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Constructive approaches towards water treatment works sludge management: An international review of beneficial re-uses

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Abstract

Till date, virtually all known drinking water processing systems generate an enormous amount of residual sludge, and what else to do with this rapidly increasing 'waste' stream in an economic and environmentally sustainable manner remains a significant environmental issue. Perhaps, the realization of this fact has led to series of concerted efforts aimed at beneficial re-uses in an effort to close the loop between efficient water treatment and sustainable sludge management. This paper therefore presents a comprehensive review of available literature on attempts at beneficial reuses of water treatment plant sludge, in an effort to provide a compendium of recent and past developments, and update our current state of knowledge. Four broad categories of uses, which included over eleven possible ways in which waterworks sludges can be reused were identified and examined. Obvious advantages of such reuse options were highlighted and knowledge gaps identified. Future issues that will assist in the development of sustainable waterworks sludge management options with a multi-prong approach were equally discussed.

***Keywords**:* Disposal, reuse, waterworks sludge, wastewater treatment

Contents

1. Introduction

For now, water treatment works sludge (referred to as waterworks sludge hereafter) remains an inescapable by product of water treatment processes. Such sludges typically contain mineral and humic matters removed and precipitated from the raw water, together with the residues of any treatment chemicals used as coagulant (commonly aluminium or iron salts) and coagulant aids (mostly organic polymers). In the practical context, alum sludge and ferric sludge refer respectively to the sludge generated when aluminium or iron salt is used as the coagulant. Only in Europe, several million tons of waterworks sludges are produced every year and this may double by next decade (Basibuyuk and Kalat, 2004), raising considerable concerns over their disposal and associated costs. In Netherlands, the total cost of disposing waterworks sludge stands at a staggering £30-£40 million as reported by Horths et al. (1994), while in Ireland, a double fold increase has been predicted by the end of next decade from a current estimate of 15,000 to 18,000 t/pa of the dried solids (Zhao et al., 2006). On a global scale, available literature estimates that a whooping 10,000t of waterworks sludge are produced daily (Dharmappa et al., 1997). Fig. 1 shows an indicative diagram of the quantity of waterworks sludge produced in some selected countries.

[Fig.1 Indicative diagram showing quantity of waterworks sludge produced in selected countries (figures based on estimated quantities from year 2000, compiled from Dharmappa et al.(1997); Goldbold et al. (2003); Pan et al. (2004); Carvalho et al. (2005) and Zhao et al. (2006))]

Oftentimes, the costs of handling the enormous quantities of waterworks sludge can account for a significant part of the overall operating costs of water treatment works and they are likely to increase due to increasingly stringent regulations. While considerable development has been made in waterworks sludge treatment, options available for its disposal are continually being dwarfed by the increasingly stringent environmental regulations. Prior to 1946, waterworks sludges were discharged to the nearest drainage course or water body and promptly forgotten, in line with the theory of "out of sight, out of mind" (Donald, 1968). Amongst possible explanation for this earlier line of thought could be the fact that waterworks sludges were regarded as inorganic even though they have some organic content, albeit somehow very low, and consequently they may not exert any worrisome oxygen demand on water bodies. This line of thought is furthermore reflected in the present approach towards waterworks sludges and whereas they are currently classified as non hazardous in the European list of wastes (code number 190902) with no specific legislations concerned with their disposal, their classification may be affected by future legislative reviews. Therefore, it is only a matter of time before the waterworks sludge issue becomes worrisome. As noted by Heil and Barbarick (1989), Elliot et al., (1990) and Viraraghavan and Ionescu (2002), the limited land available for waterworks sludge disposal and the possible environmental liabilities that may arise if disposed off in sanitary landfill sites, altogether makes it a considerable worry for water purification authorities.

On the other hand, it has been advocated that waterworks sludge could be a potential recyclable product, offering one of the greatest commercial potential for reuse (Goldbold et al, 2003; Rensburg and Morgenthal, 2003). Therefore, with a continual increase in the production of waterworks sludge certain at least for now and in line with the prevailing legislative and economic drives pointing towards waste avoidance and beneficial reuse of waste streams, a number of constructive attempts and research works have been made particularly in recent years to reuse waterworks sludges in many more beneficial ways. These include laboratory and full scale attempts at using waterworks sludge as a component in the manufacture of several materials such as concrete, cement mortars, clay materials, fired ceramic products (e.g. bricks, pipes and tiles) (Goldbold et al., 2003); as geotechnical works materials (Skerratt and Anderson 2003; Carvalho and Antas, 2005); as a potential for use in agriculture and silviculture (Cameron et al, 1997; Moodley and Hughes, 2005; Titshall and Hughes, 2005); as a primary source of aluminium and iron based coagulants through several recovery process (Petruzelli, et al.;1998; Vaezi and Batebi, 2001 and Stendahl et al., 2005); and for phosphorus reduction during wastewater treatment (Mark et al.,1987; Robert and Edward,1987; Wurzer et al, 1995; Kim et al., 2003; Babatunde et al., 2005 and Yang et al., 2006a). Fundamentally, such approaches at beneficial reuses offer two distinct advantages in terms of economic savings on overall treatment plant operation costs and environmental sustainability. However, unlike the case of sewage sludge which has several papers and reviews on its beneficial reuse already published, it appears such comprehensive review of beneficial reuses of waterworks sludge is lacking for now. Yet, it is only a fraction on the scale of time before its generation compels equal or greater attention from environmentalists, giving our increasing human population and declining tolerance for environmental pollution of any sort. It is therefore the aim of this paper to present a comprehensive review of such attempts as a contribution to the body knowledge on waterworks sludge reuse.

2. Characteristics of waterworks sludge

With regards to the reuse of waterworks sludge, the main concern lies in its nature and toxicity.

2.1 Nature

Typically, waterworks sludge can be classified into coagulant, natural, groundwater or softening, and manganese sludges, but coagulant sludges constitutes the vast majority of water treatment plants residues and are mostly referred to in this review. Coagulant sludges are commonly aluminium or iron based salts. They occur mostly in particulate or gelatinous form, consisting of varying concentrations of microorganisms, organic and suspended matter, coagulant products and chemical elements. As a guide only, typical composition of waterworks sludges are shown in Table.1.

[Table 1. Typical composition of water treatment works derived sludges (mean values ± SD)]

However, whereas the elemental constituents may not vary greatly for different sludges, their composition and relative abundance are more or less specific for each sludge being highly dependent on (1) the characteristics of the raw water source (2) coagulant type used and dosage applied and (3) other relevant but specific plant operating conditions. Particularly, elevated levels of colour and turbidity may require large chemical addition during treatment, increasing sludge generation. This influences the characteristics of the sludge largely, making it highly variable. Matter in water is broadly classified as inorganic mineral and organic carbonaceous. The former is responsible for turbidity, while the latter is responsible for colour, taste and odour in water. Fulvic acids are the major component of these natural organic materials, which also contain humic and hymathomelanic acids. These compounds are formed by the breakdown of vegetable matter and resynthesis in the soil and their presence may cause water to have an undesirable colour, mostly brown or yellow.

Typically, waterworks sludge contain several phases which differ by their physical state and/or chemical nature, but here, waterworks sludge is considered as flocs (solid phase) and bulk water (liquid phase), shown in Fig. 2 (a). The flocs forming a three-dimensional network are essentially a two - phase mixture of solid particles and water, as illustrated in Fig. 2 (b).

[Fig. 2. Schematic diagram of: (a) flocs (floc phase) and bulk water and (b) floc skeleton and interstitial water (Herwijn, 1996)]

Flocs are recognised as being primarily water with water content varying between 95-99%, this being typical of levels found in waterworks sludge before and after thickening (Twort et al., 2000). The dry matter of the floc arises from two sources: (a) the precipitation of impurities in raw water (e.g. color, turbidity, and hardness) and (b) the solids deposited by the coagulant. For example, about 50% of a floc dry mass comprised of the coagulant products (from alum) at optimum coagulation conditions as reported by Hossain and Bache (1991) in an investigation relating to the coagulation of a coloured, low-turbidity water, while a 46% composition by mass of Al_2O_3 was reported in an Irish alum sludge derived from a reservoir water (Yang et al, 2006a).

***2.2* Toxicity**

There is a lack of information about the potential toxicity of waterworks sludges from literature and the only limited information available shows some contradiction. There is therefore a crucial research need to examine the toxic effects of waterworks sludge and its metal contents. As regards reuse, George et al., (1995) studied the alum sludge toxicity from ten water treatment plants sludges throughout North America using S. capricornutum growth test, the fathead minnow survival and growth test, a protozoan mortality test, and the Microtox (R) test. Their results revealed that algal growth inhibition was observed in extracts obtained at pH 5 but generally not in circumneutral solutions. Alum sludge extracts prepared with natural receiving waters were toxic to S. capricornutum at all extract pH levels tested if receiving water hardness was less than 35 mg C_aCO_3/l. Accordingly, they concluded that water-soluble constituents from alum sludges discharged into receiving waters may affect algal growth. However, Skene et al., (1995) stated that there was no evidence that aluminium toxicity would be a problem if alum sludges were used as growth media.

