Heating Value Characteristics of Sewage Sludge: A Comparative Study of Different Sludge Types

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Summary: Heating value characteristics of three different types of sludge, i.e. domestic sewage sludge, industrial sludge, and industrial+domestic sewage sludge were investigated. Industrial+domestic sewage sludge (thickened) showed the highest heating value (5040 kcal/kg) than other sludge types. This may be due to increased amount of organic matter presents in thickened sludge than de-watered sludge. A gradual increase in organic matter of the sludge was observed with the increase of the moisture contents. Heating value of the sludge having 60% moisture contents was found in the range between 924-1656 kcal/kg and this amount was higher than the minimum heating value (800 kcal/kg) required sustaining auto thermal combustion in sludge incineration process. Energy consumption requirement for pre-drying sludge operations revealed that industrial sludge (de-watered) required the minimum cost (13 $/ton of sludge) to make it a sludge of fuel grade (60% W), while mixed sludge cost the highest amount for its pre-drying operations.

Introduction

Generation of sludge keeps on increasing corresponding to the rapid development in industries and population growth. In both developed and under developed countries, increase in sludge production is driven by the rise in household number connected to central treatment plants, day to day tightening of effluent discharge standards and introduction of technologies capable of achieving higher efficiency of wastewater treatment [1]. In Korea, sludge production increased many folds in eighties, a period regarded as a climax in the history of industrial revolution of the country. According to an estimate, around 20 million tons of sludge from all sources was generated in Korea in the year 2000.

Many operations are currently being carried out for the safe disposal of sludge like recycling of sludge as a fertilizer, landfilling, dumping in sea, and incineration, among others [2]. Use of sludge as a fertilizer bears a great risk of transforming of heavy metals to human beings through plants and animals since average content of heavy metals in municipal sludge is higher than the heavy metal ions in farming soil [3,4]. Problem associated with the landfilling of sludge is the generation of heavily polluted leachate and emission of odour and toxic gases [5] resulting in groundwater contamination and environmental concerns. Ocean disposal of sludge is expected to phase out because of the implementation of stringent water pollution control regulations [6].

These limitations on sludge disposal lead to the expectation that the role of incineration will increase in future. Sludge incineration enjoys a combination of several advantages like a large reduction of sludge volume to a small-stabilized ash and thermal destruction of toxic organic constituents [7]. Further, calorific value of dry sludge corresponds to that of brown coal, and therefore through incineration this energy content may be recovered [8]. In addition, small space requirement and the need to minimize odour generation from landfillings and aesthetic objections of the nearby population make incineration as attractive sludge disposal method. The forecasted trend in disposal routes of sludge showed (Fig. 1) that around 38% of the total sludge produced in European countries will be disposed off through incineration upto the year 2005.

Keeping in view the prospects of combustion of sludge from different sources, some researchers have conducted the study looking incineration as a mean of safe disposal of sludge. Vesilind *et al.*, [9] working on fuel value of sludge revealed that the higher heating values (HHV) of dried sludge is dependent upon the temperature to which it is

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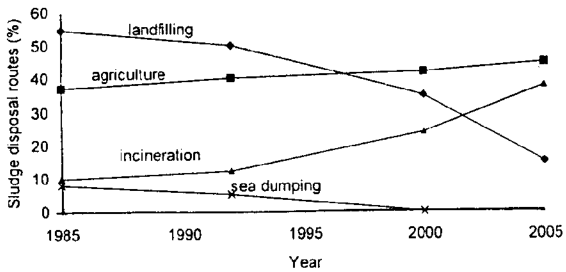

Fig. 1: Forecasted sludge disposal routes in the European Community up to the year 2005.

exposed prior to the measurement of the heat value. Sludge exposed to temperature 105° C lose enough volatile matter to have measurably lower HHVs than the sludge exposed to temperature below 105° C. Ogada *et al.*, [10] observed that sewage sludge is incinerated in the form of wet paste with high water content, typically 70-80%. Also the sludge combustion is dominated by gas-phase oxidation of the volatile matter since up to 80% of the sludge carbon might be released with the volatile matter during sludge incineration. Present study represents characterization of sludge from different sources in terms of heat value. An underlying objective of the work is to finding the ways that how incineration of sludge can be addressed in optimal heat efficient manners.

