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An Experimental Study of Permeable Concrete Pavement for Practical Use in the Field

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Abstract: In rainy weather, permeable concrete pavement has advantages such as good drainage, increased skid resistance, reduced splash and spray behind vehicles for improving the safety of driving vehicles as well as reduction of the traffic noise. It also contributes to improvement of traffic environment. In this study, the fundamental properties of permeable concrete in accordance with maximum size of aggregate, sand percentage and unit cement content were investigated for practical use of permeable concrete pavement. Although the permeability standard for typical permeable asphalt-concrete pavement is 1×10^{-2}cm/sec, the researchers determined that the coefficient of permeability of the permeable concrete should be set higher at 1×10^{-1}cm/sec. Then, the researchers measured the coefficient of permeability, strength, void ratio, and continuous void ratio of the permeable concrete while varying maximum size of the aggregate, sand percentage, unit cement content for detailed analysis. It was found that the void ratio, continuous void ratio, and flexural strength were about 15%, 12%, and 5.0 MPa, respectively, when the permeability of the concrete was set at 1×10^{-1}cm/sec. Given that the maximum size of aggregate was 10~13 mm, we reached the conclusion that the best mix design for permeable concrete was 0~20% of sand percentage and 380 kg/m^3 of unit cement content.

Keywords: void ratio, continuous void ratio, coefficient of permeability, permeable concrete

1. Introduction

Our country has experienced an improvement in level of consumption and a variety of life style unseen until recently due to rapid economic growth. Moreover, the number of people driving a car and supply of road system has increased very rapidly. The road system encompasses not only the major highways but local roads, roads for bicycle riding and neighborhood living spaces such as parking lot, plaza, park, and sports facilities.

However, the typical roads in Korea are usually paved with impermeable asphalt-concrete or cement-concrete. Since the pavement is impermeable, the drainage facility and capacity is inadequate especially in the rain season. A large amount of rain can not be drained and remains on the road to cause the slowing of traffic and even a traffic hazard due to the decreased skid resistance upon applying the break. Additionally, the water on the road surface can not permeate to underground and flows to the sewage, stream, and river, etc. It can cause flooding of urban streams and drying of underground water. Moreover, micro-organisms can not inhabit the underground, and the soil will dry up to become like a desert.[1-4] Thus, as the interest on permeable pavement was boosted in the 1980's, permeable asphalt-concrete was developed and applied to sidewalks and regular roads. Nevertheless, when the temperature on the road surface increases in the summer, the space for water to permeate through is blocked due to the viscosity of the asphalt. Furthermore, it has been pointed out that the strain on the road due to increased traffic of heavy vehicles cause deterioration and deformation of the road to lose its function of water-permeability.[2,3]

Recently, permeable concrete has been developed and applied to the field in order to deal with the short-comings of impermeable asphalt-concrete pavement. However, it is desperately required to develop the materials, which show adequacy in the strength, durability, and permeability of the permeable concrete. Moreover, a research on the optimal mixing of the concrete needs to be carried out.

2. Mechanism of permeable concrete pavement

The typical concrete has its space in the aggregate filled and compacted with cement paste. It minimizes the void space inside the concrete and is made into densely compacted concrete. On the other hand, permeable concrete forms continuous void inside the concrete for effective permeability.[1]

For the concrete to be permeable, continuous void must be formed, and the methods of forming continuous void in the concrete can be largely classified into two types. One is to use a foaming agent to create many air bubbles in the concrete, and the other is to reduce the amount (percentage) of sand to create void space between the aggregate at the time of concrete mixing.[5,6]

The permeable concrete reduces the sand percentage to the mini-

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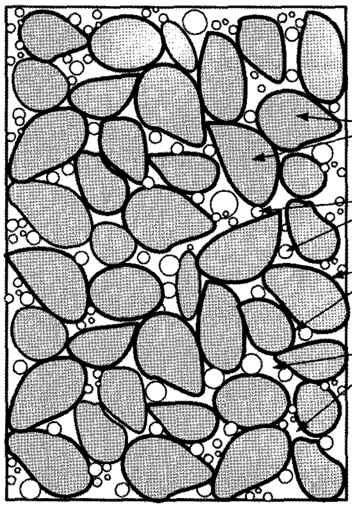

Fig. 1 Cross section of permeable concrete.

mum as shown in Fig. 1. It also uses coarse aggregate of uniform granularity so that there will be minute void space of permeable void, which is partially filled with cement paste.

