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Experimental Study of Pavement Body Configurations of the Evaporative Cooling Pavement System with a Focus on Rainwater Retention and Capillary Absorption

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Summary
This paper discusses a pavement body configuration of the evaporative cooling pavement system. The evaporative cooling duration of pavement systems, which were designed with a focus on rainwater retention and capillary absorption, was investigated through a summer outdoor experiment. The results from this experiment showed the following: (1) Surface temperature of a system which has pavement blocks with arched void kept low for 14 days or longer. The difference between the surface temperature and air temperature were below 5 degrees C in the daytime. It is because the water retention capacity is enough and the distance of pavement surface and waterproof layer is shorter than the pavement capillary absorption height. (2) Evaporative cooling duration of pavement systems with a thick roadbed was about 5 days. It shows that there is stay water (not used for evaporative cooling) in the system after capillary absorption channel from the pavement downside to the surface are disconnected.

Key Words: Evaporative cooling. Pavement system. Capillary absorption. Outdoor experiment. Rainwater retention

1. Introduction

Water-retentive pavements which retain water and have evaporative cooling effect draw attention as one of countermeasures against heat-island phenomenon. Many researches and developments of the pavements go on. But many of the water-retentive pavements have not enough water retention capacity, so their evaporative cooling durations are short.

The present writers have been proposed a basic configuration of "Evaporative Cooling Pavement System (ECPS)" which reserves rainwater on site and evaporate water by pavement brocks' capillary absorption (Marui, 2006). The heat and water balances and cooling performance have been studied through an outdoor experiment. Figure 1 shows basic configuration and design reference point of the ECPS. It can be said that this system is more effective than anamnestic water-retentive pavements from the viewpoints of water retention capacity, maintenance, energy conservation and rainwater utilization. However, specific design of the pavement body configuration and efflorescence prevention on the concrete block pavement have been remained as big issues to be solved.

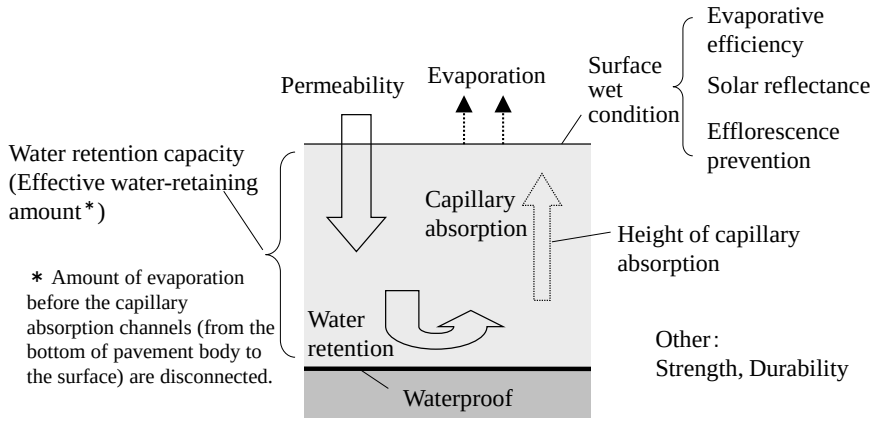


Figure 1. Basic configuration and design reference point of the "Evaporative Cooling Pavement System (ECPS)"

In this paper, configuration of pavement body including block and roadbed is discussed through a summer outdoor experiment. Research approach shows the following: (1) A design specification with focus on water retention capacity is discussed based on the characteristics of summer rainfall. In this paper, it is supposed that the ECPS used in the Tokyo metropolitan area. (2) Pavement body configurations are designed with rainwater retention and capillary absorption, and their mock-ups are made. (3) Summer outdoor experiment is launched using the mock-ups. Their evaporative cooling durations examined with a focus on pavement's surface wet condition, water content, difference between surface temperature and air temperature.

2. Design specification of the Evaporative Cooling Pavement System

2.1 Discussion about the characteristics of summer rainfall in Tokyo

The Evaporative Cooling Pavement System (ECPS) aims to keep evaporation cooling effect over a long duration in summer using only storage rainfall. In order to discuss about design target of water retention capacity, rainfall characteristics of summer (from July to September)

are surveyed using data of Tokyo district meteorological observatory from 2000 to 2009 (for ten years). As a result, average annual precipitation was 1590 mm in the decade in Tokyo. The integrating precipitation in summer three months were 300 - 710 mm and the average was 520 mm. If this 520 mm divided by 92 days of the summer three months, the water amount per day is 5.7 mm. The outdoor experiment in previous study (Marui, 2006) confirmed that daily integrating evaporation of enough wet pavement was 3 - 6 mm per day in the sun in summer sunny day (refer to Figure 3-b). Considering there are cloudy and rainy days in the period, the average amount of summer rainfall in Tokyo can balance out about integrating evaporation of the ECPS.

