Reuse of wastewater sludge with marine clay as a new resource of construction aggregates

Water Science and Technology **Vol 50 No 9 pp 189–196** © IWA Publishing 2004

J.-H. Tay*, K.-Y. Show, D.-J. Lee*** and S.-Y. Hong******

* Professor and Head of Division, Division of Environmental and Water Resources Engineering, School of Civil and Environmental Engineering, Nanyang Technological University, Block N1 #1A-29, Nanyang Avenue, Singapore 639798, Republic of Singapore (E-mail: *cjhtay@ntu.edu.sg*)

** Associate Professor, Division of Environmental and Water Resources Engineering, School of Civil and Environmental Engineering, Nanyang Technological University, Block N1 #1A-29, Nanyang Avenue, Singapore 639798, Republic of Singapore (E-mail: *ckyshow@ntu.edu.sg*)

*** Professor, Department of Chemical Engineering, National Taiwan University, Taipei, Taiwan 10617 (E-mail: *djlee@ccms.ntu.edu.tw*)

**** Research Associate, Division of Environmental and Water Resources Engineering, School of Civil and Environmental Engineering, Nanyang Technological University, Block N1 #1A-29, Nanyang Avenue, Singapore 639798, Republic of Singapore (E-mail: *csyhong@ntu.edu.sg*)

Abstract The disposal of sludge from wastewater treatment presents highly complex problems to any municipality. Most of the sludge disposal methods have varying degrees of environmental impact. Hence, it is necessary to explore potential areas of reuse in order to alleviate sludge disposal problems and to conserve natural resources. Industrial sludge and marine clay are two forms of high-volume wastes. Using these wastes as a resource of raw materials to produce construction aggregates would enable large-scale sludge reuse. The aggregates were produced at various sludge-clay combinations containing 0, 20, 50, 80 and 100% clay contents, respectively. The pelletized aggregates displayed lower particle densities ranged between 1.48 and 2.25 g/cm^3, compared to the density of granite at 2.56 g/cm^3. Good 28-day concrete compressive strength of 38.5 N/mm^2 achieved by the 100% sludge aggregate was comparable to the value of 38.0 N/mm^2 achieved of the granite control specimens. The leachate contamination levels from the aggregates after 150 days were found acceptable when used in concrete, indicating insignificant environmental contamination. The heat flow study showed increases in heat flow at the temperatures of 480°C and between 660°C and 900°C, indicating a need for the extension of heating time around these temperatures.

Keywords Clay; construction aggregates and utilization; sintered; sludge

Introduction

Increase in waste generation and shortage of land in Singapore has resulted in the high cost of landfill disposal. In addition, waste disposal through landfilling also raises health and environmental issues. Reuse of waste alleviates the problems of disposal, while offering an alternative for depleting resources. The application reuse of waste as building and construction materials would be an effective option because it provides a great potential for massive waste utilization.

Many studies have been conducted with the use of waste materials in the production of construction materials. Tay (1987) reported the use of sludge ash as a partial replacement for cement in concrete. Lightweight aggregates produced from sludge ash by Bhatty and Reid (1989) displayed higher strength than that of commercial aggregates derived from expanded clay. Alleman and Berman (1984) and Tay (1985) reported the incorporation of wastewater sludge in the manufacture of clay bricks. Tay *et al*. (1991) demonstrated that the performance of crushed aggregate produced from a mixture of municipal wastewater sludge and clay satisfied the strength specified by BS 8110 for structural concrete.

A feasibility study on the use of the industrial sludge carried out by the authors (Tay *et al.*, 2000) has indicated good potential for converting the sludge into concrete aggregate. Following the study, the present work aimed to further examine the addition of clay material and the effects on heat flow and energy requirement in the firing process.

