ExperimentalInvestigation of the Effect of Water Retentive Sidewalk Block Pavement on Improving Human Thermal Environment

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Abstract

Water retentive sidewalk block pavement (hereinafter "water retaining block pavement") is a block pavement in which highly water retaining blocks are spread over a sand layer of about 3 cm thick, and moisture of rain and water spray can be retained in the water retaining block pavement for several days. When water retained in water retaining block pavement evaporates, the heat of vaporization is removed from the pavement surface. Thus, the road surface temperature of block pavement doesn't rise much even during the daytime. In recent years, the temperature in the inner-city tends to rise due to the effects of global warming, urban heat-island phenomena and other factors, leading to an increase in the number of heat illness patients.[1)] If water retaining block pavement is applied to such places, the ambient temperature around people walking on sidewalks is lowered by retarding the increase in the road surface temperature during the daytime especially in the summer, contributing to the effects of improving the hot environment. For example, under weather conditions where the road surface temperature of common asphalt pavement reaches 60˚C, the road surface temperature of water retaining block pavement is reduced 10˚C to 20˚C to about 50 ˚C to 40˚C. Moreover, it is known that the air temperature about 1.0 meters above the pavement decreases by about 1 to 2˚C.[2)] In past studies, the effects of improvement of hot environment by the water retaining pavement have been evaluated in terms of road surface temperatures, temperatures on the pavement, humidity and environmental physical quantities such as WBGT (Wet Bulb Globe Temperature).[3)] But in cases where evaluation was made by directly measuring physiological responses (hereinafter "human physiological quantities") such as body temperatures, sweat rates and metabolic rates of people on pavements have not been found in the research of the pavement field. Therefore, for the purpose of more directly evaluating the friendliness to humans of water retaining block pavement, the authors have attempted to quantitatively evaluate the effects of improvement of hot environment by using the index called "human thermal load"[4)] that is calculated by using the results of measurement of human physiological responses, in addition to the aforementioned environmental physical quantities. As a result, it has been proven that the water retaining block pavement causes clearly less human thermal load than common asphalt pavement and is a human-friendly pavement. In this paper, we report the results of demonstration experiments in both outdoors and the climate chamber that can reproduce meteorological conditions during the daytime in the summer in a stable manner.

Key Words : water retaining block pavement; hot environment; human friendliness evaluation; human thermal load; road surface temperature; human subject research; heat transfer



1. Introduction

In the urban areas of Japan, hot environment has become severe with the highest temperature in summer reaching about 40°C. This is due to the increase of anthropogenic heat, high-rise buildings, and artificial covering of ground surface. As a result, the number of people suffering from heat stroke has increased in correlation with the aging population in Japan[5]. One of the measures to improve the hot environment where the artificial covering of the ground surface is a factor is water retaining block pavement. This is a paving technique that suppresses the road surface temperature through latent heat transport while utilizing vaporization heat when the water held in the porous block evaporates from the ground surface.

For pavement aimed at improving the hot environment such as water retaining block pavement, evaluation by questionnaires and Wet Bulb Globe Temperature (WBGT) etc. has been done[3].

However, the questionnaire is a subjective evaluation, and it is difficult to compare the measurement results under different environmental conditions. Furthermore, although WBGT has been reported to be consistent with human physiological reaction (hereinafter "physiological responses"), it was an indicator to evaluate the stress on the human body indirectly from environmental physical quantities such as temperature, relative humidity, heat radiation, and air flow, so physiological responses and the differences thereof, such as clothing effects (clothing color and clothing amount), are not taken into account[6]. In other words, these indicators do not directly evaluate the stress on humans based on the actual environment in some cases. Therefore, we consider that these indicators do not sufficiently express the effect of "human friendliness" that water retaining pavement can provide. Based on the above, the authors decided to evaluate the human friendliness of water retaining block pavementwith a more compelling and direct indicator. Specifically, in addition to the environmental physical quantity used for the calculation of the existing metrics, we measured human physiological quantities such as body temperature, perspiration and metabolic rate and utilized the human thermal load calculated from the measured values to compare the hot environment on water retaining block pavement (hereinafter "WR") and on conventional dense-graded asphalt pavement (hereinafter "AS") . The results show that the human thermal load of WR was significantly smaller compared to AS (significance level of 5% or less), and it was confirmed to also be a human-friendly pavement from the point of view of human physiological response.

