Study on Drainage Performance of Porous Asphalt Pavements by Rainfall Simulation Testing

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ABSTRACT: With the introduction of porous asphalt (PA) pavements, road surface drainage performance has been improving and accident rates during rain have been decreasing. In cases of heavy rainfall, however, flooding is often seen to occur on road surfaces where the cross slope is gentle. In this study, a rainfall simulation test was conducted with the aim of quantifying the drainage performance of PA pavements and applying the results to road surface drainage design. The rainfall simulation tests were performed using a rainfall simulator capable of reproducing rainfall according to some predetermined intensities on test pavements with road surfaces with varying cross slope and PA layer thickness. The rainfall simulation tests measured the critical amount of rainfall to cause flooding and the amount of run-off rainwater that infiltrated into the PA layer. The results of this study showed that (1) increasing the PA layer thickness or providing a cross slope makes flooding less likely to occur, (2) even if the road surface cannot be provided with a cross slope, drainage performance can be improved by providing the upper surface of the impervious layer directly under the PA layer with a cross slope to, namely, by making the PA layer have a varying cross section, and (3) the amount of water stored in the PA layer until flooding and the amount of run-off from the PA layer per unit time can be both evaluated quantitatively by a formula with cross slope, rainfall intensity, thickness and air void of PA layer as variables.

KEYWORDS: porous layer, drainage performance, rainfall, cross slope

1 INTRODUCTION

Introducing porous asphalt (PA) pavements can improve the drainage performance of a pavement surface and help decrease the number of accidents that occur when it is raining. However, the amount of rainwater that can be stored in the PA layer is limited. In addition, it takes some time to let the temporarily stored rainwater run off from the layer. Consequently, when there is a lot of rainfall, we see many spots of flooding on the road surface, including locations such as three-lane roads, sags where the cross slope of the road surface becomes locally zero percent, or antiapexes of S-curves.

To study the drainage performance of PA pavements, various kinds of research have been conducted such as a survey on the drainage behavior of some model pavement during actual rainfall or research using a large specimen and rainfall equipment (Okawa et al. 1993, Takahashi et al. 2001). These research activities involved reviewing the draining mechanism or measuring the amount of storage or run-off. But in order to have a design that considers the durability of the pavement as well as its drainage performance, it is also necessary to quantify the drainage performance.

In this study, we used a few kinds of PA pavements with different cross slopes of the PA layer and impervious layer and different PA layer thicknesses, conducted some rainfall simulation tests using the test pavements constructed with those PA pavements and quantitatively evaluated the drainage performance of the PA pavements. The major items studied are as follows:

1) Evaluation of drainage performance based on the amount of storage and run-off
2) Effective air void for storing water inside the PA layer and the flow velocity of water as evaluated from the actual drainage behavior during rainfall
3) Critical amount of rainfall that does not cause flooding, with the drainage distance (pavement width) taken into consideration

2 RAINFALL SIMULATION TEST WITH THE TEST PAVEMENT

2.1 Test Pavements

The test pavements consisted of PA layer thicknesses of 4 cm and 10 cm for the equal cross section, and 7 to 15 cm for the variable cross section and cross slopes of 0% and 2% for the PA layer or the surface of the impervious layer in Figure 1.

