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Development of a Laboratory Clarifier Test to Predict Full Scale Primary Clarifier Performance

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ABSTRACT: The objective of this research was to develop a laboratory test procedure to predict full-scale primary clarifier performance using Chemically Enhanced primary Treatment (CEPT). A method was developed that simulated actual primary clarifier performance, with chemical enhancements, based on simulating full-scale surface overflow rate (SOR) and flocculation time in the laboratory. The method used for this test was adapted from a procedure used for sizing of Lamella Separators. Validation of the developed method was done by comparison of laboratory data, with stress test data from two full-scale clarifiers, at the Blue Plains Advanced Wastewater Treatment Plant in Washington, DC, USA. The results indicated that the laboratory SOR test method could be calibrated to predict and optimize full-scale primary clarifier performance.

Key words: Chemical, primary, Treatment, Laboratory, Clarifier , Non settleable solids , Wastewater, Flocculation

INTRODUCTION

Primary treatment is used for clarification of liquid, settling of particles and thickening of sludge. The main objective of primary treatment is to reduce suspended solids content (and pollutants associated with them) of the raw influent. Efficiently designed and operated primary clarifiers should remove 50 to 70 percent of total suspended solids (TSS) and 25 to 40 percent of Biochemical Oxygen Demand (BOD) (Metcalf and Eddy, 2003). The efficiency of primary sedimentation is very important. Since primary clarification removes larger and easily settle-able solids, the treatment processes following primary clarification receive lower loads and smaller particles that are more easily degradable.

Chemically Enhanced Primary Treatment (CEPT) is a process where chemicals are used for coagulation, precipitation or adsorption of particulate/dissolved matter in the wastewater. CEPT has become one of the leading techniques for primary clarification. Although CEPT was first used around 1840 in France (Nieuwenhuijzen, 2002), its use in the United States started in the 1960s. A number of different chemicals were developed, tested and used. A single chemical or a combination of chemicals can be used. Phosphate removal, clarification of raw wastewater, and an increase in surface overflow rate (SOR) are among the common objectives of the users of CEPT. The selection of chemicals for CEPT depends on the primary objective of using them. The clarification efficiency depends not only on dose and dosing strategy but also on influent characteristics, mostly on concentration of settle-able and non-settle-able solids (NSS). NSS is defined as the TSS remaining in a sample after a specific settling period. Standard Methods (APHA, 1998) has defined NSS with a 30 min. settling time. Standard Methods does not specify any flocculation time or intensity.

In the laboratory, NSS is often determined by the jar test method, a typical experimental proce-

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*Corresponding author:Email-marija.peric@m-e.aecom.com dure to assess primary clarifier performance. However, it is a crude method for coagulant selection. It is not useful for 'scaling up' of information about flocculation rates, from the jar tests to plant operation because it is silent on simulation of surface overflow rate (SOR) and flocculation time, which are the limiting parameters for primary clarification. The jar test is not efficiently designed to predict SORs (and thus effluent TSS from clarifiers), mainly due to poor aspect ratio of jars. The jars are not sufficiently tall enough to conduct an SOR test. Therefore, another laboratory test is needed that properly simulates SOR. The flocculation parameter is very sensitive and important in the determination of full-scale NSS. The aggregation that results from flocculation decreases the NSS content during clarification. The importance of flocculation prior to settling and the need for a new standardized test which included flocculation for measurement of NSS was observed by Parker, *et al.* (2000) and Wahlberg (1999). Standard method 2540F (APHA, 1998) does not mention flocculation in the determination of NSS. Intensity of mixing is also an important factor in clarification as there is a chance of floc-breakup due to poor flocculation.

Heinke, *et al.* (1980) demonstrated that settling columns (1.8 m deep, 15 cm diameter) and tracer tests are useful tools for predicting the performance of settling tanks. Although good results were obtained, these evaluations are cumbersome and can only be performed on-site but not in the laboratory. Hetherington, *et al.* (1999) reported the evaluation of various chemicals dosages when implementing CEPT. Prior to full-scale application and pilot tests, jar tests were conducted. The settling time in 2-liter beakers was established by comparing untreated control beakers with actual primary effluent TSS as the indicator for full-scale performance. Although this approach could be considered applicable in the lab, the settling time was still based on comparison with a control beaker which could be hard to achieve with great precision.

