.92	87	44.9	42.4

The analysis of the test results obtained in each of the tests was presented in Chapter 5.

Table 4.13 ***-*** *Pulsator® start up at Kandy South water treatment plant (7-16 days), RWT, Pulsation rate and SVF, SCC and V_s of all three layers (after blanket formation started from the bottom layer)*

Day	Hour	Avg. RWT	Pul B Flow m3/hr	Pulsation rate m/hr	Daily average SVF			Daily average SCC mm/hr			V_s mm/hr			Avg. EFT
					Bottom	Middle	Top	Bottom	Middle	Top	Bottom	Middle	Top	
7	10		500	5.24	0.50	0	0	Testing not done due to non-availability of sludge blanket in all three layers			Testing not done due to non-availability of sludge blanket in all three layers			
7	13.5		500	5.24	0.30	0	0							
8	9		500	5.24	0.30	0	0							
8	11.5		500	5.24	0.27	0	0							
9	11		625	5.54	0.30	0	0							
10	0		625	5.54		0	0							
10	6		625	5.54		0	0							
10	11		625	5.54	0.32	0	0							
11	6		625	5.54		0	0							
11	16		625	5.54		0	0							
12	10	10.4	625	5.70	0.255	0.265	0.24	2.512	2.841	1.5155	2.83	2.11	2.8	3.23
12	14.5		625	5.70										
13	8	45.2	675	4.77	0.237	0.307	0.22	2.97	2.53	2.72	2.17	1.71	3	3.03
13	12.3		675	4.77										
13	12.7		675	4.77										
14	7.5	72.9	675	4.77	0.285	0.22	0.25	2.51	2.84	2.13	2.00	2.03	3.42	2.85
14	12.5		675	4.77										
14	15.33		675	4.77										
15	7.75	43.7	675	4.77	0.275	0.287	0.262	3.26	2.90	3.01	2.17	2.18	1.67	2.55
15	12.5		675	4.77										
15	15.3		675	4.77										
16	7.7	11.9	620	4.56	0.223	0.252	0.243	2.45	3.48	3.56	2.23	1.83	2.14	2.4
16	12.5		620	4.56										
16	15.5		620	4.56										

CHAPTER 5: DISCUSSION

5.1 Effect of raw water quality on floc blanket formation:

Water from natural sources is affected by climatic conditions, geographical conditions environmental conditions and anthropogenic conditions in the water catchments. Raw water quality in surface water sources and groundwater sources varies depending on the characteristics of the particular catchment. The materials present in water arise from land erosion, the dissolution of minerals, the decay of vegetation, and domestic and industrial waste discharges (Bratby, 2016). Quality of raw water can be measured based on the physical, chemical and biological properties. A water treatment process is designed to remove the impurities in water. The treatment process is decided depending on the raw water quality. The clarifier unit, which is a main component of the treatment process removes the suspended particles. The principal mechanism used in clarifier for removal of particles is by gravitation. Coagulants are used to agglomerate particles which will increase the size and weight of particles and facilitate enhanced gravitational settling.

5.1.1 Floc blanket prepared with river water

Parameters raw water turbidity, pH and coagulant dose (PACl) were considered for analysis. The cohesivity of the blanket measured using sludge cohesion coefficient (*SCC*) with respect to each of these parameters was evaluated.

Figure 5.1 (a,b) shows the variation of *SCC* with respect to raw water turbidity (RWT) and coagulant dose.

5.1.1.1 Data Analysis – effect of RWT and PACl dose on *SCC* (river water)

Correlation between the two variables *SCC* and RWT was calculated using the Pearson correlation (r) between the two parameters. The correlation is deemed to be significant when the p value is less than the significance level $\alpha=0.05$.

Statistical analysis shows that there is a significant positive linear correlation between the two variables *SCC* and RWT ($r=0.86$, p-value $0.01<0.05$) in the tested raw water turbidity range of 50 to 400 NTU. Further, it is found that *SCC* has a moderate linear correlation with coagulant dose ($r=0.65$). However this correlation is not significant (p-value $0.11>0.05$) (Table 5.1).

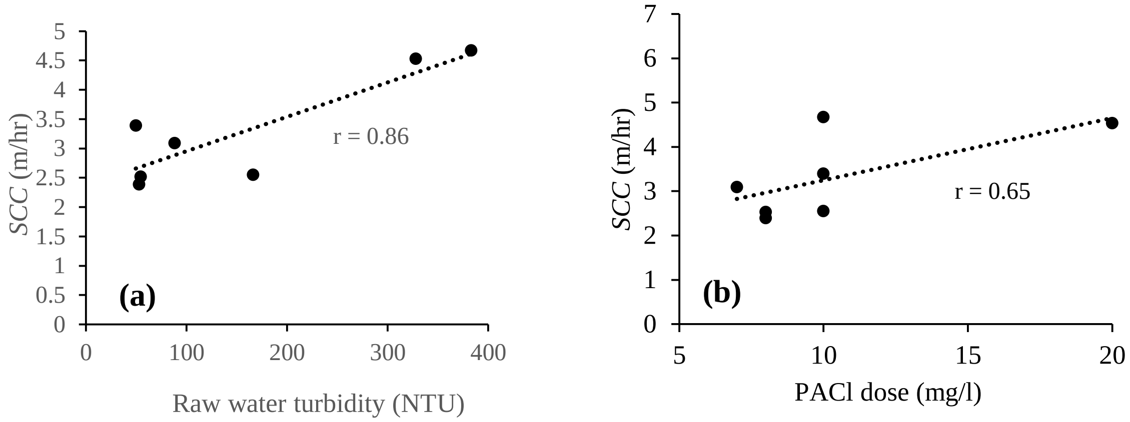


Figure 5.1 - Variation of SCC with (a) raw water turbidity and (b) PACl dose

Table 5.1 *– Relationship between RV* **(c)** *l SCC*

Variables	**r**	**Significance (P value)**
Linear Relationship		
Dependence of SCC on influent (RWT) turbidity	**0.86**	**0.01**
Dependence of SCC on PACl dose	0.65	0.11

Four mechanisms of destabilization of colloidal dispersions are defined (Bratby, 2016);

a. Double layer compression
b. Adsorption and charge neutralization
c. Enmeshment in precipitate (sweep flocculation)
d. Adsorption and inter particle bridging

The amount of electrolyte required to achieve coagulation by double layer compression is independent of the concentration of colloids.

When a sorbable coagulant of opposite charge is introduced to the solution, destabilisation will occur by adsorption on to the colloidal surfaces. The destabilization will occur at much lower dosage than in double layer compression. The destabilization is stoichiometric. Overdosing of sorbable coagulant will lead to

charge reversal and restabilisation of suspension. Hydrolyzed species of Al (III) and Fe(III) can cause coagulation by adsorption. (Bratby, 2016);
When a metal salt with sufficiently high concentration of ions (eg. $Al_2(SO_4)_3$, $FeCl_3$) is added to the solution, precipitates of metal hydroxides will form (eg. $Al(OH)_3$, $Fe(OH)_3$). These precipitates will enmesh the smaller particles with them when they settle (Packham 1965). This phenomenon called sweep floc enables complete settling of the colloids in the solution. Sweep coagulation does not depend on charge neutralisation. Depending on its solubility-pH relationships, an optimum pH exists for each coagulant. Sweep floc coagulation is the most important mechanism in coagulation.

Above test results show an increase in raw water turbidity resulted in increased blanket cohesivity, as well as the coagulant dose. As per available knowledge, the amount of electrolyte required to achieve coagulation by double layer compression is independent of the concentration of colloids. When charge neutralization by adsorption a stoichiometry in coagulation is observed. That is the coagulant dose increases with increasing colloidal concentration.
Following conclusions were arrived on the effect of raw water quality on a floc blanket, based on the blanket cohesivity measured using *SCC*.

- ➢ The blanket cohesivity has a significant positive linear relationship with the raw water turbidity within the turbidity range analysed; 0–400 NTU
- ➢ Increase in blanket cohesivity with coagulant dose is observed. However, no significant correlation has been observed.

The mechanism of particle structuring within the blanket, particle cluster formation as well as the variation of SCC with respect to RWT shall be further investigated to explain the blanket cohesivity and the relationship between cohesivity, influent turbidity, and coagulant dose.

5.1.2 Pulsator® floc blanket

A number of sludge cohesion tests were performed to understand the characteristics of the actual floc blanket (Pulsator® @ Kandy South). The cohesivity of the Pulsator® floc blanket varies within the range 2.97 – 4.06 m/hr. (0.83 to 1.13

mm/sec). As per the recommendations of Degremont (2007), the *SCC* value of quickly settled consistent sludge varies within the range of 0.8 to 1.2 mm/sec.

5.1.3 Floc blanket prepared with synthetic raw water

The relationship between the cohesivity of the blanket and the influent turbidity was analysed using test results of floc blanket prepared with synthetic raw water as reported in Chapter 4, Section 4.2.3.2 and Section 4.2.3.3. The coagulant dose at which the *SCC* was highest was plotted against the respective raw water turbidity (Figure 5.2).

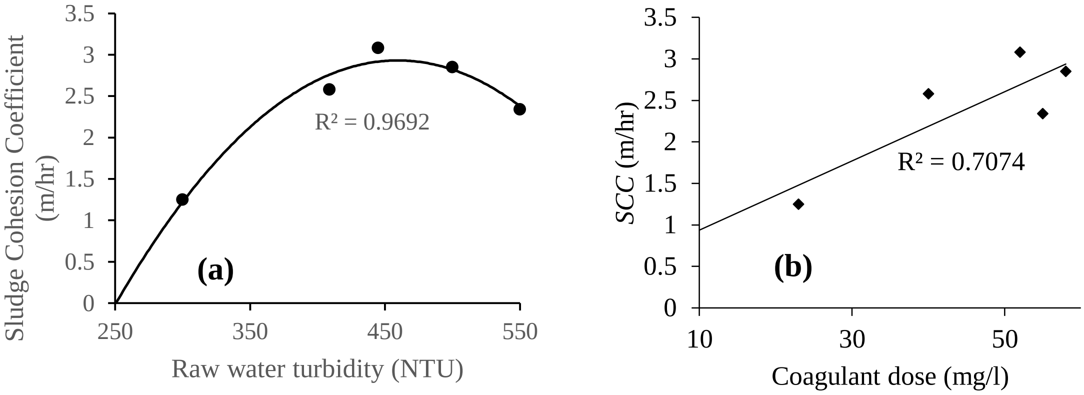


Figure 5.2 *- Variation of SCC with (a) raw water turbidity and (b) PACl dose-(synthetic)*

5.1.3.1 Data Analysis – effect of RWT and PACl dose on *SCC* (synthetic water)

The goodness of fit of the second order polynomial regression between the two variables *SCC* and RWT was calculated using the Coefficient of determination. The model is significant when the p -value is less than the significance level α=0.05.

Correlation between the two variables *SCC* and coagulant dose was calculated using the Pearson correlation (r) between the two parameters. The correlation is deemed to be significant when the p value is less than the significance level α=0.05.

Figure 5.2(a) shows that the cohesivity of the blanket (measured using *SCC*) increases with increasing raw water turbidity (RWT), up to 450 NTU. This result is comparable to the results obtained in the floc blanket formed using river water. Beyond 450 NTU, the blanket cohesivity has decreased. A quadratic relationship was established between the two variables. Statistical analysis shows that there is a significant second order polynomial relationship between the two parameters with R^2=0.97 and p-value= 0.03 < 0.05 in the tested raw water turbidity range

(250 to 550 NTU). Further, it is found that the *SCC* has a positive linear correlation with the coagulant dose. However no significance is reported (r=0.84, p-value=0.07>0.05).

Previous studies have recommended pre sedimentation or two-stage clarifier when RWT increases beyond 450 NTU (Sung et al., 2005, Chen et al., 2003).

Increased dosage of coagulant leads to restabilization of destabilized particles by charge reversal. Cohesivity of the blanket may reduce due to destabilization of the particles clusters.

Figure 5.3 shows the relationship between the same parameters using all the data of original and repeat tests. Statistical analysis confirms the significant second order polynomial relationship between the two parameters with R^2=0.75 and p-value < 0.05.

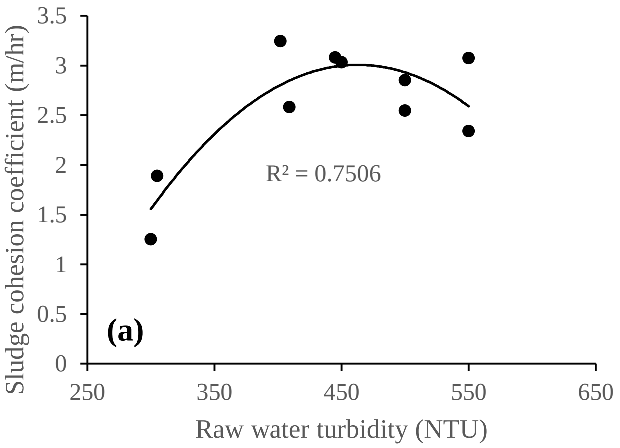


***Figure 5.3** - Variation of SCC with (a) raw water turbidity, (b) Coagulant dose (All data)*

It can be concluded that the raw water turbidity has a significant correlation with the blanket cohesivity, indicated by the *SCC*. However a significant relationship between coagulant dose and *SCC* could not be established.