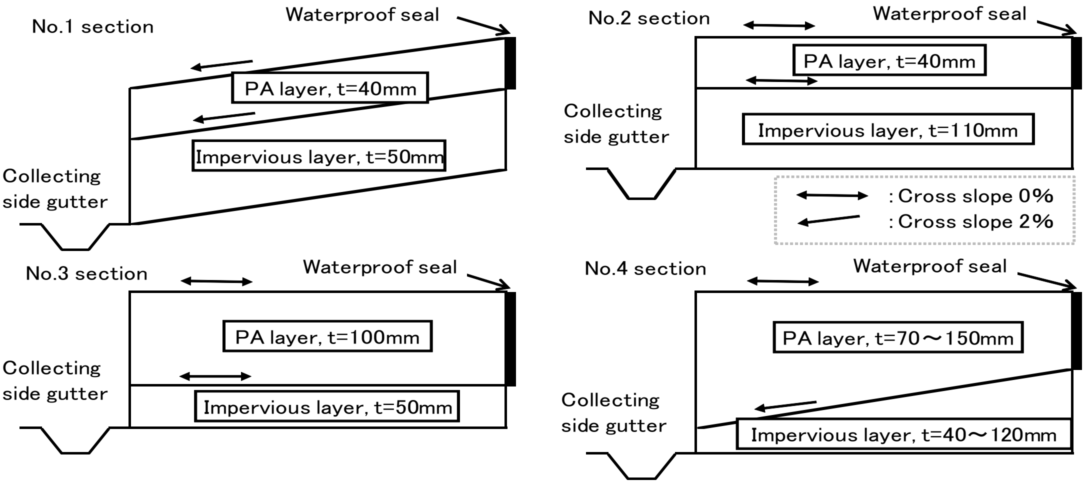


Figure 1: Test pavement sections

The following shows the method used for constructing the test pavements and the procedure for treating the pavement edges to measure run-off in the rainfall simulation test.

1) Use the typical PA mixture and dense graded mixture in Japan as the PA layer and the impervious layer respectively.
2) Apply the normal paving procedure to the PA layer and the impervious layer.
3) Cut both longitudinal ends of a test section (4 m wide × 5 m long) with a cutter and remove the cut pavement.

4) Out of the four sides of the test section, seal three sides with an impermeable material so that the rainwater that infiltrated into the PA pavement will be drained only through the remaining one side.

The thickness, air void and coefficient of permeability (Japan Road Association, 2007) of cores sampled from each test section are shown in Table 1.

Table 1: Properties of sampled cores

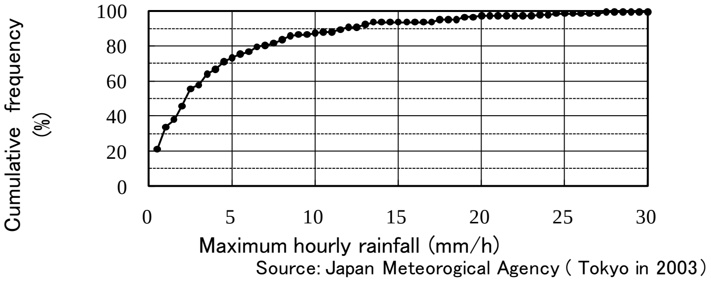
Test section	Thickness (cm)	Air void (%)	Coefficient of permeability (cm/s)
No. 1	4.0	21.4	0.289
No. 2	4.8	19.6	0.338
No. 3	11.3	15.3	0.133
No. 4	13.7 (Note)	14.6 (Note)	0.050 (Note)
Note: The data for No.4 test section are from the thickest core samples.			

2.2 Rainfall Simulation Tests

The rainfall simulator is shown in Figure 2. Twenty nozzles, attached to the simulator, slide left and right to produce a uniform amount of rain over a test section. As the simulator is also capable of keeping a constant discharge pressure, it can maintain uniform rainfall during measurements. By changing the set discharge pressure, we can produce rainfall that matches the predetermined rainfall intensity.

Figure 2: View of rainfall simulation test equipment

As indicated by Figure 3 (rainfall data of Tokyo), the frequency of rainfall with a precipitation of over 15 mm per hour is less than 10% of all rainfall events through the year. Given this data, the rainfall intensity set for the rainfall simulation test was 15 mm/h at maximum. The general range of intensity set for the test was between 3 and 15 mm/h.



Source: Japan Meteorological Agency (Tokyo in 2003)

Figure 3: Annual cumulative frequency of maximum hourly rainfall (Tokyo in 2003)

The following measurements were made in the rainfall simulation test.

(1) Whether or not there was any flooding and, if there was, the time until it occurred
Flooding was visually checked. If there was flooding, the time it took flooding to occur was measured. Those measurements were used to calculate the critical amount of rainfall until flooding and the amount of water storage in the PA layer.

(2) Amount of rainfall run-off infiltrated into the PA layer
Rainfall that infiltrated into the PA layer is run off only through the side to the collecting side drain. In the rainfall simulation test, the run-off was measured regularly at a certain time interval. This was done to identify the relationship between run-off and rainfall duration, the basic data for the rainfall simulation test.