In summary, an accurate laboratory procedure is needed to properly simulate both flocculation and SOR.The overall objective of this study was to develop a laboratory-scale method to predict and optimize primary clarifier performance. The specific objectives were the following:

1. Develop a laboratory clarifier test to predict optimized primary clarifier performance for primary clarifiers that are not performing adequately. A calibration and optimization test is needed to help understand the improvements that can to be done to improve clarifier performance. The test should work for variations in SORs, flocculation time, and other variables.
2. Validate developed laboratory test with full-scale primary clarifier performance data.

MATERIALS & METHODS

This study was conducted at the District of Columbia Water and Sewer Authority's (DC WASA) Blue Plains Advanced Wastewater Treatment Plant (AWTP). This plant is the largest advanced wastewater treatment plant in North America with an average design flow of 1.4 million m^3/d (370 million gallons per day) received from the Washington DC metro area, with combined sewer maximum flow in excess of 4 million m^3/d (> 1 billion gallons per day).

The total population served by this plant is over two million. The influent wastewater to Blue Plains AWTP arrives from two sides, one from east and another from the west, therefore the plant has two trains of circular primary clarifiers as shown in Fig. 1. The East side has 20 clarifiers with dimensions of 36.58 m (120 ft) diameter and 4.37 m (14.35 ft) side water depth and was evaluated for this study. The clarifiers were newly designed to operate with chemicals and replace older clarifiers.

Chlorine is added in the wastewater for odor control. Iron is added to the influent wastewater for coagulation and for precipitation of phosphorus. The wastewater then passes through coarse screens followed by aerated grit chambers before it enters primary clarifiers for CEPT.

Polymer is injected at the bottom of the well as it enters the tank. Mixing of polymer takes place in the energy-dissipating inlet (EDI) zone and flocculation takes place in the feed well of the primary clarifiers. The hydraulic retention time (HRT) for wastewater in EDI zone and feed well is in the range of 8 - 10 s and 2 - 5 min., respectively, depending on the flow rate.