In this paper, we provide an overviewof the WR and describe the human thermal load used as an indicator of the hot environment, and report the outline of the experiments carried out indoors and outdoors and their results.

2. Overview of water retaining block pavement (WR)

WR is pavement on which water retaining blocks are laid, and it is a unique paving technology of Japan aimed at suppressing the rise of road surface temperature. A water retaining block is a block having fine voids that hold rain water (water retention capacity of 15% or more of the block volume). Since the general dimensions of the water retaining block are: length × width = 30 × 30 cm or 10 ×20 cm, thickness = 6 or 8 cm, if thickness is 6 cm, 9 L/m² and if thickness is 8 cm, 12 L/m² or more water can be retained. The block may be made of concrete or ceramic.

04_ Benefit of BP

When WR holds water in the pavement due to precipitation, it deprives the heat of evaporation from the road surface when the water evaporates for about two days, and it maintains the effect of suppressing the rise of the road surface temperature. It also has a brighter color and lower albedo than general black AS, which facilitates to prevent heat accumulation in the pavement.

WR is generally applied not to roadways, but to sidewalks, and aims to ease a harsh hot environment in summer and provide a comfortable space for pedestrians.

Since water retaining blocks also havewater permeability in addition to water retention performance, they retain water in the voids in the block, but excess water permeates into the sand layer and crushed stone layer under the block. Therefore, it is difficult for water to pool even in the rain, and it can provide comfortable walking.

Furthermore, because water retaining blocks have plenty of color variations, they match the surrounding landscape and contribute to improving the landscape.

The standard performance of water retaining blocks is shown in Table 1, and the standard cross section of WR is shown in Figure 1.

Since WR cannot exhibit the effect of suppressing the rise of the road surface temperature when the blocks aredry, in some cases, pipes are installed in the sand layer under the blocks in order to supply water and efficiently exhibit the effect of reducing the road surface temperature. The cross section in this case is shown in Figure 2.

Table 1. Standard performance of water retaining blocks*1

Water retention amount※2	(g/cm^2)	0.15 or more
Bending strength	(N/mm^2)	3.0 or more
Suction height※3	(%)	70 or more

*1. According to the recommended specification of JIS A 5371 Annex.

*2. The maximum amount of water that can be retained in the unit volume of the block.

*3. Wb/Wa(%): Ratio of the amount of water (Wb) absorbed and retained in the absolutely dry block by immersing it in the water of only 5 mm from the bottom of the block for 30 minutes with respect to the maximum amount of water that can be retained in the block (Wa).