Figure 2 shows appearance frequency of no rainfall period (straight days which have less than 0.5 mm/day precipitation) in summer (from July to September) by data of Tokyo district meteorological observatory from 2000 to 2009. Data of less than two days are not marked in this figure. Because the daily integrating evaporation on wet pavement was 3 - 6 mm per day in summer sunny day, period of straight days which have less than 6 mm/day precipitation are also marked in Figure 2. As a result, the longest no rainfall period in summer was 20 days and average was 14.4 days in the decade. The appearance frequency of more than 14 straight days which have less than 6 mm/day precipitation were 12 times and accumulated periods were 250 days in the ten years. As far as the summer three months in ten years goes, the 250 days correspond to 27 % of the ten year's total days, and there is one day which have more than 6 mm precipitation within 14 days in more than 70 % of the total days.

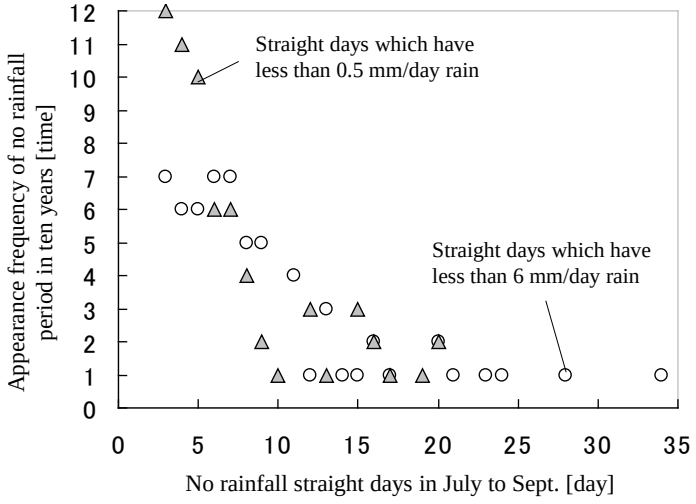


Figure 2. Appearance frequency of no rainfall period in summer

(Using data of Tokyo district meteorological observatory from 2000 to 2009.
Data of less than two days are not marked in this figure.)

2.2 Evaporation and precipitation in previous experiment

In order to grasp the relation between evaporation and precipitation concretely, experimental data of the previous research (Marui, 2006) is discussed. Figure 3 shows the experimental data of mock-up which kept pavement wet condition by water supply in the sun from August to September in 2004. Precipitations of the two months were around the same amount as in previous years. There were some 30 - 60 mm rainy days occasionally (Figure 3-a). During the two months, integration precipitation was 410 mm and integration evaporation of the mock-up which kept wet condition was 210mm (Figure 3-c). The integration precipitation was 200 mm greater than the evaporation.