Materials and methods

The industrial sludge from the recycling of copper slag from the blast cleaning of ship vessels and marine clay excavated during tunneling and excavation works were dried in an oven at the temperature of 105°C. The dried materials were then crushed into sizes below 250 μm and mixed with the optimal water ratios that provide the highest dry density for each mix, which were 35, 39, 42, 42, and 41% for 0, 20, 50, 80 and 100% clay content, to form malleable pastes. The mixtures were then rolled into pellets and dried in an oven at a temperature of 105°C before being fired in a muffle furnace at the temperature of 1,135°C. Concrete was batched with copper slag grit as fine aggregates, ordinary Portland cement as the binder, and sintered aggregate or granite as coarse aggregates, at a ratio of 1 coarse aggregate: 2 fine aggregate: 1 cement by volume, with a water-cement ratio of 0.5 by mass.

Results and discussion

Chemical properties

The chemical and physical properties of the industrial sludge and marine clay are shown in Table 1. The industrial sludge consisted of mainly iron and silica, which were 28.46% and

Table 1 Properties of industrial sludge and marine clay

Chemical contents (% by mass)		Materials Industrial sludge	Marine clay
Fe		28.46	3.97
Si		12.62	26.03
K		4.60	5.14
Al		3.64	9.75
Ca		2.38	1.98
Cu		1.41	0.12
Zn		1.38	0.08
Mg		1.07	1.41
Ni		0.62	0.89
Na		0.40	1.28
Mn		0.11	0.04
Pb		0.08	0.03
Cr		0.06	0.03
Cd		0.01	N.D.
Hg		0.0002	0.0027
Cl		0.25	0.23
SO_3		0.06	2.28
Physical properties			
Liquid limit	%	40	74
Plastic limit	%	28	33
Plasticity index		12	41
Linear shrinkage	%	4	11
Specific gravity		2.68	2.34
Particle size	Range μm	3.0–313.0	0.32–65.6
	Mean μm	52	11
Moisture content	%	43.0	42.6
Loss-on-ignition	%	9.33	11.4
pH		7.71–7.78	7.59–7.67

N.D.: not detected

12.62%, respectively. The liquid and plastic limits of 40% and 28% moisture contents indicated good cohesion properties. The sludge had an average natural moisture content of 43.0% and an average loss-on-ignition of 9.33%, which indicated the presence of organic materials in significant amounts. The marine clay consisted of mainly silica and aluminum, which were 26.03% and 9.75%, respectively. The liquid and plastic limits of 74% and 33% moisture content of 42.6% and a higher loss-on-ignition of 11.4%, which indicated a higher content of organic matter.

Samples of the aggregates from various sludge-clay proportions and control granite are shown in Figure 1. The chemical contents of the aggregates are shown in Table 2. In sludge material, the iron and silica contents decreased slightly to 20.38% and 9.48%, respectively, after sintering. In marine clay, the silica and aluminum contents decreased slightly to 23.31% and 9.08%, respectively, after sintering. The levels of chemical contents in the sintered aggregates varied in proportion with the change in sludge and clay contents.

Chloride content of sludge-clay aggregates at 0.01% complies with the limit of 0.01% specified by British Standard Specification for Aggregates from Natural Sources for Concrete (BS 882). The sulfate contents of 0.17 to 1.22% by mass of aggregates were converted by calculation to be in the range of 0.22 to 0.99% by mass of cement, conforming to the permissible limit of 1% by mass of cement as specified in the British Standard Specification for Lightweight Aggregates for Masonry Units and Structural Concrete (BS 3797).

Physical properties

The properties of the aggregates of 0, 20, 50, 80 and 100% clay content are given in Table 3. The bulk density, which includes all voids and spaces in the volume, ranged from 1.36 to 0.90 g/cm^3. The sludge-clay aggregates of all proportions have lower bulk density compared to the value of 1.27 g/cm^3 for conventional granite aggregates. The particle density ranged from 1.48 to 2.25 g/cm^3 for the sludge-clay aggregates which were lower compared with 2.56 g/cm^3 for granite aggregate. The specific gravity of the aggregates ranged from