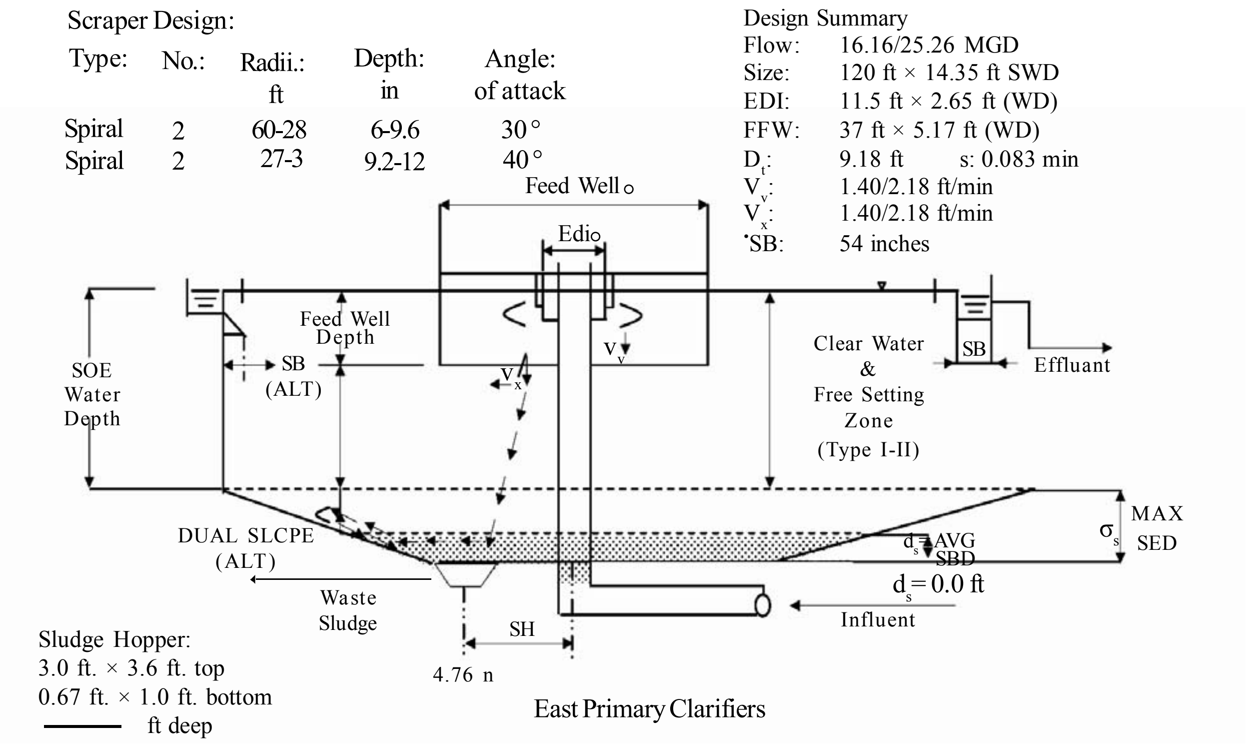

Fig. 1. Typical primary clarifier at Blue Plains AWTP

Despite modifications to the primary clarifier to achieve CEPT, the performance of these tanks at the Blue Plains plant has not been satisfactory partly due to inefficiencies in design and construction (e.g. short circuiting, jetting of flows, etc.), and partly due to operation (e.g. ongoing repair work, hence high overflow rate due to diverted flows). The average TSS removal in the new primary clarifiers during 2003 was only 18% before polymer addition. As shown in Fig. 2, when polymer was used in 2004, TSS removals increased to 48%. Of all wastewater treatment processes used, primary settling tanks probably provide the best return in treatment achieved for the capital invested (Heinke et al., 1980). A number of approaches were undertaken to further improve the performance of CEPT at Blue Plains AWTP. Since desired performance was not being achieved, changes were made to the Energy Dissipation Inlet (EDI) to one clarifier to reduce jetting and momentum effects. The size of the EDI opening was enlarged to reduce velocity in the transition between the EDI zone and the flocculation feed well. Stress tests were conducted to determine the impact of the modifications and improvements in performance. Finally, a laboratory procedure was developed to assess if the modifications helped to optimize or reach the desired performance.

The objective of the clarifier stress test is to measure the capacity of the test clarifier under a single operating condition by incrementally increasing the loading to the clarifier and measuring its response. The short term stress test was conducted over a 3 h time period. The following procedure was followed:

1.Grab samples of the test clarifier influent and effluent (total of 12 samples for each effluent and influent) were collected on a 15 min. basis using an automatic sampler (ISCO 3700, Nebraska, USA).

2.Changes in SORs were recorded every 15 minutes.

3.Three times during the test (every hour), a sample of the effluent was taken from each tank, settled in an Imhoff cone for 30 minutes, poured off the top 300 ml and analyzed for TSS by Standard Method 2540 D (APHA, 1998). This was the effluent TSS or NSS for the sample.

4.The sludge blanket level was measured every hour at three locations along the clarifier cross section (one near the center, one midway, and one near the sidewall) to determine changes in blanket level during the test period.

The basis of test was that SOR and flocculation time are defining parameters that limit primary clarifier performance, and the proper

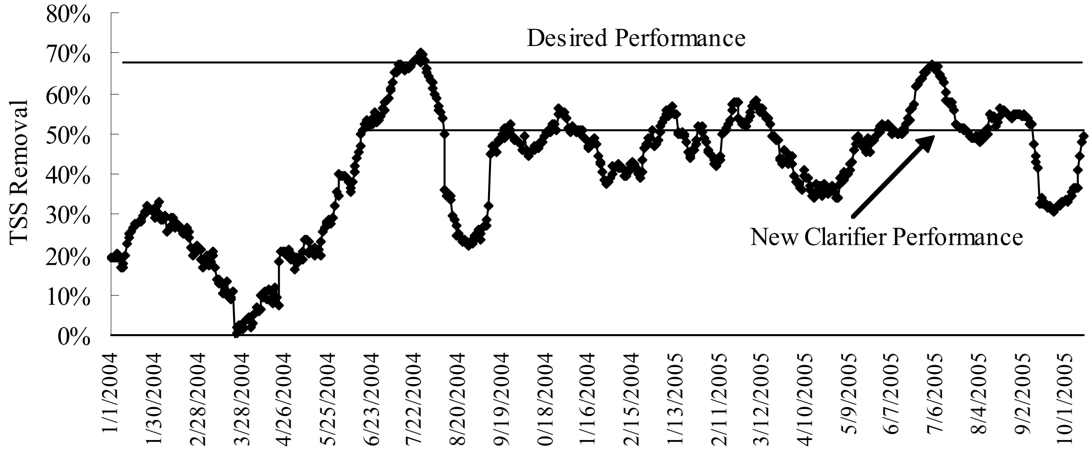

Fig. 2. Performance of new clarifiers with iron and polymer for CEPT (30-day rolling average)