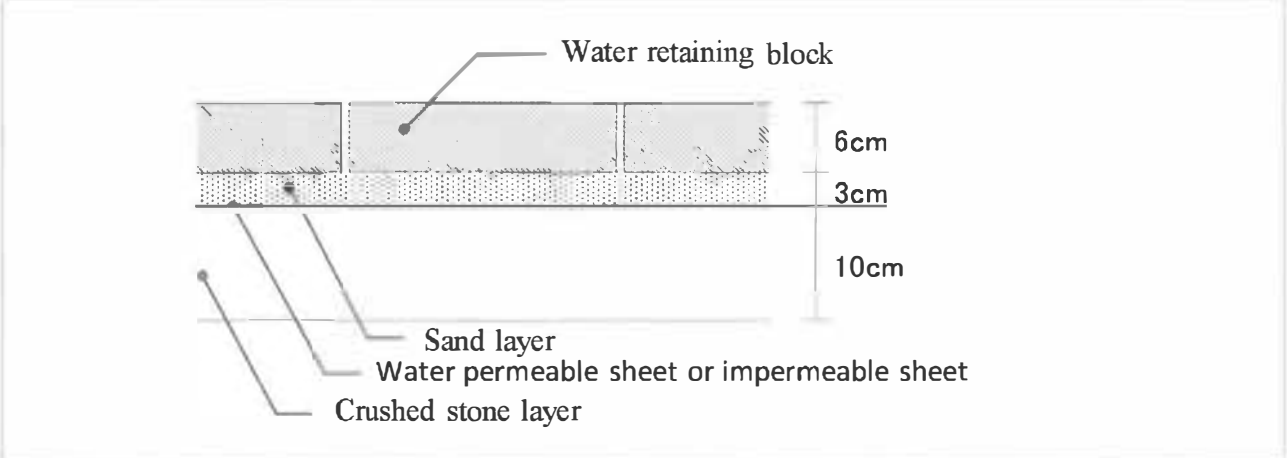


Figure 1. Standard cross section of water retaining block pavement

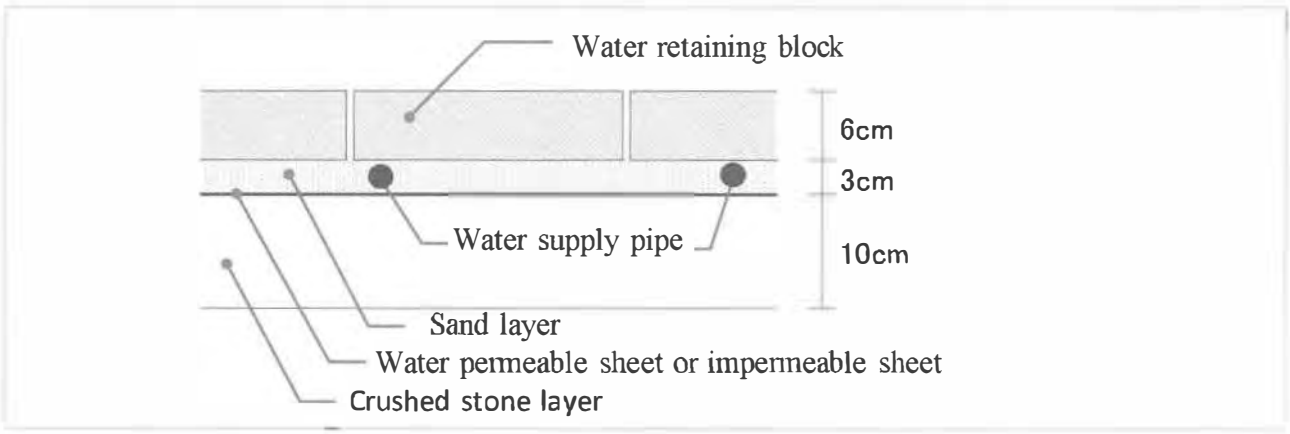


Figure 2. Standard cross section of water retaining block pavement (water supply pipe installation type)

3. Research Overview

In this study, the human thermal load was determined by measuring environmental physical quantities and human physiological responses on WR and AS both indoors and outdoors to directly evaluate the effect of improving the hot environment of WR to humans. Furthermore, the indoor experimentwas performed in an artificial climate chamber capable of keeping environmental conditions such as the surrounding temperature, humidity, wind velocity, and amount of solar irradiation constant to evaluate the effect of improving the hot environment of WRin a similar environment. In addition, the outdoor experiment was also performed to evaluate the effect of improving the hot environment of WR under the in-service condition of actual pavement. The evaluation of thermal sensation by questionnaire was also performed at the same time to confirm the relevance of the human thermal load to human sensation.