In addition, permeable concrete pavement has the function of circulating rainfall through the concrete surface and base layer to the underground soil.[11] Thus, it has many benefits. The water on the pavement surface layer due to rainfall and other reasons can permeate through the pavement so as to reduce the skid of the vehicle. It can improve the road safety by reducing the break distance. Other effects of good drainage on the road and walkways by permeable concrete pavement include 1) enhanced vision of the drivers and pedestrians by reducing diffuse reflection 2) prevention of underground water by permeated rainfall 3) provision of water and oxygen to the underground soil conducive to the inhabitation of micro-organisms for the preservation of environment.[7-9]

3. Overview of the experiment

3.1 Materials

3.1.1 Cement

The widely-used Portland cement availed, and its physical properties and chemical composition are shown in Table 1.

3.1.2 Aggregate

The fine aggregate used river sand collected from Han River and crushed sand. The coarse aggregate utilized crushed rocks of maximum size, 10 mm and 13 mm. The physical properties of fine and coarse aggregate are shown in Table 2 below.

3.1.3 Chemical additives (admixture)

Standard water-reducing agent of M company, of which the main composition is lignin sulfonate acid, was used.

3.2 Experimental method

3.2.1 Void ratio

The void ratio of permeable concrete can be computed from eq.(1) below, and the absolute unit load weight means the weight computed by specific gravity of the composing material (the weight computed with the assumption of voidless (pore-less) concrete per 1 m^3). The unit load weight was measured by following the specification of

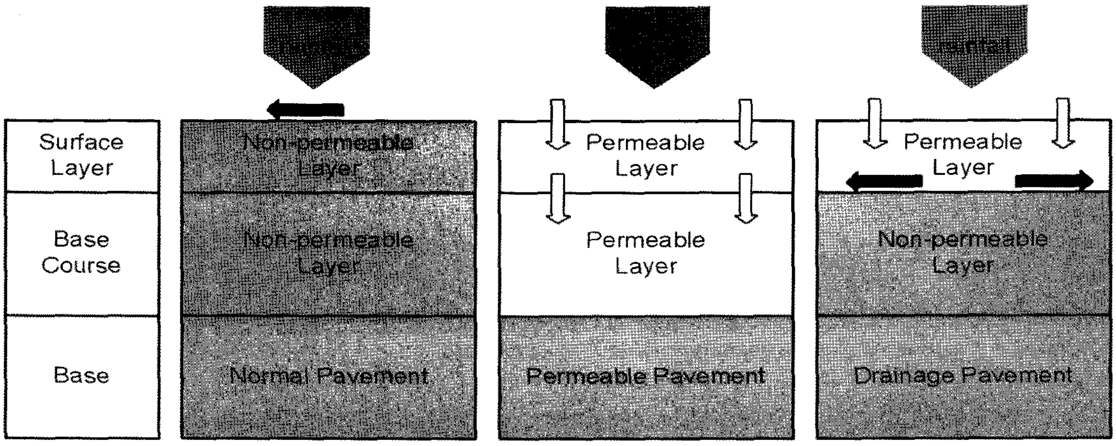

Fig. 2 Pavement types.

Table 1 Physical properties and chemical composition of cement.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Ig. loss (%)	Specific gravity	Blaine (cm^2/g)
20.3	6.2	3.2	62.4	3.0	2.0	1.9	3.14	3,265

Table 2 Physical properties of aggregate.