simulation of SOR and flocculation time in the laboratory is needed to replicate full-scale performance. In a clarifier, free settling is predominant and the settling velocity of the suspended particles can be predicted by the use of Stokes Law. Therefore, there is a direct relationship between effluent TSS from a clarifier and it's SOR. A test method was developed by the researchers, based on clarification test for sizing of Lamella Separators by Larsson (1986).

The basis of test was that SOR and flocculation time are defining parameters that limit primary clarifier performance, and the proper simulation of SOR and flocculation time in the laboratory is needed to replicate full-scale performance. In a clarifier, free settling is predominant and the settling velocity of the suspended particles can be predicted by the use of Stokes Law. Therefore, there is a direct relationship between effluent TSS from a clarifier and it's SOR. A test method was developed by the researchers, based on clarification test for sizing of Lamella Separators by Larsson (1986).

Larsson's test suggested the use of 1000 mL graduated cylinder to be filled with the test suspension. If the suspension is to be pretreated with chemicals (e.g. for CEPT), then chemicals should be added in the test cylinder and the pretreatment should be carried out. After pretreatment is complete, the sample should be stirred gently and when the convective eddies from the stirring have ceased, time required to simulate a suitable surface load should be measured. Afterwards, upper 100 mm of the suspension column in the cylinder should be siphoned out and analyzed for suspended solids. Larsson's test was vague on how pretreatment should be carried out in such a small cylinder since mixing of chemicals with accurate and constant speed is required. Also, Larsson's test was recommended for sizing of lamella separators and modifications were needed for adjusting it to simulate circular primary clarifier performance. Generalized formulae for determining flocculation and SOR are shown below. Flocculation time for the laboratory clarifier test is:

$$t_t = t_c + y \qquad (1)$$

where, t_t = flocculation time in graduated cylinder (h)

t_c = flocculation time in a full-scale primary clarifier (h)

y = additional flocculation time in settling zone of a full-scale primary clarifier (h).

The term 'y' depends on the mixing patterns in the settling zone of the clarifier, and is currently obtained by trial and error. It is anticipated that 'y' is approximately 0 to 50% of t_c. Both t_c and y will typically change with flow rate, decreasing with increasing flow. The SOR for a clarifier as proportionally simulated by a graduated cylinder is:

$$V_0 = Q/A = d/t \qquad (2)$$

where,

V_0 = surface overflow rate (m/h)

Q = full-scale clarifier rate of flow (m^3/h)

A = surface area of the cylinder (m^2)

d = sampling depth (m) (=0.1 m for 1000 mL cylinder, Larsson, 1986)

t = settling time (h)

Several modifications were made to the Larsson (1986) test. The suggested 1000 mL graduated cylinder (with diameter of 120 mm and depth of 360 mm) was found to be too narrow and therefore resulted in wall-effects during settling. It was also too shallow and resulted in a very small settling time (t) for the SORs to be adequately simulated. To decrease wall effects and increase settling time, a 4000 mL graduated cylinder, as shown in Fig. 3 (a), was used. This cylinder is wider (with diameter of 200 mm) and deeper (505 mm), and reduces artifacts and errors during testing. In addition to choosing a larger cylinder, flocculation (and rapid mixing if desired) was included to simulate full-scale flocculation time, and correspondingly predict full-scale NSS. Thus, the laboratory test was developed to simulate not only full-scale SOR, but to simulate full-scale flocculation time, an especially important parameter for predicting CEPT performance. The following procedure was adopted:

1. SOR: The sampling depth (d) was constant for the 4000 ml cylinder and defined at 140 mm from the top of the liquid surface. The settling time (t) was varied and depended on the desired SOR. A volume of liquid was siphoned after time 't' representing the required SOR (or V_0) for a depth d = 140 mm, of removed liquid.
2. Flocculation Time: The laboratory flocculation time was varied and determined based on full-scale flocculation time (determined from flow rate and full-scale flocculation tank or feed well volume). In general, the flocculation time decreased as the flow increased for a constant volume flocculation well. Therefore, an increase in SOR resulted in a decrease in flocculation time. Hence, CEPT performance at higher flows in the laboratory unit and full-scale, was very sensitive to and deteriorated with, an increase in SOR and a decrease in flocculation time (for a constant volume flocculation chamber). The laboratory simulation of these two components is key to modeling the full-scale clarifiers.
3. Mixing: Rapid mix at 200 rpm (GH”200 s^{-1}) and flocculation at 50 rpm (GH”10 s^{-1}) for a defined full-scale flocculation time was carried out in the cylinders with a high capacity mixer (L1U10 Lightnin™, by Lightnin Mixers, Virginia, USA). An axial flow impeller with diameter 6.8 cm (as shown in Fig. 3 (b)) was used for mixing and to provide vertical movement of flow. Vertical position of the paddle in the settling column was decided based on uniform movement of the liquid above and below the paddle in the column. It was set at 2/5 of the depth from the top of the liquid. Determination of mixer speed was based on a control movement of sample liquid while mixing with comparison to movement of sample liquid in jar tester. G values from Mixer calibration were then compared to G values from Jar tester. Incompatibility with the G values from jar tester was likely due to physical differences between non-deep square jars vs. circular deep settling columns. In addition, couples of other sets of experiments were performed in order to evaluate differences between jar testers and testing within cylinder with mixer; the same conditions were performed in terms of time of rapid mixing, flocculation and settling, and significant difference was not noticed. This was a clue that similar testing conditions were achieved compared to a jar tester. Also, usage of shaft with single and double paddles was considered and evaluated; results with single paddle gave slightly better performance, so use of single paddle was adopted.
4. Sampling: The samples siphoned after time 't' were analyzed for TSS by Standard Method 2540 D (APHA, 1998).

RESULTS & DISSCUSION

The Laboratory Clarifier Test procedure was validated on actual primary clarifiers, during the regular stress test on two tanks (#A and #B) during June-October 2005.

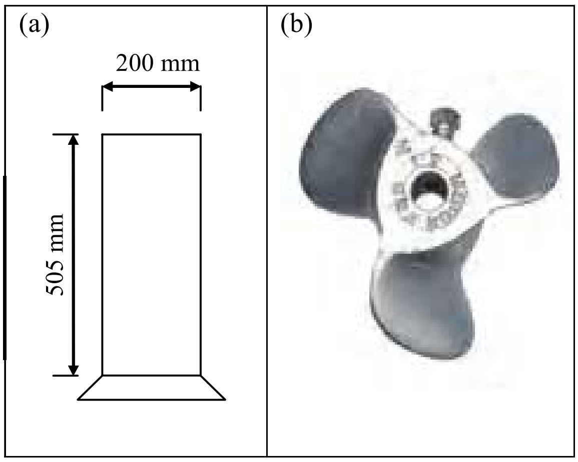

Fig. 3. (a) Diagram of 4000 mL graduated cylinder; (b) Lightnin Mixer impeller

These two primary tanks were chosen for evaluation since tank #B is still using old EDI system (and represents the poorer performance of most of the east primary clarifiers), while tank #A has been modified and hence can be evaluated for optimized performance. At the time of testing, both clarifiers were operated at the same flow rate. A total of six sets of tests (3 per clarifier) were conducted over a span of 5 months. Sampling for the Laboratory Clarifier Test was conducted by withdrawing samples directly from the rapid mix zone, alternately from tank #A and tank #B. Flocculation time and full-scale SOR were calculated based on instantaneous flow rates at the clarifier. Laboratory Clarifier Test was conducted using the 4000 ml cylinders as previously described. It required approximately 30 minutes performing 3 laboratory clarifier tests (on low, medium and high SORs).

Figure 4 shows six stress test data points. Each point represents an aggregate of several stress test runs conducted on different days at a single SOR. Each point represents the aggregate effluent TSS for a single SOR for each tank. Effluent TSS from the Laboratory Clarifier Test is compared with effluent TSS from primary clarifier. The vertical error bars represent the standard deviation of effluent TSS for a series of Laboratory Clarifier Tests, while the horizontal error bars represent the standard deviation for a series of full-scale primary clarifier stress tests. The horizontal error bars are larger and represent a more variable full-scale performance at higher SORs. It is observed that upgraded (optimized) tank #A showed much better performance than the non-upgraded tank #B. The Laboratory Clarifier Test results, which represent optimized operations, were very similar to the performance of optimized full-scale tank #A, and much better than that of tank #B. In fact, tank #A performed slightly better than the laboratory clarifier test.

