Reuse of Industrial Sludge as Pelletized Aggregate for Concrete

By Joo-Hwa Tay,[1] Sze-Yunn Hong,[2] and Kuan-Yeow Show[3]

Abstract: Industrial sludge is generated at a rate of 100 metric tons/day, from a copper slag recycling plant. The industrial sludge is currently being landfilled. However, limited availbility of landfill sites has raised the need of an alternative disposal. A renewed interest in converting the industrial sludge into construction materials has been prompted to achieve a viable disposal option in saving the depleting natural resources of raw materials as well as the environment. This study describes the use of sintered sludge pellets as a complete replacement for regular granite aggregates in concrete. The pelletized sludge was fired to a temperature of 1,135°C at which the sintering process occurs, producing a hard fused basalt-like mass. In comparison with normal granite aggregates, the sintered sludge pellets display a higher aggregate strength, a higher porosity, and a lower aggregate density that manifests attributes better than that required of construction aggregates. The concrete cast with the pelletized aggregtes achieved a compressive strength of 38.5 N/mm^2 after 28 days and was comparable to the control specimen. Leaching tests conducted on the sludge pellets and concrete showed that all leachate contamination levels determined using the column leaching test are within acceptable ranges after 130 days of stabilization. The experimental results indicated that a complete replacement of conventional aggregates with sintered sludge pellets for structural concrete is both technically and environmentally feasible.

INTRODUCTION

In the past few decades, the rapid process of industrialization and urbanization has increased the generation of waste materials at tremendous rates, and landfills are filling up faster than the exploration of new sites. This situation has raised alarming concerns over many municipalities, particularly in densely populated areas such as Singapore, an island-city-state. The sludge generated from wastewater treatment has posed a problem, as waste disposal becomes extremely costly due to the scarcity of land and the growing concern on the environment.

The situation has raised interest in the application of sludge to produce building and construction materials. Converting the sludge into useful products would alleviate the problems of waste disposal while providing a new reserve for the depleting resources of construction materials. The industrial sludge samples used in this study were obtained from a copper slag recycling plant, which recycles copper slag that has been used as an abrasive agent for blast cleaning of ships. The plant generates sludge at a rate of 100 metric tons/day from the recycling process. The sludge is currently disposed of at a cost of U.S.$30/ton.

Many studies have been carried out on the use of industrial and municipal sludge for innovative construction materials. Alleman and Berman (1984) and Tay (1985) used sludge in combination with clay to produce building bricks of normal strength, and Tay (1987) also reported that sludge could also be used as a cement filler.

Because the production of aggregates for concrete from wastes is being recognized as a great potential for the utilization of large quantities of waste materials, this possibility has received increasing attention in recent years. Buttermore et al. (1972) suggested preparing pellets from municipal incinerator fly ash of a larger size and crushing them to a size range conforming to ASTM C 300 Specification for Lightweight Aggregates for Structural Concrete after firing. Using the same type of waste, Wainwright and Boni (1981, 1983) prepared smaller-sized pellets for direct use in concrete mixes after firing.

Tay and Yip (1988, 1989, 1990) and Tay et al. (1991) produced coarse and fine lightweight aggregates from wastewater sludge. The dewatered sludge was fired within a temperature ranging from 1,050 to 1,200°C and crushed to smaller-sized aggregate for use in concrete. The aggregates exhibited high thermal insulation and fire resistance, with the 28-day compressive strength comparable to commercial lightweight aggregates. Mayfield and Louati (1990) investigated the properties of pelletized blast-furnace slag concrete and reported that as aggregate-cement bond strength and compressive strength increased with age, the bond strength was generally proportional to the compressive strength.

Utilization of sludge ash as raw materials in the production of pellet aggregates was also reported by Bhatty et al. (1992), who observed a lower aggregate specific gravity and hence a better strength-to-weight ratio with no adverse effects on concrete strength. In addition, the pellets being round in shape enhanced the workability of concrete and resulted in dense concrete specimens. Bhatty et al. (1992) found that sintering sludge ash pellets at elevated temperatures of 1,050°C developed inert aggregates of reasonable strength that can be safely used as a substitute for regular coarse aggregates in concrete when the latter are in short supply.

In view of the anticipated disposal problem of sludge and associated environmental concerns, recycling of sludge into useful materials is gaining due consideration as an alternative disposal option. The purpose of this study is to investigate the conversion of the industrial sludge generated by the copper slag recycling plant into pellet aggregates for complete replacement of conventional granite aggregate in concrete. The sludge was pelletized and sintered at high temperatures to produce concrete aggregates of high crushing strength.

The pellets were characterized and tested as a substitute for coarse aggregate in concete under standard laboratory conditions. A leaching test was also conducted on the aggregates as well as on the concrete to assess environmental contamination of the products.

[1]Head and Prof., Div. of Envir. and Water Resour. Engrg., School of Civ. and Struct. Engrg., Block N1 #1A-29, Nanyang Technol. Univ., Nanyang Ave., Singapore 639798.

[2]Proj. Offcr., Div. of Envir. and Water Resour. Engrg., School of Civ. and Struct. Engrg., Block N1 #1A-29, Nanyang Technol. Univ., Nanyang Ave., Singapore 639798.

[3]Asst. Prof., Div. of Envir. and Water Resour. Engrg., School of Civ. and Struct. Engrg., Block N1 #1A-29, Nanyang Technol. Univ., Nanyang Ave., Singapore 639798.

Note. Associate Editor: Lewis A. Rossman. Discussion open until August 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 17, 1999. This paper is part of the ***Journal of Environmental Engineering***, Vol. 126, No. 3, March, 2000. ©ASCE, ISSN 0733-9372/00/0003-0279–0287/$8.00 + $.50 per page. Paper No. 20945.

