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RELATIONSHIP BETWEEN SURFACE PROPERTIES AND SLIP RESISTANCE OF WALKWAY PAVING MATERIALS

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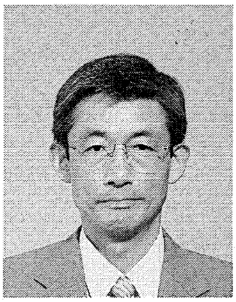

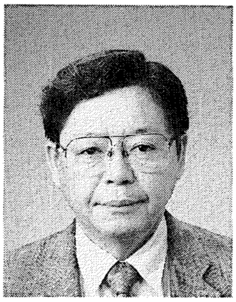

Harumi KUGE Katsuro KOKUBU

Accidents involving elderly people who slip on walkways are common. However, there has been little study of the slip resistance of walkway paving materials. In this study, we investigate the walking characteristics of elderly people and look into the porous properties, surface texture, and general slip resistance of various paving materials under several surface conditions. We found that an average inclination reflects surface texture of paving materials; that surface water absorption and surface texture correlate strongly with slip resistance; and that an O-Y・Pull Slip Meter is a good tool for measuring the slip resistance of walkway paving materials. Finally, we consider the coefficient of resistance of paving materials and make proposals with respect to anti-slip paving materials.

Key Words: paving materials, walkway, slip, slip resistance, coefficient of friction, surface texture, surface conditions, elderly people

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1. INTRODUCTION

In recent times, a variety of new paving materials have been developed for use on pedestrian walkways, and these offer improved aesthetic performance and a more pleasant environment. Pedestrian walkways aim to offer amenity to pedestrians full of friendship, flavor and energy as well as safety and comfort when walking [1]. Good walkability depends on moderate elasticity, slip resistance, and good surface permeability. Elderly people are prone to falls when the walkway slip resistance declines, especially as a result of deteriorating surface permeability.

According to the results of a survey into self-induced accidents and non-injury falls among elderly people aged 60 and upward, of outdoor accidents that occur on roads and in public spaces (station plazas, bus stops, etc.), falls account for about 70%, followed by slipping at about 20% [2]. Thus, these two causes account for most of all accidents. Self-induced accidents are those in which an elderly person suffers injuries due to a fall that involves no third party, while a non-injury fall is a tumble or fall that does not lead to injury.

Many past studies of walkway slip have investigated methods of testing slip and determining standard values of skid resistance. It is thought important to also consider the physical characteristics of walking, pavement material properties, and the characteristics of surfaces when wet and contaminated. However, only a few reports have examined these factors synthetically. With the aim of determining the properties required of safe and reliable pavement materials, the authors implemented this study in the hope of avoiding slip- and fall-related injuries among elderly people. Slip was studied synthetically through tests of walking characteristics to determine the physical characteristics of walking, investigations of surface geometry and water absorption (as properties of paving materials), and the changing slip resistance of paving surfaces under dry, wet, and mud-contaminated conditions.

2. WALKING ANALYSIS

(1) Test Outline

Since the elderly are particularly prone to accidents causing self-injury as a result of falling and slipping while walking, the authors examined anti-slip pavement materials and the walking characteristics of elderly people on anti-slip pavement materials. Foot velocity and the force exerted by the foot on the floor while walking were adopted as the walking characteristics to be measured.

(2) Analysis Method

a) Walking Analysis Equipment
To analyze walking characteristics, the ELITE three-dimensional motion analyzer and a torsion-gauge three-component floor reaction meter were used. The three-dimensional motion analyzer records the movements of reflective markers attached to the test subject using four infrared cameras, and uses the resulting data to calculate three-dimensional spatial positions. The three-component reaction meter is used to find the vertical force, Fy, exerted by the feet while walking. The horizontal force, Fx, along the walk axis and the horizontal force, Fz, perpendicular to the walk axis can also be measured (see Fig. 1). In this study, the value obtained by dividing Fx by Fy is defined as the ratio of frictional force, as indicated by Equation (1). The bed of the floor reaction meter is of hard rubber.

$$\text{Frictional force ratio} = | Fx / Fy | \tag{1}$$

b) Test Subjects
The test subjects were 10 men and 10 women in their 60s. A further five men and five women in their 20s were also investigated for comparison. The average age of the older group was 64.2, while that of the younger group was 24.3. Though the elderly are generally defined as those aged 65 and older, and there is a need to study the behavior of even older people, the survey was restricted to those in their 60s, and people in their 70s and over were omitted. Men and women were chosen so as to allow for comparison of the sexes.

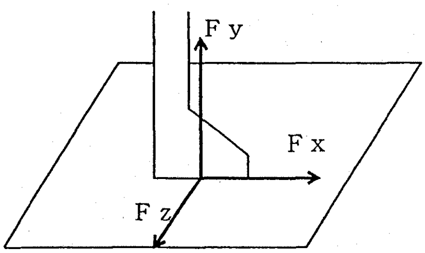


Fig.1 Three Components Measured by Floor Reaction Meter

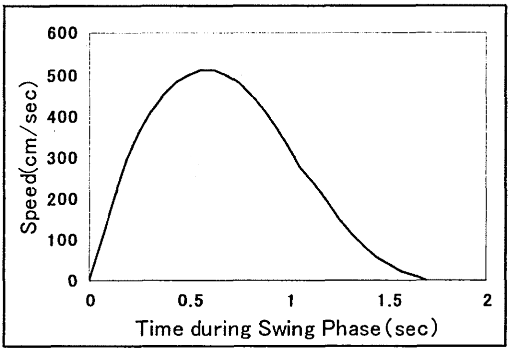


Fig.2 Sample of Changes in Speed of Toe Tips during the Swing Phase of a Step

c) Shoe Type

The subjects wore sneakers in the tests. This is because the elderly wear sneakers more commonly than leather shoes. Also, the same type of shoes could be supplied to all subjects, as sneakers are available in a greater range of sizes. Sizes ranging from 22 cm to 27 cm in size at 0.5 cm intervals were readied for the tests. The soles of these sneakers were of a material comprising natural rubber and synthetic rubber in equal ratios.

(3) Results and Consideration

a) Walk Characteristics

Changes in speed of the toe tips during the swing phase of a step, between the toes leaving the floor and the ankle touching the floor are shown in Fig. 2. This is a sample of data from the elderly subjects and indicates horizontal speed in the walking direction. Examples of the vertical force exerted by the foot on the floor, the horizontal force exerted in the walk direction, and the friction force ratio during the contact phase of a step, between the ankle reaching the floor and the toes leaving the floor, are shown in Fig. 3. Only the horizontal force in the walk direction is taken into account, because the force in the perpendicular direction varies greatly between test subjects and is quite small in comparison to that in the walk direction even at its largest.

The toes accelerate rapidly after leaving the floor before falling to almost zero just before the ankle touches the floor. Changes in speed of the ankle should be taken into consideration in the evaluation of slipping when attempting to stop. However, the speed of the toes is adopted as a measure here because ankle speed changes were not measured and the difference in speed in the walk direction is thought to be small. The friction force ratio acting while stopping is closer to the static value than the dynamic value because speed in the walk direction is almost zero at the point where the heel is about to touch the floor. R. Brungraber also reports that slippage between the foot and the floor while walking is dominated by the static friction coefficient, though the dynamic friction coefficient needs to be taken into consideration when the foot begins to slip [3].