3 RAINFALL SIMULATION TEST RESULTS

3.1 Occurrence of Flooding

The flooding condition at each test section as the amount of rainfall was changed from 3 to 15 mm/h is shown in Table 2. This table revealed the following findings:

1) When the PA layer thickness is about equal, pavements provided with a cross slope have a higher rainfall intensity with respect to the occurrence of flooding, which means they are less likely to occur flooding.
2) When the cross slope is equal, pavements with a thicker PA layer have a higher rainfall intensity with respect to the occurrence of flooding, which means they are less likely to occur flooding.

Table 2: Occurrence of flooding in the rainfall simulation tests

Test section	Cross slope of the PA pavement (%)		PA layer thickness(cm)	Rainfall (mm/h)							
	Pavement surface	Upper surface of the impervious layer		3.0	4.0	4.5	5.0	6.5	8.0	10.0	15.0
No. 1	2	2	4.0	—	○	—	○	×	—	×	—
No. 2	0	0	4.8	—	○	—	×	×	—	×	—
No. 3	0	0	11.3	○	—	○	○	—	—	×	—
No. 4	0	2	12.3	○	—	○	○	—	○	○	×

Note 1: Signs in the table: ×: flooding occurred; ○: no flooding; —: no test conducted
Note 2: The PA layer thickness is the average of the core thicknesses.
▨ : Region where flooding occurred

3.2 Drainage Behavior during the Rainfall Simulation Test

Figure 4 shows an example of the relationship between run-off and rainfall time per minute in the rainfall simulation test in the case of 5 mm/h rainfall intensity, while Figure 5 shows this relationship in the case of 10 mm/h intensity. The findings from those figures are as follows:

1) The run-off was almost the same regardless of the cross slope until the passage of 30 min. (in the case of 5 mm/h) or 45 min. (in the case of 10 mm/h) after the start of raining.
2) As the rainfall continued, the test sections with a cross slope (No. 1 and No.4) came to have a larger run-off, while those without a cross slope (No. 2 and No.3) saw flooding.

The water level of rainfall stored in the PA layer was measured for test sections No. 3 and No.4. The water level was measured by inserting a float in three holes drilled in the transverse direction of the road surface as shown in Figure 6. The measurements of the water level in the PA layer are shown in Figure 7 (No.3) and Figure 8 (No.4).

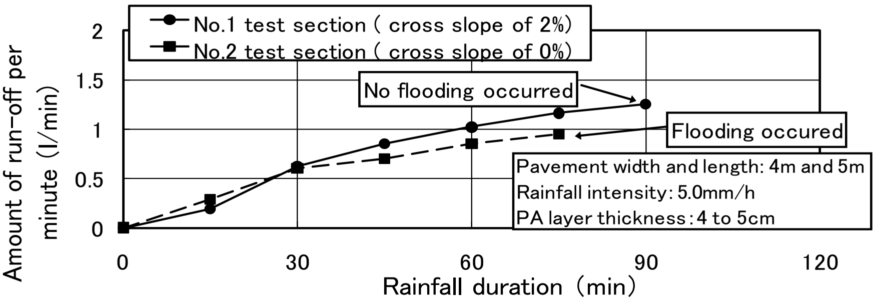


Figure 4: Relationship between run-off and rainfall duration (rainfall of 5 mm/h)

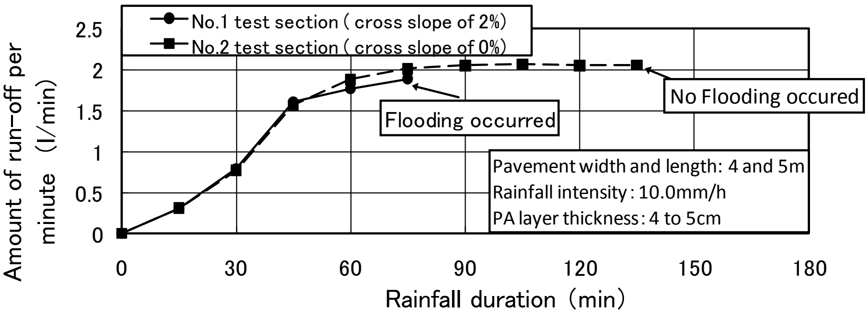


Figure 5: Relationship between run-off and rainfall duration (rainfall of 10 mm/h)

