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Utilization of municipal solid waste incineration bottom ash (IBA) aggregates in high-strength pervious concrete

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Abstract: This study presents the use of IBA for the production of eco-pervious concrete, aiming at enhancing the recycling rate of IBA in construction materials. The IBA aggregates are used to replace the natural aggregates (NA) in various percentages (0%, 25%, 50%,75% and 100% by volume). The effect of IBA replacement ratios and casting methods on the mechanical properties, water permeability, porosity, density and thermal conductivity of the pervious concrete were determined. The volume stability of the pervious concrete incorporating IBA was evaluated. The results indicated that the appropriate content of IBA could benefit the mechanical properties due to the internal curing effect of IBA. However, the excessive content of IBA in the pervious concrete led to reduced water permeability, connected porosity and mechanical properties. Even so, the pervious concrete containing 100% IBA could achieve the required permeability and compressive strength for permeable pedestrian pavers (JIS A 5371). In addition, the incorporated IBA in pervious concrete causes little volume expansion from the reaction between alkalis and components consisting of metallic aluminum and glass in IBA owing to its high connected porosity. Furthermore, the pervious concrete incorporated IBA had a low density and thermal conductivity, showing the potential to be applied in thermal insulation areas.

Key words: Pervious concrete; Incineration bottom ash aggregates; Compressive strength; Permeability; Volume stability;

1.Introduction

Waste incineration is widely used to manage municipal solid waste, as the incineration process can reduce the volume of municipal solid waste by nearly 90% and the mass by 80% [1]. This method is increasingly adopted all over the world including in developing countries such as China [2]. However, after the incineration process, there is still a large amount of incineration bottom ash needed to be managed. According to the world waste production, the annual municipal solid waste production was 1840 MT worldwide (data from 2012) [3]. As a result, approximately 360 MT of IBA was produced. The majority of IBA is currently disposed of at landfills [4]. Due to the shortage of landfill sites, it is an increasingly important issue to develop novel solutions to reuse IBA as resources.

Pervious concrete, which contains a large number of pores, was developed in the 1940s [5]. A pervious concrete normally consists of coarse aggregate, cement paste and voids [6]. Compared to conventional concrete, it contains a lesser amount of cement paste and no fine aggregate, which leads to a higher porosity and a lower strength level. Usually, the pervious concrete has a high porosity of between 11% and 35% [7-9], and hence it possesses excellent permeability, good drainage property and high noise absorption capacity [10]. Since the use of pervious concrete was reported to have multiple environmental benefits: facilitating stormwater run-off, mitigating urban heat island effect, reducing road noise and soil pollution, etc.[9, 11-13], it is widely used in various areas such as pavements, sidewalks, parks and building exteriors [14]. Hong Kong is a densely built-up urban city and located in the region where heavy rainfalls occur frequently. It is essential to promote the application of pervious concrete to avoid potential waterlogging.

Since the over-exploitation of natural aggregates (NA) has last for a long time due to rapid urbanization, NA have become a scarce resource in Hong Kong and most cities in China. Reuse of inert wastes to replace NA is one of the methods to relieve this concern. This study explored the feasibility of using IBA aggregates to replace NA to broaden the source of aggregates. Recently, some researches were carried out to use the IBA as aggregates in pervious concrete. Due to the lower hardness of IBA than that of NA, Kuo et al. used the washed IBA to replace the NA to prepare low-strength pervious concrete (4.8 MPa-12.7 MPa) [15]. Wu [2] also used IBA in place of sandstone graded material to prepare pervious concrete. The results indicated that the strength of permeable concrete blocks was less than 15 MPa, and it had lower permeability coefficients than that of conventional pervious concrete, which led to being impracticable in busy roads [2]. Generally, the mechanical properties of pervious concrete incorporating IBA are usually much lower than that of pervious concrete prepared by pure NA. Therefore, it is of great significance to explore methods to improve the compressive strength of pervious concrete incorporating IBA.

The objective of this research is to develop a high-strength pervious concrete incorporating IBA aggregates to replace NA. The ultra-high strength cement paste (UHSC) was prepared to improve its compressive strength. The influences of IBA-NA replacement ratio and different casting methods on the compressive strength, water permeability and thermal conductivity of the pervious concrete were determined. Micro-hardness, hydration heat and microscopy studies were also conducted to explore the mechanisms controlling the performance of the pervious concrete incorporating IBA.

2.Materials and experiments

2.1 Materials and mixture preparation

A 52.5 CEM I Portland cement (OPC) and fly ash (FA) sourced from Hong Kong were used, and the silica fume (SF) produced by Elkem (China) was also used as well. The oxide compositions of OPC, FA and SF are shown in Table 1. Crushed granites with the size between 2.36mm and 5 mm were served as the natural aggregates (NA). The IBA aggregate (2.36-5 mm) was produced from a municipal solid waste incineration facility in China. The compacted voids of granite and IBA were 40.8% and 41.5%, respectively. The physical properties of these aggregates are presented in Table 2. A superplasticizer high range water-reducing rate produced by BASF was also used to control the workability.

Table 1 Chemical compositions of cementitious materials (wt. %)

Oxide	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	LOI
OPC	19.61	7.32	63.15	3.32	2.03	2.14	0.13	0.32	2.12
SF	88.29	0.14	0.92	0.19	1.51	3.21	0.14	0.17	5.26
FA	54.69	12.71	17.48	4.61	0.97	1.68	1.75	3.18	1.79
IBA	40.00	9.42	29.40	6.69	1.17	1.37	2.78	1.97	5.72

Table 2 Physical properties of aggregates

Aggregates	NA	IBA
Loose Bulk Density (g/cm^3)	1.33	1.049
Specific Gravity	2.54	1.88
Water Absorption (%)	1.63	11.64
Aggregate crushing value (%)	14.8	47.9
Los Angeles abrasion value (%)	17.6	49.5

In order to improve the mechanical properties of the UHSC paste, its porosity is usually minimized by improving the packing density of the particles. In this study, the modified Andreasen and Andersen model was employed to design a UHSC paste with excellent compressive strength by using OPC, SF and FA [16]. A target function obtained from this model was used for optimizing the composition of UHSC paste. The mix proportions of each raw material can be chosen when an optimum fit between the composed mix curve and the target curve is reached by Least Squares Method. Therefore, the mixture proportion of the UHSC paste will be obtained and show in Table 3.

Table 3 Mix proportion of UHSC paste

No.	Cement	Fly ash	Silica fume	w/b	Superplasticizer
--	1	0.1	0.22	0.15	0.04

2.2 Preparation of pervious concrete

The mix proportions of the pervious concrete are shown in Table 4. A water to binder ratio of 0.15 (not include water in IBA) was chosen based on the trial tests that the mixtures condition could be agglomerated into a ball shape by hand without falling off of the aggregates [9]. Meanwhile, the UHSC paste possessed a slump flow of 165mm. After adding aggregate, a cohesive mix with very low workability (no slump value) was produced. This condition occurred when the cohesiveness of the fresh pervious concrete mixture was sufficient to hold its shape when it was hand-pressed, but the paste did not stick to the hand itself. An aggregate to binder ratio (a/b) of 4 was set to achieve high strength and permeability according to our previous research [17]. The IBA aggregate with a size ranging of 2.36-5 mm was applied to replace the NA by volume. As the water absorbed in IBA was considered, the total w/b ratio was increased. The mixing process was as following: 1) The IBA was immersed in water for 24 h and wiped dry, then the saturated IBA in surface dry condition was collected; 2) All the binders were dry mixed for 3 min, then the clean tap water with an appropriate amount of superplasticizer were poured into the mixer and slowly mixed for 3 min followed by high speed mixing for another 3 min; 3) The aggregates (including NA and IBA) were added into the mixer and the mixture was further mixed for 3 min at a low mixing speed. Afterward, the freshly prepared mixtures were cast into molds.