Max. size (mm)	Specific gravity	Absorption (%)	Fineness modulus	Organic impurities	Unit weight (kg/m^3)	Percentage of solids (%)	Remark
5	2.60	1.2	2.5	good	1,620	62.3	River sand
5	2.63	0.8	4.05	good	1,416	58.8	Crushed
10	2.62	0.8	5.83	-	1,524	58.8	Crushed
13	2.63	0.8	6.31	-	1,410	53.6	Crushed

KS F 2409.

$$v(\%) = 100 - \left(\frac{W_p}{W_a} \times 100\right) \tag{1}$$

where, v = void ratio, W_P = unit weight of permeable concrete, W_a = absolute unit weight

3.2.2 Continuous void ratio

The continuous void ratio is computed by eq. (2) below. The weight of cylindrical test specimen with dry surface (W_1) is measured. After sealing the side and bottom of the cylindrical test specimen, the test specimen completely filled with water poured from the top. Then, its weight (W_2) is measured. The latter is subtracted by the former. The difference is then divided by the volume of the test specimen (V) to yield eq. (2).

$$Cv(\%) = \frac{W_2 - W_1}{V} \times 100 \tag{2}$$

where, Cv = continuous void ratio

3.2.3 Compressive, flexural, and splitting tensile strength

A cylindrical mold of ϕ100×200 mm is filled with cement, and each of its layer is compacted with a rod of 2.5 kg at the height of 300 mm for a total of 150 repetitions in three intervals. After 48 hours of compacting, it is cured in the water at 20±2°C, and the compressive strength is measured following the method of KS F 2405. A 150×150×550 mm test specimen subjected to central loading method is prepared for the measurement of flexural strength, following the specification of KS F 2407. Additionally, the tensile strength of the cylindrical test specimen is measured based on the splitting tensile strength testing method of KS F 2423.

3.2.4 Permeability

An apparatus of 150 mm waterhead difference was prepared to carry out a permeability test on a cylindrical test specimen of ϕ100×100 mm. The test specimen was at the age of 28 days when this permeability measurement was taken following KS F 2322 of testing method for permeability of saturated soils. Then, the coefficient of permeability was computed by Darcy's law.

3.3 Mixture proportions of the concrete

The maximum size of the aggregate was set at 5 mm, 10 mm, 13 mm, and the water-cement ratio was 32%. The unit cement contents varied at 320, 380, 420 kg/m^3. The fine aggregate ratio to coarse aggregate was set at 0, 10, 20, and 30% when the maximum size of the aggregate was 13 mm. When the maximum size of the aggregate was 5 mm and 10 mm, fine aggregate not was used. This experimental design yielded a combination of a total of 16 mixes.

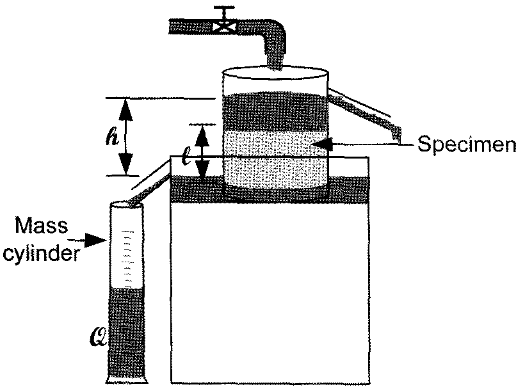

Fig. 3 Apparatus for coefficient of permeability test.

4. Experimental results and discussions

4.1 Coefficient of permeability and strength of permeable concrete in relation to factors of concrete mixing

According to a research report of Korea Highway Corporation on permeable pavement,[9] the target void ratio and maximum size of the aggregate for permeable asphalt pavement are set as shown in Table 3 for each country. However, our country does not have any guide on design and construction of permeable concrete pavement. Furthermore, it is our situation in Korea that there is no track record of research or usage despite the advantageous characteristics of permeable pavement.

Thus, as a basic investigation of practical use of permeable concrete, this study varied the maximum size of the aggregate, the content of fine aggregate, and unit cement contents. Then, the void ratio, continuous void ratio, coefficient of permeability, compressive strength, flexural strength, and tensile strength for 16 mixing types were measured and summarized in Table 4.

4.1.1 Coefficient of permeability and factors of concrete mixing

It is desirable for permeable concrete pavement to exhibit large coefficient of permeability and adequate strength and not to render adversary effects on the aesthetics and ecosystem of environment. Fig. 4 summarizes the results of experiments varying the maximum size of aggregate, sand percentage (fine aggregate contents), and unit cement contents among factors of concrete mixing.

