Void Ratio and Durability Properties of Porous Polymer Concrete Using Recycled Aggregate with Binder Contents for Permeability Pavement

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ABSTRACT: Particularly in Korea, where most roads are paved with impermeable materials such as asphalt and cement concrete, problems arise such as increased flooding as result of rainwater flowing into urban streams and the depletion of underground water. In recent years, there has been a great deal of ongoing research concerning water permeability and drainage in pavements. Accordingly, in this research, a porous polymer concrete was developed by using unsaturated polyester resin as a binder, recycled aggregate as coarse aggregate, fly ash and blast-furnace slag as filler for permeable pavement, and its physical and mechanical properties were investigated. Regardless of the type of filler and amount of binder, the standard void ratio of 8% specified in the mixture of permeable asphalt was exceeded. In all mixes, regardless of the type of filler and amount of binder, the standard compressive strength for permeable concrete of 18 MPa was exceeded. Also, in all mixes, the standard permeability coefficient of 1.0×10^{-2} cm/s for permeable asphalt mixture was exceeded. The weight reduction ratio of the porous polymer concrete that was submerged in 10% sulfuric acid solution was 1.17 to 2.3%, and it was found that there was virtually no weight reduction. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 000: 000–000, 2012

Key words: polyester; porous polymer concrete; mechanic properties; strength; void

INTRODUCTION

Most of the roads in Korea are paved with impermeable materials such as asphalt concrete and cement concrete, and in the event of heavy rainfall, rainwater directly flows into river through a drainage hole on the pavement surface. This large quantity of rainwater directly spilled into the river frequently leads to the flooding of urban streams, damaging lowlands, and the lower reaches of a river. In addition, the depletion of underground water is another problem that results from the significantly reduced infiltration of rainwater. Furthermore, the ecological system is also threatened, because the problem hinders the habitation of underground microorganisms and the growth of street trees.

As such, recently, interest has been growing in permeable or drainable pavement, a new type of pavement that offers improvements compared with the existing impermeable cement concrete or asphalt concrete in the areas of preventing flood damage and securing underground water resource. Accordingly, the use of permeable asphalt or concrete in construction works for streets, sidewalks, squares, and parking lots has been increasing, and there has been a great deal of ongoing research concerning the development of permeable blocks using porous concrete.[1,2]

Chindaprasirt et al.[3] performed a study concerning the properties of paste of concrete and the properties of porous concrete depending on vibration and compaction; Kim and Lee[4] and Park et al.[5] performed research concerning the properties in mechanics and sound absorption of porous concrete depending on the shapes of aggregate and the flow of cement paste. Park and Tia[6] evaluated the water purification properties of porous concrete depending on the cement paste-aggregate ratio (P/G) and proposed that the porous concrete had a reduction effect on total phosphorus (T-P) and total nitrogen (T-N).

However, in existing permeable cement concrete and asphalt pavement, partial settlement and destruction resulting from cracks and breakaway of aggregate when freezing and thawing are applied repeatedly in winter, which frequently take place. The fundamental cause of this problem is the low binding force of the binders used. From a long-term point of view, degradation in durability is another problem. To address this aforementioned shortcoming, the use of polymer binders has been increasing, and it is known that, among other things, unsaturated

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TABLE 1
General Properties of Unsaturated Polyester Resin

Specific gravity at 20°C	Viscosity at 20°C (g/cm s)	Styrene content (%)	Acid value
1.12	3.5	37.2	26.5

TABLE 2
General Properties of DMP

Color (APHA)	Acid value (KOH mg/g)	Water content (%)	Specific gravity at 20°C
≤20	>8	≤0.1	1.188–1.196

polyester resin with superior strength, workability, and plasticity produces excellent effects if used in porous concrete, which requires a strong binding force.[7,8] Also, using unsaturated polyester resin made by recycled PET is expected to benefit recycling.[9]

However, in Korea, the city redevelopment businesses and expansion projects for social infrastructure create 39 million tons of construction waste, of which 24 million tons are waste concrete. In the United States, Europe, and Japan, recycled aggregate concrete using such waste concrete is extensively being researched these days, and the recycling ratio for the recycled aggregate is considerably high, whereas in Korea, more than 90% of waste concrete is used as roadbed material.[10,11] In addition, given the fact that the fly ash and pulverized granulated blast-furnace slag created as byproducts from the thermal power generation and iron manufacturing industry are used as additives for cement concrete, the cost reduction effect will be substantially high, producing economic and environmental advantages if the same industrial waste and byproducts are used for polymer concrete manufacturing.[12,13]

Therefore, in this research, to address the shortcomings of regular cement porous concrete, such as its low strength, limited durability, etc., a porous polymer concrete for permeable pavement was developed by using unsaturated polyester resin with a stronger binding force and fly ash and pulverized granulated blast-furnace slag produced as industrial byproduct as filler; and data that can be used for permeable pavement were provided by closely examining the physical and mechanical properties of the porous polymer concrete, such as porosity, strength, and coefficient of permeability, depending on the types of filler and the amount of binder and the resistance to freezing-thawing and chemical agents.

EXPERIMENTAL

Materials

To manufacture the porous polymer concrete for permeable pavement, unsaturated polyester resin, for which dimethyl phthalate (DMP) solution containing 55% methyl ethyl ketone peroxide is used as an initiator, is used as a binder, the general characteristics of which are described in Table I. Also, general characteristics of DMP used are described in Table II. For coarse aggregate, recycled aggregate that was produced by one company in Korea by recycling waste concrete was used in an effort to promote the recycling of wastes, and fine aggregate collected from a river was also used. Table III shows the physical properties of the coarse aggregate and fine aggregate mentioned above. Calcium carbonate, which is frequently used as a filler for polymer concrete, fly ash scattering in a product of burning finely ground coal in a thermal power generation plant to produce electricity and the pulverized granulated blast-furnace slag (obtained by quenching molten iron slag from a blast furnace in water or steam to produce a glassy) are used as filler. This filler is used to increase the binding force between aggregate by creating viscosity of binder and paste with binder as well. Table IV shows the physical properties and shape of the filler that has been used.

