Korean J. Chem. Eng., **24**(4), 660-663 (2007)

Attrition of sewage sludge and sludge-based char in a fluidized bed reactor

Young Hean Choung, Ki Chul Cho, Won Joon Choi, Soo Gon Kim*, Young Suk Han and Kwang Joong Oh†

Department of Environmental Engineering, Pusan National University, Busan 609-735, Korea
*Division of Remediation Technology, QEN Solution, Ulsan 680-190, Korea
(*Received 30 December 2005 • accepted 16 November 2006*)

Abstract−Fluidized bed pyrolysis has been recognized as an innovative technology for sewage sludge treatment. The physical and attrition properties of sewage sludge are changed through the fluidized bed pyrolysis. The minimum fluidization velocities and attrition rate constants for sewage sludge and sludge based-char were obtained from pressure drop and attrition tests. As a result, sewage sludge with 20% moisture content and char were classified as Geldart B solids and the superficial gas velocity for bubbling fluidization was 0.2142-0.8755 m/s. In addition, attrition of the sewage sludge and char was more affected by particle size than by material type. The equations for the overall attrition rate constants are $K_a \times 10^5 = 1.09U - 14.82$ for sludge and $\ln k_a = 0.1(U - U_{mf}) - 13.63$ for char, respectively.

Key words: Sewage Sludge, Char, Bubbling Fluidized Bed, Attrition

INTRODUCTION

Generation of organic and inorganic sludge in numerous sewage treatment plants is a challenging environmental issue. In Korea (Ministry of Environment, 2004) the sludge is usually subjected to several treatment and disposal methods such as ocean dumping (67.8%), recycling (11.9%), landfill (10.5%), and incineration (9.8%). Disposing of the sludge in landfills of sewage sludge is limited by the potential of heavy metal and hazardous material pollution, and ocean dumping is prohibited by the London convention on prevention of marine pollution.

Incinerating sewage sludge was initiated in the early 1990's mainly by fluidized bed and rotary kiln. It is a promising technology for treating sludge-like waste because of the advantages given by rapid mixing and high turbulent combustion. However, incineration also has disadvantages such as the use of auxiliary fuel due to the large amount of moisture in the sludge and the emission of hazardous flue gases. These problems cause increases in operating and scrubbing costs. Researchers have focused on the development of technology for recycling residual solids. For example, there are technologies for recovering phosphorous [1], aggregate development by melting [2] and adsorbent development by activation [3]. Carbonization of sewage sludge by fluidized bed pyrolysis is the most suitable of these technologies due to the variable composition of sludge and high operating cost for melting. However, the characteristics of fluidization and attrition of sludge and char in a fluidized bed should be investigated prior to its commercialization because of the attrition caused by carbonization and fluidization of particles. In the fluidized bed, the decrease of the particle size due to the attrition affects the fluidization characteristics and causes the loss of the particle due to the entrainment. In this study, we determined the minimum fluidization velocity of sewage sludge and char with particle size and water content and examined the characterization of attrition in accordance with particle size and gas velocity.

†To whom correspondence should be addressed.
E-mail: kjoh@pusan.ac.kr

Table 1. Proximate analysis of dry sewage sludge and char used in this study

Item			Sampled sewage sludge	Char
Proximate analysis (wt%)	Moisture		77.90	0
	Incinerable	Volatile matter	9.79	3.25
		Fixed carbon		12.32
	Ash		12.31	84.43

MATERIALS AND METHODS

Dewatered sludge cakes were sampled from the wastewater treatment installation in Busan, Korea. These samples were dried in an electric dryer (Hankook Inc. Korea) at 105±5 °C for 24 hours and some of them were pyrolyzed in an electric furnace (Kantal, Korea) at 600 °C. A proximate analysis of these materials is shown in Table 1.