Fig. 4(a) shows the relationship between the coefficient of permeability and maximum size of aggregate for the concrete mix with unit cement contents of 320, 380, and 420 kg/m^3 and 0% sand percentage. It shows that the coefficient of permeability increases nearly linear as the maximum size of aggregate increases except for the case of concrete with unit cement contents of 420 kg/m^3. When the maximum size of aggregate is 13 mm, the coefficient of permeability was in the range of 0.9~1.0 cm/sec, indicating very good permeability. When the maximum size of aggregate is small at 5 mm, the coefficient of permeability was only 0.12 cm/sec, showing a large difference. Thus, it can be seen that the influence of maximum size of aggregate on the coefficient of permeability of the concrete was rather very large. Fig. 4(b) shows the relationship between sand percentage (fine aggregate contents) and the coefficient of permeability of the permeable concrete when the maximum size of aggregate and unit cement contents are set at 13 mm and 380 kg/m^3, respectively, while the sand percentage varies in four stages of 0, 10, 20, and 30%.

Table 3 Void ratio and maximum aggregate size in permeable asphalt pavement.

Country	Max. size (mm)	Void ratio (%)
U.S.A	under 12.5	15
Germany	over 8	over 18
Austria	8 ~ 11	20
Italy	-	15

Table 4 Experimental results.

Max. size of agg. (mm)	Unit cement contents (kg/m^3)	Sand percentage (%)	Void ratio (%)	Continuous void ratio (%)	Coefficient of permeability (cm/sec)	Compressive strength (MPa)		Flexural strength (MPa)	Splitting tensile strength (MPa)
						7days	28days		
5	320	0	26.9	17.4	0.16	12.3	16.5	4.3	1.7
	380	0	18.7	15.3	0.12	15.5	20.5	4.6	1.8
	420	0	12.2	10.4	0.03	18.6	23.6	5.6	2.4
10	320	0	26.9	23.8	0.65	11.8	13.6	3.4	1.5
	380	0	25.2	23.6	0.58	13.1	14.2	3.9	1.6
	420	0	21.8	17.7	0.43	14.2	18.8	4.6	1.7
13	320	0	25.8	22.0	0.99	11.2	11.7	2.1	1.2
		10	22.9	20.0	0.65	12.3	13.7	2.9	1.6
		20	17.6	13.7	0.23	13.7	15.6	5.0	1.9
13	380	0	24.3	20.1	0.92	12.3	15.6	2.6	1.5
		10	23.8	18.1	0.55	13.8	16.8	3.8	1.8
		20	14.9	11.8	0.18	14.4	18.2	5.3	2.4
		30	6.8	4.2	0.01	20.4	30.8	6.5	3.7
13	420	0	23.2	19.2	0.51	17.1	22.2	4.3	1.9
		10	19.9	15.4	0.28	21.6	29.8	5.3	2.5
		20	9.4	7.7	0.09	32.0	35.6	6.3	3.8

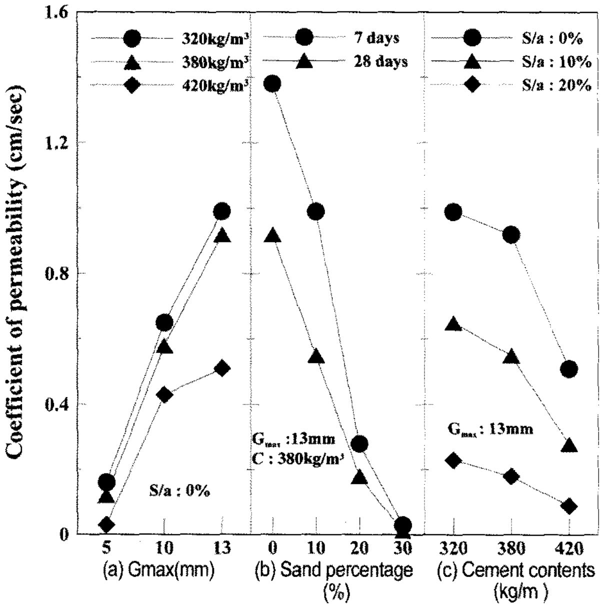

Fig. 4 Relationship between coefficient of permeability and factors of mix design.

