Innovative Wastewater Treatment in the Developing World

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Abstract

The addition of chemical coagulants to increase the performance of primary wastewater treatment settling units has gained greater recognition in recent years. While the process of adding metal salts to increase sedimentation rates is nothing new, the practice had fallen out of favor, largely due the large amounts of additional sludge produced. However, with research and application involving reduced metal salt dosages and advances in polymer technology, many earlier obstacles to use have been largely overcome. Chemical addition is a particularly appealing approach in developing countries, as it provides a non-energy intensive method to dramatically increase the performance of wastewater treatment plants. Existing plants can be easily retrofitted and increasing numbers of new plants are being designed to incorporate chemical addition. This article outlines the general principles of chemical addition, its history and recent developments. It then presents case studies in Brasil, where chemically enhanced primary treatment has been increasingly applied both to overloaded existing plants and to the design of direly needed new facilities. In addition, early findings from the operation of a major new facility in Hong Kong are presented as an example of the performance of large-scale facilities designed specifically for chemically enhanced primary treatment.

General Principles of Chemically Enhanced Primary Treatment

The first stage of treatment in a wastewater treatment plant is usually sedimentation, which relies on gravitational settling to remove a portion of the suspended solids, biological oxygen demand (BOD) and nutrients, especially phosphorus and nitrogen, in the influent wastewater. This primary treatment is often followed by a biological treatment stage such as activated sludge and then by disinfection prior to discharge into a water body. In the primary stage, some of the particles that have a higher specific gravity than water will settle to the bottom of the sedimentation tank, forming a sludge blanket that is periodically removed, treated, and disposed of, usually in a landfill.

The efficiency of primary sedimentation tanks are a function of the surface overflow rate, defined as the plant flow rate divided by the total surface area of the primary sedimentation tanks. For conventional primary settling, the overflow rate for average dry weather flow is about 40 m/d and typical removal rates are about 60% of the influent total suspended solids (TSS), 30% of the BOD, 30% of the nitrogen content, and 30% of the phosphorus. The settling of process is enhanced by coagulation – the tendency of particles to coalesce. The greater size of coalesced particles causes them to settle faster.

Chemically Enhanced Primary Treatment (CEPT), also called Direct or Pre-Precipitation in Europe, involves the addition of small amounts of chemical agents and polymers to increase this coagulation process. The addition of metal salts, such as ferric chloride, ferric sulfate or alum decreases the surface potential around the wastewater particles, decreasing the resistance that must be overcome before coalescence. Settling can be further augmented by the addition of polymers, which aid in floc formation. The best results are usually achieved when chemical salt addition is followed by a period of rapid mixing to promote coagulation followed by polymer addition and a slower mixing regime to minimize floc break-up. In contrast to conventional primary treatment, a well-operated sedimentation basin with chemical addition can achieve removals of 85% of the influent TSS, 65% of the BOD, 30% of the nitrogen, and 85% of the phosphorus at overflow rates two to three times larger than for conventional primary settling[1]. CEPT is therefore a simple, cost-effective treatment technology for upgrading the removal efficiency and increasing the flow capacity of existing overloaded treatment plants. In the case of new plants, plant size can be decreased by a factor of two or more.

Table 1 : Typical Removal Efficiencies of Primary Treatment

Criterion	Conventional Primary Treatment / percent	Chemically Enhanced Primary Treatment / percent
Total Suspended Solids	60	75-85
Biochemical Oxygen Demand	30	55-65
Phosphorus	30	55-85
Nitrogen	30	30

History and Recent Developments in CEPT

The use of chemicals to increase the level of coagulation and flocculation in municipal wastewater was widespread in England as early as the late 19th century. However, with the advent of biological treatment in the early part of the 20th century, the practice fell out of favor[2]. At the time, large dosages of chemical coagulants were added to obtain high removal efficiencies, resulting in large amounts of additional sludge. When lime was used, this increase could be as much as 100%. The expense of treating and disposing the sludge, typically a major part of the operating cost of a wastewater treatment plant, made coagulant addition uneconomical in the face of advances such as the activated sludge process. In addition, chemical dosages had to be individually tailored to the plant, requiring additional expense and expertise. By the 1930's, unaided gravitational settling followed by a biological unit became the norm.

