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THE FEASIBILITY OF USING WASHED MUNICIPAL SOLID WASTE INCINERATOR BOTTOM ASH IN COMPRESSED MORTAR PAVING UNITS

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Key words: washed municipal solid waste incinerator bottom ash, compressed mortar paving units, compressive strength, water absorption, porosity.

ABSTRACT

This study replaced natural fine aggregate with a fine aggregate of washed municipal solid waste incinerator bottom ash (WMSWIBS) in the production of compressed mortar paving units to explore the feasibility of using WMSWIBS in this application. Cement-aggregate ratios (c/a) of 0.1, 0.2, 0.3, 0.4, and 0.5 and water-cement ratios (w/c) of 0.20, 0.25, and 0.30 were selected. The results yielded a specific gravity of 2.21, aggregate absorption of 9.6%, and a fineness modulus of 3.2. The WMSWIBS's toxicity characteristic leaching procedure (TCLP) values were much lower than the limit specified by the Environmental Protection Administration (EPA, Taiwan), and its heavy metals content after the water wash was lower than that before the wash. The water absorption ranged from 5.49-13.55%, the porosity from 2.44-8.05%, the compressive strength from 12.3-45.4 MPa, the ultrasonic pulse velocity from 1,521-2,961 m/sec, and the attrition volume loss from 27.2-117.7 cm^3/50 cm^2. The results suggested that the compressive strength and ultrasonic pulse velocity increased with the cement-aggregate ratio, while the attrition loss decreased.

I. INTRODUCTION

Due to its limited geographical area, dense population, and intense economic activity, Taiwan has generated increasing amounts of municipal solid waste and must now address the challenging problem of treating waste with a variety of characteristics. Waste treatment has become an important administrative concern because of increased environmental awareness and the desire to improve residents' quality of life, and waste incineration is now regarded as an effective technology in an integrated waste management system and is expected to increase in the UK, China, and many other countries in which the availability of landfill space is limited (Porteous, 2005; Qiao et al., 2009). In 2008, three incinerators in Taipei County (Taiwan) treated a combined 1 million tons of municipal solid waste and produced approximately 140,000 tons of bottom ash (Taiwan EPA, 2008). The bottom ash from municipal incinerators must be treated and examined using the toxicity characteristic leaching procedure (TCLP) prior to reuse (Taiwan EPA, 2007). The TCLP test normally includes an analysis of the leachate for heavy metals and chlorinated organics (Chou et al., 2009; Huang et al., 2008; Lin et al., 2008).

Table 1 shows that the annual amount of waste incineration was increased from 5,690,000 tons in 2002 to 6,230,000 tons in 2010, and the maximum ash output was approximately 1,293,000 tons in 2010. Bottom ash accounted for 992,000 tons (76.7%), and fly ash (including reaction ash) accounted for 301,000 tons (23.3%). The bottom ash recycling rate is 67.5% (Taiwan EPA, 2010), and the bottom ash output (79.7%) increases with the amount of waste incinerated, while the service life of a landfill decreases accordingly. Thus, various methods of using bottom ash require improvement. Incineration bottom ash (IBA), if reused, can contribute to environmental sustain-ability pollution and environmental degradation, generating revenue, and preserving natural virgin resources (Naganathan et al., 2010; Sivakumar et al., 2012). Therefore, the EPA has set an 82% recycling rate goal for waste incineration bottom ash in 2012.

As waste disposal by incineration has increased, there has been a need to develop novel reuse applications for IBA that can provide both environmental and economic benefits. IBA is a heterogeneous mix of ceramic materials, such as brick, stone, glass, ferrous and nonferrous metals, and other non-combustible inorganic materials, together with some residual

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Table 1. The amount of waste incineration (WI), bottom ash (BA) and recycling (R) (Taiwan EPA, 2010). Unit: million tonnes

Annuals		2002	2003	2004	2005	2006	2007	2008	2009	2010
WI		569	581	576	558	582	603	611	609	623
Yields	Fly Ash	19.0	19.0	21.3	23.0	17.0	26.0	26.5	27.1	30.1
	BA	92.0	86.0	86.0	84.0	86.0	88.2	94.0	94.2	99.2
R	Amounts	--	11.0	19.4	25.6	28.0	35.5	52.0	59.8	63.1
	Percentages (%)	--	12.8	22.6	30.5	32.6	40.2	55.3	63.5	67.5

