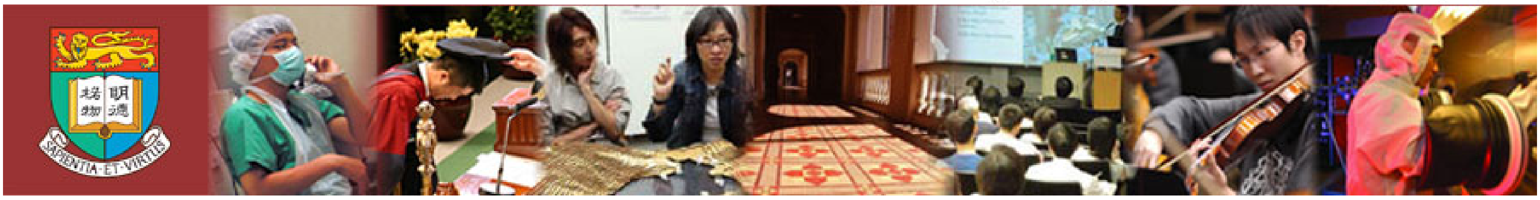

**The First Kadoorie Institute Symposium**

**How Sustainable Development Matters: The Search for Joined-up Disciplines**

Symposium Paper

# Incinerating Hong Kong Water Treatment Sludge: The Potential of Ash Reuse and Recycling

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This paper is work-in-progress and the author welcome constructive feedback. The paper should not to be quoted without the permission of the author.

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## ABSTRACT

At present, landfilling is the only means to dispose of nearly 900 tonnes of dewatered waste sludge generated in Hong Kong everyday. The Environmental Protection Department of Hong Kong has chosen sludge incineration to resolve this issue, but it should be further noticed that this approach still results in residual ashes that require proper stabilization prior to be landfilled. A sustainable solution in waste management should develop a closed-loop for material flow by reusing and recycling. Current focuses on sludge incineration planning are largely the stringency of emission standards and the impact on the facility surrounding areas. However, potential reuse and recycling strategies for incineration ash should also be taken into account to be part of the sustainable waste management plan. This paper introduces the different types of sludge generated in Hong Kong; predicts the characteristics of their ashes after incineration; and evaluates the potential of ash reuse and recycling strategies, e.g. land applications and construction materials, in according to their unique nature and application goals. Although both scientific principles and engineering feasibility are core consideration factors for beneficial uses of incineration ash, rigorous campaign for the public acceptance will be essential toward the success of such implementation.

## INTRODUCTION

Sludge is the settleable waste solids separated from liquids during industrial or wastewater treatment processes (Cheremisinoff, 2002), and its disposal has become one of the most difficult environmental problems (Tchobanoglous and Schroeder, 1987). Substantial quantities of waste sludge are generated from both public and private treatment facilities. As an important physical feature, the water content of sludge may sometime be up to 90% depending on whether the dewatering process has been applied, and it thus renders sludge a semi-solid material difficult for transportation and storage. The chemical composition of sludge is often very complicated and may contain hazardous pollutants. Some organic pollutants may be degraded by biological or photolytical reactions in the natural environment and treatment processes, but the other organic pollutants may be persistent in our environment and subject to bioaccumulation. Inorganic pollutants, such as toxic metals, are often non-degradable and persistent in our environment, though existing in different chemical forms. Biological processes in sludge can be very active, which is why sludge may sometimes be classified as putrescible waste. Together with the abundant nutrients and microorganisms, harmful bacteria and pathogens may also reside in the sludge leading to additional difficulties in sludge handling and reuse. Due to these unique physical, chemical and biological features, sludge management strategy often receives widespread attention in public media and attracts intensive technical and political debates.

The characteristics of sludge are significantly influenced by the type of water treated and the treatment method utilized. In general, the sludge property can be categorized into three different subsets depending on the source of producing the sludge. Domestic sewage enters the sewage treatment plants and its solid content is precipitated through a series of treatment techniques, such as physical settling and biological digestion. The "sewage sludge" is thus generated and can be disposed of in landfill after proper dewatering. Water treatment works turn raw water into drinking water and also generate sludge made up of solids removed from the raw water and added treatment chemicals, such as coagulants. The generated "waterworks sludge (or water treatment works sludge)" is currently discharged to sewage system or dewatered for landfilling. Most industrial wastewater is required to go through proper treatment before discharging into the environment or sewage system. The solid precipitated from such wastewater is ususlly referred to as "industrial sludge", and its composition is almost solely determined by the industrial activities and the wastewater treatment methods. Special treatment facilities are usully needed for treating industrial sludge.