Similarly, Sotero-Santos et al. (2005) did a comparative data analysis of the toxicity of alum sludge and ferric chloride sludge and reported that there was no acute toxicity (48 h exposure) upon *Daphnia similes* for both alum and ferric sludges. However, long-term exposure to ferric chloride sludge caused some mortality and decreased reproduction of daphnids while alum sludge was less toxic than ferric chloride sludge. Despite the variation in the sludge properties, such as solids contents, nutrients level, metal contents and COD concentrations, there was no relationship observed between the property variables and the degree of toxicity. Dayton and Basta (2001) further provided evidence using the toxicity characteristic leaching procedure (TCLP) on selected waterworks residual, that the heavy metal levels in the sludge residues were significantly less than the regulatory levels for TCLP and consistent with nonhazardous waste metals. This is in agreement with the result of a similar study on the average level of metals found in waterworks sludge (Elliot and Dempsey, 1991). Of concern however is ferric sludge that has been suggested to typically exhibit high levels of zinc, nickel and copper with arsenic levels up to 4g/kg dry matter of sludge found in a particular study (Forstner and Haase, 1998). Arsenic in particular remains a priority inorganic pollutant in waterworks sludge. In general, most of the concerns expressed as regards toxicity and metal content of waterworks sludge have been in respect to their use in agriculture, horticulture and other land-based applications. Forstner and Haase (1998) reported on the release of metals from waterworks sludge using the pH-stat procedure and implied a pH dependent release. Therefore, although there could be some potential toxicity effect from waterworks sludges, the magnitude of such effect has always been viewed with an alarm of disfavor and without satisfactory qualitative and quantitative assessment.

3. Categories of reuse

On the strength of the characteristics of waterworks sludge presently generated, more than eleven reuse options were identified globally and are classified into four main categories

3.1. Use of waterworks sludges in wastewater treatment processes

In several ways, waterworks sludges especially alum sludge have been used to enhance treatment performance in wastewater treatment processes. Such uses have been adjudged beneficial with great potential to increase plant treatment efficiency (Guan et al., 2005), enhance sewage sludge conditioning (Lai and Liu, 2004) and enhance P removal during wastewater treatment (Galarneau and Gehr, 1997).

3.1.1. Coagulant recovery and reuse

In water treatment plants, hydrolyzing metal salts and organic polymers are added to coagulate suspended and dissolved contaminants as a major step towards wastewater purification. The use of such metal salts or organic polymers represents a significant part of the overall treatment process cost and the coagulants form an integral part of the sludge produced. Attempts at recovering and reusing the coagulants embedded in this sludge matrix for use in wastewater treatment processes especially for the coagulation of various wastewaters contaminants, dates back to the 19th century with the first patented process by Jewel, W.M in 1903 (Moran and Charles, 1960), and at some later stages, acid treatment followed by the membrane separation techniques was built upon to recover and reuse the entrapped coagulants (Arup and Bo, 1992; Stendahl et al., 2005).

Other recovery methods have included acidifying with sulfuric acid (Abdo, 1993; Vaezi and Batebi, 2001), alkaline treatment (Masschelein and Devleminck, 1985), liquid/liquid extraction using the liquid ion exchange (LIE) technique (Dhage et al., 1985; Petruzelli et al., 1998), reduction-acidification concept (Paul et al., 1978), the Donan membrane process (DMP) (Prakash et al. 2003; 2004) and the composite membrane method (Li and Sengupta, 1995). The effectiveness of the recovered coagulants have been generally varied, but nonetheless adjudged satisfactory in most cases. However, the purity of such recovered coagulants remains a contentious issue just as the economy of the recovery process is still a subject of debate. Bustamante and Waite (1995) reported that aluminium recovered from dewatered alum sludge through alkaline leaching was used to effectively reduce phosphorus concentration in wastewater from 9 mg/l to below 1 mg/l. Recently, Stendahl et al. (2005) also reported a multi-step method called the REAL process used to recover the aluminium from the impurities in an alum sludge and thus reuse it as coagulant in water purification process.

Several other attempts have been made to recover calcium carbonate and magnesium hydroxide from water softening lime sludges through calcification. Petruzelli et al. (1998) noted that it is possible to recover metal hydroxides from sludge suspensions by modulating the system pH. Typical pH includes 1.5 and 2.5 for highly alkaline and less alkaline suspensions respectively. A common approach to this is through acidification**.** In the case of ferric sludge, the pH of the sludge is lowered by acid addition to a range where the solubility of ferric iron is significantly increased and the iron is released back into solution. However, acidification may generally imply the use of high and costly doses of acid, which may not be economically justified.

Although it is expected that recovering and reusing coagulants embedded in the waterworks sludge matrix would: (1) significantly reduce the cost of coagulants used in water and wastewater treatment plants; (2) possibly help to meet discharge standards in certain cases and at reduced cost; (3) reduce sludge volume and hence disposal costs; (4) make the waterworks sludge more suitable for landfilling without concerns over possible metal accumulation and leaching effects; (5) improve the dewatering characteristics of the residual sludge and (6) increase the life of waste disposal facilities, such coagulant recovery process can be extremely complicated. In addition, conditions that will favor the most efficient coagulant recovery from the waterworks sludge may vary from day to day.

However, despite the fact that the recovery process could present some difficulties, the results of laboratory and plant scale tests have shown that the process is practical and could provide some economic benefits. For instance, the application of recovered coagulant in wastewater treatment process is being used at the Orly works in France where coagulant recovered from alum sludge through acidification is recycled with fresh coagulant, while in the Netherlands, it has been estimated that iron recovered from waterworks sludges could potentially provide 20-70% of the iron quantity needed for phosphorus removal if chemical phosphate removal is adopted (Horth et al., 1994). However, Petruzelli et al., (1998; 2000) noted that the purity of coagulants recovered from waterworks sludge may not be sufficient to justify their reuse, especially in portable water treatment process, and economically the recovery process is expensive and laborious. For example, to recover alum, sulphuric acid is dosed to the alum sludge and the aluminium is dissolved according to:

$$2Al(OH)_3 + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + 3H_2O \qquad Eq.(1)$$

It is known that to dissolve 1 g of Al^{3+} in the form of aluminium hydroxide, 5.4 g of H_2SO_4 is needed. In one instance, the total cost of the entire recovery process is 371 USD/per ton of DS (Stendahl et al., 2005). Horth et al., (1994) further pointed out that another potential problem of the recovery option is the heavy metal accumulation in the sludge that can contaminate the recovered coagulant. There is also the possibility of metals other than iron and aluminium being solubilized, leading to coagulant contamination.

*3.1.*2 as coagulant in wastewater treatment

While purity and economic considerations have narrowed the applicability of the coagulant recovery option, several attempts have been made and reported on the direct use of waterworks sludge as a coagulant in the treatment of various wastewaters. Horth et al. (1994) reported a study on the effect of adding aluminum based waterworks sludge to a wastewater treatment plant. It was shown that under certain conditions of optimal alum sludge addition, the treatment and final sludge characteristics at the wastewater treatment plant were improved significantly. In France, it was reported that aluminium hydroxide sludge discharged to a sewer in a treatment plant has proved completely successful with phosphate removal up to 94%, at a dose ratio of 0.3 to 1 corresponding to about 3.5mmole/l of Al (Horth et al., 1994). In another study on the use of an iron based waterworks sludge as a coagulant in the treatment of vegetable oil refinery wastewater, Basibuyuk et al. (2004) reported excellent removal efficiencies for oil, grease, COD and TSS at an optimum pH of 6 and sludge dose of 1,100mg SS/l. It was noted that the iron sludge was as efficient as using alum or ferric chloride, and removal was further enhanced when combined with ferric chloride at various doses. As compared with the use of original coagulants, satisfactory removal efficiencies for colours were also reported in the use of waterworks sludge for the treatment of textile wastewaters and various dyestuffs (Chu, 2001). It was however reported to be unsuitable for dyes with hydrophilic characteristics. In another study, Alum sludge was also effectively used as a condensation nucleus in a coagulation process to enhance the removal of lead in wastewater (Wei, 1999).Removal rate of up to 94% was reported by recycling alum sludge as a unique coagulant with doses of 75-100 mg/l in a coagulation process. It was suggested that the sweep-floc mechanism is the dominant mechanism to the alum sludge reuse process.

