Thermal Stabilization of Iron-Rich Sludge for High Strength Aggregates

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Abstract: A key task in wastewater sludge management is preventing sludge from polluting the environment. Sludge invariably poses risks to both public health and the environment whether incinerated or landfilled. Alternative reuses need to be explored in order to solve the disposal problems of sludge in an environmentally sound manner. This investigation examines the potential of using an industrial sludge and marine clay to produce aggregates for replacement of regular coarse aggregate in concrete. The waste mixes were pressed into layers and sintered at elevated temperatures resulting in a fused hard solid mass. During the sintering process, the peak rates of weight loss occurred at temperatures of 80–90, 280–520, and 900°C, indicating mass loss through evaporation and volatilization of organic and metallic substances, respectively. The sintered materials were crushed into required sizes for a range of construction aggregates exhibiting varying characteristics. Laboratory test results indicated that sludge-clay aggregates of up to 20% clay content displayed better aggregate impact resistance of 23.1–28.8% Aggregate impact value (AIV) compared with 28.3–38.9% AIV for the control granite aggregate. Sodium salt and sintering temperature have significant influence on the product density. Concrete cast with the sludge-clay aggregates yielded compressive strengths ranging from 34.0 to 39.0 N/mm^2, while the sludge aggregates of 0 and 20% clay content produced concrete stronger than those cast with conventional granite aggregate. Leaching test results showed that the concentrations of the toxic elements leached from the aggregates were within acceptable levels, suggesting that the sludge-clay materials could possibly be used as concrete aggregates without detrimental effects to the environment. The experimental study indicated that conversion of the sludge and clay into construction aggregates could offer a feasible technical solution for waste management.

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Introduction

Sludge is generated as a by-product of wastewater treatment. It has become an increasingly global problem to manage wastewater sludge in a complete environmentally sound manner. The generally adopted sludge disposal is landfilling, but the option takes up valuable space and may generate methane that contributes to the greenhouse effect. As most sludge contains heavy metals, disease-causing pathogens, synthetic organic, and inorganic compounds, improper sludge disposal can pose risks to both public health and the environment.

Current development and technology advancement seem to offer a new horizon in sludge management. Increasingly, research evidence of sludge as innovative civil engineering materials may prompt sludge reuse as a promising option for sludge management. The use of wastewater sludge into construction materials could be achieved by fusing the sludge material. Sludge stabilization through fusion could prevent potential contamination of water sources from sludge. The development of artificial aggregates from wastewater sludge provides potential application in significant quantities that could resolve the sludge management problem.

Many studies have been conducted on the utilization of waste as construction aggregates. Wastes such as sludge ash, blast furnace slag, and building rubble such as bricks and concrete have been used as coarse aggregates in concrete (Ramachandran 1983). Buttermore et al. (1972) prepared pellets of a larger size from municipal incinerator fly ash, and crushed the pellets after firing to smaller sizes to be used as aggregates concrete. Wainwright and Boni (1981, 1983) prepared smaller size pellets from the same type of waste for direct application 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 sizes aggregate for use in concrete. The aggregates exhibited high thermal insulation and fire resistance, with 28 days compressive strength comparable to commercial lightweight aggregates.

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In the work by Bhatty and Reid (1989), sludge ash aggregates were produced by adding 20% of water to mold or pelletize the sludge ash particles of suitable fineness and drying the molded products prior to firing. Bhatty et al. (1992) reported the use of sludge ash pellets as coarse aggregates. It was reported that a mean particle fineness of 80 μm was required in order for the materials to be molded without the use of additional binders. Bhatty et al. (1992) found that sludge ash pellets sintered at an elevated temperature of 1,050°C developed inert aggregates of reasonable strength satisfactory for use as regular coarse aggregates in concrete. The sludge ash aggregates were lower in specific gravity hence provided a better strength-to-weight ratio with no adverse effects on concrete strength. The round-shaped pellets also enhanced the workability of the concrete (Bhatty et al. 1992). According to Okuno et al. (1997), the average particle size for sludge ash used in brick making, should be finer than 30 μm and the ignition loss of the materials should be less than 1% to prevent the development of cracking upon firing. Tay et al. (2000, 2002) conducted an investigation on the production of pelletized round-shaped aggregates from sludge and clay mixes. The study indicated that a complete replacement of conventional granite aggregates with pelletized sludge-clay aggregates was feasible, providing concrete compressive strength comparable to that of the conventional granite aggregates ranging from 31.0 to 38.5 N/mm^2. However, the effects of aggregate shapes on the integrity of concrete and the factors affecting the density of the aggregates were not looked into. Therefore, this work investigated the integrity of angular sludge-clay aggregates and the effects of sodium salt and sintering temperature on the density of aggregates.