Among the three types of sludge categorized above, sewage sludge is usually generated with the largest quantity in most urban environments. When fresh sewage is added to a settling tank, the suspended solid matter will settle out known as raw sludge or primary solids. If the sewage treatment plant is equipped with secondary treatment process (a system using microoragnisms to degrade organics in the water), the secondary sludge enriched with waste living oragnisms will also be part of the sewage sludge. Nowadays, many sewage treatment plants may also use anaerobic bacteria to decompose the sewage sludge for furtrhe volume reduction. This treatment is called "sludge digestion", and the digested sludge will take less landfill space when being disposed of. On the other hand, the sewage sludge can also be composted aerobically to be reused as fertilizer or other soil improvement material. However, satisfactory treatment and disposal of the sewage sludge can still be the single most complex and costly operation in sewage treatment system (Davis and Masten, 2009). Currently, most of the resulted solids after sewage treatment processes are still simply spread on land or disposed of in landfill sites.

Virtually all known drinking water processing systems generate an enormous amount of residual sludge. Such sludge typically contains mineral and humic matters removed and precipitated from the raw water, together with the residues of any treatment chemicals used as coagulants (commonly aluminum or iron salts) and coagulant aids (mostly organic polymers). In the practical context, alum sludge and ferric sludge refer respectively to the waterworks sludge generated when aluminum or iron salt is used as the coagulant. Prior to 1946, waterworks sludges were simply discharged to the nearest drainage course or water body with the thought of the fact that waterworks sludge was usually very low in its organic content and consequently not exerting any worrisome oxygen demand on water bodies (Babatunde and Zhao, 2007). Most waterworks sludges generated these days are either dicharged to sewage system to be treated together with domestic wastewater or dewaterd to be disposed of in landfill. On the other hand, it has also been advocated that waterworks sludge could be a potential recyclable product, offering great commercial potential for a variety of reuse and recycling strategies.

Rapid processes of industrialization and urbanization in many areas around the world have increased the generation of industrial wastewater and its resulted treatment sludge at tremendous rates (Tay et al., 2000). The chemical property of this type of sludge and its treatment goals are usually very specific. For example, electroplating shops usually generate sludges with very high hazadous metal contents, and thus the treatment process will require effective metal immobilization techniques (Shih et al., 2006). Industrial sludge is generally more toxic than sewage and waterworks sludges, and may sometimes be classfied as hazadous waste subject to very strict regulation in transportation and disposal. In many countries, special facilities are usually built and designed to handle this type of sludge.

Sludge treatment is a serious problem due to the high treatment costs and the potential risks to environment and human health. At present, sludge management methods end with land application, landfill disposal, incineration or other thermal techniques. In Europe, the main route of sludge management strategy is land application (~45% in volume) with around equal amounts of landfill disposal and thermal treatment (~20% each) (Padmanabhan, 2005). Comparing to landfilling and incineration, utilization of sludge as organic fertilizer is a more sustainable disposal method because it recycles both nutrients and organic matter (Neyens et al., 2004). However, the nature of the present wastewater treatment systems is such that toxic pollutants are concentrated in the sludge, together with a large part of the pathogens. This is thus not surprising to see the increasing awareness and pressure regarding risks for environment and human health in the practice of using sludge as a fertilizer in agricultural systems. The recent development is also influenced by the increasing insight into the possible adverse effect of these toxic pollutants and pathogens. Parallel to this development, the government policy and regulations regarding the application of sludge in agriculture have changed considerably. Nevertheless, policy and legislation regarding sludge application and sludge management in general are heavily dependent on local, national and regional circumstances and conditions (Rulkens, 2004).

