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Experimental study on municipal sludge dewatering capacity by using quicklime and slag

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ABSTRACT

Sludge dewatering was an important part of sludge treatment and disposal. Building a dewatering skeleton played a vital role in sludge dewatering. Experimental study on municipal sludge dewatering capacity was conducted by using quicklime and slag. Research indicated that sludge with 83% moisture content was conducive to establish the skeleton. Slag with large, small, or even particle diameters were disadvantageous to the skeleton formation, the effective combination range for the particle diameter was from 0.075 to 0.85 mm. When the sludge with 83% moisture content is added with 15% quicklime, it can reach the maximum dewatering rate and meet the health and epidemic-prevention safety index. The moisture content was lower than 60% with the following conditions: 83% moisture content of sludge, 15% quicklime, ≥80% slag, and 3,000–4,200 separation factors which satisfied various engineering applications such as landfills, ecological slope protection, and landscaping.

Keywords: Municipal sludge; Dewatering; Quicklime; Slag; Skeleton builder; Fractal dimension

1. Introduction

The rapid growth of industrialization and urbanization in the twenty-first century has resulted in production of unmanageable quantity of sludge from municipal and industrial wastewater treatment plants [1,2]. At present, 0.3 million tons of dry municipal sludge is annually generated in China and the average annual growth is about 10%. The major outlets for the sludge were agriculture and landfill [3]. The characteristics of municipal sludge, such as high hydrophilicity, high moisture content and organic matter content, and low permeability, lead to its poor use in engineering applications [4,5]. Therefore, sludge dewatering problems are critical in the treatment of municipal sludge. Extensive research has been conducted on the ultrasound method [6–8], thermal hydrolysis [9–12], electrochemistry [13–15], and other sludge-conditioning techniques [16,17]. The processing cost of these methods mainly involved energy and chemicals, was high, so it has been restricted in many fields for its further engineering applications.

In order to decrease the cost of dewatering and improve the dewatering capacity, physical conditioners are employed. The physical conditioners are often

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referred to as skeleton builders for the reason that, when added to sludge, they can form a permeable and a more rigid lattice structure. Such structures can remain porous under high pressure during mechanical dewatering. From the literature, fly ash, cement kiln dust, quicklime, hydrated lime, fine coal, bagasse, wood chips, and wheat dregs have been found to be effective skeleton builders for the sludge dewatering process [18–20]. They believed that, at high doses of the skeleton builders, the water permeated into the skeleton builders reducing the total amount of free water to be removed. Therefore, we should select a low water absorbing material as the skeleton builder. And, the sterilizing effect should also be considered for the sludge containing various germs that may cause secondary pollution to the environment.

Quicklime conditioning has important development significance and application prospects because of its easy availability, good economy, and sterilizing effect [16,21]. Quicklime can increase the pH of sludge to more than 12 and significantly decrease salmonella, strip ova, and other pathogens [22,23]. While, the sludge, even after quicklime treatment, cannot easily develop a high pressure-resistance dewatering channel due to its easy compressibility and strong absorption capacity. Therefore, quicklime combined with other physical conditioners should be considered to establish dewatering channel.

Slag with low water absorptive capability, meets the basic requirements of skeleton builder. And with the development of mineral resources in China, a great amount of slag needs to be disposed urgently. Sludge can be used to mine ecological restoration substrates, garden land use, or landfill after dewatering use slag as skeleton builder according to the sludge environmental characteristics.

Therefore, the experimental study on municipal sludge dewatering capacity by using quicklime and slag has important significance and application prospects.

2. Materials and methods

2.1. Test materials

Municipal sludge, with 83% moisture content, 1.14 kg/m^3 natural density, 6.96 pH, and 47.5% organic matter, was taken from a sewage plant in Wuhan City, Hubei Province, China. Quicklime powder, which had 85% calcium hydroxide, ≤1% humidity, ≤1% HCl dissolution, and ≤5% 200-mesh screen residue. Slag, with 1.58 g/cm^3 density, was taken from a chemical group co., Ltd. in Hubei Province, China. The particle size distribution of the slag was shown in Fig. 1.