Results and Discussion

Water content of dry solid

Highest amount of moisture content was recorded in mixed industrial+domestic sewage sludge (thickened) averaging at 97.4%, while industrial sludge (thickened) showed the lowest amount of moisture content averaging at 95.8%. In general, de-watered sludge showed 19% less water content than thickened sludge (Table 1). Total solid was found relatively higher in both the samples thickened (4.2%) and in de-watered (21.4%) of industrial sludge. This may be due to the presence of relatively higher amount of non-organic fraction in industrial sludge, which includes mineral salts, lime, sand, and heavy metal ions. However, industrial+domestic sewage sludge showed the least amount of total solid compared to other samples of sludge.

Relationship between water content and organic matter of sludge

Proximate analysis of sludge showed a relationship between organic matter and moisture content in respective samples of sludge. It was observed that amount of organic matter was increased with the increase of moisture content in the sludge. Both sludge types thickened and de-watered exhibited the similar trend. Figure 2 demonstrates this relationship by adopting some reference and experimental values as well. This could lead to the

Table-1: Composition of different sludge types as defined by proximate analysis

Sludge type	Sample	Sludge condition	Moisture contents (%)	Total solid (%)	Fixed solid (%)	Volatile solid (%)
**Domestic sewage sludge	A	thickened	96.1	3.9	37.3	62.7
		de-watered	79.5	20.5	37.0	63.0
	B	thickened	97.4	2.7	38.2	61.8
		de-watered	82.9	17.2	47.6	52.4
	C	thickened	97.3	2.7	39.0	61.0
		de-watered	79.4	20.6	46.0	54.0
	Average	thickened	96.9	3.1	38.3	61.7
		de-watered	80.6	19.4	43.5	56.5
**Industrial + domestic sewage sludge	D	thickened	97.6	2.4	34.9	65.1
		de-watered	84.1	15.9	42.2	57.2
	E	thickened	97.2	1.5	45.8	54.2
		de-watered	83.2	16.8	54.6	45.5
	Average	thickened	97.4	2.0	40.4	59.6
		de-watered	83.7	16.4	48.7	51.3
*Industrial sludge	F	thickened	95.8	4.2	36.2	63.8
		de-watered	78.9	21.4	39.3	60.7

**digested, *undigested

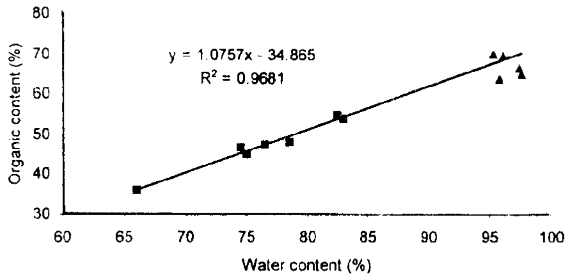

Fig. 2: Profile of water content of sludge samples regarding organic matter.■, reference values (de-watered sludge); ▲, experimental values (thickened sludge)

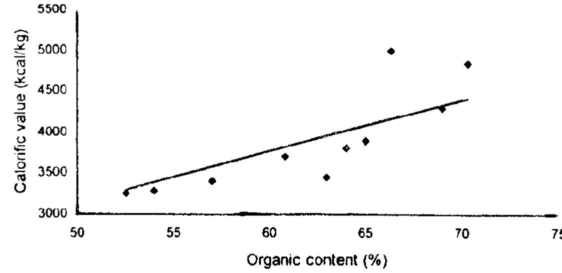

Fig. 3: Relationship between organic content and calorific value of sewage sludge.

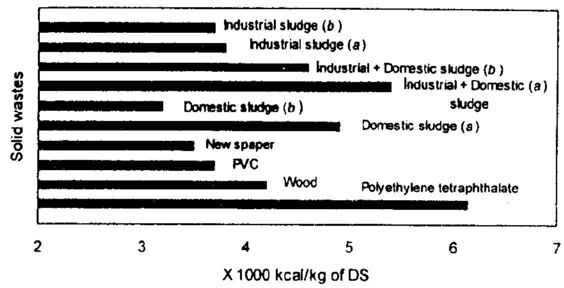

Fig. 4: Profile of heating values of different sludge types regarding other solid wastes. *a*, (thickened sludge); *b* (de-watered sludge)

conclusion that increase in organic matter in the sludge could affect economy of the sludge drying process since the phenomenon was destined to increase moisture contents of the sludge, which would, in term increase cost of the supplementary fuel in incineration operations.