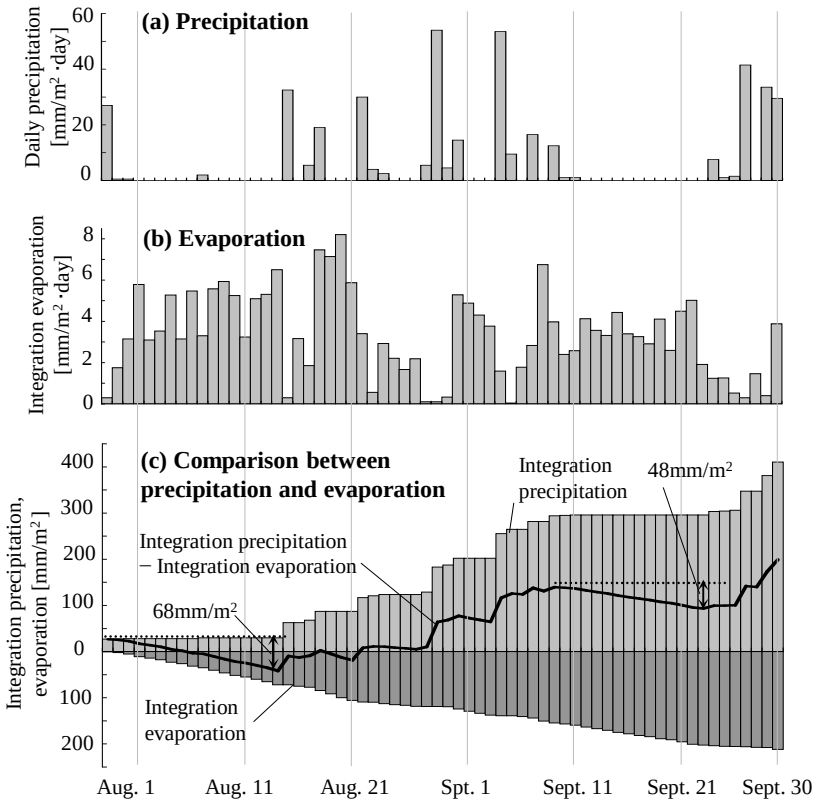


Figure 3. Comparison between precipitation and evaporation in mock-up which kept pavement wet condition by water supply in the sun

(From August to September in 2004, Yokohama)

Focus attention on early August (16 days) and mid-September (14 days) when it continued sunny days, the differences between integration evaporation and integration precipitation were 68 mm and 48mm. It can be indicated that the ECPS could keep evaporative cooling during summer in the sun using only rainfall if that had around 70 mm (kg/m2) water retention capacity.

2.3 Design specification of water retention capacity

As previously noted, there is enough rainfall for the pavement system to keep evaporation in Tokyo summer. The daily evaporation on wet pavement in the sun is around 5 mm in summer sunny day. If water retention capacity of the pavement system was 70 kg/m2 which was almost same as 14 days' integrating evaporation, the ECPS could keep enough evaporative cooling during more than 70 % of summer season. In this paper, design specification of water retention capacity of the ECPS is set 70 kg/m2 in the case of using in the sun of Tokyo.

3. Invention of pavement body configurations

In accord with above examination, pavement body of the Evaporative Cooling Pavement System (ECPS) is brought into shape. It was took note that the system had more than 70 kg/m2 water retention capacity. It was also noted that the distance between pavement surface and water stop plane was shorter than the height of capillary absorption. In this paper, the "height of capillary absorption" is defined as the water absorption height of block which set on thin free water. An arched block shape which could retain enough water in void was invented considering strength and production of block (Figure 4). The pavement block material was almost the same one used in previous experiment (Marui, 2006) (Figure 5). Figure 6 shows an "Arched block" mock-up using the above arched pavement block. Table 1 shows outline of all types of the experimental mock-ups which were devised in this paper.

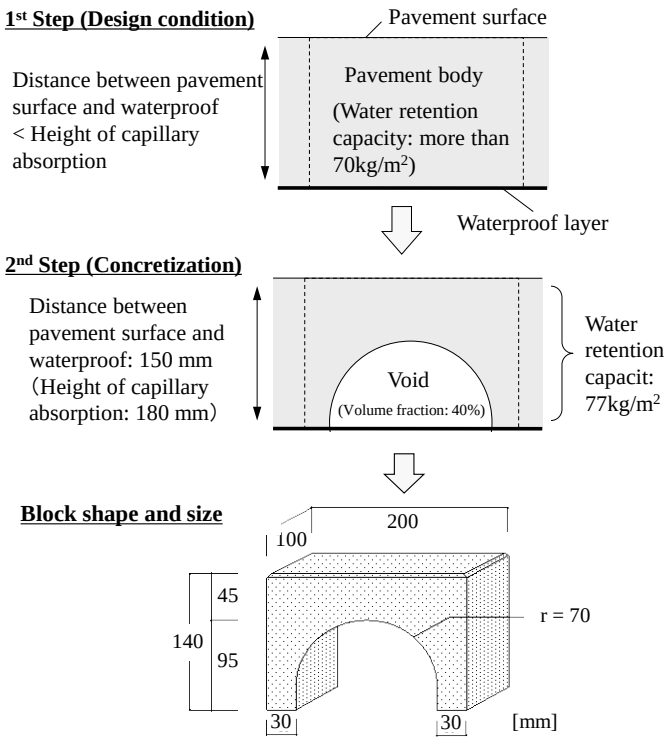
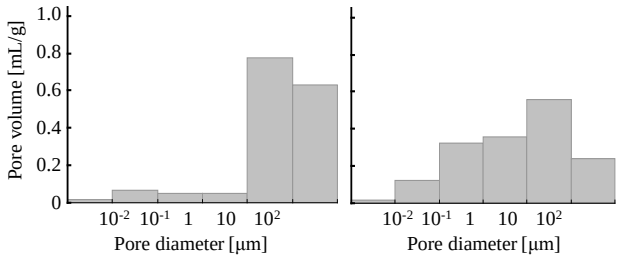