With the use of recent advances in the use of ferric or aluminum salts and in polymer technology using very low coagulant dosages, chemical sludge volume has been reduced, and the previously prohibitive cost of additional sludge treatment and disposal has been largely overcome. Not only does the proper addition of chemical salts and polymers increase the efficiency and overflow rate of the primary sedimentation basin, but in so doing it decreases the load placed on any subsequent biological stage of treatment. This translates into higher per-area plant efficiency; a smaller CEPT facility can handle the load of a larger conventional one. Conversely, existing conventional facilities that are retrofitted to incorporate CEPT can handle overflow rates higher than the original design. As seen in Table I, CEPT also greatly improves the phosphorus removal efficiency of the primary sedimentation process. This is especially significant, as it can reduce the need for expensive tertiary treatment. Indeed, the savings in terms of costs and space now make CEPT a cheaper option than conventional treatment in many cases.

It often takes a landmark case to prove the effectiveness of a new approach, and CEPT was no exception. In 1985 at the Pt. Loma plant in San Diego, plant operators were faced with new stringent effluent requirements from the EPA but little additional funds to meet them. The operators adapted well-known potable water treatment processes by experimenting with the addition of metal salts combined with a small dose of polymer in their primary sedimentation basins and reported increased removal efficiency at three times the design overflow rate and minimal amounts of additional chemical sludge[3,4]. Ultimately, this was so successful that Congress waived the usual requirement for secondary treatment, saving the city an estimated two billion dollars and allowing the construction of a reclamation facility that now reuses about 15% of the total wastewater flow, instead of discharging it into the ocean. Because chemical addition research at Pt. Loma was conducted independently by plant operators, it received little coverage in the technical engineering literature. Thus, it is only recently that awareness of CEPT is entering the general municipal wastewater treatment consciousness.

The remainder of this article will focus on CEPT in the developing world with emphasis on Brasil, where it is becoming a particularly appealing approach to low-cost wastewater treatment. Not only is it more cost-effective than a conventional treatment train, but the technology of chemical addition is non-energy intensive. Moreover, burdened existing plants can be retrofitted with minimal effort. New plants, direly needed in this fast-industrializing part of the world, are being designed to incorporate chemical addition from the outset. Remarkably, awareness of CEPT has grown to the extent that even small, private plants are choosing to include it in their treatment process. The particular appeal of CEPT in the developing world is that it produces an effluent that, unlike conventional primary effluent, can be effectively disinfected. With increasing recognition of CEPT as a high-performance, low-cost alternative, the expense of additional biological treatment for the sake of an incremental removal of BOD can rarely be justified.

Chemically Enhanced Primary Treatment in Brasil

<u>Sao Paulo - Jar and Full-Plant Tests at the Ipiranga Facility</u>

The Ipiranga wastewater treatment facility, also called E.T.E Jesus Neto has been serving the city of Sao Paolo for over 70 years. Greater Sao Paulo, the largest city in South America, has a population of about 17 million[5] distributed in 339 municipalities. The Iparanga plant is one of only a handful of major treatment plants that currently service this area, and plant performance has been steadily declining due to the burgeoning wastewater inflows. Data from the period 1993-1996 show that Ipiranga's primary sedimentation basins were only achieving removal efficiencies of 20% of influent TSS, in contrast to the 60% that is usually achieved in a well-operated plant. BOD and COD removals were also low, at 20% and 30 %, respectively. In response to falling removal efficiencies, SABESP, the state environmental authority, agreed to a study designed to show that retrofitting the existing facility with CEPT was the most economical alternative, as this would involve minimal alteration of the secondary activated sludge treatment unit.