Fixed solid

Fixed solid was found relatively higher in digested sludge both thickened and de-watered compared to the undigested ones. In general, de-watered sludge showed higher content of fixed solid than thickened sludge (Table 1). Amount of fixed solid in de-watered sludge of domestic, industrial+domestic, and in industrial sewage sludge was found 11.9%, 17%, and 7.9% higher than the corresponding samples of thickened sludge.

Heat content of sludge types

a) Measured calorific values

In comparison to de-watered sludge, heating value of thickened sludge was found higher in all the samples irrespective of the sludge types. Industrial+domestic sewage sludge (thickened) showed the highest heating value among others (Table 2). This may be due to the increased amount of organic matter found in thickened sludge than de-watered sludge. This phenomenon has also been demonstrated in Figure 3, which showed a somehow gradual increase in calorific value of sludge samples with the increase in organic content. Heating value of industrial+domestic sludge (5040 kcal/kg) was even higher than the calorific value of newspaper, polyvinyl chloride (PVC) plastic, and wood, which are 3500 kcal/kg, 3750 kcal/kg, and 4100 kcal/kg, respectively (Fig. 4). Higher heating value of mixed industrial+domestic sewage sludge could be justified since industrial sludge being one of the fractions of mixed sludge was undigested, and organic matter in undigested sludge is relatively higher than the organic fraction in digested sludge. This factor might have played a role in increased heating value of mixed industrial+domestic sewage sludge.

Domestic sewage sludge (a) showed relatively enhanced value of H_L (Table 2). It may be due to higher VS/TS (volatile solid/total solid) ratio of domestic sludge compared to other sludge since higher VS/TS value increases H_L of the sludge. Lower heating value from all sludge types was found in the range between 51–313 kcal/kg. Heating value of the sludge having 60% moisture content (60% W) was found in the range between 924-1656 kcal/kg (Table 2) and this amount is higher than the minimum heating value (800 kcal/kg) required to sustain auto thermal combustion in sludge incineration operations. Sludge having moisture content up to 40-60% are acceptable for combustion in the case of boilers firing brown coal, because the

Table-2: Ultimate analysis and heating values of sludge

Constituent	Domestic sewage sludge (B)		Industrial sludge (F)		Industrial+domestic sewage sludge (E)	
	a	*b*	*a*	*b*	*a*	*b*
VS/TS of DS	0.7	0.5	0.64	0.5	0.5	0.5
C	41.2	21.2	32.4	30.6	40.3	37.8
H	5.6	3.3	5.1	4.5	5.8	5.5
O	6.2	7.3	10.5	10.6	22.2	21.1
S	6.0	3.7	0.6	2.3	1.8	1.8
N	10.5	2.4	2.8	5.8	5.2	5.7
H_d (kcal/kg)	4985	3209	3792	3727	5040	4633
H_L (kcal/kg)	- 480	51	- 410	313	- 422	279
H (kcal/kg)	1634	924	1157	1131	1656	1493

a, thickened sludge; *b*, de-watered sludge; H, heating value of sludge (60% W)

boilers are designed to operate with relatively high moisture content fuels [11].

b) Ultimate heating values

In general considerations, C, H, O, N, and S from ultimate analysis are taken as combustibles, which correspond to volatile matter plus fixed carbon in proximate analysis. In order to calculate ultimate heating values of the sludge types, values of the combustibles were put into the conventional heat equations. Heating values calculated by applying Dulong's, Kestner's and Steuer's equations were found in close agreement with those of determined by bomb calorimeter experiments (Table 3). Heating value of domestic sewage sludge (thickened) calculated by Kestner's equation, however, showed a considerable difference of 23% from the measured one, which is too high to be accepted for practical applications. Discrepancies between measured and calculated values have also been observed by other research groups [12]. The difference of heating values among the conventional equations is caused by the assumptions on the role of oxygen that whether oxygen is bound with hydrogen as water or with carbon in the form of carbon mono oxide.

All the heavy metal ions, except nickel (Ni), were found appreciably in low amount irrespective of the sludge samples (Table 4). Economic analyses of pre-drying operations of sludge revealed that industrial sludge (de-watered) required the minimum cost (13 $/ton of sludge) to make it sludge of fuel grade (60% water). And industrial+domestic sewage sludge (thickened) required the highest cost (29 $/ton of sludge) to get it dried until required heating value. Drying cost of other sludge samples varied between these two values. Relatively cheaper pre-drying operation of industrial sludge (de-watered) gave it an economic preference over the use of other samples of sludge to be employed as fuel in incineration plant.