Materials and Methods

Sources of Raw Materials

The raw materials used in this project were iron-rich sludge and marine clay. The sludge was generated by the copper slag recycling industry. The copper slag, used as abrasives for blast cleaning of ships to remove rust and marine deposits that accumulate on the surfaces of the ship vessels, were washed and reused. The wash water from the copper slag recycling process was treated and the sludge collected from the sedimentation tank of the wastewater treatment was used in the present study. The marine clay was obtained from the construction industry arising from tunneling and excavation works. A large volume of marine clay has to be removed due to its poor engineering properties. Marine clay is present in abundance in the geological formation of Singapore. Due to the limited land space and intensity of development, the construction activities were driven deeper underground, which caused a tremendous increase in the volume of marine clay to be disposed of in recent years. There are more than 1.3 million m^3 of marine clay being dug out each year from the construction activities. The huge amount of the waste clay poses pressing disposal problems to local authority.

Materials Preparation

Tests were conducted on the raw materials to determine their chemical and physical properties. The methods and equipment used for the analyses are listed in Table 1. The moisture contents of the raw materials were inconsistent under natural conditions; therefore, the materials were dried in an oven at a temperature of 105°C to achieve consistent dryness to enabled accurate batching of the materials. The sludge and clay materials hardened and clumped together after drying and had to be broken down to sizes suitable for mixing. The materials were crushed into sizes below 250 μm that are sufficiently fine to be mixed homogeneously. With good plastic properties, molding of the materials could be executed without further reduction of the particle sizes.

Aggregate Processing

The ground materials were then combined at various proportions and mixed with water to form malleable pastes for aggregate production. The optimal water ratios for mixing were different for each mix, which were determined to be 35, 39, 42, 42, and 41% for the proportions containing 0, 20, 50, 80 and 100% clay content, respectively. It was observed that the optimal water ratios provided each mix with best surface finish and minimal cracks of the finished products. Each mix was then prepared with the corresponding optimal water ratio and kneaded into malleable pastes, which were then pressed into flat layers of approximately 10 mm thick and dried in the oven before firing.

Firing

The layers of dried sludge-clay materials were sintered in a muffle furnace. The firing profile adopted from Tay et al. (2000) as shown in Fig. 1 was used for sintering the aggregate samples. The rationale for the firing profile will be discussed in the following section, ‘‘Results and Discussion.’’ The sintered masses were then crushed into desired sizes prior to use as angular aggregates in concrete.

Thermogravimetric Analysis

The rates of weight loss of the raw materials subject to sintering were examined at different burning temperatures with the use of a Thermogravimetry Analyzer (TGA, SDT 2960 TA Instruments, New Castle, Del.). The slope of the weight-time curve yields the differential thermogravimetry (DTG) curve. Peaks on DTG curve present the high mass loss rate of sample at specific temperature.

Testing Aggregates

The aggregates were tested of their properties for evaluation of product quality. The test methods and equipment used are listed in Table 1. Due to the porous nature of the pellets, a water absorption test was conducted according to BS 812: Part 109 (BSI 1990b) to determine water absorption of the aggregates. The aggregate strength was tested according to BS 812 Part 112:1990 (BSI 1990c) (aggregate impact value).

Batching of Concrete

The sintered aggregates were intended for replacement of coarse aggregates used in paving blocks production. The blocks were made with fine aggregates of copper slag grit from the copper slag recycling plant where the sludge was generated. Therefore, the mix proportion used in the production of paving blocks (as given in Table 2) was adopted in the present study. The concrete samples were batch with copper slag grit as fine aggregates, ordinary portland cement as binder, with a water-cement ratio of 0.5. The control concrete specimens were cast with granite stones as coarse aggregate while the test concrete specimens were cast with sludge-clay aggregates as coarse aggregates. The coarse aggregate was replaced with the same volume of sintered sludge-