3.1 Outline of Human Thermal Load

The human thermal load used as an evaluation index in this study represents the energy balance of humans using formula (1), while taking into account environmental physical quantities such as temperature, humidity, radiation dose (radiation amount) and air flow; human physiological quantities such as body temperature, perspiration and metabolism; and amount of clothing[4]. Figure 3 shows the outline of human thermal load.

$$F_{\text{load}} = M - W + R_{\text{net}} - C - E \quad (1)$$

The formula is defined as follows:

Fload : Human thermal load [W/m²]
M : Metabolic rate [W/m²] (calculated from body surface area, O_2 intake, CO_2 production)
W : Work load [W/m²] (the amount of external work that the human body does)
Rnet : Net radiation [W/m²] (the amount of solar radiation and infrared radiation that the human body gives and receives)
C : Sensible heat loss [W/m²] (heat loss due to the difference between the mean skin temperature and atmospheric temperature, and the heat exchange by respiration)
E : Latent heat loss [W/m²] (heat loss due to sweating, expiration and insensible perspiration)

The human thermal load indicates that humans feel hot when heat dissipation from the human body is less than the heat that the body receives externally (human thermal load: large), and that humans feel cool when the heat dissipation is greater (human thermal load: small).

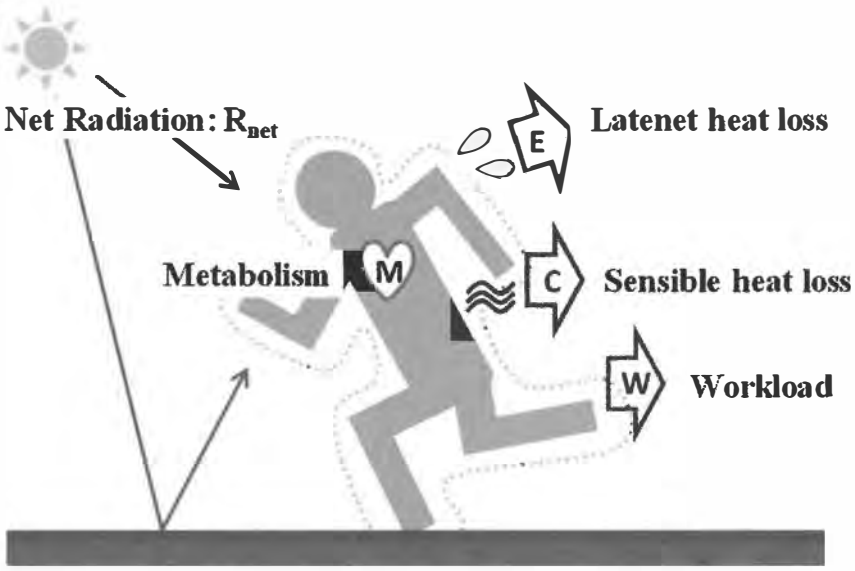


Figure 3. Outline of human thermal load

In other words, we can conclude that when the amount of heat received from the pavement is relatively small, the human thermal load is reduced and humans feel cooler. Since the research participants were standing still in this experiment, the work load W is treated as 0, but it is also possible to do the evaluation while the participants are in motion.

3.2 Measurement Items and Methods of Measuring Environmental Physical Quantity and Human Physiological Quantity

Table 2 and 2 show the measurement items and methods of measuring the environmental physical quantity and human physiological quantity that are necessary to obtain the elements (M, W, Rnet, C, E) used for calculating the human thermal load represented by formula (1). Figure 4 also shows the measurement setup. Actual human physiological quantities are measured from the participants such as seven points of skin temperature, rectal temperature, seven points of perspiration, heart beat rate and metabolic rate (see Table 3). The net radiant (Rnet) was determined by measuring the longwave and shortwave from six directions using a long-short radiometer (two directions vertically, and four directions horizontally). This is for ascertaining the direction of radiation to determine the influence of longwave radiation and shortwave radiation on the human body from the pavement (mainly from below) and solar radiation (mainly from above) separately. Incidentally, it is not possible to evaluate the direction of radiation with WBGT, which is used to calculate the amount of WBGT radiation. In addition, the participants ingested 200 ml of sports drink prior to the experiment, and the experiments were started more than two hours after a meal in order to eliminate variations in metabolism. The physical characteristics of the participants are shown in Table 4