At this time, when the sand percentage was kept the same, the coefficient of permeability showed a great difference depending on the age of the permeable concrete. The coefficient of permeability at 28 days was much less than that at 7 days. It is construed that the hydration of the concrete progressed along with the lapse of the time so that expansive hydration material like ettringite ($3C_3A\cdot 3CaSO_4\cdot 31H_2O$) densely filled the void even if the concrete was permeable. However, it showed a very small coefficient of permeability close to impermeability at the sand percentage of 30%, showing that the influence of fine aggregate contents (sand percentage) on coefficient of permeability was as large as that of maximum size of (coarse) aggregate.

The strength is a factor as important as permeability in the permeable concrete pavement. Fig. 4(c) shows the relationship between the coefficient of permeability and unit cement contents of the concrete with maximum aggregate size of 13 mm in order to find out the unit cement contents, which exhibits the desired target strength. From the figure, it can be seen that, as the unit cement contents and sand (fine aggregate) percentage changed, the coefficient of permeability also varied. When the sand (fine aggregate) percentage and unit cement contents was large, the variation of coefficient of permeability was relatively smaller. In other words, it is desirable to use less sand (fine aggregate) percentage and unit cement contents in order to obtain adequate coefficient of permeability for the concrete pavement.

4.1.2 Concrete strength and factors of concrete mixing

When permeable concrete pavement is to be applied as an all-purpose pavement to walkways, parking lots, and all kinds of traffic roads, the pavement should have the qualitative aspect of being able to withstand a certain amount of flexural, compressive, and tensile strength. Fig. 5 shows the compressive, flexural, and tensile strength measured on the permeable concrete while factors of concrete mixing such as maximum size of aggregate, unit cement contents, and sand (fine

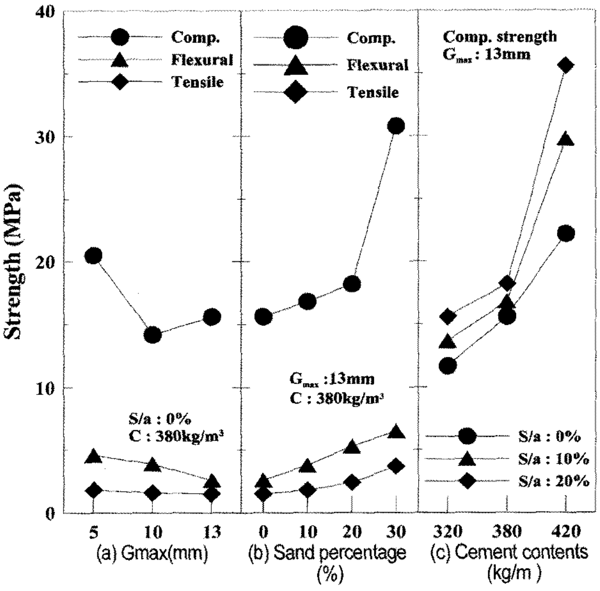

Fig. 5 Relationship between strength and design factors of permeable concrete mixing.

aggregate) percentage were varied. Additionally, the relationship among compressive, flexural, and tensile strength is depicted in Fig. 6.

Fig. 5(a) shows the change in compressive, flexural, and tensile strength of the concrete with mixing design of unit cement contents of 380 kg/m^3 and no fine aggregate used in relation to maximum size of aggregate. It shows that the strength of the concrete gets smaller as the maximum size of aggregate was larger.

The relationship of various strength of the concrete with maximum aggregate size of 13mm and unit cement contents of 380 kg/m^3 to the change in sand percentage is depicted in Fig. 5(b). It shows that the concrete strength increases a little with the increase in sand percentage, and, of particular notice is that the compressive strength increased drastically when the sand percentage increased from 20% to 30%.

Fig. 5(c) shows the compressive strength of the concrete measured while keeping the maximum aggregate size constant at 13 mm but varying each of sand percentage and unit cement contents three ways. The compressive strength of the concrete was measured highest at 36.5 MPa when the unit cement contents and the sand percentage were 420 kg/m^3 and 20%, respectively.