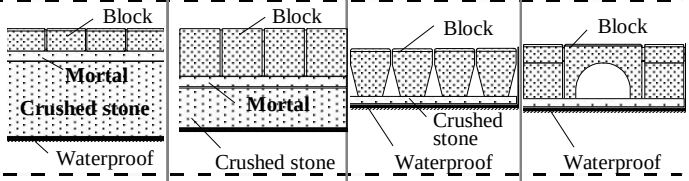
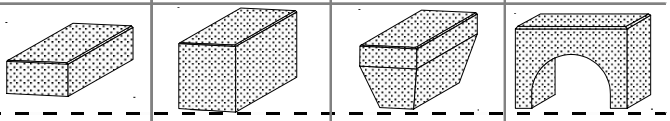
Figure 4. Concretization idea of pavement body ("Arched block" mock-up)



(a) Mountain sand block **(b) Reused tile block**

Figure 5. Pore size distribution of pavement block used in the experiment

Table 1. Outline of experimental mock-ups

Mock-up name			**Road bed improvement**	**Block thickening**	**Corner cut**	**Arched block**
Outline of pavement system	Design principle		Recycled waste-paper is mixed in road bed for improvement of capillary absorption.	Block is thickened for improvement of capillary absorption.	Distance between pavement surface and water stop plane is set shorter than the height of capillary absorption	Same as the "Corner cut" mock-up. And big void retain water.
	Section diagram					
	Water retention capacity		91 kg/m^2	68 kg/m^2	47 kg/m^2	77 kg/m^2
	Breakdown of water retention capacity		・Block : 11 ・Mortar : 6 ・Crushed-stone : 74 (kg/m^2)	・Block : 22 ・Mortar : 6 ・Crushed-stone : 40 (kg/m^2)	・Block : 19 ・Void : 24 ・Crushed-stone : 4 (kg/m^2)	・Block : 17 ・Void : 56 ・Crushed-stone : 4 (kg/m^2)
	Distance between pavement surface and water stop plane		290 mm	250 mm	130 mm	150 mm
Configurations and materials	Pavement block	Shape				
		Size	200 mm × 100 mm × D 60 mm	200 mm × 100 mm × D 120 mm	200 mm × 100 mm × D 120 mm	200 mm × 100 mm × D 140 mm
		Main material (Void ratio)	Reused tile (18%)		Mountain sand (20%)	
		Bending strength (Use application)	More than 3.0 MPa (Sidewalk or square)			
		Solar absorptance	Wet condition: 0.9 Dry condition: 0.8		Wet condition: 0.9 Dry condition: 0.8	
		Height of capillary absorption	180 mm (Water absorption height of block which set on thin free water)			
	Cushion material		Mortar		-	
	Road bed	Material	Crushed-stone and recycled waste-paper	Crushed-stone		
		Thickness	200mm	100mm	10mm	10mm
	Waterproof layer		Waterproof sheet			

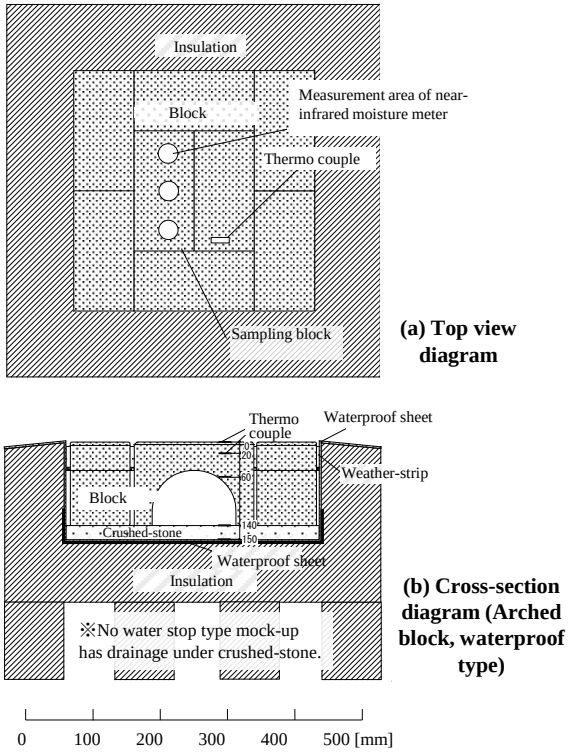


Figure 6. Top view and cross-section diagram of mock-up

4. Method of the summer outdoor experiment

4.1 Outline of the experimental mock-ups

Table 1 shows four types of the experimental mock-ups. Figure 6 shows a sample of top view and cross-section diagram. Main material of the “Arched block” and “Corner cut” mock-up is mountain sand. Main material of the “Road bed improvement” and “Block thickening” mock-up is reused tile (Figure 5). The height of capillary absorption of these blocks is around 180 mm.