Two methods of casting and vibration were used to prepare the pervious concrete as follows: Method 1) The fresh mixture was poured into the molds and compacted using a laboratory vibration table for 1 min; Method 2) the fabrication procedure of the pervious concrete simulated the production process of concrete blocks in a real block precast plant using a relatively dry concrete mix with very low workability. Thus, after casting half of the amount of the molds followed by the normal compaction using the vibration table, the remaining half of the mixtures were added, but the mixtures inside the molds were transferred to a compression machine for stronger compaction with a maximum molding pressure of 3 MPa (loading rate of 0.05 MPa/s, and kept at the maximum pressure for 60 s). This compaction parameter for fabricating the mixed specimens followed those used in previous studies [11, 18, 19], which was necessary to compact the constitutes. Afterward, the samples were overlayed by preservative films. Then, the samples were demolded at 24 h and cured in a sealing condition at 25 ℃.

Table 4 Mix proportion of pervious concrete (kg/m^3)

Notation	OPC	FA	SF	w/b	Water	PCE	Water in IBA	IBA	NA	a/b	Pressure	Total w/b
0FP	262.2	65.6	72.2	0.15	56.8	4	0	0	1600	4	3 MPa	0.15
25FP	262.2	65.6	72.2	0.15	56.8	4	34.2	295	1200	/	3 MPa	0.24
50FP	262.2	65.6	72.2	0.15	56.8	4	68.4	590	800	/	3 MPa	0.32
75FP	262.2	65.6	72.2	0.15	56.8	4	102.7	885	400	/	3 MPa	0.41
100FP	262.2	65.6	72.2	0.15	56.8	4	136.9	1180	0	/	3 MPa	0.49
0FV	262.2	65.6	72.2	0.15	56.8	4	0	0	1600	4	0	0.15
50FV	262.2	65.6	72.2	0.15	56.8	4	68.4	590	800	/	0	0.32
0FV1	349.6	87.5	96.3	0.15	76.8	5.3	0	0	1600	3	0	0.15

2.3 Experimental methods

2.3.1 Compressive strength

One intended use of the pervious concrete could be precast pervious blocks for pedestrian pavement. Thus, in this study, the geometry of the pervious concrete specimens (200 mm×100 mm×60 mm) was prepared according to BS 6717 and our previous study [20, 21]. The compressive strength of pervious concrete with a size of 200 mm×100 mm×60 mm was measured according to the procedure in ASTM C39 [22]. The pervious concrete was loaded at a rate of 0.6 MPa/s with $200 \times 100\ mm^2$ surface upward. The pervious concrete prepared with the two different casting methods and amounts of IBA was chosen for strength measurement after curing for 28 d. For samples casting with Method 2, the compressive strength of samples incorporating with 0% and 50% IBA was determined at 3 d, 7 d and 28 d.

2.3.2 Porosity

The connected porosity of pervious concrete with a size of 200 mm×100 mm×60 mm was measured according to the method provided in a previous study [23]. Firstly, the volume (V) of pervious concrete was obtained by measuring the dimension. Afterward, the pervious concrete was immersed in water for one day to saturate the pores with water. Then, the submerged weight (W_1) of pervious concrete was recorded. Finally, the weight of the specimens (W_2) in the air was measured after achieving a saturated surface dry condition. The connected porosity was calculated as follows:

$$\mathrm{P} = \left[1 - \frac{W_2 - W_1}{\rho V}\right] \times 100\% \qquad (1)$$

where P and ρ are connected porosity of pervious concrete and bulk density of water, respectively.

The total porosity of the specimens was determined in accordance with ASTM C 1754 [24]. Firstly, the specimens were immersed in water for 24 h to make sure that the pores in IBA and the cement matrix were saturated. Then the submerged weight (W_3) of specimens was recorded. Finally, the weight of the specimens was measured (W_4) after drying in an oven at 105 ℃ for 48 h, and. The total porosity (P_1) of specimens can be calculated as follows:

$$P_1 = \left[1 - \frac{W_4 - W_3}{\rho V}\right] \times 100\% \qquad (2)$$

2.3.3 Water permeability

The cylindrical specimens (Φ100 mm×50 mm) were prepared and used for water permeability measurement according to standard JIS A 5371 and GBT 25993-2010 [11, 25, 26]. Figure 1 shows the setup of permeability measurement. The water released from the bottle was collected, and the time was recorded. The permeability coefficient could be calculated based on Equation (3). It should be noted that the influence of the thickness of specimens was taken into account when the permeability coefficient was calculated. As the intended application of the pervious concrete was to produce concrete blocks for pedestrian pavement, thus a similar thickness to the real blocks (60 mm) was produced to evaluate the permeability in this study compared to the previous studies [27]. Because the pervious concrete was prepared by aggregates with small size ranging 2.36-5 mm, leading to well-distributed pore structure with small pore size. As a result, the specimens with a thickness of 50 mm were representative and accurate for permeability measurement.

$$\mathrm{C} = 10 \times \frac{VL}{AHT} \qquad (3)$$

where C is the permeability coefficient, mm/s; A is the surface area of pervious concrete, cm^2; V is the total volume of collected water, mL; L is the thickness of specimens; H is the differentials between the height of water head in tube and water head in the bottle, cm; T is the recorded time, s.

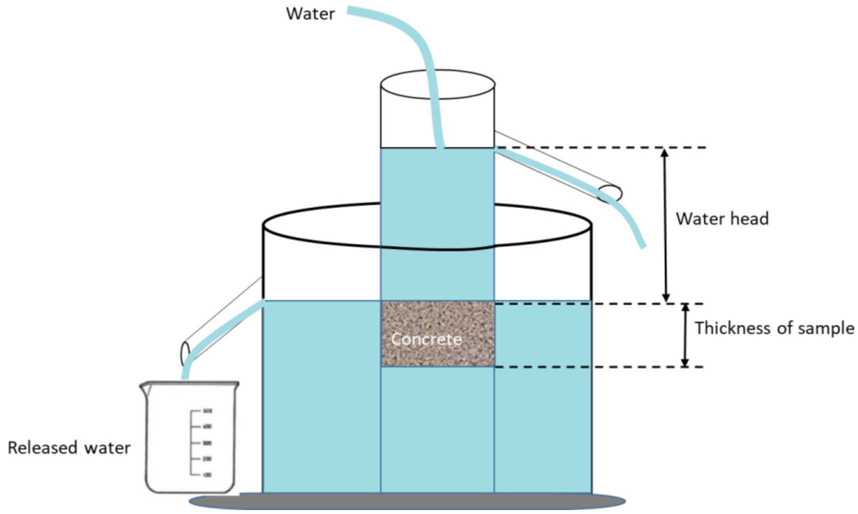


Figure 1 Set-up of water permeability measurement

2.3.4 Hydration heat

The effect of IBA on hydration heat of pervious concrete was monitored by using an I-CaI 4000 isothermal calorimeter. For each mixture, about 20 g of binders and 80 g NA or IBA were placed into a plastic ampule and put into the calorimeter. The IBA replacement ranged from 0% to 100%. The isothermal calorimetry was started immediately after mixing and record for 168 h.

2.3.5 Density

The density of pervious concrete was measured based on the method illustrating in ASTM C 1754 [24]. The weight of pervious concrete with a size of 200 mm×100 mm×60 mm was measured after drying in the oven at 105 ℃. In addition, the dimensions of specimens were determined to calculate the volume. The density of specimens can be calculated as follows:

$$\rho = \frac{M}{V} \qquad (4)$$

where the ρ is the density of specimens, g/cm^3; The M is the weight of pervious concrete after drying in an oven at 105 ℃, g; V is the volume of pervious calculated based on the dimensions, cm^3.