The better performance of tank #A could easily be due to additional aggregation and flocculation within the settling zone of the tank, that were not taken into account in this Laboratory Clarification Test (as suggested in the next section). Nevertheless, the full-scale optimization is very close to the optimum prediction of the Laboratory Clarifier Test. These results further suggest that the full-scale EDI modification to reduce momentum related jetting effects has improved the primary clarifier performance.

Paired t-Test was performed to see if there was any difference between the effluent TSS data from the actual clarifier and Laboratory Clarifier Test, using a five percent level of significance for a two-sided test. Total of 25 pairs (50 data points) of measured data was used in each t-Test. The results indicated that there was no significant difference between upgraded tank #A and Laboratory Clarifier Test, indicating that full-scale performance and Laboratory Clarifier

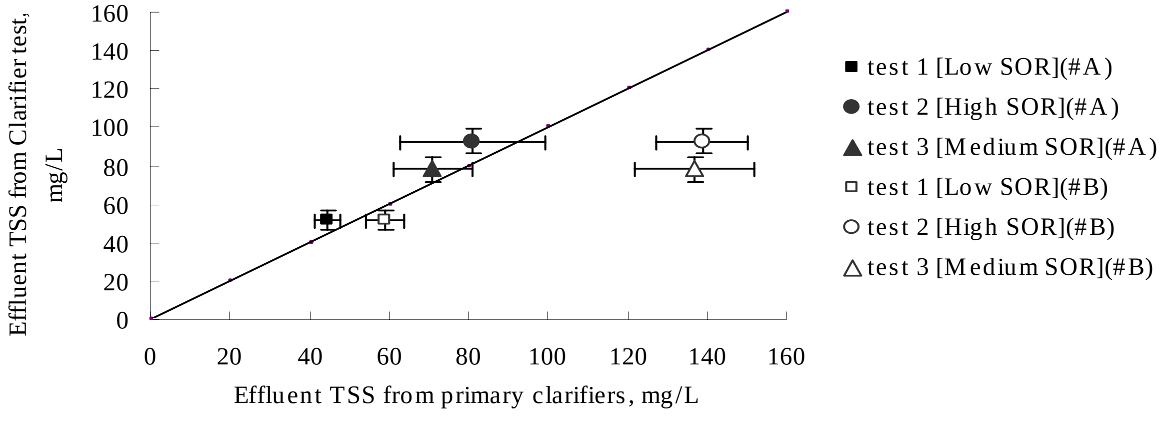

Fig. 4. Comparison between simulated Laboratory Clarifier Test effluent TSS and actual clarifier effluent TSS, with standard deviations; in legend #A refers to upgraded clarifier and #B to non-upgraded clarifier

performance were similar and that the clarifier had been optimized. There was a significant difference between tank #B and Laboratory Clarifier Test, due to large differences in actual and optimized performances.

Although NSS can only be obtained under idealized conditions, it is an important parameter to understand the flocculation efficiency during primary treatment. Full-scale NSS was determined by Standard method 2540F (APHA, 1998), by settling a sample in an Imhoff Cone for 1 h and sampling the supernatant for TSS. Sampling for the NSS measurement was conducted by obtaining a sample from the bottom of the feed (flocculation) well where the flow exits the well. The unsettled portion represents the NSS for a full-scale clarifier. For validation of full-scale flocculation, the laboratory determined NSS should be similar to the full-scale NSS. Since there is additional flocculation taking place in the settling zone of the full-scale primary clarifier, this effect on NSS was also observed in this experiment. Figure 5 summarizes the average results of TSS from Laboratory Clarifier Tests conducted using influent obtained from the rapid mix zone of primary clarifiers. The Laboratory Clarifier Tests were conducted at the same time as the full-scale NSS sampling and testing. This data trend in Fig. 5 is typical for a Laboratory Clarifier Test, where the effluent TSS increases with an increase in SOR. Corresponding TSS removals for Fig. 5 were, without additional flocculation 67 %, 57 % and 43 % for low, medium and high SORs, respectively. With additional flocculation of 25%, removals were 70 %, 63% and 51 %; and for additional flocculation of 50%, removals were 72 %, 66 % and 53 % for low, medium and high SORs, respectively.