In order to improve SS and COD removal in primary sewage treatment, the feasibility of re-using aluminium based waterworks sludge to enhance particulate pollutant removal was studied by Guan et al. (2005). The concept lies in the utilization of large portion of insoluble aluminium hydroxides in alum sludge as a coagulant in chemical coagulation/flocculation which is applied in primary sewage treatment. It was found that both SS and COD removal efficiencies were improved by 20% and 15% respectively at a sludge dose of 18-20mg Al/l. It was however reported that charge neutralization did not contribute to enhancing particulate pollutant removal since both the sewage and the alum sludge used carried the same negative surface charges. Therefore, it was postulated that the removal of SS and COD is due mainly to a combination of floc sweeping and physical adsorption.

3.1.3. Adsorbent for pollutants and metals in wastewater

Currently, the development of cost-effective composite adsorbents from by-products is gaining considerable attention, as a possible alternative to commonly used adsorbents. Waterworks sludge is no exception and so far it has been preliminarily studied as a potential adsorbent for the removal of various pollutants and metals in wastewaters, e.g. lead, Copper (Wu et al., 2004a) and fluoride (Sujana et al., 1998). Wu et al. (2004b) also reported that sintered waterworks sludge adsorbed significant amount of toxics from a synthesised toxic wastewater and noted in particular that the sintering process can effectively prevent the release of harmful substances in the waterworks sludge to the environment. An adsorption capacity of 1.40mg/g at pH 4.6 for Cr (III) and 0.43mg/g at pH 6.0 for Hg (II) was reported.

As regards major pollutants in wastewaters, extensive studies have been conducted into the feasibility of using waterworks sludge as an adsorbent for phosphorus removal in wastewaters (Huang and Chiswell, 2000; Zumpe et al., 2002; Georgantas and Grigoropoulou, 2005; Kim et al., 2003; Babatunde et al., 2005 and Yang et al, 2006a&b). The basic idea is that the abundant amorphous aluminium and ferric ions in waterworks sludge can become valuable for phosphorus removal in wastewaters since such ions have been demonstrated to enhance the processes of adsorption and chemical precipitation that aids phosphorus immobilization (de-Bashan and Bashan, 2004). It has been reported that the P-adsorption capacity is largely dependent upon the pH of the P-containing solution, being enhanced in the acidic region (Kim et al., 2003; Babatunde et al., 2005 and Yang et al, 2006a&b). In addition, Yang et al. (2006b) in a detailed study on the fundamental mechanisms of P adsorption onto alum sludge, highlighted the insignificant competitive effect of SO_4^{2-} and Cl- (which are typical anions found in wastewaters) on P- adsorption onto the alum sludge surface. It was proposed that phosphate adsorption onto the alum sludge is through a kind of inner-sphere complex reaction, which occurs when phosphate replaces the functional groups on the surface of alum sludge and becomes bound to the surface. As a result, phosphate is adsorbed via a precipitation reaction with the aluminium ions, as explained by Eq. (2), indicating that ligand exchange is the dominating adsorption mechanism.

$$2\equiv Al{-}OH + H_2PO_4^- \rightleftharpoons (\equiv Al)_2HPO_4 + H_2O + OH^- \qquad \textit{Eq.}\ (2)$$

The adsorption capacity of waterworks sludges for phosphorus and other pollutants reported in literature are summarized in Tables 2 & 3 while maximum P-adsorption capacities of coarse and fine grained alum sludge using a broad range of P species as reported by Zhao et al. (2006) are shown in Table 4. It is noted from Tables 2-4 that pH plays a key role in the phosphorus adsorption capacity. However, it should be pointed out that considerable research still needs to be done on phosphorus adsorption by the waterworks sludge as the influence of solution pH and the effect of phosphorus speciation, surface charge and characteristics of the sludge, alum sludge dosage and other process variables still needs to be examined and understood as a guide to further extending its application. It is however certain that, the need for enhanced phosphate removal during wastewater treatment process will create ample opportunities for the beneficial integration of such findings into a wastewater treatment system.

[Table 2 Maximum P-adsorption capacity of waterworks sludges reported in the literature]

[Table 3 Maximum adsorption capacity of waterworks sludges reported in other studies]

[Table 4 Maximum P-adsorption capacities of alum sludge using three models P at varied pH conditions (Zhao et al., 2006)]

3.1.4. Co-conditioning and dewatering with sewage sludge

Although attempts at co-discharging waterworks sludge and sewage sludge are not entirely new, the use of waterworks sludge in co-conditioning and enhancing sewage sludge treatability remains an attractive option in research and practice. Studies have shown the beneficial effect of waterworks sludge as a co-conditioner in sewage sludge conditioning and dewatering process. For example, the findings of a study into the feasibility of co-conditioning and dewatering of alum sludge and waste activated sludge by Lai and Liu (2004) showed that sludge dewaterability and settleability was enhanced with increasing proportion of alum sludge in the mixed sludge and with a corresponding decrease in the required dosage of the cationic polyelectrolyte. The presence of aluminium hydroxide in the sludge enhanced the settling velocity and dewaterability of biological sludge. It was therefore reasoned that the alum sludge acted as a skeleton builder, making the mixed sludge more incompressible and rendering the dewatering process more effective. Such attempts at co-conditioning and co-disposal of wastes have been noted to be economically advantageous and particularly aid in enhancing sludge dewaterability (Lin et al., 2001; Zhao, 2002; Lai and Liu, 2004).

However, emphasis has always been placed on the likely disadvantages that may occur rather than the potential advantages such attempts offer. In addition, considering the fact that it is unlikely that a water treatment plant would be cited in close proximity to a sewage treatment facility, the cost and economics of sludge transport/haulage might become a potential deciding factor. The capacity, process control capabilities and willingness to accept the sludge are also other important factors (Elliot and Dempsey, 1991).

*3.1.5.*Cconstructed wetlands substrate

In recent years, constructed wetlands (CWs) have been increasingly used worldwide as a popular alternative technology for the treatment of numerous wastewaters (IWA, 2000). Due to their low energy requirement and aesthetical appearance, CWs are seen as a ‘green’ wastewater treatment technique. The media in CWs play an integral role in various biological, physical and chemical processes that remove pollutants from the wastewater. One of the main objectives of research in wetland technology today is to discover new medium material that will increase the effectiveness and, hopefully reduce the capital cost. Traditionally, different combinations of soil, sand and gravel have been used as media in the wetlands. Numerous studies have shown that the wetlands based on these conventional media are capable of meeting the requirement of BOD_5 and COD reductions. However, it is often difficult to achieve substantial removal of certain inorganic nutrients, e.g. orthophosphate and ammoniacal-nitrogen, in wetlands with the conventional media.

The possible use of dewatered waterworks sludge as a medium in CWs is thus another prospective option open to active research. It has been suggested that since typical waterworks sludges are rich in aluminium, iron and calcium residues, which are strong adsorbents for pollutants in wastewaters, especially phosphorus, their use in CWs to enhance phosphorus reduction could be a possibility. Leader et al. (2005) reported a study on the use of lime and iron sludges respectively as potential wetland co-treatment substrates for both dairy and municipal wastewater treatment. Zhao and Babatunde (2006) similarly studied the reuse of dewatered alum sludge cake as the main substrate in a constructed wetland system for wastewater treatment. One-year’s run of experiments have demonstrated great potential for the successful incorporation of waterworks sludge in a CWs. Earlier on, the Irish dewatered alum sludge used was investigated as a potential adsorbent and/or wetland substrate with results indicating stable pollutant removal efficiency especially for phosphorus reduction (Babatunde et al, 2005; Yang et al, 2006a; Zhao and Babatubde, 2006 and Zhao et al, 2006).