J. Environ. Eng., 2000, 126(3): 279-287

EXPERIMENTAL DETAILS

Sludge

The industrial sludge samples were collected at the copper slag recycling plant from the wastewater-treatment unit. The wastewater from the copper slag recycling process is treated with polymer flocculant in the thickener, and the effluent is collected for reuse in the system. The sludge, which requires proper handling and disposal, was examined in this study for reuse as construction aggregates.

Pelletization

The sludge was dried in an oven at 105°C to remove moisture to achieve consistency in the water ratio for pelletizing. According to Bhatty et al. (1992), material of particle size not exceeding 100 μm with a mean particle size of approximately 30 μm requires no additional binder for pelletizing to achieve a reasonable dry strength after pelletizing. The predried sludge was crushed and grounded to particle sizes finer than 70 μm using a mechanical pulverizer.

The Atterberg limits of the sludge were determined in order to estimate a suitable proportion of water for preparing the sludge pellets. The relationship of the water ratio to the density of dried pellets was examined by preparing sludge pellets at five different water ratios within the plastic and liquid limits of the sludge. The water contents below the plastic limit and above the liquid limit were not examined because at a water content below the plastic limit the material can crumble easily and at a water content above the liquid limit the paste being in a liquid state is unable to retain its shape. At low values of water content, most materials tend to be stiff and are difficult to compact. As the water content is increased the soil becomes more workable, facilitating compaction during pelletizing, thus resulting in higher dry densities. The value of the water content at which the maximum value of dry density is achieved is known as the optimum water content. At water contents higher than optimal, however, the dry density decreases with increasing water content, as an increasing proportion of the soil volume is occupied by water.

Following the determination of the optimum water ratio, a water ratio of 40% by mass was used throughout the study in pelletizing. The sludge was observed to undergo a linear shrinkage of 5% upon drying and an overall shrinkage of 21% after firing. Therefore, the sludge was rolled manually into pellets approximately 13 mm in diameter so that after firing the aggregates would fall within the size range of 10–14 mm for the convenience of experimental requirements.

Firing

The green sludge pellets were predried overnight in an oven at a temperature of 105°C before being sent to the furnace for firing. The temperature profile of the firing process is shown in Fig. 1. The firing temperature was held at 550°C for 1 h to ensure thorough removal of organic matters and at 900°C for another hour to reach complete oxidation thus preventing black coring (Okuno et al. 1997). The pellets were then sintered at 1,135°C for 4 h. The rate of cooling was delayed to promote recrystallization in order to produce stronger aggregates. Each batch of approximately 2.5 kg of green pellets was spread on ceramic plates for firing.

Batching of Concrete

The concrete mixes had sintered sludge pellets as coarse aggregates in test cubes and regular gravel aggregates for the control cubes. The recycled copper slag of sizes 0.2–2 mm, which is currently being used in the production of pavement blocks at an industrial plant, was used as fine aggregates in both test and control cubes. Ordinary portland cement was used in all mixes. The mixes were batched according to the proportions used in the production of the pavement blocks as given in Table 1. The water-to-cement ratio in the mixes was kept at 0.47 based on the best mix. The pellets were substituted by volume in all mixes due to the difference in particle density to ensure an equivalent volume replacement. The concrete cubes were cured in the laboratory under wet conditions and tested for compressive strength at 3, 7, 14 and 28 days of age. The average value of three specimens was taken in each test for the compressive strength.

TABLE 1. Mix Proportion for 1 m^3 of Concrete

		Coarse Aggregates		Copper Slage Fine Aggregates	
Cubes (kg) (1)	Cement (2)	Sludge pellets (3)	Granite aggregates (4)	0.15–0.6 mm (5)	0.7–1.7 mm (6)
Specimen	400	545	0	775	825
Control	400	0	620	775	825

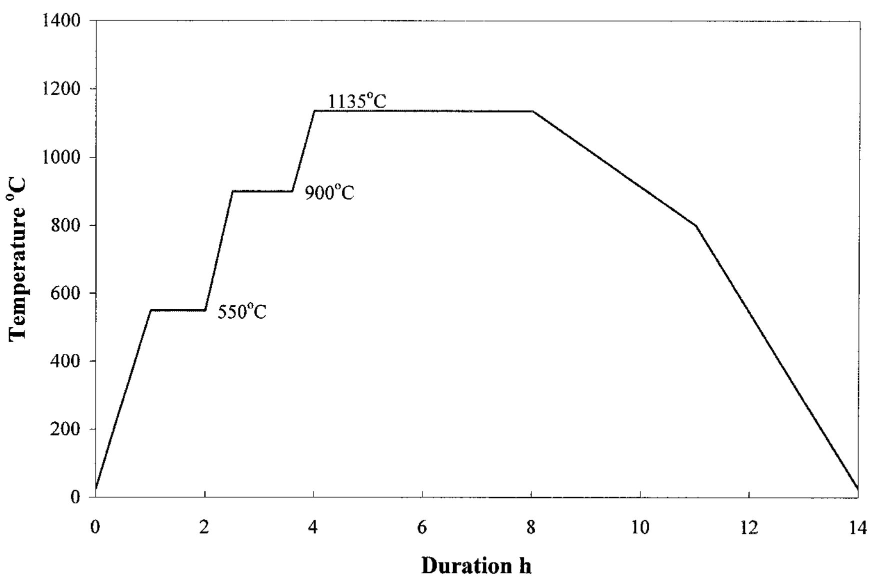

FIG. 1. Temperature Profile of Firing Process

J. Environ. Eng., 2000, 126(3): 279-287

Tests for Material Properties

The sludge was tested for moisture content, loss on ignition, pH, specific gravity, and chemical composition. The evaluation tests for the pellet aggregates consisted of measuring the drying shrinkage, absorption, density, aggregate strength, and concrete compressive strength. The concrete compressive strength test was conducted in accordance with BS 1881: Part 116. The methods and equipment used in the analysis and testing can be found in Table 2.