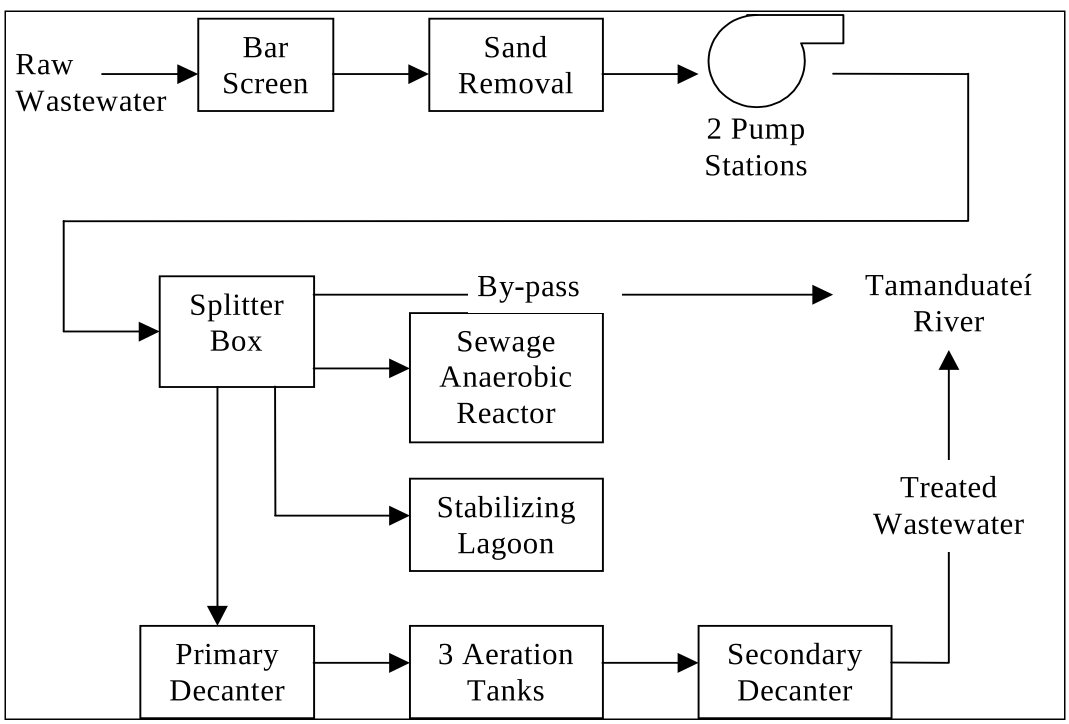

Figure 1 - Schematic of Treatment Train at Ipiranga

Full-scale tests began in 1996 to optimize the chemical dosage regime. Based on jar-test studies, dosages were varied between 25 and 50 mg/L of ferric chloride (dosed proportional to flow at the pumping station) and 0.25 and 0.5 mg/L of anionic polymer. As shown in Table II, the full-scale test results were extremely encouraging. With a dosage of 50 mg/L of ferric chloride and 0.25 mg/L of polymer, 62% of influent BOD was removed in the primary stage alone. When the polymer dosage was increased to 0.5 mg/L, the BOD removal efficiency dropped slightly (to 58%) but an excellent TSS removal efficiency of 80% in the primary treatment stage was achieved. This marked increase in primary treatment performance resulted in removal efficiencies of both BOD and TSS in excess of 90% from the biological treatment unit. Prior to CEPT, the removal efficiency after secondary treatment was only 70% for BOD and 60% of the suspended solids. The two types of polymers used were an emulsion-based product manufactured in Brasil, designated 'E' in Table 2, and a polymer that was soluble in water, designated 'S', that was manufactured in the United States.[6,7,8].

Table 2 : Results of Full-Plant Tests at Ipiranga, Sao Paulo

Dose of $FeCl_3$ (mg/L)	Dose and Type of Polymer (mg/L)	Flow Rate (L/s)	COD Removal Rate (%)	BOD Removal Rate (%)	TSS Removal Rate (%)
None added	None added	25	34	37	52
None added	None added	50	27	28	36
25	0.5 (E)	50	45	44	50
50	0.5 (E)	50	52	52	64
25	0.25 (S)	50	58	60	52
50	0.25 (S)	50	63	62	69
50	0.5 (S)	50	62	58	80

<u>Sao Paulo - Jar Tests at the Pinheiros Facility</u>

The Pinheiros plant was constructed in the 1970's to serve the city of Sao Paolo and handles a flow of 110,000 m^3/day. The waste is of residential and industrial origin, with the former contributing 70% of the flow. The facility is designed for sand removal, contains a conventional primary settling basin and secondary treatment. The primary sedimentation basin achieved removal rates of 32% of the influent BOD, 28% of COD and 33% of TSS. Due to its inadequacy in meeting effluent standards and maintenance problems (only one of three sludge digesters were operational), plant operation was discontinued in 1995 and wastewater rerouted to the Barueri plant through the construction of an underground feed channel. However, with the Brasilian government's interest in exploring treatment alternatives, the plant was chosen as a testing site to determine CEPT feasibility. While the problems of handling two different influent streams prevented full-scale tests of CEPT, bench-scale tests conducted in 1995 show promise. A dosing regime of 25 mg/L of metal salt combined with between 0.3 and 5 mg/L of anionic polymer achieved removal rates of over 75% of the influent BOD in the first influent stream. This satisfies the 60 mg/L effluent BOD limit for the state of Sao Paolo without recourse to secondary, biological treatment. TSS removals for the first influent stream were also reported at greater than 70%, far in excess of the 48% achieved with unaided gravitational settling.[9]