A force is exerted during walking when the foot is in contact with the floor, as indicated in Fig. 3, and it is static when the friction force ratio reaches a peak. The vertical force and the friction force ratio rise to two peaks during the contact phase. The first peak occurs when the ankle touches the floor, while the second arises during the pushing motion as the toes leave the floor. The friction force ratio is larger while pushing off than when contact is made, and this tendency is common to all test subjects.

Both vertical and horizontal forces tend to be larger as the heel comes to a halt on the floor than during pushing off. As the heel touches the floor, the body's center of gravity shifts over the whole ankle. Once it comes into contact with the floor, the vertical force reaches a peak and then the horizontal force reaches a peak. During pushing off, the horizontal force reaches a peak as the body's center of gravity moves over the toes, and the vertical force then reaches a peak. Thus, the vertical and horizontal forces reach their maxima at different times. The time-lag between them is greater during pushing off. In consequence, the friction force ratio, or the ratio of horizontal force to vertical force, generally tends to be larger during pushing off than as heel contact is made. If the coefficient of friction between the foot and the floor surface is less than the friction force ratio during walking, then the horizontal resistance between the soles and the surface is lower than the horizontal force in the walking direction, and slipping occurs. Thus, pushing off is the more dangerous motion from the viewpoint of friction force ratio. However, the shift in the center of gravity of the body needs be taken into consideration when looking at falls due to slipping. In this light, slipping during stopping is thought to be more dangerous because, when pushing off the center of gravity is shifting toward the other foot, whereas in the contact phase the center of gravity is over the heel that is coming to a halt on the floor. It is safer that larger friction force ratio during pushing is taken into consideration.

b) Friction Force Ratio

Table 1 shows average values of friction force ratio for each test group, the standard deviations (σ), and the 90% reliability section of average values.

The average value of friction force ratio is smaller for elderly people than for younger, both during pushing off and contact from one side official approval of 5 % risk ratio. Accordingly, the young tend to slip more easily, but the elderly suffer more accidents through a lack of physical strength and agility. There is no significant difference between friction force ratios measured for elderly men and elderly women, either during pushing off or contact, from one side official approval of 5 % risk ratio.

Since both the floor surface (the surface of the reaction meter used in the test) and the test subjects' soles were of rubber, which tends to inhibit slipping during walking, it can be considered that horizontal forces during the walking tests were measured without loss. Therefore, the friction force ratios obtained in this walk analysis should be treated as maxima for the ideal combination of materials. The frictional coefficient of an actual road surface needs be greater than the friction force ratio in order to ensure that slipping does not occur. Slipping can occur both during pushing off and heel contact, but the required frictional coefficient at the road surface can consider that needed to prevent slipping during pushing off, as the friction force ratio is less during heel contact. Phenomena does not occur when deviation is larger than 3 σ in normal distribution but the elderly are highly likely to experience accidents due to slipping on road surfaces. The required frictional coefficient, assuming the average value plus 3 σ for safety, is 0.42 or more. The value is 0.43 or more for young people, so a suitable frictional coefficient for a slip-free road surface should be approximately 0.45.

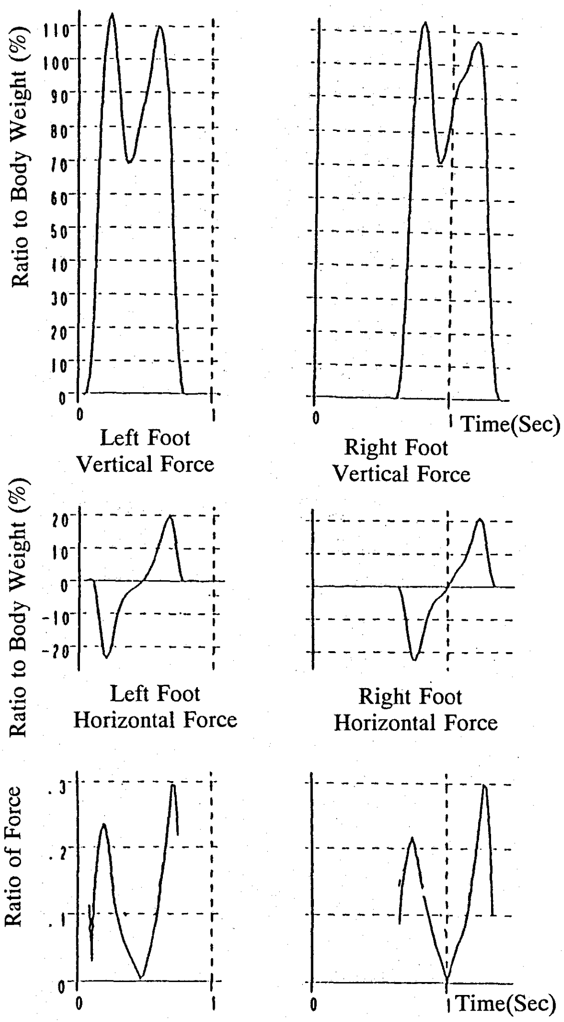


Fig.3 Examples of Vertical Force, Horizontal Force, and Friction Force Ratio

Table 1 Friction Force Ratio of Each Test Group

Test Group			Friction Force Ratio		
			Average	Standard Deviation	90% Reliability Section
Stop-ping	Elderly	Total	0.204	0.025	0.194 ~ 0.214
		Men	0.213	0.023	0.199 ~ 0.227
		Women	0.195	0.023	0.181 ~ 0.209
	Young	Total	0.231	0.015	0.222 ~ 0.240
Push-ing	Elderly	Total	0.306	0.038	0.291 ~ 0.321
		Men	0.304	0.036	0.282 ~ 0.326
		Women	0.308	0.040	0.284 ~ 0.332
	Young	Total	0.340	0.028	0.323 ~ 0.357

3. Properties of Paving Materials

(1) Outline of Experiment

Slipping while walking outdoors is considered to be greatly influenced by the surface geometry of the paving material, and in particular by height changes and the steepness of surface variations. Also, since paving materials become dirty and wet outdoors, and slipping then becomes a lubricated friction problem, the water absorption of paving materials is also considered important. Thus the water absorption and surface geometry of paving materials were measured.

(2) Material Property Test Method

a) Materials Used

The paving materials used for tests consisted of commonly used sidewalk materials and a new material in test production. The conventional materials included four types of cement concrete, one asphalt concrete, two types of baked earth, and two types of natural stone for a total of nine surface types. In measurements of the micro surface geometry of these common paving materials, the surface geometry of a concrete block pavement where the granite surface aggregate had been exposed by washing was very large. One of the other materials indicated a particularly small surface geometry. Those paving materials with a moderate surface geometry were test-produced and used in experiments. The test-produced material was concrete. The paving materials used for the tests are listed in Table 2.

b) Method of Material Characteristic Testing

The properties listed below were evaluated as a measure of the characteristics of the paving materials.

① Apparent density: apparent density (g/cm3) measured by density test method for compacted asphalt mixtures [4]

② Water absorption: water absorption measured by the gravity and water absorption test method for coarse materials [5] after immersing a 10 × 10 cm cut specimen for 24 hours. Water absorption is expressed as a value per unit volume and evaluated regardless of the characteristics of the paving materials.