organic matter (Poon and Chan, 2006). Many recent studies have shown that IBA can be chemically reactive under certain conditions (Al-Rawas et al., 2005) and that the addition of a calcium chloride-based (but not Na-based) chemical activator can increase the low chemical reactivity of IBA in cement mortar. The medium-sized fraction (14-40 mm) of aged IBA has been deemed usable in the production of lightweight concrete blocks (Qiao et al., 2008). Other extensively recycled products have included concrete paving units, road and roadbed materials, ceramic materials, cement, mineral admixtures, and alternative aggregate materials for use in concrete and controlled low-strength materials (CLSM) (Bertolini et al., 2004; Forteza et al., 2004; Jurič et al., 2006; Lin et al., 2006; Müller and Rübner, 2006; Ferraris et al., 2009; Lancellotti et al., 2010; Weng et al., 2010; Lin et al., 2011; Cheng, 2012). Several European countries, such as the Netherlands, Germany, France, Sweden, and the United Kingdom, have been working to replace natural gravel with municipal solid waste incinerator bottom ash in road construction. However, the leaching of contaminants, such as metals and salts, into the surrounding environment, (i.e., soil and groundwater) has become a main environmental concern associated with this practice. Few studies have been performed to assess the environmental impact of bottom ash using bioassays (Clément et al., 2005; Triffault-Bouchet et al., 2005; Ore et al., 2007). Only 10-20% of aggregates are substituted with bottom ash in Taiwan, and the attainable level of substitution is limited by the chloride ion concentration in the aggregate, specified in the relevant regulations.

Bottom ash was used as the fine aggregate in concrete in a 2006 German study, and laboratory and on-site observations indicate that the aluminum hydroxide component reacts with metallic aluminum in the basic environment to produce hydrogen. This reaction behavior is concluded to be the primary cause of concrete surface cracking. The product of the alkali-silica reaction has also been observed, and the damage resulting from the aluminum reaction is more serious than that from the alkali-silica reaction (Soutsos et al., 2011). In addition, 70-95% dried sewage sludge from municipal waste bottom ash was used in a 2006 Taiwanese study to form permeable clay concrete paving units after separating out metallic contaminants by extruding the sludge at 110 kgf/cm^2 and then sintering it at 900-1,200°C for 60-360 min. The results showed that when the bottom ash addition level is 20% after sintering at 1,150°C for 360 min, the compressive strength of the clinker brick is 256 kgf/cm^2, the water absorption is 2.78%, and the coefficient of permeability is 0.016 cm/sec (Xiao et al., 2011).

Taiwan produces a large amount of ash every year, and the waste issue has become an ash treatment issue. Washed municipal solid waste incinerator bottom ash (WMSWIBS) is often used as a low-cost replacement for more expensive sand in the production of concrete blocks. In many countries, WMSWIBS has even been used as a base in road construction (Lin et al., 2008; Chang et al., 2012; Wang et al., 2010). In this study, natural fine aggregate was replaced by WMSWIBS in the production of compressed mortar interlocking paving units to increase the reutilization ratio of bottom ash, to reduce the exploitation and importation of natural resources, and to increase sustainable resource utilization.

II. MATERIALS AND METHODS

1. Materials

This study used type I Portland cement with a specific gravity of 3.15 and a Blaine fineness of 3,851 cm^2/g. The natural fine aggregate was obtained from the Kaoping River and conformed to the ASTM C33 regulations for concrete aggregate. The natural sand particles passed through a #4 sieve. The WMSWIBS fine aggregate was derived from incinerator bottom ash obtained south of Kaohsiung City, was passed through a #4 sieve, and had a specific gravity of 2.21.

2. Experimental Variables and Mixtures

Cement contents of 0.1, 0.2, 0.3, 0.4, and 0.5 times the oven-dried (OD) WMSWIBS content, based on the weight of the WMSWIBS fine aggregate, and water-cement ratios (w/c) of 0.20, 0.25, and 0.30, were used to form compressed mortar paving units in which were cured in water and air for 7 and 28 days. The maximum w/c at which the form did not leak water when compressed to 10 MPa was selected as the upper w/c limit, while the lower limit was the minimum w/c at which the compressed mortar paving units could still agglomerate after removing their forms. Specimens cannot be formed at a cement-aggregate ratio of 0.5 when the w/c is greater than 0.24. Therefore, cement contents of 0.5 times the WMSWIBS content were used so that the w/c ratio could be limited to 0.24. The unit weights of the mixes are shown in Table 2.