J. Mater. Civ. Eng., 2003, 15(6): 577-585

Table 1. List of Test Methods and Equipment used in Analyses and Testing

Properties	Test methods/equipment or instruments used
Elemental analysis	BS EN 196: Part 21: 1992 (raw materials)
Cl	
	BS 812: Part 117: 1988 (aggregates)
SO_3	BS EN 196: Part 2: 1995 (raw materials)
	BS 812: Part 118: 1988 (aggregates)
Concentrations $<$ 0.01 mg/L	Microwave digestion procedure/Perkin-Elmer simultaneous multielement analysis graphite furnace atomic absorption system 6000
Concentrations $>$ 0.01 mg/L	Lithium metaborate fusion procedure Perkin-Elmer ICP-atomic emission spectrometer 400
Atterberg limits	BS 1377: Part 2: 1990/Cone penetrometer
Liquid limit	BS 1377: Part 2: 1990
Plastic limit	BS 1377: Part 2: 1990
Linear shrinkage	BS 1377: Part 2: 1990
Specific gravity	Ultrapycnometer 1000
Moisture content	BS 1377: Part 2: 1990
Loss-on-ignition	BS EN 196-2: 1994
pH value	BS 7755: 3.2: 1995 pH meter
Particle size distribution	Malvern mastersizer micro particle analyzer thermogravimetry
Thermogravimetry	analyzer (TGA) TA Instruments SDT 2960
Bulk density	BS 812: Part 2: 1995
Particle density	BS 812: Part 2: 1995
Water absorption	BS 812: Part 2: 1995
Aggregate impact value	BS 812: Part 112: 1990
Concrete density	BS 1881: Part 114: 1983
Concrete compressive strength	BS 1881: Part 116: 1983
Leaching test	Column leaching test (Francis and White 1987)
Leachate analysis	Perkin-Elmer simultaneous multielement analysis graphite furnace atomic absorption system 6000 and Perkin-Elmer ICP-atomic emission spectrometer 400

clay matrix of the same size range between 10 and 14 mm. The concrete samples were tested after 28 days of curing at a temperature of 20±2°C, as specified in BS 1881: Part 111: 1983 (BSI 1983) Method of normal curing of test specimens.

Leaching Test

Leaching characteristics of the aggregates were also examined to evaluate potential environmental contamination. The column-leaching test was conducted based on the study by Francis and White (1987). The test procedure was adopted because the column-leaching test is able to simulate field conditions and the development of leachate with respect to time could be monitored. The sludge products were intended for pavement and masonry purposes where leaching effect is most likely to be dynamic. A blank column was used as the control for baseline and comparison studies. The leaching test was conducted as described by Tay et al. (2000).

Distilled water was passed through the samples in cylindrical columns in a down flow mode. The flow rate of 1 mL/min was used in order to provide an adequate time of contact of 30 h to meet the standard contact time of 24 h specified in most protocols as given by Conner (1990). The leachate was generated over a duration of 150 days to obtain a total leachate volume of at least

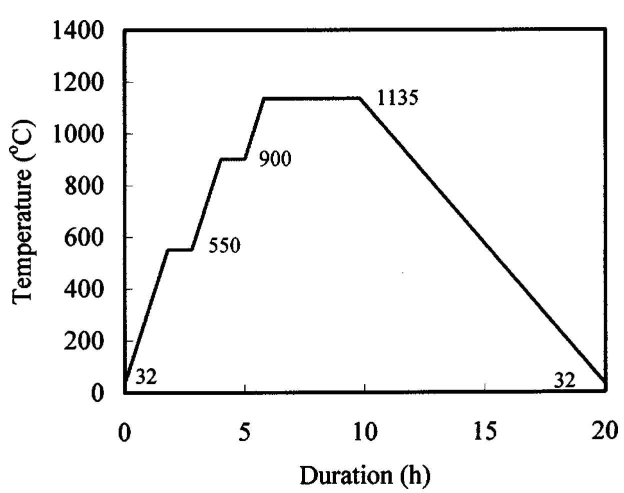

Fig. 1. Temperature profile of firing process

Table 2. Mix Proportions of Concrete by Mass

	Proportions (g)			
	Aggregates			
Types of coarse aggregates	Coarse	Fine	Cement	Water
0% clay	6,089	19,250	5,000	2,500
20% clay	5,126	19,250	5,000	2,500
50% clay	3,993	19,250	5,000	2,500
80% clay	3,059	19,250	5,000	2,500
100% clay	4,050	19,250	5,000	2,500
Granite	7,250	19,250	5,000	2,500

J. Mater. Civ. Eng., 2003, 15(6): 577-585

Table 3. Properties of Raw Sludge and Clay

	Materials	
Chemical contents (% by mass)	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

Note: N.D.=not detected.

20 times of the concrete sample mass [as specified in the USEPA Toxicity Characteristic Leaching Procedure (USEPA 1992)]. In the first month of flow, leachate from the test columns was collected twice weekly and thereafter, once a week for a total of 26 samples. The samples were then preserved with concentrated nitric acid and analyzed for various inorganic chemical concentrations using the inductively coupled plasma atomic emission spectrometry (Perkin-Elmer ICP-AES 400). The levels of mercury and other elements that fall below the detection limits ICP were determined using simultaneous multielement analysis graphite furnace atomic absorption system (Perkin-Elmer SIMAA 6000).

Results and Discussion

Raw Materials

The chemical content, Atterberg limits, specific gravity, particle sizes, moisture content, loss-on-ignition, and pH of both the sludge and clay were determined and the test results of raw materials' properties are given in Table 3.