2.3.6 Microhardness

The surface of pervious concrete containing different amounts of IBA was polished for the microhardness test. The pervious concrete was well grinded to achieve a smooth surface. A digital Vickers microhardness tester (HVX1000A, China) was used to determine the microhardness of the matrix around aggregates. For pervious concrete incorporating IBA, 50 points near IBA were tested. In case of pervious concrete without IBA, the 50 points were conducted in matrix near NA.

2.3.7 Autogenous shrinkage and expansion behavior

The effect of IBA on the expansion behavior of the pervious concrete was tested according to ASTM C 1260 [28]. The specimens with a size of 25 mm×25 mm×285 mm were prepared and demolded at 24 h after casting, and then placed into 80 ℃ water for 24 h. The zero value was recorded after the hot water curing. Afterward, the specimens were soaked in 1 mol/L NaOH solution at 80 ℃ for 28 d. The dimensional development of the samples was determined at 1 d, 3 d, 7 d, 14 d, 21 d and 28 d, respectively.

The autogenous shrinkage of the samples was measured according to the Chinese standard [29]. The specimens with a size of 25 mm×25 mm×285 mm were also used. The autogenous shrinkage test was started at the age of 24 h, then until the age of 60 d.

3. Results and discussion

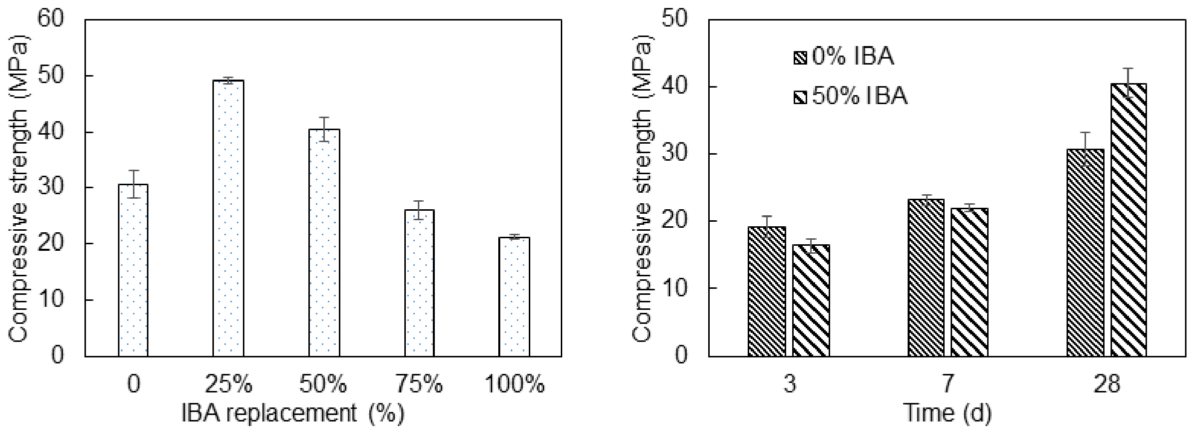
3.1 The mechanical properties

3.1.1 Effect of IBA replacement

Generally, as the IBA is a porous aggregate with low strength, it is expected to be the weakest zone in the prepared pervious concrete. Hence, an understanding of the effect of IBA on the mechanical properties of pervious concrete is necessary. The compressive strength of specimens containing different contents of IBA is shown in Figure 2. It is observed that the incorporation of IBA had a rather inconsistent effect on the compressive strength. Compared to the reference sample, the compressive strength of the pervious concrete incorporated with 25% IBA was improved by 60%. This may be explained by the water absorbed in IBA and the reduction in porosity (shown in Figure 4). However, the compressive strength was obviously reduced when the replacement of IBA was higher than 75%. Figure 2 (b) shows the development of compressive strength of the concrete prepared with and without IBA. It can be observed that the 3 d and 7 d compressive strengths of the reference sample were higher than that of the samples containing 50% IBA, while the 28d-compressive strength of the reference sample was lower than that of the concrete prepared with IBA.

For the reference sample, the UHSC paste was prepared with a low w/b ratio of 0.15, and the mixing water would be exhausted at the early age [30]. Hence, the increment of compressive strength was limited between 7 d and 28 d. In contrast, the porous IBA can act as an internal curing material in the pervious concrete, which increased the internal relative humidity of the matrix at both the early and later ages. Therefore, the hydration degree of the cement paste in pervious concrete was improved due to the water released from IBA [31], thus leading to the higher 28 d-compressive strength. This effect is similar to the effect of lightweight aggregates on the strength of ultra-high performance concrete with low water to binder ratio [32].

These results indicated that the controlled addition of IBA could improve the compressive strength of the pervious concrete. When the content of IBA was lower than 50%, an improved compressive strength could be observed although the NA was replaced by the porous IBA with poor mechanical properties. This might be related to the pre-soaked in IBA, as the release of pre-soaked water contributed to the improved hydration degree. As a result, the bonding strength between the aggregates and the cement paste was improved, contributing to the increased compressive strength. Some of the pre-soaked water in IBA would be released before setting due to the low relative humidity in UHSC paste according to the internal curing theory [33]. This would increase the volume of UHSC paste, resulting in the reduction of porosity, which also contributed to the enhancement of compressive strength. Although the compressive strength was reduced by 31.1% while the IBA content reached 100%, it could still meet the requirement of permeable concrete for pedestrian pavement according to JIS A 5371 [34].



(a) Effect of IBA replacement (b) Development of compressive strength

Figure 2 Effect of IBA on the compressive strength of pervious concrete

3.1.2 Effect of casting method

As indicated in Figure 3, the compressive strength of the pervious concrete could be increased by applying molding pressure during production. For the concrete prepared without IBA, the compressive strength was only slightly improved. However, significant enhancement was observed with the use of IBA. It is expected that the use of molding pressure would produce a denser pervious concrete, thus resulting in a higher strength compared to the reference sample prepared without molding pressure. Generally, the individual pellet strength of IBA was quite low [35]; thus, some of the particles would be crushed when subjected to the molding pressure, leading to a low porosity (shown in Figure 4) and a higher compressive strength.