Preparation of specimens

Unlike regular concrete, the porous concrete for permeable pavement should have a series of voids to offer permeability, and it is necessary to increase the permeability coefficient and void ratio of the concrete to allow the rapid permeation of rainwater when it rains. However, the increase in the permeability coefficient and void ratio to improve permeability may lead to degradation in strength of the porous polymer concrete, and therefore, it is critical to find an optimum mix of the porous polymer concrete for permeable pavement that satisfies both strength and void ratio, two opposing requirements.[3,5] The strength, permeability coefficient, void ratio, and durability such as resistance to freezing-thawing of the porous concrete for permeable pavement depend on the characteristics and the amount of the binder in use. If too much of the binder,

TABLE 3
Physical Properties of Aggregates

Type	Size (mm)	Bulk density (kg/m^3)	Specific gravity (20°C)	Absorption ratio (%)	Fineness modulus
Recycled coarse	5–10	1,597	2.64	1.28	6.84
Fine	0.15–5	1,675	2.62	0.87	2.66

TABLE 4
Physical Properties of Fillers

Type	Specific gravity (20°C)	Specific surface (cm^2/g)	Grain size (mm)	Color
$CaCO_3$	2.92	3,150	<0.15	White
Fly ash	2.39	3,152	<0.15	Gray
Blast furnace slag	2.92	4,401	<0.15	White

unsaturated polyester resin, is used, the aggregate will be coated with the binder and the voids will be filled with extra binders, which lead to the creation of an impermeable layer in the pavement. In short, the permeability of the pavement will be lost.

Table V shows the specified mixes for the porous polymer concrete depending on the type of fillers. In this research, the specified mix was performed in a manner satisfying the Korean standard void ratio for permeable pavement of 8%, and the standard permeability coefficient for permeable asphalt mixture of 1×10^{-2} cm/s.[14] The amount of binder set as 6 to 9% to evaluate the strength and void ratio according to the amount of binder regardless of the type of filler. For hardener, 1% of the weight of the binder was used given the temperature at the time of work and the time spent for manufacturing. For the ratio between coarse aggregate and fine aggregate, more coarse aggregate was used than in regular concrete to ensure a series of voids in larger quantity, and the amount of fine aggregate was reduced accordingly. For filler, 8% of the total weight was used so that the volume in which aggregate could be coated by paste created with binder may be secured.

For the mixing of the porous polymer concrete for permeable pavement, filler and aggregate were first put into a mixer and dry mixed. Next, the binder, unsaturated polyester resin, was added and mixed for 3 min so that the aggregate may be fully coated with the binder. The coated aggregate was placed in a mold and the vibrating compaction was performed by vibrator. The cast mold was demolded after 3 h, and then retained in a curing room at a temperature of 28 ± 1°C for curing age of 7 days.

Test method

The void ratio test and measurement for the porous polymer concrete were performed in accordance with the volume method of the test methods for void ratio set forth by the Research Committee for Eco Concrete in Japan, and the following eq. (1) was used for estimation.[15]

$$V_0 = \left[1 - \frac{(W_2 - W_1)}{V}\right] \times 100 \tag{1}$$

where, V_0= void ratio (%);
W_1 = underwater weight of specimen (g);
W_2 = weight of specimen in dry air (g); and
V = volume of specimen (cm^3).

For compressive strength test, cylinder specimen with Φ100 × 200 mm was made. Compressive strength test was performed in an UTM with a dynamic capacity of 200 tf in accordance with the method set forth in ASTM C 39.[16] The load was applied at a rate of movement corresponding to a stress rate on the specimen of 0.28 MPa/s. For flexural strength test, prism specimen with 60 × 60 × 240 mm^3 was made, and it was subject to a weight load at the speed of 5 kgf/s in accordance with the method set forth in ASTM C 590.[17] The permeability coefficient of the porous polymer concrete was measured using the test apparatus shown in Figure 1, in the manner set forth in the test method for the permeability coefficient provided by Japan's Eco

TABLE 5
Mix Types of Porous Polymer Concrete with Fillers for Permeability Pavement (unit: wt %)

Mix type	Maximum size of coarse aggregate	Binder: Unsaturated polyester resin	Aggregate: Coarse	Aggregate: Fine	Filler: $CaCO_3$	Filler: Fly ash	Filler: Blast furnace slag
PC-CA	10	6	72	14	8	–	–
		7	71	14	8	–	–
		8	70	14	8	–	–
		9	69	14	8	–	–
PC-FA		6	72	14	–	8	–
		7	71	14	–	8	–
		8	70	14	–	8	–
		9	69	14	–	8	–
PC-BS		6	72	14	–	–	8
		7	71	14	–	–	8
		8	70	14	–	–	8
		9	69	14	–	–	8

Figure 1 Water permeability test apparatus. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Concrete Research Committee, and was calculated using eq. (2) on the basis of Darcy's principle.

$$K = \frac{HQ}{Ah(t_2 - t_1)} \tag{2}$$

where, K = permeability coefficient (cm/s);
H = height of specimen (cm);
A = cross-section area (cm^2);
h = difference in water levels (cm); and
Q = volume of water passed from t_1 to t_2 (cm^3).

For the test on the resistance to freezing-thawing, prism specimen with 60× 60 × 240 mm was made and a fast underwater freezing-thawing test was performed in accordance with ASTM C 666.[18] During the test, the temperature of the bend specimen was −18°C during freezing and 4°C during thawing, and 4 h were spent per cycle of freezing and thawing. Weight change ratio was measured at the interval of every 50 cycles, and the test was completed when 300 cycles of freezing-thawing was reached.