2.2. Test methods

The quicklime power was added to a sludge sample first. The dose of quicklime was expressed as a percentage of the dry sludge. Doses in the range of 5–80% were examined. After quicklime addition, the sludge was subjected to 30 s of rapid mixing followed by 1 min of slow mixing to ensure dispersion.

Following quicklime addition, the slag (skeleton builders) was added. The dose of slag was expressed as a percentage of the dry sludge. The dosage of the slag ranged from 0 to 200%. Then the sludge was subjected to 30 s of rapid mixing followed by 1 min of slow mixing to ensure dispersion.

Fifty grams of samples were frozen and dried, and then used a microscope to observe the pore structure of the sludge. The test picture was obtained by using electron microscopes, whereas the area (A) and corresponding perimeter (P) were obtained by image analysis software to calculate the fractal dimension. Fractal dimension applies the A–P relation, which measures the area and corresponding perimeter continuously under different periods or states of the fractal structure to create the lnA–lnP curve. The A–P relation also uses the slope of the straight-line portion of the lnA–lnP curve to estimate the fractal dimension of the fractals. The fractal dimension was used to describe the associated literature [24–28].

Centrifugal dewatering was conducted by centrifugal machine LXJ-IIB (Shanghai Anting Scientific Instruments Plant) after sample was prepared at relative centrifugal force in the range of 3,000 × g–4,200 × g. The dewatering time was set at 20 min to guarantee

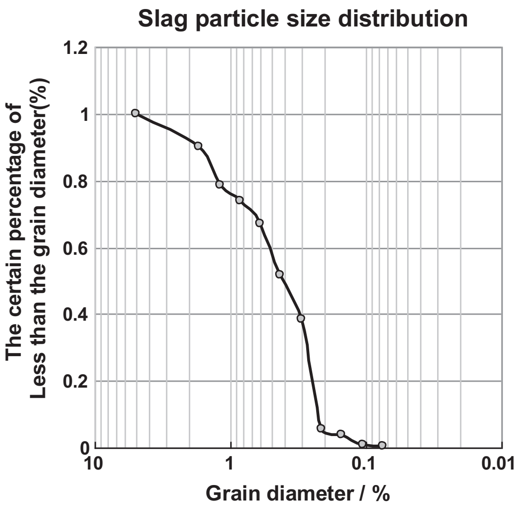


Fig. 1. Slag particle size distribution.

thorough dewatering under the established separation factor. The dewatering rate was expressed as dehydrated water divided by the original water.

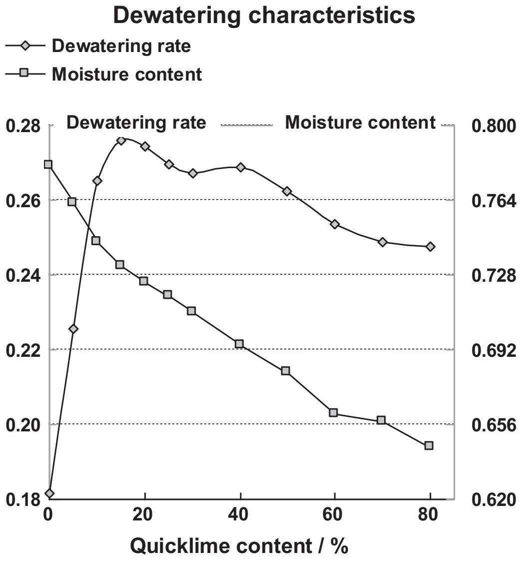
Three parallel samples were made for the same test group. Their average value was taken as the test result.

3. Results and discussion

3.1. Effect of quicklime on dewatering capacity and pH of sludge

The dewatering rate under different quicklime dosages was shown in Fig. 2. The dewatering rate achieved peak (0.278) at 15% quicklime content, increasing by 53.5% compared with that of original sludge (0.181). The results showed that if the quicklime content was too low, it was difficult to establish the skeleton effect, but if the quicklime content was too high, the strong water absorption capacity of quicklime would weaken the skeleton effect of quicklime. Thus, the dewatering rate of sludge was decreased directly.