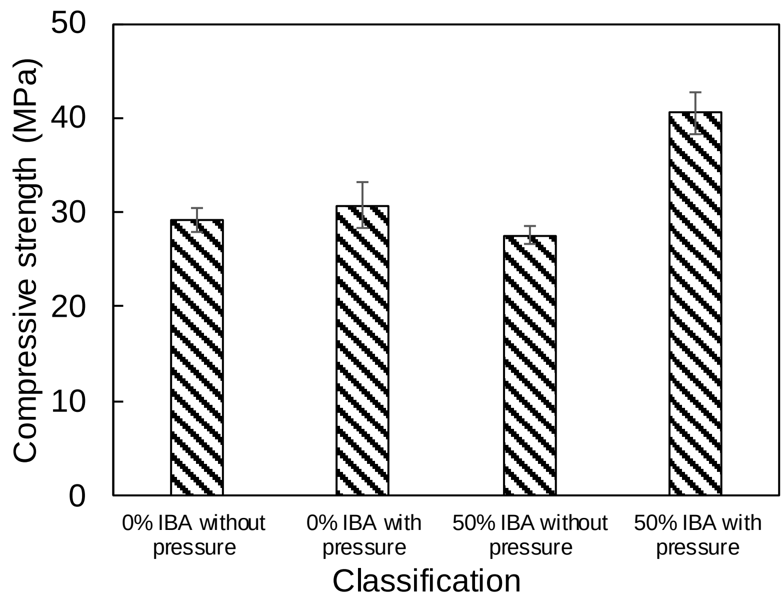
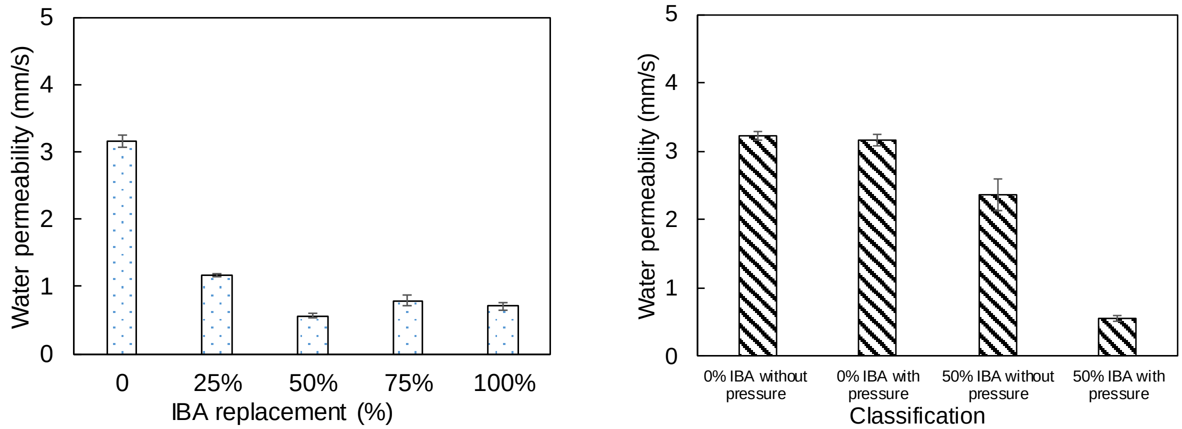


Figure 3 Effect of casting methods on the compressive strength of pervious concrete

3.2 Water permeability and connected porosity

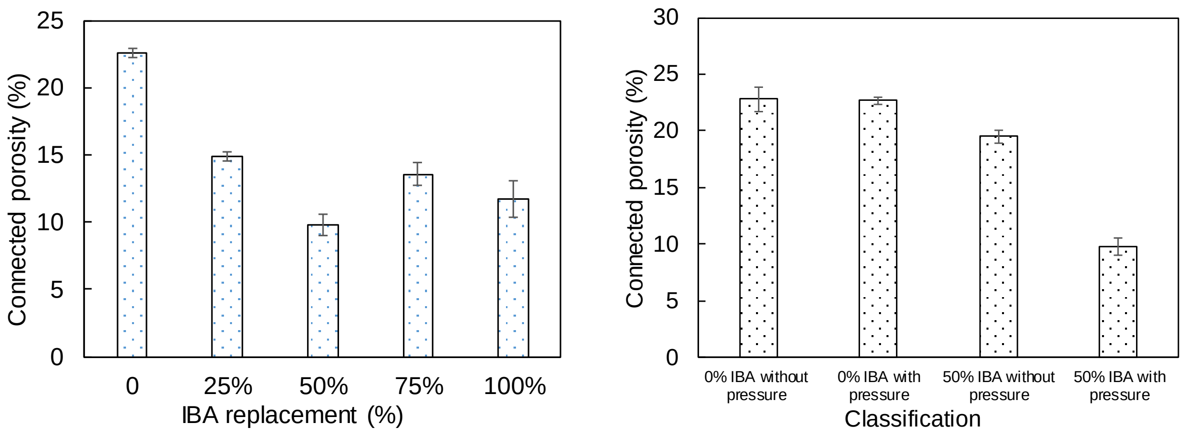
Figure 4 (a) shows the effect of IBA replacement on the water permeability of the pervious concrete. It is indicated that the pervious concrete containing IBA had lower permeability than that of the reference sample, which was attributed to the reduced connected porosity (shown in Figure 5(a)). Besides, for the pervious concrete prepared without IBA, the casting method had little effect on the water permeability, and the values were about 3 mm/s. But for the samples incorporating 50% IBA, the permeability coefficient was reduced to 2.4 mm/s (Figure 4(b)), although the connected porosity was slightly decreased (Figure 5(b)). It might be due to the different grading of IBA and the increased volume of cement paste due to desorption of water from IBA, which can reduce the connected porosity and the connectivity of voids. Meanwhile, with the application of 3 MPa molding pressure, the water permeability of pervious concrete incorporating 50% IBA was significantly reduced to 0.6 mm/s. The damage of IBA under molding pressure and increase of cement paste are believed to induce the reduction in the porosity and connectivity of the pores of the pervious concrete. It should be noted that the use of IBA is detrimental to the water permeability, but it was still higher than the permeability requirement of JIS A 5371 (0.1 mm/s).



(a) Effect of IBA replacement (with molding pressure)

(b) Effect of casting methods

Figure 4 Effect of IBA replacement ratio and casting methods on water permeability



(a) Effect of IBA replacement

(b) Effect of casting method

Figure 5 Connected porosity of pervious concrete

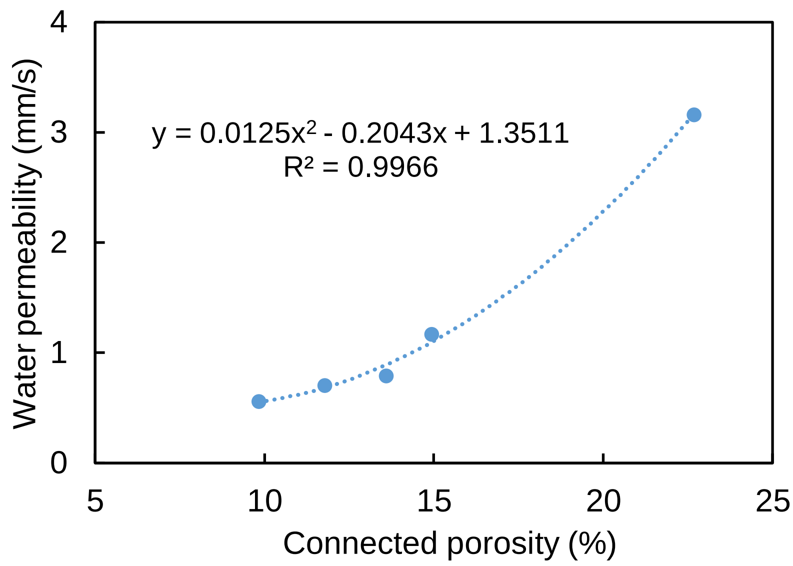


Figure 6 Relationship between connected porosity and permeability

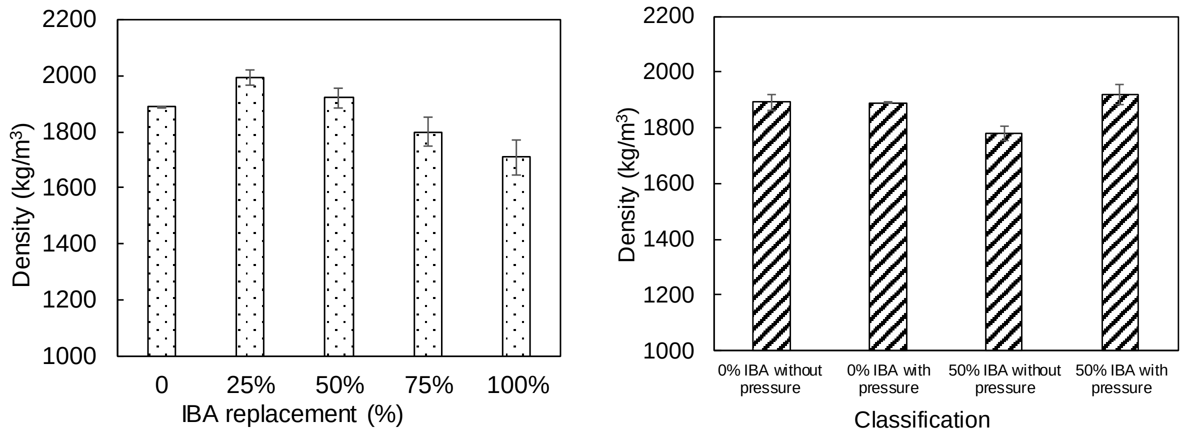
Figure 6 shows the relationship between the connected porosity and permeability. Overall, the water permeability increased with the increasing connected porosity, but no definitive relationship could be found. The porosity of the pervious concrete incorporating 25% IBA was a little higher than that of the concrete containing 75% and 100% IBA. This might be attributed to the changes in pore structure between the aggregate particles. Usually, the water permeability of pervious concrete is not only related to the connected porosity but also its pore structure [23]. So, it showed the presence of IBA would likely influence the characteristics of the pore structure.