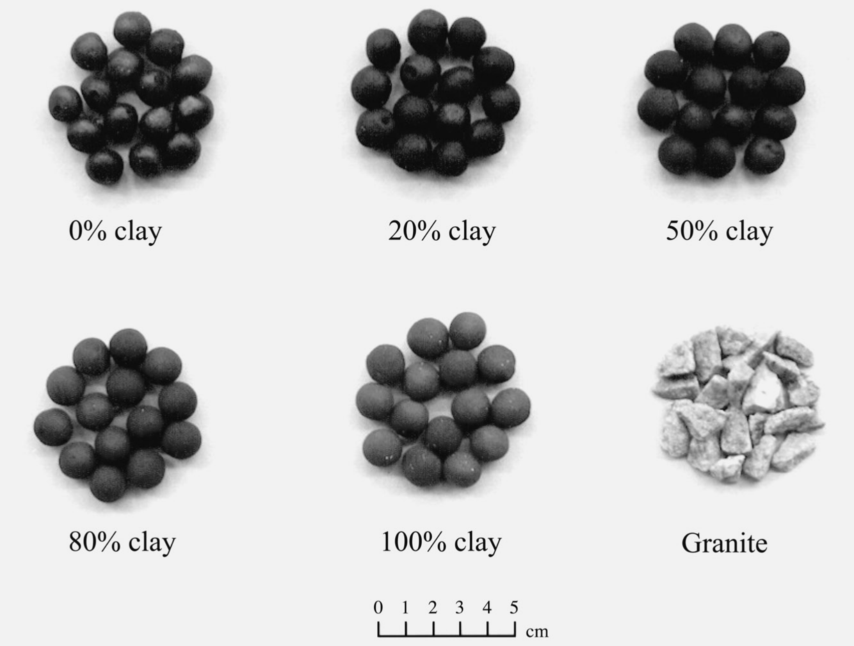

Figure 1 Samples of pelletised sludge-clay aggregates of various clay content and granite control

Table 2 Elemental compositions of sludge-clay aggregates

Chemical content (% by mass)	Clay contents of sludge-clay aggregates % 0	20	50	80	100
Fe	20.38	10.84	6.90	4.92	3.62
Si	9.46	14.95	16.90	20.04	23.31
K	1.89	1.25	1.41	1.55	3.76
Al	4.28	5.16	6.90	8.68	9.08
Ca	2.61	2.14	2.09	1.88	1.86
Cu	2.26	1.53	1.31	0.38	0.10
Zn	0.86	0.87	0.59	0.18	0.02
Mg	1.17	1.25	1.37	1.40	1.50
Ni	0.99	0.93	0.91	1.04	1.60
Na	0.99	0.94	0.89	0.71	0.70
Mn	0.10	0.07	0.04	0.01	0.03
Pb	0.06	0.06	0.04	0.02	0.01
Cr	0.02	0.02	0.02	0.01	0.01
Cd	N.D.	N.D.	N.D.	N.D.	N.D.
Hg	0.0006	0.0006	0.0004	0.0003	0.0002
Cl	0.01	0.01	0.01	0.01	0.01
SO_3	0.17	0.31	0.64	0.92	1.22

N.D.: not detected

3.25 to 2.46, which were moderate compared to 2.63 for granite. The porosity of the sludge-clay aggregates increased with the clay content from 30.77% to a maximum of 50.50% at 50% clay, where the particle density was at a minimum and decreased again to 28.05%. The water absorption of the sludge-clay aggregates was determined to be 0.36%, 2.06%, 2.80%, 2.49% and 1.81% for 0, 20, 50, 80 and 100% clay respectively, which were comparable to 1.58% for the granite aggregates. Concrete cast with high porosity aggregates normally exhibits better sound insulation and fire resistance properties (Tay and Yip, 1988). The aggregate impact value (AIV) is a measurement of susceptibility of the aggregates to crushing; hence a lower value denotes a better aggregate quality. The sludge clay aggregates displayed moderate strength of AIV between 19.9 to 30.4% under dry condition and 18.1 to 27.3% under wet condition, compared to the granite aggregate, which has the AIV of 28.3% when dry and 38.9% when wet. The results showed that the sludge-clay aggregates produced a lower AIV after soaking, indicating an improvement in impact resistance. The improvement in strength could be due to the pore water pressure effect brought about by the highly porous nature of the sludge clay aggregates.