The condition of high pH, especially >12, severely stressed micro-organisms [22]. The results of the pH tests were given in Table 1. As shown below, the sludge mixtures indicated the increase of pH with the increase of lime amount. The sludge mixture by 5% of lime showed high pH (more than 12) which meets the criteria.



Sludge moisture content : 83%

Relative centrifugal force : 3000×g

Fig. 2. The dewatering rate of different quicklime content.

Sludge treated for landfill or land utilization should meet the health and epidemic-prevention safety index. Based on the laboratory, the results of the health and epidemic-prevention safety index were provided in Table 2. The sludge mixture by 10% of quicklime meets the criteria.

To sum up, the optimal quicklime dosage was 15%. The optimal quicklime dosage not only satisfies sterilization but also provides an optimal dewatering effect. However, the pH value of quicklime-treated sludge can be affected by the content and purity of quicklime and the quality of the sludge. The optimal dosage of different batches of quicklime can be determined through testing.

When the treated sludge was used practically as the cover soil in landfill, the neutralization of organic acid produced from solid wastes can be expected as an additional effect. For the application of treated sludge to ecological restoration-base material, the high pH value of the treated sludge could be lowered with acidic material.

3.2. Effect of slag on dewatering capacity of sludge

The moisture content of sludge affected skeleton formation significantly shown in (Fig. 3). When the moisture content of sludge was 83%, the moisture content of the sludge sample after centrifugation reached the lowest level (76.8%). When the moisture content of sludge was lower than 89%, the skeleton effect by adding slag was beneficial. However, when moisture content was higher than 89%, the slag could not serve as the skeleton. Under high moisture content, the added skeleton builder sank to the bottom quickly because of the centrifugal force (Fig. 4), and did not interact with sludge particles for the development of a high pressure-resistance dewatering channel. The test results revealed that the moisture content of the sludge sample should be considered in order to increase the skeleton effect and dewatering efficiency.

The moisture content and dewatering rate of the sludge sample with 83% moisture content and different slag contents were shown in Fig. 5. The dewatering rate of sludge increased with the increase of the slag because the slag did not have strong water absorption ability as quicklime. When the slag content was larger than 120%, the moisture content of the sludge sample was lower than 60%, thus satisfying the required moisture content of landfill and land utilization. However, excessive slag increased the solid mass of the sludge and occupied landfill space; thus, it should be combined with other methods to reduce the dosage of the skeleton builder.

Table 1
pH with curing time

Sludge	Quicklime (% dry sludge)	0	3 d	7 d	15 d
83%	0	7.49	7.48	7.47	7.47
	5	12.26	12.03	12.02	12.01
	10	12.42	12.15	12.15	12.14
	15	12.43	12.47	12.48	12.46
	20	12.56	12.65	12.65	12.65

Table 2
Health and epidemic-prevention safety index (sludge moisture content: 83%)

Quicklime	Control items	Limiting value	5%	10%	15%	20%
1	Fecal coliform bacteria	>0.01	0.018	0.015	0.013	0.012
2	Total bacterial count	<108MPN/kg DS	120	90	80	66
3	Ova of roundworm mortality（%）	>95%	80	96	98	99

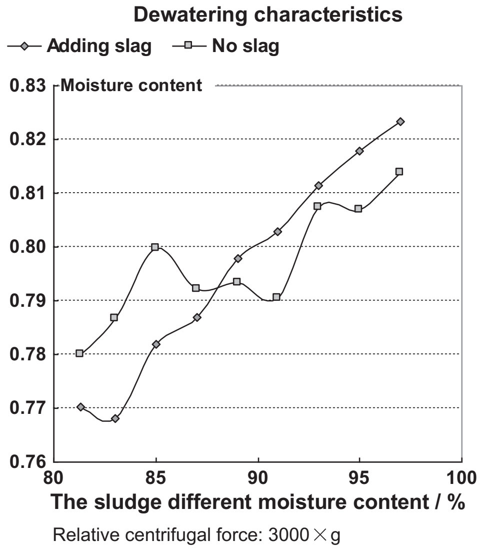


Fig. 3. The dewatering characteristics of different moisture content sludge in adding slag and without slag.