In accordance with the waste hierarchy, landfill is the last option for organic waste. Some developed countries have even started to ban the disposal of sewage sludge in landfill (Dichtl et al, 2007). For example, starting from June 2005, the disposal of sewage sludge with an organic content more than 5% has become illegal in Germany according to the Technical Guidance on Settlement Waste (TASi). The untreated sewage sludge can usually contain up to 70 - 90% of organic content. Besides the biological means of reducing the organic content through degradation reactions (such as anaerobic digestion), another ways of effectively reducing the organic content is through thermal treatment (such as incineration/combustion) to mineralize the organics. The increase of sludge incineration/combustion has been predicted particularly with the possibility of energy recovery from such practice (Padmanabhan, 2005). The major concern over this method is largely due to its potential of releasing harmful air pollutants. Therefore, the difficulty of gaining public acceptance and feasible facility site are often the main hurdles in planning the practice of sludge incineration/combustion. Moreover, although incineration/combustion can provide a very effective way to reduce the sludge volume and organics, the remaining ashes and residues will still need to be disposed of at controlled landfills. In developing countries, proper sludge management is still very limited, although people are aware of its importance and starting to recognize it as a priority in the short term (Jimenez et al., 2004). The investment in sludge management programs should be increased and, at the same time, the costs of sludge treatment should consider the public health and environmental savings to make those programs more attractive to decision makers. Many decision making processes and results now experienced in developed countries are expected to create huge impacts in the future actions of developing countries. Future sludge management strategy will be progressively focused on the improved treatment efficiency and environmental sustainability of the approach.

At present, landfilling is the only means for disposal of sludge generated in Hong Kong. In the waste management policy framework of 2005-2014, the Environmental Protection Department of Hong Kong has chosen to develop the integrated waste management facilities with incineration as the core treatment technology to resolve the key problem of insufficient landfill space (HKEPD, 2005). Currently, the operational planning is starting with the incineration of sludge generated in Hong Kong. Although the primary focus now is on adopting stringent emission standards and minimizing the impact on the facility surrounding areas, potential reuse and recycling strategies for incineration ash should also be taken into account to be part of the sustainable waste management plan. The aims of this paper are to demonstrate the different types of sludge generated in Hong Kong; to predict the characteristics of their ashes after incineration; and to evaluate the potential of ash reuse and recycling strategies. Within the efforts of creating beneficial uses of incineration ash, both scientific principles and engineering feasibility are the core consideration factors for such technological development.

## SLUDGES IN HONG KONG

The sources of waste sludge in Hong Kong are mainly sewage treatment and drinking water treatment. A small amount of sludge may also come from the industrial wastewater and chemical waste treatment processes. Therefore, the three types of waste sludge generated in Hong Kong are sewage sludge, waterworks sludge and chemical sludge, which are managed by Drainage Service Department, Water Supplied Department and Chemical Waste Treatment Centre, respectively.

### Sewage Sludge

Similar to many major cities in the world, the sewage sludge generated from treating the domestic sewage in Hong Kong is of the largest quantity and the most challenging sludge problem. In Hong Kong, about 93% of the 7 million population are now served by the public sewage system with over 98% of the sewage produced being collected and treated. There is some 2.6 million cubic meters of sewage produced everyday in Hong Kong and the treatment system includes around 275 plants ranging from preliminary treatment plants to tertiary treatment plants treating sewage from residential, commercial and industrial sectors. The operation of Drainage Service Department is generating average 871 tonnes of dewatered sewage sludge for being disposed of in four strategic landfill sites in Hong Kong everyday (HKEPD, 2008). As mentioned in the introduction, the sewage sludge is putrescible due to the richness in water and organic contents, and it will trigger strong biological degradation reactions in landfill. The sewage sludge in Hong Kong is mechanically dewatered before sending for landfilling, and the dewatered sludge is with 65-75% of water content depending on the dewatering process in each treatment plants (Ng, 2009). The organic content within the dried solids of sludge can be analyzed by heating the sludge at various temperatures. Figure 1 shows the weight loss of sewage sludge samples generated from Shatin treatment plant, the largest secondary treatment plant in Hong Kong. The weight loss of around 65% after 400$^{o}$C heating is largely due to the oxidation of organic content in the dried solids. Further minor weight loss (~10%) at higher temperature (>800$^{o}$C) was usually due to the decomposition of inorganic compounds, such as carbonates. The same analysis derived from the sludge samples of Stonecutters Island treatment plant, the largest chemically enhanced primary treatment (CEPT) plant in Hong Kong, has indicated around 83% of organic content in its dried solids.