Sludge

The sludge was brown in color and had an inoffensive odor, and consisted of mainly iron and silica at 28.46 and 12.62%, respectively. The high amount of iron present in the sludge could be

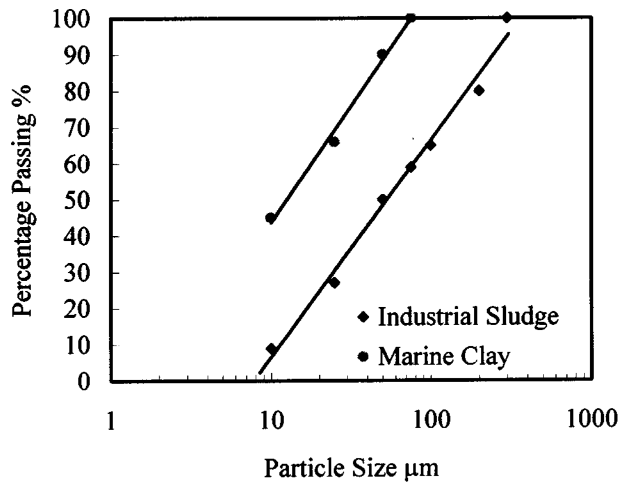

Fig. 2. Original particle size distribution of industrial sludge and marine clay

attributed to the high iron content in copper slag and rust deposits from the blast cleaning of ship vessels. The liquid and plastic limits of sludge were determined to be at 40 and 28% moisture content, respectively. This corresponded to a plasticity index of 12, indicating a good cohesion property. The sludge was determined to have a linear shrinkage of 4% and a specific gravity (SG) of 2.68. The sizes of unprocessed raw sludge particles ranged from 3 to 313 μm with a mean of 52 μm. The particle size distribution of the materials is analyzed and presented in Fig. 2. The sludge material had an average in situ moisture content of 43.0% and an average loss-on-ignition of 9.33%, which indicated the presence of significant amount of organic materials. The sludge was slightly alkaline, with the pH varying between 7.71 and 7.78.

Marine Clay

The marine clay was bluish gray in color, soft in texture, and occasionally contained shell fragments of marine organisms. The marine clay consisted of mainly silica and aluminum, which were 26.03 and 9.75%, respectively. The marine clay had a high content of silicon and aluminum as they are the most common elements in earth materials. The liquid and plastic limits of the marine clay were determined to be at the moisture contents of 74 and 33%, respectively, providing a plasticity index of 41%, which indicates a good cohesion property of the material. The marine clay was determined to have a linear shrinkage of 11% and a specific gravity of 2.34, indicating a higher organic content as compared with sludge. Materials with higher linear shrinkage and lower specific gravity usually have higher organic content. This indication was supported by the higher loss-on-ignition of 11.4% of the marine clay material. The high values of loss-on-ignition indicated the presence of a significant amount of organic materials; hence special considerations for product quality were given when subjecting the materials to elevated temperatures. The material had particle sizes ranging from 0.32 to 65.6 μm with a mean of 11 μm (Fig. 2). The clay material had an average natural moisture content of 42.6% and a pH level that was less alkaline than that of the sludge, varying between 7.59 and 7.67.

Thermogravimetric Analysis

The rates of weight loss of the materials subject to sintering were examined at different burning temperatures with the use of a ther-