③ Surface water absorption: Surface absorption is the amount of water absorbed through a unit surface area (g/cm 2) measured after applying a 15-cm water head for 24 hours on a 9-cm diameter area of the top surface of the material. The test method used was devised during the course of this study.

Table 2 Paving Materials used for Tests

Type		Mark	Characteristics	Size(mm)
Materials Normally Used	Cement Concrete	CP	Concrete block by normal curing	300 × 300 × 60
		CS	Concrete block with chippings of granite	300 × 300 × 60
		CW	Concrete block with top aggregate of granite exposed by washing	300 × 300 × 60
		CL	Concrete block by instant demolding	297 × 197 × 80
	Asphalt Concrete	AC	Asphalt concrete block	300 × 300 × 50
	Baked Earth	BL	Brick for paving	234 × 115 × 60
		TP	Porcelain tile for paving	300 × 300 × 17
	Natural Stone	RN	Granite plate with surface dressed by hammer	300 × 300 × 45
		RA	Granite plate with surface finished by burning	300 × 300 × 45
Materials by Test Production	Cement Concrete	NF	Concrete block with surface finished by shot blasting after 2 days of curing	300 × 300 × 60
		BF	"NF" dressed by hammer	
		KF	"NF" dressed by 2 types of hammers	
		SC	Concrete block with 1.2 ~ 0.6mm chippings	
		LC	Concrete block with 2.5 ~ 1.2mm chippings	

④ Pore structure: the distribution of pores 0.2 - 7.5 mm in diameter was measured using a mercury porosimeter at a mercury pressure of 6.5 kPa - 200 Mpa. This yielded the total pore volume (ml/cm3) and average pore diameter (μ m) [6]. Test specimens measuring 3-5 mm in diameter were cut from the surface of the paving materials for this test.

c) Method of Surface Geometry Testing

A method in which the height variation of surface roughness is measured to obtain an average roughness, much like a Doken-type roughness meter [7], is typically used in the field to measure the surface geometry of roads. Also possible is measurement of micro surface geometry by observations using a microscope [8]. Neither was practical in this case, so surface geometry was measured using two laser-based methods. Such non-contact methods of measuring surface roughness have become quite simple recently, using high-precision laser displacement meters.

① Laser displacement measuring device

A laser displacement measurement system was trial-produced for this study. The surface of the sample is irradiated almost perpendicularly with a laser beam, and the surface roughness of the sample is measured at 0.02-mm pitch and to an accuracy of 0.001 mm. The results are directly input into a computer. This gives the method great flexibility as regards data processing and outputs such as graphs. The measuring length was 15 cm.

② The Mini Texture Meter

The Mini Texture Meter (MTM) was developed by TRL. It measures the surface roughness of a sample at a 0.3-mm pitch and with an accuracy of 0.01 mm. The root mean square roughness is obtained. The laser strikes the surface of the sample at an angle of 45 $^\circ$, and surface roughness is measured using the laser light reflected from the surface at an angle of 45 $^\circ$

MTM is a device for measuring the surface roughness of an actual road surface over a long distance, so it is not suitable for measuring the surface roughness of samples such as used in this study. However, surface roughness measurements were obtained by repeatedly evaluating samples up to an equivalent length of 10 m.

(3) Results and Discussion

a) Material Characteristics

The results of the material characteristic tests are shown in Table 3. Incidentally, only density of the trial production material was measured because it is made of cement concrete to obtain medium surface roughness and the water absorption is considered similar to that of concrete flags normally used for paving sidewalks.

Table 3 Material Characteristics of Paving Materials

Paving Materials	Density (g/cm^3)	Water Absorption (g/cm^3)	Surface Water Absorption (g/cm^2)	Total Pore Volume (ml/cm^3)	Average Pore Volume (μ m)
CP	2.26	0.112	0.432	0.0824	0.061
CS	2.30	0.094	0.208	0.0357	0.037
CW	2.32	0.080	0.241	0.0102	0.545
CL	2.31	0.077	0.626	0.0931	0.044
AC	2.36	0.006	0.134	0.0047	0.216
BL	2.15	0.071	0.053	0.0569	0.226
TP	2.29	0.011	0.019	0.0174	0.263
RN	2.60	0.014	0.035	0.0117	0.970
RA	2.60	0.014	0.014	0.0117	0.970
NF	2.38	—	—	—	—
BF	2.38	—	—	—	—
KF	2.37	—	—	—	—
SC	2.41	—	—	—	—
LC	2.41	—	—	—	—

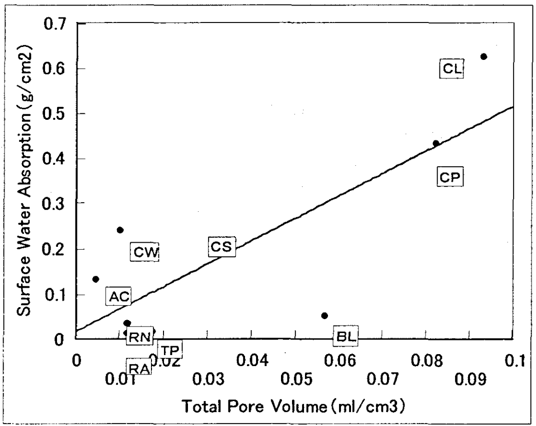


Fig.4 Correlation between Total Pore Volume and Surface Water Absorption

The correlation between total pore volume and surface water absorption is shown in Fig. 4. Absorption by cement concretes is generally large, while asphalt concrete, porcelain tile for paving, and granite tiles exhibit little absorption. The surface water absorption of concrete blocks made by instant demolding is little considering their total pore volume. The reason for this is that the pore volume of the mortar used as the surface course is greater than that of the ultra-stiff concrete used for the base course. Paving materials may be made of only one material, made of two layers for design reasons, or made of different materials inside and out to give different surface finishes. Brick for paving is considered to have low water absorption after surface treatment for this reason.

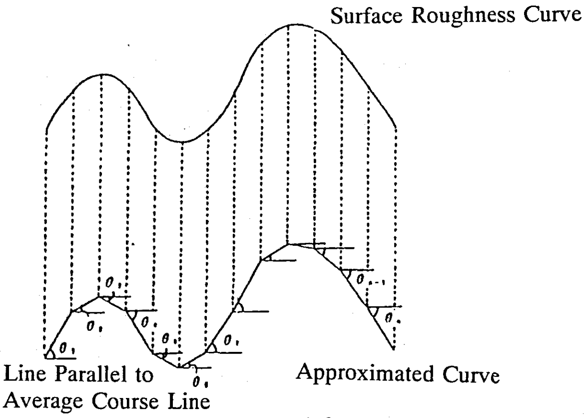
b) Representation of Surface Geometry

Two methods are used to represent the surface geometry of a road surface: one expresses longitudinal roughness in terms such as maximum height, ten-point average roughness, arithmetic average roughness, and root mean square roughness; the other expresses transverse roughness as the average roughness interval, average spacing of roughness peaks, load length ratio, and correlation length [9].