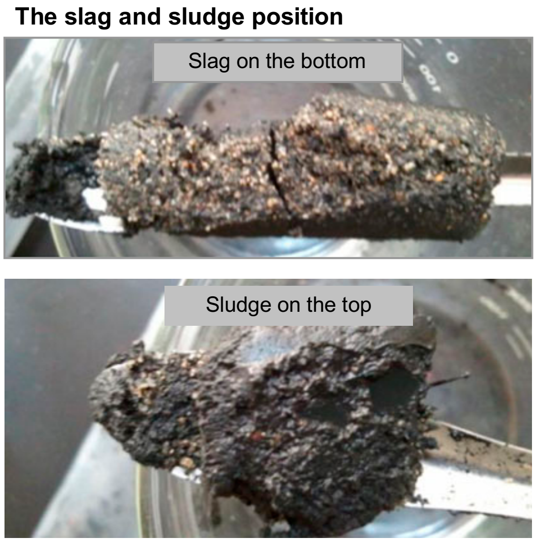
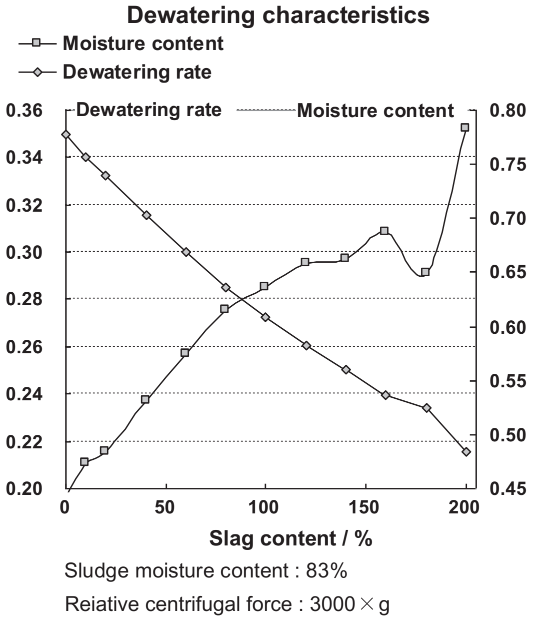


Fig. 4. The slag and sludge position of conditioning sludge directly add slag after centrifugal.

3.3. *Effect of slag grain diameter on dewatering capacity of sludge*

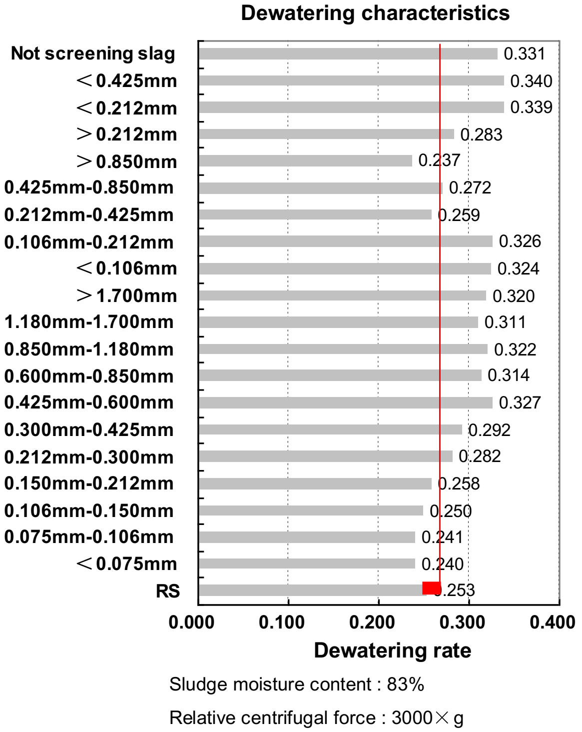
The slag was screened with standard screen. Slag of different particle diameters was used to test the skeleton formation (Fig. 6). The red line in Fig. 6 represented the dewatering rate of original sludge. Slag whose particle diameters were <0.075, 0.075 to 0.106 mm, 0.106 to 0.150 mm, and >0.850 mm achieved smaller dewatering rate than the original sludge. This result indicated that such slag were disadvantageous for the skeleton formation (Fig. 6). Slag with particle diameters less than 0.425 mm achieved the maximum dewatering rate (0.340), 9% higher than that of original sludge, and 1% higher than unscreened slag. The test demonstrated that slag with too large, small, or very even particle diameters hindered the skeleton formation. Therefore, when slag was selected as skeleton builder, the large particles of slag should be removed as much as possible, to increase skeleton