3.2. Use of waterworks sludges as building and construction materials

Waterworks sludges have also been preliminarily studied and used as building and construction materials. However, despite the obvious advantages and increasing researches into the incorporation of waterworks sludges in building and construction materials, they are yet to be fully accepted in the industry. Of particular concern is the variability in the final product made from such sludges due to the variability in their chemical composition and water and organic content, even when such products wholly conform to industry standards. In other words, for sludge products to become fully integrated into the industry, they must be seen to be reliable, with a high degree of compositional stability to make them cost effective and justify their use. Some of the efforts made so far at incorporating them into the industry are highlighted below:

3.2.1. Brick making

Concerns over the compressive strength and shrinkage characteristics of bricks made from waterworks sludge have not dampened increasing efforts at such attempts. Generally, the sludge is characterized to determine the components that may affect the brick making process, e.g. organic and water content. Thereafter, the sludge is substituted into the brick at different levels to determine the optimum percentage of incorporation. A 100% success was reported for trials on bricks made from waterworks sludge at a ratio of 80:20 (Goldbold et al, 2003). It was however noted that such sludge bricks are more feasible with ferric sludge than with aluminum sludge, due to their iron and organic matter content, but this has not been particularly emphasized in other studies that were reported. In fact, Horth et al. (1994) reported that although up to 5 or 10% addition of ferric sludge to clay in brick making produced good result, the brick quality is affected with a reduction in mechanical strength and frost resistance if a higher proportion of the sludge is used. Even at lower percentages (1,1.04 and 5%) of sludge incorporation by mass, there was still a reduction in brick mechanical properties with a higher water absorption probably due to the lime content of the sludge used (Carvalho and Antas, 2005). Huang et al. (2001) reported that mixtures containing 0-20% sintered waterworks sludge with dam sediments meet the first or second level brick criteria of the Chinese national standard at firing temperatures from 1,050 to 1,100^{o}C, while noting that a 40-50% firing shrinkage was detected for the sludge, but with no cracking or distortion observed on the sintered surface.

In a review of sludge bricks, Goldbold et al. (2003) reported that waterworks sludge especially ferric sludge provided some energy savings in brick making by acting as a fluxing agent, thereby reducing the firing temperature used in the kiln and in addition it provided some raw material savings in the use of water and clay resulting in reduced shrinkage and improved colour of the final product. It was however noted that using a high proportion of alum based waterworks sludge could lead to a decrease in tensile strength with increased sludge addition. Anderson et al. (2003) successfully incorporated a blended mixture of an iron based waterworks sludge and sewage sludge incineration ash into a brick mix-design on a 5% dry weight basis. Little difference was observed in the performance of the experimental brick and the control, showing that the introduction of the waterworks sludge into the overall brick mix had little impact on the fired properties of the product. In addition, no discharge levels in excess of specific limits were produced and the trial product exhibited lower levels of proscribed emission levels than the standard product.

3.2.2. Manufacture of cement and cementitious materials

Generally**,** recycling of waterworks sludge in the cement industry can be a practical alternative as reported by Pan et al. (2004), in that the waterworks sludge is virtually non-hazardous, and the chemical composition of the inorganic sludge is similar to the clay used in cement production. In their report, fresh waterworks sludge was successfully incorporated in the making of Portland cement through the sintering process. It was reported that the addition of the waterworks sludge in the cement clinker increased the compressive strength of the concrete and benefited the clinker burnability, without any detrimental effect on the long-term strength property. Setting times and soundness test results were equally satisfactory. However, it was noted that the preferred waterworks sludge should have a considerable low chlorine level as it has been noted that chlorine could corrode the cement kiln and block its duct (Kikuchi, 2001). The chlorine level in the waterworks sludge used was 335.5ppm.In addition, Carvalho and Antas (2005) in a review of studies on sludge incorporation into cement noted the following: (1) during drying at 105^{o}C, sludge suffered agglomeration and had to be grind before use; (2) sludge dewatered or heated at 105^{o}C prevents the setting and hardening of paste and mortar; (3) thermally treated sludge decreases the compressive strength of mortar, but promotes the increase of it’s consistency; (4) compressive strength decreased with an increase in sludge content and treatment temperature and (5) sludge treated at 700^{o}C induced the formation of lime and calcium aluminates, which might have caused the observed decrease of initial setting time. It was therefore concluded that sludge incorporation into mortar cement could only be feasible at temeperatures above 450 °c, with an increase of the initial setting time but a decrease of the mechanical strength. More research work is still needed particularly to clarify specific effect of the characteristic component of the sludge on the cement quality and setting process and the optimum operating conditions.

In addition, there seems to be a lack of result of extensive research into the compressive strength of such ‘sludge cement’ for it to gain practical acceptance, indicating an area of further research. As noted by Joo-Hwa et al. (1991) in a review of the properties of cement made from sludge, the compressive strength of sludge cement was found to decrease as the replacement amount of sludge ash was increased. Godbold et al. (2003) further remarked that in order to determine the full commercial viability of such sludge cement, the quantity of the raw product available and the transportation economics were of equal importance. In particular, it was noted that their suitability for recycling is dependent on the quantities likely to be available and source location in relation to potential manufacturing plant.

Although it was noted by Godbold et al. (2003) that any potential problematic contaminants such as phosphorus or sulphate in the sludge could be diluted out by mixing with other raw materials, there are still concerns over the possibility of the inclusion of some other potentially deleterious components such as iron which may produce rust stains, hydrogen generation and aluminum expansion, retardation of the setting process due to re-mobization of zinc and lead at high pH (12-14), and possible concrete expansion due to alkali-silica reaction from the glass content in the waste material. All these have raised significant concerns over possible inclusion of waterworks sludge in cement production and it was particularly concluded that such reuse of waterworks sludge especially alum sludge may be more aesthetically beneficial. However, literature evidence of successful incorporation of the sludge into brick making at various levels suggests that ‘sludge brick’ production could nonetheless be economically and environmentally beneficial to the industry, giving proper development. In fact, giving our technical competence, there seems to be no technical reason why the production of bricks from waterworks sludge cannot be fully developed, moreso as such bricks have been successfully produced using sewage sludge.

3.2.3. Use in pavement and geotechnical works

Although still in the preliminary stage and yet to be widely studied and reported, the possibility of using waterworks sludge as geotechnical works material (e.g. waste containment barriers, soil modelling, structural fills) and incorporation into construction materials (bituminous mixtures, subbase material for road construction) and as landfill liner have been reported (Ronald and Donald, 1977; Raghu, et al 1987; Carvalho and Antas, 2005). This is particularly based on preliminary characterization test results on the geotechnical and geo-environmental characteristics of waterworks sludge which shows some promise as a suitable geotechnical and construction material. Carvalho and Antas (2005) reviewed the feasibility of sludge incorporation as a filler material in bituminous mixtures for use in general pavement works. It was recommended that sludge should be thermally treated to at least a temperature of 450^{o}C to volatize all the organic components. Such thermally dried sludge suffered agglomeration and needed to be grind before use. However, the dried and grind sludge had heterogenic granulometria which was incompatible with fillers granulometria range. Therefore, the need to eliminate organics in the sludge may lead to incompatibility between the sludge and traditional filler material. Consequently, an optimum temperature that would maximise sludge organic removal and minimize incompatibility with traditional fillers is desirable. However, such thermal treatment may present some environmental problems, as there are concerns over malodorous emissions during the thermal drying. Obviously, such odorous emissions may limit large-scale industrial application of the process.

Ronald and Donald (1977) also investigated the feasibility of sludge incorporation into a stabilized subbase material used in road construction. Results show that up to 0.5 to 3% sludge incorporation produced a corresponding 150 to 113% increase in the optimum seven day unconfined compressive strength result respectively, as compared to the control mix. However, a gradual strength decrease was observed at higher levels of incorporation and this was adduced to the possibility of a significant increase in the proportion of fine materials in the mix because of increased sludge addition. This may have reduced the interparticle friction of larger aggregates, causing a loss of strength. Raghu et al. (1987) also evaluated the feasibility of using waterworks sludge as a liner for sanitary landfills. Water was leached through the samples and chemical analyses show that the concentration of heavy metals and organic matter were too low to create any pollution problems.

3.3. Land based applications

Land-based application of waterworks sludge is the controlled spreading of the sludge onto or incorporation into the surface layer of soil to stabilize, degrade and immobilize the sludge constituents (Elliot and Dempsey, 1991). Historically, the most notable land application of waterworks sludge is the use of lime softening sludge as a substitute for agricultural limestone. Currently land based applications of waterworks sludges are gaining increasing attention as alternative disposal means (Basta, 2000; Titshall and Hughes, 2005). This is most probably hinged on the fact that the physical, chemical and biological properties of soils can be used to assimilate the applied waste without adverse effects on soil quality (Elliot and Dempsey, 1991) and even with the possibility of enhancing soil quality (Roy and Coulliard, 1998). In comparison with land filling option, land based applications are viewed as a low cost and favourable alternative, which may not necessarily require regulatory permits, although considerable land area may be needed. Over the years, the scope of such applications have typically been as a sustainable means to dispose waterworks sludge, improve or reclaim certain soil qualities or used as part of growing medium for crops. The major concern however has been its perception as a metal hydroxide waste, which could have potential deleterious effect on both soil and crop planted. On the basis of this review, three main factors are crucial to the success of the land based applications:(1) Determining the optimum effective application rate with the least consequences (2) The particular nature of the sludge and (3) The exact intent of the application.