Rio de Janeiro - Retrofit of the ETIG Facility

Guanabara Bay in Rio de Janeiro suffers from extensive environmental contamination and algae growth due to high nutrient inputs, especially that of phosphorus. Discharge of untreated or poorly treated waste of industrial and residential origin has resulted in high levels of coliform, eutrophication problems and low dissolved oxygen in the surrounding waters. The Bay's wastewater treatment facility at Ilha do Governador, ETIG, which was constructed in 1980, has been hard-pressed to meet effluent requirements. Four pumping stations provide the influent to the treatment train, which consists of a grit chamber, a conventional primary settling basin, followed by an activated sludge process. The effluent from this process is discharged into the Bay.

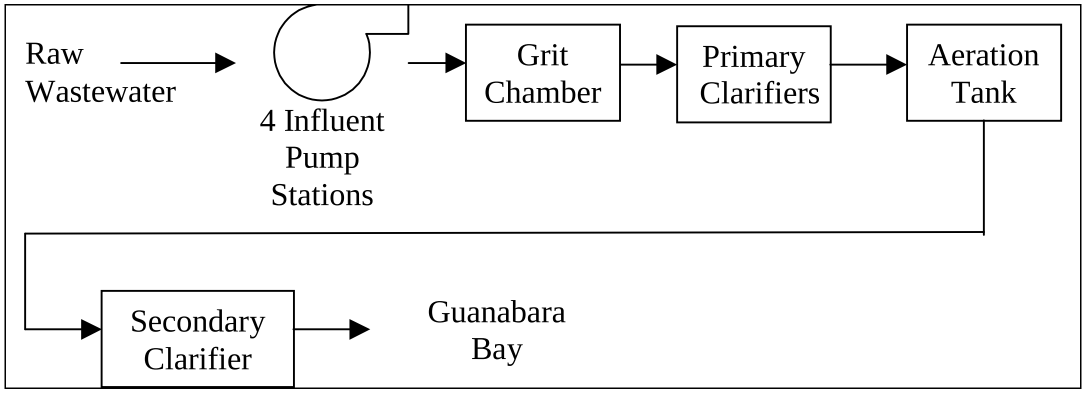

Figure 2 : Schematic of Treatment Train at ETIG

To address increasing evidence of contamination in the Bay and the poor performance of the facility, the state of Rio de Janeiro chose ETIG as a test-site to explore the possibility of using CEPT in new plants. Extensive jar tests were conducted to optimize the chemical dosage.[10] Subsequently, a full-plant test was performed. This test was comparative; the influent was divided into two streams, one which was fed to a conventional settling tank and the other was routed through a parallel sedimentation tank with the addition of metal salts and polymer. This full-scale procedure was run during two periods, December 15-21 of 1998 and January 3-9 of 1999. Ferric chloride was dosed at 35, 56 and 59 mg/L. Although the testing period was too short to provide a wealth of data, all indications were that removal efficiencies were doubled. In contrast to unaided primary settling which achieved maximum removal rates of 43% of the influent TSS, 44% of the BOD (though as low as 37% and 29%) and only 29% of the COD, the chemically dosed stream reported levels of as high as 76% of TSS, 75% of BOD and 65% of COD.