To determine the NSS for the Laboratory Clarifier Test, the laboratory SOR curve (Fig. 5) is extended to the y-axis, and the y- intercept represents the NSS. The NSS in the Laboratory Clarifier Test is compared with full-scale NSS, for the same primary influent. In this case, the laboratory simulated NSS (28 mg/L) is closer to the flocculation zone NSS (29 mg/L) rather than the clarifier effluent NSS (26 mg/L) which is lower, suggesting that additional flocculation and aggregation (y from Equation (1)) is occurring in the settling zone. Here 'y', a flocculation function of settling zone hydraulics, is estimated as the additional flocculation required to achieve clarifier effluent NSS, suggesting about 25% additional flocculation occurs in the settling zone to attain a lower NSS value (Fig. 5).

Viraraghawan, *et al.* (1996) showed that exponential curve is the best fit for correlation between SOR and TSS removal. However, in this case a linear relationship produced a better correlation. The Laboratory Clarifier Test showed

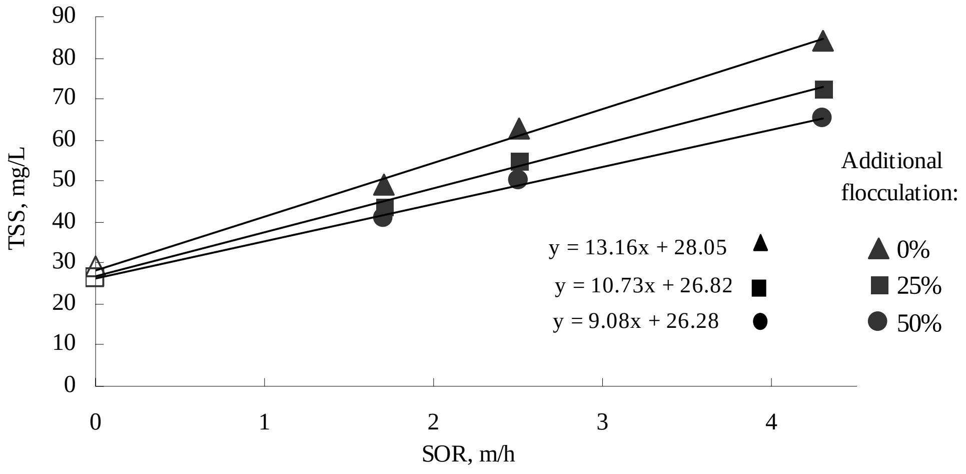

Fig. 5. Effect of Additional Flocculation in Laboratory Clarifier Test to predict effluent TSS (Influent TSS=148 mg/l); also shows full-scale NSS data for comparison (f&^{2}% % Laboratory test data, “ NSS from flocculation zone of clarifier, ν NSS from clarifier effluent) Units on x-axis: 1.7 m/h = 1000 gpd/ft^2, 2.5 m/h = 1500 gpd/ft^2, 4.3 m/h = 2500 gpd/ft^2

that NSS was 28 mg/L representing 18 % TSS. With additional flocculation, NSS values obtained were 27 mg/L and 26 mg/L for additional 25 % and 50 % respectively. In comparison, the NSS from flocculation zone of clarifier was 29 mg/L. These values are very similar, suggesting that the flocculation has been optimally simulated. The NSS for the primary clarifier effluent was slightly lower (26 mg/L), showing that additional flocculation and aggregation is occurring in the settling zone. The slightly higher removals obtained during optimized full-scale operation compared to laboratory scale test in Fig. 5 could be explained by this additional flocculation in the settling zone.

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CONCLUSIONS

The Laboratory Clarifier Test developed in this study is a rapid and convenient test that can have wide application in evaluating the performance of primary clarifiers. The Laboratory Clarifier Test was validated by comparing the effluent TSS and NSS obtained in the laboratory against full-scale measurements. The procedure was found to reasonably simulate full-scale optimized primary clarifier performance under varying surface overflow rates. Furthermore, the procedure was capable of predicting full-scale NSS. Additional flocculation of 25% was found to be needed for the Laboratory Clarifier Tests since additional flocculation is occurring in the settling zone of a full-scale clarifier. It is also a valuable simulation tool to rapidly estimate process control regimes for a range of full-scale SORs, in order to achieve desired removal efficiencies.

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