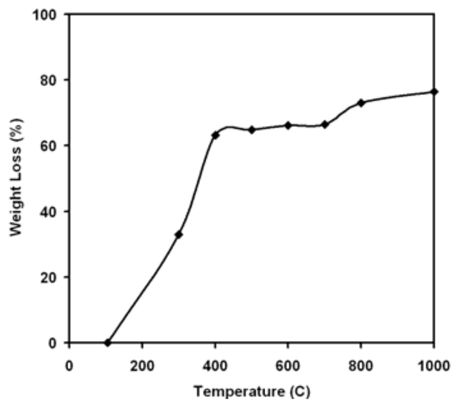


Figure 1. Weight loss of heat treating dried sewage sludge obtained from Shatin sewage treatment plant in Hong Kong. The dried sewage sludge was prepared by heating the received sludge samples at 105$^{o}$C for overnight. The weight loss measurements were then carried out by heating the dried sludge at designated temperatures for 1 hour.

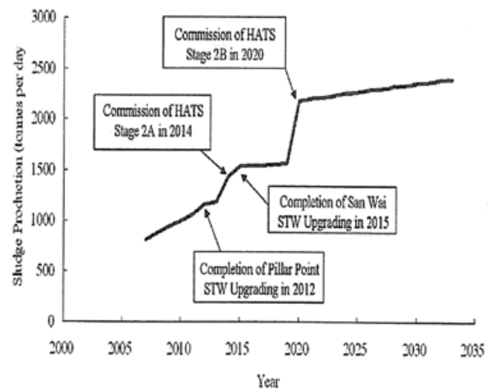


Figure 2. Sewage sludge production forecast in Hong Kong (Ng, 2009). The estimation has reflected the significant influence from the future implementations of Harbour Area Treatment Scheme (HATS) and the expansion/upgrade of existing sewage treatment works (STW).

To improve the water quality, especially the renowned Victoria Harbour, the government of Hong Kong is continuingly carrying out sewage improvement projects, such as Harbour Area Treatment Scheme (HATS) and the expansion/upgrade of existing sewage treatment works (Ng, 2009). Together with the growth of population, it is forecasted that the HATS as well as the expansion/upgrade of existing sewage treatment works will increase the quantity of sewage sludge to 1500 tonnes per day by 2014 and over 2000 tonnes per day by 2020 (Figure 2). Therefore, the quality of sewage sludge in Hong Kong is expected to substantially influence the selection of sludge management plan and the final characteristics of incineration ash.

## Waterworks Sludge

The Water Supplied Department provides the need of on average 2.605 million cubic meters of fresh water every day through 21 water treatment works in Hong Kong. Around 0.742 million cubic meters of sea water is also pumped with simple chlorination to supply the use of toilet flushing and reduce the fresh water consumption (HKWSD, 2008). To remove the harmful substances or pathogens that are usually hosted by the small particles in raw fresh water, coagulation chemicals are added into the water treatment process to assist the precipitation of small particles. Such process will generate “waterworks sludge” that discharges as a type of solid waste, and most waterworks sludge generated on-site is dewatered by filter press for converting into sludge cakes before disposal. Figure 3 shows the weight loss of heating waterworks sludge samples generated from Ma On Shan water treatment works in Hong Kong. The weight loss of merely around 10% after 400°C heating reflects the typical property of waterworks sludge, which is often much less in organic content comparing to sewage sludge.

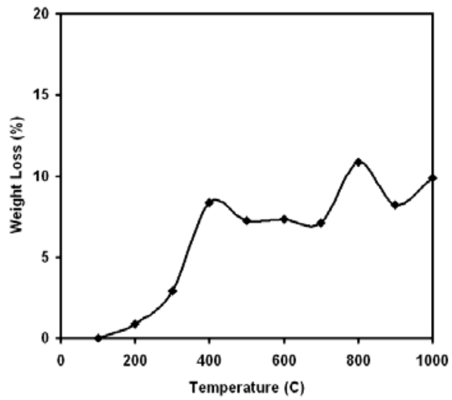


Figure 3. Weight loss of heat treating dried waterworks sludge obtained from Ma On Shan water treatment works in Hong Kong. The dried sewage sludge was prepared by heating the received sludge samples at 105°C for overnight. The weight loss measurements were then carried out by heating the dried sludge at designated temperatures for 1 hour.

The water treatment works in Hong Kong use aluminum-based coagulation chemicals to facilitate the particles precipitation. Therefore, it is expected that the waterworks sludge generated in Hong Kong is rich in aluminum hydroxide or other hydrated alumina forms. Everyday, around 14 tonnes of waterworks sludge is produced in Hong Kong. Although comparing to sewage sludge the quantity of waterworks sludge is of much smaller fraction to the overall sludge issue, the entirely different features of waterworks sludge may provide the option of separate management planning for better metal recycling potential or a message of the need for special incineration method due to its very low organic content.