Sludge moisture content : 83%

Reiative centrifugal force : 3000 × g

Fig. 5. The moisture content and dewatering rate of different slag content.



Sludge moisture content : 83%

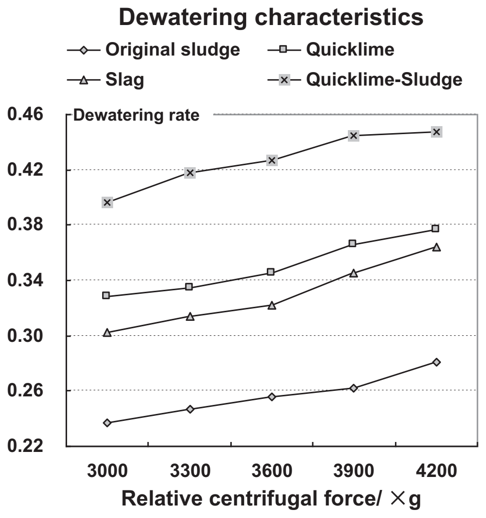
Relative centrifugal force : 3000× g

Fig. 6. The dewatering rate of different particle diameter ranges.

efficiency. If the slag particles were too small, it was easy to back dewaterting channel and cannot serve as skeleton. And as the slag particles were too big, it was difficult to establish a suitable dewatering channel for sludge.

3.4. Effect of relative centrifugal force and working condition on dewatering capacity of sludge

The dewatering rate of original sludge, quicklime, slag, and quicklime-slag (15% quicklime and 80% slag) under different relative centrifugal force was shown in Fig. 7. The results revealed that increasing the centrifugal force caused the dewatering rate of all working conditions to increase to some extent. Under the same relative centrifugal force, the dewatering rate ranked from high to low as follows: quicklime-slag, quicklime, slag, and original sludge. The dewatering rate of quicklime-slag achieved linear growth under relative centrifugal force of 3,000 × g–3,900 × g. However, the dewatering rate of quicklime-slag increased slowly under relative centrifugal force of 3,900 × g–4,200 × g. This finding indicated that a nonlinear relationship existed between dewatering rate and the increase of relative centrifugal force. Centrifugal force was too small and difficult to remove moisture, while too big, the sludge structure was easy to be damaged and blocked the dewatering channel. Under certain working conditions, selecting an appropriate relative centrifugal force was necessary to achieve an ideal dewatering effect and reduce energy costs in dewatering. Experimental results also showed the internal free water of sludge reduction



Sludge moisture content: 83%

Fig. 7. The dewatering rate of different relative centrifugal force.

after dewatering rate reached a certain value, so it was difficult to further improve the dewatering rate by physical method to establish skeleton, or increasing mechanical force. In order to achieve better dewatering rate, it also should be considered in combination with other means, such as heat treatment, ultrasonic treatment, microwave treatment, chemical treatment, and so on, to improve the sludge particles skeleton effect, which also means an increase in dewatering costs.

The moisture content of sludge could be lowered to less than 60% after adding 15% quicklime and 80% slag under relative centrifugal force of 3,000 × g (Fig. 8); these values satisfy the standard requirement. Therefore, slag dosage should be determined according to the practical purpose of treated sludge. Treated sludge for landfill purposes will lower the slag content and increase relative centrifugal force when the moisture content requirement to save landfill space was satisfied. Treated sludge for ecological restoration-base material or other non-landfill purposes will increase slag content and lower relative centrifugal force when the moisture content requirement to save energy cost was satisfied. The results also showed that sludge dewatering method of the slag skeleton effect combined with centrifuge could satisfy certain disposal requirements, such as landfill and ecological-base material. This method had the advantages of treat waste with waste and low cost, therefore, it had a good prospect of engineering application.