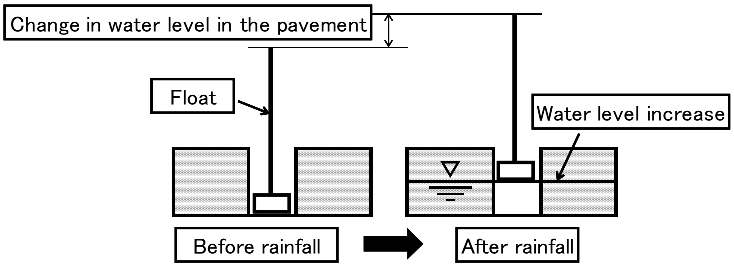


Figure 6: Measurement of water level change

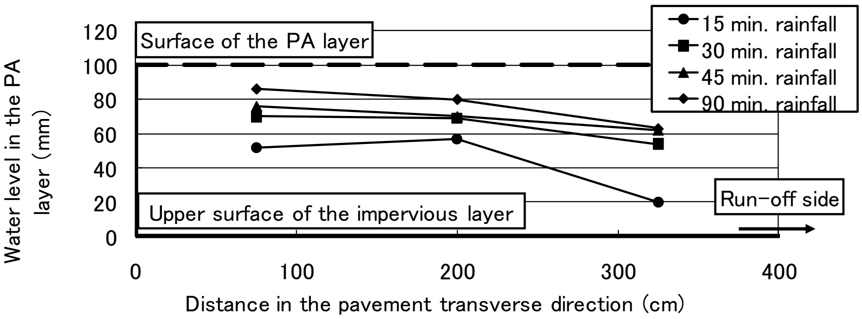


Figure 7: Changes in water level in rainfall (test section No.3; rainfall of 10 mm/h)

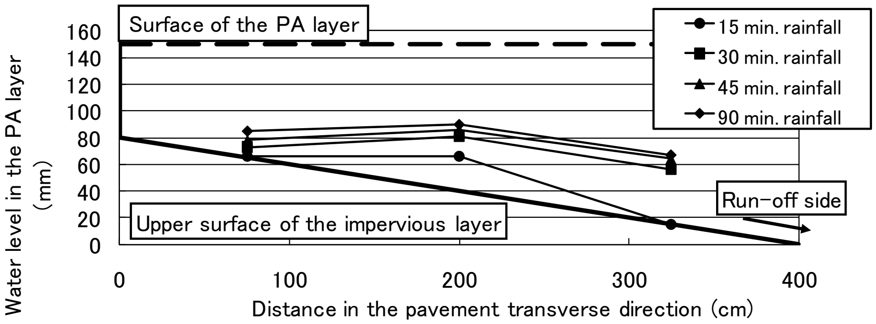


Figure 8: Changes in water level in rainfall (test section No. 4; rainfall of 10 mm/h)

As indicated by Figures 7 and 8, there is a sufficient level difference between the water level and the road surface at test section No. 4 with a cross slope on the impervious layer, meaning there is a low possibility of flooding. At test section No. 3, which has no cross slope, the possibility of flooding is high because of the small difference between the water level and the road surface.

4 EVALUATION OF DRAINAGE PERFORMANCE

4.1 Evaluation Method of Drainage Performance

The drainage performance of PA pavements is affected by the amount of storage in the PA layer, and the amount of run-off from the PA layer to the side (Okawa et al. 1993).

According to the rainfall simulation test results, the run-off for each rainfall duration was obtained, for example, as a per-minute run-off vs. rainfall duration curve as shown in Figure 4. The amount of rainfall is obtained from the value calculated (rainfall intensity × rainfall duration). This concept is schematically illustrated in Figure 9.