## Chemical Sludge

The Chemical Waste Treatment Centre (CWTC) on Tsing Yi Island treats a variety of Hong Kong chemical wastes, e.g. waste oil, solvent, acids, and etchants, to prevent the release of these extremely harmful substances into the environment (HKEPD, 2006). The treatment process usually proceeds with the oil/water separation and then uses the physical/chemical treatment to generate the chemical sludge/residue. The incineration method is performed to eliminate all the organic fractions in the chemical sludge/residue and results in small volume of ashes enriched with inorganic components. The incineration ash together with any other solid residue are stabilized by cementation technique and disposed of in landfill. Although belongs to a very detrimental type of waste to the ecosystem and human health, the chemical waste generated in Hong Kong is well-controlled by CWTC. There is around 15 thousands tonnes of chemical waste generated in Hong Kong every year. But, due to the very large fraction of liquid and organic content in the waste, the quantity of incineration ash generated by the chemical sludge is thus insignificant to the current waste management problem. Moreover, since the chemical waste may usually be classified as hazardous and has to be stabilized with cement materials for landfilling, the potential of reuse or recycling this type of material or its ashes is very low.

## ASH CHARACTERISTICS AND REUSE/RECYCLING

The dewatered sludge contains a significant amount of water and can cause stability and operational problems at landfill. To overcome these problems, it is necessary to mix the sludge with around ten times its volume of solid waste during disposal. A review of different treatment technologies aiming for providing a feasible treatment and disposal strategy for Hong Kong sludge was conducted in 2005. The review looked into various types of proven sludge treatment methodologies including composting, heat drying and incineration. Composting was first ruled out largely because of the need for very large site area and the lack of suitable outlets for the vast quantity of compost end-product. A more comprehensive evaluation on incineration and heat drying was then carried out and concluded that incineration as the preferred option due to its advantages of larger volume reduction, better energy efficiency and biologically inert product (Ng, 2009). In the global scale, the practice of sludge incineration is also in an increase trend due to current debates about safe sludge disposal methods and new legal requirements aiming to eliminate biohazard concerns.

Sustainable development, meaning economic growth that is environmentally sound, is a practical necessity. Environmental goals cannot be achieved without development. Nor can development goals be achieved and sustained without sound environmental management (Sachs and Reid, 2006). When developing or adapting new technology for environmental problems, it is important to not only carry out the “cradle-to-grave” analysis for the best technological choice, but also to approach the problem with potential “cradle-to-cradle” design for a more sustainable environmental solution. During the management planning of solid waste issues, such as sludge treatment and disposal, one should develop a closed-loop for material flow by appreciating the waste hierarchy concept, i.e. to reduce, reuse and recycle (3Rs) the waste materials in the management strategy. Reduction of ash volume generated from sludge incineration can be achieved by selecting quality facilities and keeping good operation to ensure the complete combustion of intake sludge. Strategies of reusing incineration ash are mostly on land applications, such as used for daily landfill cover or soil improvement (hold water, supply minerals and buffer acidity). Successful experiences of recycling incineration ash include using it as the raw materials of concrete/cement products, construction ceramic products and metals/minerals recovery. Depending on the sludge characteristics, the discussion on the reuse/recycling potential of the incineration ash of Hong Kong sludge is provided in the following sections.

### Sewage Sludge Ashes

The water content of mechanically dewatered sludge is usually around 70%. As indicated previously, the weight loss of heat treating the Hong Kong sewage sludge was 65-83% of the dried solids. Therefore, the waste reduction by incinerating the dewatered sludge generated in Hong Kong is expected to be 90-95% by weight, if with complete combustion. The characteristics of incineration ash are largely controlled by the intake sludge, which is the product influenced by the wastewater quality and the treatment method. The ash compositions derived from incinerating the sludge from three local sewage treatment plants, representing the three major treatment methods currently used in Hong Kong, are listed in Table 1.

Table 1. Major compositions of ashes incinerated from the sewage sludge of (a) Stonecutters Island treatment plant, (b) Shatin treatment plant, and (c) Stanly treatment plant. The sludge samples were heated at 1000$^{o}$C for 30 min in muffle furnace to simulate the complete combustion. The elemental compositions of the ashes were analyzed by Bruker X-ray fluorescence (XRF) spectrometer and expressed by the basic oxide forms in the tables.