Experimental

Three types of sludge were sampled from different sludge treatment plants located in Daegu city and Kyung-San regions of Korea. Sludges were categorized as domestic sewage sludge, industrial sewage sludge, and a mixture of sludge from industrial and domestic wastewater treatment plants. Samples were taken from two different stages of sludge processing unit. First from sludge thickening tank before digestion and second at the outlet of belt de-watering process after digestion.

Moisture contents were determined by heating the samples at 105 °C to a constant weight. The resulting sludges were used as samples for ultimate

Table-3: Heating values of sludge calculated by conventional heat equations

Heat equation	Domestic sewage sludge (B)		Industrial sludge (F)		Industrial+domestic sewage sludge (E)	
	a	*b*	*a*	*b*	*a*	*b*
Dulong's eq. (kcal/kg)	5128	2621	4062	3616	4338	4080
Kestner's eq. (kcal/kg)	6461	2015	3111	3909	4478	4447
Steuer's eq. (kcal/kg)	5019	2594	4045	3693	4675	4393

a, thickened sludge; *b*, de-watered sludge

Table- 4: Heavy metal content in different sludge types

Heavy metal ions (mg/l)	Domestic sewage sludge (B)		Industrial sludge (F)		Industrial+domestic sewage sludge (E)		Average value	
	a	b	a	b	a	b	a	b
Zn	360	250	1260	1050	674	780	765	693
Mn	793	767	760	650	737	1650	763	1022
Pb	1.4	1.4	1.9	2.6	88	45	30.4	16.3
Cd	14	24	12	15	4	4	10	13.7
Cu	553	830	498	620	318	303	456	584
Ni	150	336	637	703	158	452	315	497

analysis. Isothermal treatments were performed in an electric furnace by heating a crucible made up of quartz filled with dry sludge at a temperature 550 °C for 30 minutes. These experiments were conducted in an oxidizing atmosphere (air), and no other gas was purged inside the furnace. Contents of carbon, hydrogen, nitrogen, and oxygen were measured by an elemental analyzer (model: Perkin-Elmer 2400 CHN), and sulfur content was measured by C/S analyzer (model: 444, Leco). Heavy metal ions were determined by atomic absorption spectrophotometer (Varian Spectr AA-800, Japan). Economy analyses were done by using diesel oil as energy fuel in pre-drying operations of sludge. Specific gravity and heating value of the diesel oil were 0.08 and 10,752 kcal/kg, respectively and its price was set at 0.5 $/l.

Higher heating contents of the sludge in terms of calorific value were measured by using an adiabatic oxygen bomb calorimeter (model: 1341EB, PARR instrument company, USA). Data from bomb calorimeter was applied into the following equation to get the lower calorific values of the samples.

$$H_L = H_d\,(100 - N)/100 - 600\,W/100$$

Where, H_L is the lower calorific value of the sludge (kcal/kg), H_d is higher calorific value of dry sludge (kcal/kg), and W is the moisture content.

Calorific values measured from calorimeter were compared with the net calorific values calculated from the elementary components of the sludge in an ultimate analysis using various conventional empirical equations as given below.

Dulong's equation: $H_h = 8100C + 34{,}200[H - O/8] + 2500S$

Kestner's equation: $H_h = 8100[C - (3/4)O] + 34{,}250N + 2{,}250S$

Steuer's equation: $H_h = 8100[C - (3/8)O] + 34{,}500[H - O/16] - 2500S + 5700\,(3/8)O$

Where H_h is the higher heating value (kcal/kg of dry sludge (DS) content and the atomic symbols represent weight fractions of respective atoms (%/100).

Conclusions

Heating value characteristics of different sewage sludge types revealed that the mixed industrial+domestic sewage sludge (thickened) contained the highest heating value (5040 kcal/kg) than other types of sludge. Domestic sewage sludge (de-watered) showed the lowest heating value (3209 kcal/kg). Increase in calorific value was somehow related to the gradual increase in the organic matter of the sludge. Domestic sewage sludge (thickened) showed relatively enhanced value of H_L since its VS/TS ratio was higher than other sludge. Irrespective of the sludge types, heating value of the sludge having 60% moisture contents was found in the range between 924-1656 kcal/kg and this amount was higher enough than the minimum heating value (800 kcal/kg) required to sustain auto thermal combustion. Industrial sludge (de-watered) got the economic preference over the use of other sludge since it cost minimum to make it sludge of fuel grade.

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