Performance in concrete

Performance of the aggregates was evaluated by determining the compressive strengths of the concrete specimens cast from the aggregates. Results of the compressive strengths over a curing period of 28 days are shown in Table 4. The 28th day compressive strengths of the

Table 3 Properties of sludge-clay aggregates and granite as control aggregate

Properties		Clay contents of sludge-clay aggregates %					Granite
		0	20	50	80	100	
Bulk density	g/cm^3	1.36	1.20	0.90	0.90	0.96	1.27
Particle density	g/cm^3	2.25	1.84	1.48	1.65	1.77	2.56
Specific gravity		3.25	3.08	2.99	2.69	2.46	2.63
Porosity	%	30.77	40.26	50.50	38.66	28.05	2.66
Water absorption	%	0.36	2.06	2.80	2.49	1.81	1.58
Aggregate impact value							
Dry	%	19.9	20.9	26.3	29.1	30.4	28.3
Wet	%	18.1	18.3	23.7	26.3	27.3	38.9

concrete specimens with coarse sludge-clay aggregates were determined to be in the range of 31.0 to 38.5 N/mm^2. Concrete specimens cast with 100% sludge aggregates displayed the highest compressive strength of 38.5 N/mm^2, which is marginally stronger than the concrete cast from normal granite aggregate. The densities of concrete specimens made from the sludge-clay aggregates of 0, 20, 50, 80 and 100% clay are 2,520, 2,510, 2,450, 2,520 and 2,530 kg/m^3 respectively, which are lower compared with that of 2,680 kg/m^3 for normal granite aggregates. This exhibits a further improvement in strength to mass ratio of the concrete cast with the sludge-clay aggregates.

Leaching study

The concentrations of the toxic chemicals released from broken concrete cast from the sludge-clay aggregates were examined using the column-leaching test, which closely simulates the field leaching conditions. The concentration level of cadmium was not analyzed because the element was not detected in the sintered materials. The leaching trends of the health-based contaminants over a test period of 150 days and the peak concentration levels detected in the leaching test are shown in Table 5 along with the limits given in the Guidelines for Drinking-Water Quality specified by World Health Organization (1993). The results showed that the concentrations of the toxic elements leached from the aggregates were within acceptable levels, which suggests that the sludge-clay materials could possibly be used as concrete aggregates without detrimental effects to the environment.

Energy assessment

Sludge has long been targeted as a major renewable resource for construction purposes. However, due to the large energy demand, it is important to examine heat flow into the materials, to assist the development in the use of this technology. Data obtained from differential scanning calorimetry will be used to determine energy requirement and to make a reasonable estimate of the energy demand.

Table 4 Concrete compressive strength

Aggregate	Concrete density kg/m^3	Compressive strength N/mm^2 day 3	7	14	28
Clay content %					
0	2,530	22.0	28.5	32.5	38.5
20	2,520	21.0	27.5	30.5	35.5
50	2,510	20.0	24.5	28.0	31.0
80	2,450	21.0	26.5	29.0	31.0
100	2,520	21.0	25.5	29.0	32.5
Granite	2,680	22.0	30.0	33.5	38.0

Table 5 Peak levels of health-based contaminants in aggregate leaching test

Concentrations mg/L	WHO limits	Blank Distilled Water	Sludge-clay aggregates Clay content % 0	20	50	80	100
Cr	0.05	0.01	0.04	0.03	0.03	0.03	0.02
Cu	2.00	0.01	0.02	0.02	0.02	0.03	0.03
Hg	0.0010	0.0008	0.0009	0.0008	0.0006	0.0002	0.0004
Mn	0.50	0.01	0.07	N.D.	N.D.	N.D.	N.D.
Ni	0.02	0.11	0.23	0.41	0.33	0.57	0.28
Pb	0.01	0.04	0.04	0.13	0.15	0.13	0.16