The Evaporative Cooling Pavement System (ECPS) has a waterproof layer. But in this experiment, both mock-up which has waterproof layer and no were made in order to grasp surface wet conditions and compare cooling performances.

4.2 Measurement method and item

Table 2 shows measurement method and item. The following is epexegeses.

(1) Surface wet condition (Surface wet ratio)

The surface wet condition of pavement is one of the important parameter which concern evaporation efficiency and solar reflectance. In order to grasp moisture state of surface neighborhood, relative surface wet conditions are measured and indexed using a near-infrared moisture meter (Kett Electric Laboratory, KJT-100). Measured values are linearly interpolated

in such a way that the value of saturated moisture state indicates 1 and the value of absolute dry state indicates 0 (Formula 1).

$$\omega = (x - L_d) / (L_w - L_d) \qquad (1)$$

ω: surface wet ratio [-], x: Instrument reading of a near-infrared moisture meter in any surface wet condition [-], L_d: Reading of a near-infrared moisture meter in absolute dry state [-], L_w: Reading of a near-infrared moisture meter in saturated moisture state [-].
The surface wet ratio data of daytime (9 am to 5 pm) is dealt with in this report. Moisture absorption during nighttime has been confirmed in the preceding study (Marui, 2010).

Table 2. Measurement item

	Item	Equipment	Note	Period	Interval
Heat balance	Surface temperature	φ 0.1 mm T thermocouple	set on block surface	Entire period	1 minute
	Cross-section temperature	φ 0.3 mm T thermocouple	20, 60, 120 mm depth, and bottom of road bed		
	Surface temperature distribution	Infrared camera (8～14μm, 1.5mrad)		Short-term	
Water balance	Evaporation	Weight scale (resolution: 2 g)	previous research mock-up (Marui, 2006)	Entire	1 minute
	Volume water content of block	Weight scale (resolution: 0.2 g)	one block is sampled	Short-term	
	Surface wet condition	Near-infrared moisture meter	on 3 fixed point		
		Digital camera			
Weather condition	Amount of global solar radiation	Pyranometer (0.3～2.8 μm)		Entire period	1 minute
	Precipitation	Rain gauge (resolution: 0.5 mm)			
	Air temperature	Wet-and-dry-bulb thermometer			
		φ 0.1 mm T thermocouple	in ventilation pipe		
	Relative humidity	Wet-and-dry-bulb thermometer			
		Polymeric humidity sensor	in ventilation pipe		
	Wind direction, velocity	Vane anemometer (minimum wind velocity: 0.3 m/s)			

(2) Volume water content of pavement block

In order to grasp the relation between volume water content and surface wet ratio, one block was sampled from each mock-up and weighed every 2 to 3 hours in daytime. Volume water content of the pavement block was obtained by this weighing method.

(3) Experimental site and period

Experimental site was on rooftop of two-story building of Tokyo Institute of Technology in Yokohama, Japan. Measurement period was from late July to the end of September in 2005.

5. Experimental result and consideration

5.1 Evaporative cooling performance

In order to confirm evaporative cooling performance of the four mock-ups (waterproof type), experimental data of August 1 to 22 in when sunny day continued was picked out and analyzed (Figure 7).