3.3.1. For structural soil improvement

The physico-chemical properties of waterworks sludge makes them suitable for land spreading and in some instances their alkaline property perhaps, have encouraged their use as an ameliorative conditioner for soils, while improving other soil properties. Dayton and Basta (2001) noted that waterworks sludge might be suitable for use as soil substitutes since they predominantly contain humic substances and sediments from the raw water, which makes them similar to fine textured soils. A classification analyses based on British standards BS 3882 revealed that water treatment works sludges could be classified as ‘economy grade-high clay content’ soil indicating their possible use as soil or in soil making materials (Owen, 2002).Such approaches may provide an economical disposal means for the sludge while probably serving to improve certain soil qualities and enhance plant growth. In other instances, there have been attempts to reuse waterworks sludge as a source of biofertilizer, although there are concerns over lack of potassium and other nutrients in the sludge, which makes it incomparable with commercial grade fertilizers. However, the limiting metal levels in the waterworks sludge is important for long term land application as it determines the useful life of such application sites on the basis of cumulative metal loadings (Elliot and Dempsey, 1991). At typical field pH levels, Elliot and Dempsey (1991) documented that the oppositely charged Al and Fe oxide colloidal particles tend to flocculate the soil silicate particles, and upon dehydration, the Al and Fe hydroxides acts as cementing agents between soil particles, imparting favourable structural properties to soils such as reduced swelling and increased aggregate stability. In particular, Elliot and Dempsey (1991) further remarked that water treatment sludges may favourably modify the pH and water-holding capacity of soils, but noted that they generally have little fertilizer value. Methods used have included application to cropland, reclamation of strip-mined areas and use as a cover material for landfills.

However, it is important to modify such land applications to favourably induce soil properties and recycle valuable sludge components. Otherwise, uncontrolled application may lead to adverse and undesirable effects on typical soil properties. Therefore, for such approach to be justified as in the case of waterworks sludge, it is very important to examine the long and short-term effects of such applications on soil quality, particularly from the physico-chemical and biological point of view (Cameron et al, 1997; Titshall and Hughes, 2005). Contrasting however, is the fact that while some studies have reported considerable improvements in typical soil qualities like water retention and pH, and by extension good crop growth (Rengasamy et al., 1980; Robert and Edward, 1987; Moodley and Hughes, 2005; Pecku et al., 2005), others have noted some undesirable impacts (Young et al., 1988; Heil and Barbarick, 1989; Owen, 2002). In most cases, plant available phosphorus and crop yield were significantly reduced at higher application rates. Typically, soil phosphorus availability is significantly reduced at sludge application rates above 10% (Dayton and Basta, 2001). Therefore, developing soil substitutes by blending residual materials (e.g. alum based waterworks sludge and alkaline stabilized biosolids) according to each other physical and chemical properties may serve to mitigate these effects (Lindsay and Logan, 1998). Evidences from literature review on the effects of such waterworks sludge application to land seem to be producing some desirable results. Owen (2002) reported the result of a trial application of ferric sludge to agricultural land and recommended the ferric sludge as being beneficial to agricultural grassland and livestock production, provided the application rates comply with regulations. In particular, the possible adverse effects of sludge-borne metals on crops and soils could be minimal, more so as such effects are pH dependent and have been noted to be minimal at relatively neutral to alkaline soil pH (Elliot and Dempsey, 1991). Moodley and Hughes (2005) in a study on the effect of waterworks sludge application on four South African soils, reported that at an application rate of between 0-1280Mg WTR ha^{-1} and an incorporation depth of 0.20m, the saturated hydraulic conductivity of the soils was increased linearly with the application rate, while total porosity was also increased due to a decrease in bulk density. Although significant adverse soil effect was observed at a high application rate, it was concluded that such effects are only significant when the application rates are extremely high. In addition, it was found that the water retention capability of the soils studied was improved and this was ascribed to the sustained performance of the polymer in binding the silt and clay into gravel sized aggregates. In a separate study on the effects of waterworks sludge addition on soil structure, Pecku et al. (2005) also reported that soil basal respiration was greatly influenced and increased within a certain range of waterworks sludge application, with an associated change in the soil microbial community structure. The structural change in the soil microbial community structure did not however adversely affect the soils microbial diversity and even the observed waterworks sludge induced pH increases were not considered to be detrimental to soil health, but were beneficial since they were within typical pH ranges. These results are in good agreement with those of Rengasamy et al. (1980) where at an alum sludge application rate up to 2 tonnes/ha, an increase in water retention in the three soil types studies was observed.

However, most of the studies have been conducted on short terms and it may not be logical to extrapolate long-term effects from such tests. In addition, the nature of waterworks sludge is highly varied even when from the same source and therefore a single and general conclusion on their specific effects on land application may not be sufficient. More importantly, application rates would have to be determined on individual basis, otherwise there would be a potential for fixation of plant available phosphorus, although this might be beneficial in certain cases. As regards potential fixation of plant available phosphorus, Hyde and Morris (2004) noted that amendment of waterworks sludge with phosphorus before application to agricultural land may eliminate the problem of P deficiencies in plant growth. Therefore, they amended waterworks sludge with phosphorus at rates of 0.0-77.4g P/Kg of sludge and compared with equivalent fertilizer application. It was found that rates between 14.6 and 19.4g P/Kg of sludge were sufficient to make the waterworks sludge a supplier of P and that the rate of P addition to the soil was much less than predicted based on the amount of P adsorbed by the sludge in the laboratory and this was thought to be due to the release of P from the cationic polymer used in the coagulant.

3.3.2. As soil buffer

Few studies have evaluated the feasibility of utilizing the alkaline properties of waterworks sludge to act as soils pH buffer. Particularly, lime-containing sludge has been used for soil conditioning and pH adjustment. George (1975), AWWA (1981) and Elliot and Dempsey (1991) have all reported on the soil neutralizing capacity of lime-softening sludges and were found to increase soil pH more than limestone. This is in contrast with the reduced soil pH observed and reported in the case of alum sludge derived from municipal wastewater treatment plant, used as a soil amendment in a greenhouse study with barley (Wang et al., 1998).

In separate studies using waterworks sludge, Heil and Barbarick (1989) and Dayton and Basta (2001) reported that waterworks sludge may be an effective liming agent and this was corroborated by the findings of Rensburg and Morgenthal (2003), in which waterworks sludge was effectively used as an ameliorant for acid-generating mine tailings. Elliot and Dempsey (1991) however noted that most coagulation sludges have limited ability to serve as agricultural liming materials because their calcium carbonate equivalence (CCE) generally range from 10-20% of commercial limestone, in contrast to the CCE of lime softening sludges which is typically 80-103%. Coagulant sludges have highly varied plant nutrients and a comparatively low CCE values and these have limited their use as soil stabilizers or conditioners (Elliot and Singer, 1988). In any case, refinement of the application volume might be needed for different media particle size and the possibility of micronutrient or P-deficiencies above a certain threshold imposes an upper limit on the amount of sludge that can be used. In addition, elevated magnesium concentrations, occurrence of Calcium to magnesium imbalances and increase in the salinity of the limed medium are potential chemical growth limiting factors that were noted. Goldbold et al. (2003) reported that waterworks sludge conditioned with lime proved beneficial to plant growth and it was concluded that the resultant increase in soil pH more than compensate for any decrease in availability of phosphorus and in addition, the leaching of aluminium from acidic soil amended with alum sludge was negligible at typical agricultural pH values.

3.3.3. Nutrient reduction in laden soils and runoffs

Application of manures and biosolids to improve soil quality is a well-known agricultural practice. Unfortunately, long term application of such soil amendments often lead to soil nutrients level (P and N) in excess of crop needs and thus becomes a potential source of incidental nutrient leak to water bodies, which is not desirable. Sharpley et al. (1994) noted that application of animal manure in amounts that exceed agronomic rates based on the N requirement for crop production often results in increased loss of P from agricultural lands in surface run offs and potential eutrophication of surface waters. Poultry litter, when used as an inexpensive fertilizer source to improve soil quality has also been shown to increase NH_4 concentration in addition to P in surface run offs (Liu et al., 1997; Sharpley, 1997; Gallimore et al. 1999).

This has led to the use of chemical amendments to nutrients in soils and biosolids applied to land, and run offs from such lands/soils, such as the use of aluminium, iron and calcium salts to decrease P solubility in poultry manure and runoff from manure-amended soils (Moore and Miller, 1994). However, since waterworks sludge contain hydrous oxides with substantial P-fixing capacity (Elliot et al., 1990), they have been utilized as a low-cost alternative and chemical based best management practice to remediate phosphorus laden soils and prevent phosphorus loss in runoffs, especially from agricultural lands. In this context, concerns have also been expressed over the potential phytotoxicity of inorganic aluminium and fixation of plant available phosphorus. It is therefore desirable that efforts at using waterworks sludge to attenuate phosphorus pollution should include retrospectively, an evaluation and assessment of these potential negative impacts. Notwithstanding this, several studies have used waterworks sludge to mitigate the tendency of P-loss from surface runoffs and soils (Peters and Basta, 1996; Cox et al., 1997; Gallimore et al., 1999 and Elliot et al., 2002).