Table 2. Mix proportions of samples. Unit: (kg/m^3)

Mix ID	B1-20	B1-25	B1-30	B2-20	B2-25	B2-30	B3-20	B3-25	B3-30	B4-20
WMSWIBS (SSD)	1619.7	1634.1	1648.4	1512.7	1520.5	1528.2	1423.3	1426.2	1429.1	1347.5
Cement	147.8	149.1	150.4	276.0	277.5	278.9	389.6	390.4	391.2	491.8
Water	29.6	37.3	45.1	55.2	69.4	83.7	77.9	97.6	117.4	98.4
w/c	0.20	0.25	0.30	0.20	0.25	0.30	0.20	0.25	0.30	0.20
Mix ID	B4-25	B4-30	B5-20	B5-24	N2-20	N2-25	N2-30			
WMSWIBS (SSD)	1346.7	1345.9	1282.5	1282.5	–	–	–			
Natural Aggregate	–	–	–	–	1706.8	1712.2	1717.5			
Cement	491.5	491.2	585.1	585.1	334.0	335.1	336.1			
Water	122.9	147.4	117.0	140.4	66.8	83.8	100.8			
w/c	0.25	0.30	0.20	0.24	0.20	0.25	0.30			

*B5-25 and B5-30 are not included in the study because they are in the process of leakage of water.

Table 3. Physical properties of aggregate and bottom ash.

Stuff	Specific Gravity	Absorption (%)	Unit Weight (kg/m^3)	Porosity (%)	Soundness (%)
Fine Washed WMSWIBS	2.21	9.6	1194.3	43.54	9.7
Natural Fine Aggregate	2.62	2.19	1794.5	31.42	1.3

3. Test Methods

The basic aggregate chemical property tests conducted as part of the study included the TCLP and chloride ion content, dioxin, and furan tests, while the physical property tests included specific gravity, water absorption, unit weight, porosity, and soundness tests. Compression tests, water absorption tests, and tests of attrition loss were conducted in accordance with ASTM C936. Water permeability testing was conducted based on Darcy's formula, as in Eq. (1), and variable-head permeability tests were performed to measure the specimens' permeability.

$$k = 2.3\frac{aH}{At}\log\frac{h_0}{h_1} \tag{1}$$

where a is the area of the vertical tube (cm^2), H is the specimen height (cm), A is the specimen area (cm^2), t is the water penetration time (s), h_0 is the initial head difference (cm), and h_1 is the final head difference (cm).

The specimens' ultrasonic pulse propagation velocities were measured by direct transmission using an ultrasound device, which measures the propagation times of ultrasonic pulses in a sample over the range of 0.1-9,999.9 μs with a precision of 0.1 μs. The transducers used for the test measured 28 mm in diameter and had maximum resonant frequencies, as measured in our laboratory, of 42.5 kHz. A JSM-633OTF field emission sweep electron microscope (SEM) produced by JEOL Corp. was used for microstructure observation.

III. RESULTS AND DISCUSSION

1. Physical and Chemical Properties of WMSWIBS

1) Basic Physical Properties

Table 3 shows that the WMSWIBS used in this study contained a large amount of sintered material and glass ceramics and that the particles were irregularly shaped and porous. Thus, its specific gravity was lower and its void ratio and water absorption were higher than those of natural fine aggregate. When natural aggregate was completely replace by WMSWIBS, the water absorption, porosity, and permeability coefficient for paving units with WMSWIBS replacement were greater than that of natural aggregate compressed paving units; however, the compressive strength, ultrasonic velocity, and volume loss of abrasion for paving units with WMSWIBS replacement were lower than natural aggregate compressed paving units. The water-washed bottom ash had a sodium sulfate soundness of 9.7%, which was higher than that of natural fine aggregate (1.3%) but still conformed to the sodium sulfate soundness limit of ≦ 10% specified in ASTM C33.

2) Sieve Analysis

According to Table 4, the accumulated percentages of the WMSWIBS fine aggregate retained on standard-sized sieves were higher than those of natural fine aggregate. The percentage of WMSWIBS fine aggregate passing the #8 sieve (2.36 mm) was slightly lower than the value specified in ASTM C33, but the percentages of WMSWIBS passing through the other sieves conformed to ASTM C33 because the WMSWIBS was a heterogeneous mixture. When washed with water, the smaller aggregates in the WMSWIBS were washed into the sedimentation tank.

3) TCLP

As indicated in Table 5, the WMSWIBS's heavy metal content was far below the limit specified by the EPA,

Table 4. Gradation Distribution of Natural Fine Aggregate and Fine Washed WMSWIBS.