Slipping while walking outdoors is considered to be affected by height changes and the steepness of surface variations. Height changes are expressed in terms of longitudinal roughness and arithmetic average roughness or root mean square roughness in the case of the road industry. Though both these measures are considered to express height changes of paving materials well, root mean square roughness, as used more often in the road industry, is adopted in this study and referred to as the "standard deviation." Also, the steepness of surface variations is generally expressed as a transverse roughness or wavelength [10]. However, though wavelength can express the average roughness spacing, the steepness of surface variations is not large when the height variations are small even if the average roughness spacing is small, so it does not always express steepness well.

As for the steepness of surface roughness, the surface roughness curve was divided at equal intervals along the average course line and approximated to a broken line shown in Fig. 5. The gradients of these straight lines with respect to the average course line were averaged. This expresses the steepness of surface roughness and is referred to as "average gradient." When average gradient is large, roughness is sharp and the steepness is large. Goto et al. examine the correlation with slip resistance using a digital surface roughness meter by touch with needle and report that the average gradient as an index of roughness correlates well with slip resistance [11]. The average gradient is equivalent to the average gradient as adopted in this study and expresses the steepness of surface roughness. Indeed, it is called surface roughness by Goto et al.

The profiles of samples used in this study, measured by laser displacement measuring device, are shown in Fig. 6. There are two groupings in Fig. 6 with different peak surface roughness heights. The former are samples whose surface is finished by pressing (CP, CL, AC), samples whose surface are finished with chippings (CS, SC, LC), and earth-based samples fired after finishing (BL, TP). The latter are samples whose surface is roughened by washing before hardening (CW) and samples whose hard surface is planed (RN, RA, NF, BF, KF).



$$\text{Average Gradient} = \frac{1}{n}\sum_{i=1}^{n}|\tan\theta_i|$$

Fig.5 Method of Obtaining Average Gradient

Table 4 Standard Deviation(mm) and Average Gradient of Surface Roughness

Materials	Standard Deviation	Average Gradient
CP	0.042	0.128
CS	0.184	0.332
CW	1.003	0.928
CL	0.095	0.365
AC	0.246	0.524
BL	0.191	0.212
TP	0.130	0.325
RN	0.160	0.215
RA	0.277	0.357
NF	0.773	0.575
BF	0.546	0.595
KF	0.488	0.590
SC	0.154	0.590
LC	0.324	0.848

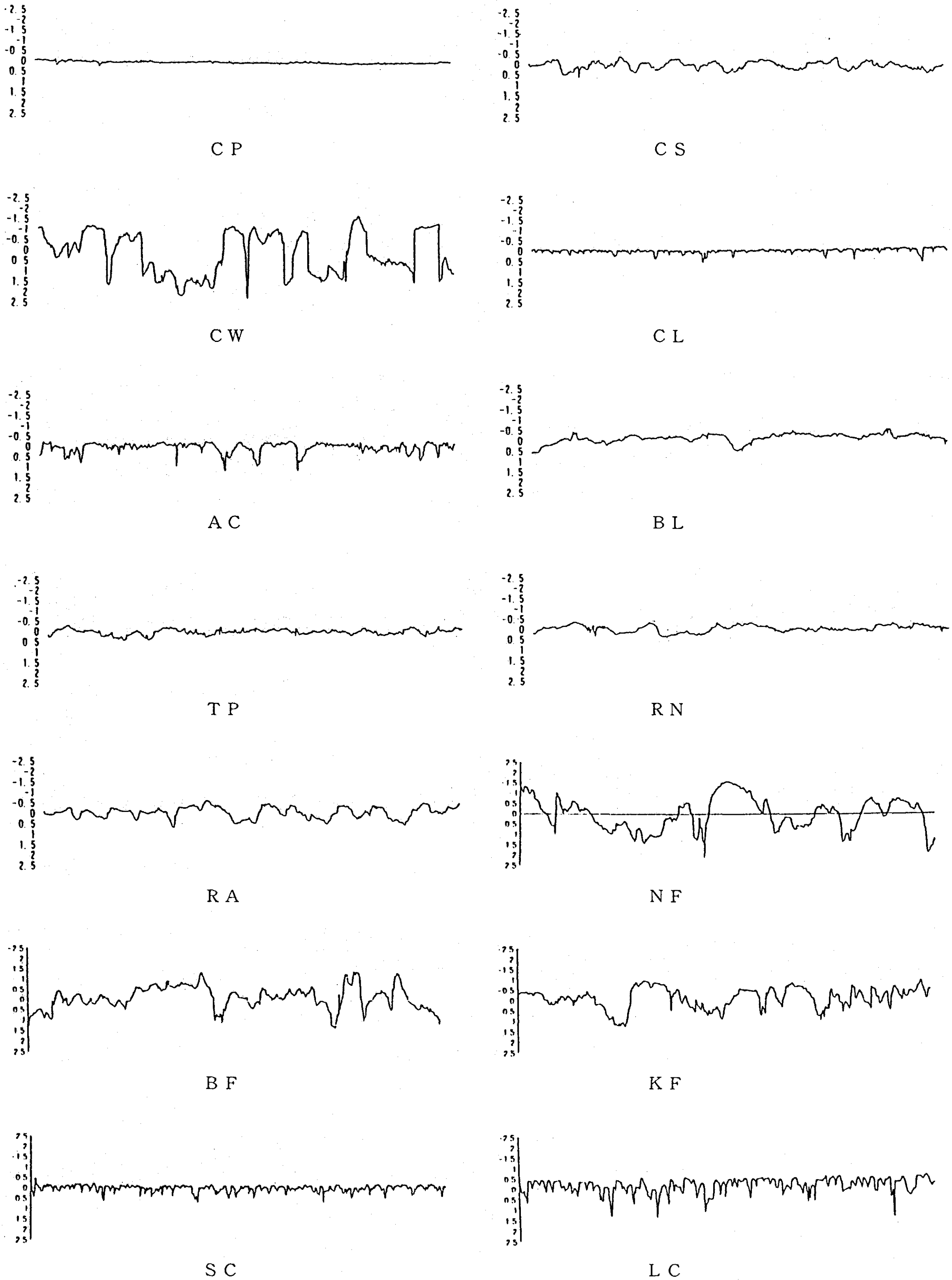


Fig. 6 Test Results of Samples' Surface Roughness (Length : 8cm, Vertical Line Unit : mm)

Surface roughness is listed in order of standard deviation and average gradient in Table 4. The pitch used for calculating surface gradients is 0.02 mm. The height difference of surface variations for CP, CL, and TP is small, while that of CW, NF, BF, and KF is large as indicated in Fig. 6. The steepness of surface variations on CP, CS, BL, TP, and RN is small while that on CW and LC is low. Therefore, the standard deviations and average gradients shown in Table 4 are taken to reflect surface geometry.

4. Evaluation of Slip Resistance

(1) Outline of Experiment

The slip resistance of typical sidewalk paving materials was evaluated by the selected three methods, and slip-free paving materials were examined in terms of their relationship with material properties. The effects of wetness and contamination on slip resistance were studied as well.

(2) Test Methods

a) Slip Resistance Test

It has been reported that slip resistance tests can be classified into ten different types according to the conditions affecting slipping [12]. Further, there is another method in which well-trained subjects walk on slippery floors and the coefficient of slip resistance is obtained from their walking pace [13]. Three methods were used in this study, as listed below. This choice was based on the fact that The British Portable Skid Resistance Tester is often used, while the coefficient of friction as obtained by Dynamic Friction Tester and O-Y Pull Slip Meter compares well with functional tests by humans.