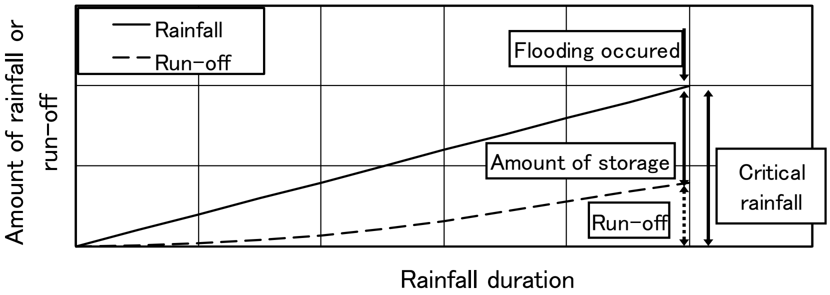


Figure 9: Schematic illustration of drainage performance of the PA pavement

As shown in Figure 9, the drainage performance is quantitatively evaluated as the critical rainfall until the occurrence of flooding, the amount of run-off, and the amount of storage (critical rainfall minus run-off). The slope of the run-off vs. rainfall duration curve then gives the amount of run-off per unit time. For the rainfall simulation tests in this study, it took about 15 minutes after the start of rainfall before the run-off reached an almost constant amount.

4.2 Storage

(1) Effects of PA Layer Thickness, Cross Slope and Rainfall Intensity

Figure 10 shows the amount of storage. The storage is expressed in the term of amount of rainfall when flooding occurred.

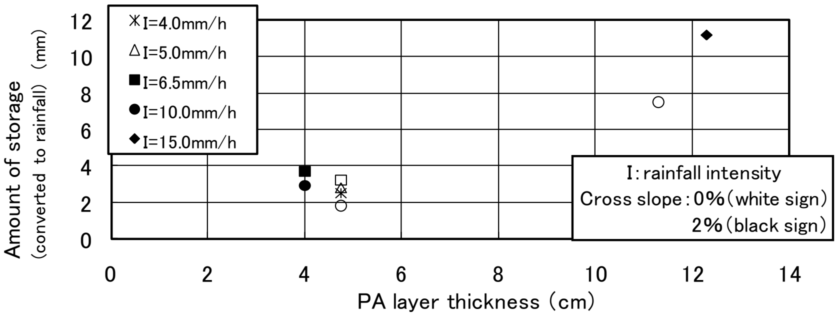


Figure 10: Relationship between PA layer thickness and storage

The storage is affected by the PA layer thickness and cross slope; the storage increases as the PA layer thickness increases, and the storage is larger for the pavements with cross slope. With the same PA layer thickness and cross slope, the storage tends to slightly decrease as the rainfall intensity increases. This is presumably because the rainfall intensity is higher for the amount of rainwater infiltrated under the road surface and flooding occurs before the entire PA layer reaches saturation.

(2) Ratio of Effective Air Void for Storage and the Amount of Storage

Figure 11 shows the ratio of effective air void for storage to the total air void. Although the ratio is generally considered to be about 0.5 (Okawa et al. 1992), this study has identified the range of ratio between 0.2 and 0.6 depending on the PA layer thickness, cross slope and rainfall intensity.

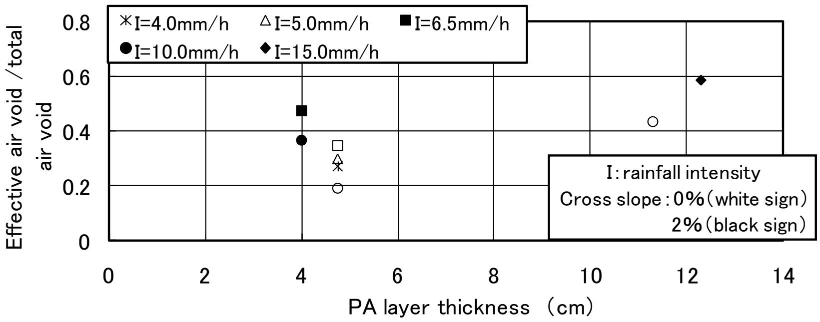


Figure 11: Raito of effective air void to total air void for storage

When the ratio (F_S) is multiple-regressed by the PA layer thickness, cross slope and rainfall intensity, Equation 1 is obtained. Therefore, the amount of storage is quantified by Equation 2. This indicates that the storage can be set by the PA layer thickness and the total air void. Equation 1 should be applied when the value of F_S is less than 0.6. This is because 0.6 is the maximum value of Fs obtained from the rainfall simulation test and is almost the same as the ratio of the continuous air void to the total air void (including independent air void), the value may be taken as a practically feasible maximum.

$$F_S = 0.0312 + 0.842(i+1) - 0.0177I + 0.292(T \cdot V_{\mathrm{air}}/100) \quad (R = 0.97), \tag{1}$$

$$S = 10(T \cdot V_{\mathrm{air}}/100)F_S, \tag{2}$$

where

F_S: ratio of effective air void to total air void for storage
i: cross slope of the road surface or the upper surface of the impervious layer (%)
I: rainfall intensity (mm/h)
T: PA layer thickness (cm)
V_{air}: total air void (%)
S: amount of storage (expressed in the term of rainfall when flooding occurred) (mm).