Sieve Size	Cumulative Retained %		Percent Passing %		
	Natural Fine Aggregate	Fine WMSWIBS	Natural Fine Aggregate	Fine WMSWIBS	ASTM C33
3/8” (9.5 mm)	0	0	100.0	100	100
#4 (4.75 mm)	0	4.1	100.0	95.9	95~100
#8 (2.36 mm)	4.4	25.6	95.6	74.4	80~100
#16 (1.18 mm)	17.2	48.7	82.8	51.3	50~85
#30 (600 μm)	42.5	66.8	57.2	33.2	25~60
#50 (300 μm)	71.8	81.7	28.2	18.3	10~30
#100 (150 μm)	93.1	94.6	6.9	5.4	2~10
Fineness Moldulus	2.3	3.3	—	—	

Table 5. TCLP of WMSWIBS.

Test items	WMSWIBS (Washed)	WMSWIBS (Unwashed)	Second Type Quality Standards
Arsenic	< 0.002	ND	≦ 0.50
Barium	0.603	0.396	≦ 100.0
Cadmium	ND < 0.050 (0.008)	0.074	≦ 1.0
Chromium	ND < 0.017	0.643	≦ 5.0
Chromium^{VI}	< 0.05	ND	≦ 0.25
Cuprum	1.96	3.36	≦ 15.0
Mercury	< 0.0010 (0.0006)	ND	≦ 0.02
Lead	ND < 0.100	2.25	≦ 5.0
Selenium	ND < 0.005	ND	≦ 1.0

Note 1: Unit: mg/L.

Note 2: “ND”: Below the method detection limit of the measured values;
“< lowest concentration of calibration curve”: Below the lowest point concentration of calibration curve.

Table 6. The results of water-soluble chloride, dioxin and furan of WMSWIBS.

Test items	Test Value	Test Methods
Water-Soluble Chloride (%)	0.0118	CNS 13407
Dioxins and Furans	0.009 (ng I-TEQ/g d.w.) 0.008 (ng I-TEQ/g d.w.)	NIEA M801.11B

Note 1: All other concrete CNS provides their maximum allowable chloride ion content of 0.024%

Note 2: Dioxins and furans of WMSWIBS reuse the second type of quality standards: ≦ 0.1(ng I-TEQ/g d.w.)

suggesting its potential for reuse. This heavy metal content was low, indicating that the water washing procedure was effective at reducing the pollution concentration in the bottom ash. Thus, WMSWIBS was deemed suitable for use in applications where the leaching of heavy metals would be a potential concern.

4) Chloride Ion, Dioxin, and Furan Contents

Table 6 shows that the chloride ion content of the WMSWIBS conforms to the CNS 13407 requirements and the first types of quality standards issued by the EPA for WMSWIBS recycling. The dioxin and furan contents were below the limits specified by the EPA and conformed to the second quality standards issued by the EPA for WMSWIBS recycling.

2. Engineering Properties of WMSWIBS-Based Compressed Mortar Paving Units

1) Unit Weight

Table 7 indicates that the difference between the unit weight of compressed mortar paving units used in practice and those made with WMSWIBS fine aggregate in this experiment ranged from 0.03-0.41%. The compressed mortar paving units made in the laboratory were consistent in quality and conformed to the designed mix ratio. In addition, the unit weight of the compressed mortar paving units made using WMSWIBS fine aggregate was identical to that of compressed mortar paving units made with 10% furnace slag substitution for cement.

2) Compressive Strength

Fig. 1 shows that the compressive strength was highest (45.4 MPa) when the cement-aggregate ratio measured 0.5 and the w/c measured 0.24 at a curing age of 7 days. A high cement-aggregate ratio and high w/c enhanced the cementation

Table 7. Test mix and the actual mix of unit weight error percentages (compressed mortar paving units).

Mix ID	Unit Weight of Test Mix (kg/m^3)	Unit Weight of Actual Mix (kg/m^3)	Unit Weight Error Percentages (%)
B1-20	1797.0	1791.2	0.33
B1-25	1820.5	1819.5	0.05
B1-30	1843.9	1839.0	0.26
B2-20	1843.9	1836.3	0.41
B2-25	1867.3	1865.6	0.09
B2-30	1890.8	1887.3	0.19
B3-20	1890.8	1888.6	0.11
B3-25	1914.2	1912.6	0.08
B3-30	1937.7	1937.3	0.02
B4-20	1937.7	1935.3	0.12
B4-25	1961.1	1958.9	0.11
B4-30	1984.5	1983.9	0.03
B5-20	1984.5	1982.4	0.11
B5-24	2008.0	2007.4	0.03

Table 8. Compressive strength of compressed mortar paving units (curing in water and air; unit: MPa).