3.3 Density and total porosity

The density and total porosity of the pervious concrete are shown in Figures 8 and 9, respectively. The density of the pervious concrete was obviously affected by IBA content and the casting method. The density values ranged from 1709.2 to 1994.2 kg/m^3, which were much lower than that of the normal concrete. In addition, as indicated in Figure 8 (a), the density of the concrete incorporating IBA increased first and then decreased with the increasing amount of IBA. the connected porosity of the pervious concrete incorporating IBA was decreased (shown in Figure 5).

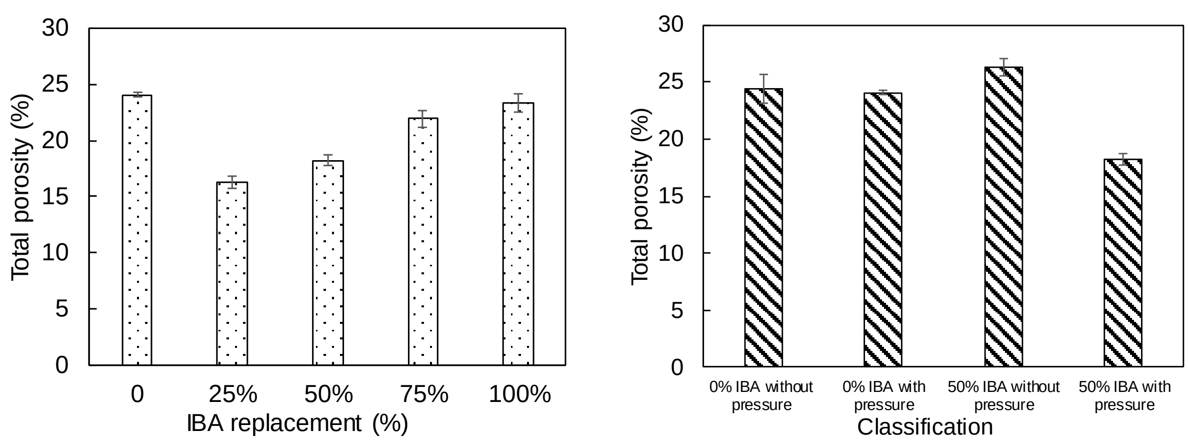
The decreased connected porosity would contribute to the reduced total porosity and increased density. The increased density from decrease of connected porosity surpassed the decreased density due to replacement of the high-density NA by low-density IBA when 25% of NA are replaced with IBA. As the connected porosity of pervious concrete only shows a slight decrease with the increasing IBA content (shown in Figure 5), the increased in density resulted from the decrease of connected porosity stabilized when a higher IBA replacement was applied (>25%). However, with the increasing IBA amount, the density of pervious concrete was governed by the large amount of low density IBA. This trend was consistent with the opposite trend of the total porosity shown in Figure 9. The IBA had a porosity of 21.9%, which was much higher than that of NA. Thus, the increased content of IBA would increase the total porosity of the pervious concrete. However, when 25% of NA was replaced by IBA, the decreased in total porosity was caused by the decreased connected porosity (shown in Figure 5). As a result, a sudden reduced total porosity could be observed in sample 25FP. As the connected porosity of the pervious concrete only slightly decreased with the increasing IBA content, the decreased in total porosity resulted from the decrease of connected porosity stabilized when a higher replacement was applied (>25%). Meanwhile, many pores from IBA were induced and increased as increasing IBA content, which overwhelmed the decreased total porosity from decrease of connected porosity when the IBA replacement reached 50%. Besides, both the density and total porosity showed a linear relationship with the compressive strength (shown in Figure 10), indicating the critical influences of these two parameters on the compressive strength.

For the specimens prepared without IBA, the casting method had only a slight influence on the density and porosity, as well as the compressive strength and water permeability (shown in Figure 2 and Figure 4) of the pervious concrete. However, the density of pervious concrete containing IBA was increased with the application of the molding pressure. The density of FP50 prepared with 50% IBA was 1920.5 kg/m^3, which was much higher than that of those prepared without applying the molding pressure (1781.3 kg/m^3). This means that the packing density was increased when the molding pressure was applied to the mix prepared with the inhomogeneous, weaker and more porous IBA. The total porosity of the concrete prepared with 50% IBA was decreased by 30.4% when the molding pressure was used during sample preparation.



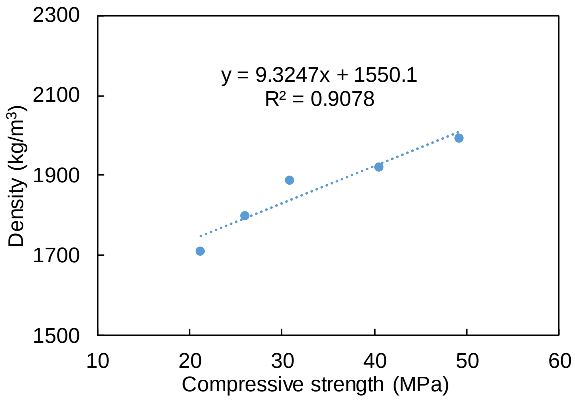
(a) Effect of IBA replacement (b) Effect of casting method

Figure 8 Effect of IBA replacement and casting method on the the density of pervious concrete

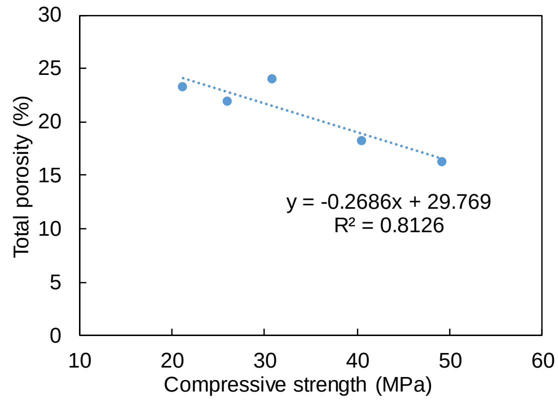


(a) Effect of IBA replacement (b) Effect of casting method

Figure 9 Effect of IBA replacement and casting method on the the total porosity of pervious concrete



(a) Density vs. compressive strength



(b) Porosity vs. compressive strength

Figure 10 Relationships between density or porosity and compressive strength

3.4 Thermal conductivity

The thermal conductivity of pervious concrete incorporating with IBA is shown in Figure 11. Apparently, the pervious concrete prepared with 25% IBA showed the highest thermal conductivity. But the thermal conductivity decreased with the further increase in IBA replacement. The thermal conductivity of the pervious concrete containing 100% IBA decreased to 0.61W/mK. The is mainly attributed to the low thermal conductivity of IBA aggregates. IBA is a type of porous material and its thermal conductivity is much lower than that of natural granite aggregates [36]. Therefore, the pervious concrete containing 100% IBA presented the minimum thermal conductivity. It should be noted that the thermal conductivity of pervious concrete incorporating 100% IBA was comparable to the thermal conductivity of lightweight concrete [37].

