PERMEABILITY OF DRAINAGE BASE COURSE MATERIALS AT LABORATORY TESTS

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The permeability of five types of drainage base course materials (i.e. single-sized crushed stones that were either asphalt treated or untreated, sand, mechanical stabilized crushed stones, and drainage asphalt mixtures) were studied through constant-head permeability tests at laboratory. Three parameters (permeability coefficient *k*, turbulent flow parameters *m* and *n*) were introduced to describe the drainage behavior. Four aspects of the material properties, in terms of the average grain size d_{mean}, void ratio, $p_{2.36}$ and $p_{0.075}$, were used to analyze the experimental results. The relevant findings were presented. It was indicated that errors might have been induced while using Darcy's law to estimate the discharge velocity irrespective of the flow states.

Key words: *Permeability, drainage base course, laminar flow, turbulent flow, critical hydraulic gradient, Darcy's law*

1. INTRODUCTION

It is well known that excessive water on a pavement surface can reduce skid resistance, and that water inside the pavement structure can result in a series of pavement distresses and decrease its bearing capacity. Therefore, in addition to surface drainage systems that get rid of water through pavement surface gradients or grooves, pavement subdrainage system are being used more and more, because in surface drainage systems water can inevitably flow into the pavement through joints, cracks, and/or high ground water tables. In such subdrainage systems, drainage base course materials like ATPM (asphalt treated permeable material) or CTPM (cement treated permeable material) have been widely applied [1), 2)]. However, the permeability of these materials has been investigated only locally, and for airport pavements the designing criteria of the subdrainage systems have not been fully established yet [1)~5)].

In general, the permeability of drainage materials is strongly related to their composition and the applicable hydraulic gradients. That is, water might flow in different states ranging from laminar to turbulent at a specific hydraulic gradient, depending on the composition of materials, and even for materials with the same composition, the flow might be one of these two states at different hydraulic gradients. The purpose of this study is to determine:

1)The relationships between various composition of materials and their permeability coefficients;
2)The discharge behavior of turbulent flow; and
3)The critical hydraulic gradients.

In this paper, we present the laboratory constant-head permeability testing results of five types of drainage base course materials (i.e. single-sized crushed stones that were either asphalt treated or untreated, sand, mechanical stabilized crushed stones, and drainage asphalt mixtures). Three parameters (permeability coefficient *k*, turbulent flow parameters *m* and *n*) were introduced to describe the drainage behavior. Four aspects of the material properties, in terms of the average grain size d_{mean}, void ratio, $p_{2.36}$ and $p_{0.075}$ (percentage of weight passing through the 2.36 mm and 0.075 mm sieves, respectively), were used to analyze the experimental results. The relevant findings are presented below.

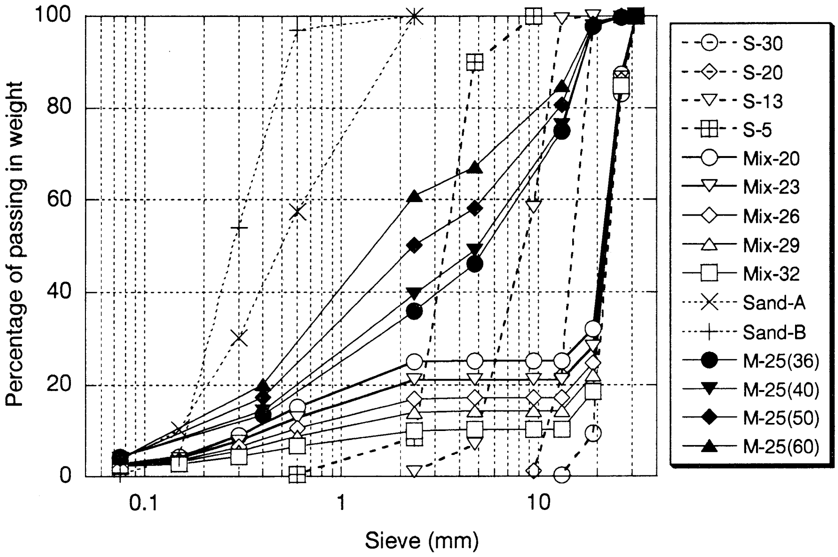


Fig. 1 Gradation of the tested materials

2. LABORATORY TESTS

(1) Materials

Five types of drainage base course materials were tested at laboratory. As shown in **Fig. 1** for their gradation, these materials are:

1)Single-sized crushed stones: S-30, S-20, S-13 and S-5 in accordance with JIS A 5001 [6].

