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Use of washed municipal solid waste incinerator bottom ash in pervious concrete

Wen-Ten Kuo [a,*], Chih-Chien Liu [b], De-Sin Su [a]

[a] Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung 807, Taiwan, ROC
[b] Department of Civil Engineering, ROC Military Academy, Fengshan 830, Taiwan, ROC

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ABSTRACT

Washed municipal solid waste incinerator bottom ash (MSWIBA) was used in this study as a substitute for natural aggregate in pervious concrete. The mix proportions of the concrete were first determined using a vertical flow test. Other tests, including permeability, compressive strength, bending and split tensile strength tests, were also performed. The test results show that the unit weight of the fresh pervious concrete made with MSWIBA was approximately 1653–2080 kg/m^3 and increased with the ratio of cement paste filling. In specimens with the same water–cement ratio, the compressive, bending and split tensile strengths all increased with the ratio of filling paste. The split tensile and bending strengths were approximately 1/9 and 1/4 of the compressive strength, respectively. The connected porosity and permeability coefficients are linearly correlated; both decrease as the filling ratio is increased.

1. Introduction

Current global trends are focused on the use of recycled materials and energy conservation to reduce carbon emissions. High-temperature and combustion incineration treatments for waste are universally used in developed cities. The bottom ash produced by incinerators must be pretreated by sieving, crushing or filtering before recycling and then subsequently pretreated by stabilization, aging or water washing, in accordance with the requirements for specific reused product categories. Before reuse, the toxicity characteristic leaching procedure (TCLP) is conducted and the dioxin toxicity equivalent concentration value of the pretreated bottom ash is determined to ensure that the material meets the appropriate standard for hazardous industrial waste [1]. In Taiwan, for example, the annual reporting of the statistics office for waste incineration plants shows that in 2011, the total waste input was 6,507,763 tons, the incineration treatment capacity was 6,355,422 tons, and the bottom ash output was 1,357,557 tons [2]. If the majority of the incinerator bottom ash were to be buried, the available burial grounds would not be sufficient to accommodate it. Therefore, this incinerator bottom ash must be reused effectively to reach the goals of zero waste and full recovery. Presently, several of the most mature applications involve incorporation of incinerator bottom ash in road base layers, pavement, dikes, concrete blocks and controlled low-strength materials [3].

Waste incinerator bottom ash accounts for approximately 20% of the original weight of municipal solid waste. Studies have shown that the constituents of bottom ash are silica, calcium oxide, ferric oxide, alumina, sodium oxide, magnesium oxide and other trace metal oxides [4–8]. These components account for more than 90% of the dry weight, which means that the bottom ash is compositionally similar to terrestrial crushed stone and soil. Landfilling of waste incinerator bottom ash prevents sustainable development of the environment. Belgium, the Netherlands, Germany and France have all established criteria for the recycling of municipal solid waste incinerator bottom ash (MSWIBA) [9]. The use of MSWIBA in engineering applications is an important recovery application, which should conform to laws and regulations. Specifically, after pretreatment (dry or wet sieving) and confirming that it conforms to weathering and leaching limits, MSWIBA is can be recovered as a nonstructural construction material and road base aggregate [10].

Pervious Portland cement concrete (PPCC) is an environmentally friendly paving material. PPCC consists of Portland cement, water, uniformly graded coarse aggregate, and little or no fine aggregate. Hence, the porosity and permeability of PPCC are much greater than those of conventional concrete, and as a result, rainwater is rapidly drained from it [11–16]. The porosity of concrete results from the use of coarse aggregate gradations with maximum particle sizes of 12.5 mm and 9.5 mm, and the paste volume is formed from inadequate water and cement, which prevents the voids between the aggregate from filling [17]. Based on its environmentally friendly characteristics, which can reduce the effect of heat islands on the environment, PPCC has recently passed the

* Corresponding author.
E-mail address: wtkuo@cc.kuas.edu.tw (W.-T. Kuo).

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Leadership in Energy and Environmental Design (LEED) Green Building evaluation system promoted by the U.S. Green Building Council (USGBC) [12]. Roads in urban areas typically cover large areas with impervious road materials, which increases the concentration of hot gases in the vicinity of the roads; in contrast, the open structure of pervious concrete allows air to flow, which reduces the concentration of hot gases. This has been shown in previous studies in which traditional concrete technologies have been applied to road surfaces [18–20]. The pores in pervious concrete tend to vary in size from 2 to 8 mm [21]. The porosity of pervious concrete typically varies from 18% to 35% [22], and the compressive strength typically varies from 2.8 to 28.0 MPa [23]. Pervious concrete has been used in many countries, particularly in the UK and the US, for more than 30 years [11]. It has been used in the construction of parks, low-traffic regions, pedestrian walkways, tennis courts, greenhouses and other civil engineering and architectural applications [11,23–29].