Fig. 6 shows the relationship among compressive, flexural, and tensile strength of permeable concrete. The coefficient of determination (R^2) for the relationship of flexural strength and tensile strength to compressive strength was 0.69 and 0.84, respectively. The flexural strength of permeable concrete was in the range of 1/4~1/5 of compressive strength, but it was about 1/5~1/8 larger than that of regular concrete. The tensile strength of permeable concrete was in the range of 1/9.5~1/10 of compressive strength and about 1/10~1/12 larger than that of regular concrete. Thus, the flexural and tensile strength of permeable concrete exhibited larger values than regular concrete.

4.2 Analysis of coefficient of permeability and strength of the concrete in relation to void ratio and continuous void ratio

4.2.1 Relationship of coefficient of permeability to void ratio and continuous void ratio

Fig. 7 shows the relationship of coefficient of permeability to void ratio and continuous void ratio of permeable concrete.

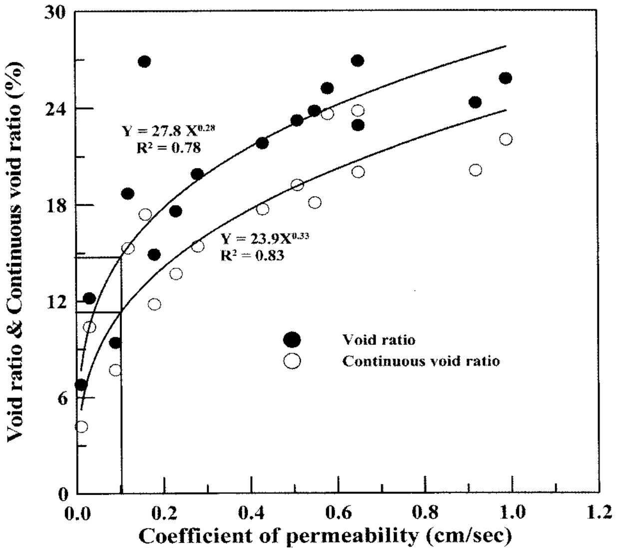

Fig. 7 Relationship of void ratio and continuous void ratio to coefficient of permeability.

Tracing the coefficient of permeability, that corresponds to the target void ratio of 15% as suggested in Table 3 by the USA and Italy, in Fig. 7, it was about 1×10^{-1}cm/sec. This figure is larger than the coefficient of permeability, 1×10^{-2}cm/sec[10], as specified by "Guide for Road Pavement Design and Construction" of Ministry of Construction and Transportation (1992) in the order of ref. 10. Meanwhile, Yashusaki, et al.[4] reported that it was desirable to keep the coefficient of permeability above 1×10^{-1}cm/sec right after the field construction of permeable concrete pavement. This study set the coefficient of permeability of 1×10^{-1}cm/sec as the target coefficient of permeability, which corresponded to the void ratio of 15% as in Fig. 7. In addition, it can be seen in Fig. 7 that the continuous void ratio corresponding to the coefficient of permeability of 1×10^{-1}cm/sec was about 12%. Moreover, the same figure shows that the relationship between the void ratios to the coefficient of permeability was more like exponential than linear.

Fig. 8 illustrates the relationship between void ratio and continuous void ratio. It shows that there is a good correlation between the two as indicated by a high coefficient of determination ($R^2 = 0.91$). From the scope of this experiment, the void ratio and continuous void ratio, which satisfied the constraint of target coefficient of permeability for the permeable concrete pavement, were found to be about 15% and 12%, respectively.

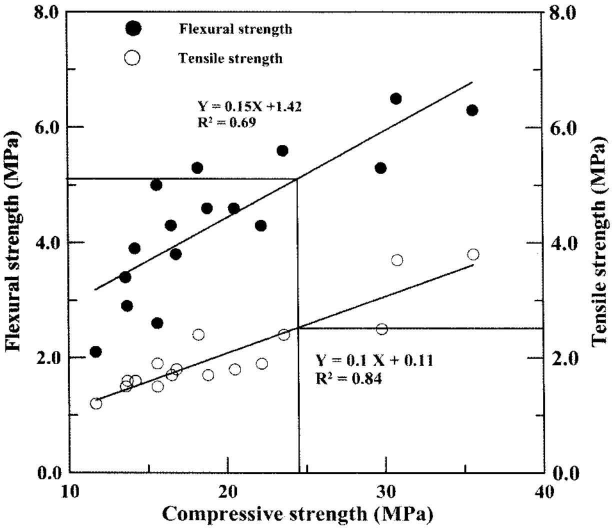

Fig. 6 Relationship of flexural and tensile strength to compressive strength.