Samson and George (2005) concluded and provided evidence in their study to show that waterworks sludge is an effective amendment to control labile P in P-impacted soils and that the sludge-immobilized P will remain fixed for a long time, independent of common soil pH values. Their findings were in agreement with results obtained by using waterworks sludge to reduce soil extractable P-concentrations (Peters and Basta, 1996; Codling et al., 2000) and offsite P transport from manure treated soils (Elizabeth, et al., 2003). Novak and Watts (2004) also reported similar findings but noted that in their study, the waterworks sludge could be more effective at reducing potential runoff P loses than its use as an amendment to lower p-concentration, and that the waterworks sludge may not be applicable for all manure treated soils due to the logistic challenge of applying large amounts of the sludge which may limit its usefulness as a P-fixing agent. There are also concerns over the stability and longevity of the waterworks sludge P-immobilization, especially when important soil parameters like pH changes. In the case of N reduction, the CEC (cation exchange capacity) sites of the waterworks sludge were reported to be responsible.

Gallimore et al. (1999) however reported that although the CEC sites of the waterworks sludge adsorbed soluble NH_4-N, NO_3 and organic-N were observed to have little affinity for the CEC sites. Notwithstanding this, there were still significant reductions in N concentrations from poultry litter amended soils used in the study. Despite these advantages, some concerns are still expressed over the composite effect of such applications. For example, although waterworks sludge are generally quite low in trace elements of environmental concern, they contain a variety of salts as a result of the chemical purification process, and this may raise significant soil fertility and other environmental issues, particularly if these ions significantly alter basic soil properties (Novak and Watts, 2005**).** However, Peters and Basta (1996) and Codling et al., (2000) both showed through laboratory studies that waterworks sludge mixed into high P-laden soils will not severely lower soil qualities important for plant growth. Clearly, any observed effects would be specific to the conditions of application, such as application rate and the nutrient requirement of the intended crops. It however seems that there are some ambiguities as regards the optimum application rate and conditions, especially soil pH, which influences P availability, and such rates are best decided on a case by case basis. Extensive research is also still needed to establish the threshold application rate of the waterworks sludge, which would not perturb the phosphorus cycle of the soil or land, bearing in mind that waterworks sludge can differ substantially in their phosphorus binding maxima, due to variation in their oxalate extractable Al and Fe concentrations (Elizabeth, et al., 2003; Novak and Watts, 2004). In addition, several studies have suggested some relationships between application rates, soil pH and P-fixation/availability (Robert and Edward, 1987 and Elliot and Singer, 1988).

Another potential environmental concern is the possibiltity of elevated level of aluminium in the soils leading to Al-phytotoxicity, and generation of phytotoxic level of NO2-N in certain instances (Dayton and Basta, 2001). Fenghai et al. (1998) noted that in the case of alum sludge ammendment, organic matter (e.g. humics) and anions (e.g. F^-, SO_4^{2-} and PO_4^{3-}) contained in the sludge and the receiving soil will interact with Al, modifying its chemical speciation and affecting its phytotoxicity. Therefore the effect of such sludge ammendement would be expected to vary according to the physical and chemical characteristics of the sludge. However, it has been shown that applying alum sludge to land does not increase aluminium concentration in both the surface run offs and in the soil extractable aluminium (Elliot et al., 1988 and Peters and Basta, 1996). Peters and Basta (1996) further reported that there were no excessive increases in soil salinity and extractable heavy metals in soils. Perhaps, in some cases, the alkalinity tendency of the sludge, particularly alum sludge affects soil pH by increasing the pH level to favour Al insolubility. As reported by Gallimore et al., (1999), alkaline aluminium-based sludge treatment of a nutrient laden acidic soil increased the soil pH from 5.3 to 7; while the treatment of the same soil with another aluminium-based waterworks sludge (pH 7.0) increased the pH from 5.3 to 5.6. There was no notable elevated concentration of aluminium in any form and it was reasoned that since aluminium in waterworks sludge exists as an insoluble form of aluminium oxide, it is unlikely to dissolve in soil environments that are not strongly acidic (pH >5). Consequently, it is conceivable that since most waterworks sludge would have neutral to alkaline pH, and aluminium will expectedly exist as insoluble Al oxides, the dissolution of aluminium and the potential acidity effect on soils and or run offs may almost be impossible, except there is a shift in soil conditions, such as decrease in soil pH.

3.4 **Other uses**

Several other uses of waterworks sludges have been reported in literature. These include the use of palletized softening sludge as soil conditioner, animal feed, dispersion dye and filler material. Others include its use as chicken feed, for lake restoration, tile production, paper filler, dyes and paints, use of iron containing sludge as raw material in the iron and steel industry and the use of coagulant and backwash sludges to suppress hydrogen sulphide concentrations in sludge digesters (Horth et al. 1994). Raghu and Hsieh (1985) reported on some feasibility on the use of lime sludge as a landfill liner while Owen (2002) also reported attempts to use waterworks sludges to cap an inert landfill site and in turf production. Preliminary results show that the turf was well developed with well formed root structure thereby reducing the need for topsoil. It was suggested that the root action of the grass helped to mineralize the active metal hydroxides. In an extensive experimentation by Robert and Edward, (1987) alum sludge was applied to forests at an application rate of 1170m^3/ha with a solid content of 1.5%. Result obtained showed that the sludge blanket was substantially dewatered within two weeks and that given a limited application of the alum sludge, the phosphate cycle and forest growth pattern would not be upset. Recently, use of alum sludge as raw material for ceramic products was also reported by Vicenzi et al. (2005). Properties of the alum sludge based fired bodies were comparable to similar commercial products, offering a potential opportunity for recycling and reuse of alum sludge.

4. Discussion

With regards to the disposal of waterworks sludges, potential toxicity to the surrounding environment is a primary concern to both the public and environmental authorities. It is apparent from the literature that waterworks sludges have shown toxicity to some degree and may therefore impair receiving water quality. However, it is noted that the studies on the waterworks toxicity were based on the assumption when waterworks sludges remained untreated and were discharged directly into receiving water bodies. Little was known on the case of treated or dewatered waterworks sludges being landfilled or reused. In other words, there is an extreme lack of information on the toxicity of any released substances from the reuse of waterworks sludge. Undoubtedly, this reflects an important aspect of further research. Nevertheless, the potential toxicity of waterworks sludges does not dim further development of their reuse potentials.

It should be noted that, in most cases, a common misconception is that waterworks sludge could almost be treated and disposed off in similar ways as sewage sludge, creating unnecessary restrictive and burdensome legislations. However, while this could be true in some instances particularly as regards disposal routes, both sludges differ in characteristics and reuse potential and consequently, the characteristics and properties of products and processes from reuse applications will vary appreciably. As an example, possible transfer of pathogen into the food chain is a major concern in land application of sewage sludges, but this does not pose any evident problem in the case of waterworks sludge, as their pathogen levels would expectedly be low (Elliot and Dempsey, 1991). In fact, barring a grossly contaminated raw water source, waterworks sludges are relatively clean with respect to heavy metals and organics, and pose few environmental risks as compared to sewage sludges.

It is however noted that a critical factor that will contribute to the successful development and implementation of any beneficial reuse of waterworks sludge is legislation. Currently, there is yet to be any specific legislation on both sides of the Atlantic, concerning waterworks sludge with emphasis on reuses guidelines. Clearly, this is a pending issue that needs critical attention in view of the increasing attempts at waterworks sludge reuse. There are however concerted efforts to address this issue at the EU through the CEN (European Committee for standardization) which established the Technical Committee 308 (TC308) charged with (1) standardization of methods for sludge characterization and (2) preparation of draft guidelines for good practice in the production, utilization and disposal of sludges. The committee specifically concentrates on a range of sludges, which include waterworks sludges. The essence of reliable qualitative and quantitative data is recognized and as regards waterworks sludge, a German proposal has been adopted for data collection (Reimar and Ludovico, 1998). This review also reveals the paucity of adequate and/or published information on the quantity, quality and management costs of waterworks sludge produced in many countries. Thereofre, it is expected that the CEN TC308 would act as a springboard for the development of a unified database and operational guidelines for the disposal and reuse of waterworks sludge, particularly in the EU.