Table 2. Measurement items and methods of measuring environmental physical quantities

Measured Item	Procedure	Instrument	Measurement interval
Radiation balance (Long-, and Short-wave radiation)	Six directions at 1.5 m (North, south, east, west, above, and below)	Radiometer; EKO MR-60, Cambell Scientific NR01	Every 1 min
Temperature and humidity	Five points in vertical direction (at 0, 0.35, 0.5, 1.0, and 1.5 m)	Pt-100 resistance and capacitance hygrometer; T and D TR-73U, Shinyei Technology THP-728	
Wind velocity	3D wind profile at 1.5 m	Ultrasonic anemometer"GYoung CYG-81000	
Ground surface temperature	Five points (the center, and 0.5 m distant from the center in north, south, east and west direction)	Thermocouple J type	

Table 3. Measurement items and methods of measuring human physiological quantities

Measured Item	Procedure	Instrument	Measurement interval
Body temperature	Seven point at skin (Head, upper arm, hand, abdomen, thigh, leg, and foot), and rectum	Thermistor; Nikkiso Thermo N542	Every 1 min
Sweat evaporation	Seven point at skin Head, upper arm, hand, abdomen, thigh, leg, and foot) Weight loss (human and clothes)	Hygrometer; SysCom Corporation SHTDL-3 Weight scale; A and D FG150KBM and Shimadzu ELB3000	
Heart rate	ECG signal from chest	Heat rate meter; Polar RS800CK	
Metabolism	O_2 intake and CO_2 exhaust	Gas analyzer; S and ME VO2000	Every 20 sec

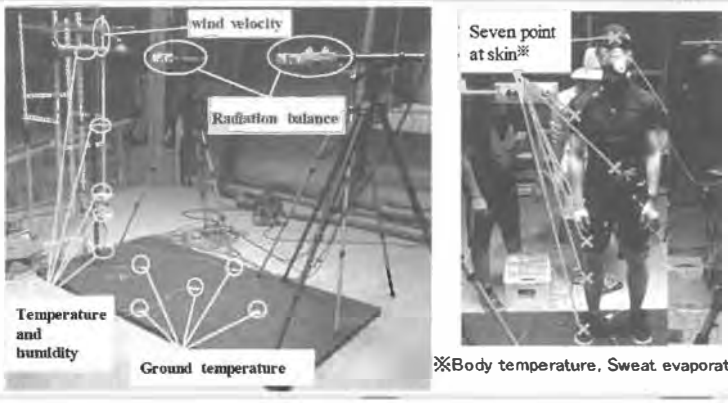


Figure 4. Measurement setup for environmental physical quantities and human physiological quantities

Table 4. Physical characteristics of the participants.

Height(cm)	171±4
Weight(kg)	62.2±5.3
age(year's old)	224±0.9

4. Indoor Experiments in an Artificial Climate Chamber

4.1 Experiment Outline

The environmental setting of the artificial climate chamber is as shown in Table 5 with a summer day in Japan taken as the weather condition.

The size of the pavement used in the experiment of AS and the WR are both 1 m by 2 m, and the measurement of environmental physical quantity and human physiological quantity and the evaluation of thermal perceptions by questionnaires were performed on the pavement (Total participants: 28). Figure 5 shows the schematic and experimental conditions of the artificial climate chamber, while Table 6 gives a summary of the AS and the WR used in this experiment. Watering was done as appropriate during the experiment on the WR surface to retain the wet state constantly.

