EXPERIMENTAL STUDIES FOR EVALUATION OF A STUMBLE AND A SLIP OF THE ELDERLY ON CONCRETE BLOCK PAVEMENTS

HARUMI KUGE, MANAGER, QUALITY SYSTEM DEPT., THE NIPPON ROAD CO., LTD
11-20, Tamagawa 2-chome, Ota-ku, Tokyo, 146-0095 Japan
TEL +81-33759-4885 FAX +81-33759-4898
E-Mail harumi.kuge@nipponroad.co.jp
KATSURO KOKUBU, PROFESSOR, FACULTY OF ENGINEERING, TOKYO METROPOLITAN UNIVERSITY
TETSUO AKIYAMA, ASSISTANT PROFESSOR, FACULTY OF ENGINEERING, TOKYO METROPOLITAN UNIVERSITY

ABSTRACT

Since the elderly, compared with the young, often fall over due to stumbling and skidding during walking and become bedridden due to injuries, leading to drastic changes in their later lives or even death, it is important to examine the safety of walking in regard to the elderly. With the aim of forming a safe walk space, the authors investigated the actual injuries of elderly people and examined their walking characteristics compared with young people, as well as the relationship between the surface characteristics of sidewalks and stumbling and skidding.
Choosing block pavement that has popularly been adopted because of its scenic performance as an object, this paper discusses the height of fault at joints, surface geometry and material as its surface characteristics related to the safety of walking.
Specifically, the locus of tiptoe is functionally approximated based on analyses of walking, the probability distribution of height of fault at joints of existing block pavements is measured, and thereby a permissible height of fault at joints that prevents the elderly from stumbling is examined. Also, using fourteen kinds of sidewalk pavement materials having different qualities and surface shapes, dynamic and static skidding is examined, with the parameters being the material characteristics, including the surface geometry and water absorption, and six surface conditions, including air dry, wet, and contaminated.

1.INTRODUCTION

According to data by the Tokyo Fire Defense Agency, 84% of the elderly and 52% of the young experienced general injuries due to tumbling or falling excluding traffic accidents. Also, according to traffic statistics by the National Police Agency, the elderly aged 65 and up often suffer injuries during walking. Namely, since the elderly, compared with the young, often suffer injuries due to tumbling or falling during walking, it is important to examine the safety of walking in regard to the elderly.
With the aim of forming a safe walk space, the authors investigated the actual injuries of elderly people and examined their walking characteristics compared with young people, as well as the relationship between the surface characteristics of sidewalks and stumbling and skidding. Block pavement that has popularly been adopted because of its scenic performance was chosen as an object in this paper.

2. ACTUAL CONDITION OF SELF-INJURY ACCIDENTS

According to the result of an inquiry survey on the "self-injury accident" and "injury-free tumbling" of the elderly aged 60 and up, occurring outdoors, particularly at roads and public squares (station plazas, bus stops), 11% experienced self-injury accidents and 15% experienced injury-free tumbling during the past one year, namely about 30% experienced tumbling. "Self-injury accidents" refer to those in which the elderly suffer injuries due to their own tumbling, falling, etc., and "injury-free tumbling" refers to tumbling, falling, etc. that did not lead to accidents. Also, among self-injury accidents, 64% of the total are tumbling due to stumbling and 20% are tumbling due to skidding; more than 80% are attributed to these two causes. As for the injury-free incidents, tumbling due to stumbling is 70%, followed by tumbling due to skidding at 28%, with these two causes occupying the most part.

3. WALKING CHARACTERISTICS OF ELDERLY PEOPLE

3.1 Method of Walk Analysis

As the test equipment for the analysis of walking, a three-dimensional motion analyzer, ELITE, and a torsion gauge-type three-component floor reaction meter were used. The three-dimensional motion analyzer captures movements of the infrared-ray reflection markers attached to the test subject by four units of infrared-ray emitting cameras and calculates the three-dimensional spatial positions, by which the height of tiptoe and stride length during walking were measured. Also, using the three-component floor reaction meter, the vertical force, Fy, which the foot exerts to the floor during walking, and the horizontal force, Fx, in the walking direction and the horizontal force, Fz, perpendicular to the walking direction were measured. In this study, the value obtained by dividing Fx by Fy is defined as the friction force ratio.

3.2 Test Conditions

Test subjects were 10 men and women in their 60s, and 5 men and women in their 20s, for comparison. Though the elderly are generally defined as 65 and older and it is also important to study the behavior of older people, people in 60s were employed for the sake of survey. In the test, test subjects wore sneakers, of which the soles were made of a material composed of 50% each of natural rubber and synthetic rubber.