In the acid resistance test for concrete, the standard for density of sulfuric acid solution is not proposed, and generally, durability is judged after conducting tests in 5% and 10% solution of sulfuric acid and setting a weight decrease rate of 20% as the limit. In this research, a 10% solution of sulfuric acid in 20°C of treatment temperature was used to analyze acid resistance under extreme environment. For the test of resistance to acidic attack, prism specimen with 60 × 60 × 240 mm^3 was dipped into 10% sulfuric acid solution, and the weight under saturated surface-dried condition was measured after 14, 28, 42, 56, and 91 days, respectively, after the rusted surface was cleaned with a metallic brush. The weight change ratio was calculated using eq. (3).

$$W.C = \frac{W - C}{C} \times 100 \tag{3}$$

where, $W.C$ = weight change ratio (%); C = weight of specimen before dipping (g); and W = weight of specimen after dipping (g).

RESULTS AND DISCUSSION

Void ratio

Figure 2 shows the void ratio of the porous polymer concrete for permeable pavement according to the amounts of binder and filler. It shows that the void ratio is more than 8%, as specified in KS F 2385 (permeable asphalt mixture), regardless of the type of filler in use, and the void ratio tends to decrease as the amount of binder increases.[19] Considering the void ratio depending on the type of filler, the void ratio for porous polymer concrete using blast furnace slag as filler (PC-BS) mix is in the range of 9–18%, which is slightly lower compared with 11 to 21% and 11 to 22% for porous polymer concrete using $CaCO_3$ as filler (PC-CA) and porous polymer concrete using fly ash as filler (PC-FA), respectively. The void ratio of the porous polymer concrete is affected not only by the grading and mix for coarse aggregate and fine aggregate but also by the amount of use and specific surface area of filler, which creates a paste through binding with binder. The more

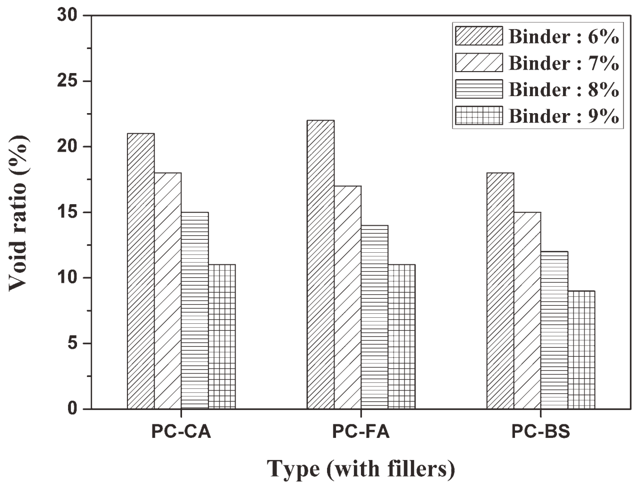

Figure 2 Void ratios with fillers and binder contents.

and larger the amount and specific surface area of the filler, the thicker the coat of aggregate becomes because of the increased viscosity of the paste, and this causes the void ratio to decrease. However, the less and smaller the amount and specific surface area of the filler, the thinner the coat of aggregate becomes because of the decreased viscosity of the paste, and this causes the void ratio to increase. Therefore, in the mix of porous polymer concrete in which pulverized granulated blast-furnace slag with a larger specific surface area was used as filler, the viscosity of paste (binder + filler) was higher than that of the mix in which fly ash or calcium carbonate with a relatively smaller specific surface area was used. Accordingly, the thickness of the coat on the aggregate also increased, causing the void to decrease because of the aggregate interlocking that resulted from the increased coat thickness.

However, when we examine the relationship between the void ratio and the amount of binder, we notice that the void ratio tends to decrease as the amount of binder increases, regardless of the type of filler in use. In the mix where 9% of binder amount depending on the type of filler was used, the void ratio was in the range of 9 to 11%, which was slightly higher than the void ratio standard of 8% specified for permeable pavement. Furthermore, in the mix where 9% of binder amount was used, paste ran down, shutting off the lower end of the bend specimen. Attention needs to be paid to this problem when the bend specimen is made. In terms of void ratio, it is considered that an amount of binder not exceeding 9% would be desirable when porous polymer concrete is manufactured.

Compressive strength

Compressive strength, one of the typical mechanical properties of concrete, varies depending on the type of aggregate, mix condition, etc. It is the standard for the design of mix proportion, and tensile strength, flexural strength, elasticity coefficient, durability, etc. can be estimated based on the compressive strength. It also becomes a standard that must be determined at the time of placement when formwork shuttering needs to be removed. Unlike regular concrete, in which strength is manifested by fine structures of binder and aggregate, it is generally known that the strength properties of porous concrete depend on aggregate interlocking because of characteristics specific to the porous structure. Figure 3 shows the compressive strength of the porous polymer concrete for permeable pavement according to the amounts of filler and binder. Regardless of the type of filler in use, the compressive strength tends to increase as the amount of binder in use increases in PC-CA, PC-FA, and PC-BS mixes. Regardless of the type of filler in use, with a 6% binder amount, the compressive strength was in the range of 18.2 to 18.9 MPa, which was slightly higher than the standard compressive strength of 18 MPa required for concrete for permeable pavement.[20] In addition, regardless of the type of filler, with a 9% binder amount, compressive strength was in the range of 23.2–24.8 MPa, which is much higher than the standard compressive strength of 18 MPa required for concrete for permeable pavement. This implies that it is advantageous in terms of compressive strength to increase the amount of binder in use. This result, like the result from the void ratio test, shows that as the amount of binder increases, the amount of paste (binder + filler) and its viscosity increase, resulting in increased thickness of coat and increased aggregate interlocking effect. In addition, as seen in the result of void ratio test, when the amount of binder exceeds 9%, the void ratio is reduced significantly, degrading permeability at the time of application for permeable pavement. It is thus determined that a binder amount of 7–8% that satisfies both void ratio and compressive strength is appropriate to the mix of porous polymer concrete for permeable pavement.