Two kinds of apparatus were used in this study. One was used to determine minimum fluidization velocity, and the other for an attrition test. The fluidization test equipment consisted of an inlet for fluidization gas, one fluidized bed, two dust collectors, and a pressure drop recorder. Inlet air was constantly supplied by a compressor and passed through the water trap and the flow meter. The fluidized bed, 6 cm in diameter and 95 cm in height, was made of acryl to allow observation of the status of fluidization and elutriated fine particles that were collected through the cyclone. The logged data measured every 10 seconds by DPT cells was saved on a computer. The other piece of equipment, the three-hole air jet, used by Gwyn [4] on the basis of research by Forsythe and Hertwig [5], was used to investigate the attrition of particles with fluidization. Moisture and particles in the air supplied from the compressor were removed by the trap, and then a constant flow rate was supplied by mass flow controller (5850E, Brooks Co.). The dried sludge and char after attrition were collected, and their particle sizes were measured by Tyler sieves of 80, 100, 140, 170, 230, and 270 meshes.

The particle size of sludge was measured by a ball mill test and its mean diameter was about 334 μm. Most of sludge particles were 20/40 mesh and 40/60 mesh except for the fine (under 100 mesh) and coarse (over 20 mesh) particles, which were inadequate for fluidization.

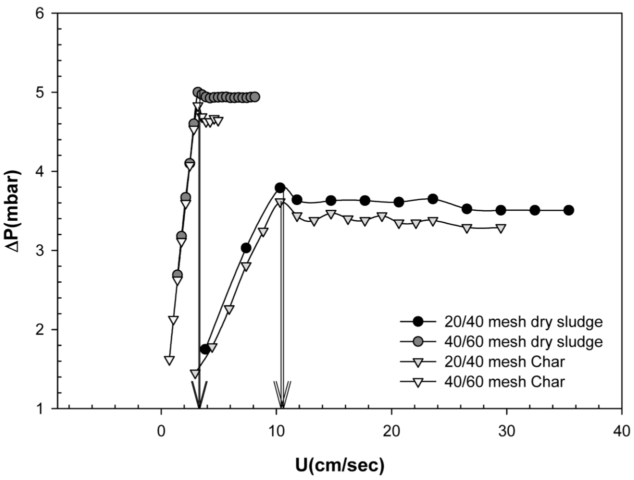

Fig. 1. Minimum fluidization velocity for dried sewage sludge and char by particle size.

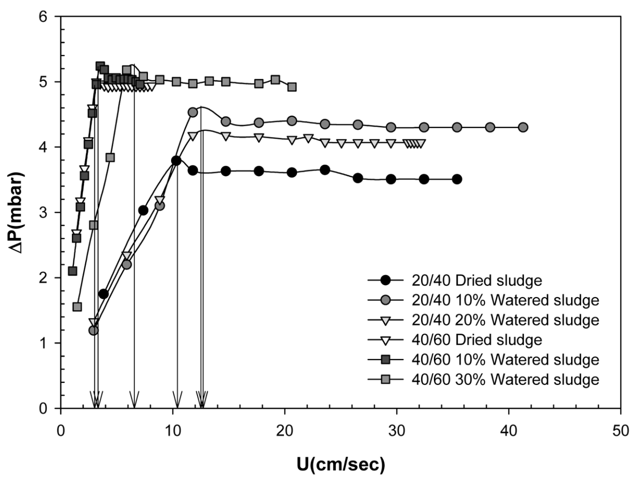

Fig. 2. Minimum fluidization velocity for dried sewage sludge and char by moisture content.

RESULTS AND DISCUSSION

The minimum fluidization velocity for sewage sludge and char with particle sizes of 20/40 and 40/60 mesh is shown in Fig. 1. The minimum fluidization velocities with particle sizes for dry sewage sludge were 10.55 cm/s and 3.28 cm/s, respectively, and those for char were 10.34 cm/s and 3.25 cm/s, respectively.