Leachate Test

The presence of heavy metals causes the process of leaching to become a major concern in the usage of the sludge products. Therefore, the leachate test has to be conducted to ensure that the sludge products will not cause pollution to the environment. Currently, there are no standard guidelines in relation to leaching testing in Singapore. The experiment was set up according to the column leaching test as described by Francis and White (1987). The proposed test procedure was adopted to simulate landfill conditions as close as possible. The simulated infiltration dynamic leaching tests were carried out on the sludge pellet as well as on the resulting concrete cast with the sludge pellets. One advantage of this setup is that it enables relatively larger samples to be tested in comparison with other waste extraction tests. Four columns, each containing blank, pellets, control cube, and specimen cube, were leached under simulated conditions using distilled water as the leaching medium. All samples were placed between two layers of fine sand (layers approximately 100 mm above and 50 mm below the sample) in perspex columns with a diameter of 150 mm and a height of 500 mm as shown in Fig. 2. Each column contained 2.5 kg of sample, which measures approximately 100 mm in height, except the blank column with only the sand layers.

Distilled water was passed through the columns in a down flow motion and pumped from the outlets by a peristaltic pump. The flow rate was fixed at 1.44×10^{-3} m^3/d to generate at least 20 times by mass as much leachate as the sample tested (as specified in the U.S. EPA extraction procedure test) while maintaining a steady flow over a duration of 150 days. In the first month of flow, leachate from the test columns was collected twice weekly and, thereafter, collected once a week for a total of 26 samples. pH and electrical conductivity of the leachates were determined before the samples were preserved. The samples were then preserved by adding ultrapure concentrated nitric acid to a pH value lower than 2. The preserved samples were then analyzed for various inorganic chemical concentrations using the Inductively Coupled Plasma atomic emission spectrometry (Perkin-Elmer USA ICP-AES 400).

TABLE 2. Test Methods Used

Material (1)	Test method/equipment or instrument used (2)
(*a*) Sludge	
Moisture Content	BS 1377: Part 2
Loss on Ignition	BS EN 196-2
pH Value	BS 7755: 3.2 pH Meter
Particle Size	Malvern laser particle distribution analyzer
Particle Density	Ultrapycnometer 1000
Atterberg	
Liquid Limit	Cone penetrometer (BS 1377)
Plastic Limit	BS 1377: Part 2
Plasticity Index	BS 1377: Part 2
Linear Shrinkage	BS 1377: Part 2
Chemical Composition	
0.01% accuracy	Atomic Emission Spectrometer
0.0001% accuracy	Graphite Furnace
(*b*) Aggregates	
Specific gravity	Ultrapycnometer 1000
Particle density	BS 812: Part 2
Bulk density	BS 812: Part 2
pH	BS 7755: 3.2 pH Meter
Water absorption	BS 812: Part 2
Moisture Content	BS 812: Part 109
Aggregate Impact Value	BS 812: Part 112
(*c*) Concrete	
Compressive Strength	BS 1881: Part 116
Density	BS 1881: Part 114

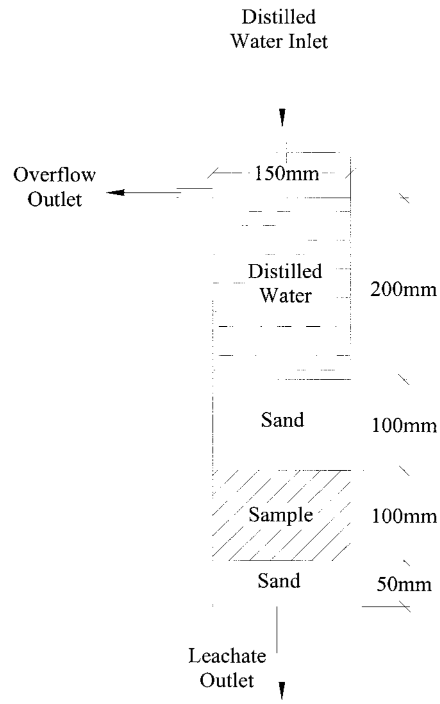

FIG. 2. Column Leaching Test

RESULTS AND DISCUSSION

Properties of Sludge

The sludge is brown in color and has an inoffensive odor. The chemical properties and composition of the sludge are given in Table 3. Results were obtained from five batches of sludge and were analyzed in triplicates. The predominant chemical constituents in the industrial sludge are iron and silica, in the proportion of 28.46 and 12.62%, respectively. The amounts of heavy metals are low. The sludge is alkaline in nature and has an average pH value of 7.75, with a loss-on-ignition of 9.33% (which includes CO_2, trapped water, and organic substances) and a moisture content ranging from 32.2 to 50.7%.

The physical properties of the sludge are shown in Table 4. The specific gravity of the sludge ranges from 2.67 to 2.70 with an average of 2.68. The sludge samples had an original particle size ranging from 3.0 to 313.0 μm, which exceeded the coarse size limit for pelletizing. Therefore the sludge had to be pulverized to a particle size smaller than 100 μm with a mean size of approximately 30 μm or smaller. After pulverizing, the particle-size range was reduced to 0.3–65.6 μm with a mean of 13 μm. The coarse limit for pelletizing and the particle-size distribution of the sludge are shown in Fig. 3.

As shown in Table 4, plastic and liquid limits of the sludge were determined to be 28 and 40% respectively, yielding a plastic index of 12%. The results were obtained from one batch of sludge tested in accordance with BS 1377 Soils for

J. Environ. Eng., 2000, 126(3): 279-287

TABLE 3. Chemical Composition and Properties of Industrial Sludge

Elements (1)	Range (2)	Average (3)
(*a*) Chemical composition (% by mass)		
Fe	22.96–33.16	28.46
Si	11.84–13.12	12.62
K	3.35–6.12	4.60
Al	2.80–4.15	3.64
Ca	2.04–2.67	2.38
Mg	0.95–1.23	1.07
Na	0.00–0.86	0.40
Mn	0.08–0.14	0.11
Zn	0.97–1.74	1.38
Cu	0.78–1.72	1.41
Ni	0.34–0.92	0.62
Pb	0.06–0.11	0.08
Cr	0.03–0.08	0.06
Cd	0.00–0.01	0.01
Hg	ND	<0.0002
Cl	0.12–0.37	0.25
SO_3	0.03–0.11	0.06
(*b*) Chemical properties		
pH	7.7–7.8	7.75
Loss on ignition (%)	5.97–12.94	9.33
Moisture content (%)	32.2–50.7	43.0

Note: ND = nondetectable.