Published research on the use of MSWIBA as an aggregate for pervious concrete, however, is still limited. Li [22] used finite element analysis to simulate the compressive strength of a pervious recycled concrete with no fine aggregate. To verify the simulation, a relatively high-strength epoxy was used as the bonding agent in the recycled aggregate, but the bonding agent was not cement.

In this study, washed MSWIBA was used in place of natural aggregates to make pervious concrete. The mix proportions were selected based on vertical flow tests. The characteristics of the washed MSWIBA used in the pervious concrete are discussed in terms of the results of permeability tests and compressive, flexural and split tensile strength tests.

2. Experimental program

In this study, washed MSWIBA with a maximum size of 12.5 mm (the most abundant size of washed MSWIBA particles) was used as the main experimental aggregate. First, the toxicity characteristic leaching procedure (TCLP) was conducted. Table 1 shows the TCLP test data for washed and unwashed MSWIBA. Next, other experiments were performed, including chlorine, dioxin and furan content tests; tests of volume proportions, unit weight and porosity (ASTM C29); sieve analysis (ASTM C136); water absorption measurement (ASTM C127); and shape factor analysis. Coincidentally, washed MSWIBA of this size has the highest volume proportion of MSWIBAs.

A wide range of values of the water–cement ratio (also known as the w/c ratio) and the pore filling paste ratio was used to fabricate pervious concrete samples for testing. Cylinders measuring 150 mm in diameter and 300 mm in length were fabricated as test specimens. The pervious concrete mix design was based on the results of vertical flow tests, permeability tests, and tests of compressive strength, split tensile strength, and bending strength of the concrete after hardening. Based on the test results, the experimental mix proportions of the concrete specimens (shown in Table 2) were determined. The mix proportions of the concrete mixes with the best test results were selected (w/c ratios of 0.35, 0.40 and 0.45 and pore filling ratios of 60%), and a natural aggregate with the same maximum aggregate size as the control aggregate as well as a washed MSWIBA with a maximum aggregate size of 9.5 mm (the comparison group, representing the second most abundant particle size in washed MSWIBA) were used. The same tests were then performed to investigate the differences in the properties of the concretes made using washed MSWIBA and natural aggregate in order to assess the effects that the use of washed MSWIBA with a smaller dimension has on the properties of pervious concrete.

The test methods used are described below.

2.1. Shape factor analysis

Shape factor analysis of aggregates involves the determination of three items: the triaxial shape factor, the flatness indicator and the spherical coefficient [30]. The lengths of the longest axis, the intermediate axis and the shortest axis are referred to as a, b and c, respectively. The triaxial shape factor, the flatness indicator and the spherical coefficient are $\sigma_1 = \frac{c}{\sqrt{ab}}$, $\sigma_2 = \frac{a+b}{2c}$ and $\sigma_3 = \sqrt[3]{(b/a)^2(c/b)}$, respectively. A higher flatness indicator indicates a flatter shape, and a higher spherical coefficient indicates a more spherical shape [31].

2.2. Vertical flow testing

Vertical flow tests were conducted using an electric flow table. Samples of freshly mixed pervious concrete were placed inside a #4 sieve and vibrated 25 or 50 times for 15 or 30 s, respectively. The flow table apparatus used in this study conforms to the requirements of the ASTM C136 test. The weight loss rate of the slurry was calculated using the following equation:

$$L(\%) = \frac{W_2}{W_1} \tag{1}$$

where W_1 and W_2 are the weights of the original fresh concrete and mortar passing through the #4 sieve mesh after the vertical flow test.

2.3. Permeability testing

Permeability tests were conducted based on Darcy's law, in accordance with ASTM D2434, using the constant water head method. Eq. (2) was used to calculate the permeability coefficient:

$$K_T = \frac{L}{h} \cdot \frac{Q}{A(t_2 - t_1)} \tag{2}$$

where K_T is the permeability coefficient (cm/s), L is specimen thickness (cm), h is head difference (cm), t_1 is start time of the

Table 1
Test data of TCLP for the washed and unwashed MSWIBA.

Metals	Washed MSWIBA (mg/l)	Unwashed MSWIBA (mg/l)	Second type regulatory level of EPA in Taiwan (mg/l)
Arsenic	ND < 0.002	ND < 0.002	≦0.50
Bstium	0.396	0.603	≦100.0
Cadmium	ND < 0.050	0.074	≦1.0
Chromium	ND < 0.017	0.643	≦5.0
Hexavalent chromium	ND < 0.05	ND < 0.05	≦0.25
Copper	1.96	3.36	≦15.0
Mercury	ND < 0.0010	ND < 0.001	≦0.02
Lead	ND < 0.100	2.25	≦5.0
Selenium	ND < 0.005	ND < 0.005	≦1.0

Note: ND: below the method detection limit of the determination.