Rio de Janeiro – Construction of New Facilities at Pavuna and Sarapui

Based on the promise that CEPT has shown in bench and full-scale studies, the State of Rio de Janeiro is in the process of constructing plants that are designed for CEPT. The most ambitious of these projects are the Pavuna and Sarapui plants in Rio de Janeiro, shown in Figure III, at projected costs of $120 million for the Pavuna facility and $100 million for the Sarapui. The location of these facilities is outlined in Figure 3 and and both are scheduled for completion in the summer of 2000. The construction of these two facilities are expected to make a significant contribution to alleviating the present water contamination problem; the Sarapui plant is designed to handle wastewater that is currently discharged into streams and rivers which flow only a short distance before emptying into Guanabara bay. Due to the previous lack of an organized sewerage system, the influent to the Pavuna facility is currently discharged into open ditches with obvious groundwater contamination consequences. Once built, the two plants will serve the inhabitants of 90 neighborhoods in the municipalities of Rio de Janeiro. Additional infrastructure for the plants will include over 800 kilometers of new sewerage, the lack of which hinders wastewater treatment efforts, and over 135,000 new household connections. Three and a half kilometers of pumping line will have to be installed.[11]

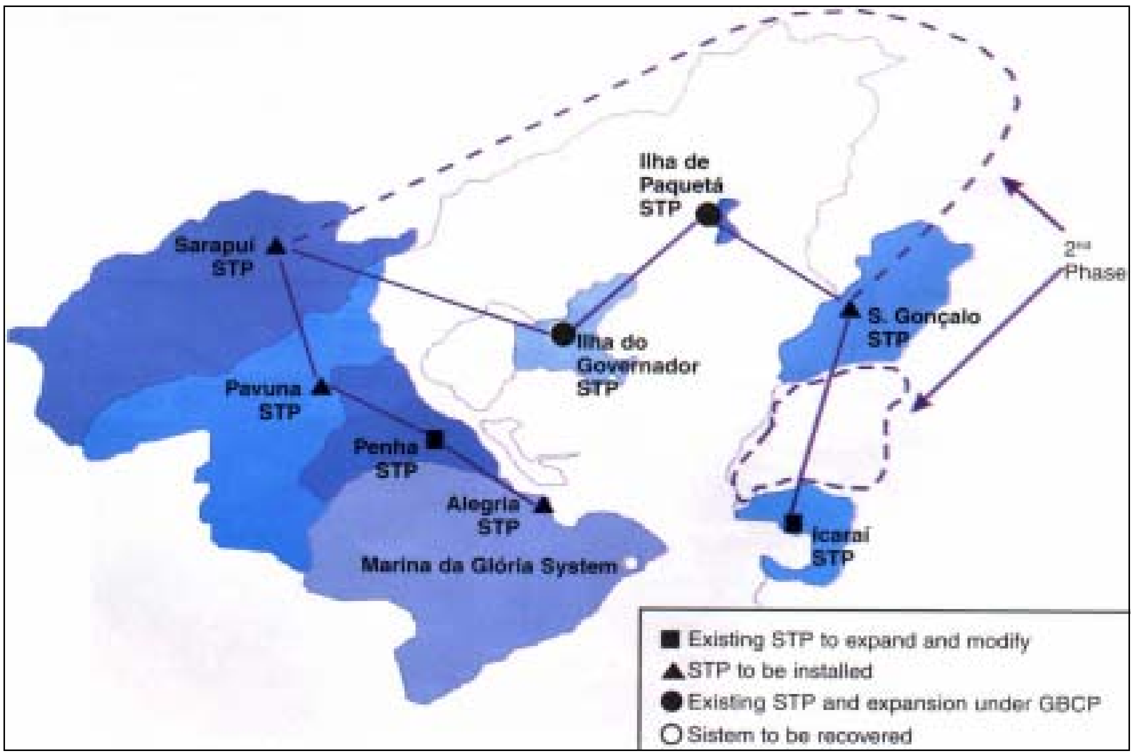

Figure 3 : Location of Treatment Plants at Rio de Janeiro

CEPT at Private Treatment Facilities – Riviera de Sao Lourenço

Riviera de Sao Lourenço, a small, private resort community on the Atlantic Coast, has a reputation for environmental consciousness and includes one of the best small-scale wastewater treatment facilities in the state of Sao Paulo. The present treatment system, consisting of an anaerobic lagoon followed by three facultative lagoons in parallel, provide treatment prior to chlorine disinfection and discharge into the Itapanhau River and thence to bathing beaches on the coast. Treatment efficiency is becoming an increasing concern during the summer months, when the area population doubles to 80,000 people. Due to the popularity of this resort, the summer population is expected to climb even higher to over 100,000 people in the near future. Anticipating the inadequacy of the present system to deal with the increased load from this projected population increase, the treatment train was modified to incorporate chemical addition.