When the sludge and char had the same particle size, the dry sludge had a higher minimum fluidization velocity than the char, but the difference could be ignored. Therefore, the minimum fluidization velocity of dry sludge and char was affected exclusively by particle size, and the superficial gas velocity for fluidization of dry sludge at ambient condition should be higher than 10.55 cm/s. Fig. 2 shows the pressure drop versus velocity diagram of sludge with moisture content of 0, 10, 20, and 30%. Sludge particles of 20/40 mesh showed that the minimum fluidization velocity increased as the moisture content increased, but sludge with 30% moisture content could not be fluidized due to slugging, while 40/60 mesh sized sludge with 40% moisture content was inadequate for fluidization because of axial channeling. Therefore, it was concluded that the moisture content for fluidization of sewage sludge should be less than 30%.

The comparison of minimum fluidization between experimental measurements using a DPT cell and the results calculated by Wen and Yu, Richardson, and Chitester et al. [6] is shown in Table 2.

As a result, the calculated results using a real density of particles were 2-3 times higher than the experimental results, while those from bulk density of particles were almost the same. Moreover, the results measured by the relationship between the extrapolation of standard deviation and gas velocity could be adopted to determine minimum fluidization velocity.

Using Richardson's equation, which shows optimum results of minimum fluidization velocities, the plots in the flow regime diagram of d_p* versus U* by Grace (1986) coincided. Therefore, expansion of the regime to bubbling fluidization showed that the bubbling fluidization regime for sludge existed with gas velocities between 21.42 and 87.55 cm/s.

Because particle size, particle type, and gas velocity largely affected the characteristics of attrition, the dry sludge and char with particles of 20/40 and 40/60 mesh were weighed at the beginning of treat-

Table 2. The comparison of minimum fluidization velocity by calculation, experiment, and extrapolation methods with real and bulk density

Material	Mesh (μm)	Water (%)	Real density (g/cm³)	Bulk density (g/cm³)	$U_{mf.cal.}$(cm/sec)						$U_{mf.exp.}$ (cm/s)	$U_{mf.extra.}$ (cm/s)
					Wen and Yu		Richard-son		Chitester et al.			
					True	Bulk	True	Bulk	True	Bulk		
Dry sewage sludge	20/40 (637.5)	0	2.183	0.81	24.01	9.63	26.62	11.00	31.86	13.25	10.55	11.37
		10	2.423	0.90	26.32	10.64	29.08	12.12	34.78	14.59	12.65	13.38
		20	2.729	1.01	29.21	11.89	32.12	13.51	38.38	16.25	12.85	14.30
		30	3.119	1.16	32.78	13.47	35.86	15.25	42.81	18.33	-	-
	40/60 (337.5)	0	2.183	0.65	7.78	2.34	8.96	2.74	10.82	3.31	3.28	2.47
		10	2.423	0.72	8.57	2.60	9.91	3.04	11.97	3.68	3.62	3.82
		30	3.119	0.93	10.95	3.34	12.62	3.89	15.23	4.71	6.45	4.08
Char	20/40 (637.5)	-	2.878	0.64	30.58	7.71	33.57	8.84	40.09	10.66	10.34	9.08
	40/60 (337.5)		2.878	0.60	10.71	2.29	12.34	2.67	14.90	3.24	3.25	2.64

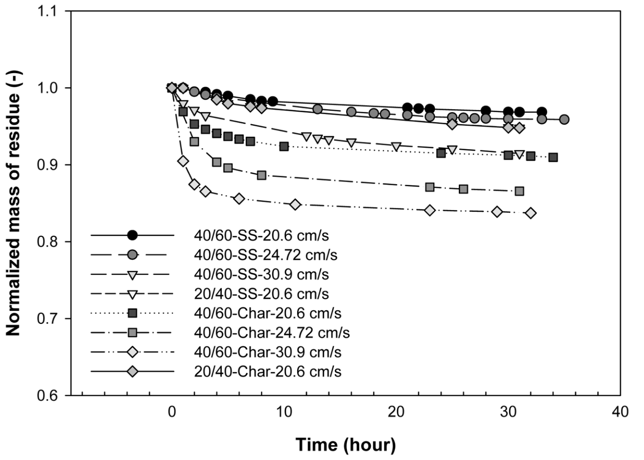

Fig. 3. Remaining weight over time for attrition of 40/60 and 20/40 mesh dry sewage sludge at 10, 12, 15 L/min gas flow rate.