2)Single-sized crushed stones treated with asphalt: S-30, S-20, S-13 and S-5 were treated with 2% of asphalt (in weight ratio), and named S-30a, S-20a, S-13a and S-5a, respectively

3)Drainage asphalt mixtures: using different contents (in weight ratio) of single-sized crushed stones S-30 (75-93%), sand (5-23%), limestone filler (2%) and asphalt (2-4.5%), the Marshall test was conducted and the mixtures with target void ratios of 20%, 23%, 26%, 29% and 32% were selected. They are named Mix-20, Mix-23, Mix-26, Mix-29 and Mix-32, respectively.

4)Sand: sand-A and sand-B

5)Mechanical stabilized crushed stones: M-25 (JIS A 5001) with percentages of passing (in weight ratio) through the 2.5mm sieve at 36%, 40%, 50% and 60% (the last one is beyond the gradation specifications for M-25), which are named M-25(36), M-25(40), M-25(50) and M-25(60), respectively.

(2) Specimens

Two diameter sizes, 210 mm and 100 mm, were used for the specimen. The 210 mm diameter was used for materials with the maximum grain size of 13-30 mm, and the 100 mm diameter was used for materials with the maximum grain size of less than 13 mm.

All specimens were 500 mm in height and compacted with 50 times of Marshall blow at both sides, which is specified for the asphalt mixtures as the base course. Thus, it was applied to all the materials to simulate the compaction efforts at construction. For the sand and mechanical stabilized crushed stones, the optimal water content was used to achieve the maximum density.

(3) Permeability tests

The apparatus used for the constant-head permeability tests is shown in **Fig. 2**, where the diameter of the permeameter was appropriate for the dimension of the specimens. The hydraulic gradient was tested from 0.5% to 100% by adjusting the height of the water tank.

The volumetric flow rate Q and the water-head loss Δh through the specimens were tested. Then the discharge velocity q ($q = Q/A$, A - cross-sectional area of the permeameter) at different hydraulic gradient i ($i = \Delta h/L$, L-length of specimen) was calculated.

As shown in **Fig. 3**, the relationships between the discharge velocity and the hydraulic gradient can be classified into two types:

1)Linear, and

2)Non-linear.

The linear relationship indicates that the flow is in a laminar state, which was described by the

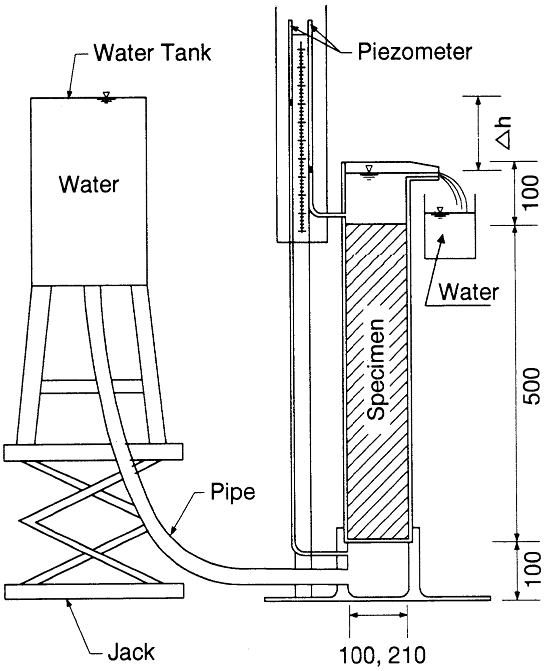


Fig. 2 Apparatus for the constant-head permeability test

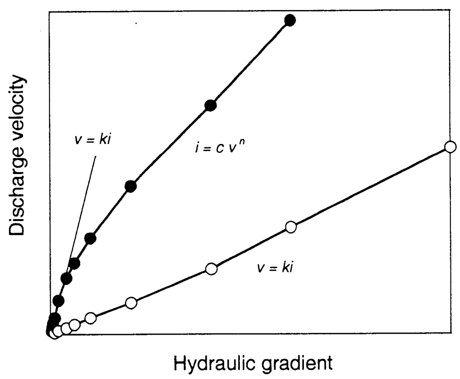


Fig. 3 Relationships between the discharge velocity and the hydraulic gradient

Darcy's law, as expressed in Eq. (1)[7]. The non-linear relationship indicates that the flow is in a turbulent state, which can be expressed by Eq. (2)[8].

$$v_0 = k \cdot i \quad (i \le i_c) \tag{1}$$

$$i = cv^n \quad (i \ge i_c) \tag{2}$$

where

k - permeability coefficient (cm/s)
i - hydraulic gradient
i_c - critical hydraulic gradient
c, n - coefficients

The parameters k, c and n were obtained from the experiments, as shown in **Table 1**.