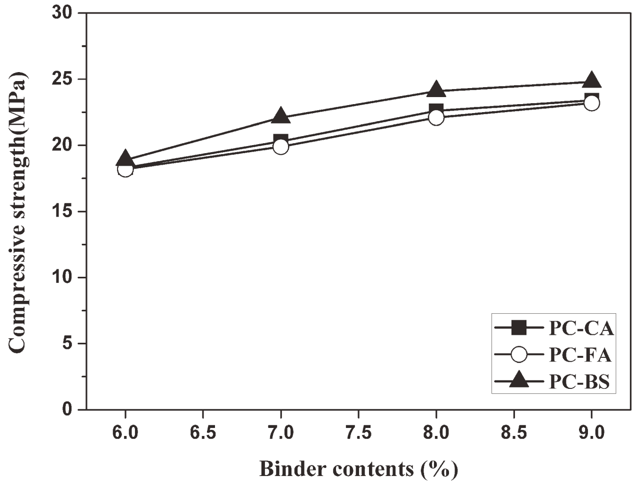

Figure 3 Compressive strengths with fillers and binder contents.

For the compressive strength in PC-CA, PC-FA, and PC-BS mixes depending on the type of filler in use, the highest compressive strength was seen from PC-BS mix where pulverized granulated blast-furnace slag was used, regardless of the amount of binder in use, and similar compressive strength was recorded in PC-CA and PC-FA mixes where calcium carbonate and fly ash were used. This result was produced because the coat thickness of aggregate caused by paste increased significantly, causing aggregate interlocking to further increase, because the specific surface area of the pulverized granulated blast-furnace slag was larger compared with other

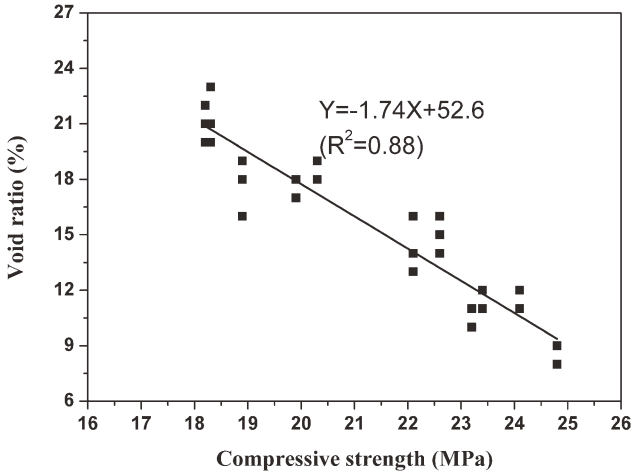

Figure 4 Relation between void ratio and compressive strength with fillers and binder contents.

fillers such as calcium carbonate and fly ash. In particular, the compressive strength recorded in the mix of porous polymer concrete in which the pulverized granulated blast-furnace slag and fly ash, industrial waste, and byproduct used was similar to or slightly higher than that of the mix of the porous polymer concrete in which calcium carbonate was used as filler, and this indicates that pulverized granulated blast-furnace slag and fly ash will be useful in manufacturing the polymer concrete in terms of aspects such as environmental friendliness and economic efficiency.

Figure 4 shows the relationship between compressive strength and void ratio for porous polymer concrete for permeable pavement according to the amount of filler and binders. Regardless of the type of filler and the amount of binder, void ratio decreases as compressive strength increases. This shows that the compressive strength and void ratio are opposing requirements, meaning that increased compressive strength requires a thicker coat of aggregate, whereas an increased void ratio requires thinner coat of aggregate.

Table VI and Figure 5 show the flexural strength of the porous polymer concrete for permeable pavement according to the amount of filler and binders. As seen in the test result for compressive strength, the flexural strength tends to increase as the amount of binder increases, regardless of the type of filler in use, and the flexural strength in PC-BS mix was higher compared with other mixes. For porous cement concrete in which cement is used as a binder, the flexural strength is significantly degraded compared with compressive strength because of the low binding force of cement, whereas the porous polymer concrete in which unsaturated polyester resin is used as a binder offers excellent compressive and flexural strength as a result of the high binding force of the binder.

TABLE 6
Flexural Strength with Fillers and Binder Contents

Type	Flexural strength (MPa) 6% Binder	7% Binder	8% Binder	9% Binder
$CaCO_3$	7.9	8.7	9.5	10.4
Fly ash	7.7	8.5	9.3	10.2
Blast furnace slag	8.3	8.9	10.2	11.3

Permeability coefficient

Permeability coefficient of the porous polymer concrete is very important to ensure proper design and work for permeable pavement, and rainwater should be fully permeated when it rains, regardless of how heavy the rainfall is. It is generally known that permeability coefficient increases and strength decreases as serial void ratio increases.

Table VII and Figure 6 show the permeability coefficient of the porous polymer concrete for pavement according to the type of filler. In PC-CA, PC-FA, and PC-BS mixes, the permeability coefficient of the porous polymer concrete according to the amount of binder in use was 4.8×10^{-2} to 4.4×10^{-1} cm/s, 2.7×10^{-2} to 3.1×10^{-1} cm/s, and 1.8×10^{-2} to 2.9×10^{-1} cm/s, respectively, and the permeability coefficient tended to decrease as the amount of binder increased. In addition, like the result of the void ratio test, the permeability coefficient of PC-BS mix was a little lower than those of PC-CA and PC-FA mixes, but regardless of the type of filler and amount of binder, they all exceeded the standard permeability coefficient of 1.0×10^{-2} cm/s for permeable asphalt mixture. Figure 9 shows the relationship between compressive strength and permeability coefficient of the porous polymer concrete for permeable pavement. It can be observed that the