J. Mater. Civ. Eng., 2003, 15(6): 577-585

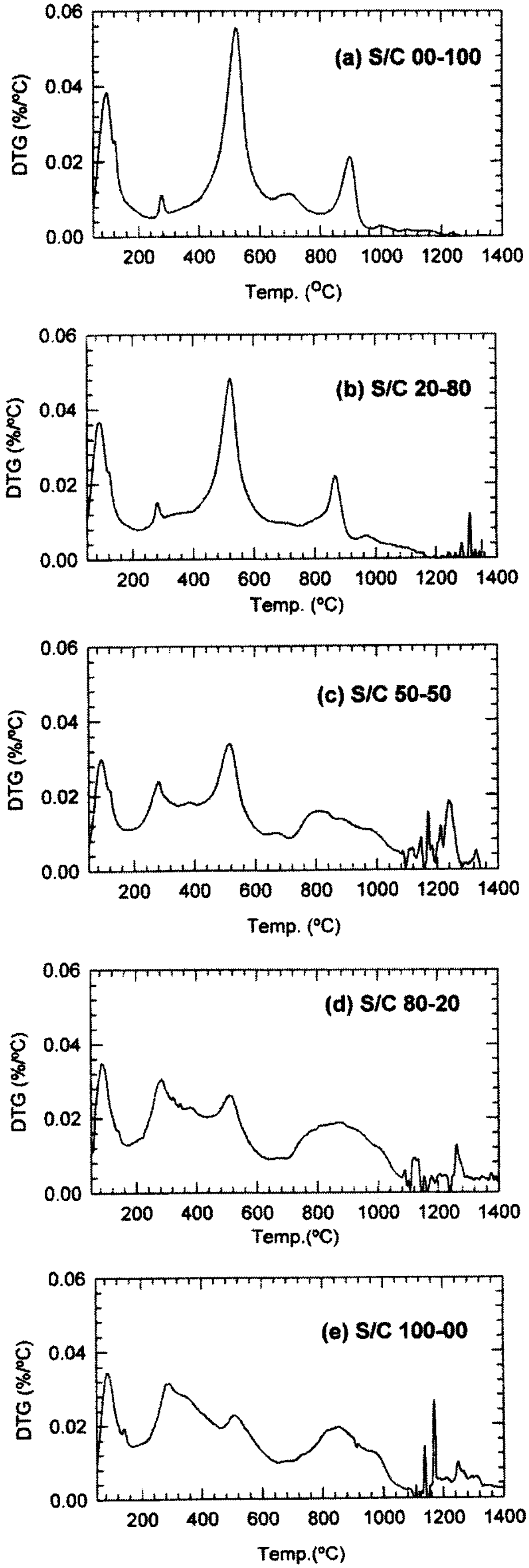

Fig. 3. Differential thermogravimetry of various sludge-clay mixes

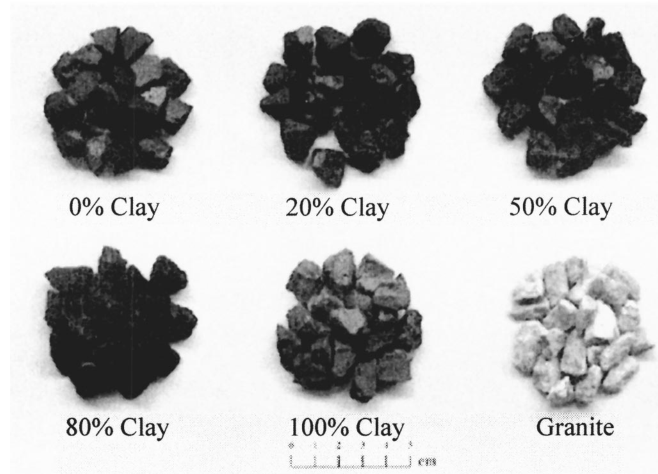

Fig. 4. Samples of crushed sludge-clay aggregates and granite control

mogravimetry analyzer (TGA). The results of differential thermogravimetry (DTG) analysis are presented in Fig. 3. The peaks of the rates of weight loss were detected at temperatures of 80–90, 280–520, and 900°C for all the sludge-clay mixes. The peak of weight loss at 80–90°C indicated the mass of moisture lost through evaporation. The loss in weight within 280–520°C indicated the oxidation and volatilization of mainly organic matter and certain inorganic salts. Mixes containing greater proportions of the sludge exhibited a higher rate of weight loss at 280°C and the mixes containing greater proportions of marine clay exhibited a higher rate of weight loss at 520°C. The loss of weight at the temperature of 900°C signified the oxidation and volatilization of mostly inorganic substances, which released mainly carbon dioxide (CO_2) and water. The results of the DTG analysis reinforce the basis of the temperature profile adopted from Tay et al. (2000) as depicted in Fig. 1. The firing temperature was raised slowly and sustained at 550°C for one hour to boost organic removal, which alleviates bloating, and sustained at 900°C for another hour to allow complete oxidation to prevent the development of black core, before sintering for 4 h at 1,135°C.

Aggregate Properties

A range of construction aggregates has been developed from five sludge-clay mixes of 0, 20, 50, 80, and 100% marine clay. Samples of the crushed aggregates of various sludge-clay proportions are shown in Fig. 4, together with conventional granite aggregates. The chemical contents of the sintered aggregates as reported in Tay et al. (2002) are shown in Table 4 and the physical properties of the aggregates at various clay contents are given in Table 5.

Analysis of Chemical Elements

In raw sludge, the iron content was 28.46% and the silica content was 12.62%. After sintering, the iron and silica contents decreased slightly to 20.38 and 9.48%, respectively. In marine clay, the silica content was 26.03% and the aluminum content was 9.75%. After sintering, the silica and aluminum contents decreased slightly to 23.31 and 9.08%, respectively. The chemical contents in the mixes varied with the proportions of the sludge

J. Mater. Civ. Eng., 2003, 15(6): 577-585

Table 4. 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

Note: N.D.=not detected.

and clay lying between the values of the pure sludge and marine clay. Toxic metals such as chromium, manganese, and lead, were reduced after the materials were subjected to elevated temperatures except for mercury, which had a slight increase in sludge. It should be noted that the differences in the chemical contents could be resulted from changes in the mass of the materials after firing. Cadmium, which was previously present in the sludge, was not detected in the aggregates after firing.