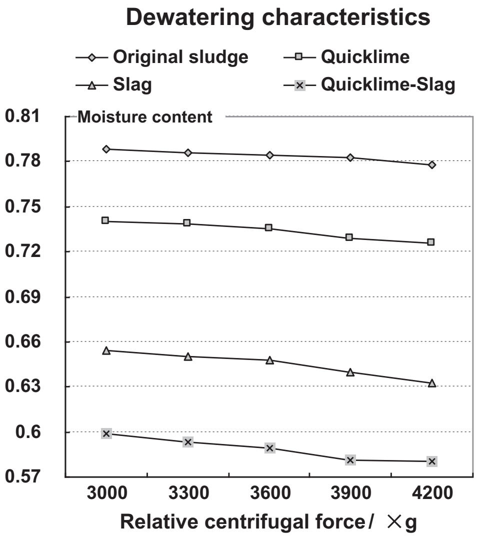
3.5. The fractal dimension representation of dewatering capacity of sludge

In this study, image analysis provided further evidence to demonstrate that quicklime associated with slag played a controlling role for forming the more compact structure.

As is known, fractal dimension is a quantitative measurement of floc structure and it describes how the particles organized with the floc interior. Bache and Hossain [25] found that the humic flocs could be characterized by fractal dimension. Wu et al. [16] reported the fractal dimension of original sludge to be 1.18. These generally suggest that original sludge could be characterized by low degree of floc compaction, (see Fig. 9). The fractal dimension of original sludge, quicklime, slag, and quicklime-slag was 0.84, 1.096, 1.194, and 1.389, respectively, in this study.

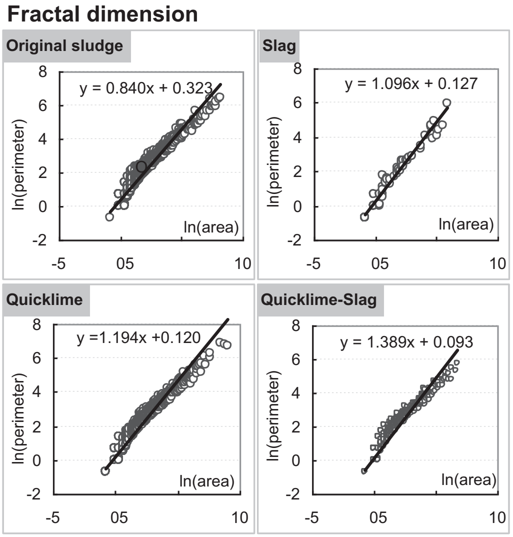
According to the result of image analysis in this study, it was reasonable to postulate that the improved structure formed by the interaction between quicklime and slag can remain porous under high pressure. The enhancement of the dewatering rate may mainly be attributed to the improvement of sludge compressibility and the change of the sludge structure.

The dewatering rate was in good agreement with the fractal dimension of original sludge, quicklime, slag, and quicklime-slag (Fig. 10), indicating that fractal dimension can accurately reflect the dewatering



Sludge moisture content: 83%

Fig. 8. The moisture content of different relative centrifugal force.



Sludge moisture content: 83%
Relative centrifugal force: 3000×g

Fig. 9. The fractal dimension of original sludge, quicklime, slag, and quicklime-slag.

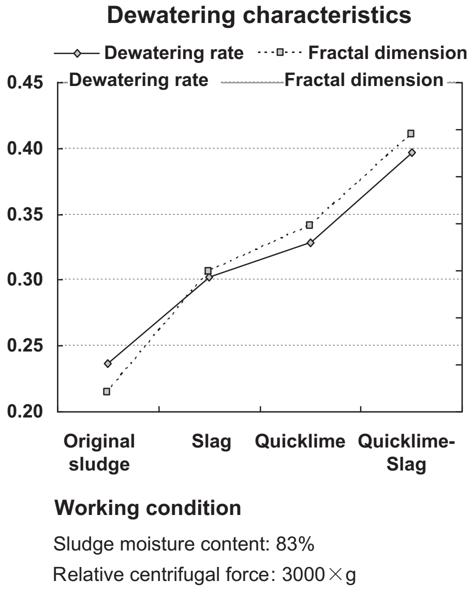


Fig. 10. The fractal dimension and dewatering rate of original sludge, quicklime, slag, and quicklime-slag.