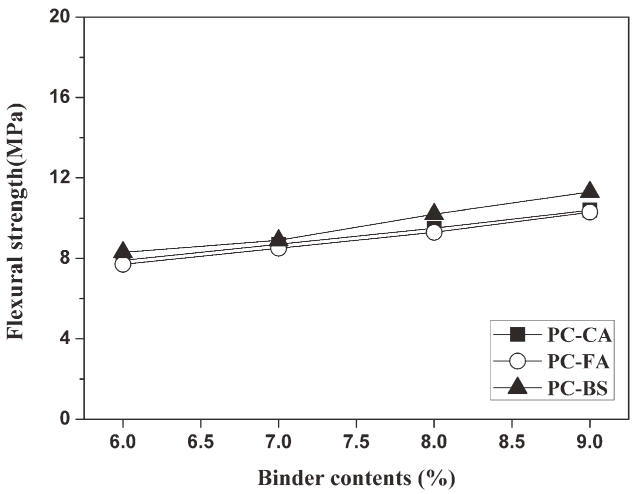

Figure 5 Flexural strengths with fillers and binder contents.

TABLE 7
Water Permeability Coefficient with Fillers and Binder Contents

Type	Water permeability coefficient ($\times 10^{-2}$ cm/s) 6% Binder	7% Binder	8% Binder	9% Binder
$CaCO_3$	44	22	8.9	4.8
Fly ash	31	24	4.9	2.7
Blast furnace slag	29	18	4.4	1.8

two are contrary to each other, because the permeability coefficient decreased while the compressive strength increased. Correlation coefficient for compressive strength and permeability coefficient was $R^2 = 0.87$, a high level of significance and was expressed with the following equation.

$$y = -0.056x + 1.375 \quad (R^2 = 0.87)$$

To increase compressive strength, the coat thickness of aggregate caused by paste (binder + filler) should be increased, whereas the permeability coefficient required for the rapid permeation of rainwater because of the characteristics of permeable pavement should create sufficient voids that exceed a certain level. In other words, it is absolutely necessary to find an optimum mix which satisfies the opposing requirements of compressive strength and permeability coefficient. As seen in Figure 9, in any and all mix conditions, the standard compressive strength of 18 MPa and standard permeability coefficient of 1×10^{-2} cm/s ensuring permeable pavement were met. However, this result was achieved in an indoor test, and the actual application on the work site and long-term use may cause such problems as degraded quality and durability, void shut-off, etc., and therefore the mix that satisfies the boundary condition as seen in Figure 7 may be deemed an optimum mix.

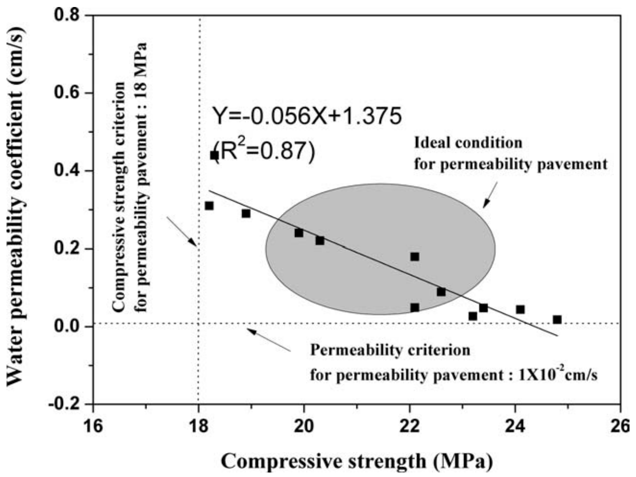

Figure 7 Relation between compressive strength and water permeability coefficient.

Figure 8 shows the relation between permeability coefficient and void ratio for porous polymer concrete for permeable pavement. Both permeability coefficient and void ratio are related to the size and the number of voids, and therefore, the void ratio increased as the permeability coefficient increased. The correlation coefficient for permeability coefficient and void ratio was $R^2 = 0.84$, which indicates a high level of significance and was expressed with the following equation.

$$y = 27.43x + 10.76 \quad (R^2 = 0.84)$$

In the meantime, as seen in Figure 8, the void ratio standard of 8% and permeable coefficient of 1×10^{-2} cm/s for permeable pavement were met in any and all mixes. However, voids may be filled because

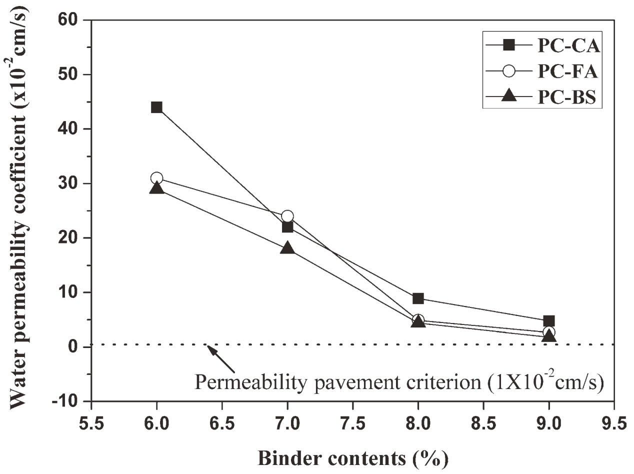

Figure 6 Permeability coefficients with fillers and binder contents.