Table 2
Mix proportion of concrete.

Material	w/c ratio	Pore filling paste ratio (%)	Mix proportion (kg/m^3)		
			Cement	Aggregate (OD)	Water
12.5 mm MSWIBA	0.30	40	284	1404	112
		50	355	1404	134
		60	426	1404	155
		70	497	1404	176
		80	568	1404	198
	0.35	40	263	1404	106
		50	328	1404	126
		60	394	1404	145
		70	460	1404	165
		80	525	1404	185
	0.40	40	244	1404	101
		50	305	1404	119
		60	367	1404	137
		70	428	1404	156
	0.45	40	228	1404	96
		50	286	1404	113
		60	343	1404	130
	0.50	40	214	1404	92
		50	268	1404	108
9.5 mm MSWIBA	0.35	60	394	1350	175
	0.40		367	1350	167
	0.45		343	1350	160
12.5 mm natural aggregate	0.35	60	394	1578	137
	0.40		367	1578	129
	0.45		343	1578	122

Table 3
Basic properties of washed MSWIBA and natural aggregate used in the experiment.

Material	Specific gravity			Water absorption (%)	Unit weight (kg/m^3)	Porosity (%)
	OD	SSD	Apparent			
12.5 mm MSWIBA	2.45	2.50	2.58	1.94	1404	43.83
9.5 mm MSWIBA	2.28	2.37	2.52	4.21	1350	43.03
12.5 mm natural aggregate	2.59	2.62	2.67	1.21	1578	39.78

Table 4
Classification of washed MSWIBA and shape factor.

Aggregate type	Percentage	Shape factor	Flatness indicator	Spherical coefficient
Natural	64.3	0.47	2.49	0.09
Sinter	18.0	0.63	1.69	0.13
Ceramic tile	8.5	0.30	3.96	0.06
Glass plastic	7.9	0.32	3.93	0.06
Red brick	1.0	0.51	2.17	0.10
Other	0.3	0.16	9.66	0.03

experiment (s), t_2 is experiment termination time (s), Q is quantity of water collected between times t_1 and t_2 (cm^3), and A is the pervious area (cm^2).

2.4. Designed porosity and the experimental connected porosity

The designed porosity was calculated as the void content in the aggregate minus the pore-filling paste ratio. The void content in the aggregate was obtained in accordance with ASTM C29.

The experimental connected porosity (P) was calculated using Eq. (3) [32].

$$P = \left[1 - \frac{W_4 - W_3}{V_1}\right] \times 100 \quad (3)$$

where W_3 is the specimen weight in water after 24 h of soaking, W_4 is the specimen weight after the specimen was removed from the water and dried to a constant weight at room temperature, and V_1 is the volume of the specimen.

3. Results and discussion

3.1. Basic properties of the aggregates

Table 3 shows that the washed MSWIBA has a smaller unit weight, a higher porosity and greater water absorption than the natural aggregate. The unit weights of the 12.5-mm and 9.5-mm MSWIBA were 1404 and 1350 kg/m^3, respectively, lower than that of 12.5-mm natural aggregate, which was 1578 kg/m^3. The porosities of 12.5-mm and 9.5-mm MSWIBA were 43.83% and 43.03%, respectively, higher than that of 12.5-mm natural aggregate, which was 39.78%. The water absorptions of 12.5-mm and 9.5-mm

Fig. 1. Photo of washed MSWIBA.

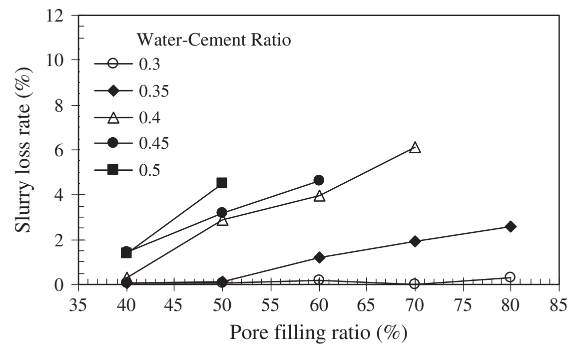

Fig. 2. Slurry loss rate of the washed MSWIBA pervious concrete (25 vibrations).