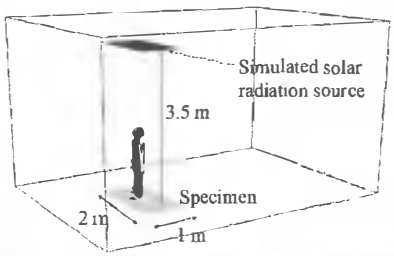
Table 5. Artificial climate chamber environment settings and measured values.

Measured Item	Setting value	Measurement value		
		Average	Max	Min
Air temperature[°C]	35	36.2	40.0	29.8
Humidity[%]	50	43	57	32
Radiation [W/m^2]	900	895	921	865

Table 6. Summary of paving materials

Types of pavement	AS	WR
Thickness of specimen [m]	0.04	0.09(Block : 0.06, Laying sand : 0.03)
Surface color	Black	White
Percentage of reflected Solar radiation [%]	8.5	25.0
Maximum water retention capacity [kg/m^2]		8.76

(a) Schematic view of experimental site.



(b) Experimental setting.



Figure 5. Schematic and experimental conditions of the artificial climate chamber



4.2 Experiment Results

We expressed the results of physiological response and questionnaire using the average value of the measurement results of all participants. In addition, we did statistical processing by using a t-test with two samples assuming equal variances, and the significance level was set to 5% or less. Incidentally, we also noted the air temperature and relative humidity on the pavement in the vertical direction, which are generally measured as an evaluation of the performance of WR.

(1) Environmental Physical Quantity

Among the environmental physical quantities, the measurement results of the pavement surface temperature and the radiation amount are shown in Table 7 and the measurement results of temperature and humidity in Figure 6. As shown in Table 7, the pavement surface temperature of WR was 20.0°C lower than AS. In addition, the amount of longwave radiation from below was reduced by 11 W/m^2. Meanwhile, the amount of shortwave radiation from below increased by 18 w/m^2. The significance level of each result was 1%. It is assumed that the low pavement surface temperature affected the longwave radiation amount and the high solar reflectance affected the shortwave radiation amount. Furthermore, as shown in Figure 6, the air temperature of the WR was about 2°C lower regardless of the measurement position. Meanwhile, the humidity of WR was 7.7% higher than that of AS in the vicinity of the pavement surface, but the humidity difference roughly 1.5 m above the ground was 1.3% smaller.

Table 7. Average value of environmental physical quantity

Measured Item	Average	
	AS	WR
Ground Temperature[°C]	55.4	35.4
Longwave radiation From below[W/m^2]	581	570
Shortwave radiation From below[W/m^2]	28	46