As part of the effort to maximize the benefit of the CEPT upgrade, the authors were invited for a site visit in January of 2000. This was within the context of the Master of Engineering program of the Civil and Environmental Engineering Department of MIT, which is a intensive nine-month course designed for graduate students seeking to enter professional practice. Jar scale tests were conducted to gain an idea of the type of chemicals and dosages that would be best suited to the Riviera wastewater. Subsequent full-plant tests calibrated the results of the jar scale study to the larger system. Furthermore, a site-specific biosolids management study was prepared to maintain and extend Riviera's reputation for ecological goodness. To aid in plant monitoring and decision support, a data management scheme was also submitted to ensure that operators could quickly and effectively judge plant performance.

CEPT was a particularly appealing alternative for Riviera since chemical addition could be discontinued with minimal effort during the off-season winter months. Two CEPT clarifiers were added anterior to the existing lagoon system in January 2000, and early results show a marked increase in treatment efficiency.

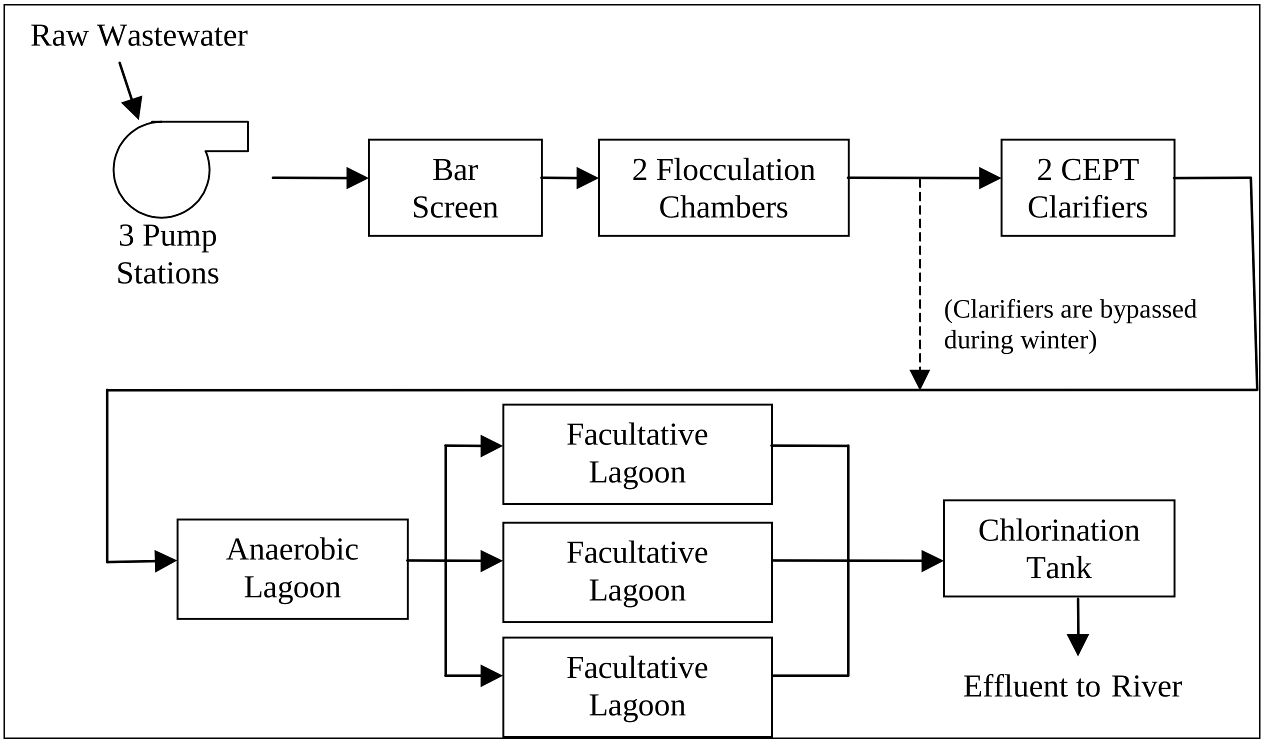

Figure 4 : Schematic of Treatment Train at Riviera de Sao Laurenco

Before the implementation of CEPT, the overall treatment efficiency of the combined lagoons during the 1999 Carnival period of February 13-16 was 79% for BOD. During the comparable 2000 Carnival period (March 3-7), after the installation of the CEPT clarifiers, removal efficiencies of 85% BOD were observed. While the increase in BOD removal efficiency does not seem large, it must be remembered that this was achieved with a BOD loading of 1700 kg/d as compared to 1200 kg/d the year before, about a 40% increase.