The *SCC* of the blankets prepared using river water and synthetic raw water as well as the pulsator sludge blanket varies within the range 0.3 to 1.29 mm/sec. The recommended range 0.3 – 1.2 mm/sec (Degremont, 2007).

With the above results it is concluded that;

- With increasing raw water turbidity, the cohesivity of the blanket increases up to a turbidity of 450 NTU. There is a significant linear relationship between the raw water turbidity and the cohesivity within this region.
- Beyond 450 NTU the blanket cohesivity reduces due to charge reversal and re-stabilisation of particles.
- When turbidity is > 450 NTU pre-sedimentation is recommended to improve blanket properties.

Further analyses on the mechanism of particle structuring within the blanket, particle cluster formation and changes in blanket cohesivity were made to explain the above observations.

5.2 Effect of operating conditions on sludge blanket

In section 5.1 it is observed that the *SCC* increases with increasing raw water turbidity up to raw water turbidity of 450 NTU.

At present, the optimum coagulant dose to be used in a water treatment plant is determined by laboratory flocculation test (Jar Test). The correlation between the blanket cohesivity and the optimum coagulant dose determined by jar test is unknown.

Under this section, experiments were made to analyse the variation of coagulant dose with respect to the raw water turbidity and determine the correlation between the blanket cohesivity and optimum coagulant dose obtained by jar test. Considering the large number of variables involved in the natural water sources, which will influence the results, tests were performed on synthetic raw water prepared at the laboratory.

5.2.1 Trial tests using synthetic raw water

The test results indicate that the *SCC* varies within the range of 0.91–3.31 m/hr. (0.25 to 0.92 mm/sec). As per the recommendations of Degremont (2007), the *SCC* value of quickly settled consistent sludge varies within the range of 0.8 to 1.2 mm/sec. The *SCC* value of a flocculate that is fragile, light and rich in water, the value of *SCC* might not exceed 0.3 mm/sec. The results of the trial series show that the sludge blankets prepared displays a range of cohesivity depending on the coagulant dosage used in the individual experiment.

Hence it will be useful to find out the coagulant dose at which the optimum cohesivity of the blanket could be obtained.

5.2.2 Results of Test Series

5.2.2.1 Test Series 1- Raw water turbidity 20 NTU to 200 NTU

Even though the test series were planned to start with synthetic raw water turbidity of 20 NTU, it was noted that producing sufficient sludge to carry out the test was not possible with low raw water turbidity samples. The necessary sampling was possible beyond 100 NTU only.

Jar test and *SCC* test were conducted with 30 samples; raw water turbidity 100, 150, 200 NTU and PACl dose ranging from 5-50 ppm.

Optimum coagulant dose for each raw water turbidity and coagulant dose combination was first established using Jar test procedure. The coagulant dose at which the maximum cohesivity of the blanket is observed has also been established.

Figure 5.4 gives the residual turbidity as a function of coagulant dose in each sludge sample. The pH range of the raw water varies within 5.1 to 7.

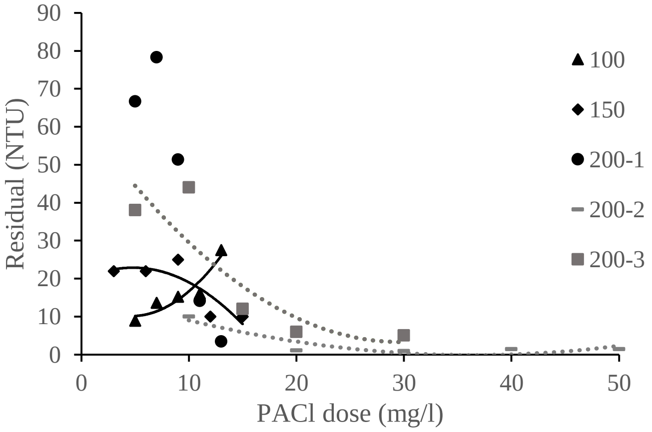


Figure 5.4 *- Residual turbidity versus coagulant dose observed in jar tests*

The coagulation curves developed in the tests were compared with the schematic representation of coagulation observed in jar tests using aluminum and iron salts at constant pH, (Figure 5.5, Weber, 1972). As discussed by O'Melia and Stumm (1967) and Stumm and O'Melia (1968), for systems containing low colloid concentration, coagulation requires the production of a large excess of amorphous hydroxide precipitate. It has been proposed that insufficient contact opportunities exist to produce aggregates of even completely destabilized particles in a reasonable detention time. Such conditions may prevail in many water treatment plants when the turbidity of raw water is low (Packham, 1965).

When the concentration of colloid is increased a smaller coagulant dose is required due to increased contact opportunities. However, a re-stabilization of destabilized particles is experienced with increasing coagulant dose.

The coagulation curves obtained in test series 1 (Figure 5.4) could be explained using the above phenomena. The results of Jar test for 150 NTU and 200 NTU are observed to be in destabilization zone 4 where considerable amount of precipitates of metal hydroxides will form, enmeshing the colloidal particles and sweep floc will occur. However the 150 NTU series test results are not sufficient to capture the minimum residual turbidity and corresponding coagulant dose. The curve relevant to raw water turbidity 100 NTU test series indicates the destabilization being in Zone 2 where particle destabilization due to double layer compression occurs. Coagulant dose for destabilisation in 150 NTU and 200 NTU is in the range of 20 to 25 mg/l whereas it is around 5 ppm for 100 NTU.

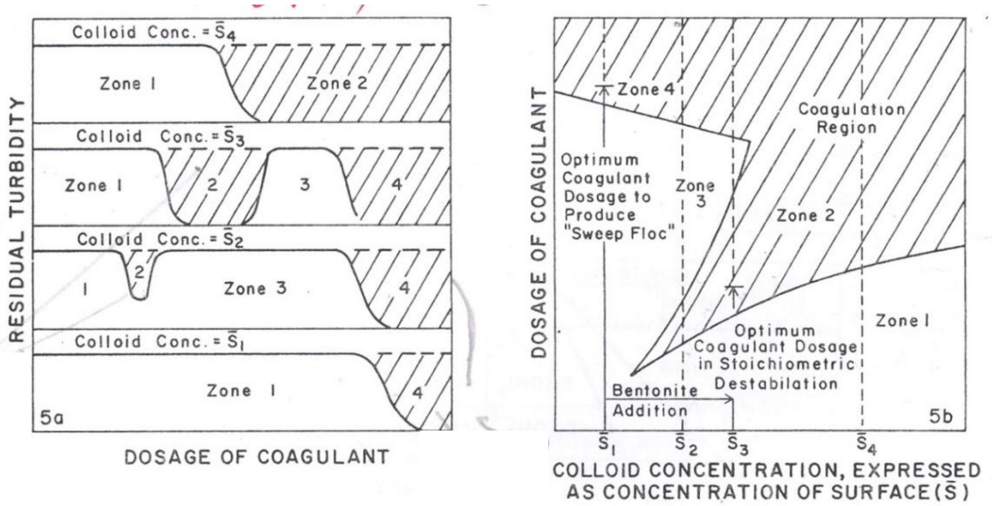


Figure 5.5 - Schematic representation of coagulant observed in jar tests using aluminum (III) or iron (III) salts at constant ph (Weber, 1972)

Figure 5.6 shows the variation of *SCC* with coagulant dose in the same set of samples prepared using the raw water turbidity.

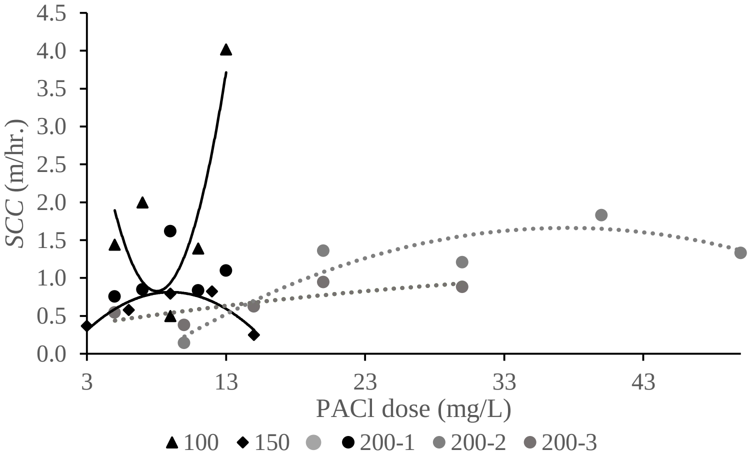


Figure 5.6 *- SCC vs coagulant dose obtained in sludge cohesion test*

The samples prepared with turbidity 150 NTU and 200 NTU shows an optimum coagulant dose where *SCC* was the highest in the range of 5 – 35 mg/l. The sample prepared with 100 NTU shows a lowest *SCC* after which *SCC* keeps on increasing.

When annual seasonal raw water turbidity variation is considered, most of the time the turbidity is below 100 NTU. However, due to the inability of sludge sample preparation, further testing could not be conducted within this range. It is not possible to arrive at reasonable conclusions due to the limited test results available.

5.2.2.2 Tests Series 2 – Turbidity 250 – 550 NTU

Next test series was conducted with sludge prepared using raw water turbidity 250–550 NTU. Figures 5.7 and 5.8 give the outcome of jar test and *SCC* test respectively. A quadratic curve fit was made for supernatant turbidity vs PACl dose and average *SCC* vs PACl dose at different raw water turbidity values.

Sufficient sludge samples could be produced during this test series enabling carrying out the test plan. It is observed that depending on the PACl dose used, the characteristics of the sludge varies. Sludge formed with PACl dose closer to optimum (PACl dose at lowest supernatant turbidity) was consistent, and the raising and lowering of sludge blanket was easy to distinguish. Sludge formed with other PACl doses were light and fragile compared with the sludge at the optimum PACl dose.

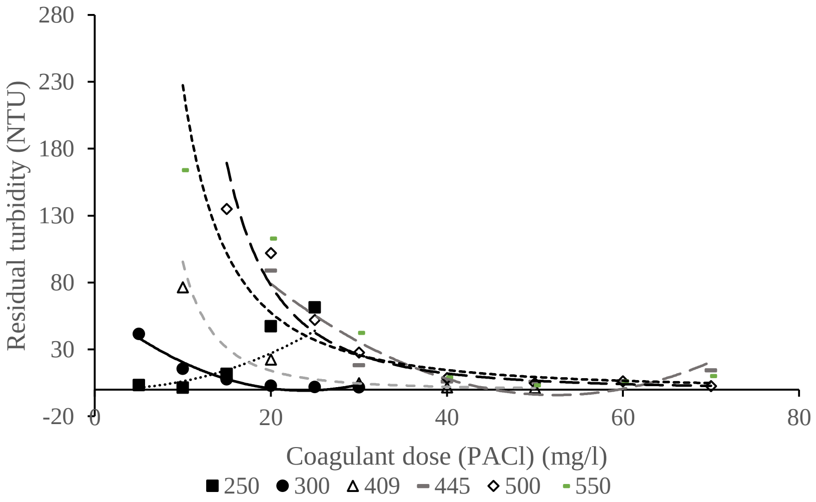


Figure 5.7 *- Residual turbidity versus coagulant dose (250-550 NTU)*

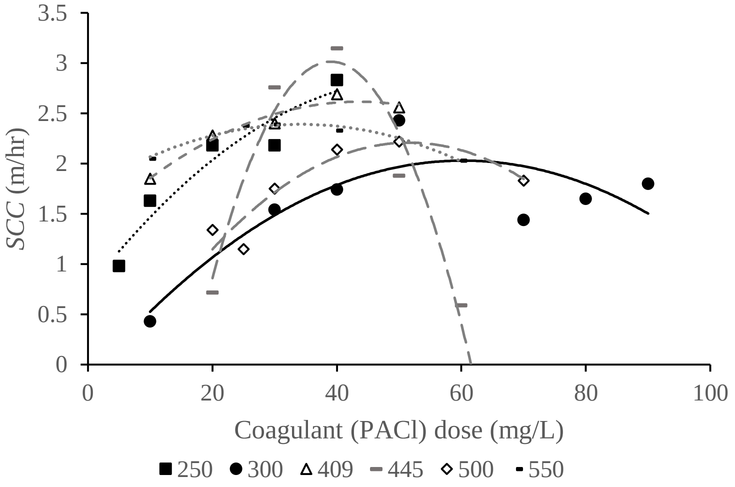


Figure 5.8 *-* SCC *vs coagulant dose (250 – 550 NTU)*

5.2.2.3 Data Analysis – effect of operating conditions

The goodness of fit of the second order polynomial regression between the two variables supernatant turbidity (jar test) and *SCC* (sludge cohesion test) against the coagulant dose was calculated using the Coefficient of determination. The model is significant when the p -value is less than the significance level α=0.05.

After establishing these models, the optimum coagulant dose of jar test where the supernatant turbidity is lowest and coagulant dose which give the highest *SCC* were calculated for each raw water turbidity. The goodness of fit of the second order polynomial regression between the two optimum doses and the respective RWT was then established.

Correlation between the two optimum doses, obtained from the two tests was calculated using the Pearson correlation (r). The correlation is deemed to be significant when the p value is less than the significance level α=0.05.