TABLE 4. Properties of Industrial Sludge

Properties (1)	Range (2)	Average (3)
Specific gravity	2.67–2.7	2.68
Particle size		
Original (μm)	3.0–313.0	52
Pulverized (μm)	0.3–65.6	13
Atterberg limits		
Liquid limit (%)	—	40
Plastic limit (%)	—	28
Plasticity index (%)	—	12
Shrinkage limit (%)	—	5

Civil Engineering Purposes. This indicates that the material will crumble easily below the moisture content of 28% and not be able to retain its shape above the moisture content of 40%. Therefore, the optimal proportion of water in the sludge should lie between 28 and 40% of its dry mass. In the determination of the optimal water content, pellets were prepared with moisture contents of 28, 31, 34, 37, and 40% by mass, and the corresponding dry densities were measured. The optimum water ratio curve determined is shown in Fig. 4. The water ratio of approximately 40% is determined to be the optimal one as it gives the highest dry density for the green sludge pellets. It is also observed to be the water ratio that gives the best surface finish of the fired product without forming any cracks.

The dried pellets were then fired at different temperatures ranging from 1,000 to 1,160°C. Based on physical observations, the sludge pellets were sintered completely under a firing temperature of 1,135°C. The pellets have a tendency to fuse together above 1,135°C and exhibited a corrosive nature when produced below this temperature due to incomplete firing. Corrosion was not observed on completely fired pellets when soaked into water. Incomplete firing may result in rust marks due to high iron content and may affect the strength and aesthetic properties of the concrete.

Evaluation of Pellets

The sintered pellets are dark gray in color, with a smooth and shiny surface texture owing to the presence of fused metallic compounds. Samples of pellet and normal aggregates are shown in Fig. 5. Evaluation of pellet properties consisted of chemical compositions, water absorption, density, aggregate strength, and concrete compressive strength. The chemical compositions of the raw sludge and sintered sludge are listed in Table 5. The results indicate that the incinerated sludge has a high content of iron and silica measuring 29.7 and 11.8%, respectively, remaining close to the values before incineration, as they are stable to heat. Iron gives the strength upon firing, and silica provides the ceramic nature to the artificial aggregates.

As specified by BS 882, the maximum chloride content for aggregate is 0.06% by mass for use in reinforced concrete. From the test results, the chloride content decreases from 0.25 to 0.01% after firing, which is within the limit, and will have no detrimental effects on steel reinforcements. The reduction in chloride content could be due to the effect of volatilization of metal chlorides and chloride containing organic matters during the sintering process. As for sulfate content, BS 3797 specifies that the level should not exceed 1%. The test results indicate a marginal increase from 0.06 to 0.17% through firing, which is still within the specified limit.