In the summer of 2000, the Riviera treatment facility was also the test site for the simplest form of retrofit – the addition of chemical salts directly into the existing lagoon system, a procedure called In-pond CEPT. This was done as an emergency measure, as the new CEPT clarifiers were not operational during the peak summer season and plant operators were concerned about meeting effluent requirements. In-Pond CEPT is widely used in Scandinavia to improve the efficiency of waste stabilization lagoons during the winter, and studies show that treatment efficiencies are similar to those achieved by chemical addition in a separate clarifier anterior to the treatment train. The drawback of adding chemicals directly to the treatment lagoon is that the sludge blanket at the bottom of the lagoon builds up quickly and must be periodically removed, usually once a year. The advantage is that skilled operators are not required to maintain a clarifier with an automated sludge removal system as in the case of Pre-Pond CEPT, and the construction and operating costs of the clarifiers can be dispensed with.[12] When 50 mg/L of ferric sulfate and 0.5 mg/L of anionic polymer was added directly into the anaerobic lagoon, COD removal efficiency in that lagoon jumped from 36% to 52%. Remarkably, TSS removal efficiency was recorded at 77%, extremely high for an anaerobic lagoon.

Construction of a New CEPT Facility
Stonecutters Island, Hong Kong

The recent developments in CEPT cannot be considered complete without a discussion of the success story of Stonecutters Island in Hong Kong. The booming economy of Hong Kong and its resultant increase in population to its current levels of 6 million people has created a massive increase in the quantity of wastewater that must be efficiently treated. In 1997, about 1.65 million m^3/day were discharged through local outfalls, prompting beach closures, high bacterial levels, and depletion of dissolved oxygen content in the waters around Hong Kong. To address this problem, the Environmental Protection Department (EPD) of Hong Kong commissioned a strategy study in 1989 to formulate a comprehensive wastewater treatment solution that would address not only the demands of the current population, but plan for projected increases. The study recommended the construction of two new wastewater facilities with implementation in three stages. Stage I called for the collection and delivery of all wastewater from Kowloon and the eastern portion of Hong Kong Island to a new facility to be built at Stonecutters Island. Treated wastewater was to be discharged a short distance away into the Hong Kong Harbor through an interim outfall. Stage II would be the construction of a 30 km long effluent tunnel that would end in an ocean outfall in the Lema channel, outside the territorial waters of Hong Kong. Stage III would be the construction of a new facility on Hong Kong Island, which would service the areas not already covered by Stonecutters Island.

The original plans for the Stonecutter's Island facility called for conventional primary treatment in 58 sedimentation tanks. It was anticipated that the plant would be dosed with lime at 120 mg/L to raise the effluent pH to 9.7 and provide some degree of disinfection. Lime addition was to be a temporary measure until the Stage II outfall was completed. However, further studies showed that disinfection would be ineffective at this lime dosage and that enormous quantities of chemical sludge would be produced. Faced with the possibility of a new plant that did not meet effluent requirements even at the outset, the EPD appointed an International Review Panel in 1994 to assess costs and benefits of higher levels of treatment and alternative outfall locations.

The recommendation of the Panel was that the design of the Stonecutters Island facility be adapted to permanently incorporate CEPT - a recommendation that was implemented in early 1995, with plant operation by 1998. A major pilot plant study in 1996, upon which the Review Panel based their recommendation, achieved removal rates of 91% of influent suspended solids, compared with 71% for conventional treatment, and 80% of the influent BOD, compared with 42% for a conventional treatment train. Furthermore, the number of sedimentation tanks could be decreased from to 38 because of the higher overflow rate. Not only did this reduce construction costs but also saved valuable space allowing flexibility in implementing future treatment options, a huge benefit in an area where land is at a premium. Furthermore, the performance at Stonecutters Island allowed the EDP to dispense with plans for Stage III – the construction of a new facility, resulting in large additional savings.