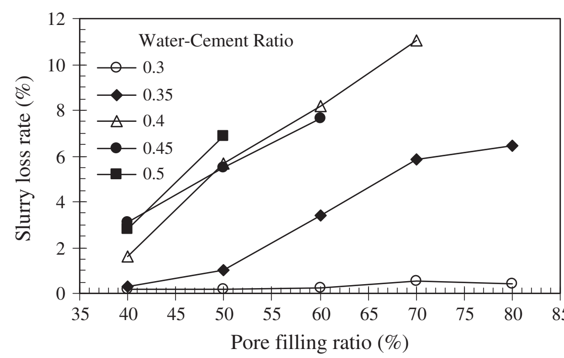

Fig. 3. Slurry loss rate of the washed MSWBA pervious concrete (50 vibrations).

MSWIBA were 1.94% and 4.21%, respectively, higher than that of 12.5-mm natural aggregate, which was 1.21%.

Following classification, the washed MSWIBA used in this study was separated into six different components: natural aggregate (with extra aggregate added), sintered block, ceramic tile, glass plastic, red brick and "other." The experimental results used to determine the shape factors are shown in Table 4. The shape factor for river gravel usually ranges from 0.3 to 1.0, with 0.7 being the most common shape factor. The shape of river gravel is typically spherical. Aggregates with higher flatness factors tend to have flatter shape, while those with higher spherical coefficients tend to be more spherical [31]. Most of the washed MSWIBA aggregates were flat. A photo of the washed MSWIBA is shown in Fig. 1.

The TCLP test results for the washed MSWIBA showed that its heavy metal content was far less than the maximum specified by the Taiwan EPA, which means that the MSWIBA could be reused. Compared to the unwashed MSWIBA from the same source, the washed MSWIBA had a significantly lower heavy metal content, which indicates that the washing procedure was able to remove the majority of the heavy metals present in the bottom ash. The chloride ion content was tested in accordance with AASHTO T-260, and with a content of 0.012% by weight, its concentration proved to be lower than the 0.024% limit for aggregate in ordinary concrete. Dioxin and furan were tested using the NIEA M801.11B method, and their yield concentrations were found to be 0.009 and 0.008 ng I-TEQ/g d.w. (the international toxic equivalent factor), respectively, both of which are lower than the second MSWIBA quality standard of ≦0.1 ng I-TEQ/g d.w.

3.2. Results for the pervious concrete made with 12.5-mm washed MSWIBA

3.2.1. Properties of the concrete

3.2.1.1. Unit weight of the freshly mixed concrete. The unit weight of the newly mixed pervious concrete was found to be in the range of 1653–2080 kg/m^3, as shown in Table 5. This concrete exhibited a trend of increasing unit weight with increasing filling paste ratio, and because the filling ratio does not reach 100%, the concrete has a lighter unit weight than ordinary concrete.

3.2.1.2. Connected porosity. The connected porosity is the main factor that affects the permeability of concrete. As shown in Table 5, the porosity decreases with the filling paste ratio; nonetheless, the experimental results demonstrate that the porosity of the tested mixes was slightly greater than the design porosity. This difference might be due to the coarse surface of the washed MSWIBA.

3.2.1.3. Vertical flow rate. The vertical flow rate test is a simple yet effective assessment of whether a concrete mix of specific proportions is sufficiently but not excessively fluid. If the vertical flow rate is too high, an accumulation of cement paste will cause a blockage at the bottom of the pervious concrete, thereby affecting its permeability. Figs. 2 and 3 show the loss rate of the slurry for 25 and 50 vibrations, respectively. Except for the 0.30 w/c ratio mix, which did not exhibit a significant vertical flow phenomenon,

Table 5
Unit weight and connected porosity of freshly mixed pervious concrete.

Water–cement ratio	0.30					0.35				
Pore filling paste ratio (%)	40	50	60	70	80	40	50	60	70	80
Unit weight (kg/m^3)	1677	1789	1804	1842	1992	1653	1789	1839	1927	2080
Connected porosity (%)	28.1	27.9	23.9	20.7	10.3	31.4	28.6	24.5	15.7	11.4
Designed porosity (%)	26.3	21.9	17.5	13.1	8.8	26.3	21.9	17.5	13.1	8.8
Water–cement ratio	0.40				0.45			0.50		
Pore filling ratio (%)	40	50	60	70	40	50	60	40	50	
Unit weight (kg/m^3)	1670	1735	1803	1851	1673	1786	1849	1627	1870	
Connected porosity (%)	31.8	22.2	22.5	18.6	32.1	30.5	26.6	32.7	30.7	
Designed porosity (%)	26.3	21.9	17.5	13.1	26.3	21.9	17.5	26.3	21.9	

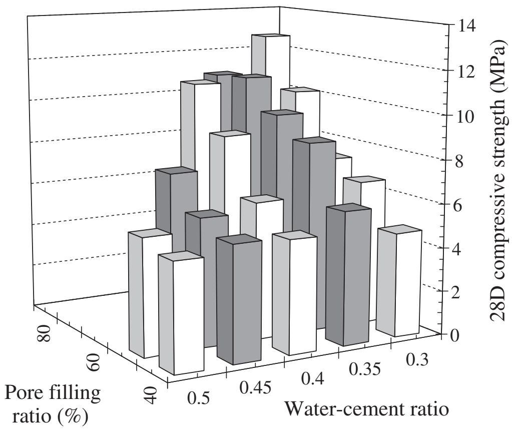

Fig. 4. Compressive strength of the washed MSWBA pervious concrete.