① British Portable Skid Resistance Tester: BPST

The BPST [14], as shown in Fig. 7, is designed to determine the slip resistance value from the loss of energy due to friction between a prescribed rubber slider attached to a pendulum and the test surface. The slip resistance value is expressed in BPN. The speed of the rubber slider on the pendulum immediately before touching the test surface is 50 km/h.

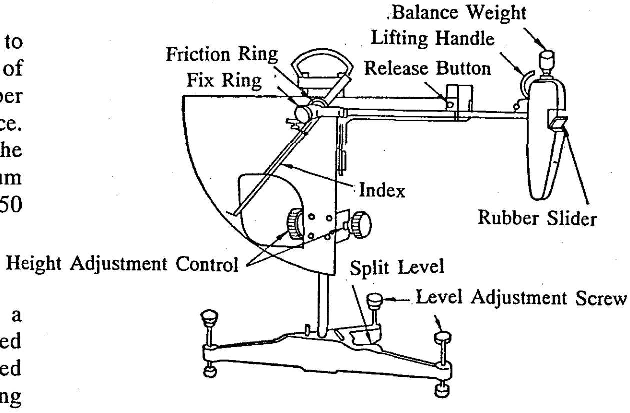


Fig. 7 Outline of BPST

② Dynamic Friction Tester: DFT

The DFT [15] [16] [17], shown in Fig. 8, is a rotary skid tester with a disk to which a prescribed tire rubber is affixed. It rotates under a prescribed vertical load, and the friction coefficient at running speeds between 0 and 80 km/h is determined from the friction force and the speed of rotation.

The theory of this measurement method is that coefficient of friction μ is obtained from the following equation when a rubber chip is forced against the test surface and rotated, and the frictional force F acting on the rubber chip is measured.

$$\mu = F / W$$

The static coefficient of friction is obtained with the DFT by measuring when a rubber chip placed on the test surface begins to move, while the dynamic coefficient of friction is obtained when the disk rotating at certain speed is brought into contact with the test surface. In this study, the frictional force ratio obtained from walking analysis is compared

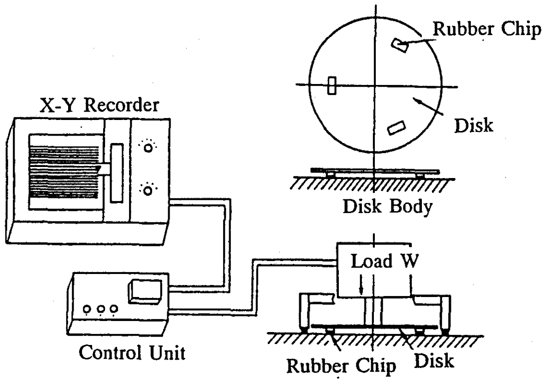


Fig. 8 Outline of DFT

with the dynamic coefficient of friction at walking speed. In this study, values at 8 km/h were used because the walking speed of the elderly is around 4 km/h and the dynamic coefficient of friction at speeds from 0 to 15 km/h could be measured by DFT. The speed when a rotating disk was touched to the test surface was 10 km/h.

③ O-Y Pull Slip Meter: O-Y PSM
The O-Y PSM [18], as shown in Fig. 9, measures the tensile load-time characteristic of a 7 × 8 cm sliding section cut from a shoe sole by pulling it over the test surface under a vertical load of 80 kgf, at a tensile load speed of 80 kgf/s, and with an initial tensile load of 3 kgf and a pulling angle of 18 °. The result is generally expressed in terms of CSR (Coefficient of Slip Resistance) obtained by dividing the maximum value of tensile load measured by O-Y PSM by 80 kgf. When the testing machine was developed, functional tests were conducted with respect to various combinations of floor and sole materials, and favorable CSR ranges were determined [19]. The O-Y PSM method is thought to test materials under conditions close to those when slipping is initiated as shown in " 2. WALK ANALYSIS " because test values when rubber chip is put on the test surface and is beginning to move are obtained. Furthermore, favorable CSR ranges for indoors is considered to be referred to outdoors because walk behavior is not different between indoors and outdoors.

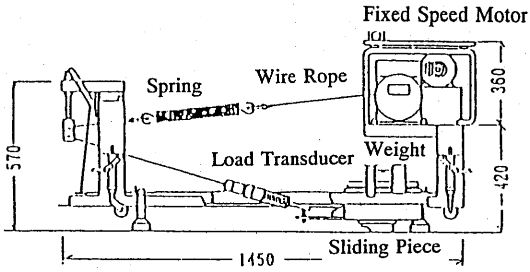


Fig. 9 Outline of O-Y・PSM

b) Test Conditions
It is necessary to consider the effect of rain and mud when evaluating slip on outdoor paving materials. Six surface conditions were tested. BPST and DFT are normally used in wet conditions, but here were also used under conditions besides wet in order that effects under various surface conditions could be taken into consideration. Contamination conditions, aside from air dry and surface dry, were simulated by scattering contaminants on the pavement surface before testing. With the normal DFT test method, water was sprayed on the surface to produce wet conditions. However, DFT was tested with water sprayed just before testing because the value only at 8 km/h was intended to obtain in this study and it is impossible to test scattering the other contaminant.

① Air dry: samples are naturally dried indoors. The surface is dry and there is no water content within the material.

② Surface dry: samples are dried after 24 hours of immersion. There is no surface water, but there is water content within the material.

③ Wet: water is sprinkled on the surface of a sample after immersion for 24 hours. As a result, there is surface water as well as water content within the material.

④ Dry mud: testing dust No. 7 (as prescribed in JIS Z 8901) is scattered at 10 g/m² over the surface of a sample. Testing dust No. 7 is a dry Kanto loam powder that leaves an 88 ± 5% residue on a 5 μm sieve and less than a 20% residue on a 75 μm sieve.

⑤ Wet mud: wet mud is spread at 400 g/m² over the surface of a sample. Wet mud comprises 67% water, 30% testing dust No. 1 (as prescribed in JIS Z 8901), and 3% testing dust No. 7 (as prescribed in JIS Z 8901). Testing dust No. 1 is sand that leaves a 100% residue on a 45 μm sieve and 0% residue on a 300 μm sieve.

⑥ Oil contaminated: cooking oil is spread at 40 g/m² over the surface of a sample.

The amount of contaminants scattered in ④, ⑤, and ⑥ [20] is double the amount at which the slip resistance reaches a constant value when more and more contaminant is added to a flat floor. In some cases, however, the slip resistance may not reach a constant where the surface is coarse.

(3) Results and Discussion

Test results of BPN, coefficient of friction μ , and CSR are shown in Tables 5, 6, and 7, respectively.

a) Evaluation of Test Methods

The surface roughness, as measured by laser displacement measuring methods, and its correlation with the three slip measuring methods, is shown in Table 8 in terms of standard deviation and average gradient of surface roughness. The correlation between MTM roughness and slip measurements is also shown in this table. The MTM roughness is the root mean square roughness obtained by the MTM method.