Table 1 Parameters k, c and n

Material		k	c	n
Single-sized crushed stones	S-30	-	1.47E-02	1.80
	S-20	32.80	3.80E-02	1.35
	S-13	19.34	8.06E-02	1.50
	S-5	1.88	-	-
Single-sized crushed stones treated with 2% of asphalt	S-30a	-	1.50E-02	1.82
	S-20a	-	4.07E-02	1.56
	S-13a	19.12	9.14E-02	1.58
	S-5a	1.90	1.2019	1.40
Drainage asphalt mixtures	Mix-20	6.20	0.5848	1.55
	Mix-23	10.22	0.3554	1.61
	Mix-26	14.58	0.1742	1.61
	Mix-29	26.66	8.28E-02	1.64
	Mix-32	-	4.36E-02	1.65
Sand	Sand-A	1.90E-03	-	-
	Sand-B	1.70E-02	-	-
Mechanical stabilized crushed stones	M-25(36)	9.00E-03	-	-
	M-25(40)	7.00E-03	-	-
	M-25(50)	5.60E-03	-	-
	M-25(60)	4.60E-03	-	-

3. ANALYSIS AND DISCUSSION

(1) Material properties

Four aspects of the material properties, in terms of the average grain size d_{mean}, void ratio, $p_{2.36}$ and $p_{0.075}$, were introduced to analysis the experimental results.

a) Average grain size - d_{mean} [4)]

The average grain size is defined as Eq. (3). It represents the composition of large-sized grains, because small-sized grain (e.g. less than 4.75 mm) contribute little to d_{mean}.

$$d_{mean} = \sqrt[3]{\frac{\sum n_s d_s^{\,3}}{\sum n_s}} \tag{3}$$

where d_s is arithmetic mean of openings in any two consecutive sieves, and n_s is the number of gains of diameter d_s.

b) Void ratio

The void ratio represents the pore spaces. It is the ratio of voids to solids in volume. The void ratio is dependent not only on the composition of materials, but also on the compaction.

c) $p_{2.36}$

This represents the composition of small-sized grains that cannot be represented by d_{mean}.

d) $p_{0.075}$

This represents the composition of very fine particles that might clog the pore space and reduce the permeability.

The material properties at the laboratory tests are

Table 2 Material properties at the laboratory tests

Material		d_{mean} (mm)	Void ratio (%)	$p_{2.36}$ (%)	$p_{0.075}$ (%)	Asphalt content (%)
Single-sized crushed stones	S-30	23.6	40.0	0		
	S-20	15.5	39.7	0		
	S-13	9.3	43.1	1.1		
	S-5	4.2	43.6	8.5		
Single-sized crushed stones treated with 2% of asphalt	S-30a	23.6	38.0	0		2.0
	S-20a	15.5	38.3	0		2.0
	S-13a	9.3	39.6	1.1		2.0
	S-5a	4.2	41.0	8.5		2.0
Drainage asphalt mixtures	Mix-20	21.5	20.5	25.0	2.8	4.0
	Mix-23	21.8	22.7	21.2	2.7	3.8
	Mix-26	22.2	26.7	17.0	2.5	3.6
	Mix-29	22.5	29.6	14.0	2.4	3.5
	Mix-32	22.8	31.8	10.0	2.3	2.5
Sand	Sand-A	1.1	45.2	100	3.6	
	Sand-B	0.5	56.5	100	0.7	
Mechanical stabilized crushed stones	M-25(36)	11.4	23.3	36.0	4.3	
	M-25(40)	11.2	24.5	39.6	4.2	
	M-25(50)	10.5	25.0	50.2	4.1	
	M-25(60)	9.7	26.1	60.9	4.0	

Table 3 Dominant factors to the permeability coefficients

Material	d_{mean} (mm)	Void ratio (%)	$p_{2.36}$ (%)	$p_{0.075}$ (%)
Single-sized crushed stones	○		○	
Single-sized crushed stones treated with 2% of asphalt	○		○	
Drainage asphalt mixtures		○	○	
Sand		○		○
Mechanical stabilized crushed stones	○		○	

listed in **Table 2**. By using multiple regression method to analyze the experimental results, the dominant factors which have significant impacts on the permeability coefficients were identified, as shown in **Table 3**.