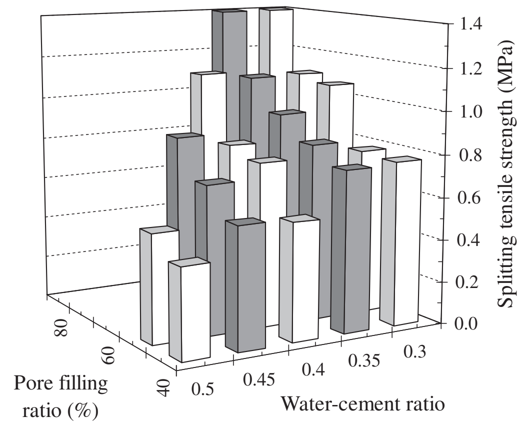

Fig. 5. Splitting tensile strength of the washed MSWBA pervious concrete.

when the w/c ratio of the pervious concrete was fixed, the loss rate of the slurry increased with the amount of paste filling. The trend lines for the slurry weight loss rate at 25 and 50 vibrations are similar, indicating that both are suitable for use in assessing the appropriateness of the pervious concrete.

The test results shown in Fig. 2 were obtained for a vibrational frequency in the vertical flow rate test of 25 times per 15 s. It was found that when the vertical flow rate exceeded approximately 6%, the voids in the concrete at the bottom were filled with paste to the extent that the concrete's permeability was reduced. The test results shown in Fig. 3 were obtained for a vibrational frequency in the vertical flow test of 50 times per 30 s. Similar results were obtained when the vertical flow rate exceeded approximately 12%.

3.2.1.4. Compressive strength. The compressive strength values after a 28-day moist curing period are shown in Fig. 4. For specimens with the same w/c ratio, the compressive strength increased with the filling paste ratio. The concrete with a low w/c ratio (0.3) and a high pore-filling paste ratio (80%) had the highest compressive strength, which was found to be 12.68 MPa. The concrete with a w/c ratio of 0.3 and a filling ratio of 40% had the lowest compressive strength (4.75 MPa) because a low w/c ratio and a low filling ratio were used together, which resulted in an uneven mix and a low compressive strength. Observing the specimen after the compressive test, it was found that fracture occurred along the interface between the paste and the aggregate. At a lower pore-filling paste ratio, the specimen might have undergone complete disintegration.

3.2.1.5. Split tensile strength. The split tensile strength values after a 28-day moist curing period are shown in Fig. 5. For specimens with the same w/c ratio, the split tensile strength increased with the pore-filling paste ratio. The concrete with a 0.35 w/c ratio and an 80% filling ratio had the highest split tensile strength value, at 1.40 MPa. The value of the split tensile strength of concrete was approximately 1/9 of the value of the compressive strength.

3.2.1.6. Flexural strength. The bending strength values after a 28-day moist curing period are shown in Fig. 6. For specimens with the same w/c ratio, the bending strength increased with the filling paste ratio. The concrete with a 0.40 w/c ratio and a 70% pore-filling paste ratio had the highest value, at 3.11 MPa. The value of the bending strength of concrete was approximately 1/4 of the value of the compressive strength.

3.2.1.7. Permeability coefficient. The permeability coefficient values after a 28-day moist curing period are shown in Fig. 7. For specimens with the same w/c ratio, the permeability coefficient

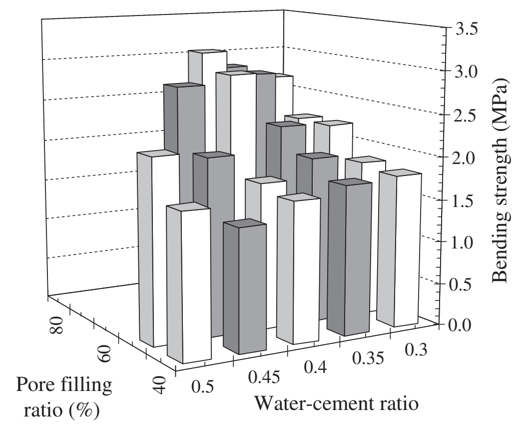

Fig. 6. Bending strength of the washed MSWBA pervious concrete.