ments; and the ASTM Method D 5757-95 as the AI test method, which characterizes the phenomena of attrition, was used with gas velocities of 20.6, 24.72, and 30.9 cm/s. The results are shown in Fig. 3. As a result, the regression lines of the resulting plots decreased exponentially; therefore, W_{min}, which possibly ignores attrition over time, was determined and the value was the weight after 100 hours of treatment.

The results of the experiment concerning attrition and particle sizes showed that the initial amount of attrition was greater for the larger particles than for the smaller particles, and that the total attrition was similar to the initial attrition. However, the effect of particle size on attrition was negligible when compared to the effects of gas velocity.

Fig. 4 shows the remaining weight of the sludge after attrition tests with different gas velocities. We found that the faster the gas velocity, the greater the initial attrition. As a result, Cook's 2nd order attrition equation (1996), which depends on particle size and gas velocity, fit the results.

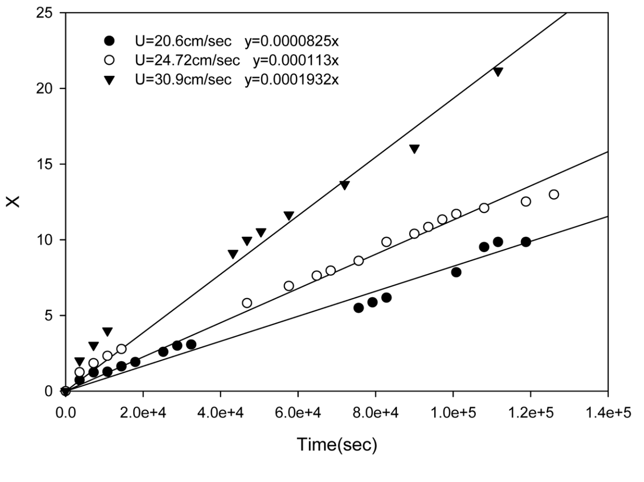

Fig. 4. Modified Cook's 2nd order model for dry sewage sludge $\left(\mathbf{X}=\frac{(\mathbf{U}-\mathbf{U}_{mf})^2}{2\mathbf{W}_{min}}\left[\ln\left(\frac{\mathbf{W}_0-\mathbf{W}_{min}}{\mathbf{W}_0+\mathbf{W}_{min}}\right)-\ln\left(\frac{\mathbf{W}-\mathbf{W}_{min}}{\mathbf{W}+\mathbf{W}_{min}}\right)\right]\right)$.

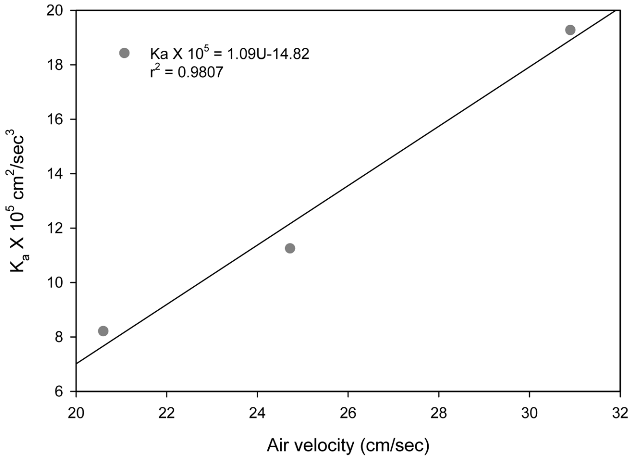

Fig. 5. K_a values of dry sewage sludge with gas velocity.