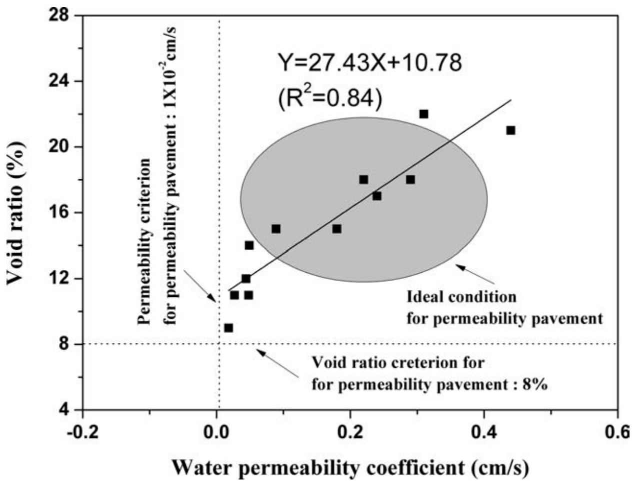

Figure 8 Relation between water permeability coefficient and void ratio.

of pedestrian and vehicle traffic in actual use after application on the sites, and thus the boundary condition as seen in Figure 8 can be proposed as an optimum mix condition.

Resistance to freezing-thawing

Generally, if freezing and thawing are repeatedly applied, concrete surface detachment may take place because of scaling or pop-out that occurs to concrete, resulting in reduced mass. In addition, it is also known that volume expansion may occur due to the repeated application of freezing and thawing of moistures inside concrete, which reduces the density of concrete. This phenomenon will further lead to a decrease of the relative dynamic modulus of elasticity, and the degradation of durability.[21] However, unlike regular concrete, porous and permeable concrete, which are based on aggregate interlocking, have a mechanism that is different from that of regular concrete when freezing and thawing are applied. Because of the porous structure of porous concrete, there is always a lot of water contained inside the concrete, and when this water is frozen, it usually expands, decreasing the binding force of aggregate and causing aggregate to fall and break. In short, it is reported that porous concrete has a lower resistance to freezing-thawing than regular concrete.

However, the resistance to freezing-thawing is usually evaluated by durability factor by obtaining the relative dynamic modulus of elasticity on the basis of measurement of the dynamic modulus of elasticity coefficient, but for porous concrete, it is difficult to measure the coefficient because of there being too many voids as seen in Figure 9 (7% binder); furthermore, the measured coefficient is also inaccurate. Therefore, in this research, the resistance to freezing-thawing was evaluated by monitoring the change in weight depending on the freezing-thawing cycle and appearance such as aggregate fall, etc.

Figure 10 shows the change in weight depending on the type of filler and amount of binder used for the porous polymer concrete for permeable pavement. In PC-CA mix, the weight reduction ratio of the porous polymer concrete according to the amount of binder after 300 cycles of freezing-thawing was 1.1 to 2.9%, which indicates that virtually no change occurred to the surface of the porous polymer concrete, regardless of the amount of binder.

In PC-FA and PC-BS mixes where fly ash and pulverized granulated blast-furnace slag, industrial waste, and byproduct were used, the weight reduction ratio of the porous polymer concrete according to the amount of binder after 300 cycles of freezing-thawing was 1.1 to 3.6% and 0.9 to 3.8%, respectively, which are almost similar to the weight reduction ratio seen in the PC-CA mix. For cement porous concrete, aggregate fall and degradation in durability as a result of decreased aggregate interlocking force resulting from low attaching force of cement noticeably take place when freezing-thawing is applied, whereas for the porous polymer concrete in which unsaturated polyester resin with excellent attaching force is used, the degradation of durability such as aggregate fall, etc., does not take place even after 300 cycles of freezing-thawing because of there being a stronger aggregate interlocking force.

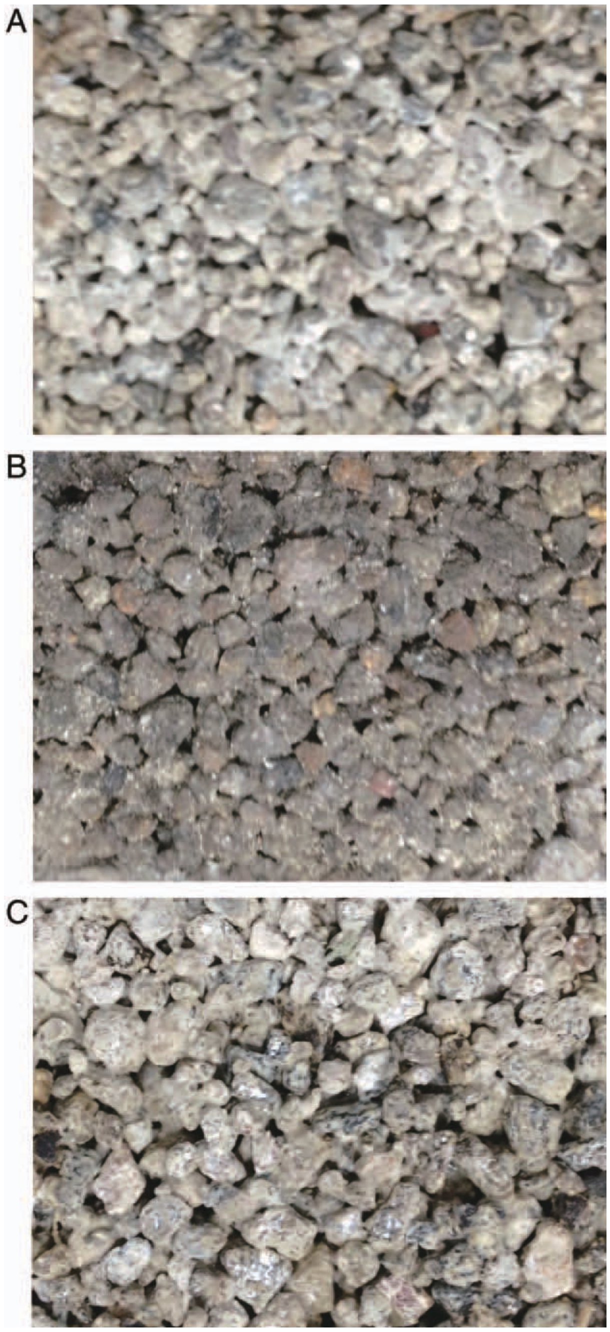

Figure 9 Surface of porous polymer concrete with filler (7% binder) (a) PC-CA; (b) PC-FA; and (c) PC-BS. Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.