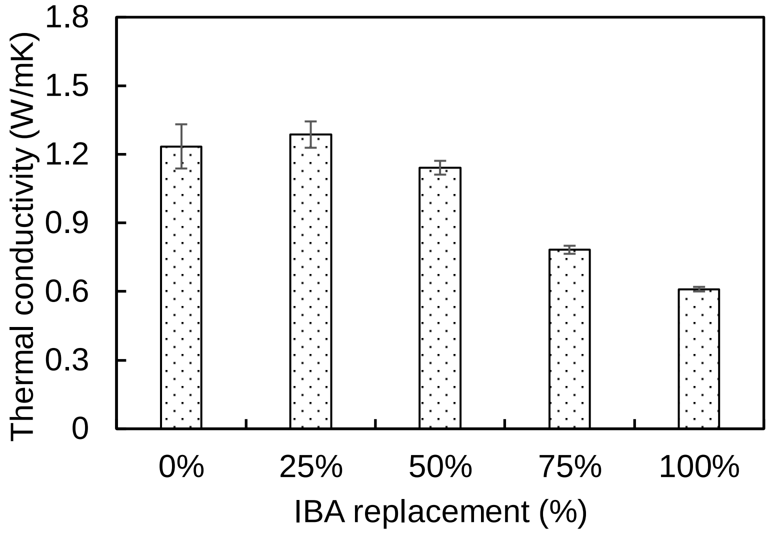


Figure 11 Thermal conductivity of pervious concrete containing different amounts of IBA

3.5 Volume stability

Figure 12 shows the effect of IBA replacement on the autogenous shrinkage of the pervious concrete. Generally, ultra-high performance concrete has a very high autogenous shrinkage owing to its characteristics of low w/b ratio and high content of superfine particles [38]. It can reach 2000 με at 28 d [30]. Thus, the UHSC paste would also possess a high shrinkage value. However, as there is a large amount of coarse aggregate in the pervious concrete, the autogenous shrinkage was mitigated by the skeleton of the aggregate. The 28 d-autogenous shrinkage of the pervious concrete was very lower (<140 με (shown in Figure 12)), which was also contributed by the internal curing effect of the pre-saturated porous IBA. The autogenous shrinkage value decreased with increasing IBA content.

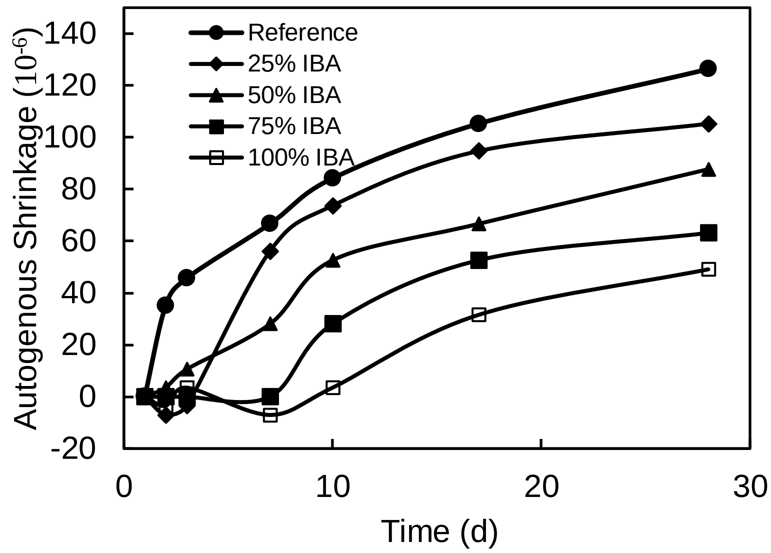


Figure 12 Autogenous shrinkage of pervious concrete containing different amounts of IBA

The expansion behavior caused by the chemical reactions of the contaminants in IBA (such as metallic aluminum, glass and gypsum [39]) was measured and shown in Figure 13. An expansion behavior could be observed in all the samples prepared with different amounts of IBA. This expansion of the reference sample may be attributed to the alkali-silica reaction of the amorphous silica in the granite [40]. But the expansion values of samples containing different contents of IBA were relatively low compared to that of the expansion in conventional concrete incorporated IBA [39]. Meanwhile, the expansion of the samples consisting of high IBA content was lower compared to concrete incorporating the low amount of IBA. This might be attributed to its porous structure, which could accommodate the volume expansion induced by the formation micro expansive materials (i.e., H_2 gas and ASR gel etc.). This phenomenon is in agreement with the expansion behaviors in dry-mixed concrete glass blocks [18].

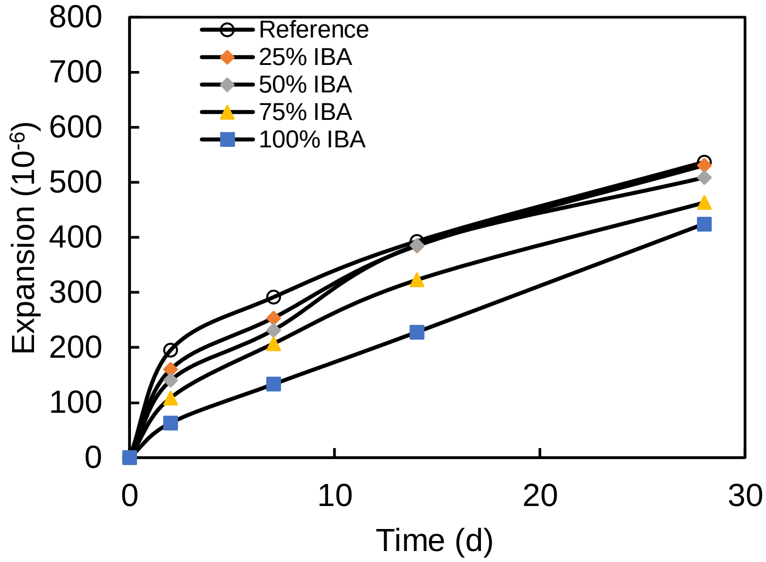


Figure 13 Expansion of pervious concrete in 1M 80 ℃ NaOH solution

4. Further discussion

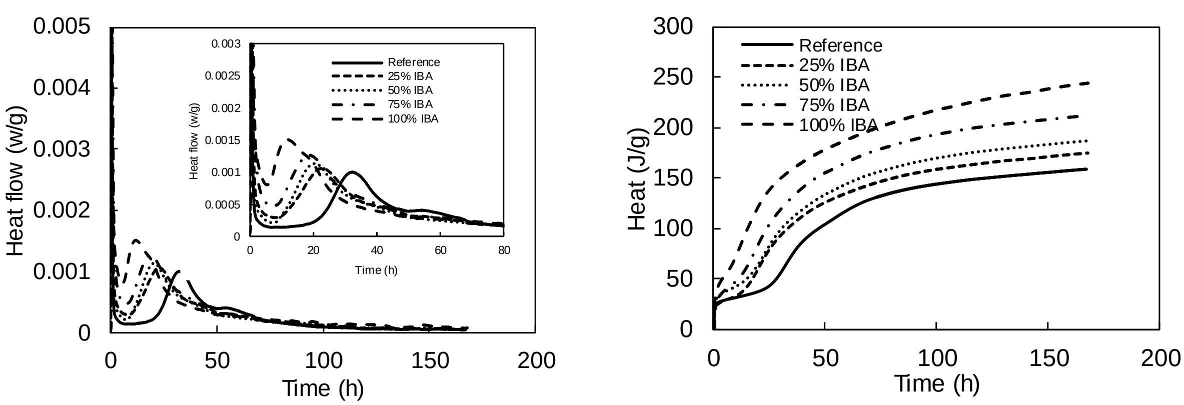
4.1 The enhancement of strength by internal curing