4.3 Amount of Run-off

(1) Relationship between run-off and PA layer thickness, total air void and cross slope

Figure 12 shows the amount of run-off per unit time in a pavement area that was 4 m wide and 1 m long. The run-off is more greatly affected by the PA layer thickness and cross slope and is relatively less affected by rainfall intensity.

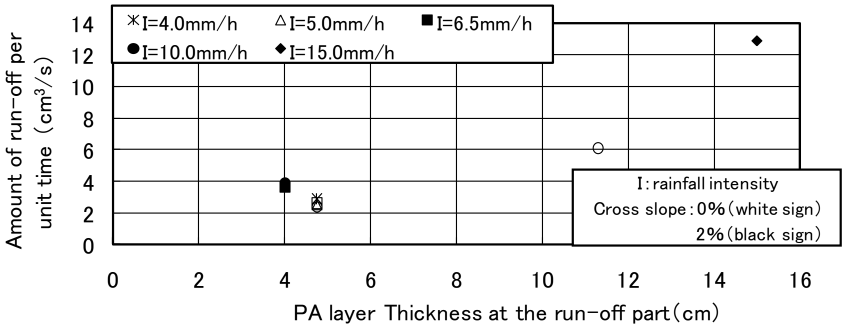


Figure 12: Relationship between PA layer thickness and run-off

The run-off per unit time may be quantified by Equation 3, a formula multiple-regressed by influencing factors such as PA layer thickness. This indicates that the amount of run-off can be set by the PA layer thickness and total air void as in the case of the amount of storage.

$$q = 0.0101(i+1)^{0.512} I^{-0.100} (100T \cdot V_{\mathrm{air}}/100)^{1.262} \quad (R = 0.99), \tag{3}$$

where q is run-off per unit time (cm^3/s).

The term $100T$ in Equation 3 shows the run-off sectional area (in cm^2 per meter in length) when the PA layer thickness is T (cm).

(2) Effects such as cross slope on the run-off velocity

The run-off velocity is taken as the actual velocity of water movement in the PA layer. It was obtained by dividing the run-off per unit time by the value calculated (run-off sectional area of the PA layer × effective air void). In other words, the idea behind it is that the effective air void for storage is also effective for water movement.

Figure 13 shows the run-off velocity as compared with the coefficient of permeability obtained from the laboratory permeability test. The run-off velocity tends to increase for the roads with a cross slope and a higher rainfall intensity, but such an increment is about 0.1 cm/s, which is in the range of 0.25 to 2.5 times the coefficient of permeability.

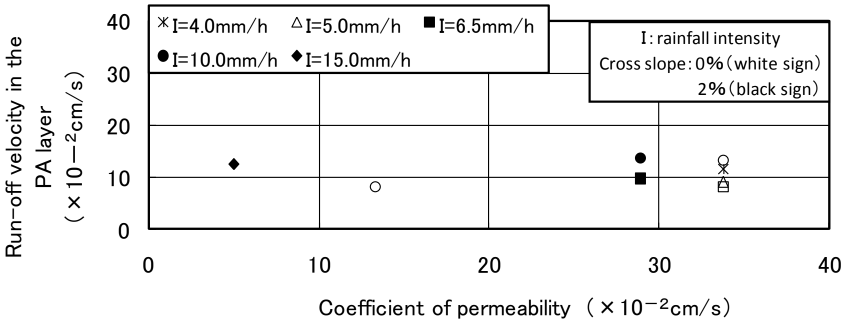


Figure 13: Run-off velocity in the PA layer

Multiple-regressing the run-off velocity by cross slope, rainfall intensity and coefficient of permeability produced Equation 4. The run-off velocity was quantified as a function of those influencing factors.

$$v = 0.0747(i+1)^{0.248} I^{0.225} k^{0.120} \quad (R = 0.55), \tag{4}$$

where v is run-off velocity (cm/s) and k is coefficient of permeability (cm/s).