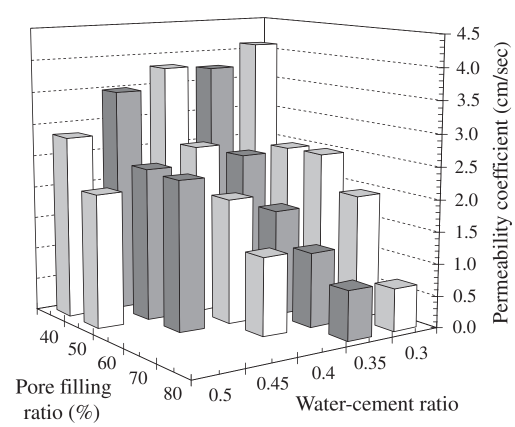

Fig. 7. Permeability coefficient of the washed MSWBA pervious concrete.

decreased as the pore-filling paste ratio increased. The concrete with a 0.30 w/c ratio and a 40% filling ratio had the highest value, at 4.11 cm/s. The permeability ratios of all of the mixes met the requirement of being at least 1×10^{-2} cm/s for pedestrian pavement in Taiwan.

3.2.2. The effect of the connected porosity on the permeability of concrete

For specimens with the same w/c ratio, it was found that both the connected porosity and the permeability coefficient decreased as the pore-filling paste ratio increased. The relationship between

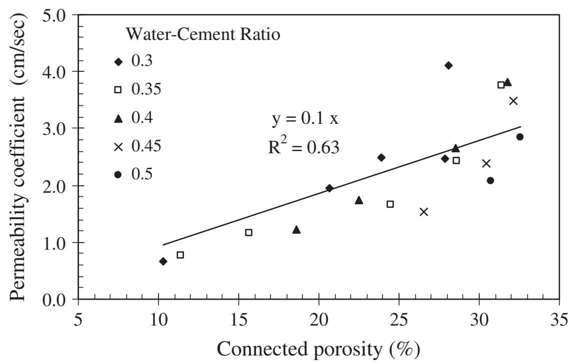

Fig. 8. Relationship between permeability coefficient and connected porosity.

the connected porosity and the permeability coefficient is shown in Fig. 8. The relationship between connected porosity and the permeability coefficient is approximately linear.

3.2.3. The effect of the w/c ratio and the pore-filling paste ratio on the permeability and the compressive strength of concrete

When the w/c ratio of the pervious concrete was fixed, an increase in the pore-filling paste ratio decreased the permeability coefficient, as shown in Fig. 7, but increased the compressive strength, as shown in Fig. 9. Because the engineering requirements for pervious concrete vary, when designing mix proportions, care must be taken to satisfy the requirements for both permeability and strength.

3.3. Comparison of the properties of pervious concrete made with 12.5-mm washed MSWIBA versus pervious concrete made with a natural aggregate

A comparison of pervious concrete samples made with 12.5-mm washed MSWIBA (the experimental group) and pervious concrete samples made with 12.5-mm natural aggregate (the control group) is described in this section.

The unit weights of the freshly mixed concretes in the experimental group were lighter. The connected porosities were 24.5–30.5% and 25.9–27.2% for the experimental and control groups, respectively, although the differences were not significant. The slurry weight loss rate of the experimental group was higher than that of the control group. The highest 28-day compressive strength values were 9.59 and 9.12 MPa for the experimental and control groups, respectively, for the same w/c ratio of 0.35. The highest 28-day split tensile strengths were 0.91 and 1.06 MPa, respectively, for the same w/c ratio of 0.35. The bending strengths of the concretes in the experimental group were higher. The permeability coefficients were 1.67–2.34 and 2.49–2.89 cm/s for the experimental and control groups, respectively.

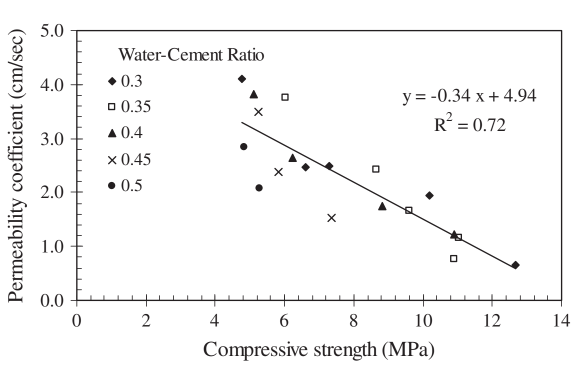

Fig. 9. Relationship between permeability coefficient and compressive strength.