According to this table, CSR tends to give high values of standard deviation and gradient under all surface conditions, indicating that CSR reflects the surface geometry on average more than other skid measurements. O-Y PSM is often used for slip measurements of flooring materials, but it is not often applied to paveing materials. Though there were doubts that good test results would be obtained with paving materials, which tend to be rougher than floor materials, CSR appears to measure slip resistance well.

Table 8 also reveals that the correlation coefficients of the standard deviation are almost the same as those of the average gradient with all three methods. It may be as shown in Fig. 10, because the correlation between standard deviation and average gradient of surface roughness is relatively strong and the samples used for the tests were prepared on the assumption of outdoor use in mind, so samples with larger height variations had steeper gradients. The correlation of average gradient with CSR is stronger than that of standard deviation because values t^2 of the average gradient of the multiple correlation of the standard deviation, average gradient and CSR as one of skid measurements is larger than that of the standard deviation at almost all surface conditions.

Given these results, in the discussion that follows the average gradient is used as an index of surface geometry on the assumption that paving materials with a larger average gradient have a larger standard deviation. Also, the surface roughness can be evaluated on site using MTM roughness, because the correlation of MTM roughness with slip resistance equal to or smaller than that with average gradient.

The correlations between average gradient and slip measurements shown in Table 8 suggest that BPN

Table 5 Test Results of BPN

Sample	Air Dry	Surf -ace Dry	Wet	Dry Mud	Wet Mud	Oil
CP	93	78	74	58	36	24
CS	87	80	79	74	46	38
CW	94	70	81	93	81	52
CL	84	84	74	64	40	30
AC	90	80	74	79	60	53
BL	92	78	77	67	47	32
TP	87	51	47	68	47	29
RN	84	74	72	64	49	26
RA	89	80	79	77	57	39
NF	93	74	79	86	77	50
BF	90	76	78	84	75	48
KF	88	80	76	83	71	46
SC	89	79	73	75	58	42
LC	92	77	80	85	70	48
Average	89	76	75	76	58	40

Table 6 Test Results of Coefficient of Friction μ

Sample	Air Dry	Surf -ace Dry	Wet	Dry Mud	Wet Mud	Oil
CP	0.85	0.74	0.75	0.46	0.63	0.56
CS	1.06	0.83	0.83	0.92	0.47	0.32
CW	1.11	0.70	0.75	1.10	0.86	0.46
CL	0.52	0.95	0.75	0.52	0.29	0.46
AC	0.78	0.99	0.93	0.69	0.54	0.55
BL	1.04	0.70	0.78	0.84	0.42	0.38
TP	0.69	0.33	0.34	0.64	0.33	0.51
RN	0.64	0.60	0.56	0.57	0.34	0.42
RA	0.69	0.69	0.72	0.65	0.38	0.43
NF	0.97	0.90	0.89	0.96	0.72	0.63
BF	0.89	0.60	0.60	0.81	0.61	0.50
KF	0.85	0.69	0.69	0.86	0.61	0.46
SC	0.81	0.53	0.64	0.74	0.46	0.34
LC	0.90	0.86	0.85	0.86	0.69	0.57
Average	0.84	0.72	0.72	0.76	0.53	0.47

Table 7 Test Results of CSR

Sample	Air Dry	Surf -ace Dry	Wet	Dry Mud	Wet Mud	Oil
CP	.761	.806	.769	.707	.460	.641
CS	.819	.850	.840	.863	.569	.642
CW	.894	.874	.891	.908	.849	.594
CL	.777	.805	.789	.681	.529	.583
AC	.845	.838	.846	.816	.679	.589
BL	.810	.785	.792	.734	.564	.533
TP	.722	.650	.675	.778	.530	.413
RN	.789	.744	.750	.725	.540	.430
RA	.828	.793	.781	.792	.672	.539
NF	.904	.932	.922	.971	.880	.913
BF	.980	.945	.903	.970	.875	.908
KF	.912	.893	.918	.896	.812	.823
SC	.877	.881	.883	.880	.701	.858
LC	.883	.895	.871	.897	.841	.811
Average	.843	.835	.831	.830	.679	.663

Table 8 Correlation of Skid Measurements with Surface Roughness (14 Paving Materials)

Surface Conditions	Surface Roughness / Slip	Correlation with Laser Roughness: Standard Deviation	Correlation with Laser Roughness: Average Gradient	Correlation with MTM Roughness
Air Dry	BPN	0.54	0.42	0.44
	μvalue	0.56	0.38	0.45
	CSR	0.70	0.72	0.73
Surface Dry	BPN	0.30	0.14	0.01
	μvalue	0.11	0.15	0.09
	CSR	0.59	0.64	0.58
Wet	BPN	0.49	0.41	0.50
	μvalue	0.22	0.25	0.20
	CSR	0.67	0.72	0.64
Dry Mud	BPN	0.86	0.90	0.84
	μvalue	0.80	0.70	0.72
	CSR	0.74	0.76	0.70
Wet Mud	BPN	0.89	0.87	0.89
	μvalue	0.78	0.71	0.68
	CSR	0.83	0.87	0.83
Oil	BPN	0.73	0.85	0.69
	μvalue	0.30	0.24	0.25
	CSR	0.42	0.54	0.39

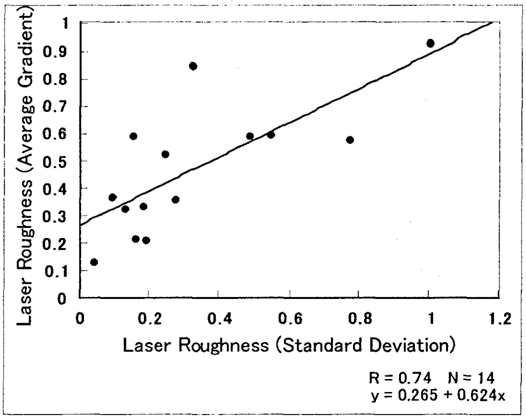


Fig.10 Relationship between Standard Deviation and Average Gradient

and values of frictional coefficient (μ) barely relate to average gradient under air dry, surface dry, and wet conditions. On the other hand, the relationship is strong under conditions of contamination with dry mud, wet mud, and oil. CSR is strongly related to the average gradient except with oil contamination. The speed of the rubber slider in the BPN method immediately before contact with the test surface is 50 km/h, and slip measurements made by this technique are said to have a good correlation with automobile slip characteristics [21]. The frictional coefficient (μ) is measured at a speed of 8 km/h with the DFT method. In these dynamic test methods, particularly when the surface roughness is low, lubricants such as dry mud, wet mud, and oil reduce slip resistance more than water, reflecting the viscosity properties of the lubricants and the surface geometry. Tatushita et al. report that the correlation of average roughness depth as measured with a Doken-style roughness meter with BPN is small [22], and BPN (wet) does not reflect the surface geometry well. CSR is skid resistance obtained when sliding piece is pulled from 0 km/h test speed and is considered to test at the condition in which slipping during walking occurs shown in " 2. WALK ANALYSIS ". Surface geometry is generally well reflected because water tends to reduce the slip resistance when the surface roughness is low.

b) Relationship between Surface Geometry and Skid Resistance

The relationship between average gradient (X) with BPN, friction coefficient value (μ), and CSR is given by the following equations:

Air dry BPN = 5.70 X + 86.7 (R = 0.42) (4)
Surface dry BPN = -3.01 X + 78.1 (R = 0.14) (5)
Wet BPN = 10.5 X + 70.3 (R = 0.41) (6)
Dry mud BPN = 39.0 X + 57.1 (R = 0.90) (7)
Wet mud BPN = 53.6 X + 32.9 (R = 0.87) (8)
Oil contaminated BPN = 36.5 X + 22.6 (R = 0.85) (9)

Air dry μ value = 0.274 X + 0.714 (R = 0.38) (10)
Surface dry μ value = 0.112 X + 0.667 (R = 0.15) (11)
Wet μ value = 0.160 X + 0.645 (R = 0.25) (12)
Dry mud μ value = 0.539 X + 0.505 (R = 0.70) (13)
Wet mud μ value = 0.505 X + 0.287 (R = 0.71) (14)
Oil contaminated μ value = 0.093 X + 0.427 (R = 0.24) (15)

Air dry CSR = 0.213 X + 0.743 (R = 0.72) (16)
Surface dry CSR = 0.215 X + 0.734 (R = 0.64) (17)
Wet CSR = 0.224 X + 0.725 (R = 0.72) (18)

$$\text{Dry mud CSR} = 0.308\,X + 0.685 \quad (R = 0.76) \tag{19}$$
$$\text{Wet mud CSR} = 0.548\,X + 0.421 \quad (R = 0.87) \tag{20}$$
$$\text{Oil contaminated CSR} = 0.39\,X + 0.479 \quad (R = 0.54) \tag{21}$$

At BPN and frictional coefficient values (μ), the equations are different under air dry conditions, surface dry conditions, and wet conditions. With CSR, the equations do not differ under these conditions, and there is no difference by water membrane of wet condition. This is because slip piece is placed on the surface of a test sample and water sprayed on the surface of a test sample is removed, so solid friction is at work and conditions are close to those when slipping during walking occurs. Slipping can occur under wet conditions, as discussed later, in the case of materials with little absorption, special materials, or materials containing mud.

BPN and frictional coefficient values (μ) have stronger relationships to surface geometry when contaminated with dry mud, wet mud, and oil than under air dry, surface dry, and wet conditions. As noted before, this is because lubricants like dry mud, wet mud, and oil reduce the slip resistance more than water when the surface roughness is low. CSR has a stronger relationship to surface geometry under wet mud conditions and dry mud conditions than under wet conditions, so it is clear that the slip resistance indicated by CSR falls for flat, smooth surfaces ($X = 0$). This is because the materials involved at the friction surface act like lubricants. They penetrate the bottom of irregularities on a coarse surface, so CSR has a less strong relationship with surface geometry.

Because oil contaminated condition cause a significant decline in slip resistance, there is a notable fall in slip resistance even on coarse surfaces. The relationship with surface geometry is considered to be smaller under wet mud conditions.

The correlation coefficients of both surface dry CSR and oil contaminated CSR with average gradient are a little smaller than those for CSR under other conditions, and the effect of absorption properties needs be taken into consideration.

c) Relationship between Surface Water Absorption and Surface Geometry with Skid Resistance

Using nine samples of conventional paving materials, multiple correlations among surface water absorption, average gradient, and CSR under various surface conditions are shown in Table 9. For these nine samples, Table 10 also compares the correlation between average gradient and CSR with the multiple correlations among surface water absorption, average gradient, and CSR. This table reveals that, under surface dry and oil contaminated conditions, the coefficients of single correlation of the average gradient and CSR are small but coefficients of multiple correlation are large. This is because the effect of the surface water absorption under surface dry and oil contaminated conditions is greater than that under other conditions due to the effect of porosity, as determined from the ratio of t^2 for surface water absorption and average gradient in Table 9. This tendency is particularly notable under oil contaminated conditions, indicating that oil contaminated conditions are effected almost by the surface water absorption. The ratio t^2 is small in the case of air dry, wet, dry mud, and wet mud, and the difference between the single correlation and the multiple correlation is small.

The regression equations for surface dry and oil contaminated conditions, in which the effect of surface water absorption is greater than under other conditions, are as follows:

$$\text{Surface dry CSR} = 0.12 \times (\text{surface water absorption}) + 0.14 \times (\text{average gradient}) + 0.72$$
$$\text{Oil contaminated CSR} = 0.23 \times (\text{surface water absorption}) + 0.065 \times (\text{average gradient}) + 0.48$$

d) Effects of Surface Conditions on Slip Resistance

Slip tests were executed under six different surface conditions. Table 11 shows the average slip test values of representative paving materials under each surface condition. The effects of surface conditions on slip resistance are discussed below.

① Table 11 shows that BPN and friction coefficient values (μ) are smaller under surface dry and wet conditions than under air dry conditions. On the other hand, CSR is almost unchanged under air dry, surface dry, and wet conditions. This may be because water is present between the sample surface and the rubber sliding piece of the BPST and DFT testers, reducing the slip resistance when the sliding piece comes into contact with the sample surface at a particular speed, whereas water sprayed over the sample surface is dispersed when the sliding piece of the O-Y PSM tester is placed on the test surface.

Table 9 Multiple Correlation of Surface Water Absorption, Average Gradient and CSR

Surface Conditions	Multiple Correlation	Hypothesis Aproval p Value	Ratio of t^2 (%)	
			Surface Water Absorption	Average Gradient
Air Dry	0.76	7%	3	97
Surface Dry	0.62	23%	38	62
Wet	0.70	13%	9	91
Dry Mud	0.84	2.5 %	18	82
Wet Mud	0.96	0.05 %	7	93
Oil	0.63	22%	91	9

Table 10 Single Correlation of Average Gradient and CSR, Multiple Correlation of Surface Water Absorption, Average Gradient and CSR (9 Paving Materials)

Surface Conditions	Single Correlation	Multiple Correlation
Air Dry	0.75	0.76
Surface Dry	0.50	0.62
Wet	0.67	0.70
Dry Mud	0.76	0.84
Wet Mud	0.93	0.96
Oil	0.21	0.63

Past studies have shown that BPN should ideally be 40 or more [23] [24] [25], the frictional coefficient 0.5 or more [16] [26], and CSR 0.5 to 0.8 so as to protect the elderly [19]. Since BPN, the frictional coefficient values (μ), and CSR comfortably satisfy these requirements in the case of the tested materials under air dry, surface dry, and wet conditions (see equations (4)-(18)), slipping can be discounted as a problem. This is true of conventional paving materials that are porous and have good water absorption. However, slipping can occur in wet conditions, as discussed later, in the case of materials with low absorption, special materials, and materials containing mud.

Incidentally, Tables 5 and 6 reveal that BPN and frictional coefficient values (μ) for porcelain tiles are almost within the desirable range under surface dry and wet conditions, but CSR values are above the desirable level.

② Table 11 shows that BPN, frictional coefficient values (μ), and CSR measurements are significantly lower under wet mud and oil contaminated conditions than under other conditions. This is because wet mud and oil both act as lubricants. Slip resistance under wet mud conditions is the same as that under surface dry conditions when the surface roughness is large, from equations (8), (14), and (20), and the variation in slip resistance with changing surface roughness is greater under these conditions than under all other conditions. Further, slip resistance with oil contamination is very low, as indicated by equations (9), (15), and (21), when the surface roughness is small. In this case, the variation in slip resistance with changing surface roughness is relatively great. Though the BPN obtained by one test operation is different between wet mud conditions and oil contaminated conditions, the frictional coefficient values (μ) are not different. This is because the slip-measuring chip in the DFT method moves on the same orbit and materials such as wet mud and oil are rubbed off during testing.