Chemical Properties

Chloride content of sludge-clay aggregates was determined to be 0.01% after firing which complies with the limit of 0.01% specified by British Standard Specification for Aggregates from Natural Sources for Concrete (BS 882 1992) for aggregates used in reinforced concrete. The chloride content of the raw materials ranged from 0.23 to 0.25%, and the concentrations were reduced upon firing. The reduction in chloride content could be due to the effect of volatilization of chloride-containing organic matter and certain metal chlorides releasing the chlorides as chlorine gas.

The sulfate contents of 0.17–1.22% by mass of aggregates were converted by calculation to be in a range of 0.22–0.99% 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 1990a). However, the sulfate content of sludge-clay aggregates with more than 50% clay content may exceed the limit, when the sulfate contents contributed by other constituents were taken into account. Above this level, the excessive sulfate content may lead to sulfate attack. The crushed aggregates exhibited high water absorption capacities, and therefore, only up to 50% clay contents are recommended for use to avoid possible sulfate attack.

Physical Properties

Bulk Density and Specific Gravity (SG). The bulk density, which includes all voids and spaces in the volume, ranged from 0.91 to 0.54 g/cm^3 for the crushed sludge-clay aggregates. The sludge-clay aggregates of all proportions have a lower bulk density compared to the value of 1.27 g/cm^3 for conventional granite aggregates. The true specific gravity (excluding all voids) of the aggregates ranged from 3.25 to 2.46 were moderate compared to 2.63 for granite. As the specific gravity of marine clay is relatively lower, the increase in clay content reduces the true specific gravity of the sludge-clay aggregates.

Particle Density. The particle density which is also the apparent specific gravity of the aggregates includes all intraparticle voids. The particle density ranged from 1.08 to 2.15 g/cm^3 for the sludge-clay aggregates were lower compared with 2.56 g/cm^3 for granite aggregate. The particle density of the aggregates decreased from 2.15 g/cm^3 at 0% clay to a minimum of 1.08 g/cm^3 at 80% clay content, after which the density increased to 1.43 g/cm^3 at 100% clay.

Porosity. The sludge-clay aggregates have a higher SG but a lower particle density as compared to granite, indicating the presence of many intraparticle voids, hence a higher porosity. The porosity of the sludge-clay aggregates increased with the clay content and reached a maximum of 59.85% at 80% clay, where the particle density was at a minimum. Higher porosity of the sludge-clay aggregates may affect the physical and chemical stability of the aggregates.

Water Absorption. The water absorption of the sludge-clay aggregates were determined to be 1.62, 5.56, 9.97, 22.69, and 9.09% for 0, 20, 50, 80, and 100% clay respectively. The water absorption of the sludge-clay aggregate was considerably higher compared with that of granite due to the higher porosity and open pores on the broken surfaces. The highly porous nature of the aggregates would result in high water absorption, which would

Table 5. 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)	0.91	0.73	0.61	0.54	0.62	1.27
Particle density (g/cm^3)	2.15	1.81	1.41	1.08	1.43	2.56
Specific gravity	3.25	3.08	2.99	2.69	2.46	2.63
Porosity (%)	33.85	41.23	52.84	59.85	41.87	2.66
Water absorption (%)	1.62	5.56	9.97	22.69	9.09	1.58
Aggregate impact value						
Dry (%)	28.8	28.6	37.1	41.1	42.9	28.3
Wet (%)	23.6	23.1	30.4	33.7	35.0	38.9

J. Mater. Civ. Eng., 2003, 15(6): 577-585

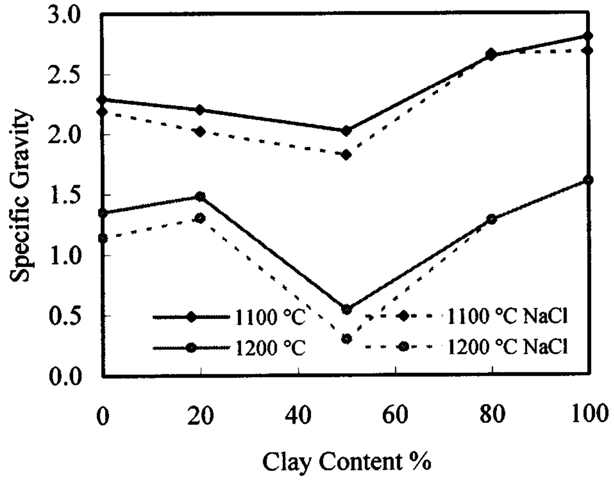

Fig. 5. Specific gravities of sludge-clay aggregates with and without NaCl addition fired at 1,100 and 1,200°C