Reuse of waterworks sludge offers a unique and sustainable end point solution, and this has been appropriately preferred as a credible alternative to sludge disposal. Typically, the characteristics of waterworks sludge will usually govern the beneficial reuse option. It is desirable that such reuse will be beneficial with a view to protecting public health and the environment while enhancing sustainability. As a complimentary effort, it may be necessary that in the future, water treatment plant processes and operations would be geared towards generating sludge with a high degree of recycling potential and reliability for reuse. However for now, giving the current situation and the likely future trend, there is an obvious need for considerable attempts and researches globally, into the possible beneficial reuses of waterworks sludges with a complimentary and critical assessment of the possible negative effects of such applications. Happily, as noted by Godbold et al. (2003), reuse of waterworks sludges in various commercial and manufacturing processes has already been reported in UK, Europe, USA and Australia. Table 5 summarizes most of these current reuse attempts, citing their advantages and disadvantages.

[Table 5 Summary of current attempts at reusing waterworks sludges]

Overall, use of waterworks sludges in these and perhaps many more unexplored-ways would transform waterworks sludges from ‘wastes’ into useful materials, in tandem with the theme of sustainable development.

5. Conclusions and recommendations

Generation of waterworks sludge remains inevitable for now, and its disposal is emerging as a significant element in water resources planning and management. Socio-economic and environmental constraints have continuously limited the applicability of currently used disposal methods, creating an acute need for other sustainable sludge end-uses. While current sludge disposal methods may still suffice for the time being, the need for environmental sustainability and fiscal responsibility coupled with population increases will continually provide the drive towards beneficial reuse. Such reuse of the waterworks should have a “multi-pronged” approach, offering both economic and environmental sustainability. According to this review focused on the beneficial reuse of waterworks sludges, four categories of reuse (summarized in Fig. 3.) which included over eleven possible ways of reusing the sludge were identified. In addition, it is expected that with worldwide efforts and research into sustainable development, many more new and unexplored reuse routes would still emerge.

[Fig. 3 Summary of current reuse routes and future prospectives]

As regards future work, the following recommendations have been made.

- Currently, it could be assumed that waterworks sludge are non-hazardous under current legislation, however their future status will depend on outcome of current and future legislative reviews. There is therefore a need for critical public health assessment of possible risks associated with long-term application of some of the beneficial reuse options such as the land application of waterworks sludge, so as not to compromise public health and safety while ensuring sustainability. A quantitative prediction of the impacts of most of the reuse options would be desirable.
- Research is still needed to develop application guidelines for most of the reuse options. Accordingly, there is a need for updated and coordinated database on quantity and quality of waterworks sludge produced in most countries as well as current disposal practices. This would improve the commercial and industrial viability of those options and provide significant reductions in present and future sludge disposal costs. In the meantime, it may also be beneficial to review treatment plant process to enhance the sludge reuse potential.
- Waterworks sludge are highly varied in elemental composition and concentration, even when from a single source, therefore it is not presently possible to come up with a single guideline for each reuse option. While most of the beneficial reuse options are similar in approach and method selection, they are specifically unique and tailored to each set of operating conditions.
- A rigorous public relations campaign is essential towards a successful implementation of all the reuse options, notwithstanding their technical and economical feasibility and/or minimal environmental impact. However, the most limiting factors for beneficial reuse of waterworks sludges are their chemical composition in terms of coagulants contents, organic matter, ions and metal levels. Obviously, these still require further extensive investigations.
- While land application is one of the economical advantageous options, regulatory clarifications are essential. In addition, although such applications have

the potential to capture excessive nutrients in bio-ammended soils and runoffs, more long-term research information is needed to establish the desired rate of application with minimal or no adverse environmental impact. Similarly, in the case of beneficial reuse of waterworks sludges as soil conditioners in preference to their use as possible low-grade fertilizers, the application rates and conditions should be compatible with sound agronomic practices.

- In the building and construction industries, an important key to a full-scale application of the various waterworks sludge reuse options remains a steady and reliable source of the sludge, with minimal compositional variability. In all cases, the minimum sludge solids concentration that optimizes product quality needs to be determined.
- Resource recovery from waterworks sludge may present some significant chemical savings and reduction in sludge volume, but such gains may be lost to the many recovery operational problems that need to be overcome. Therefore, a sound economic assessment is desirable in such case.
- The use of dewatered waterworks sludge as the main substrate in constructed wetland for wastewater treatment is a novel idea with a multi-pronged approach. However, for this beneficial reuse option to be continually feasible, large scale and long-term extensive research is desirable to test the steady treatment efficiency and the possible release of any toxic substances such as polymer residues to the surrounding environment.
- In view of the widely held public belief about sludge, and the apprehension over health, environmental and safety compliance of products and processes recycling sludge, a rigorous and convincing public education is very necessary.

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Table and Figures Captions

Table Captions

Table 1. Typical composition of water treatment works derived sludges (mean values ± SD)

Table 2 Maximum P-adsorption capacity of waterworks sludges reported in the literature

Table 3 Maximum adsorption capacity of waterworks sludges reported in other studies

Table 4 Maximum P-adsorption capacities of alum sludge using three model P at varied pH conditions (Zhao et al., 2006)

Table 5. Summary of current attempts at reusing waterworks sludges

Figure Captions

Fig.1 Indicative diagram showing quantity of waterworks sludge produced in selected countries (figures based on estimated quantities from year 2000, compiled from Dharmappa et al.(1997); Goldbold et al. (2003); Pan et al. (2004); Carvalho et al. (2005) and Zhao et al. (2006))

Fig. 2 Schematic diagram of: (a) flocs (floc phase) and bulk water and (b) floc skeleton and interstitial water (Herwijn, 1996)

Fig. 3 Summary of current reuse routes and future prospectives

Table 1. Typical composition of water treatment works derived sludges (mean values ± SD)

Parameter	Unit	Alum sludge	Ferric sludge	Lime sludge
Aluminium	% dry weight	29.7 ± 13.3	10.0 ± 4.8	0.5 ± 0.8
Iron	,,	10.2 ± 12	26.0 ± 15.5	3.3 ± 5.8
Calcium	,,	2.9 ± 1.7	8.32 ± 9.5	33.1 ±21.1
Magnesium	,,	0.89 ± 0.8	1.6	2.2 ±1.04
SiO_2	,,	33.4 ± 26.2	nd	54.57
pH		7.0 ± 1.4	8.0 ± 1.6	8.9 ± 1.8
BOD_5	mg/l	45 (2-104)	nd	nd
P	% dry weight	0.35	0.36	0.02
Zinc	mg/kg	33.9 ± 28	18.7 ± 16	2.5 ± 0.7
Lead	,,	44.1 ± 38.2	19.3 ± 25.3	1.87 ± 1.13
Cadmium	,,	0.5	0.48 ± 0.26	0.44 ± 0.02
Nickel	,,	44.3 ± 38.4	42.9 ± 39.2	0.98 ± 0.52
Copper	,,	33.72 ± 32.5	18.7 ± 25.8	3.6 ± 3.1
Chromium	,,	25.0 ±20.1	25.7 ±21.6	1.3 ± 0.2
Cobalt	,,	1.06	1.61 + 1.1	0.67 + 0.05
Total solids	mg/l	(2500-52345)	(2132-5074)	nd

Note: 1. Data compiled from Elliot and Dempsey (1991); Dymaczewski et al. (1997); Fenghai. (1998); Gallimore et al. (1999); Georgantas et al. (2003); Godbold et al. (2003); Sotero-Santas (2005); Titshall and Hughes (2005); Yang et al. (2005).

2. nd refers to no data.

3. Data in parentheses indicates range.

Table 2 Maximum P-adsorption capacity of waterworks sludges reported in the literature

Sludge	Model P-solution used	P-adsorption capacity (mg-P/g sludge)	Reference
Lime softening sludge	–	0.89	Leader et al. (2005)
Iron(ferric sulfate)	–	0.95	Leader et al. (2005)
Alum sludge	Wastewater	0.30 – 0.33	Huang & Chiswell (2000)
Alum sludge	Ortho-P *	25.0 (at pH 7.1)	Kim et al. (2003)
	Pyro-P*	16.6 (at pH 7.1)	
	Tri-P*	14.3 (at pH 7.1)	
	Adenosine-P*	12.5 (at pH 7.1)	
Alum sludge	Ortho-P *	0.7 - 3.5 (at pH 9 – 4.3)	Yang et al. (2005)
Alum sludge	Poly-P*	0.1 - 3.2 (at pH 8.5 – 4.3)	Babatunde et al. (2005)
Alum sludge	Adenosine5-P*	1.2 - 1.9 (at pH 4.0 - 9)	Zhao et al. (2006)

* Synthetic solutions

Table 3 Maximum adsorption capacity of waterworks sludges reported in other studies