Cook's 2nd order attrition equation is

$$\frac{(U-U_{mf})^2}{2W_{min}}\left[\ln\left(\frac{W_0-W_{min}}{W_0+W_{min}}\right)-\ln\left(\frac{W-W_{min}}{W+W_{min}}\right)\right]=K_a t \quad (1)$$

The relationship between the overall attrition rate constant (K_a) values and air velocity calculated from the results of the plots is shown in Fig. 5. The values of K_a for sludge increased linearly as the superficial gas velocity increased. The equation for the overall attrition rate constants for dry sewage sludge with superficial gas velocity was determined to be $K_a \times 10^5 = 1.09U - 14.82$ and the relationship between the AI and K_a values was linear as shown in Fig. 6.

Where, Attrition Index (AI) was calculated as follows:

$$\text{AI}(\%) = \frac{\text{loading weight (50 g)} - \text{remaining weight after 5 hr}}{\text{loading weight (50 g)}} \times 100 \quad (2)$$

But, the char had a different profile of weight loss because attrition for char occurred rapidly at an early stage and was affected by gas velocity. So, the attrition rate constant for char was calculated by Lingwan Lin's 1st order equation (1980) and the results agreed well with the experimental data as shown in Fig. 7. The equation

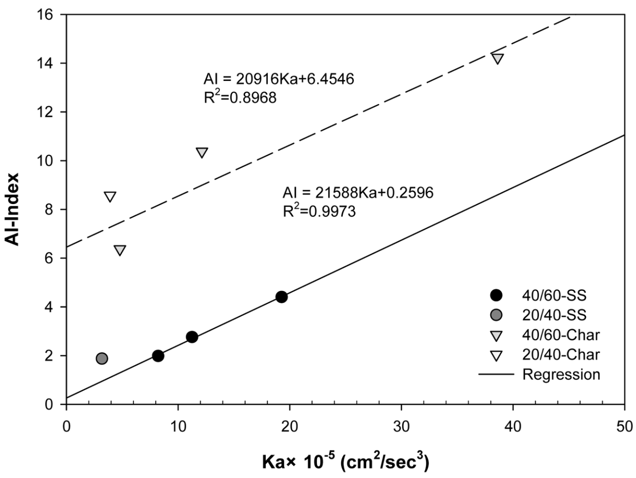

Fig. 6. The relationship of K_a with AI.

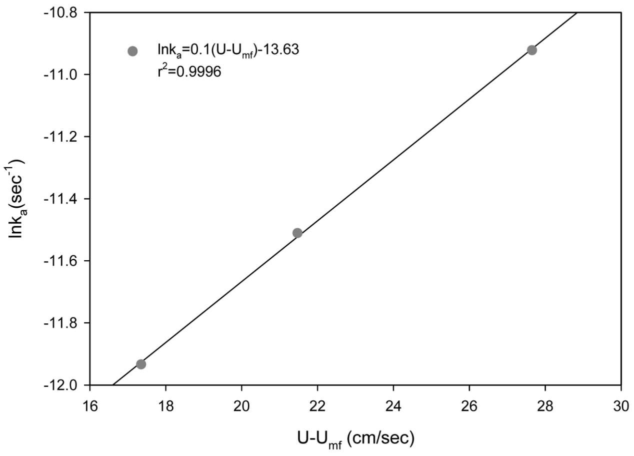

Fig. 7. First-order model for 40/60 mesh char.

of attrition rate constants for char with gas velocity was determined to be $\ln k_a=0.1(U-U_{mf})-13.63$.

When the overall attrition rate constant (K_a) was zero, the velocities for sludge and char with 40/60 mesh particles were 13.7 cm/s and 20.0 cm/s, respectively, which was 4-6 times larger than the minimum fluidization velocities for each particle. Therefore, the effects on attrition for bubbling fluidization could be ignored.