Curing	In Water (7 day)	In Air (7 day)	In Water (28 day)	In Air (28 day)
Average	27.44	26.79	30.95	30.15
Average Standard Error	3.18	3.12	3.10	3.04
Standard Deviation	11.92	11.67	11.61	11.39

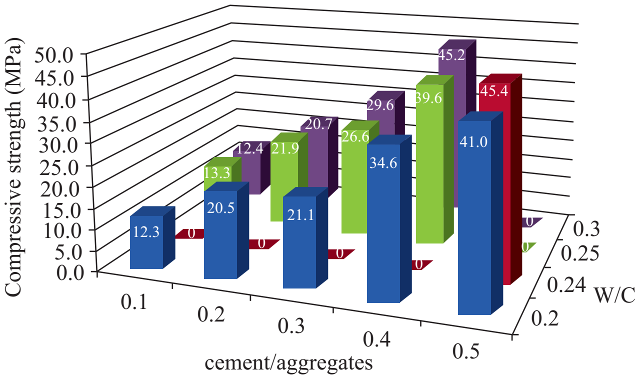


Fig. 1. Effect of WMSWIBS content on compressive strength.

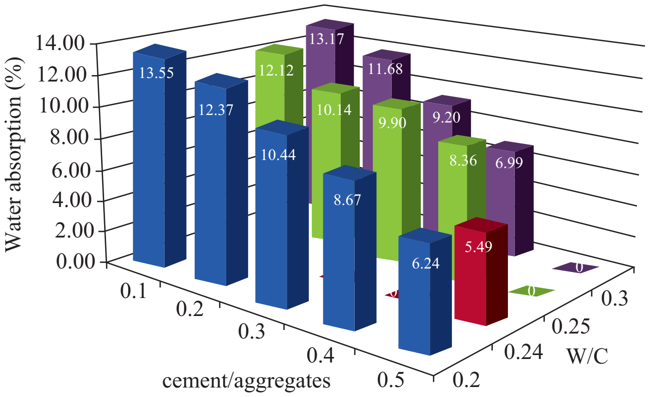


Fig. 2. Effect of WMSWIBS content on absorption.

between the mortar and aggregate, which increased the unit weight and density of the compressed mortar paving units. Conversely, the compressive strength was lowest (12.3 MPa) when the cement-aggregate ratio measured 0.1 and the w/c measured 0.2. Table 8 suggests no obvious differences in the compressive strengths of compressed mortar paving units cured in water and air for 7 and 28 days and having cement-aggregate ratios of 0.1-0.5 and w/c ratios of 0.2-0.3 because the WMSWIBS-based compressed mortar paving units used fine aggregate and were pressurized. The mortar's compressive strength was 45.2 MPa for a cement-aggregate ratio of 0.4 and a w/c of 0.3 and rose to 45.4 MPa for a cement-aggregate ratio of 0.5 and a w/c of 0.24. The compressive strengths of these two mixes met the requirements of ASTM C936 for Class C brick (> 45 MPa), and the cement-aggregate ratios of 0.3-0.5 complied with the requirements for mortar curbs (> 21 MPa).

3) Absorption of Compressed Mortar Paving Units

Fig. 2 shows that the mix design with a cement-aggregate ratio of 0.5 and a w/c of 0.24 yielded the minimum aggregate absorption because this design had a high cement-aggregate ratio and an appropriate w/c for compacting the mortar paving units, as was also demonstrated by this mix's higher unit weight. The mix design yielding the maximum aggregate absorption had a cement-aggregate ratio of 0.1 and a w/c of 0.2. With a lower cement-aggregate ratio and less water, this mix ratio created more pores inside the mortar paving units, which

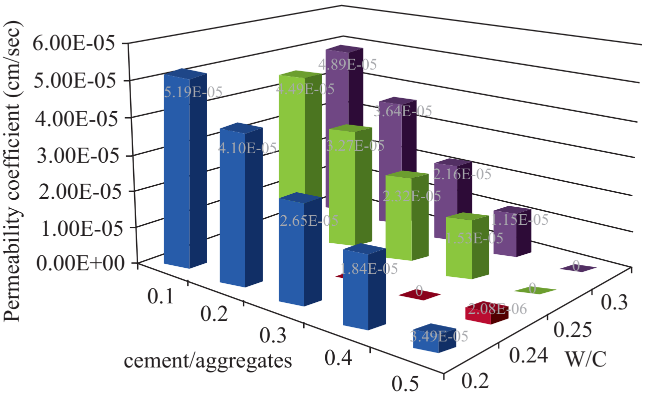


Fig. 3. Effect of WMSWIBS content on permeability coefficient.