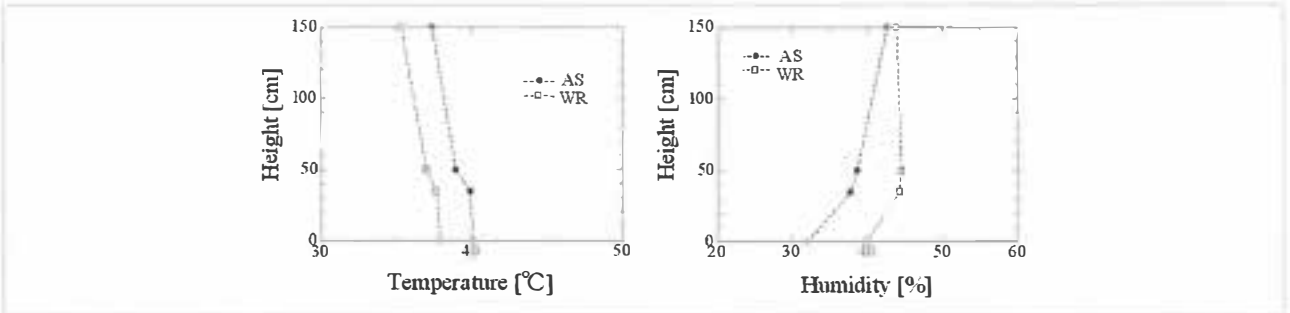


Figure 6. Distribution of temperature and humidity

(2) Human Thermal Load

Table 8 shows the measurements of physiological responses and the calculation results of the human thermal load. The human thermal load of WR was 224 W/m^2, which was 78 W/m^2 smaller than that of AS at 302 W/m^2 and a significant difference was observed (significance level 1%). This was found to be due to the large amount of metabolism in the AS and the net radiation. In the WBGT index measured simultaneously (1.5 m point), AS was 32.9°C while WR was 31.3°C (i.e., WR was 1.6°C lower.)

Table 8. Physiological response and human thermal load

Physiological response	AS	WR
Metabolic rate : M[W/m^2]	89	83
Net radiation : Rnet[W/m^2]	243	173
Sensible heat loss : C[W/m^2]	2	3
Latent heat loss : E[W/m^2]	28	29
Human thermal load : Fload[W/m^2]	302	224

5. Outdoor Experiment

5.1 Experiment Outline

Outdoor experiments were performed on the AS and WR measuring 7 m by 7 m built in the Okayama Prefectural University campus in Okayama Prefecture, which is located in western Japan.The test was implemented over five days in August 2016, with a total numberof 30 participants. The summary of the paving material is the same as Table 2. The measurement time was from 10 a.m. to 4 p.m. each day. The measurement results of the environmental physical quantity during the measurement period are shown in Table 9, andthe schematic and experimental conditions study site are shown in Figure 9. In the outdoor experiment, two participants performed on adjacent pavements at the same time, as shown in Figure 9. In addition, similar to the indoor experiment, water was sprayed on the WR surface as needed, and WR was kept wet at all times during the experiment.

Table 9. Environment measurements in the outdoor experiment

Measured Item	Measurement value		
	Average	Max	Min
Air temperature [°C]	33.2	36.1	28.4
Humidity [%]	52	82	33
Radiation [W/m^2]	583	1175	139

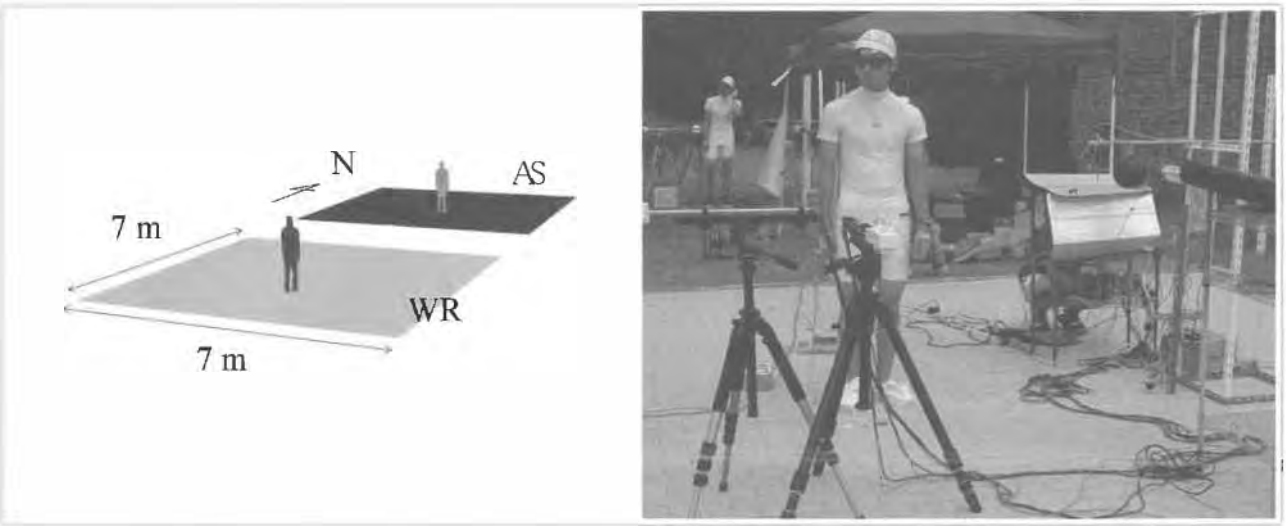


Figure 7. Outline and the experimental condition of the outdoor experiment



5.2 Experiment Results

We conducted statistical processing on the results of the outdoor experiments in a similar manner as the indoor experiments.