4.4 Critical Rainfall

The critical rainfall is the amount of rainfall measured upon (amount of rainfall minus amount of run-off) exceeding the storable limit and is obtained from Equation 5.

$$\begin{aligned} &R - Q = S', \\ &R = I \cdot t \cdot A, \\ &Q = q(t - C_M), \\ &S' = S \cdot A, \end{aligned} \tag{5}$$

where

R: critical rainfall (mm)

t: rainfall duration (s)

A: pavement width × pavement length (cm^2)

q: amount of run-off per unit time calculated from Equation 3 (cm^3/s)

C_M: time it takes q to become constant after the start of rainfall (15 × 60 s for the rainfall simulation tests in this study)

S: the amount of storage converted to the amount of rainfall calculated from Equations 1 and 2 (mm).

Figure 14 is an example of the calculation results of critical rainfall. In this calculation example, a typical PA mixture is assumed, and the total air void is set to 20%, while the coefficient of permeability is set to 0.25 cm/s. This figure is applicable to drainage design with the occurrence of flooding taken into consideration.

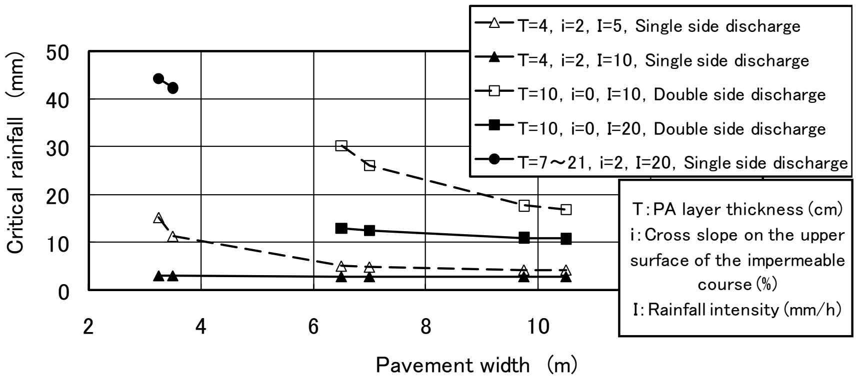


Figure 14: Relationship between critical rainfall and pavement width

5. CONCLUSIONS

From the rainfall simulation test results, several findings can be summarized as follows:

1) The amount of storage until the occurrence of flooding and the amount of run-off per unit time can either be quantitatively evaluated by the equations using cross slope, rainfall intensity, PA layer thickness and total air void as variables. When drainage design is conducted while considering the occurrence of flooding, the drainage performance can be set by the PA layer thickness and total air void.
2) The ratio of effective air void to total air void for storage of rainwater in the PA layer is within the range of 0.2 to 0.6. The run-off velocity of water in the PA layer (that is, actual coefficient of permeability) was evaluated and is related to coefficient of permeability tested in laboratory.
3) The critical rainfall by changing PA layer thickness, cross slope, rainfall intensity, and pavement width was calculated by using the quantified drainage performance, and it indicated that such process can be applied to drainage design.

Although this study was a successful and quantified evaluation of the drainage performance immediately after construction, it is necessary to monitor changes of the drainage performance over time in service.

REFERENCES

Japan Road Association 2007:*B012 Method of Test for Water Permeability of Open Graded Asphalt Mixture*, Manual for Condition Survey and Testing of Pavements (in Japanese)

Okawa, H., Hara, T., and Hokari, K., 1992. *Drainage Behavior of the Drainage Pavement*, Hoso 27-7 (in Japanese)

Okawa, H., Sato, T. and Taguchi, H., 1992. *Parameters Affecting Drainage Behavior and Its Application*, presentation for the Porous Asphalt Study Meeting (in Japanese)

Takahashi, S.,Ono, S and Motomatsu, S., 2001. *Research on Drainage Characteristics of Porous Pavement*, No. 9125, the 24th Japan Road Conference (in Japanese)