(2) Permeability coefficient

The permeability coefficient of the drainage base course materials are shown by **Fig. 4**. It shows that the permeability coefficient for different types of drainage base course materials is quite different. In terms of magnitudes, the permeability coefficients of single-sized crushed stones or drainage asphalt mixtures are thousands of times higher than that of either the sand or the mechanical stabilized crushed stones.

Fig. 4(a) shows the permeability coefficient of single-sized crushed stones. It was found that the larger the d_{mean}, the higher the permeability coefficient. Contrastingly, the larger the $p_{2.36}$, the lower the permeability coefficient. No significant difference in the permeability coefficient was observed for the single-sized crushed stone with asphalt treated and untreated. In addition, a laminar flow was not observed when the d_{mean} is larger than 9.3 mm for asphalt treated single-sized crushed stones and 15.5 mm for untreated single-sized crushed stones.

Fig. 4(b) shows the permeability coefficient of drainage asphalt mixtures. It shows that the larger the void ratio and the smaller the $p_{2.36}$, the higher the permeability coefficient. However, a laminar flow was not observed for higher void ratios.

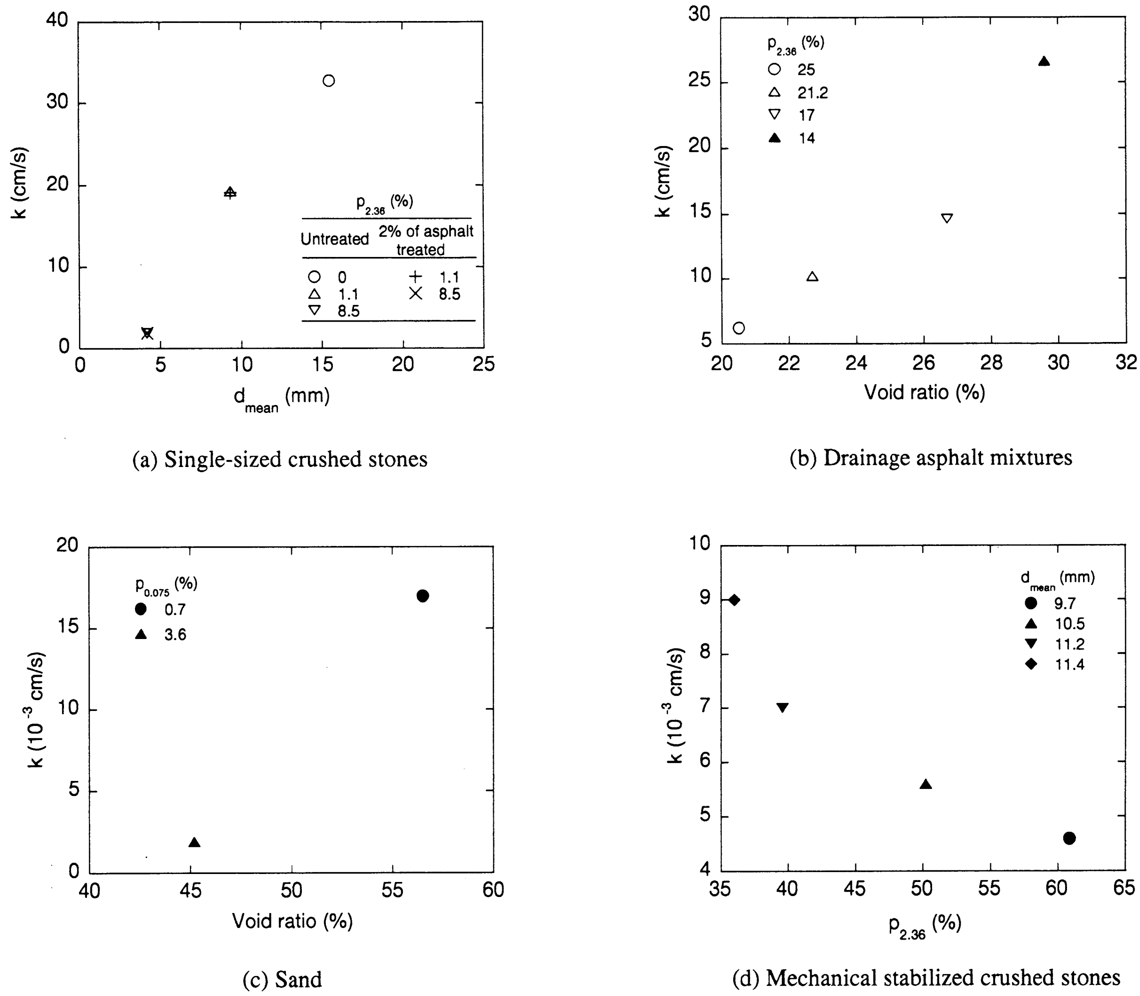
Fig. 4(c) shows the permeability coefficient of sand. It shows that the larger the void ratio and the smaller the $p_{0.075}$, the higher the permeability coefficient. No turbulent flow was observed.