Statistical analysis of quadratic relationships established between the two variables and coagulant dose at each RWT tested (Figure 5.7 and Figure 5.8) show that there is a significant second order polynomial relationship between the two variables and coagulant dose having R^2 in the range 0.7 to 0.98.

Optimum coagulant dose which gives the minimum residual turbidity and the coagulant dose at which the highest sludge cohesion coefficient is recorded are reported in Table 5.2.

Table 5.2 *- Optimum coagulant dose and respective values at each test*

Raw water turbidity NTU	**Optimum PACl dose @ Jar test**	**Residual NTU**	**Optimum PACl dose @ SCT**	**Highest *SCC* m/hr**
250	5	0.74	8.9	3.19
300	20	2.6	19.9	1.25
409	35	4	42	2.58
445	48	3	39	3.08
500	44	2	42	2.85
550	50	1.2	32	2.34

The plot of optimum coagulant dose in each test series vs raw water turbidity is given in Figure 5.9.

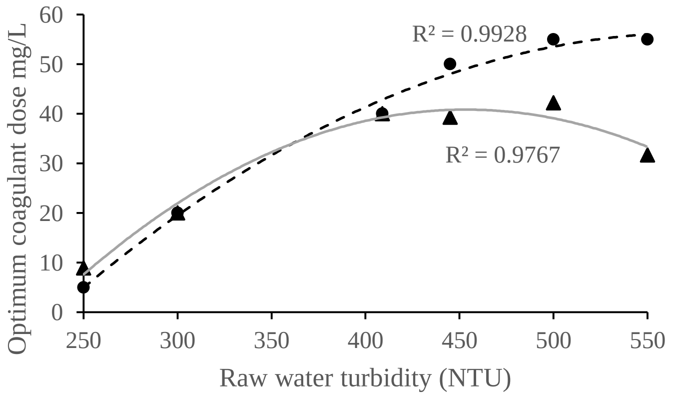


Figure 5.9 *- Optimum coagulant dose at jar test and* SCC *test vs raw water turbidity*

As per Figure 5.9, beyond 300 NTU the optimum dose reported in the SCT is lower than the Jar test results. Both the optimum doses show a significant second order polynomial relationship with RWT. The coefficient of determination (R^2) of the quadratic fit in both cases is 0.98 with a p-value < 0.05. The deviation is in the range 6-24% with respect to the Jar test results.

In practice, the optimum coagulant dose to be used in a water treatment plant is assessed using the laboratory flocculation test (Jar Test). As an outcome of this test series, beyond raw water turbidity 300 NTU, a deviation has been observed between the optimum doses found by the jar test and the dose at which the highest cohesivity is reported (based on the highest *SCC*).

The correlation between the optimum coagulant doses found by the two tests was examined in Figure 5.10. Analysis indicates that there is a significant positive linear correlation between the two parameters (r=0.91, P -value < 0.05).

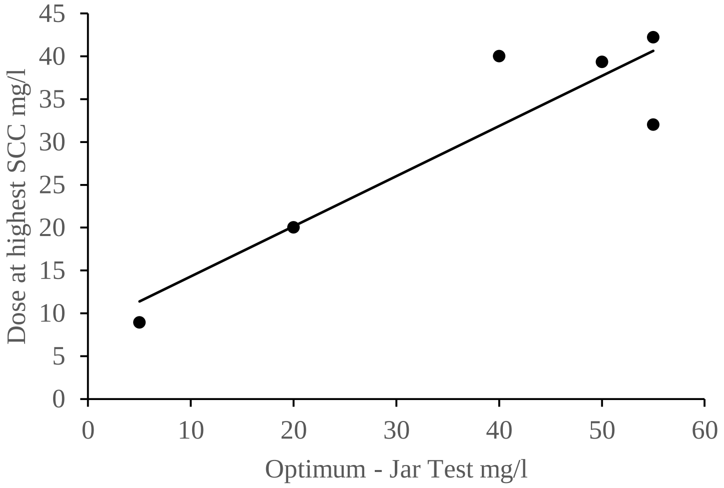


Figure 5.10 *- Relationship between the optimum coagulant doses*

Following observations could be made on the characteristics of sludge blankets formed with respect to its cohesivity. With low *SCC* values, the blanket is light and fragile. High *SCC* values indicate a consistent sludge blanket. Further, it is noted that blanket characteristic observed in the sludge samples prepared with higher turbidity and PACl doses which are far away from the respective optimum dosage are light and fragile, similar to the characteristics of blankets prepared with low turbidity and PACl doses.

Accordingly it is noted that the characteristics of the floc blanket could not be explained solely dependent on the concentration of colloids and coagulant dose. The mechanism of particle structuring within the blanket, cluster formation and blanket cohesivity shall be further investigated to comprehend the floc blanket formation and its characteristics.

In conclusion, with increasing raw water turbidity the optimum PACl dose at which the supernatant turbidity is a minimum (jar test) as well as the PACl dose at which highest SCC is observed also increases (Sludge Cohesion Test). Beyond 300 NTU the PACl dose at which the highest SCC reported is less compared with the standard jar test optimum. A linear correlation is observed between the jar test and SCC test optimum PACl doses as given Figure 5.10.

Further studies have to be carried out in order to establish this relationship.

As an outcome of this study it is found with increasing raw water turbidity highest cohesivity of the blanket is observed at lower coagulant doses than that reported in the laboratory flocculation test (Jar test).

5.2.2.4 Tests Series 2 – Turbidity 250 – 550 NTU (Repeat)

The repeat test series was conducted to ascertain the findings of original test series. Data analysis was done using the methodology elaborated in 5.2.2.3.

Figures 5.11 and 5.12 give the outcome of residual turbidity and the sludge cohesion coefficient of test series 3.

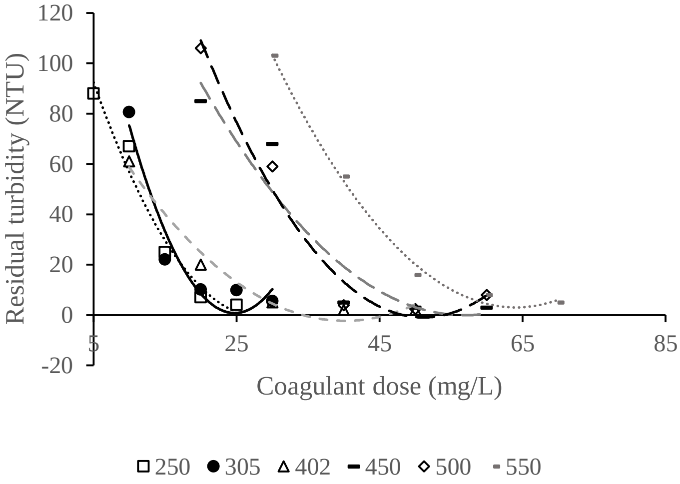


Figure 5.11 *- Residual turbidity versus coagulant dose (250–550 NTU)*

The repeat test also demonstrates results comparable to the original test series.

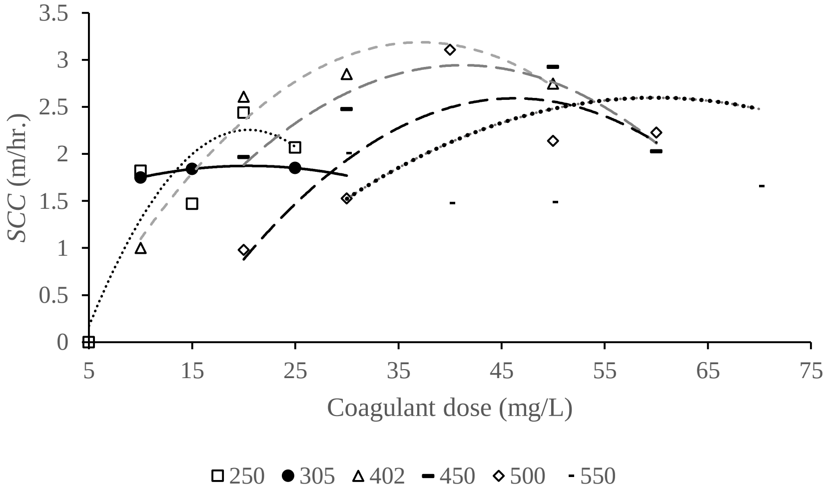


Figure 5.12 **-** SCC *vs coagulant dose (250–550 NTU)*

Table 5.3 gives the results obtained in the repeat test, calculated optimum dose using

Table 5.3 - Optimum coagulant dose derived from the two tests

Raw water turbidity NTU	**Optimum PACl dose @ Jar test**	**Residual NTU**	**Optimum PACl dose @ SCT**	**Highest *SCC* m/hr**
250	28	2	21	2.27
300	25	0.7	21	1.89
409	40	0.2	38	3.24
445	57	0.2	42	3.03
500	51	0.1	46	2.55
550	64	2.9	61	3.07

The relationship between optimum coagulant dose of Jar test and optimum coagulant dose of sludge cohesion test was re-established using all the values of original and repeat tests as given Figure 5.13. A statistically significant linear correlation exists between the two parameters with r= 0.89 and p-value < 0.05.

Since the interceptor is not significant (p-value= 0.17), a linear model is generated without the interceptor. The model gives the relation between the two parameters;

$$Y = 0.78\,X \quad \text{--- 5.1}$$

The model has a correlation r=0.98 and p-value=0.000<0.05. The root mean square error is ±6.11 mg/l. The standard error at 95% confidence interval is 13.62 mg/l. 95% confidence interval for the observed values are given in Table 5.4.

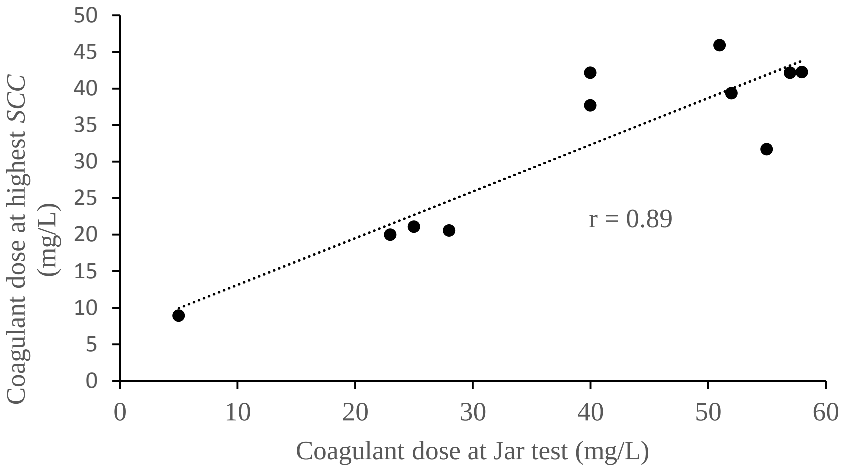


Figure 5.13 *- Relationship between the optimum coagulant doses of the two tests*

Table 5.4 95% confidence interval

Observed value mg/l	**Lower Bound mg/l**	**Upper bound mg/l**
8.9	-9.7	17.5
19.9	4.4	31.7
42.1	17.7	45.0
39.3	27.2	54.4
42.2	31.8	59.1
31.7	29.5	56.8
20.5	8.3	35.6
21.0	5.9	33.2
37.7	17.7	45.0
42.1	31.1	58.3
45.9	26.4	53.6

Therefore it is concluded that equation 5.1 can be used to predict the optimum dose to be used in a treatment plant after finding out the optimum by commonly used laboratory jar test with an accuracy of ± 6.11 mg/L. At higher raw water turbidities (> 300 NTU) this will give savings of coagulant use in the range of 6 - 25%.

5.2.3 Blanket settling velocity

In addition to sludge cohesion test, settling velocity tests were performed on sludge blanket prepared using seven synthetic raw water/coagulant combinations (sludge samples prepared with raw water turbidity 396 ± 0.25%) to understand the variations of blanket settling velocity. The results were presented in Section 4.2.4, Table 4.7.

The settling tests show that the settling velocity of the blanket varies in the range of 0.35 to 1.72 mm/sec. Figure 5.14 gives variation of blanket cohesivity and settling velocity with varying coagulant dose. The graph indicates *SCC* as well as settling velocity varies depending on the coagulant dose used. In addition decrease in settling velocity is observed with increase in blanket cohesivity (Figure 5.15).