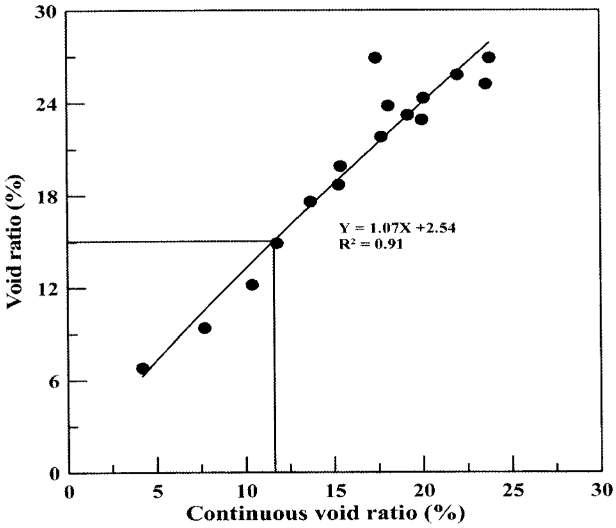

Fig. 8 Relationship between void ratio and continuous void ratio.

4.2.2 Relationship of concrete strength to void ratio and continuous void

In general, for permeable concrete to maintain the necessary permeability, a certain percentage of continuous void ratio and a certain amount of void space in the concrete is required.[1] However, if the void ratio is too excessive, it can have an adverse effect on the strength of the concrete. Thus, it is necessary to minimize the amount of discontinuous voids and to keep the continuous void ratio at a desired level in order to obtain the strength and permeability necessary for the concrete pavement.[4]

Thus, the relationship of compressive strength of the permeable concrete to its void ratio and continuous void ratio is shown in Fig. 9. From the figure, it can be seen that the compressive strength, which corresponds to the target coefficient of permeability of 1×10^{-1}cm/sec, the void ratio of 15%, and the continuous void ratio of 12%, is about 24.2 MPa. However, since the coefficient of determination for this relationship is rather low at 0.61, its validity may be of concern. Meanwhile, when this compressive strength of permeable concrete is converted into flexural strength based on Fig. 6, it yields a rather large value of 5.0 MPa. This figure for the flexural strength is rather high, even surpassing the design standard for the strength of concrete pavement, i.e. 4.5 MPa.

4.2.3 Relationship of coefficient of permeability to void ratio, continuous void ratio, and compressive strength

The relationship among the coefficient of permeability, void ratio, and continuous void ratio of permeable concrete as measured by this study is summarized and depicted in Fig. 10. The coefficient of permeability is shown in the vertical axis. The horizontal axis is taken by the void ratio, continuous void ratio, and compressive strength. From this figure, it can be seen that the correlation between coefficient of permeability and compressive strength is poor. Moreover, the correlation of the coefficient of permeability to void ratio and continuous void ratio was not so high, also. However, the figure consistently showed that the compressive strength, void ratio, and continuous void ratio, which corresponded to the target coefficient of permeability of 1×10^{-1}cm/sec for permeable concrete pavement, were 15%, 12%, and 25.0 MPa.

Summarizing the results of this research, it is deemed that the design concrete mix, which can satisfy the constraint of target coefficient of permeability of 1×10^{-1}cm/sec in making of economic, permeable concrete, should be set at sand percentage (fine aggregate contents) of 10~20% and unit cement contents of 380 kg/m^3 when the maximum aggregate size is between 10~13 mm.