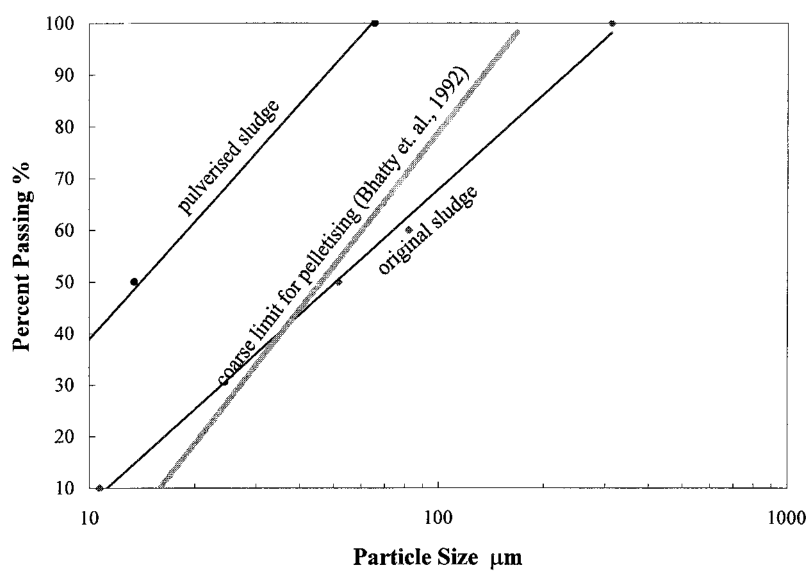

FIG. 3. Particle-Size Distribution of Sludge and Coarse Size Limit

J. Environ. Eng., 2000, 126(3): 279-287

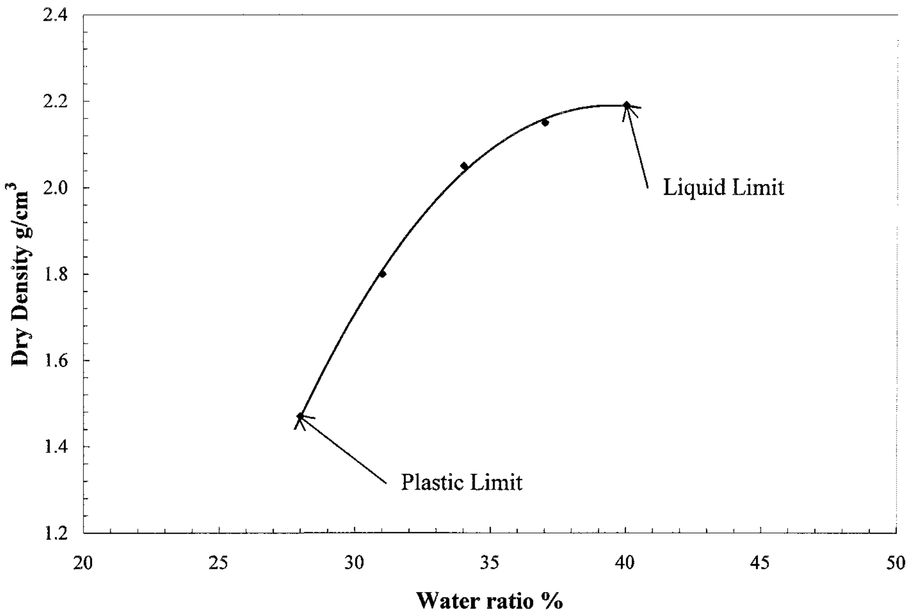

FIG. 4. Influence of Water Ratio on Dry Sludge Pellet Density

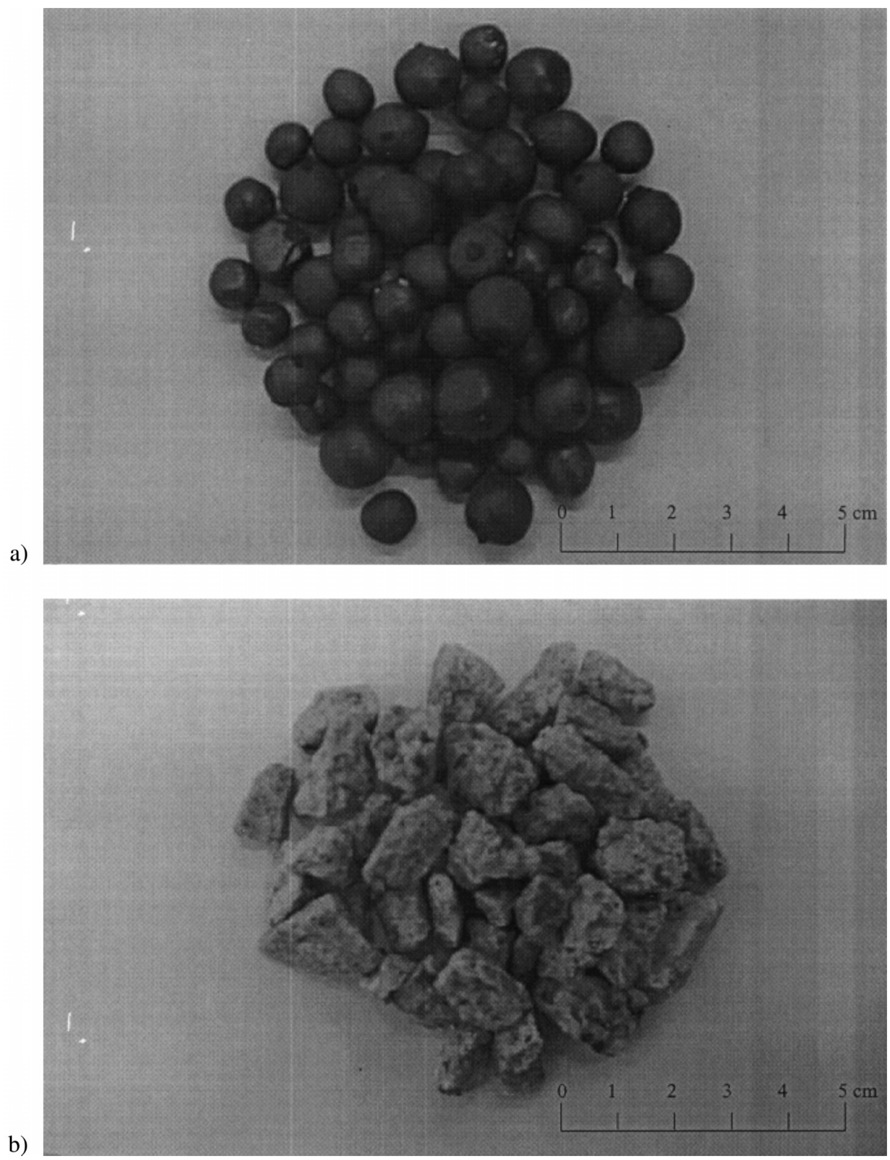

FIG. 5. Samples of Aggregates: (a) Sintered Sludge Pellets; (b) Granite Aggregates

J. Environ. Eng., 2000, 126(3): 279-287

TABLE 5. Chemical Composition of Sludge and Sintered Sludge Pellets

Element (% by weight) (1)	Material: Sludge (2)	Material: Sintered sludge (3)
Fe	28.46	29.70
Si	12.62	11.8
Al	3.64	3.11
Ca	2.38	2.69
Na	0.40	2.13
K	4.60	1.31
Mg	1.07	1.07
Mn	0.11	0.15
Cu	1.41	1.44
Zn	1.38	1.15
Ni	0.62	0.62
Cr	0.06	0.14
Pb	0.08	0.10
Cd	0.01	0.02
Hg	0.0002	0.00002
SO_3	0.06	0.17
Cl	0.25	0.01

TABLE 6. Properties of Sintered Sludge Pellets and Regular Coarse Aggregates

Properties (1)	Materials: Sintered sludge pellets (2)	Materials: Granite control aggregates (3)
Specific gravity	3.25	2.63
Particle density (g/cm^3)	2.25	2.56
Porosity (%)	30.8	2.7
Bulk density (g/cm^3)	1.36	1.27
Moisture content (%)	0.01	0.2
pH	8.0	8.5
Water absorption (%)	0.4	1.02
Aggregate impact value		
Dry (%)	19.9	28.3
Wet (%)	18.1	38.9

A comparison of the properties of the pellets and regular coarse aggregates is given in Table 6. The pH value of approximately 8.0 was measured when the pellets were placed in an aqueous medium. The value was slightly lower as compared to 8.5 for regular aggregates.