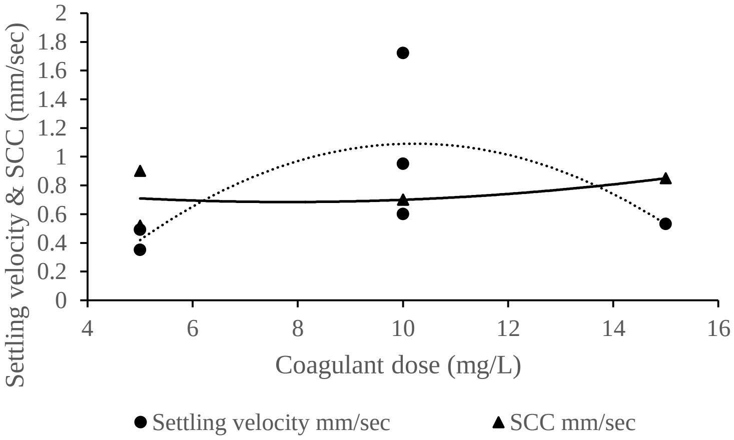


Figure 5.14 *- Variation of blanket cohesivity and the settling velocity with coagulant dose and SCC*

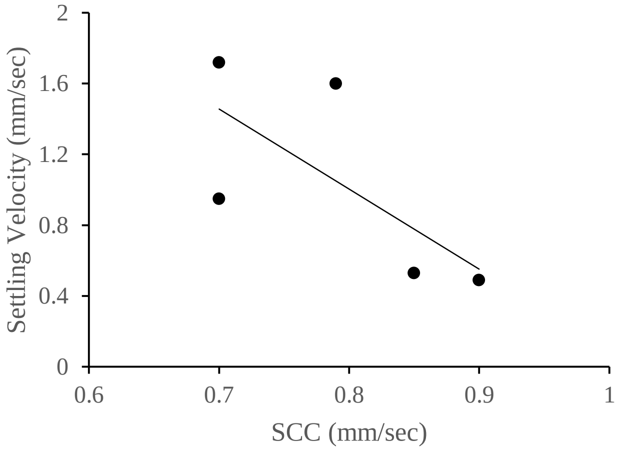


Figure 5.15 *- Variation blanket settling velocity with the SCC*

Sections 5.2.2.2 and 5.2.2.4 concluded there is an optimum cohesivity where the blanket gives the best effluent quality. The coagulant dose to be used derived from the sludge cohesion test is lower than the Jar test optimum when RWT > 300 NTU.

It is proposed that particle structuring within the blanket and particle cluster formation leads to changes in blanket cohesivity. The blanket settling velocity is decreasing with increasing blanket cohesivity. This hypothesis will be further verified during a series of tests conducted to find the blanket behavior at full scale.

5.2.4 Results of testing at full scale using Pulsator® unit Kandy South WTP

Analysis of test results at Pulsator® unit is presented below. The *SCC* and V_s of particles were studied in detail to find the characteristics of sludge blanket with respect to time of the day (Figure 5.16), depth of sampling (Figure 5.17) and temperature. Further the relationship between *SCC* and V_s were studied (Figure 5.18).

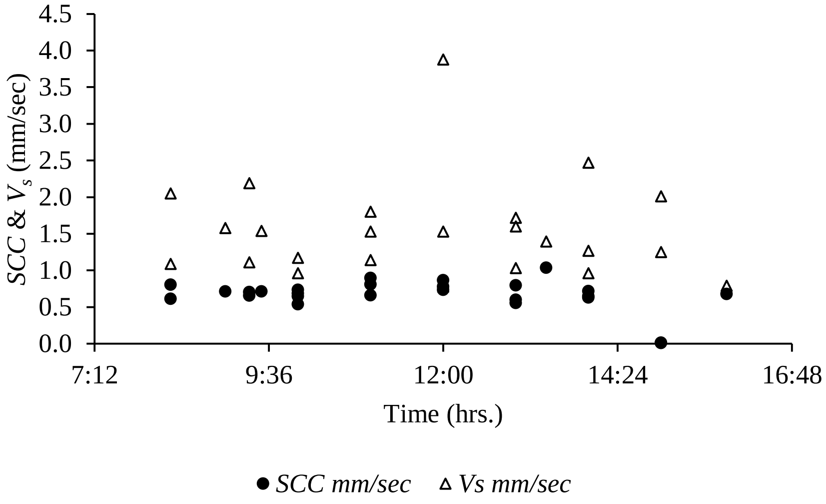


Figure 5.16 *- Variation of* SCC *and* $\mathrm{V_s}$ *with time of the day*

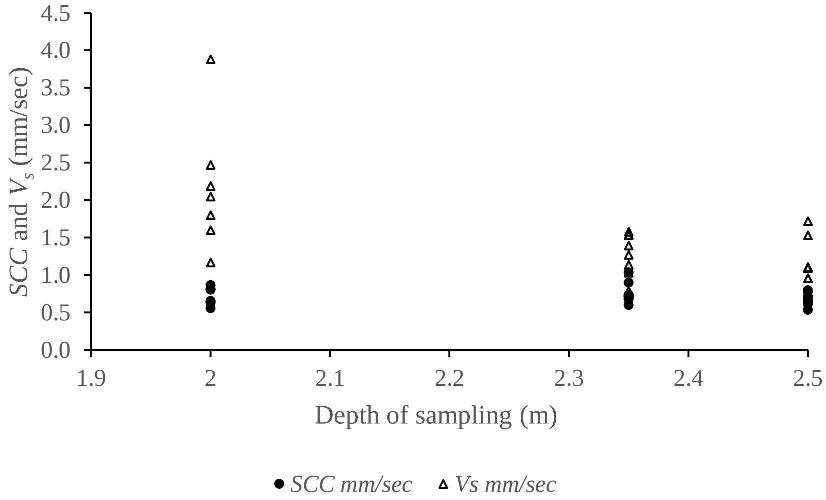


Figure 5.17 *- Variation of* SCC *and* $\mathrm{V_s}$ *with depth*

The *SCC* and V_s varies within the range of 0.01 to 1.04 mm/sec and 0.78 to 3.88 mm/sec respectively. The mean and standard deviation of *SCC* are 0.66 mm/sec and 0.22 mm/sec. The mean and standard deviation of V_s are 1.52 mm/sec and 0.69 mm/sec respectively.

A significant relationship between cohesivity of the blanket and settling velocity could not be found when plotted against time of the day and depth of sampling.

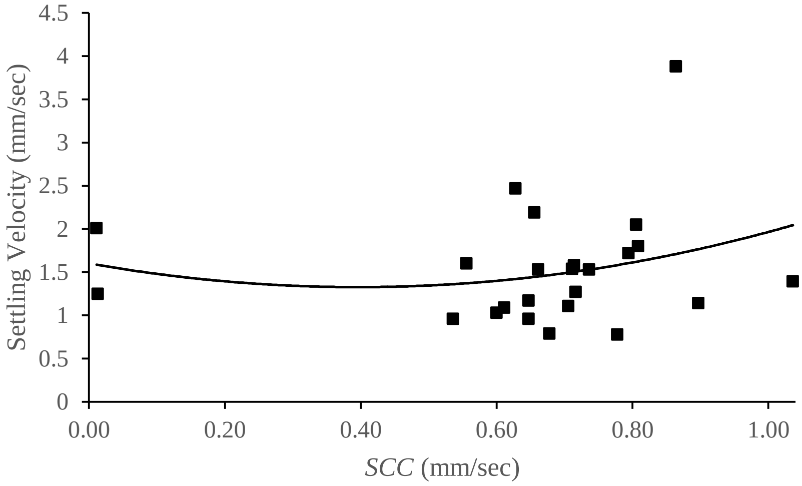


Figure 5.18 *- Variation of settling velocity with SCC*

The second degree polynomial trend lines plotted between the two variables, settling velocity vs *SCC,* shows there might be a decrease in settling velocity with increasing blanket cohesivity (Figure 5.18).

This hypothesis is further analysed with more experimental data under Section 5.3.

5.3 Formation of floc blanket and effect of temperature on the blanket

5.3.1 Laboratory testing using synthetic sludge samples

5.3.1.1. Discussion on Experiment 1

Figure 5.19 shows the variation of sludge blanket height and effluent turbidity until water reached outflow level (Up flow velocity 2.63 mm/sec) (Table 4.9A). The figure shows the formation of floc blanket with the introduction of up-flow.

As stated by Su et al. (2003), Bratby (2006) and Hurst et al. (2014b), two distinct stages were identified in the blanket formation: thickening of the blanket and reaching a steady state. Studies on floc blanket dynamics show that the blanket initially rises with the upward flow of water. The blanket thickens thereafter, reaching a steady state and stabilizing when the up-flow velocity is equivalent to the settling velocity of the floc particles (Gregory et al., 1996; Head et al., 1997; Su et al., 2003; Sung et al., 2005; Bratby 2006; Hurst et al., 2014b).

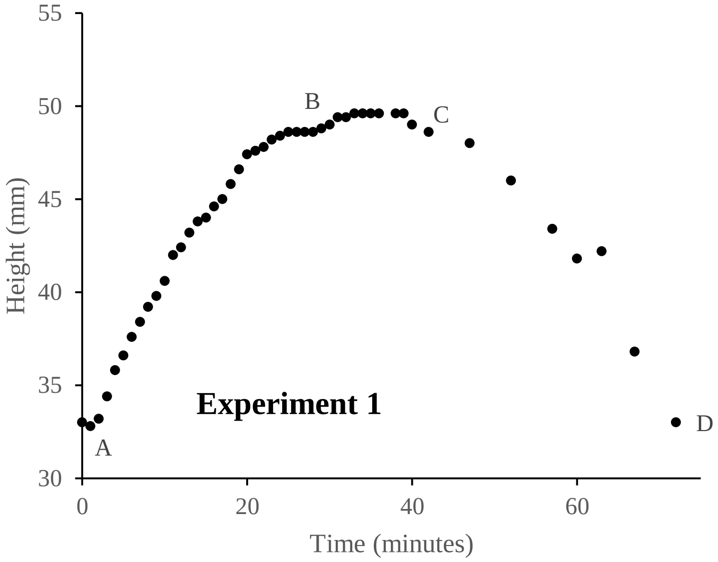


Figure 5.19 - Variation of blanket height and effluent turbidity with time-Experiment 1

As shown in Figure 5.18, during Experiment 1, the floc blanket started to rise with the introduction of upflow due to re-suspension of settled solids by the influent jet. The agglomerated floc particles were disintegrated and released to the supernatant layer. With continued influent loading of solids into the supernatant layer, the re-accumulation of particles occurred. The concentration of the floc blanket continued to increase and thickening of blanket took place (A–B). After some time, the blanket reached a steady state (B–C). Thickening of the blanket continued, becoming steady with a relatively constant height and solid concentration. A third stage (C–D) was observed, in which the blanket showed compression.

The re-establishment of the blanket in the supernatant layer observed in this experiment after introduction of the upflow was due to increases in floc size as a result of particle-particle interactions. Larger flocs with higher settling velocities than the upflow velocity were retained in the blanket. The blanket reached a steady state with a relatively constant height when the settling rates of particles were equivalent to the upflow rate. Hurst et al. (2014a, 2014b) postulated this to be the result of a change in floc size and/or density.

With a high concentration of particles, adjacent particles are essentially in contact with each other. Further settling can occur only by adjustments within the matrix. Compression settling occurs as the settled solids are compressed under the weight of overlying solids, the void spaces are gradually diminished, and water is squeezed out of the matrix.

Literature survey explains the behaviour of the blanket formation observed in this experiment; the blanket initially raises with upward flow until the velocity of up flow is equivalent to the settling velocity of floc particles at which the blanket height remains constant (Bratby J., 2006).

Su et al. (2003) and Hurst et al. (2014b) experiments on blanket dynamics of an upflow suspended bed also reported similar blanket behavior. Hurst et al. (2014b) identified three distinct stages in the floc blanket formation.

1. Thickening (increasing suspended solids concentration) in the absence of an observable floc-water interface.
2. Thickening with an interface (AB)
3. Steady state (BC)

Since this experiment is started with an already formed blanket the solids concentration of the blanket remains unchanged. However the stages 2 and 3 described above is visualized. In addition a fourth stage (CD) depicting the compression of the blanket is identified.

The behavior of blanket in section AB can be explained as follows; the sludge blanket starts raising with introduction of upflow due to resuspension of settled solids by influent jet. The agglomerated floc particles were disintegrated and released to the supernatant layer. With continued influent loading of solids in to the supernatant layer, re-accumulation of particles will occur leading to increase in particle size due to particle-particle interactions. The low energy dissipation rates in a floc blanket coupled with large solids residence time in the floc blanket (Hurst et al., 2010) leads to the expectation that floc have potential to grow in size (Hurst et al., 2014a). This suggests that floc properties change during blanket formation.

Once the sedimentation velocity of the blanket as a whole becomes equivalent to the upflow velocity, blanket will reach a steady state as observed in section BC of the Figure 5.19.

In a typical sludge blanket clarifier, provisions are made to have a quiescent zone above the blanket which creates a density gradient, causing the sludge to flow in the direction of sludge withdrawal cone. Sludge is bled (withdrawn) regularly ensuring that sludge blanket is maintained at the highest density and optimum thickness. When sludge bleeding is not possible blanket top will rise and floc will be decanted to the clear water area. This will gives rise to the effluent turbidity.

Sludge blanket height reduces after sometime due to compression settling. When high concentrations of particles are available, adjacent particles are actually in contact. Further settling can occur only by adjustments within the matrix which is known as compression settling. Compression settling occurs as the settled solids are compressed under the weight of overlying solids, the void spaces are gradually diminished and water is squeezed out of the matrix. Section CD in the Figure 5.19 depicts the compression settling in the blanket.

5.3.1.2. Discussion on Experiment 2

During this experiment upward flow velocity varied in three steps; 1.15, 3.4 and 7.9 mm/sec within a period of 40 minutes; (Figure 3.10) Variation of the effluent turbidity during blanket formation are plotted in Figure 5.20.