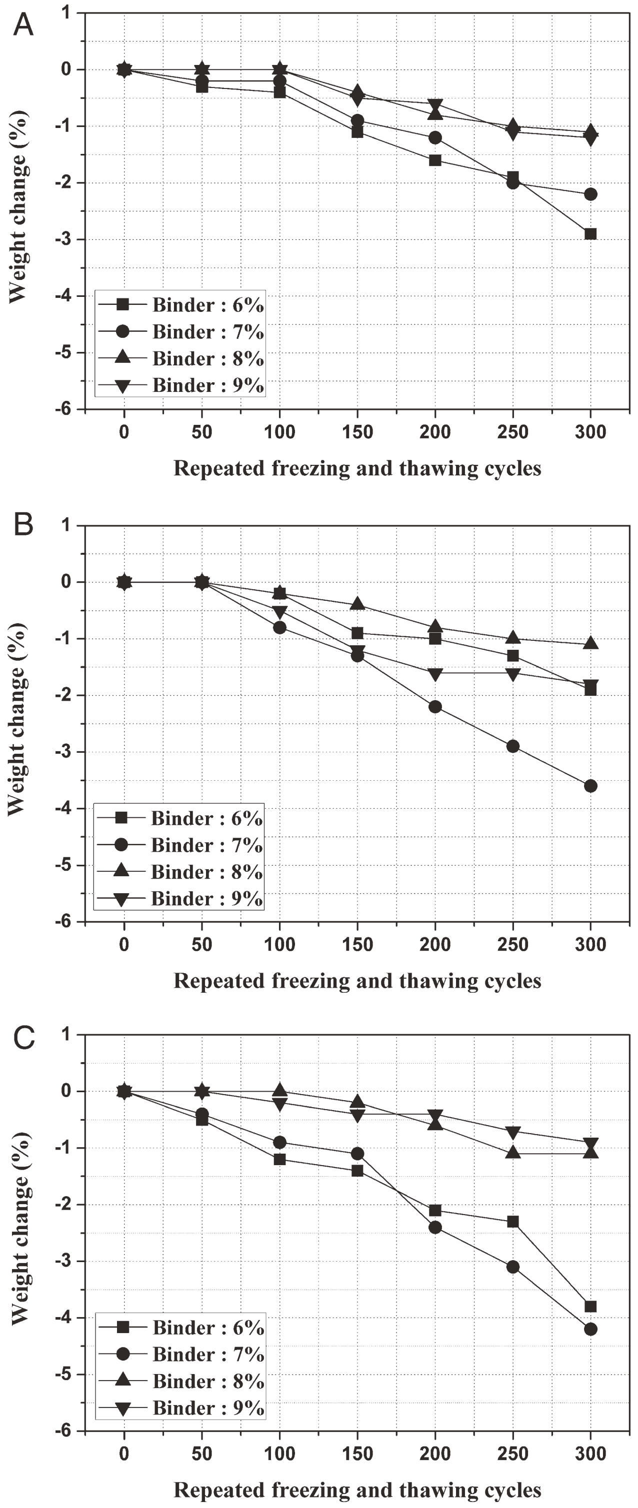

Figure 10 Weight change for 300 cycles of freezing and thawing (a) PC-CA; (b) PC-FA; and (c) PC-BS.

The fact that the resistance to freezing-thawing was excellent in all kinds of mixes regardless of the type of filler in use indicates that the resistance to freezing-thawing of the porous polymer concrete largely depends on the attaching force of the binder in use, not the aggregate or filler in use. Furthermore, the fact that the weight change ratio was around 4% in any and all mixes regardless of the amount of binder means that the attaching force of aggregate that results from the binding force of unsaturated polyester resin used as filler is greater than the shrinking and expanding force created when the water inside the concrete is frozen and thawed.

Resistance to acidic attack

It is generally known that in regular concrete in which cement is used as binder, alkaline calcium hydroxide, which exists in large quantities in hydrates, has high solubility and easily reacts with acid; furthermore, C-S-H (calcium silicate hydroxyl) and C-A-H (calcium aluminates hydroxyl), which are hydraulic compounds, are decomposed, and salt is created in large quantities, causing erosion and degradation through accumulation and crystallization.[22] In particular, calcium chloride, calcium nitrate, and insoluble calcium sulfate, all of which are hydraulic, are created by the erosion action of sulfuric acid and hydrochloric acid, which also create silica and alumina gel by dissolving silicic acid and alumina, and in the worst case even aggregate can be eroded. For concrete for pavement and permeable concrete, high resistance to chemical agents is required, as degradation in durability may occur due to salt damage from calcium chloride used for snow removal in winter, and chemical erosion as a result of the carbon dioxide discharged from vehicles. In particular, the strength and durability of porous concrete are subject to greater degradation than regular concrete, and it is necessary to increase the resistance to chemical agents by coating the surface of aggregate with a substance that has excellent chemical resistance. Figure 11 shows the weight change depending on the filler of the porous polymer concrete for permeable pavement that was submerged in 10% sulfuric acid solution for 13 weeks. The weight reduction ratio of the porous polymer concrete that was submerged in 10% sulfuric acid solution was 1.17–2.3%, and it was found that there was virtually no weight reduction and aggregate fall in any and all mixes, regardless of the type of filler used. This result shows that the unsaturated polyester resin with which aggregate was coated inhibited the infiltration of the 10% sulfuric acid solution, thus preventing the aggregate from being eroded. It is determined, therefore, that the unsaturated polyester resin has a very high resistance to sulfuric acid.

CONCLUSIONS

The physical and mechanical properties of the porous polymer concrete according to the type of filler and amount of binder used were investigated, and the following conclusions were reached.