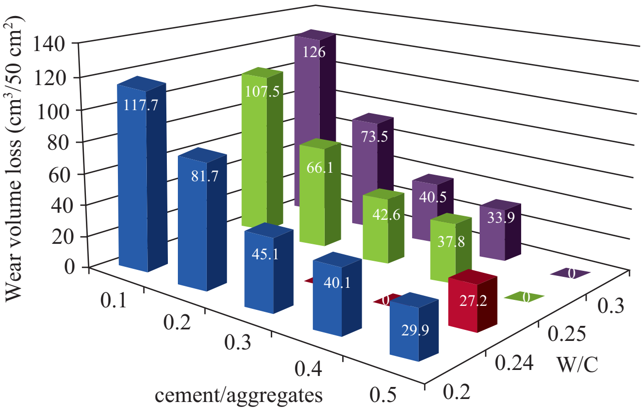


Fig. 5. Effect of WMSWIBS content on volume loss of abrasion.

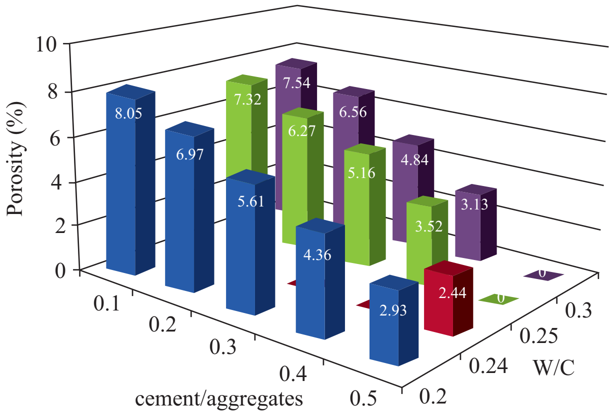


Fig. 4. Effect of WMSWIBS content on porosity.

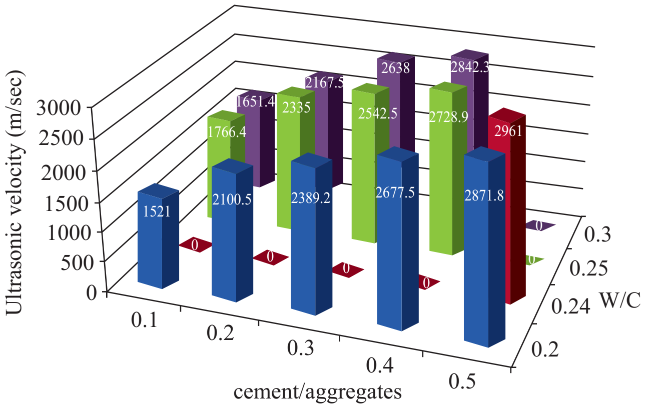


Fig. 6. Effect of WMSWIBS content on ultrasonic velocity.

was also demonstrated by its lower unit weight. In addition, the water absorption of the paving units with cement-water ratios of 0.4-0.5 met the < 9% requirement for Class C bricks.

4) Coefficient of Permeability

According to Fig. 3, the mortar's coefficient of permeability was lower (2.08×10^{-6} cm/sec) at 7 days when the cement-aggregate ratio measured 0.5 and the w/c measured 0.24 because this mix design had a high cement-aggregate ratio and an appropriate w/c for compacting the mortar paving units. In contrast, the coefficient of permeability reached its maximum (5.19×10^{-5} cm/sec) when the cement-aggregate ratio measured 0.1 and the w/c measured 0.2.

5) Porosity

Fig. 4 shows that the porosity was lower (2.44%) at 7 days when the cement-aggregate ratio measured 0.5 and the w/c measured 0.24 because this mix ratio had a high cement-aggregate ratio and an appropriate w/c for compacting the mortar paving units. Conversely, the porosity reached its maximum (8.05%) when the cement-aggregate ratio measured 0.1 and the w/c measured 0.2.

6) Test of Abrasion Loss

Fig. 5 shows that the abrasion loss at 7 days was lower (27.2 cm^3/50 cm^2) when the cement-aggregate ratio measured 0.5 and the w/c measured 0.24 because this mix ratio had a higher unit weight that resulted in a higher compressive strength. In contrast, the abrasion loss reached its maximum (117.7 cm^3/50 cm^2, or approximately 7.4 times the minimum) when the cement-aggregate ratio measured 0.1 and the w/c measured 0.2. The compressive strength increased as the abrasion volume loss decreased.

7) Ultrasonic Pulse Velocity

Fig. 6 shows that the ultrasonic pulse velocity at 7 days was higher (2,961 m/sec) when the cement-aggregate ratio measured 0.5 and the w/c measured 0.24. The ultrasonic pulse velocity increased with the unit weight and compressive strength and reached its minimum (1,521 m/sec) when the cement-aggregate ratio measured 0.1 and the w/c measured 0.2.