Sludge composition/Type	Adsorbate studied	Adsorption capacity (mg-P/g sludge)	Reference
SiO_2(54%),Al_2O_3(21%),Fe_2O_3(6.6%)	Chromium	1.40 (at pH 4.6)	Chu (1999)
	Mercury	0.43 (at pH 6.0)	
SiO_2(1.6%),Al_2O_3(47.2%),Fe_2O_3(7.18%)	Fluoride	5.4 (at pH 6.0)	Sujana et al.(1998)
Sintered water treatment sludge	Copper	NR	Simpson et al.(2004)
	Lead	NR	

NR: Not reported

Table 4 Maximum P-adsorption capacities of alum sludge using three model P at varied pH conditions (Zhao et al., 2006)

Phosphate type	Chemical name & formula	pH	Adsorption capacity (mg -P/g sludge)	
			Coarse air-dried*	Fine air-dried*
Ortho-phosphate	Potassium dihydrogen phosphate KH_2PO_4	4.0	2.25	4.88
		5.5	1.40	4.48
		7.0	0.87	3.97
		9.0	0.99	3.75
Poly-phosphate	Sodium hexametaphophate $Na(PO_3)_6$	4.0	0.99	2.76
		5.5	0.79	2.64
		7.0	0.53	1.86
		9.0	0.32	1.53
Organic Phosphate	Adenosine 5'-monophosphoric acid monhydrate $C_{10}H_{14}N_5O_7P.H_2O$	4.0	0.58	1.91
		5.5	0.44	1.69
		7.0	0.31	1.44
		9.0	0.27	1.24

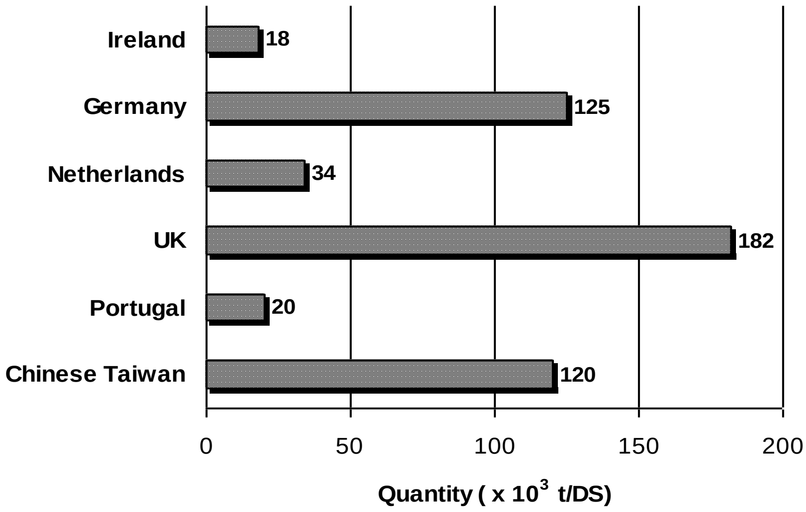
* Moisture content for air-dried sludge = 23.4-23.7%, particle size of coarse air-dried sludge = 0.420 mm and fine air-dried sludge = 0.125mm

Table 5. Summary of current attempts at reusing waterworks sludges

Application	Specific use	Advantage	Disadvatage	Remarks	Status
Wastewater treatment process	Source of chemical coagulant	Cheap, reduces sludge volume and disposal cost	Recovery process could be complicated, laborious and expensive. Limited purity and possible contamination	Continued use is doubtful in light of purity, technical and economic factors	1 & 2 (1 indicates laboratory scale and 2 indicates full scale application)
	As a coagulant for various pollutants in wastewaters	Comparable removal efficiency, enhanced particulate, COD and SS removal	Use may be restricted		1
	As adsorbent for various pollutants in wastewaters	Cost effective, good for P-removal. Removes metals and pollutants as well	Risk of clogging and possible release of substances	Mechanism and extent of adsorption still needs to be researched.	1
	Co-conditioning and co-discharge with sewage sludge	Improves final sewage sludge characteristics e.g sludge settling velocity and dewaterability	Haulage costs		1 & 2
	Addition in wastewater treatment plants and as a main substrate in constructed wetlands	Enhanced phosphate removal. Reduces scum and bulk forming. Improves settling of activated sludge and the process efficiency. Increases gas production	Operational logistics as it is very unlikely for a wastewater treatment plant to be cited close to a water works. Need for extra sewer lines and/or	Could be a sustainable alternative barring haulage distances and costs. Use in constructed wetlands still in laboratory	1 & 2

		in sludge digester and capacity of centrifuges for sludge dewatering	increased capacity at extra budgetary cost	scale	
Building and construction	Cement manufacture	Non hazardous, high solids concentration, similar chemical component with cement clay. Alum sludge forms calcium aluminium hydrates which helps to prevent chloride corrosion of steel reinforced structures, good calorific power	Organic content in final product may affect mechanical properties. Risk of hydrogen generation, inclusion of deleterious components, aluminium expansion, retardation of settling, malodorous emissions and high water content. Risk of corrosion in cement kiln and production of iron oxides from ferric sludge may produce undesirable colour in tainting in final product	Assurance of consistent quality and quality is needed,as well as adequate knowledge of content to determine applicability.	1 & 2
	For making bricks	Organic content may present some energy savings temperature. Reduced shrinkage and enhanced aesthetics of the final product, metal hydroxide content help	Reduction in mechanical and tensile strength and frost resistance with increasing proportion of sludge used. Sulphur concentration	Process still viable despite all the drawbacks. A good example is the case of bricks made from sewage sludge. Constant monitoring	1 & 2

		to generate a low porosity brick which becomes structurally acceptable	limits percentage of addition.	of stability performance essential due to variable nature of oraganic content	
	Pavement and Geotechnical works materials, construction and filler material and liners for sanitary landfills	Significant reduction in materials cost	The need to eliminate organics often leads to sludge incompatibility with standard materials. Malodorous emissions during thermal treatment to remove organics	Holds great promise as a potential reuse outlet but needs to be researched further	1
Land based applications	Structural soil improvement	Reduced swelling, increased aggregate stability, water retention and soil basal respiration	Risk of metal accumulation in the soil, little fertilizer value and Potential fixation of P	It's use can be controlled to maximize benefits with minimal impact	1 & 2
	Soil buffer	Effective for soil pH amendment and soil conditioning/remediation	Potential fixation of plant available P leading to reduced yield	Performance can be enhanced	1 & 2
	Nutrient reduction in laden soils and run-offs	Effective P reduction at low cost	Phytotoxicity of inorganic aluminium,potential fixation of P	Optimum application rates should be decided on a case by case basis.	1 & 2



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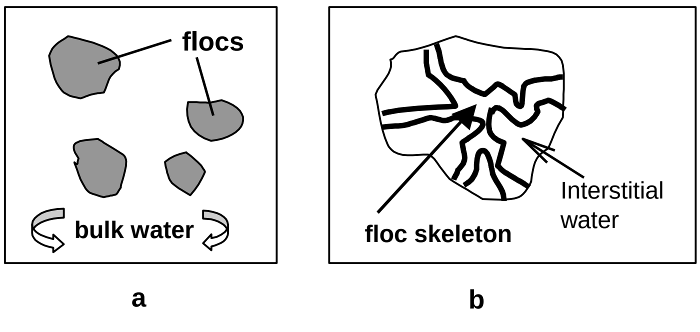

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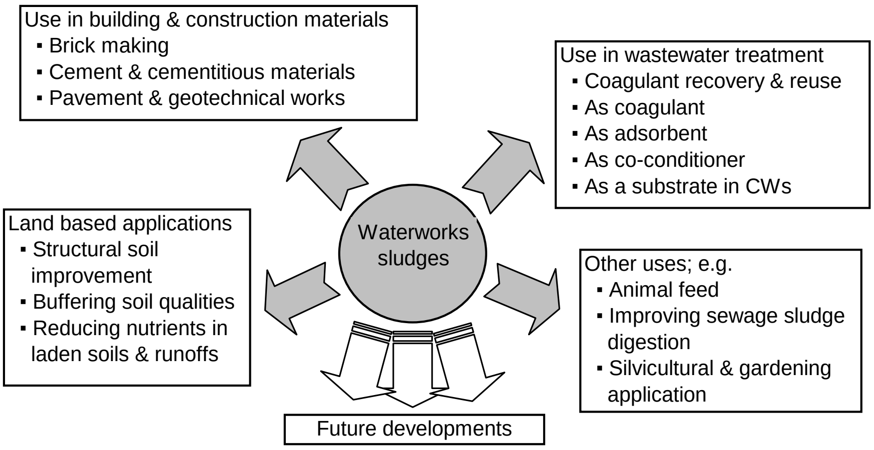

Fig. 3 Summary of current reuse routes and future prospectives