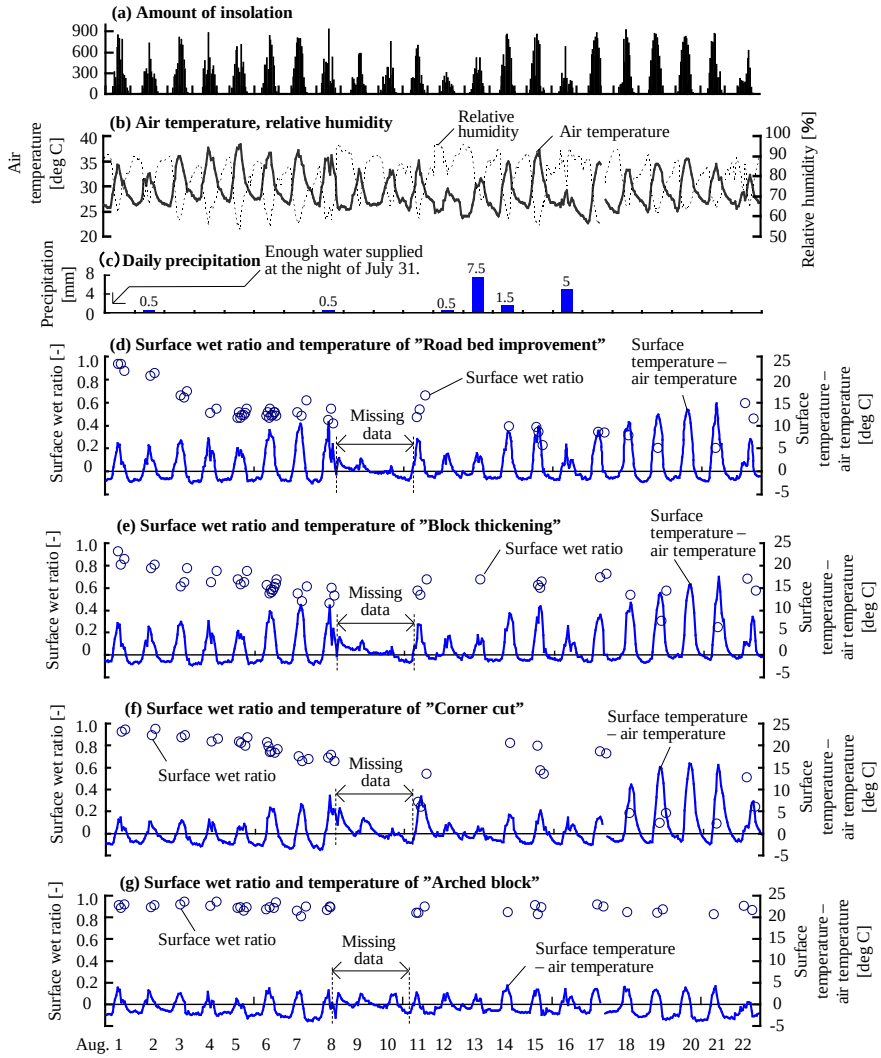


Figure 7. Measurement result (August 1 – 22, 2005) (Waterproof type mock-ups)

(1) Aspersion and weather condition

All mock-ups were supplied water more than their maximum water retention capacity at the night of July 31. Figure 7-a shows amount of global solar radiation, figure 7-b shows air temperature and relative humidity, and figure 7-c shows daily precipitation. There was 7.5 mm rain on Aug. 13 and 5 mm on Aug. 16.

From night of Aug. 8 to morning of Aug. 11, the mock-ups were covered with plastic sheets for certain reasons. Data was missed in this period.

(2) Surface wet condition

Figure 7-d,e,f,g show the surface wet ratio of each mock-up. Surface wet ratio of the "Road bed improvement" mock-up reduced to 0.5 the first 4 days. Surface wet ratio of the "Block thickening" mock-up showed a gradual decline and 0.5 on Aug. 8.

Surface wet ratio of the "Arched block" kept around 0.9 and surface kept wet during experiment period. It means that water retention capacity was enough and capillary absorption speed was higher than evaporation speed in the Arched block mock-up. There was free water in block void during the measurement period. With respect to "Corner cut" mock-up on Aug.18, there was no free water and surface wet ratio declined to 0.2

(3) Difference between surface temperature and air temperature

In order to confirm the evaporative cooling performance, difference between surface temperature and air temperature (ΔT) of each mock-up is discussed. Figure 7-d,e,f,g also show the ΔT (difference between surface temperature and air temperature). Basically, ΔT increases with a reduction in surface wet ratio. Period that surface wet ratio was higher than 0.5 and also ΔT was lower than 7 degrees C was around 5 days on the "Road bed improvement" and "Block thickening" mock-up. The period (that surface wet ratio was higher than 0.5 and also ΔT was lower than 7 degrees C) on the "Corner cut" mock-up was 8 - 9 days exclusive of missing data days. ΔT of the Arched block mock-up kept lower than 5 degrees C during all of the experimental period. It is due to the fact that the water retention capacity of the Arched block mock-up is enough and capillary absorption speed was higher than evaporation speed under condition of continuous summer sunny days. It was confirmed that evaporative cooling duration of the Arched block mock-up was 14 days or more even excluding missing data days, rainy days and water content amount by the rain. It is said that the Arched block mock-up cans reach the ECPS's aim of design specification described above 2.3.

5.2 Discussion about effective water-retaining amount

It was confirmed that the "Arched block" mock-up had enough effect and duration of evaporative cooling. Cooling duration of the "Corner cut" mock-up was shorter than the "Arched block". It is due to the fact that water retention capacity of the "Corner cut" was

designed relatively smaller (47 kg/m2). On the other hand, cooling duration of the "Road bed improvement" and "Block thickening" mock-up was short (around 5 days) even though they had large water retention capacity ("Road bed improvement" was 91 kg/m2, "Block thickening" was 68 kg/m2). It can be said that the relation between "height of capillary absorption" and "distance between pavement surface and water stop plane" affects the evaporative cooling duration.