Table 9 shows results of the Pearson correlation coefficient analysis for relationships between various engineering properties of compressed paving units, w/c, and c/a. The Table 9 indicates that the cement-aggregate ratio had a significance correlated to various mortar engineering properties. When the compressive strength and ultrasound measured 0.93 to 0.96,

Table 9. Analysis of pearson correlation coefficient for engineering properties of compressed mortar paving units.

	Compressive Strength				Absorption		Permeability Coefficient	
	Curing in Water		Curing in Air					
	7 day	28 day	7 day	28 day	7 day	28 day	7 day	28 day
c/a	0.95**	0.96**	0.95**	0.95**	-0.96**	-0.93**	-0.99**	-0.95**
w/c	0.02	0.04	0.03	0.04	0.02	-0.03	0.05	-0.01
	Loss of Abrasion				Porosity		Ultrasonic Velocity	
	Loss of Volume		Loss of Thickness					
	7 day	28 day	7 day	28 day	7 day	28 day	7 day	28 day
c/a	-0.92**	-0.93**	-0.92**	-0.94**	-0.98**	-0.99**	0.95**	0.93**
w/c	0.09	0.005	0.08	0.03	0.003	0.05	-0.001	0.05

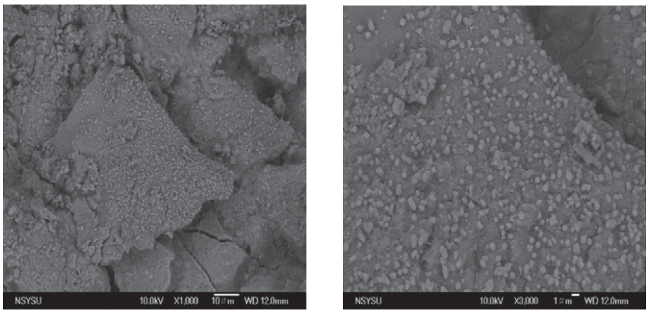
the compressive strength and ultrasonic pulse velocity increased with the cement-aggregate ratio. When the absorption of aggregate, the coefficient of permeability, the porosity, and the attrition loss are -0.92 to -0.99, the absorption of aggregate, the coefficient of permeability, the porosity, and the attrition loss decrease with the increasing c/a. The w/c had no significant correlated on these properties, and the correlation coefficients were lower than that of the cement-aggregate ratio, which ranged from 0.001 to 0.09.

3. Comprehensive Analysis

When the designed mixture ratio with a high cement-aggregate ratio and an appropriate w/c ratio, the compressed paving units became denser with higher unit weight, compressive strength, and ultrasonic velocity; but with lower absorption, coefficient of permeability, and attrition loss. When natural aggregate was completely replaced by WMSWIBS, the absorption, porosity, and permeability coefficient for compressed paving units with WMSWIBS replacement were greater than that of units with natural aggregate; but, the compressive strength, ultrasonic velocity, and volume loss of abrasion for compressed paving units with WMSWIBS replacement were smaller than that of units with natural aggregate. Moreover, test results show that the compressive strength for compressed paving units with a higher cement-aggregate ratio and an appropriate w/c conformed to the ASTM C936 Class C brick (> 45 MPa) and curbs (> 21 MPa) requirements and the water absorption (< 9%). It suggests in this study that the application of WMSWIBS to manufacture compressed paving units is feasible.

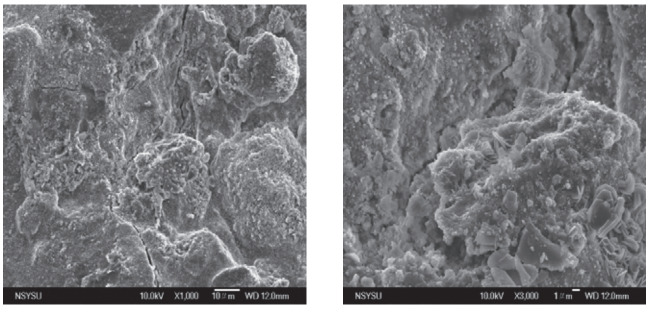
4. Microscopic Properties Measured with SEM

1) Compressed Mortar Paving Units with Low Cement Contents (Cement-Aggregate Ratios of 0.1 to 0.2)



(1) 1000X (2) 3000X

7 day



(3) 1000X (4) 3000X

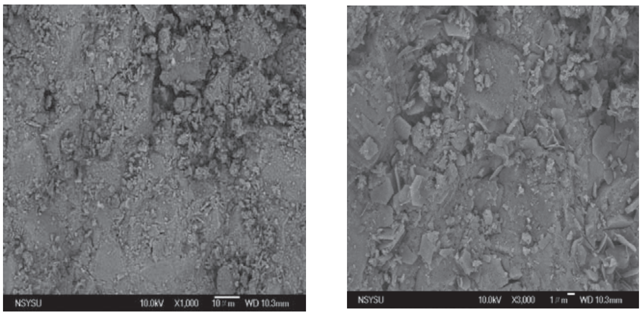
28 day

Fig. 7. SEM image of compressed mortar paving units (c/a = 0.1, w/c = 0.2).