rate. Thus, the dewatering rate of quicklime-slag (0.163) was larger than the sum (0.157) of that of quicklime (0.091) and slag (0.066). This result verified that the combined use of quicklime and slag could effectively increase the sludge dewatering rate.

4. Conclusions

In summary, the dewatering rate and fractal dimension revealed that the combined use of quicklime and slag played a critical role in sludge dewatering. When the sludge with 83% moisture content contains 15% quicklime, the dewatering rate of sludge can reach the maximum value and meet the health and epidemic-prevention safety index. Slag played the best role in skeleton when the sludge with 83% moisture content. Slag with too large, small, or very even particle diameters were disadvantageous for skeleton formation, the effective combination range for the particle diameter was from 0.075 to 0.85 mm. The moisture content was lower than 60% with the following conditions: 83% moisture content of sludge, 15% quicklime, ≥80% slag, and 3,000–4,200 separation factors which satisfied various engineering applications such as landfills, ecological slope protection, and landscaping.

Acknowledgments

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References

[1] X.S. Wang, H.Q. Lin, Adsorption of basic dyes by dried waste sludge: Kinetic, equilibrium and desorption studies, Desalin. Water Treat. 29 (2011) 10–19.
[2] S. Pilli, P. Bhunia, S. Yan, R.J. LeBlanc, R.D. Tyagi, R.Y. Surampalli, Ultrasonic pretreatment of sludge: A review, Ultrason. Sonochem. 18 (2011) 1–18.
[3] Y. Chen, Y. Chen, G. Gu, Influence of pretreating activated sludge with acid and surfactant prior to conventional conditioning on filtration dewatering, Chem. Eng. J. 99 (2004) 137–143.
[4] X. Wang, T. Chen, Y.H. Ge, Y.F. Jia, Studies on land application of sewage sludge and its limiting factors, J. Hazard. Mater. 160 (2008) 554–558.
[5] L.L. Wei, K. Wang, Q.L. Zhao, C.M. Xie, Characterization and transformation of dissolved organic matter in a full-scale wastewater treatment plant in Harbin, China, Desalin. Water Treat. 46 (2012) 295–303.
[6] A. Grönroos, H. Kyllönen, K. Korpijärvi, P. Pirkonen, T. Paavola, J. Jokela, J. Rintala, Ultrasound assisted method to increase soluble chemical oxygen demand (SCOD) of sewage sludge for digestion, Ultrason. Sonochem. 12 (2005) 115–120.
[7] X. Feng, J. Deng, H. Lei, T. Bai, Q. Fan, Z. Li, Dewaterability of waste activated sludge with ultrasound conditioning, Bioresour. Technol. 100 (2009) 1074–1081.
[8] M. Li, Y. Wang, C.P. Gong, Effect of on-line ultrasound on the properties of activated sludge mixed liquor and the controlling of membrane fouling in SMBR, Desalin. Water Treat. 51 (2013) 3938–3947.
[9] W.J. Catallo, J.L. Comeaux, Reductive hydrothermal treatment of sewage sludge, Waste Manage. 28 (2008) 2213–2219.
[10] F. Morgan-Sagastume, S. Pratt, A. Karlsson, D. Cirne, P. Lant, A. Werker, Production of volatile fatty acids by fermentation of waste activated sludge pre-treated in full-scale thermal hydrolysis plants, Bioresour. Technol. 102 (2011) 3089–3097.
[11] J. Abelleira, S.I. Pérez-Elvira, J. Sánchez-Oneto, J.R. Portela, E. Nebot, Advanced thermal hydrolysis of secondary sewage sludge: A novel process combining thermal hydrolysis and hydrogen peroxide addition, Resour. Conserv. Recy. 59 (2012) 52–57.
[12] P. Romero, M.D. Coello, J.M. Quiroga, C.A. Aragón, Overview of sewage sludge minimisation: Techniques based on cell lysis-cryptic growth, Desalin. Water Treat. 51 (2013) 5918–5933.
[13] S. Glendinning, J. Lamont-Black, C.J. Jones, Treatment of sewage sludge using electrokinetic geosynthetics, J. Hazard. Mater. 139 (2007) 491–499.
[14] K. Chen, H. Lei, Y. Li, H. Li, X. Zhang, C. Yao, Physical and chemical characteristics of waste activated sludge treated with electric field. Process Saf. Environ. 89 (2011) 327–333.