(1) Idea of effective water-retaining amount

Figure 8 shows the daytime relation between volume water content and surface wet ratio of pavement block in each no water stop mock-ups. These trends of relation are almost the same as experimental result of the previous study (Marui, 2006). Figure 9 shows an idea of effective water-retaining amount using the data of "Arched block" mock-up. After capillary absorption channels from the pavement body bottom to the pavement surface were disconnected, surface dries out gradually and evaporative cooling effect decreases.

It is considered that "amount of evaporation before the capillary absorption channels (from the bottom of pavement body to the surface) are disconnected" contributes evaporating cooling effect in a pavement system, and it is defined as "effective water-retaining amount" in this paper (Figure 9). A judgmental standard that the capillary absorption channels are disconnected was under 0.5 of the surface wet ratio in this discussion.

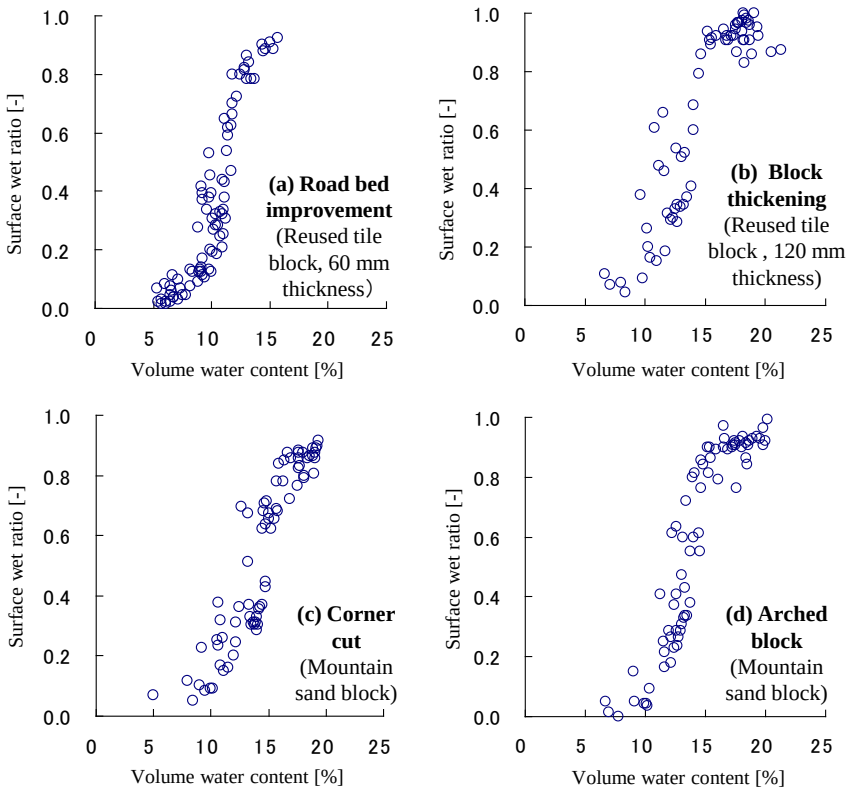
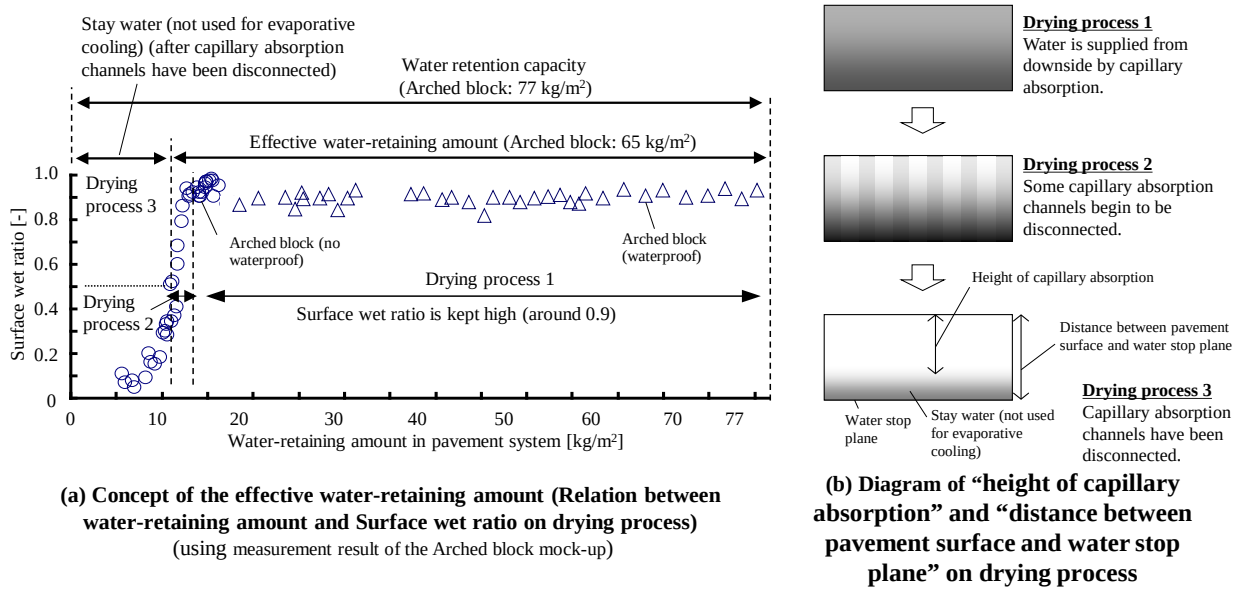