(a) Stonecutters Island treatment plant

| Composition | $Fe_2O_3$ | CaO | $SiO_2$ | $P_2O_5$ | $SO_3$ | $Al_2O_3$ | $K_2O$ | Others |
|---|---|---|---|---|---|---|---|---|
| Concentration (%) | 37.9 | 21.9 | 13.0 | 7.7 | 6.8 | 5.0 | 3.3 | 4.4 |

(b) Shatin treatment plant

| Composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $P_2O_5$ | CaO | $Na_2O$ | $K_2O$ | MgO | Others |
|---|---|---|---|---|---|---|---|---|---|
| Concentration (%) | 33.9 | 30.2 | 15.5 | 8.9 | 3.5 | 2.5 | 2.3 | 2.2 | 1.0 |

(c) Stanly treatment plant

| Composition | $P_2O_5$ | $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | CaO | $K_2O$ | MgO | Others |
|---|---|---|---|---|---|---|---|---|
| Concentration (%) | 34.4 | 23.6 | 22.8 | 7.4 | 3.4 | 3.0 | 2.3 | 3.1 |

The Stonecutters Island plant is the largest sewage treatment plant in Hong Kong and contributes around 76% of the generated sewage sludge (Leong, 2009). It is a chemically enhanced primary treatment (CEPT) plant using ferric chloride as the coagulation chemical, and its intake sewage includes the sea water used for toilet flushing. As Table 1(a) shows, the ashes contain a significant amount of iron (Fe) due to the use of ferric chloride coagulant. High calcium (Ca) content may also be due to the other chemicals used in the process of conditioning the sludge. Such iron content in the ashes may be of economical value to be the raw material in iron and steel industry, depending on the market availability and the influence of impurity to the product quality. The alkaline property of ashes due to high content of calcium may make them suitable for land spreading to act as an ameliorative conditioner for soils. The enrichment of potassium in ashes is also beneficial for nutrient supply, although the supplying rate may be much lower and need to rely on soil chemistry and microorganisms activities to mobilize the nutrient from oxide form(s). The application of high iron solid to agricultural land can be recommended as long as suitable application rate can be complied. Adverse effects on crops and soils are possible with uncontrolled application of sludge-borne metals. In addition, potential use by mixing with the regular soil for daily landfill cover is feasible, as long as the levels of hazardous metals are low. On the other hand, recycling such ashes for construction materials can also be a practical alternative. Sludge and sludge derived products have been long considered for using in construction purpose, mainly in the form of either cement-based or ceramic-based material. However, high iron ashes may be deleterious to be used in cement-based material due to the chance of developing rust stains. In addition, the residue chlorine level in ashes obtained from incinerating such saline sludge derived should also be carefully evaluated, as it has been noted that chloride could corrode the cement kiln and block its duct (Kikuchi, 2001). Nevertheless, iron is a common element in ceramic raw materials, especially for brick products. Other major elements such as calcium and silicon are also commonly found in clays and feldspars, which are major minerals of ceramic raw materials. Studies of mixing incinerated sewage sludge ash into clay-based building products have concluded no adverse effect on final fired body or ceramic texture (Anderson, 2002; Anderson and Skerratt, 2003). Moreover, recent work of the author further indicates that the ceramic sintering process may have additional advantage in promoting iron oxide to stabilize hazardous divalent cations ($Ni^{2+}$, $Cu^{2+}$, $Zn^{2+}$ etc.) in the products by spinel formation mechanism (Shih et al., 2006a).

The Shatin plant is the second largest sewage treatment plant in Hong Kong and contributes around 5.7% of the generated sewage sludge (Leong, 2009). However, it is the largest "secondary treatment plant" in Hong Kong, using biological method (activated sludge process) to aerobically degrade organics after primary sedimentation process. It also carries out anaerobic digestion for sludge to reduce the sludge volume. Similar to Stonecutters Island plant, its intake sewage also includes the sea water used for toilet flushing. Table 1(b) shows the first three major elements in its incineration ash are silicon, aluminum and iron. The high temperature phases of these elements are quite inert, so the value of using this ash to benefit the soil property or agriculture purpose is very limited. Moreover, the potential hydration of aluminum oxides will produce aluminum hydroxides as the end products, which need to adsorb hydroxyl ions from the soils and thus reduce the soil pH. The use of such ashes for daily landfill cover is still a feasible option, if the hazardous metals levels in ashes are low. It is of average quality to be used in cement industry due to its low calcium content, and special attention needs to be paid with its alumina content. High alumina cement cures more quickly and can resist to weak acids, especially sulfates, but it has been suspected with decrease of mechanical strength (Babatunde and Zhao, 2007). On the other hand, the use of such ashes for ceramic raw material also offers attractive prospects. Both silicon and aluminum oxides are the major components of a variety of construction ceramic products (tiles, bricks, pipes), and the author also found both aluminum oxide and iron oxide can be used to stabilize hazardous divalent cations at ceramic sintering temperatures (Shih et al., 2006a,b). The combination of aluminum and iron oxides can reach 45.7% of the total ash weight to effectively trigger the stabilization reactions for hazardous metals in the products.