N.D.: not detected

Differential scanning calorimetry (DSC) was used to characterize the endothermic reactions occurring in the respective raw materials and the mixtures of the materials. From Figure 2, it can be observed that the samples absorbed relatively small amount of energy as the temperature was raised to 400°C, after which it entered into an endothermic state. The increase in heat flow indicated an increase in the endothermic reactions. This reaction occurred most significantly over the temperature of 660–900°C. Industrial sludge entered an endothermic state slightly later than the marine clay, at the temperature of about 480°C and displaying similar peak between the temperatures of 660 and 900°C. The DSC results suggested that long holding time at the temperature of 550°C used in our previous study may not be necessary as there was no significant absorption of heat around the temperature of 550°C, and that peak absorption of heat occurred at approximately between 660 and 900°C. Mixes of the two materials at various proportions appeared to have an intensified effect on the two endothermic peaks. The mix containing 20% sludge has the highest heat flow peaks followed by the mixes containing 80% and 50% sludge, respectively.

During the peak endothermic transitions, the heat demand for pre-sintering has to be met prior to the rise in temperature. Hence, the previously discussed DSC data (Figure 2) enables us to calculate the energy uptake of the samples, which indicates the intrinsic energy requirement of the aggregates. The energy required for raising the temperature of each mix to reach specific temperatures in the pre-sintering treatment up to the temperature of 900°C and 1,400°C are shown in Table 6. The range of intrinsic energy demands of the

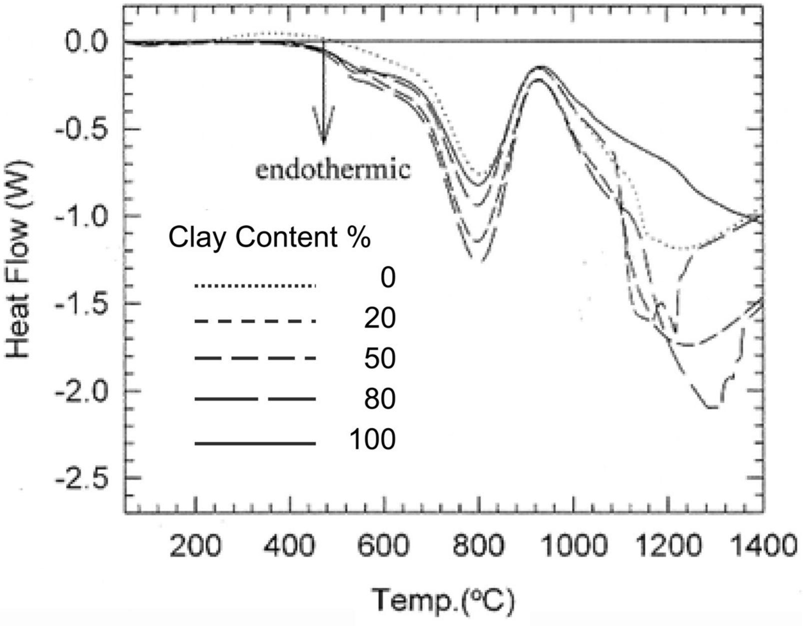

Figure 2 Differential scanning calorimetry (DSC)

Table 6 Energy uptake of materials in the firing process

Sludge content %	Energy absorbed by aggregates kJ/g Up to 900°C	Energy absorbed by aggregates kJ/g Up to 1,400°C	Ratio
0	25.43	70.71	1/3
20	38.25	128.89	2/7
50	27.41	94.56	2/7
80	32.62	117.81	2/7
100	20.35	80.25	1/4

aggregates up to the temperature of 900°C were determined to be 20 to 38 kJ/g, with the 100% sludge material to be the lowest and 80% clay to be the highest. The energy demands of the aggregates up to the temperature of 1,400°C were determined to be 70.71 and 128.89 kJ/g.