Figure 8. Relation between volume water content and surface wet ratio of pavement block (No waterproof type mock-ups, daytime)



(a) Concept of the effective water-retaining amount (Relation between water-retaining amount and Surface wet ratio on drying process) (using measurement result of the Arched block mock-up)

(b) Diagram of "height of capillary absorption" and "distance between pavement surface and water stop plane" on drying process

Figure 9. Idea of the effective water-retaining amount on pavement drying process

(2) Estimation of evaporative cooling duration by the effective water-retaining amount

Table 3 shows an estimation of evaporative cooling duration by the effective water-retaining amount in the four mock-ups. The effective water-retaining amount was estimated by pavement body configurations and experimental data. The evaporative cooling duration was estimated by supposition that daily evaporation of sunny summer day is 5 kg/m2.

It was estimated that the effective water-retaining amount of Arched block mock-up was 65 kg/m2 and the evaporative cooling duration was 13 days. This is almost the same as the experimental result in consideration that there were some cloudy days.

Table 3. Estimation of effective water-retaining amount and evaporative cooling duration

	Road bed improvement	Block thickening	Corner cut	Arched block
Water retention capacity	91 kg/m^2	68 kg/m^2	47 kg/m^2	77 kg/m^2
Distance between pavement surface and water stop plane	290 mm	250 mm	130 mm	150 mm
Which is greater: "height of capillary absorption" or "distance between pavement surface and water stop plane"	Distance between pavement surface and water stop plane	Distance between pavement surface and water stop plane	Height of capillary absorption	Height of capillary absorption
Effective water-retaining amount (estimation)	25 kg/m^2	25 kg/m^2	35 kg/m^2	65 kg/m^2
Evaporative cooling duration in continuous summer sunny days (estimation)	5 days	5 days	7 days	13 days

As discussed above, it is important for a pavement system which aims to keep evaporative cooling for a long period to be designed with a focus on the “effective water-retaining amount”. It was confirmed the “Arched block” mock-up which was proposed in this paper had enough “effective water-retaining amount” and reached the design goal.

6. Conclusion

On the subject of the “Evaporative Cooling Pavement System (ECPS)” which the present writers have been proposed in previous paper, design specification of water retention capacity was discussed and pavement body configuration was invented. The evaporative cooling performance was confirmed through a summer outdoor experiment. The results from this study showed the following.

(1) It can be said that pavement system can keep evaporative cooling during summer in the sun using only rainfall if that has around 70 mm (kg/m2) water retention capacity in Tokyo. However, it is important for a pavement body configuration to be designed based on the idea of “effective water-retaining amount” mentioned in the following.

(2) Evaporative cooling duration of the pavement mock-up with thick roadbed was about 5 days. It shows that there is stay water (not used for evaporative cooling) in the system after capillary absorption channel from the pavement downside to the surface are disconnected.

In this paper, the “amount of evaporation before the capillary absorption channels are disconnected” was defined as “effective water-retaining amount”. This “effective water-retaining amount” is one of the important factors in design of evaporative cooling pavement system.

(3) Surface temperature of a system which has pavement blocks with arched void kept low for 14 days or longer. The difference between the surface temperature and air temperature were below 5 degrees C in the daytime. It is because the water retention capacity is enough and the distance of pavement surface and waterproof layer is shorter than the pavement capillary absorption height. It has been a big issue for the ECPS to keep evaporative cooling for long duration. The ECPS can accomplish the issue by using arched block invented in this paper.

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