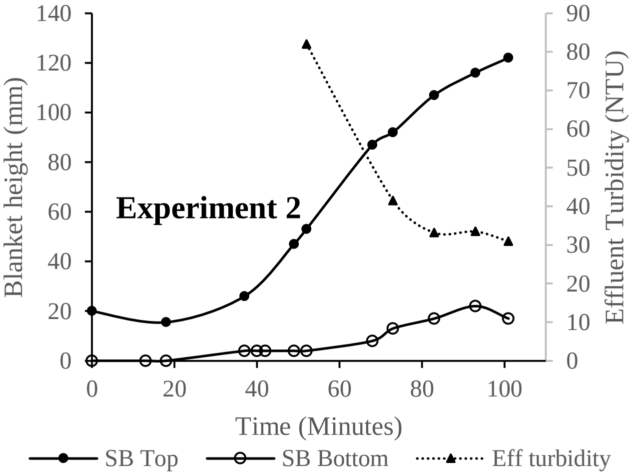


Figure 5.20 - Variation of blanket height and effluent turbidity with time – Experiment 2

This experiment was able to capture the effluent turbidity from the 52nd minute at which the water level inside the cylinder reached the outlet level of the experiment setup. The top and bottom levels of the blanket during the experiment were also recorded. Experiment 2 shows that the effluent turbidity has reduced with blanket thickening. Flocs with settling velocities lower than the upflow velocity were carried into the supernatant layer, resulting in higher initial effluent turbidity. As settling velocity increased with the thickening of the blanket, the effluent quality improved. At the onset of steady state, the effluent turbidity was reduced to 38% of the original value. Accordingly, floc blanket thickening during formation has been confirmed to occur at both variable and constant upflow velocities. This observation is confirmed by Hurst et al. (2014b); thickening of a blanket can occur during either constant or changing floc blanket interface velocity.

5.3.1.3. Discussion on Experiment 3

Figure 5.21 shows the variation of sludge blanket height, effluent turbidity and inflow temperature with time perceived in Experiment 3. The floc blanket was established at an average height of 58 cm during forty to sixty six minutes after introducing the upward flow. After the floc blanket reached a plateau, the inflow temperature was increased. Due to the temperature difference between the higher temperature bottom layers and cooler top layers, a rising buoyant plume was observed in the inner cylinder. After ten minutes of inflow of heated water, the blanket started rising. The convective vertical mixing induced by the rising plume made the blanket to rise gradually. At the same time a gradual increase in effluent turbidity was observed. These observations were comparable to the observations of various researches. (McCorquodale and Zhou, 1993, Wells and LaLiberte, 1997, Taebi-Harandy and Schroeder, 2000, Mahmood et al., 2005).

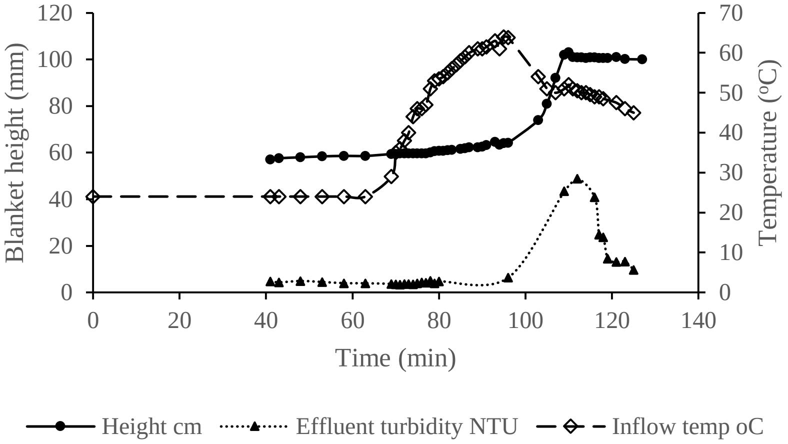


Figure 5.21 *- Variation of sludge blanket height and effluent turbidity and inflow temperature with time- Experiment 3*

During the temperature recession phase, after switching off the heater and allowing the inflow temperature to gradually decrease up to the ambient temperature, the blanket settled at a higher level and effluent turbidity gradually reduced. The behavior of blanket at the temperature recession phase was comparable to the findings of Goula et al. (2008).

Due to the rising buoyant plume produced by the influent temperature rise, convective currents were formed which kept the particles in suspension, leading to a higher effluent suspended solids concentration. As the warmer water kept coming in, the temperature differential decreased and the suspended solids concentration decreased.

5.3.1.4. Discussion on Experiment 4

Experiment 4 was carried out to verify the observations of previous experiments. Figure 5.22 (a) gives the variation of effluent turbidity, blanket height, inflow temperature and effluent temperature with time during experiment 4. Figure 5.22 (b) shows the expansion of sludge blanket with warm water inflow.

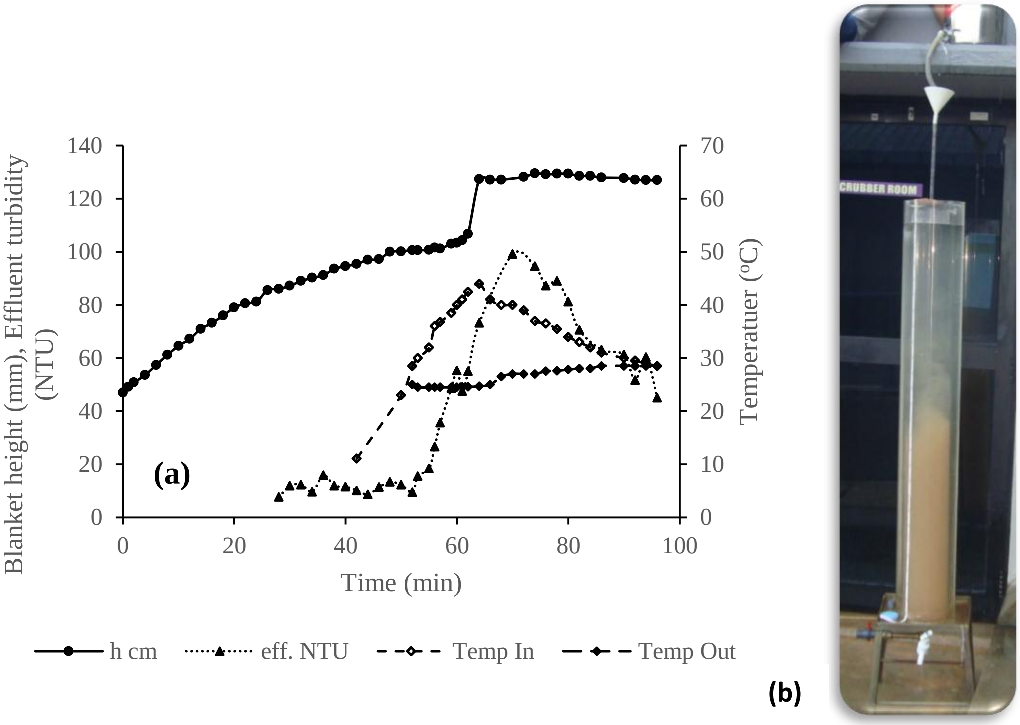


***Figure 5.22 – (a)** Floc blanket height, effluent turbidity, Inflow and outflow temperature variation with time, (b) Expansion of sludge blanket*

Rise of blanket height and rapid increase of effluent turbidity with increasing inflow temperature were confirmed in this experiment. Complete scatter of the blanket was observed after 14 minutes and the blanket height reached the outlet level. A distinct interface between the blanket and clear water could not be observed. When the warm water reached the top levels of the cylinder, the temperature differential decreased, and the blanket started re-stabilising. A second plateau was observed at a higher level after heating the inflow water was terminated. Effluent turbidity has gradually reduced.

Goula et al. (2008) showed a relationship between the slope of influent temperature with time and sedimentation efficiency. When the slope of influent temperature is positive the density of water current is lower than the density of water in the cylinder and hence buoyancy drives it upwards preventing the deposition of particles in it. On the other hand when the slope is negative, the temperature difference between top and bottom layers reduces and buoyancy effect diminishes allowing the particles to settle back and reduce the effluent turbidity. This study confirms the above finding.

Detailed analysis of the blanket formation, response to temperature variations and effluent quality behavior were made using the test results of experiment 4.

Figure 5.23 gives the variation of influent temperature and effluent turbidity with time during the temperature increasing and decreasing phases. Figure 5.24 gives the variation of effluent turbidity with temperature.

It is noted that the rate of change of effluent turbidity is different in temperature increase and recession phases. The temperature variation in recession phase is higher.

5.3.1.5. Data analysis – effect of temperature variation on sludge blanket

Correlation between the effluent turbidity and inflow temperature were calculated using the Pearson correlation (r). The correlation is deemed to be significant when the p value is less than the significance level α=0.05.

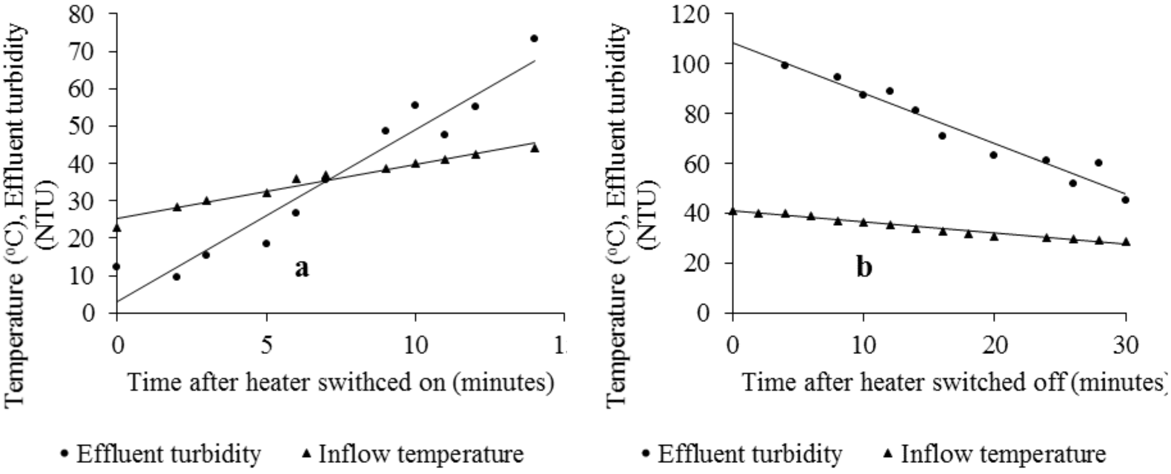


Figure 5.23 *- Variation of (a) temperature with time, (b)effluent turbidity with time*

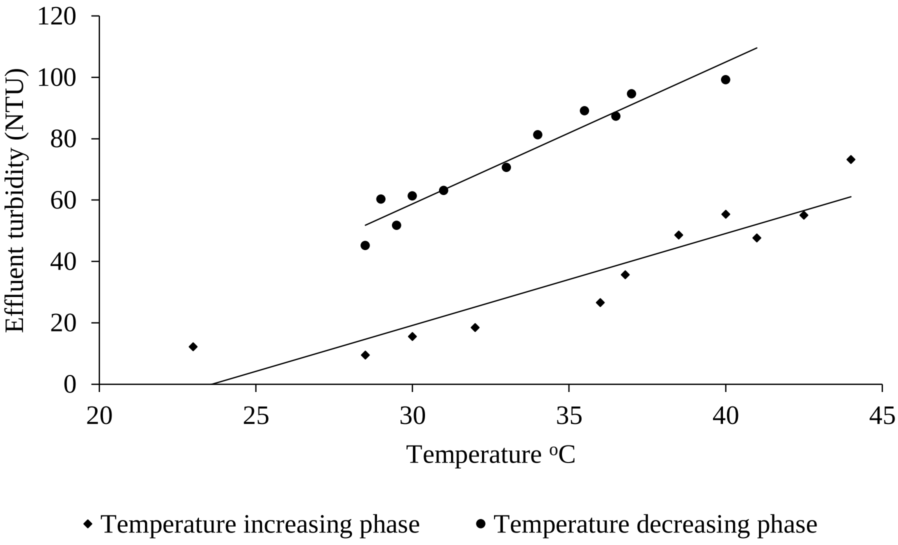


Figure 5.24 *- Variation of effluent turbidity with temperature*

Statistical analysis show that the effluent turbidity has a significant positive linear correlation with the temperature in the temperature increasing as well as decreasing phases. The Pearson coefficient and the p-value in the two phases are (r=0.93, p-value=0.00001<0.05, r=0.97, p-value=0.002<0.000001) respectively.

Increased effluent turbidity is associated with large positive slopes (with time) of the influent temperature. The rate of decrease of effluent turbidity in the temperature decreasing phase is 1.6 times higher than the rate of increase in effluent turbidity in the temperature increasing phase.

The outcome of the laboratory testing on synthetic sludge samples for effect of influent temperature variations can be used to develop following hypothesis on sludge blanket behavior with influent temperature variations.

The effluent quality is susceptible to change of temperature of a floc blanket. There is a positive linear relationship between the temperature increase and reduction of the effluent quality. When the temperature increase, the floc blanket gets disturbed and the effluent quality deteriorates. The effluent turbidity increases with increasing temperature. Once the blanket allowed returning to the ambient temperature, the effluent quality recovers at a higher rate than the temperature increasing phase with a negative linear relationship.

The above hypothesis will be verified using the sludge blanket at the full scale treatment plant in the following section.