③ The effect of surface roughness is greater under dry mud conditions than under surface dry conditions, as a comparison of equations (16) and (19) shows. Dry mud dust acts like a bearing when the surface roughness is small and the surface becomes slippery, while dry mud enters the bottom of surface depressions when the roughness is large, reducing the influence of surface roughness.

The value of CSR substantially exceeds 0.5 even when the surface roughness is small, so slipping may be considered out of the question with the quantities of dry mud dust used in this study, although slipping can be problem with larger quantities. Frictional coefficient values (μ) of paving materials with small surface roughness are equal to or below the ideal values.

④ CSR does not differ between air dry conditions and wet mud conditions when the surface roughness is large, as is seen by comparing equations (16) and (20). Further, CSR declines little under air dry conditions even when the surface roughness is small, while it does decline considerably under wet mud conditions and the difference of both becomes large. Wet mud acts like a lubricant when the surface roughness is small, so the surface becomes slippery. On the other hand, it enters the bottom of surface depressions when the surface roughness is large, and there is little decline in CSR.

The average gradient from equation (20) needs be more than 0.2 in order for CSR to exceed 0.5 under wet mud conditions. Flat paving materials such as concrete flags, paving bricks, and natural stone flags (smoothened) can lead to slipping when contaminated with wet mud.

⑤ CSR is a little lower under oil contaminated conditions than under air dry conditions when the surface roughness is large, as seen by comparing equations (16) and (21). It is considerably lower when the surface roughness is small. Oil acts as a lubricant when the surface roughness is small and the surface becomes slippery. On the other hand, oil does not enter depressions in a rough surface because its viscosity is higher than that of wet mud; some oil attaches itself to the top of the surface roughness so the CSR declines somewhat.

The average gradient from equation (21) needs be over 0.1 in order for CSR to exceed 0.5 under oil contaminated conditions. When CSR values are used for evaluation because the coefficients of correlation are small, flat paving materials such as concrete flags, paving bricks, porcelain tiles, and natural stone flags (smoothened) can lead to slipping on pavements contaminated with oil.

e) Relationship between Slip Test Values

As for the 14 samples of paving materials used in this study, the relationships between slip test values under six different surface conditions are shown in Fig. 11 (BPN and CSR) and Fig. 12 (BPN and frictional coefficient values (μ)).

Frictional coefficient values (μ) over 0.45 are required, as noted in Chapter 3, in order to ensure that slipping does not occur while walking. The methods used to obtain frictional coefficient values (μ), CSR, and friction force ratios are different. However, frictional coefficient values (μ) and CSR values over 0.5 are needed to ensure the safety of the elderly, and this corresponds to desirable values of frictional coefficient (μ) by DFT and CSR. Some institutions and researchers in the U.S.A. have also reported that frictional coefficient values over 0.5 are desirable.

Taking CSR values over 0.5 by the O-Y・PSM method, which is found to be suitable for evaluating slip resistance during walking in this study, a BPN of over 19 is needed. On the contrary, a BPN of over 40, which is considered the standard in Japan, a CSR value greater than 0.619 is needed. Further, on the basis of the ideal frictional coefficient (μ) of over 0.5 by DFT, from Fig. 12, a BPN greater than 49 is needed. On the contrary, on the basis of a BPN value of greater than 40, frictional coefficients (μ) over 0.422 are needed. The reason for the lack of correspondence among test values recommended by various slip test is that the mechanisms used to measure slip differ. Further, only 14 materials were tested here, and it is normal to obtain BPN and frictional coefficients (μ) under wet conditions. In the U.K., BPN 35-50 is recommended for pedestrian areas in wet conditions [27].

Table 11 Average Skid Test Values under 6 Surface Conditions

Test Values	Surface Conditions					
	Air Dry	Surface Dry	Wet	Dry Mud	Wet Mud	Oil
BPN	89	76	75	76	58	40
μ	0.84	0.72	0.72	0.76	0.53	0.47
CSR	0.843	0.835	0.831	0.830	0.679	0.663

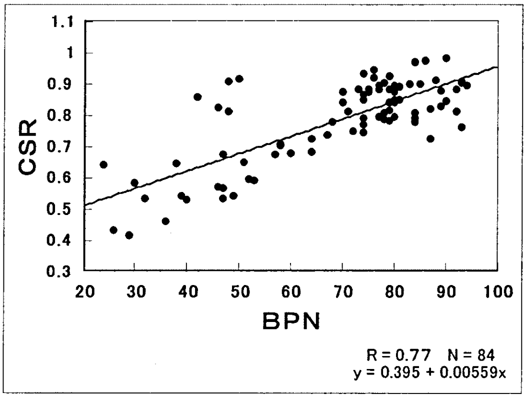


Fig.11 Relationship between BPN and CSR

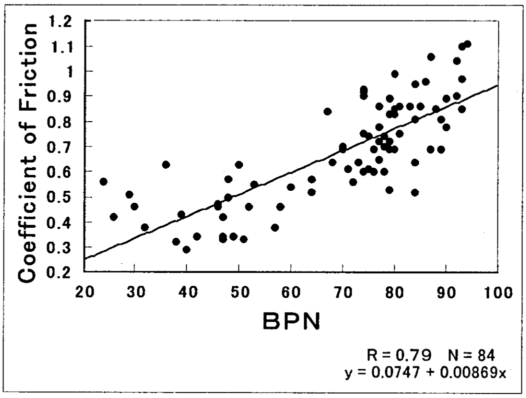


Fig.12 Relationship between BPN and Coefficient of Friction μ

5. CONCLUSION

The authors studied slipping on various paving materials in consideration of walking characteristics, paving material properties, and several surface conditions. We reach the conclusions given below and make proposals regarding test methods, slip resistance standards, and non-slip materials.

(1) The surface absorption and surface geometry of a paving material correlate strongly with slip resistance. Under surface dry and oil contaminated conditions, the correlation with surface absorption is stronger. Under other conditions, surface geometry has a greater effect.

(2) To evaluate the surface geometry of paving materials for slip characteristics, it is desirable to obtain the standard deviation and average gradient of surface roughness using a laser displacement measuring system. In this study, the average gradient proved to be a better index of surface geometry.

(3) The O-Y PSM method is suitable for evaluating static slipping while walking. However, the BPST method better reflects changes due to wet conditions or contamination.

(4) A comparison of friction force ratio (a characteristic of walking) and frictional coefficient values shows that frictional coefficients (μ) over 0.45 are needed in order to prevent slipping. The means used to obtain frictional coefficients (μ), CSR, and friction force ratios are different. However, it can be said that frictional coefficients (μ) and CSR values over 0.5 are needed to ensure the safety of the elderly.

(5) The average gradient of surface roughness of a paving material needs to be over 0.2 where contamination with wet mud or oil is expected. To achieve this, surface treatment measures may be required on flat paving materials such as concrete flags, paving bricks, porcelain tiles, and natural stone flags (smoothened).

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