Early full-plant operational results of CEPT treatment at Stonecutters Island are extremely encouraging. Influent wastewater, containing an average BOD of 143 mg/L, is treated to an effluent level of 42 mg/L, a removal efficiency of 71%. Influent suspended solids levels of 212 mg/L are treated to 36 mg/L, an efficiency of 83%. These removal efficiencies were attained at an average influent flow of 315,000 m^3/d and are far above those usually achieved in primary treatment. In addition, these treatment levels are achieved at overflow rates of 50-60 m/d, which is twice that of conventional treatment plants of the same size. It has been found that the optimal dosing regime is 10 mg/L of ferric chloride combined with 0.1 mg/L of anionic polymer, extremely low concentrations that make the increase in plant performance and the cost of its operation all the more remarkable[13].

Conclusions

The success of San Diego's Point Loma plant in 1985 has reawakened interest in chemically enhanced primary treatment as an effective and economical way to increase the performance of wastewater treatment facilities. With dosages as low as 10 mg/L of ferric chloride and 0.1 mg/L of polymer, the new landmark facility in Hong Kong has reported highly effective pollutant removal at twice the original design overflow rate. In fast-industrializing regions of the world, such as Brasil, communities are increasingly discovering that chemical addition can be used to improve the performance of existing over-burdened plants and in maximizing the removal efficiency of their new facilities. Plants at Rio de Janeiro and Sao Paolo are being modified to include CEPT and new facilities under construction in Rio de Janeiro are being pre-designed to incorporate chemical addition. This trend is not limited to Brasil and Hong Kong. Major facilities in Cairo, Egypt and San Juan, Puerto Rico incorporate CEPT in their design and a new plant at Mexico City may do the same. It appears that the chemically enhanced primary treatment, a century-old technology that had fallen out of favor, is now back in vogue.

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References

[1] Morrissey, Shawn P., Julia S. Altshul, and Donald R.F. Harleman. "Preparatory Bench Scale testing for Chemically Enhanced Primary Treatment." Final MIT/AUB Report. Feb. 1992.
[2] Metcalf & Eddy, Wastewater Engineering, Treatment, Disposal and Reuse. Boston : Irwin McGraw-Hill, 1991., p.486
[3] Hansson, B. and Langworthy, A. "Upgrading Point Loma Treatment Plant in San Diego with Improved Advanced Primary Treatment", Chemical Water and Wastewater Treatment III. New York: Springer-Verlag, 1994: 257-268.

[4] City of San Diego, The: 1998 Annual Reports and Summary, Point Loma Wastewater Treatment Plant Ocean Outfall, 1998: II-5, VI-1, IV-56-57.
[5] http://www.brazil.com/html/allabout_sao_paulo.shtml
[6] Fundação Salim Farah Maluf and SABESP. "Relatório no. 2JN do Teste de Aplicabilidade do "CE.P.T. – Tratamento Primário Quimicamente Aprimorado" ao Esgoto da E.T.E. Jesus Neto - SABESP" Unpublished Report. 1996.
[7] Fundação Salim Farah Maluf and SABESP. "Segundo Relatório do Teste de Aplicabilidade do "CE.P.T. – Tratamento Primário Quimicamente Aprimorado" ao Esgoto da E.T.E. Jesus Neto - SABESP" Unpublished Report. 1996.
[8] Fundação Salim Farah Maluf and SABESP. "Relatório Final do Teste em Escala Real da Tecnologia C.E.P.T. na E.T.E. Jesus Neto (B. Ipiranga – SP)." Unpublished Report. Nov 1996.
[9] Harleman, Donald R.F., and S.E. Murcott. "Chemically Enhanced Primary Treatment (CEPT) at Pinheiros Wastewater Treatment Plant." Unpublished Report. MIT November, 1995.
[10] Harleman, Donald R.F., and S.E. Murcott. "Low Cost Nutrient Removal Demonstration Study Report on ETIG Bench Scale Tests Rio de Janeiro, Brasil." Unpublished Report. MIT April, 1997.
[11] Associação das Empresas de Engenharia do Rio de Janeiro. GBCP Guanabara Bay Cleanup Program. Rio de Janeiro, not dated.
[12] Odegaard, H., Balmer, P., Hanaeus, J. "Chemical Precipitation in Highly Loaded Stabilization Ponds in Cold Climates : Scandinavian Experiences." Wat. Sci. Tech. Vol 19, No 12, pp. 71-77.
[13] Harleman, Donald R.F., Poul Harremöes, and Qian Yi. "Hong Kong Harbor Cleanup." Water Environment and Technology. March 1997:47-50.