The pellets have a higher specific gravity of 3.25 as compared with that of 2.63 for granite. However, its particle density of 2.25 g/cm^3 is slightly lower compared with the granite density of 2.56 g/cm^3. The pellets have a higher specific gravity but lower density because, even though the solids of the material are dense, the pellet contains many intraparticle voids that lower the overall density of the pellet. Correspondingly, the pellet has a higher porosity of 30.8% as compared with that of 2.7% for granite. The high pellet porosity may affect the physical and chemical stability of aggregates. Due to the porous nature of the pellets, a water absorption test (BS 812: Part 109) was carried out to determine absorption capacity of the pellets when batched in concrete. Water absorbed by the aggregates may have a drawback on the workability, thermal insulation, creep, and shrinkage of the concrete. The sludge pellets were tested to have a lower water adsorption of 0.40% compared with that of 1.02% for granite. The results indicated that the porous nature of the aggregates had not affected the water adsorption, as most of the pores are not permeable to water due to the fused surface texture, which acts as a protective coat. The impermeable pores might even provide good sound insulation and fire resistance properties.

The aggregate impact value test was conducted in accordance with BS 812: Part 112, to determine the aggregate strength. In the test, both the control aggregates and the sludge pellets were subjected to the same crushing impact, and the percentage of fines passing the 2.63-mm sieve were measured to be 19.9% for pellets and 28.3% for granites, showing that sludge pellets have a better impact resistance and are thus higher in strength.

Hardened Concrete

The concrete cubes samples were cast in 100-mm cube molds and cured under standard laboratory conditions for periods of 3, 7, 14, and 28 days before being tested for compressive strength. The proportion of coarse aggregates used for all mixes was 25% by volume. The cement content of 400 kg/m^3 of concrete was used, and mix proportions are as given in Table 1. Fig. 6 illustrates the development of compressive strengths of specimens cured in air and water. Details on the compressive strength data and the density of concrete specimens are given in Table 7.

Compressive strength and density are two of the most important parameters of concrete. The 28-day compressive

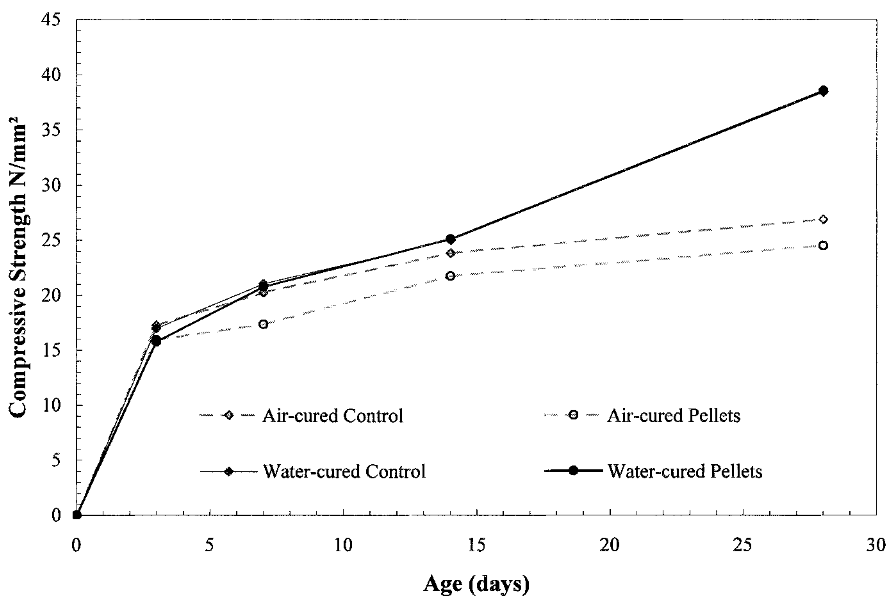

FIG. 6. Development of Compressive Strength

J. Environ. Eng., 2000, 126(3): 279-287

TABLE 7. Properties of Hardened Concrete

Hardened concrete (1)	Density (kg/m^3) (2)	Compressive Strength (N/mm^2)			
		Day 3 (3)	Day 7 (4)	Day 14 (5)	Day 28 (6)
Air cured					
Control	2,650	17.3	20.3	23.8	26.9
Pellet aggregate	2,610	15.9	17.3	21.7	24.5
Water cured					
Control	2,580	17.0	21.0	25.0	38.4
Pellet aggregate	2,560	15.8	20.8	25.1	38.5

strength and density of water-cured concrete with sintered sludge pellets were 38.5 N/mm^2 and 2,560 kg/m^3, respectively. The concrete cast with regular granite aggregates yielded a strength of 38.4 N/mm^2 and a density of 2,580 kg/m^3 under the same curing conditions. The air-cured concrete with regular aggregates obtained a 28-day compressive strength of 26.9 N/mm^2 and a density reaching 2,650 kg/m^3. However, the cubes cast with sintered sludge pellets gave a slightly lower compressive strength of 24.5 N/mm^2 and a lower density of 2,610 kg/m^3. The lower strength of the concrete containing sludge pellets under air curing could be due to more water evaporating from the less densely packed concrete, in turn reducing the hydration of cement. The lost of water resulting in incomplete hydration of cement can be prevented by the curing of concrete in water as indicated by the strength results of the water-cured concrete. This suggests that proper curing is important for the concrete containing sludge pellets. The strength of sludge aggregate concrete is similar to that given in the work done on pelletized blast-furnace slag by Mayfield and Louati (1990) with a similar mix proportion.

The complete replacement of regular aggregates with sludge pellets was expected to give a better strength to the resulting concrete, based on their higher aggregate crushing strength. However, the strength of the concrete was not increased. In fact, the compressive strength of concrete made with sludge pellets was lower under air-cured conditions, likely due to the weaker aggregate-cement bond and/or the lack of interlocking packing of the sludge pellets' matrix.