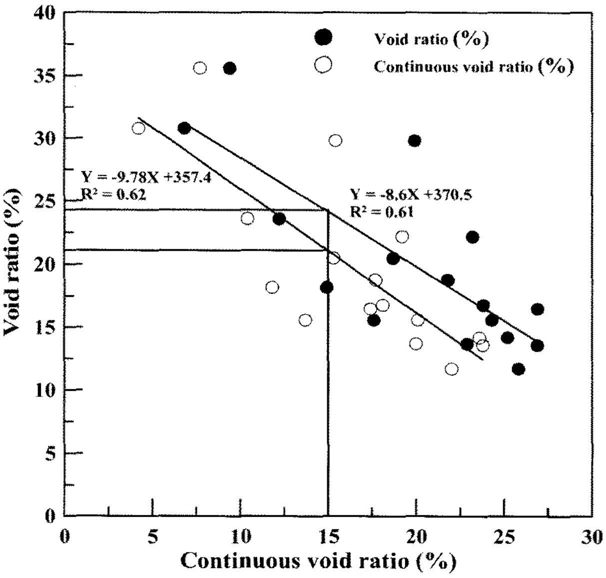

Fig. 9 Relationship of compressive strength to void ratio and continuous void ratio.

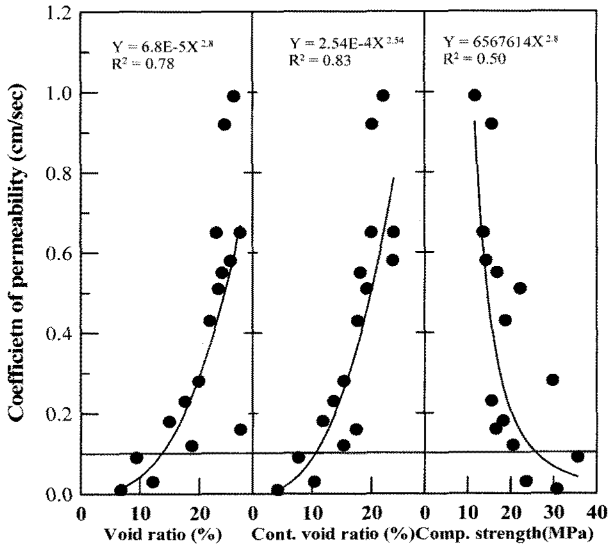

Fig. 10 Relationship of coefficient of permeability to void ratio, continuous void ratio, and compressive strength.

5. Conclusions

The following conclusions are reached from the aforementioned experimental results.

1) The coefficient of permeability gets larger as the maximum aggregate size, the sand percentage, and unit cement contents vary to 5, 10, and 13 mm, 20, 10, and 0%, and 420, 380, and 320 kg/m^3, respectively, in the increasing order. This point is illustrated by comparing the coefficients of permeability of concrete pavements while keeping the maximum aggregate size constant at 13 mm. The coefficient of permeability was the lowest at 0.9×10^{-1}cm/sec when the unit cement contents and sand percentage were 420 kg/m^3 and 20%, respectively. In comparison, it increased by about ten-fold to 9.9×10^{-1}cm/sec when the unit cement contents was set at 320 kg/m^3 and no sand was used to fill the void.

2) Among measurements of concrete strength, compressive strength at age of 28 days was chosen for the comparison analysis. It became larger as the unit cement contents, the sand percentage, and maximum aggregate size varied to 320, 380, and 420 kg/m^3, 0, 10, and 20%, and 13, 10, 5 mm, respectively, in the increasing order. The ratio of flexural strength and tensile strength to the compressive strength was in the range of 1/4~1/5 and 1/9.5~1/10, respectively, exhibiting rather larger strength than regular concrete.

3) The void ratio and continuous void ratio, corresponding to the target coefficient of permeability, 1×10^{-1}cm/sec, for permeable concrete pavement, was determined to be 15% and 12%, respectively. There was a good correlation established between the two. The flexural and compressive strength at this target coefficient of permeability was measured at 5.0 MPa and 20.0~25.0 MPa. Finally, it was determined that the design concrete mix, which could satisfy these constraints, should be set at sand percentage (fine aggregate contents) of 10~20% and unit cement contents of 380 kg/m^3 when the maximum aggregate size was between 10~13 mm.

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