Although the Stanly sewage treatment plant only contributes 0.14% of the sewage sludge generated in Hong Kong (Leong, 2009), it is a secondary treatment plant treating non-saline sewage. In the region where Stanly plant serves, fresh water treated to drinking water standard is used for toilet flushing, similar to the mainstream practice in the world. In addition, sludge digestion is not implemented due to its small operation scale and sludge quantity. Besides common major elements of silicon, iron, and aluminum, phosphorus was found to be the most abundant element is the incineration ash as shown in Table 1(c). Phosphorus is an important nutrient for biomolecules. The organic matter in the sludge of secondary treatment is highly enriched with the growth and reproduction of microorganisms after harvesting phosphorus from the wastewater. Without going through sludge digestion to further decompose the microorganisms in sludge, large portion of phosphorus resides in the sludge and its incineration ash. Phosphorus can be recovered as a valuable nutrient element for agriculture fertilizers or for garden chemicals to supply the fast consumption of world phosphorus reserves. Therefore, although with a small production quantity, the sewage sludge or ash generated from treatment plants such as Stanly should first be considered for phosphorus recovery before mixing with other types of sludge or ashes. Incineration ash possesses the advantage of very high phosphorus content for efficient recovery. However, if possible, extracting phosphorus directly from sludge may be of an easier route and also reduce the need of separate incineration. The decision on recovery strategy should be made according to an overall evaluation of engineering costs and environmental impacts.

**Waterworks Sludge Ashes**

The property of waterworks sludge ashes generated in Hong Kong can be represented by our analysis on sludge samples obtained from Ma On Shan water treatment works. As indicated previously, the weight loss of heat treating the sludge samples was less than 10% of the dried solids. Assuming 70% of water content in mechanically dewatered sludge, the waste reduction of incinerating the dewatered waterworks sludge generated in Hong Kong is expected to be only about 27% by weight even with complete combustion. In addition, more than 95% of such weight loss was actually contributed by the evaporation of physically-bound water, which can be removed simply by heating the sludge over 100$^{o}$C. The organic content in the dried solids of Hong Kong sewage sludge can provide an average caloric value of 17.1MJ/kg, which allows autothermic combustion, i.e. no requirement for additional fueling during regular operation provided that the combustion air is preheated to approximately 400$^{o}$C (Ng, 2009). However, the much lower organic content in waterworks sludge can only provide around one-tenth of the caloric value of sewage sludge (i.e. ~1.7MJ/kg), and thus it is necessary to add fuels or to co-incinerate sewage sludge to facilitate the incineration of waterworks sludge. According to these findings, it can be concluded that the incineration of Hong Kong waterworks sludge is not a sustainable treatment strategy due to its inefficient waste reduction and unnecessary energy consumption.

The major compositions in the incineration ash of Ma On Shan waterworks sludge are listed in Table 2. The aluminum content in the ash is very high due to the use of aluminum-based coagulants, and the observed silicon content was mostly from the removal of natural sediment particles during coagulation process. Other compositions are in relatively insignificant amounts, which also reflect the pristine condition of the source water. Alumina ($Al_2O_3$) is the high temperature form of aluminum compounds and is also an important raw material for many industrial applications. If the use of incineration is to generate alumina for better aluminum recovery or for industrial raw materials, such operation may therefore warrant the need of incinerating the waterworks sludge generated in Hong Kong.