Fig. 7 shows that the hydrate structure was loose, disordered, and spread over the entire aggregate surface. Some pores and cracks existed near the aggregate. The cracks may have resulted from the specimen treatment, and the micro-cracks may already have been present in the aggregate. Irregular, flaky, spiny C-S-H gel and unreacted hydrates were visible on the aggregate surface at a magnification of 3000X, while reacted, irregular, flaky, and spiny C-S-H gel, uniformly distributed over the aggregate surface, was visible at an age of 28 days at a magnification of 1000X, and the hydrate structure was denser and more complete than at 7 days. At a magnification of 3000X, the pores and microcracks appeared to be spread and filled with flaky, spiny C-S-H gel and flaky AFm hydrate.

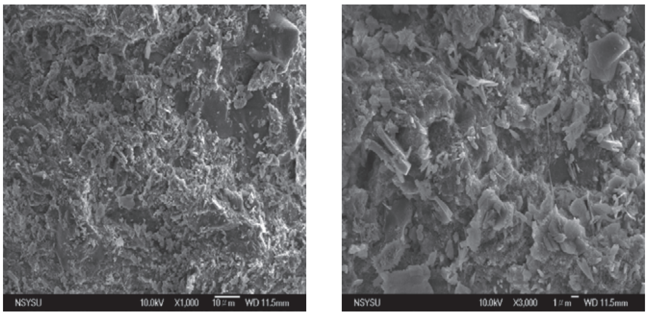
2) Compressed Mortar Paving Units with High Cement Contents (Cement-Aggregate Ratios of 0.3 to 0.5)

Fig. 8 indicates that, compared to the interface crystal phase diagrams for mortars with low cement contents at 7 days, many reacted cement hydrates, such as spiny C-S-H gel colloid, were spread densely over the aggregate surface and the hydrate structure was more complete in mortars with high



(1) 1000X (2) 3000X

7 day



(3) 1000X (4) 3000X

28 day

Fig. 8. SEM image of compressed mortar paving units (c/ a = 0.4, w/c = 0.2).

cement contents. Some pores and microcracks existed in the aggregate. Spiny C-S-H gel colloid and hexagonal flaky Afm hydrates were visible on the aggregate surface at a magnification of 3000X. More reacted cement hydrates became visible at a magnification of 1000X and were distributed more densely and completely at 28 days than at 7 days. Compared to the interface crystal phase diagrams for mortars with low cement contents at 28 days, the hydrates were distributed over the entire aggregate surface more uniformly and extensively in mortars with high cement contents and the hydrates were denser and more complete. At a magnification of 3000X, the aggregate surface was uniformly covered with irregular, flaky, honeycomb-shaped C-S-H gel and flaky Afm hydrates.

IV. CONCLUSIONS

1. The TCLP test values of the mortar created and tested in this study complied with the EPA standard, and the heavy metals content was reduced after washing. Thus, WMSWIBS was deemed suitable for use in applications in which the leaching of heavy metals would be a potential concern.
2. The most important factor affecting the engineering properties of WMSWIBS-based compressed mortar paving units was the cement-aggregate ratio, when the w/c ratio is assigned between 0.2 and 0.3.
3. The mix with a cement-aggregate ratio of 0.4 and a w/c of 0.3 had a compressive strength of 45.2 MPa, while the mix with a cement-aggregate ratio of 0.5 and a w/c of 0.24 had a compressive strength of 45.4 MPa. The compressive strengths of these two mixes complied with the requirements of ASTM C936 for Class C brick, and cement-aggregate ratios in the range of 0.3-0.5 met the requirements for mortar curbs.
4. When the cement-aggregate ratio fell within the range of 0.1 to 0.2, the compressed mortar paving units possessed the best engineering properties at a w/c of 0.25. When the cement-aggregate ratio fell within the range of 0.3 to 0.4, the compressed mortar paving units possessed better engineering properties at higher w/c values.
5. An examination of the mortar's microinterface showed that hydration increased with increasing cement-aggregate ratio and age, filling up the pores in the bottom ash and enhancing the cementation between aggregates. This behavior was consistent with the trends observed for various engineering properties in the mortar.

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