Fig. 4(d) shows the permeability coefficient of the mechanical stabilized crushed stones. It shows that the larger the $p_{2.36}$ and the smaller the d_{mean}, the lower the permeability coefficient. No turbulent flow was observed.

(3) Turbulent flow

It can be induced from Eq. (2) that the discharge velocity of the turbulent flow can be expressed as:

$$v = \sqrt[n]{i/c} \tag{4}$$



(a) Single-sized crushed stones

(b) Drainage asphalt mixtures

(c) Sand

(d) Mechanical stabilized crushed stones

Fig. 4 Permeability coefficients

If Darcy's law was applied and the discharge velocity was estimated as v_0, then $i = {v_0}/{k}$; thus,

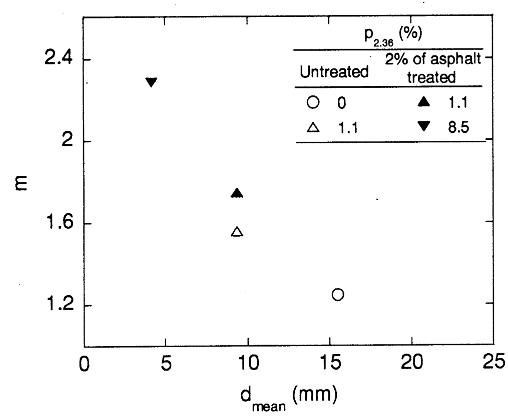
$$v = \sqrt[n]{{v_0}/{m}} \tag{5}$$

where $m = c \cdot k$. It implies that the discharge velocity of a turbulent flow can be related to the velocity estimated by Darcy's law. Therefore, parameters m and n are introduced to describe such a relationship.

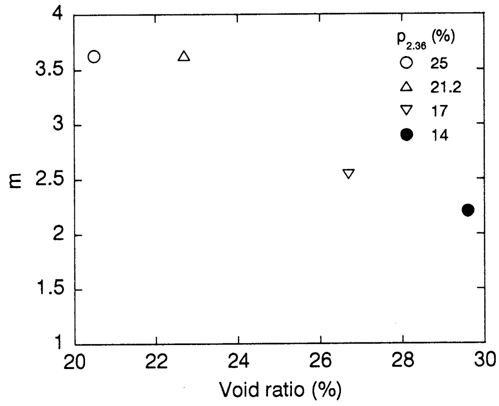
Fig. 5 shows parameter m in the experiments. It can be found from **Fig. 5(a)** that for single-sized crushed stone the parameter m decreases as d_{mean} increases and as $p_{2.36}$ decreases, regardless of whether the materials are treated by asphalt or not. It can be found from **Fig. 5(b)** that for drainage asphalt mixtures the parameter m decreases as the void ratio increases and as $p_{2.36}$ decreases. It is worthwhile to mention here that in both cases the parameter m is more than 1.

Fig. 6 shows parameter n in the experiments. It can be found from **Fig. 6(a)** that the parameter n ranges from 1.3 to 1.8 for the single-sized crushed stones, regardless of whether the materials were treated by asphalt or not. It can be found from **Fig. 6(b)** that the parameter n is around 1.6 for the drainage asphalt mixtures.