3.4. Comparison of the properties of pervious concrete made with 9.5-mm versus 12.5-mm washed MSWIBA

The pervious concrete made with 9.5-mm washed MSWIBA was used as the comparison group, and a comparison of the experimental results between the experimental group and the comparison group is given in this section.

The unit weights of the freshly mixed concretes in the comparison group were lighter. The connected porosities were 24.5–30.5% and 20.62–27.94% for the experimental and comparison groups, respectively. The coarser MSWIBA resulted in higher connected porosities for the same w/c ratio. There was no significant difference between the two slurry loss rates. The highest 7-day compressive strength values were 8.40 and 8.24 MPa for the experimental and comparison groups, respectively, for the same w/c ratio of 0.35. The highest 28-day split tensile strengths were 0.91 and 0.97 MPa, respectively, for the same w/c ratio of 0.35. The bending strengths of the concretes in the comparison group were lower than those of the concretes in the experimental group. The permeability coefficients were 1.67–2.34 and 1.09–2.03 cm/s for the experimental and comparison groups, respectively.

3.5. Discussion

Pervious concrete is a macro-porous concrete that is rapidly gaining popularity in many parts of the world because of its applications in sustainable construction [21]. Pervious concrete has been used in Europe in the construction of parking lots, parking garages, and some minor roads in Switzerland and England. In the United States, the first successful uses of porous pavement were for parking lot and service roads [33]. Pervious concrete can also be used for squares, footpaths, vehicle roads, paths in parks, subbases for conventional pavement, low-speed pavements, greenhouses and other civil engineering and architectural applications [17,27,29,34]. Its high void content makes it suitable for use in other applications such as thermal insulation, acoustic absorption, concrete beds for vegetation or living organisms, and water purification [29].

Pervious concrete is typically made with natural aggregate (NA). Recycled aggregate (RA) has rarely been used in pervious concrete, perhaps due to doubts concerning the resulting strength of the concrete. In fact, pervious concrete typically must have a compressive strength below 30 MPa for most applications, so its permeability, rather than its strength, is emphasized [22]. Quite a few studies have been performed on no-fines pervious recycled concrete (NPRC). The available experimental results indicate that it is workable to use NPRC in base courses, pavement surfaces and other applications [35].

The results of this study showed that washing can decrease the amount of chloride in MSWIBA. The TCLP test results for the washed MSWIBA demonstrate that it can conform to the second type of MSWIBA quality standard in Taiwan. Washed MSWIBA can therefore be expected to conform to the chloride content and TCLP test requirements for typical concrete aggregates. In this study, the mix proportions, fabrication methods, and engineering properties of pervious concretes made using washed MSWIBA were examined to assess the feasibility of washed MSWIBA pervious concrete, based on its engineering properties. The mix proportions of washed MSWIBA pervious concrete can be developed before testing, but reasonable mix proportions should satisfy the permeability coefficient and compressive strength requirements associated with practical applications.

For washed MSWIBA pervious concrete, the vertical flow rate test can be used for preliminary evaluation of the feasibility of a mix design. When using washed MSWIBA with a maximum aggregate size of 12.5 mm, w/c ratios of 0.3–0.5, and pore filling paste ratios of 40–80%, vertical flow rates of 6% and 12% should be the upper limits for vibrational frequencies of 25 times per 15 s and 50 times per 30 s, respectively. When the w/c ratio of the pervious concrete is greater than 0.4, the use of a higher pore-filling paste ratio will cause the voids at the bottom of the concrete to become filled with paste, which will reduce the permeability of the concrete. In addition, the practical connected porosities of the selected mix proportions are higher than the designed porosities, so the permeability coefficients of washed-MSWIBA pervious concrete can satisfy the design objective. Therefore, the vertical flow rate test is considered useful as a preliminary screening tool for mix proportions for pervious concrete. For pervious concrete made with natural aggregates, the consecutive pores in the pervious concrete may vary in size in the range of 2–8 mm [21], the porosity may vary in the range of 18–35% [22], and the compressive strength may vary in the range of 2.8–28.0 MPa [23]. According to Environment Canada, the maximum intensity of a rainfall of 2 h duration every 2 years in Ontario, Canada, is approximately 14 mm/h (0.0004 cm/s). Therefore, 0.0004 cm/s was selected as the lower bound for the permeability rate [33]. In Taiwan, the permeability coefficient of pervious concrete bricks used in squares, footpaths, and bicycle roads must meet the construction specifications of Chapter 02795, i.e., the permeability coefficient must be greater than 1×10^{-2} cm/s [36] . In this study, the predominant dimension of particles in the washed MSWIBA was 12.5 mm. Using this as the aggregate in the pervious concrete with w/c ratios in the range of 0.30–0.50 w/c ratios and pore-filling paste ratios in the range of 40–80%, the connected porosities, permeability coefficients, and compressive strengths were 10.3–32.7%, 0.6–4.1 cm/s, and 4.8–12.7 MPa, respectively. In addition, using particles of the second most abundant dimension, 9.5 mm, in the washed MSWIBA as the aggregates of pervious concrete, the connected porosities, permeability coefficient, and compressive strength were lower than that of the washed MSWIBA pervious concrete made with recycled aggregate made with 12.5-mm particles, although none were significantly lower. The porosity, permeability, and strength results obtained for the washed-MSWIBA pervious concrete are consistent with the results of previous research on pervious concrete made with natural aggregates and meet the engineering requirements for pervious concrete. Therefore, using washed MSWIBA as the aggregate in pervious concrete is considered workable.