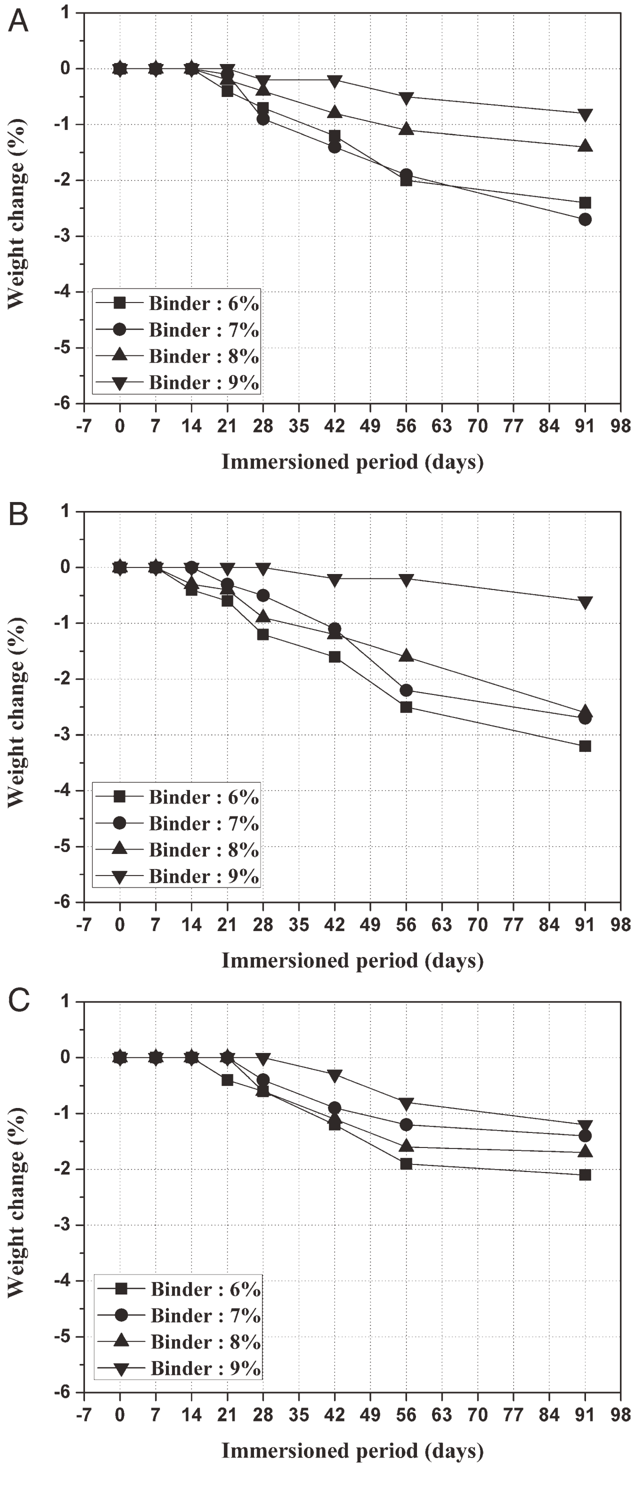

Figure 11 Weight change for immersion in 10% sulfuric acid (a) PC-CA; (b) PC-FA; and (c) PC-BS.

Regardless of the type of filler and amount of binder in use, the standard void ratio of 8% specified in the mixture of permeable asphalt was exceeded in any and all mixes, and the void ratio tended to decrease as the amount of binder increased. The void ratio for porous polymer concrete using blast furnace slag was 9–18% depending on the type of binder. The unsaturated polyester resin used, with viscosity of 3.5 g/cm s and gel hardening time of 7–12 min, enabled smooth formation of paste and coating of aggregates by combination with filler and thus was shown to be help void formation by combination among aggregates.

In porous polymer concrete using $CaCO_3$, fly ash, and blast furnace slag as filler, compressive strength and flexural strength increased as the amount of binder increased, and the standard compressive strength for permeable concrete of 18 MPa was exceeded. Unsaturated polyester resin, because it has good adhesive characteristics as a result of reaction of styrene monomer and unsaturated polyester with good adhesive power, was shown to be very effective in increasing the strength of porous concrete that manifests strength by adhesion among aggregates coated by paste (binder + filler).

In porous polymer concrete using $CaCO_3$, fly ash, and blast furnace slag as filler, regardless of the type of filler and amount of binder, the permeability coefficient was 4.8×10^{-2} to 4.4×10^{-1}cm/s, 2.7×10^{-2} to 3.1×10^{-1}cm/s, and 1.8×10^{-2} to 2.9×10^{-1}cm/s, respectively, and in any, the standard permeability coefficient of 1.0×10^{-2}cm/s for permeable asphalt mixture was exceeded.

In porous polymer concrete using $CaCO_3$, fly ash, and blast furnace slag as filler, the weight reduction ratio according to the amount of binder after 300 cycles of freezing-thawing was 1.1 to 2.9%, 1.1 to 3.6%, and 0.9 to 3.8%, respectively, and virtually no surface changes such as weight reduction, aggregate fall, etc. were noticed. After submersion for 13 weeks in 10% sulfuric acid solution, the weight reduction ratio in all mixes was 0.8 to 2.7%, 0.6 to 3.2%, and 1.2 to 2.1%, respectively. Even though it was submerged in 10% sulfuric acid solution, virtually no changes such as weight reduction, aggregate fall, etc. were noticed in any and all mixes, which means that it has excellent chemical resistance.

It was shown that because water absorption rate of porous polymer concrete using unsaturated polyester resin is close to 0, such concrete not only suppressed water penetration in the freezing and thawing test but also manifested little change in weight from repeated freezing and thawing as a result of good adhesive power among coated aggregates. Also, because unsaturated polyester resin used, itself has very good acid resistance and thus suppresses erosion of aggregates, its resistance to 10% solution of sulfuric acid was shown to be very good.

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