A pervious concrete with the a/b of 3 was also prepared by NA without molding pressure. The compressive strength, total porosity, density and permeability of this pervious concrete were 46.15 MPa, 17.85%, 2007.3 kg/m^3 and 0.95 mm/s, respectively. The connected porosity (13.67%) and water permeability (0.95 mm/s) were a little smaller than those of pervious concrete containing 25% IBA and aggregate to binder ratio of 4, but the pervious concrete prepared with 25% IBA and aggregate to binder ratio of 4 showed higher compressive strength than the specimens with aggregate to binder ratio of 3. In other words, the addition of IBA can promote the enhancement of compressive strength. Although the IBA possesses a lower hardness than that of NA, the internal curing of IBA may overwhelm the reduced compressive strength owing to the inhomogeneous, weak and porous characteristics of IBA. Therefore, the micro-hardness of matrix and hydration heat of pervious concrete containing different contents of IBA were measured to explore mechanisms governing the compressive strength enhancement of pervious concrete incorporating appropriate IBA.

Figure 14 shows the hydration heat flow and cumulative heat of pervious concrete incorporating 0%, 25%, 50%, 75% and 100% IBA. It can be observed from Figure 14 (a) that the dormant period was reduced with the increased amount of IBA. Usually, the dormant period depends on the water to cement ratio and the content of the superplasticizer in concrete [41-43]. As the dosage of water and superplasticizer is the same in all the specimens, the acceleration of dormant period is likely due to the water release and ion dissolution of IBA [44]. Meanwhile, some water in internal curing materials would release before setting in UHSC paste due to its low relative humidity [45]. Similarly, some pre-soaked water in IBA can also be released during the dormant period. As a result, the increased w/b further influences the dormant period.

Furthermore, an accelerating period was followed by a main peak. The appearance of this main peak was ahead by adding more IBA obviously, and the location of this main peak shifts from 35 h to 15 h while the IBA content increased from 0% to 100%. Accordingly, the cumulative heat of hydration increased with the increase of IBA additions, especially for the early age. Nevertheless, the heat flow of pervious concrete containing IBA was higher than that of the blank sample at 3 d, which was due to the water desorption of IBA. However, the 3 d and 7 d compressive strengths of the reference sample were still higher than that of the samples containing 50% IBA. This might be attributed to the low strength of porous IBA. Usually, the compressive strength of pervious concrete was controlled by the strengths of cement paste and aggregates, and their bonding. Although the cement paste was strengthened by the internal curing of porous IBA at an early age (3d and 7d), the low crushing strength of IBA would govern the overall strength of the pervious concrete. Compared to the reference sample, an improved compressive strength could be observed in samples incorporated 50% IBA at 28d. This was related to the continually internal curing effect of IBA at the age between 7 d and 28 d (a higher heat flow was observed at 7d) during which the hydration of the reference sample was limited due to lack of water [46]. Because the improved compressive strength from the strengthened cement paste due to internal curing surpassed the reduced compressive strength due to low-strength IBA.

Generally, the pervious concrete incorporating IBA can not only accelerate the hydration of UHSC paste at the early age but also promote its hydration at the later age. The high internal relative humidity due to the water desorption plays the main role in controlling the hydration, leading to the improvement of hydration heat and hydration degree [47, 48]. It is expected that the UHSC paste in pervious concrete incorporating IBA has a lower porosity compared to that of the reference sample. Although the IBA is a type of porous material with low hardness and acts as the weakest zone in pervious concrete, the enhancement of the matrix owing to its internal curing effect partly compensated for the adverse influence of IBA. Therefore, an enhancement or limited reduction of compressive strength can be observed when the appropriate amount of IBA is used.



(a) heat flow (b) cumulative heat

Figure 14 The heat hydration of pervious concrete

The average microhardness of matrix around IBA in pervious concrete containing different IBA contents is shown in Figure 15. The test results indicated that the average microhardness increased with the increasing amount of IBA. The increase of microhardness is mainly attributed to the increasing degree of the matrix (shown in Figure 14). Generally, compared to the reference sample, a denser matrix around the aggregate can be obtained due to the internal curing of IBA, which exhibits excellent micro-mechanical performance [49]. Herein, although the addition of porous IBA gives rise to weakness zones into pervious concrete, the improvement of matrix acts as a dense wall, which can prevent the crack of IBA.

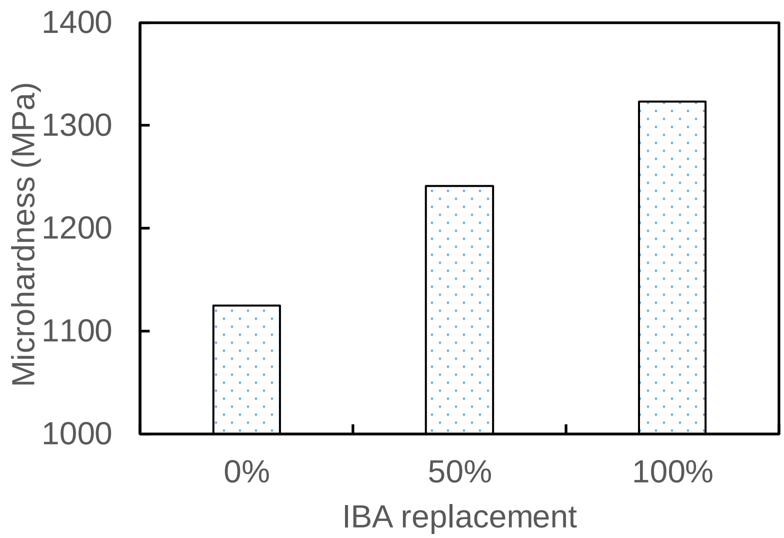


Figure 15 The micro-hardness of the matrix in pervious concrete

The pre-saturated water in IBA not only promotes the hydration of cement paste but also enhances its mechanical property. The microhardness of cement paste in pervious concrete is significantly improved, which means that the cement paste around aggregate acts as the dense wall with low porosity and high mechanical strength. This dense wall is formed, as shown in Figure 16. As the w/b ratio of pervious concrete is very low, the pre-saturated water in IBA will be motivated by relative humidity gradient and releases into the cement paste during hydration. The hydration of cement paste near IBA will be promoted and the microstructure becomes denser than that of the reference sample. This dense wall has a higher mechanical strength than that of the reference sample, which may act as a skeleton in pervious concrete containing IBA and will be of benefit to the bonding strength between aggregates and mechanical strength of pervious concrete.

In this study, the compressive strength of pervious concrete containing 25% IBA was higher than that of the other specimens. This was ironic because the presence of porous IBA aggregate with poor mechanical properties should have reduced the strength. This can be explained by a number of factors. Usually, the compressive strength of pervious concrete depended on the compressive strength of cement paste and aggregate, porosity and the bonding characteristic between cement paste and aggregate [17]. From the hydration results, the absorbed water in IBA promoted cement hydration which densified the UHSC paste. Also, the increased micro-hardness facilitated the formation of dense shell around the IBA and the interfacial transition zone around the aggregates would be improved due to the internal curing provided by the IBA and the pozzolanic reaction between IBA and cement paste [50, 51], which was confirmed by the result of increased micro-hardness. The improvements of the UHSC paste and the interfacial transition zone contributed to the increased compressive strength. Furthermore, the connected porosity of pervious concrete incorporated with 25% IBA was decreased (shown in Figure 5), which benefited the compressive strength. Therefore, the above benefits surpassed the negative effects with 25% IBA incorporation. But the adverse effect increased obviously with the further increase in IBA replacement. For pervious concrete incorporating a high amount of IBA (larger than 75%), the reduction of compressive strength was higher than the enhancement. As a result, the highest compressive strength could be obtained in pervious concrete incorporating 25% IBA.