5.3.2 Discussion- Testing at full scale- Pulsator® (25th Dec 2016)

The inflow raw water temperature and the temperature at three levels of the sludge blanket; top, middle and bottom are plotted against the time of the day in Figure 5.25. A temperature increase of 2 degrees Celsius is observed between 10:00 hrs. to 14:30 hrs. after which the raw water temperature started declining. However the average temperature variation within the sludge blanket is 0.5° C indicating that the raw water temperature variation throughout the day is cushioned off in the blanket.

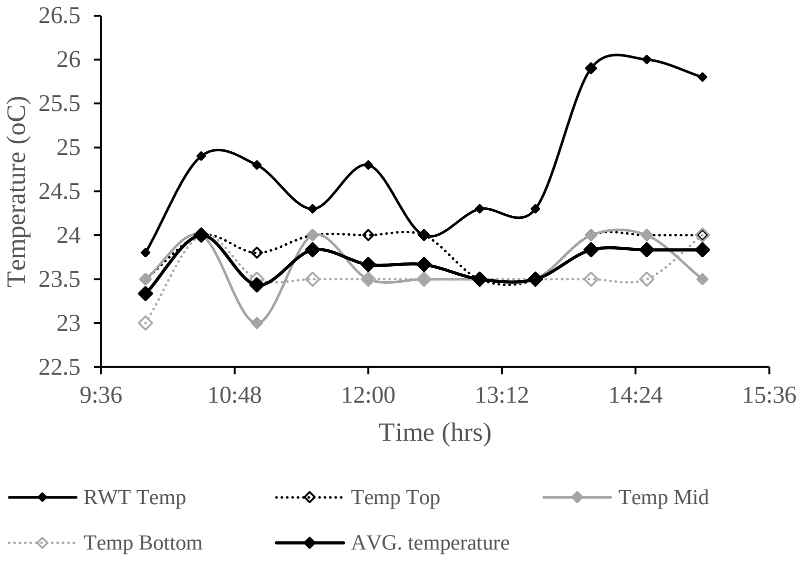


__Figure 5.25__ - Variation of temperature with time

The variation of influent and effluent turbidity with time is given in Figure 5.26.

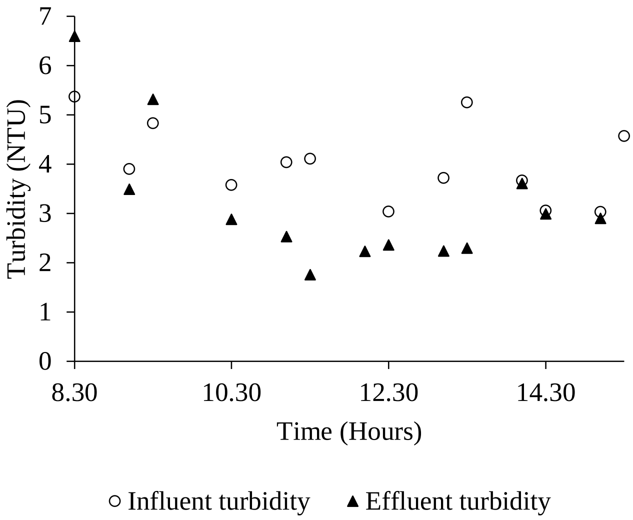


__Figure 5.26__ - Variation of influent and effluent turbidity with time

Variation of effluent turbidity with raw water temperature and average blanket temperature is given in Figure 5.27. The data were analysed using the same method given in section 5.3.1.5.

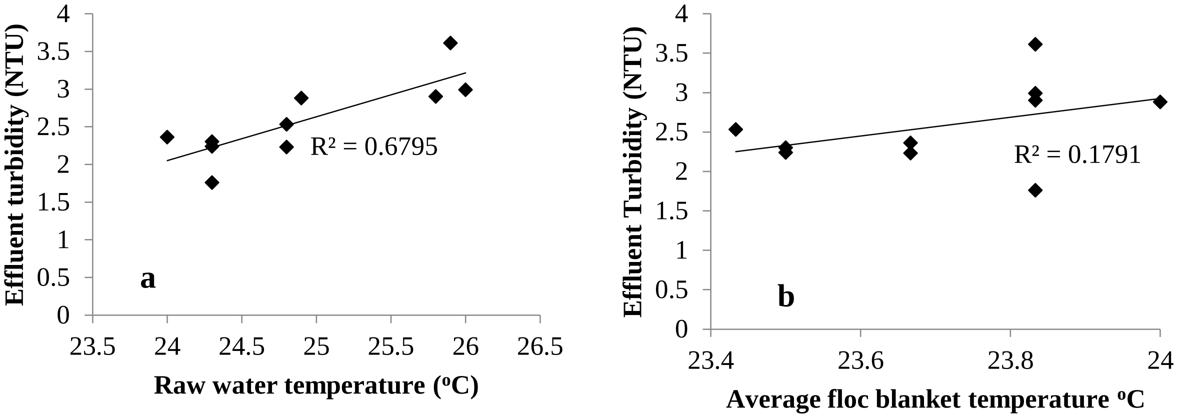


Figure 5.27 *- Variation of effluent turbidity with (a) raw water temperature, (b) average blanket temperature*

The effluent turbidity has a significant positive correlation with raw water temperature having r=0.82 and p-value=0.003<0.05. However effluent turbidity does not show a good correlation with average floc blanket temperature (r=0.42, p-value=0.22>0.05).

The sludge volume of the blanket at all three levels was tested. Figure 5.28 indicates the variation of *SV* fraction with respect to the blanket temperature.

The average *SV* fraction shown in this particular blanket (0.12–0.19) is not acceptable as a satisfactory blanket as per the recommendations of Degremont (2007). As per their recommendations, typical sludge volume fraction of a homogeneous sludge blanket which produces satisfactory effluent quality shall have a SVF between 0.2–0.25.

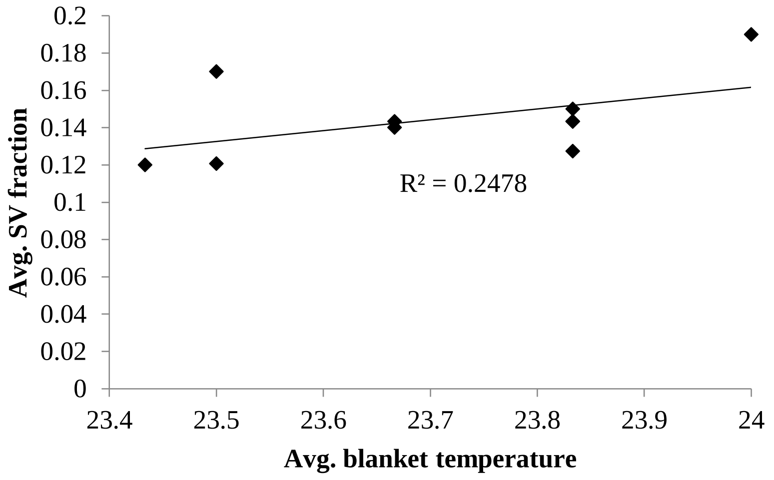


Figure 5.28 *- Variation of blanket sludge volume with temperature*

Table 5.4 summarises the outcome of the statistical analysis to determine the dependence of effluent turbidity on the variables; influent temperature, influent turbidity, sludge volume fraction, and average blanket temperature.

The hypothesis established using laboratory tests of synthetic sludge; effluent turbidity increases with influent temperature has been confirmed by analyzing the Pulsator® sludge blanket. However rate of increase of effluent turbidity with respect to temperature increase is higher in the laboratory samples.

Table 5.4 *- Statistical Analysis- Effect of influent quality parameters on effluent turbidity*

Variables	**Pearson r**	**(p-value)**
Linear Relationship		
Dependence of EFT on influent (RW) temperature	**0.82**	**0.003**
Dependence of EFT on RW turbidity	0.41	0.24
Dependence of EFT on SVF	0.28	0.43
Dependence of EFT on avg. blanket temperature	0.42	0.22

In order to comprehend the floc blanket behavior and blanket settling velocity with temperature variation using the blanket cohesivity, the data reported in Chapter 4, Section 4.2.5 (Table 4.8) is analysed. The data related to a single day (19th Dec 2013) from 8:15 to 15:00 hrs were taken into consideration.

The variation of *SCC* with blanket temperature is plotted in figure 5.29.

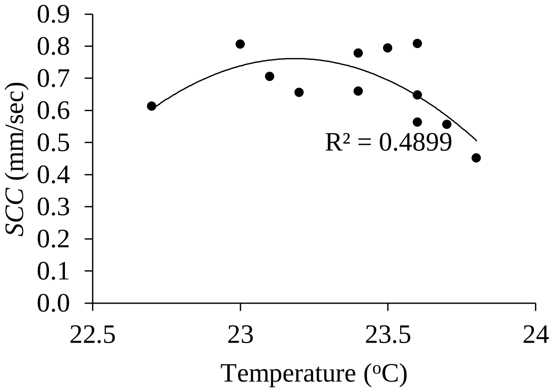


Figure 5.29 - *Variation of SCC with blanket temperature*

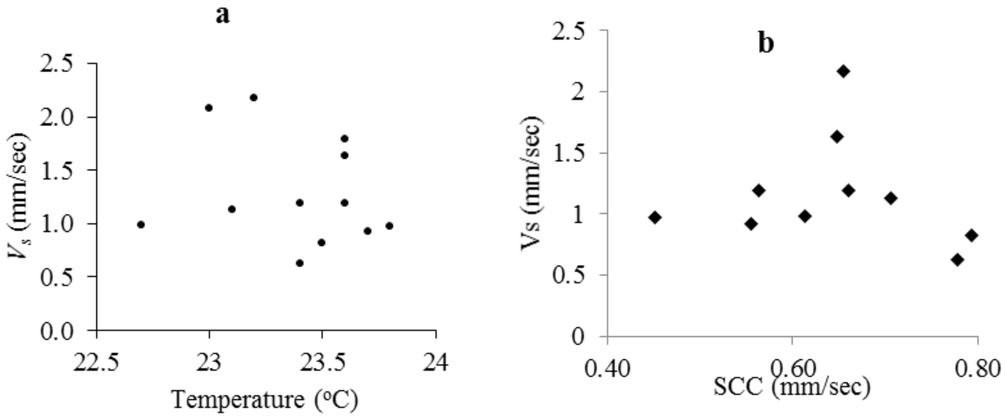


Figure 5.30 - *Variation of V_s with (a) blanket temperature, (b) SCC*

The blanket shows and optimum cohesivity at temperature 23.2 °C and *SCC* of 0.7 mm/sec, after which the cohesivity decreases with increasing temperature. Experimental results show a blanket settling velocity variation of 0.82 to 2.08 mm/sec. A relationship between influent temperature and *SCC* with V_s could not be comprehended.

The goodness of fit of the second order polynomial regression between the variables *SCC*, V_s and temperature were calculated using the Coefficient of determination. The model is deemed to be significant when the p-value is less than the significance level $\alpha=0.05$. (Table 5.5)

Table 5.5 *- Statistical analysis- SCC,* V_s *and temperature*

Variables	R^2	**p-value**
Second Degree Polynomial Relationship		
Dependence of *SCC* on temperature	**0.49**	**0.03**
Dependence of V_s on temperature	0.12	0.56
Dependence of V_s on *SCC*	0.06	0.42

Particle movement in a suspension is due to hydrodynamic forces counteracted by the viscous forces. As reported by Kotlyar et al. (1998), particle movement in a liquid-solid suspension is due to the dissipation of energy by viscous or turbulent conditions. The cohesivity of the blanket, which is influenced by hydrodynamic forces and cohehesive forces between particles and/or particle clusters, increases resulting in an increase in the SCC (Illangasinghe et al., in press). At optimum cohesivity short ranged cohesive forces are dominant in the blanket enabling clustering of particles as a result of particle-particle attractions due to short ranged cohesive forces. (Bhatty, 1986; Subbarao, 2010). With increase in temperature, inertial forces will increase. Particles moves rapidly and hydrodynamic forces overcome cohesive forces, dislodging the clusters. The turbulent conditions created by larger and faster settling clusters lead to destruction of clusters and reduction of blanket cohesivity.

The variation of settling velocity of particles with respect to the blanket tempertaure and *SCC* is shown in Figure 5.28. Blanket settling velocity varies between 0.82 to 2.08 mm/sec. However no correlation could be established between the settling velocity and the temperature or *SCC*. Past studies done on the effect of temperature variations found that a vertical convective current originates within the clarifiers due to the difference in temperature between the upper layers and the bottom layers of a floc blanket. This difference takes place when the surface layers get cool/ warm due to environmental conditions when the temperature of inflow water is significantly different from the temperature inside the tanks etc. A density difference will occur by the change of viscosity of water due to the change in temperature. Vertical convective currents will be generated due to this density difference, which will, in turn, affect the stability of the blanket. Particles will be kept in suspension leading to higher solids concentration in the effluent. Wells and LaLiberte (1998), McCorquodale and Zhou (1993), Taebi-Harandy and Schroeder (2000), Mahmood et al. (2005), Goula et al. (2008)

Results of this study found that convective currents created by difference in temperature causes reduction of viscosity and drag forces which leads to increased disentanglement of particle clusters. Frequent particle collision, forcing particles to move independently makes the particles to move with upward flow and increase the effluent turbidity.