Table 2. Major compositions of ashes incinerated from the water treatment works sludge of Ma On Shan treatment plant. The sludge was heated at 1000$^{o}$C for 30 min in muffle furnace to simulate the complete combustion. The elemental compositions of the ashes were analyzed by Bruker X-ray fluorescence (XRF) spectrometer and expressed by the basic oxide forms in the table.

| Composition | $Al_2O_3$ | $SiO_2$ | $Fe_2O_3$ | $P_2O_5$ | MnO | Others |
|---|---|---|---|---|---|---|
| Concentration (%) | 63.0 | 25.4 | 5.1 | 3.5 | 1.1 | 1.9 |

Using ashes incinerated from waterworks sludge for construction purposes can also be a practical strategy, and most application attempts are either in the form of cement or ceramic product. With very low organic content, the property of the incineration ash of waterworks sludge may be quite similar to that of its sludge, at least in terms of recycling potential. Fresh waterworks sludge was successfully incorporated in the making of Portland cement, and it was reported that such addition increased the compressive strength (Pan et al., 2004). Due to the possible production of rust stains, it was particularly concluded that the reuse of waterworks sludge, especially aluminum sludge, may be more aesthetically beneficial. However, Goldbold et al. (2003) reported the ferric sludge was more suitable for ceramic brick making than aluminum sludge due to the role of iron acting as a fluxing agent. High proportion of aluminum-based waterworks sludge could also lead to a decrease in tensile strength with increased sludge addition. Most other work observed little difference in the performance of experimental brick and the control when sludge addition was within 10% of the dry weight basis. If the market of ceramic products is seriously targeted, the co-incineration of this aluminum-based sludge and the ferric sewage sludge of Hong Kong may provide a feasible plan, solving both problems of low caloric value and high aluminum content of waterworks sludge. Recent work of the author also found aluminum oxide can stabilize hazardous divalent cations during ceramic making process and achieve very low metal leachability (Shih et al., 2006b; Shih and Leckie, 2007)

## CURRENT CHALLENGES

At present, landfilling is the only disposal means of dewatered sewage sludge in Hong Kong, and the existing landfill space is anticipated to be fully exhausted in early to mid 2010 decade. Incineration of solid waste and sludge can significantly reduce the waste volume, but it should be further noticed that this approach still results in residual ashes that require to be disposed of. The disposal of ashes in landfill is not environmentally sustainable due to the additional consumption of non-renewable resources, including material (cement to stabilize the ashes), space (increased volume due to added cement), and energy (operation and monitoring). Opportunities of reusing or recycling incineration ashes need to be sought to promote the "cradle-to-cradle" design in the waste management plan. While agricultural application has proven to be an economical route for recycling sludge/ashes, concerns of human health, food safety and ecological impact have fuelled recent debates on continuing this practice. In addition, the market of such sludge/ash products can sometimes be very limited in highly urbanized areas, such as Hong Kong, and provides very little incentive for government and industry to support this strategy.

Despite the obvious advantages and increasing researches of incorporating incineration ash into building and construction products, such as concrete and ceramics, it is yet to be fully accepted in the industry. The major concern is the variability in the final product made from such materials, due to the variability in their chemical composition, organic residues and deleterious components, especially in the concrete applications. One particular example in Hong Kong is the problem of saline sludge due to the use of sea water for toilet flushing. As it is well-known that chlorine can result in a significant increase of iron corrosion, a considerable low chlorine level (less than a few parts per thousand) in the concrete is required to prevent the corrosion of steel reinforcement. Multiple water washings can effectively reduce the chlorine level in the ashes, but will produce large amounts of wastewater that must be treated prior to discharge. Ceramic products do not have metal corrosion concern, but its product market is much smaller than that of concrete. In addition, “fly ash” generated from air pollution control units is not suitable for ceramic sintering and still needs to be stabilized by cementation. Volatile metal species, if any, may usually condense on the particle surface of fly ash, and the high temperature sintering will re-vaporize them during the ceramic making. Only the “bottom ash” generated from the incineration boilers can be incorporated into ceramic products. Therefore, the current technical challenge of integrating incineration ash products into the industry is to develop a treatment strategy to achieve high degree of compositional stability, make the products cost effective, and justify their use.

Finally, it is sometimes very difficult to avoid the Not-In-My-Backyard (NIMBY) perception in waste management planning. For example, the suitable site for incineration plant can be very hard to locate, and the acceptance of using recycled building materials is generally not easy to obtain, even when such products wholly conform to regulatory standards. A rigorous public relations campaign is extremely essential toward the successful implementation of reuse and recycling sludge incineration ash, notwithstanding their technical and economical feasibility and/or minimal environmental impact.

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