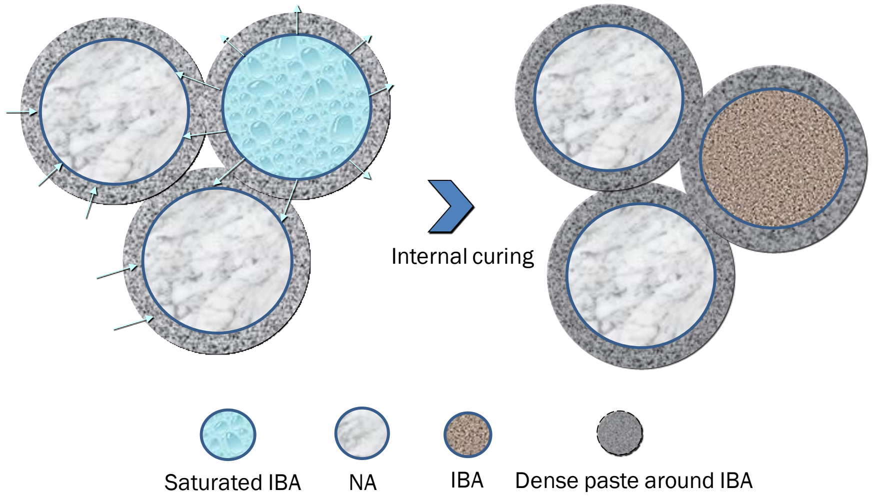
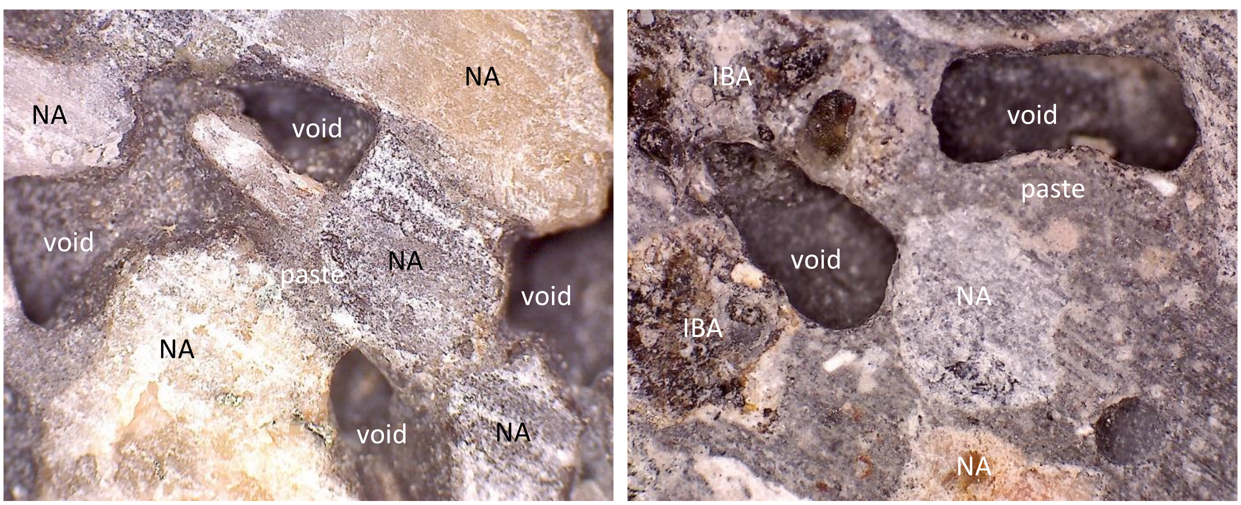


Figure 16 The skeleton effect of UHSC paste

4.2 The mechanism of volume stability

The incorporated IBA in pervious concrete has limited effect on the expansion level. This is mainly attributed to the high porosity (shown in Figure 17), which is able to accommodate the alkali-silica-reaction gel produced [52]. In addition, the silica fume and fly ash in the matrix will also mitigate the alkali-silica-reaction expansion of the glass in IBA [53]. Furthermore, the aggregates (including NA and IBA) are coated by cement paste, and the thickness of coatings around aggregate is low. Therefore, the H_2 gas from the alkaline-metallic Al reaction in IBA can release easily; thus, the expansion from H_2 release can be reduced. As a result, a relatively low expansion can be obtained for pervious concrete incorporating IBA. According to ASTM C1260, an expansion of less than 1000 $\mu\varepsilon$ is indicative of innocuous behavior of aggregates in most cases. Therefore, in case of pervious concrete, the IBA can be used as aggregate safely and effectively without considering the crack risk from the expansion of IBA.

Indeed, the presence of heavy metals in IBA is an issue. The proposed procedure was able to address the potential expansion of concrete incorporated IBA, which produced pervious concrete with good quality even when the replacement of IBA reached 100%. However, the porous structure might provide the route for potential chemical leaching (i.e. heavy metals and salts) of IBA[54]. But it is generally recognized that the IBA from MSW incinerators is not a hazardous waste and it can be reused/disposed of by normal means. Furthermore, a dense wall with ultra-high micro-mechanical properties was formed on the surface of IBA, which will be of benefit to the bonding strength between aggregates and mechanical strength of pervious concrete. This dense structure of cement paste could certainly reduce the potential leaching of heavy metals. A balance between adverse effect of porous structure of pervious concrete and benefits from the dense wall around IBA might be obtained when the appropriate amount of IBA with a dense wall was were applied. Therefore, further studies will be carried out to evaluate the leaching behaviors of heavy metals from pervious concrete incorporated IBA, and the process and factors that influence the potential leaching of heavy metals will be explored.



(a) without IBA (b) with IBA

Figure 17 The porous structure of pervious concrete with and without IBA

5. Conclusion

In this study, the physical properties, hydration and volume stability of pervious concrete incorporating with IBA were systemically characterized. From the performance point of view, it is potential to use IBA in the production of eco-pervious concrete. Based on the experimental results and discussions, the conclusion can be drawn as follows.

(1) The use of IBA to replace the NA in pervious concrete led to an enhancement of compressive strength when the appropriate amount of IBA was utilized (lower than 50%). The IBA can act as an internal curing material and motivated the hydration of UHSC paste, leading to a higher hydration degree and microhardness. The use of molding pressure during production could produce a denser pervious concrete, thus resulting in a higher strength.

(2) The use of IBA led to the reductions of water permeability and connected porosity due to the damage of IBA during casting under pressure and increased volume of cement paste. Although 100% IBA was used as aggregates, the compressive strength and the water permeability could meet the requirement of JIS A 5371 specification.

(3) The density of developed eco-pervious concrete ranged from 1709.2 to 1994.2 kg/m^3, which was lower than that of normal concrete. Both the density and the total porosity showed a linear relationship with compressive strength, which indicated that the density and porosity played key roles in affecting the compressive strength.

(4) The thermal conductivity decreased with the increase of IBA replacement due to the porous structure of IBA. The proposed pervious concrete with low thermal conductivity offered an alternative option to be used as a thermal insulating partition wall.

(5) The presence of the high amount of aggregates and internal curing of IBA compensated the autogenous shrinkage of pervious concrete. The incorporated IBA in pervious concrete had limited effect on the expansion level due to the high porosity and thin coating around IBA. Hence, it was possible to use as aggregates in pervious concrete without considering the crack risk from the expansion of IBA.

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