5.4 Formation of the floc blanket at pulsator start up, Kandy South WTP

5.4.1 Analysis of test results

As elaborated in Section 3.7, the results of various tests carried out during the pulsator startup will be utilized to understand the parameters affecting formation of the blanket as well as verifying the conclusions arrived based on the experiments up to now. In the previous sections, the effect on the sludge blanket due to individual parameters; raw water quality, coagulant dose, and temperature were anlaysed independently. However, these parameters are acting upon the sludge blanket simultaneously. Thus the analysis under this section will enable to establish the behavior of the sludge blanket with natural occurrence and verify the outcome of test results obtained throughout this research study.

Figure 5.31 depicts the variation of raw water turbidity (influent) and Pulsator® out (effluent) turbidity during the 17-day experimental period. The raw water turbidity during the first five days (120 hours) was lower than 18 NTU, during which the sludge blanket could not be observed. Due to rainy weather that was prevailed in the area during the following four days, the inflow turbidity increased up to a maximum of 367 NTU and gradually settled back to values below 15 NTU. With the increase of suspended particles in the influent, the sludge blanket formation was first observed on the 8th day (178 hours) at the bottom layer. Gradually the blanket established in the upper layers. By the 13th day (288 hours) the blanket had established in all three layers. The tests on blanket characteristics were performed from the 13th day (288 hours) up to the 17th day (400 hours) by which a homogenous sludge blanket was satisfactorily formed.

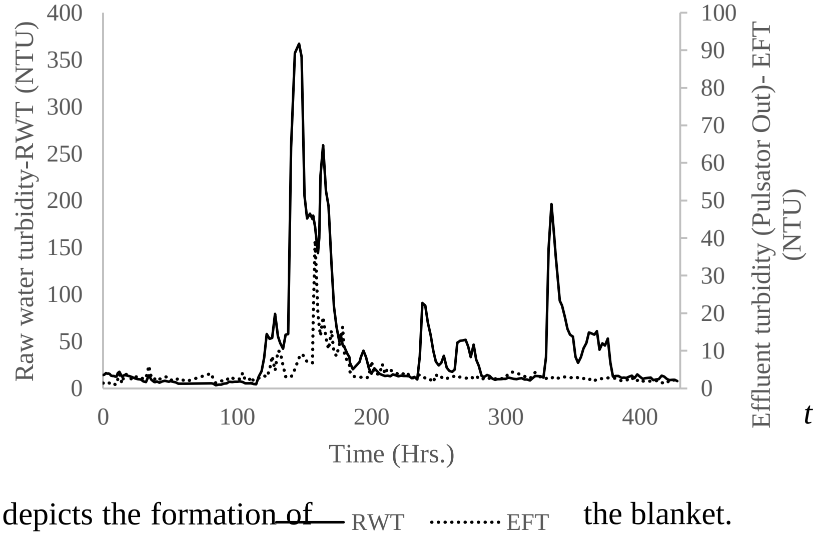


Figure 5.31 - *Variation of raw water and effluent (Pulsator®) turbidity with time*

Figure 5.32 depicts the formation of the blanket.

Figure 5.32 - Formation of floc blanket (Kandy South WTP)

The daily average *SV* of the blanket, average V_s, and average *SCC* of all three layers during blanket formation are presented in Figure 5.33.

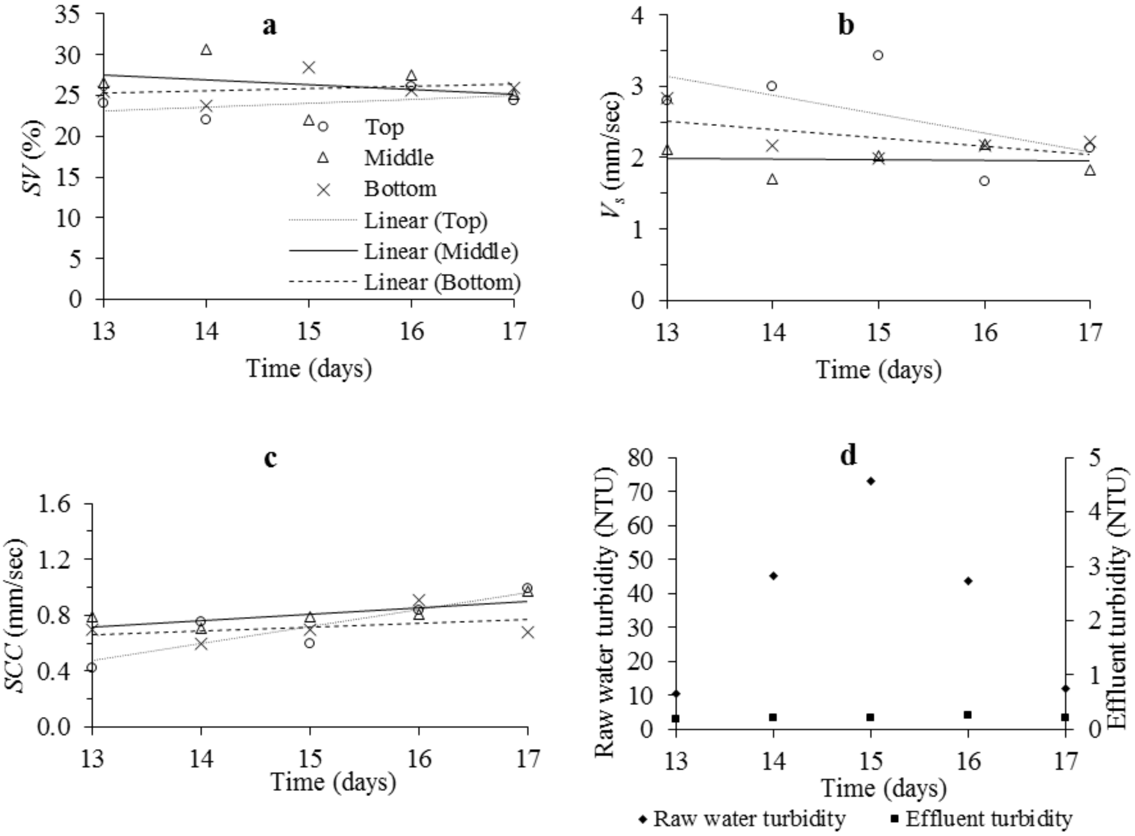


***Figure 5.33** - Variation of (a) SV (%), (b)V_s, (c) SCC,* (d) *effluent turbidity with time (days)*

By the end of the test period, the variation in the *SV* between layers was within the range of 5–6%, and the average *SV* was approximately 24% (Figure 5.33a), indicating that an effective homogeneous blanket formed (Degrémont 2007). The Pulsator® was effectively treating the inflow raw water turbidity variations up to 73 NTU, producing effluent turbidity values between 0.1–0.3 NTU (Figure 5.33d).

During this period, the V_s of the blanket varied from 3.4 to 1.5 mm/sec. The V_s was significantly higher (4.8 to 2.1 times) than the operating upflow velocity of the Pulsator®, 0.7 mm/sec (Figure 5.33b). This observation confirms the previous postulations that the sedimentation velocity of flocs in blankets with higher solids concentrations and higher volume fractions must be significantly higher than the average upflow velocity (Gregory 1979; Hurst et al. 2014b).

The cohesivity of the blanket increased with time (Figure 5.33c). The SCC varied from 0.42 to 0.99 mm/sec. Degrémont (2007) reported that, for a quickly settled consistent sludge, the SCC can reach 0.8 to 1.2, whereas for sludge composed of a flocculate that is fragile, light and rich in water, the SCC might not exceed 0.3. Therefore, at the steady state, the blanket cohesivity reached the desired levels during field tests.

The experimental results obtained for SV, V_s and SCC using field tests done during the Pulsator® start-up confirmed the established norms of an effective floc blanket.

5.4.2 Examining floc blanket characteristics using SCC

To establish blanket characteristics with respect to the selected indicative parameter, SCC, a non-dimensional parameter defined as SCC/V_s was calculated, and the results were compared with Equation 2.2 (Richardson and Zaki, 1954) for hindered settling, which predicts the non-dimensional parameter V_s/V_t (Figure 5.34).

Curve A, established using the experimental results, gives the following relationship between $\log V_s/SCC$ vs. $\log(1 - SV)$:

$$\log\frac{V_s}{SCC} = 3.9\log(1 - SV) + 0.98 \qquad \text{--- 5.2}$$

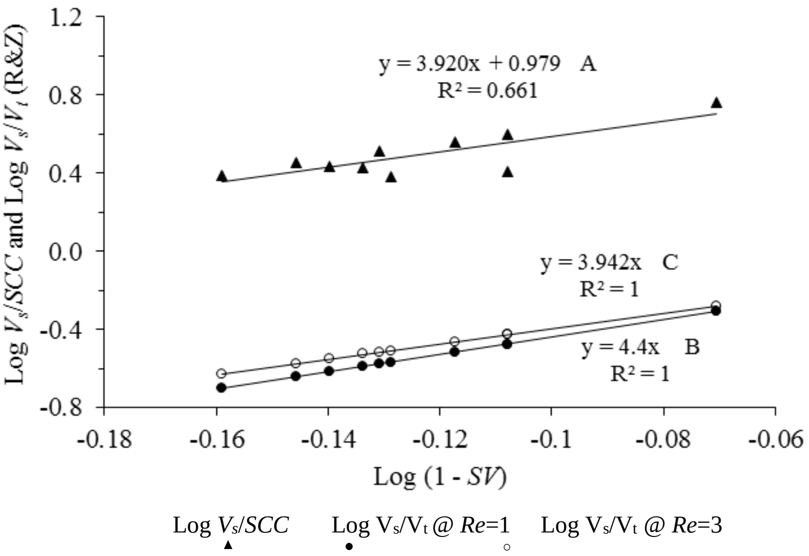


Figure 5.34 *- Variation of the ratios of V_s to SCC [i.e., V_s/SCC (field data)] and V_s to V_t [i.e.,* V_s/V_t *(using equation of Richardson and Zaki)] with (1 – SV) and Re.*

Curve B was plotted using $\log V_s/V_t$, calculated based on Equation 2.2 for *Re* = 1. The curve derived from field data is a transformation of the plot from Equation 2.2. A range of *Re* values were checked and, at *Re* = 3, the relationship derived using *SCC* is comparable to Equation 2.2 with a transformation of 1 unit in the intercept of the log axis.

For *Re* = 3:

$$\log\frac{V_s}{V_t} = 3.9\log(1 - SV) \qquad \text{--- 5.3}$$

Using Equations 5.2 and 5.3, a relationship can be developed between the particle terminal settling velocity and the *SCC*.

$$V_t = 10 \times SCC \qquad \text{--- 5.4}$$

Therefore, it can be concluded that the experimental results conform to Richardson and Zaki’s (1954) equation with a transformation given by $V_t = 10 \times SCC$ at *Re* = 3. The particular sludge blanket studied had an *SV* in the range of 0.15–0.3 (Figure 5.33a). Per the above derivation (as shown in Figure 5.34), the *Re* of the blanket was 3. The existing knowledge of fluidized beds does not clearly explain the behavior of a blanket in this range of *SV* and *Re*. Consequently, the variation of V_s was investigated with respect to *SV* and *SCC*.

During the steady state, a decrease in the blanket settling velocity was observed with increasing floc volume fraction as well as with increasing *SCC* (Figure 5.35). This contradicts the existing hypothesis on blanket settling velocity, which states that increases in blanket concentration during thickening result in an increase in the floc sedimentation velocity (Hurst et al. 2014b). However, the variation of blanket velocity during steady state was not discussed in the above study. Based on the observations shown in Figure 5.35, the decrease in blanket settling velocity could be due to variations in floc size and/or density.

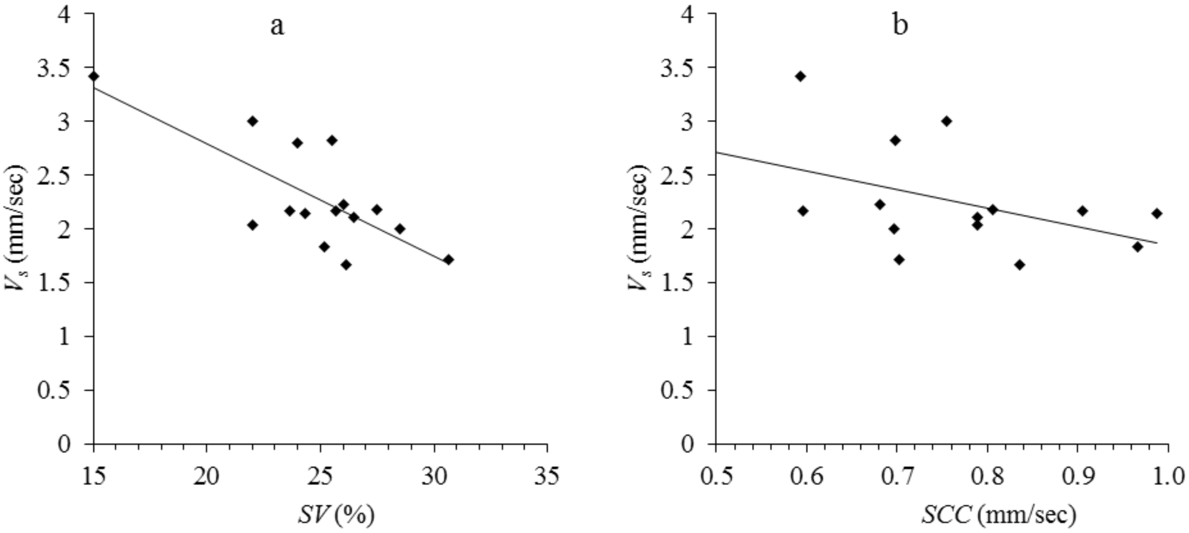


Figure 5.35 *- Variation of* V_s *with* SV *(a) and* SCC *(b)*

The variation of floc volume fraction with respect to blanket cohesivity is presented in Figure 5.36 Notably, the floc volume fraction did not significantly vary with increasing *SCC.*

Considering the dynamic viscosity of the fluid (μ) to be a constant, the blanket was at steady state when *Re* = 3, and there was no significant variation of *SV* as per the experimental results, according to Equation 3.4, V_s decreases only if the particle density and/or particle size increases.