It was also inferred from Eq. (5) that errors might be induced while using Darcy's law to estimate the discharge velocity irrespective of the flow states. As demonstrated by **Fig. 7** that if m=2, n=1.6 and the discharge velocity estimated by the Darcy's law were assumed to be 5, 20 and 50 cm/s, the discharge velocity of the turbulent flow should be 36%, 21% and 15%, respectively, of that assumed. Therefore, the critical hydraulic gradient was investigated in order to identify the flow states before estimating the discharge velocity.

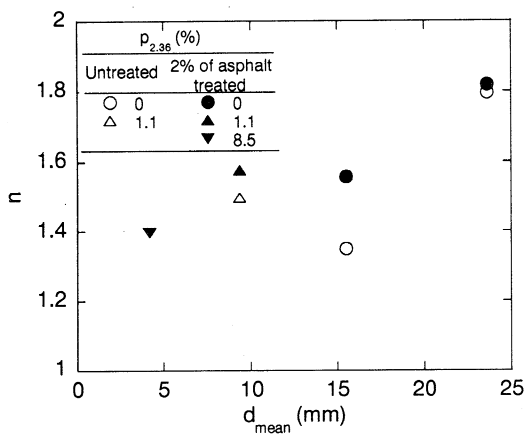


(a) Single-sized crushed stones

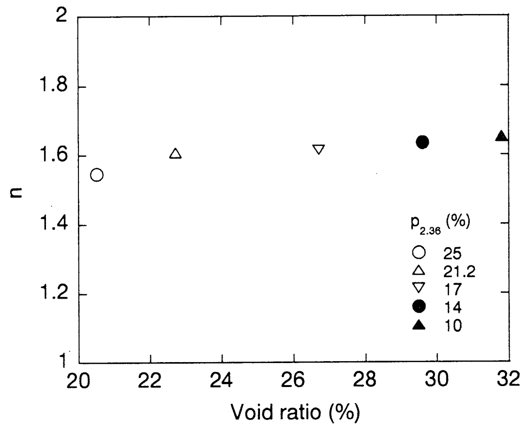


(b) Drainage asphalt mixtures

Fig. 5 Parameter *m*



(a) Single-sized crushed stones



(b) Drainage asphalt mixtures

Fig. 6 Parameter *n*

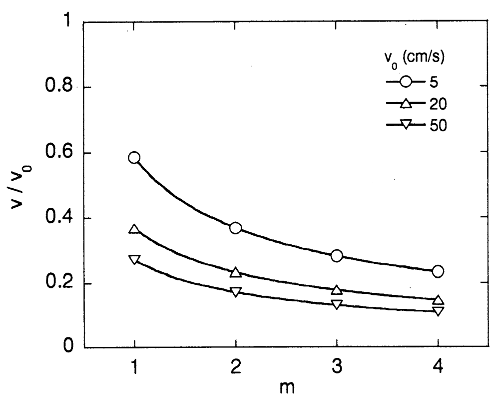


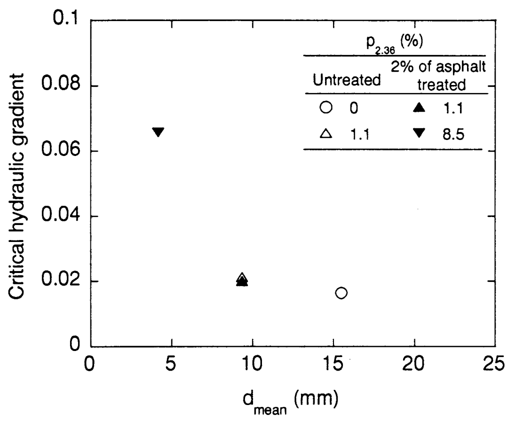
Fig. 7 Comparison of the discharge velocity at different flow states

(4) Critical hydraulic gradient

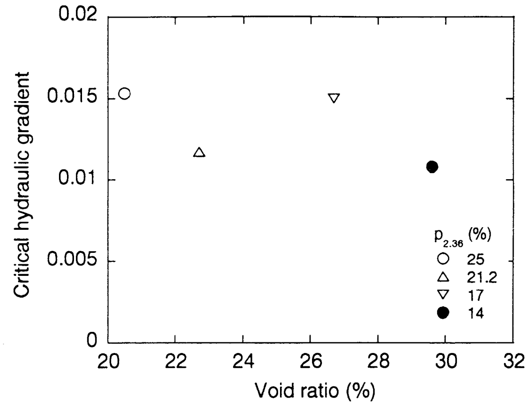
By combining Eqs. (1) and (2), the critical hydraulic gradient can be obtained, as expressed by Eq. (6).

$$i_c = \frac{1}{\sqrt[n-1]{m \cdot k}} \tag{6}$$

Since parameter *n* has an almost constant value ranging from 1.3 and 1.8, it can be found from Eq. (6) that as either *k* or *m* increases, the critical hydraulic gradient might decrease. This was confirmed by the fact that a laminar flow was observed for mechanical stabilized crushed stones and sand with lower permeability coefficients, while a turbulent flow was observed for the single-sized crushed stones or drainage asphalt mixtures with higher permeability coefficients.