Leachate

A comparison of the peak concentration levels of heavy metals obtained from the leaching test conducted for a period of 150 days is shown in Table 8. The results show that the contamination levels of the toxic elements leached from the pellets and the secondary concrete product were close to the values obtained for the controls and were within the U.S. EPA (1993) drinking water standards except for lead (Pb) and cadmium (Cd). The concentration levels of heavy metals in the leachate over the test period are shown in Fig. 7. The concentration of Cd in the leachate practically diminished after 130 days for all samples including the blank. Whereas the concentrations of Pb in the leachate samples, including the blank, continue to fluctuate in an unstable trend up to the last day of the test period. The unstable leachate result of Pb does not allow any conclusive evaluation with regard to Pb contamination to be made. However, it was noted that the fluctuation is possibly due to unidentified external interference because the leachate from the blank column also fluctuated in the same manner. The nonleachable and nontoxic nature of the sintered sludge pellets further suggests that they would neither contribute to any complex chemical reaction affecting the long-term soundness of concrete nor present environmental problems such as ground-water and land contamination.

CONCLUSIONS

The aggregate produced has a higher specific gravity of 3.25, a higher porosity of 30.8%, with a lower particle density of 2.25 g/cm^3 and water absorption of 0.40% as compared with the regular aggregate. The pellets exhibited a higher strength and better durability characteristics with a higher impact resistance of 19.9% as compared with that of 28.3% for granites from the aggregate impact value test.

The replacement of granite with sintered sludge pellets in concrete as coarse aggregate attained a strength equivalent to that of the regular concrete. The results of compressive strength showed that the concrete cast from sludge pellets cured under different conditions could produce structural grade concrete with the 28-day strength ranging from 24.5 to 38.5 N/mm^2. Water-cured specimens showed equivalent compressive strengths for both pellets and granites. However, under the air-curing conditions, the sludge pellets give a lower concrete strength than the granites. This may be due to the under developed bond strength and the lack of interlocking effect between the smooth and rounded pellets.

The study indicated that the incinerated sludge pellets obtained by firing to a temperature of 1,135°C can be used for complete replacement of regular aggregate in concrete. The pellet concrete has a lower unit weight and hence a higher-strength-to-weight ratio. The strength of pellets substituted for regular coarse aggregates in concrete exhibited satisfactory performance with regard to their use as a coarse aggregate.

For long-term strength development, it is essential to have proper curing for the concrete cast with the sludge pellets. The need to protect the environment from ground-water and land contamination arising from the use of the sludge pellets could be satisfied from the leaching test results.

ACKNOWLEDGMENTS

The writers wish to thank the JPL Singapore Pte. Ltd. (JPL) for their permission to publish the findings of this investigation and their support of resources during the research. The writers are thankful to B. C. Tay and her team of environmental laboratory technicians for their kind as-

TABLE 8. Results of Column Leaching Test

Heavy metals (1)	Peak Concentration Levels (mg/L)				U.S. EPA[a] limit, maximum (mg/L) (6)	Detection limit (mg/L) (7)
	Blank (2)	Sludge pellets (3)	Granite concrete (4)	Sludge pellet concrete (5)		
Copper	0.06	0.06	0.07	0.09	1.30	0.001
Zinc	0.18	0.04	0.08	0.06	5.00[b]	0.003
Cadmium	0.02	0.03	0.05	0.03	0.005	0.002
Chromium	0.03	0.05	0.05	0.07	0.10	0.003
Lead	0.13	0.10	0.06	0.09	0.00	0.002
Mercury	ND	ND	ND	ND	0.002	0.0005

Note: ND = not detectables.
[a]U.S. EPA (1993a); Sawyer et al. (1994).
[b]U.S. EPA (1993b); Sawyer et al. (1994).