From the flow regime diagram by Grace, the expansion of the regime to bubbling fluidization showed that it was possible to use Chapman-Enskop theory explaining gas viscosity within velocities of 26.38 and 106.91 cm/s for a bubbling fluidization regime at 600 °C under nitrogen conditions.

CONCLUSIONS

In this study, the minimum fluidization velocities and attrition rate constants for sewage sludge and sludge based-char were determined by using the pressure drop and attrition tests and the results were as follows:

Gas velocity should be greater than 10.55 cm/s for fluidizing dried sewage sludge and char in the fluidized bed process. Sewage sludge and char used in this study were classified as Geldart B solids because the minimum fluidized velocities of the sludge and char were suitable for Richardson's experimental equation. Also, the attrition rate constant of the dried sludge was suitable for Cook's 2nd order attrition model. The equation for the overall attrition rate constant for dried sewage sludge with gas velocity was derived as $K_a\times10^5=1.09U-14.82$. Because char was influenced by attrition at an early stage, it was suitable for the 1st order attrition model. The equation for the attrition rate constant for char with gas velocity was derived as $\ln k_a=0.1(U-U_{mf})-13.63$.

ACKNOWLEDGMENT

This work was supported by the Brain Korea 21 Project in 2007.

NOMENCLATURE

AI : attrition index [-]
K_a : overall attrition rate constant [-]
k : attrition rate constant [s^{-1}]
t : time [s]
U : superficial gas velocity [cm/s]
U_{mf} : minimum fluidization velocity [cm/s]
W : weight of solids [g]
W_{min} : minimum weight of parent solids in a bed [g]
W_0 : initial weight of solids [g]
d_p : initial diameter of solids [μm]

REFERENCES

1. M. Takahashi, S. Kato, E. Sarai, T. Ichioka, S. Htayakawa and H. Miyajiri, *Chemosphere*, **44**, 23 (2001).
2. Y. S. Yun and G. B. Lee, *Energy Engg. J.*, **13**(1), 82 (2004).
3. F. Rozada, L. F. Calvo, A. I. Garcia, J. M. Villacorta and M. Otero, *Bioresource Technology*, **87**, 221 (2003).
4. J. E. Gwyn, *AIChE J.*, **15**(1), 35 (1969).
5. W. L. Forsythe and W. R. Hertwig, *Ind. Eng. Chem.*, **41**, 1200 (1949).
6. D. Kunii and O. Levenspiel, *Fluidization engineering*, Butter worth-Heinemann (1991).
7. B. Cagnon, X. Py, A. Guillot and F. Stoeckli, *Microporous and Mesoporous Materials*, **57**, 273 (2003).
8. Y. M. Chang, C. M. Chou, K. T. Su, C. Y. Hung and C. H. Wu, *Waste Management*, **25**, 249 (2005).
9. J. L. Cook, S. J. Khang, S. K. Lee and T. C. Keener, *Powder Technology*, **89**, 1 (1996).
10. D. Geldart and J. Baeyens, *Powder Technology*, **42**, 67 (1985).
11. M.-R. Kim, J.-G. Jang and J.-K. Lee, *Korean J. Chem. Eng.*, **22**, 61 (2005).
12. S.-S. Lee, J.-S. Yoo, G.-H. Moon, S.-W. Park, D.-W. Park and K.-J. Oh, *Am. Chem. Soc., Div. Fuel Chem.*, **48** (2003).
13. C. L. Lin and M. Y. Wey, *Korean J. Chem. Eng.*, **20**, 1123 (2003).
14. C. L. Lin and M. Y. Wey, *Korean J. Chem. Eng.*, **22**, 154 (2005).
15. L. Lin, J. T. Sears and C. Y. Wen, *Powder Technology*, **27**, 105 (1980).
16. Y.-S. Park, H.-S. Kim, D. Shun, K.-S. Song and S.-K. Kang, *Korean J. Chem. Eng.*, **17**, 284 (2000).