(a) Single-sized crushed stones



(b) Drainage asphalt mixtures

Fig. 8 Critical hydraulic gradients

Fig. 8 shows the critical hydraulic gradients in the experiments. It shows that the critical hydraulic gradients for the single-sized crushed stones are around 0.02, while those for the drainage asphalt mixtures range from 0.010 to 0.015. This means that if the hydraulic gradients are within these ranges, a laminar flow might occur and Darcy's law could be adopted to estimate the discharge velocity, while the hydraulic gradients exceed these ranges, a turbulent flow might occur and the turbulent flow equation should be used.

4. SUMMARY

The permeability tests of five types of drainage base course materials were conducted at laboratory, and the experimental results were analyzed. Three parameters (permeability coefficient k, turbulent flow parameters m and n) were introduced to describe the permeability behavior. Based on the experiments, these parameters were studied. Meanwhile, four aspects of the material properties were used to analyze the connection between the material composition and the permeability parameters. The following findings were obtained from the study:

1)The permeability coefficient k of single-sized crushed stones and the drainage asphalt mixtures are thousands of times higher than that of either the mechanical stabilized crushed stones or the sand. A larger grain size and higher void ratio might be beneficial to obtain a higher permeability coefficient, but a larger $p_{0.075}$ or $p_{2.36}$ might be harmful.

2)From the experiment, the turbulent flow parameter m was more than 1.0, and the parameter n ranged from 1.3 to 1.8. No turbulent flow was observed for the sand and the mechanical stabilized crushed stones.

3)The critical hydraulic gradients are up to 0.02 for single-sized crushed stones and 0.010-0.015 for drainage asphalt mixtures. Errors might have been induced while using Darcy's law to estimate the discharge velocity irrespective of the flow states.

REFERENCES

1)Cedergren, H. R.: *Drainage of Highway and Airfield Pavements*, John Wiley & Sons, 1974.

2)National Asphalt Pavement Association: Asphalt Treated Permeable Material - Its Evolution and Application, Translated by Japanese Road Construction Association, Vol. 1-6 (in Japanese).

3)Ohkawa, H., Sato, T. and Hokari, K.: Study on the Estimation of Permeability Coefficient of Drain Asphalt, *JSCE*, No. 478/V-21, pp.101-108, 1993 (in Japanese).

4)Randolph, R. W., Cai, J., Heydinger, A. G. and Gupta, J. D.: Laboratory Study of Hydraulic Conductivity for Coarse Aggregate Bases, *Transportation Research Record 1519*, pp. 19-27, 1996.

5)Elsayed, A. S. and Lindly, J. K.: Estimating Permeability of Untreated Roadway Bases, *Transportation Research Record 1519*, pp. 11-18, 1996.

6)Japanese Standards Association: *JIS Handbook - Civil*, pp.963-966, 1995 (in Japanese).

7)Cedergren, H. R.: *Seepage, Drainage, and Flow Nets*, Second edition, John Wiley & Sons, 1977.

8)JSCE: Reports of Pavement Engineering Research Committee, pp. IV12-17, 1997 (in Japanese).

室内試験による路盤材料の透水性能

殷　建軍・八谷　好高

本論文では，単粒径砕石（アスファルト処理・無処理），排水性アスファルト混合物，砂，粒度調整砕石という 5 種類の路盤材料に対して，室内定水位透水試験を行い，それらの透水性能について研究している．材料の透水性能を表すパラメーターとして 3 種類（k：層流，m，n：乱流）が導入され，物理特性を表すパラメーターとして 4 種類（平均粒径 d_{mean}，空隙率，$p_{2.36}$・$p_{0.075}$ (2.36mm，0.075mm ふるい通過分)）が導入された．一連の試験結果として，路盤材料の透水性能を表す場合の Darcy 則の適用性について明らかにしている．