Conclusion

The study demonstrated promising application of industrial sludge and marine clay sintered into hard fused masses as complete replacement of regular coarse granite aggregates in concrete. Concrete made with the sludge-clay aggregates had a lower density and hence a higher strength to mass ratio as compared with that produced from conventional granite aggregates. The incorporation of marine clay reduced the particle density of the aggregates; however, the impact resistance of the aggregates was concurrently reduced. The particle densities of the sludge-clay aggregates were in the range of 1.48 to 2.25 g/cm^3, which is relatively lower compared to 2.56 g/cm^3 for the control granite aggregate. The sludge-clay aggregates of up to 50% clay content displayed better aggregate impact resistance of 18.1 to 26.3% AIV compared with 28.3 to 38.9% AIV for the control granite aggregate. However, the increase in clay content beyond 50% reduced the aggregate resistance. The 100% sludge aggregates showed a marginal improvement in concrete integrity, over the control aggregates, providing a maximum concrete compressive strength of 38.5 N/mm^2. The sludge-clay aggregates with up to 20% clay content are suitable for structural applications while the aggregates with up to 50% clay content could be used for other general applications where strength is not a critical requirement. The leaching test results showed that the peak levels of all health-based contaminants were within the respective safety limits specified in the WHO guidelines for drinking water. The compliance to WHO safety limits indicates that the use of these sludge-clay aggregates should not have significant impact on human health or the environment.

Obtaining the intrinsic energy demand of the aggregates allows an accurate assessment of the energy requirement. High energy demands, as our research shows, can be attributed to the constituents of the materials, as well as the efficiency of the heating system. The process could be effectively optimized by selecting a mix proportion that requires the lowest energy and firing temperature to achieve the desired properties.

References

Alleman, J.E. and Berman, N.A. (1984). Constructive sludge management: biobrick. *Journal of Environmental Engineering, ASCE*, **110**(2), 301–311.

Bhatty, J.I. and Reid, K.J. (1989). Moderate strength concrete from lightweight sludge ash aggregates. *International Journal of Cement Composites and Lightweight Concrete*, **11**, 179–187.

British Standards Institution (1992). *Specification for aggregates from natural sources for concrete*. BS 882: 1992, London, UK.

British Standards Institution (1985). *British standard structural use of concrete*. BS 8110: 1985, London, UK.

British Standards Institution (1990). *Specification for lightweight aggregates for masonry units and structural concrete*. BS 3797: 1990, London, UK.

British Standards Institution (1995). *Testing aggregates: Methods for determination of physical properties*. BS 812: Part 2: 1995, London, UK.

British Standards Institution (1990). *Testing aggregates: Methods for determination of aggregate impact value (AIV)*. BS 812 Part 112: 1990, London, UK.

British Standards Institution (1983). *Testing concrete: Method of normal curing of test specimens (20°C method)*. BS1881: Part 111: 1983, London, UK.

Guidelines for Drinking-Water Quality (1993). 2nd edn, World Health Organisation. Geneva, Switzerland.

Tay, J.H. (1985). Sludge as brick making material. *Proceedings, On New Directions and Research in Waste Treatment and Residual Management, Vancouver, Canada*, **2**, 611–668.

Tay, J.H. (1987). Sludge ash as filler for Portland cement concrete. *Journal of Environmental Engineering, ASCE*, **113**(2), 345–351.

Tay, J.H. and Yip, W.K. (1988). Lightweight concrete made with sludge ash. *Structural Engineering Review*, **1**, 49–54.

Tay, J.H., Yip, W.K. and Show, K.Y. (1991). Clay-blended sludge as lightweight aggregate concrete material. *Journal of Environmental Engineering, ASCE*, **117**(6), 834–844.

Tay, J.H., Hong, S.Y. and Show, K.Y. (2000). Reuse of industrial sludge as pelletized aggregate for concrete. *Journal of Environmental Engineering, ASCE*, **126**(3), 279–287.