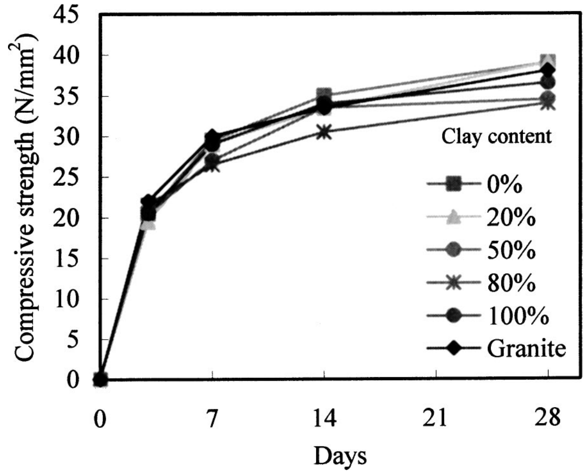

Fig. 6. Development profile of concrete compressive strengths

reduce workability, and increase the creep and shrinkage of the concrete. On the other hand, concrete cast with high porosity aggregates normally exhibits better sound insulation and fire resistance properties (Tay and Yip 1988).

Aggregate Impact Value. The aggregate impact value (AIV) test was conducted to determine the aggregate strengths. 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 28.6–42.9% under a dry condition and 23.1–35.0% under a wet condition, compared to the granite aggregate, which has the AIV of 28.8% 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. The results of aggregate strength shows that the sludge-clay aggregates of clay contents of up to 20% met the requirements for use in concrete for wearing surfaces and clay contents of up to 50% met the requirements for use in normal concrete.

The highly porous nature of the aggregates was suspected to be attributed to two factors, viz, the firing temperature and the amount of sodium in the aggregates. To validate this hypothesis, a separate investigation was carried out by Chien (2001), to examine the aggregates produced with and without the addition of sodium chloride (NaCl) fired under the temperature of 1,100 and 1,200°C. NaCl was added to the aggregates, which increased the amount of sodium by 1.5 times. The apparent specific gravity of the aggregates was then measured and the results are given in Fig. 5. The results showed a reduction in the densities of the aggregates with the addition of NaCl and the increase in firing temperature.

Both the addition of NaCl and the increase in firing temperature show the effect of bloating leading to a reduction in apparent specific gravity, which in turn lead to an increase in porosity of the aggregates. The result indicates that NaCl enhanced the expansion of the aggregate through bloating during sintering. At the present stage of study, the mechanism of bloating involving NaCl remains unclear.

Performance in Concrete

Performance of the sludge-clay 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 Fig. 6. The concrete specimens made from the sludge-clay aggregates have a similar compressive strength development rate as the granite control. The 28th day compressive strengths of the concrete specimens with coarse sludge-clay aggregates were determined to be in the range of 34.0–39.0 N/mm^2. The concrete specimens made from crushed sludge-clay aggregates provided good compressive strengths that meet the strength requirements for structural grade concrete of 20–40 N/mm^2. Concrete specimens cast with aggregates of up to 20% in clay content displayed the highest compressive strength of 39.0 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 2,580, 2,530, 2,440, 2,440, and 2,500 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 sludge-clay aggregates were examined using the column-leaching test, which closely simulates the field leaching conditions. The level of leachate contamination was evaluated against the limits specified for health-based contaminants in the World Health Organization (WHO) guidelines for drinking water, which includes cadmium, chromium, copper, lead, manganese, nickel, and mercury. However, 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 are shown in Fig. 7. Peak concentration levels detected in the leaching test are shown in Table 6 along with the limits given in the *Guidelines for Drinking-Water Quality* specified by the World Health Organization (1993). The results showed that the concentrations of the toxic elements leached from the aggregates were within acceptable levels, which suggest that the sludge-clay materials could possibly be used as concrete aggregates without detrimental effects to the environment.