J. Environ. Eng., 2000, 126(3): 279-287

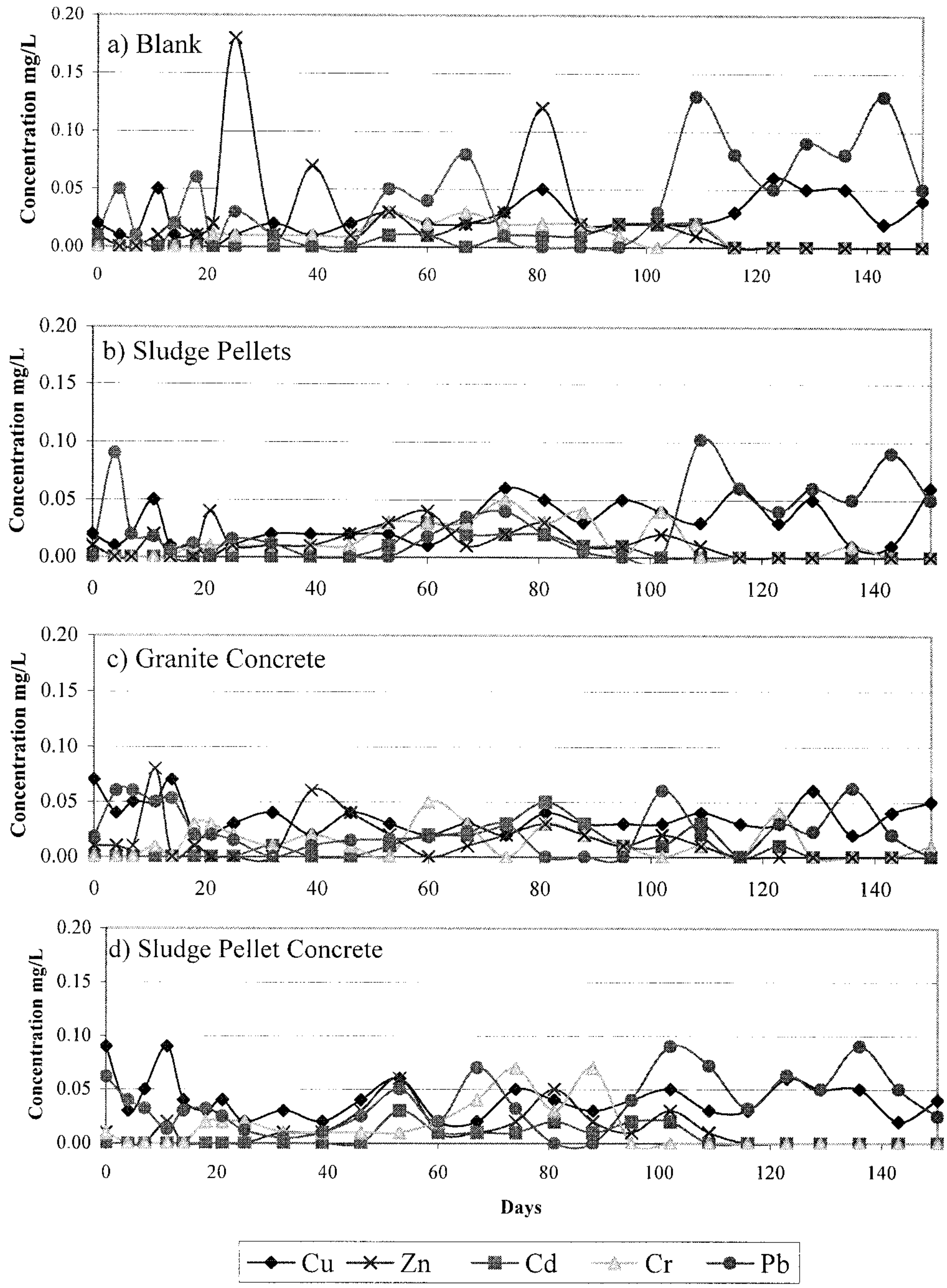

FIG. 7. Concentration Levels of Contaminants in Leachate

sistance. In addition, the writers wish to thank C. S. Woon from JPL for his invaluable help in this project. The funding of this research is provided by the Nanyang Technological University Applied Research Fund.

APPENDIX I. BIBLIOGRAPHY

''British standard testing concrete. Part 114, Methods for determination of density of hardened concrete.'' (1983). *BS 1881:Part 114*, British Standards Institution, London.

''British standard testing concrete. Part 116, Method for determination of compressive strength of concrete cubes.'' (1983). *BS 1881:Part 116*, British Stnadards Institution, London.

''Soils for civil engineering purposes. Part 2, Classification tests.'' (1990). *BS 1377:Part 2*, British Standards Institution, London.

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

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

''Standard specification for lightweight aggregates for structural concrete. (1998). *C 330-98*, ASTM, West Conshohocken, Pa.

''Testing aggregates. Part 109, Methods for determination of moisture content.'' (1990). *BS 812:Part 109*, British Standards Institution, London.

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

APPENDIX II. REFERENCES

Alleman, J. E. and Berman, N. A. (1984). ''Constructive sludge management: Biobrick.'' *J. Envir. Engrg.*, ASCE, 110(2), 301–311.

Bhatty, J. I., Malisci, A., Iwasaki, I., and Reid, K. J. (1992). ''Sludge ash pellets as concrete aggregates in concrete.'' *Cement, Concrete, and Aggregates*, 14(1), 55–61.

Buttermore, W. H., Lawrence, W. F., and Muter, R. B. (1972). ''Characterization, beneficiation and utilization of municipal incinerator fly ash.'' *Proc., 3rd Mineral Waste Utilization Symp.*, U.S. Bureau of Mines and IIT Research Institute, Chicago, 397.

Francis, C. W., and White, G. H. (1987). ''Leaching of toxic metals from incinerator ashes.'' *J. Water Pollution Control Fed.*, 59(11), 979–986.

Mayfield, B., and Louati, M. (1990). ''Properties of pelletized blastfurnace slag concrete.'' *Mag. of Concrete Res.*, 42(150), 29–36.

J. Environ. Eng., 2000, 126(3): 279-287

Okuno, N., Takahashi, S., and Asada, S. (1997). ''Full scale application of manufacturing bricks from sewage.'' *Water Sci. and Technol.*, 36(11), 243–250.

Sawyer, C. N., McCarty, P. L., and Parkin, G. F. (1994). *Chemistry for environmental engineering*, 4th Ed., McGraw-Hill, New York.

Tay, J. H. (1985). ''Sludge as brick making material.'' *Proc., On New Directions and Res. in Waste Treatment and Residual Mgmt.*, Vol. 2, 611–668.

Tay, J. H. (1987). ''Bricks manufactured from sludge.'' *J. Envir. Engrg.*, ASCE, 113(2), 278–284.

Tay, J. H., and Yip, W. K. (1988). ''Light weight concrete made with sludge ash.'' *Struct. Engrg. Rev.*, 1, 49–54.

Tay, J. H., and Yip, W. K. (1989). ''Sludge ash as lightweight concrete material.'' *J. Envir. Engrg.*, ASCE, 115(1), 56–64.

Tay, J. H., and Yip, W. K. (1990). ''Aggregate made from incinerated sludge residue.'' *J. Mat. in Civ. Engrg.*, ASCE, 2(2), 84–93.

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

U.S. EPA. (1993a). ''Maximum contamination level goal for trace inorganic chemical in drinking water.''

U.S. EPA. (1993b). ''Secondary maximum contamination levels for trace contaminants in drinking water.''

Wainwright, P. J., and Boni, S. P. K. (1981). ''Artificial aggregates from domestic refuse.'' *Concrete*, 15(5), 25.

Wainwright, P. J., and Boni, S. P. K. (1983). ''Some properties of concrete containing sintered domestic refuse as a coarse aggregate.'' *Mag. of Concrete Res.*, 35(123), 75.

J. Environ. Eng., 2000, 126(3): 279-287