(1) Environmental Physical Quantity

The mean values of the environmental physical quantities are shown in Table10. From the table, the average pavement surface temperature of WR was 9.5°C (minimum 2.7°C and maximum 18.9 °C) lower than that of AS. Accordingly, the average value of longwave radiation from below was 77 W/m² smaller (minimum 20 W/m² and maximum 281 W/m² with a significance level of 1%). Meanwhile, the average value of shortwave radiation from below in WR was 112 W/m² larger compared to AS (significance level of 1%).

Table 10. Average value of environmental physical quantity

Measured Item	Average	
	AS	WR
Ground Temperature[°C]	50.2	40.7
Longwave radiation from below[W/m²]	620	543
Shortwave radiation from below [W/m²]	49	161

(2) Human Thermal Load

Table 11 shows the measurements of physiological responses and the calculation results of the human thermal load. The human thermal load of WR was 215 W/m², which was 22 W/m² smaller than that of AS at 237 W/m², and a significant difference was observed (significance level of 5%). It was found that this is due to the particularly small longwave radiation amount from the pavement of WR out of the net radiation amount (amount of solar radiation and infrared radiation that the human body gives and receives). In the WBGT index (1.0 m point), AS was 30.2°C while WR was 29.1°C (i.e., WR was 1.1°C lower than AS.)

Table 11. Physiological response and human thermal load

Physiological response	AS	WR
Metabolic rate : M[W/m²]	87	87
Net radiation : Rnet[W/m²]	193	181
Sensible heat loss : C[W/m²]	15	18
Latent heat loss : E[W/m²]	29	35
Human thermal load : Fload[W/m²]	237	215

6. Summary

With the new indicator of human thermal load, which is calculated by adding the human physiological quantity to the evaluation using environmental physical quantity that has been generally carried out so far, we compared and evaluated the effect of improving the hot environment of WR both indoors and outdoors (i.e., its human friendliness) with AS.

The findings obtained by the experiment are described below.

04_ Benefit of BP

(1) The results of measuring the environmental physical quantities in indoor and outdoor experiments show that the pavement surface temperature of WR is 10 to 20˚C lower than AS. As a result, the longwave radiation from the pavement surface of WR becomes smaller than that of AS. On the other hand, the shortwave radiation amount of WR became larger than AS due to the influence of solar reflectance.

(2) The human thermal load of WR was smaller than that of AS for both indoor and outdoor experiments and it can be concluded that it is a human-friendly pavement in hot environment. We discovered that the influence of decreasing metabolic rate and net radiation was great.

(3) It is possible to quantitatively determine that WR is a human-friendly pavement with a small heat load on the human body, based on the index of human thermal load. We have also determined its effectiveness.

7. Conclusion

In this study, we evaluated the effect of improving the hot environment of WR using the human thermal load index, which is directly added to the physiological response of humans through human subject research. As a result, it was once again possible to verify that WR is a human-friendly pavement. Since this experiment is a new attempt to evaluate the effect of improving the hot environment of pavements that suppress the rise of road surface temperature, the number of participants is not large and the age composition is relatively limited. Going forward, we will further proceed with the experiments while taking into consideration the age of participants, the presence or absence of exercise, etc., and we intend to conduct verification under various situations. We hope this paper will help to promote the spread of pavements that suppress the rise of road surface temperature including WR and provide ideas to improve the environment in other countries with hot environment problems that are similar to Japan.

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