The pore-filling paste ratio can be adjusted in the mix design for washed-MSWIBA pervious concrete. The results of this study show that the connected porosity of pervious concrete can be calculated by subtracting the volume of paste from the void volume of the aggregate. The permeability coefficient is approximately 1/10 of the value of the connected porosity. The split tensile strength and bending strength of washed-MSWIBA pervious concrete are 1/9 and 1/4, respectively, of the compressive strength.

In this research, an aggregate size of 12.5 mm was used as an example to compare the engineering properties of pervious concrete made with washed MSWIBA and pervious concrete made with natural aggregate. The results show that the unit weight of the pervious concrete made with washed MSWIBA was lower than that of the pervious concrete made with natural aggregate. The connected porosities, compressive strength and split tensile strength of pervious concrete made with washed MSWIBA and pervious concrete made with natural aggregate were not significantly different. The permeability coefficient of the pervious concrete fabricated with washed MSWIBA was lower than that of the pervious concrete made with natural aggregate by approximately 20–30%.

As mentioned above, the washing process can decrease the amount of chloride and heavy metals in MSWIBA to the extent that washed MSWIBA can conform to the chloride content and TCLP test result requirements for concrete aggregates. Because the hardness of washed MSWIBA is lower than that of natural aggregate, it is suitable for use in low-strength concrete but not normal-strength concrete. The pore content, permeability, and compressive strength results obtained in this study demonstrate that using washed MSWIBA as pervious concrete aggregate is practical. However, several aspects of this application warrant further research, including the influences of the washed MSWIBA size and higher pore-filling paste ratios on the engineering properties of pervious concrete, other engineering properties of washed-MSWIBA pervious concrete, use and performance of washed-MSWIBA pervious concrete in structural applications, and differences between laboratory testing and field requirements of concrete.

4. Conclusions

In this study, washed MSWIBA was used to make pervious concrete. The following results were obtained:

(1) The unit weight of freshly mixed pervious concrete made using 12.5-mm washed MSWIBA was approximately 1653–2080 kg/m^3 and increased with increasing filling paste ratio.
(2) In vertical flow tests of freshly mixed pervious concrete made with washed 12.5-mm MSWIBA particles as aggregate, for mixes with w/c ratios of 0.3–0.5 and pore-filling paste ratios of 40–80%, vertical flow rates of 6% and 12% were the upper limits for vibrational frequencies of 25 times per 15 s and 50 times per 30 s, respectively.
(3) For pervious concrete mixes with the same w/c ratio, the compressive, split tensile and bending strengths all increased with increasing filling paste ratio. The split tensile strength and the bending strength were approximately 1/9 and 1/4, respectively, of the compressive strength. Both the connected porosity and the permeability coefficient decreased with increasing filling paste ratio. The relationship between connected porosity and the permeability coefficient is approximately linear.
(4) No significant differences in connected porosities, compressive strengths or permeability coefficients were observed between pervious concrete made with washed MSWIBA and pervious concrete made with natural aggregate. The former had a higher slurry loss rate, a higher compressive strength and a lower permeability coefficient than the latter.
(5) Pervious concrete made with 9.5-mm washed MSWIBA had a lower connected porosity, bending strength and permeability coefficient than pervious concrete made with 12.5-mm washed MSWIBA.
(6) For 12.5-mm washed-MSWIBA pervious concrete mixes with w/c ratios of 0.30–0.50 and pore-filling paste ratios of 40–80%, the connected porosities, permeability coefficient, and compressive strength were 10.3–32.7%, 0.6–4.1 cm/s, and 4.8–12.7 MPa, respectively. These results are consistent with the results of previous research on pervious concrete made with natural aggregates and indicate that 12.5-mm washed-MSWIBA pervious concrete can satisfy practical engineering requirements for pervious concrete. Therefore, using washed MSWIAB as the aggregate in pervious concrete is considered practical.

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