J. Mater. Civ. Eng., 2003, 15(6): 577-585

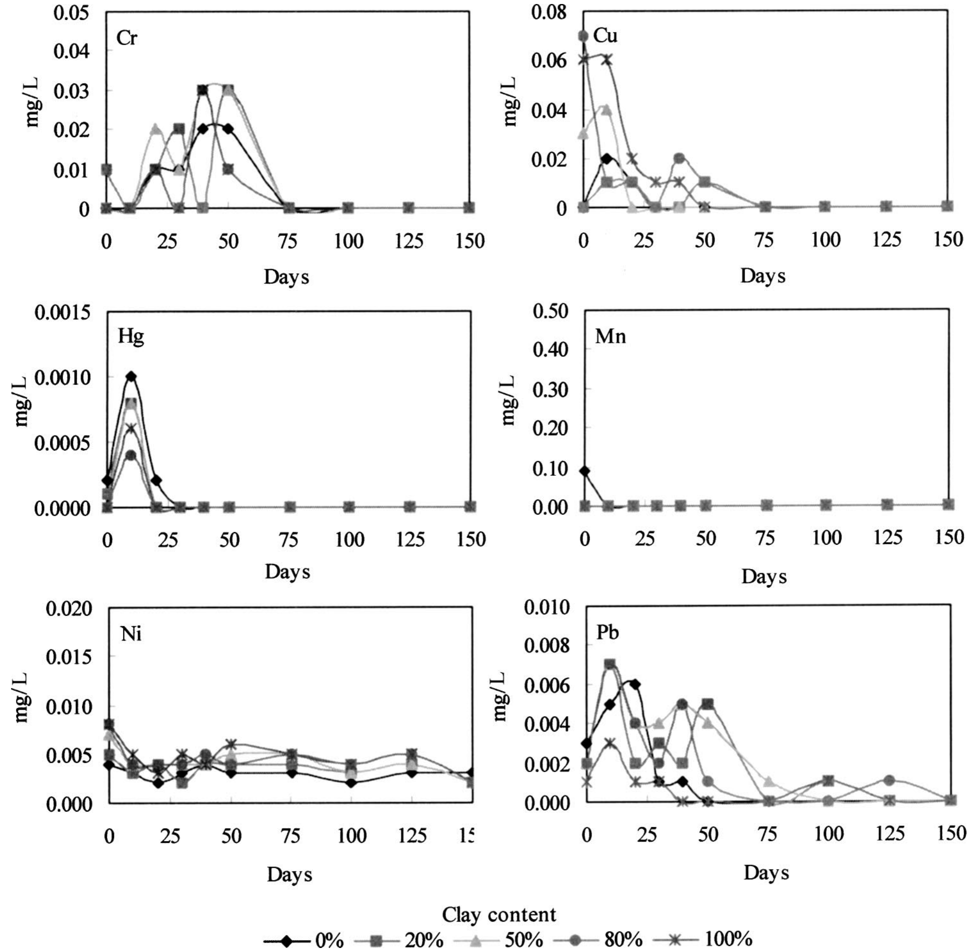

Fig. 7. Leaching trends of some harmful contaminants from sludge-clay aggregates

Conclusion

The study demonstrated a 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 aggregates made from sludge manifested the attributes required of construction 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 2.15–1.08 g/cm^3, which is relatively lower compared to 2.56 g/cm^3 for the control granite aggregate at. The sludge-clay aggregates of up to 20% clay content displayed better aggregate impact resistance of 23.1–28.8% AIV compared with 28.3–38.9% AIV for the control granite aggregate. However, the increase in clay content beyond 20% reduced the aggregate resistance. Sodium salt and sintering temperature have a significant influence on the product density.

The angular shaped aggregates showed a marginal improvement in concrete integrity, over the control aggregates, providing a maximum concrete compressive strength of 39.0 N/mm^2. The sludge-clay aggregates with up to 20% marine clay provided the highest compressive strength of 39.0 N/mm^2, and the compressive strength of concrete reduced to between 34.0 and 36.5 N/mm^2 with the addition of marine clay in the aggregates beyond 20%.

Table 6. 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	0.02	0.03	0.03	0.03	0.03
Cu	2.00	0.01	0.02	0.01	0.04	0.07	0.06
Hg	0.0010	0.0008	0.0010	0.0008	0.0008	0.0004	0.0006
Mn	0.50	0.01	0.009	N.D.	N.D.	N.D.	N.D.
Ni	0.02	0.004	0.004	0.005	0.007	0.008	0.008
Pb	0.01	0.008	0.006	0.007	0.007	0.007	0.003

Note: N.D.=not detected.

J. Mater. Civ. Eng., 2003, 15(6): 577-585

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.

However, special attention should be given to the sulfate content and water absorption of some aggregates. The aggregates of clay content beyond 50% may exceed the sulfate content level of 1% by mass of cement as specified in BS 3797, when the sulfate contributed by other sources were taken into account. The water absorption of the aggregates containing more than 0% clay is high, ranging from 5.56 to 22.69%. This may result in a significant negative impact on the required binder content of mixes containing the aggregates that can in turn affect the mixture economics and aggregate use in a negative way.

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.

It is recommended that further research work be conducted on long-term durability and leaching effects. Tests should be conducted for specific applications where products may be subjected to extreme conditions.

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J. Mater. Civ. Eng., 2003, 15(6): 577-585