[15] H. Moreno, J.R. Parga, A.J. Gomes, M. Rodríguez, Electrocoagulation treatment of municipal wastewater in Torreon Mexico, Desalin. Water Treat. 51 (2013) 2710–2717.

[16] C.C. Wu, J.J. Wu, R.Y. Huang, Effect of floc strength on sludge dewatering by vacuum filtration, Colloids Surf. A 221 (2003) 141–147.

[17] K.T. Wai, A. Idris, M.M.N.M. Johari, T.A. Mohammad, A.H. Ghazali, S.A. Muyibi, Evaluation on different forms of *Moringa oleifera* seeds dosing on sewage sludge conditioning, Desalin. Water Treat. 10 (2009) 87–94.

[18] D. Kalderis, E. Tsolaki, C. Antoniou, E. Diamadopoulos, Characterization and treatment of wastewater produced during the hydro-metallurgical extraction of germanium from fly ash, Desalination 230 (2008) 162–174.

[19] Q. Chen, Z. Luo, C. Hills, G. Xue, M. Tyrer, Precipitation of heavy metals from wastewater using simulated flue gas: Sequent additions of fly ash, lime and carbon dioxide, Water Res. 43 (2009) 2605–2614.

[20] B. Nowak, A. Pessl, P. Aschenbrenner, P. Szentannai, H. Mattenberger, H. Rechberger, L. Hermann, F. Winter, Heavy metal removal from municipal solid waste fly ash by chlorination and thermal treatment, J. Hazard. Mater. 179 (2010) 323–331.

[21] K.J. Ptasinski, C. Hamelinck, P.J.A.M. Kerkhof, Exergy analysis of methanol from the sewage sludge process, Energy Convers. Manage. 43 (2002) 1445–1457.

[22] S. Lim, W. Jeon, J. Lee, K. Lee, N. Kim, Engineering properties of water/wastewater-treatment sludge modified by hydrated lime, fly ash and loess, Water Res. 36 (2002) 4177–4184.

[23] A. Pathak, M.G. Dastidar, T.R. Sreekrishnan, Bioleaching of heavy metals from sewage sludge: A review, J. Environ. Manage. 90 (2009) 2343–2353.

[24] Y.Q. Zhao, D.H. Bache, Conditioning of alum sludge with polymer and gypsum, Colloids Surf. A 194(1–3) (2001) 213–220.

[25] D.H. Bache, M.D. Hossain, Optimum coagulation conditions for coloured water in terms of floc properties, J. Water SRT Aqua. 40(3) (1991) 170–178.

[26] D.H. Bache, E. Rasool, A. Ail, J.F. McGilligan, Floc character: Measurement and role in optimum dosing, J. Water SRT Aqua. 44(2) (1995) 83–92.

[27] C.C. Wu, C. Huang, D.J. Lee, Effects of polymer dosage on alum sludge dewatering characteristics and physical properties, Colloids Surf. A 122(1–3) (1997) 89–96.

[28] Y.Q. Zhao, E.N. Papavasilopoulos, D.H. Bache, P.A. Mackinnon, Effects of polymer conditioning on alum sludge characteristics: A review, 2001 (Water Pollution VI: Modelling, Measuring and Prediction, ISBN: 1-85312-878-3, Proceedings of the Sixth International Conference on Modelling, Measuring and Prediction of Water Pollution, September 2001, Rhodes, Greece, pp. 167–176.