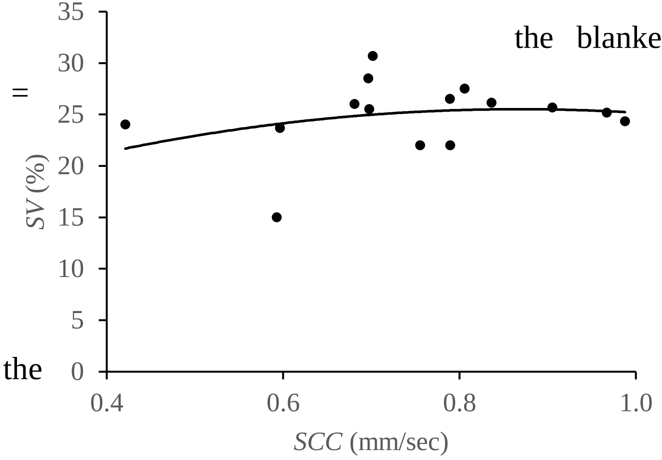


Figure 5.36 *- Variation of* SCC *with* SV

Zaidi et al. (2015), who studied the dynamics of particle settling with respect to the solid volume fraction and *Re*, proposed that hindered settling velocity deviates from the pattern suggested by the Richardson and Zaki (1954) equation for increasing *Re* and decreasing *SV*. This was explained to be due to the formation/destruction of particle clusters within the sludge blanket due to interparticle wake interactions. Stronger wakes are created by upstream particles when *Re* is high (> 1), leading to frequent drafting (D - fast moving of a downstream particle due to reduced drag created by the upstream particle), kissing (K - touching of leading/following particles) and tumbling (T - horizontal separation of the two particles due to imbalance). The frequency of DKT depends on *Re*; the larger the *Re* is, the more frequently DKT will occur.

The observations of Zaidi et al. (2015) about the destruction of clusters are comparable to the observations of Bhatty (1986) about fluidized beds with high solid volume fraction. Using a glass Ballotini suspension of 0.45 mm radii, the onset of hindered settling was observed at a solid volume fraction of approximately 41%. The clusters were more stable, and laminar flow was considered to occur with *Re* up to 0.6. When *Re* > 0.6, more destruction of clusters was expected due to turbulent flow conditions.

The sludge blanket of the Pulsator® in this experiment had an *Re* of 3. With high blanket *Re*, hydrodynamic forces overcome adhesive forces, dislodging the clusters. The turbulent conditions created by larger and faster settling clusters led to destruction and formation of smaller sub-clusters or separate particles.

Clustering of particles in the floc blanket is due to particle-particle attractions due to short-ranged cohesive forces. (Bhatty, 1986; Subbarao, 2010). The cohesivity of the blanket, which is influenced by hydrodynamic forces and adhesive forces between particles and/or particle clusters increases, resulting in an increase in the *SCC.* The interstitial space between flocs will be higher, leading to reductions in the interstitial water velocity and V_s of the blanket.

Fractal geometry explains the changes in floc density and sedimentation velocity as a function of floc size. Due to the fractal nature of flocs, the floc density decreases as floc size increases (Weber-Shirk and Lion, 2010). Accordingly, as a reduction of floc size is predicted due to the breakage of clusters at the steady state, floc density tends to increase.

Considering the large number of variables involved in water entering a clarifier, elucidating the formation of a sludge blanket and establishing appropriate parameters for properly maintaining the blanket using experimental results is complex. Further studies on the relationships between floc size, floc density and blanket cohesivity at the steady state will assist in establishing the relationships between these parameters.

Computational simulation of cohesivity, formation of particle clusters and blanket settling will open new avenues for research.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Objective of this study was to develop criteria for forming and maintaining a floc blanket in an up flow clarifier. Mechanisms of blanket formation were to be established, using which the response of the blanket to varying raw water quality, operating conditions and ambient conditions were to be explained. Recommendations were to be given for improved plant operations.

The study was carried out in three steps.

Step 1: Effect of raw water quality on sludge blanket formation: As the literature studied suggested, one of the most significant raw water quality parameters influencing the sludge blanket is the turbidity. Under this segment the effect of raw water turbidity on the floc blanket was studied.

Step 2: Effect of operating conditions on sludge blanket: The independent variable in the operation of the sludge blanket is the dosing of chemicals. Thus, under this segment, the effect of coagulant dose on the floc blanket was studied.

Step 3: Effect of ambient conditions on the formation and operation of sludge blanket: One of the ambient conditions that vary in the field, where the operator has no control, is the diurnal variation of temperature. Under this segment, the effect of inflow temperature variations on the behaviour of the floc blanket was studied.

The cohesivity of the blanket, measured using the sludge cohesion coefficient (*SCC*) was the parameter using which the conclusions were derived. It is defined as the interceptor of the curve representing variation of upward velocity according to the volume of expanding sludge. Knowledge of the *SCC* gives an understanding of the behaviour of a particular floc blanket. Literature reported that with low *SCC* (<0.3 mm/sec) the blanket is light and fragile, whereas with high *SCC* (0.7-1.2 mm/sec), the blanket is consistent (Degremont, 2007). Results of the present study, where the building up of the sludge blanket was studied in a field test series, where the cohesivity of the top, middle and bottom layers of the sludge blanket were determined, confirmed the above range of *SCC* for producing a consistent blanket.

At a given raw water turbidity, there is an optimum coagulant dose that produces the highest *SCC* and hence a consistent sludge blanket.

Particle settling mechanism within the blanket and blanket settling velocity were discussed using the experimental results of this study and available knowledge.

6.1 Raw water turbidity

The study found that formation of floc blanket is influenced by the raw water turbidity. Tests were carried out for a raw water turbidity range of 250-550 NTU. *SCC* of the floc blankets studied varied within the range 0.3 – 1.3 mm/sec. Up to a turbidity of 450 NTU, cohesivity of the blanket increases with the raw water turbidity. Beyond 450 NTU, blanket cohesivity appeared to reduce with increasing raw water turbidity.

The reduction in blanket cohesivity may be attributed to restabilization of the destabilized particles by charge reversal, as a result of increased coagulant dose.

From the above results of the study, it is recommended to introduce preliminary sedimentation (prior to clarifier) during high turbidity periods.

6.2 Coagulant dose

The *SCC* test and Jar test both indicate the optimum coagulant dose increases with increasing raw water turbidity. Beyond raw water turbidity 300 NTU, optimum coagulant dose reported from *SCC* test is lower than that of Jar test.

A linear relationship was established between the optimum coagulant doses (PACl) of the two tests with Pearson correlation coefficient of r=0.98 and p-value < 0.05.

$$Optimum\ dose_{SCT} = 0.78 \times Optimum\ dose_{Jar}$$

When using PACl as the coagulant, the relationship can be used to determine the optimum dose to be used in a clarifier after carrying out the Jar test. The coagulant dose for optimum *SCC* predicted by the model and the values observed in the laboratory tests has a root mean square difference of $\pm$ 6.11 mg/L. At higher raw water turbidities (> 300 NTU) the optimum dose calculated using the model will give savings of coagulant use in the range of 6-25%.

6.2 Effect of inflow temperature

The effluent quality is susceptible to change of temperature of a sludge blanket. There is a positive linear relationship between the increasing influent temperature and the effluent turbidity.

Full-scale plant observations showed that an increase of 2 ^{o}C in the influent temperature causes the effluent turbidity to increase by 1 NTU. The cohesivity of the blanket varies with varying temperature with an optimum cohesivity at a specific temperature. This study has observed an optimum cohesivity (*SCC* of 0.7 mm/sec) at an influent temperature of 23.2 ^{o}C, after which the cohesivity decreased. Increased temperature leads to a decrease in cohesivity of the blanket, which affects clustering of floc particles. Thus, at increased temperature, frequent collisions due to high inertial forces cause particles to move with the upward flow and increase the effluent turbidity.

However, a correlation between *SCC* and the blanket settling velocity could not be established at elevated influent temperatures. As explained in Chapter 5 Section 5.3.2., this may be attributed to the formation of convection currents within the floc blanket due to differential temperatures.

The laboratory tests showed that settling efficiency improves at a faster rate in the temperature recession phase (1.6 times faster) than in the temperature rising phase.

6.4 Particle settling mechanism within a floc blanket and blanket settling velocity

Cohesivity of the blanket and blanket settling velocity (V_s) is related to the particle structuring within the blanket and cluster formation. Particle movement in a suspension which may be visualized as a fluidized bed is due to hydrodynamic forces counteracted by the viscous forces. Particles move as a result of the dissipation of energy by viscous or turbulent conditions. Short-ranged cohesive forces between particles lead to clustering of particles. The interstitial space between clusters varies with cluster size.

The floc blanket under this study reached a steady state where the top surface of the blanket remains a constant when the *SCC* of the blanket was 0.6 mm/sec. The blanket settling velocity at steady state was two to four times higher than the upflow velocity. During this state, the *SCC* increased with time (0.6 to 0.8 mm/sec) and V_s decreased. However no significant variation was observed in the sludge volume. Reynolds number of the floc blanket has been established as 3.

Using the experimental results and the available knowledge on particle structuring within the floc blanket, blanket behavior and physiognomies during steady state are explained as follows;

At low Reynolds numbers (< 1), particle clustering within the blanket is improved and a steady blanket is formed. The interstitial space between clusters will be less leading to increased water velocity and V_s. Fast moving larger clusters which are formed at steady state create inter-particle wake interactions. During steady state ($Re = 3$) hydrodynamic forces overcome cohesive forces. Turbulent conditions created by larger and faster settling clusters lead to the destruction of larger clusters and formation of smaller sub-clusters. Cohesivity increases due to short-ranged cohesive forces between smaller and stable sub-clusters. The interstitial space between flocs will be higher, leading to reductions in the interstitial water velocity and V_s of the blanket.

6.5 Practical applications of this work

It is generally understood that the quality of raw water, the type and dosage of coagulants and the ambient conditions govern the formation of a floc blanket in a clarifier. However, as the blanket characteristics and particle structuring within the blanket have not been clearly understood, maintenance of a floc blanket has been dependent on trial and error and the long-term experience of plant operators. This study was undertaken to shed light on this situation and give some guidelines to form and maintain the floc blanket of a solids contact clarifier.

In practice, the optimum coagulant dose needed for establishment and maintaining the floc blanket in the clarifier is determined using the Jar Test. However, the settling mechanism during the Jar test is not representative of the settling mechanism within the floc blanket, as the water column is moving upwards through the floc blanket. Thus, it is necessary to use a more representative indicator to study the behaviour of the floc blanket.

In this study, the condition of the floc blanket was represented by the indicator *SCC* to understand its characteristics. The study showed that at very high raw water turbidity occurrences (> 450 NTU) the blanket cohesivity is reduced, thus deteriorating the effluent quality. Preliminary sedimentation to reduce the raw water turbidity entering the clarifier to below 450 NTU would help maintain the *SCC* within the optimum range.

The optimum coagulant dose to be used required according to *SCC* test when raw water turbidity is larger than 300 NTU, is less than the dose given by the Jar test. If the operators are not familiar with the *SCC* Test procedure, they can do the Jar test and use the mathematical model developed during this research to find the optimum dose to achieve a consistent, cohesive floc blanket.

When the raw water turbidity is in the range 300-450 NTU, using the optimum coagulant dose according to the *SCC* Test would result in a saving of 6 to 25% on coagulant usage.

The study found effluent quality is susceptible to change of temperature of a sludge blanket. High inflow temperature reduces blanket cohesivity, and thus affects the effluent quality. There is a positive linear relationship between the increasing influent temperature and the effluent quality. The laboratory tests show that settling efficiency improves at a faster rate in the temperature recession phase (1.6 times faster) than in the temperature rising phase.

Floc blanket reaches a steady state at the optimum blanket cohesivity. During this state, the blanket settling velocity decreases with increasing solid volume fraction as well as increasing blanket cohesivity. Plant operators can use the *SCC* obtained by conducting laboratory experiments on the floc blanket of a clarifier unit to maintain the cohesivity of the blanket within the recommended range as explained in 6.1. Maintaining blanket cohesivity enables improved effluent quality.

6.6 Recommendations for future studies:

Further studies on the floc blanket behavior to establish particle structuring and blanket settling velocity using computational simulation of cohesivity, formation of particle clusters and blanket settling will open new avenues for research. Variation of the floc size and density and blanket concentration also can be considered in such studies.

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