3.3 Test Results

(1) Changes in Tiptoe Height
Changes in tiptoe height during the swing phase are schematically shown in Figure 1, where the movement of the tiptoe forms a quartic curve having two maximum values and one minimum value. In the period between points S and H of Figure 1, the tiptoe height is particularly small at parts immediately after S and before and after L; in the part immediately after S, the gravity center of body weight is shifting to the other leg, while in the parts before and after L the test subject is about to support the gravity center of body weight by the leg under analysis. The parts before and after L therefore involve more danger. Thus L is defined as the minimum tiptoe height to pay special attention to the part.
(2) Stride Length
Average stride lengths of each test group are shown in Figure 2. The average stride length of young people is larger than that of elderly people, and among elderly, men's stride length is larger than women's.
(3) Minimum Tiptoe Height
Average values of the minimum tiptoe height of each test group and the standard deviations (σ) are shown in Table 1. The average value of elderly people is smaller than that of youth people.

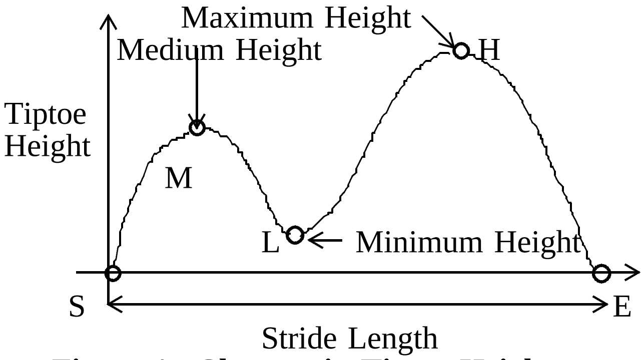


Figure 1 Changes in Tiptoe Height

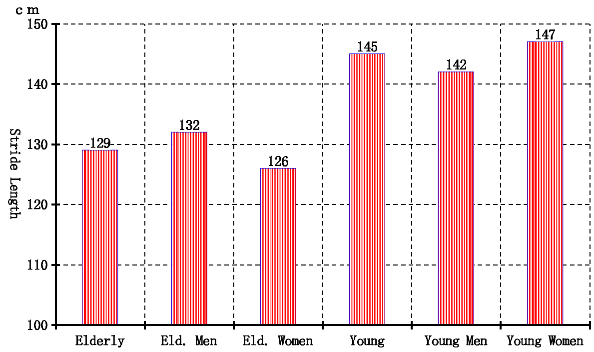


Figure 2 Stride Lengths of Each Test Group

Also, for elderly people, the difference between men and women is small, while among young, women's average value is larger than men's. For elderly people, the average value of tiptoe height minus 2 σ is 10 mm, and for young it is 16 mm. That is, it can be assumed that the elderly easily stumble where the irregularity of road surface exceeds 10mm. 2 σ is employed because it is not possible to construct a road with a surface almost free of irregularity, though 3 σ should be adopted to minimize the surface irregularity to ensure safety during walking.

(4) Friction Force

Average values of the friction force ratio of each test group and the standard deviations (σ) are shown in Table 2. The results show that generally the friction force ratio is larger during pushing forward than during stopping. Also, the average value of friction force ratio of elderly people, both during pushing and stopping, is smaller than that of young. Accordingly, from the engineering viewpoint, the young cause skidding more easily, but it does not directly lead to accidents. Accidents of the elderly are considered due to a lack of physical strength and agility. Since both the floor surface of the floor reaction meter used for the test and the material of test subjects' shoe soles were rubber, which does not cause skidding during walking, it is considered that the horizontal force was measured without a loss. When the friction coefficient of the road surface is larger than the friction force ratio obtained by walk analysis, it can be said that skidding does not occur. Therefore, it can be considered that the friction coefficient necessary for the road surface can be that during pushing forward. Since the elderly are highly likely to experience accidents due to skidding on road surfaces, the friction coefficient, when applying the average plus 3 σ for safety, is required to be 0.42 or larger. In this connection, the value is 0.43 or larger for young, and the friction coefficient of a skid-free road surface is approximately 0.45.

4. INVESTIGATION INTO PERMISSIBLE HEIGHT OF FAULT AT JOINTS

4.1 Hight of Fault at Joints of Block Type Pavement

4.1.1 Object

The height of fault at joints of a flag pavement and a block pavement may vary depending on the placing accuracy of flags and blocks during laying and time after laying. As no reference was available about the influence of height of fault at joints on safety during walking, height of fault of flag pavements and block pavements were measured so as to clarify a permissible height from the safety viewpoint.

4.1.2 Objective Sidewalks

The height of fault at joints were measured at two sites within the metropolis area: a concrete flag pavement and an interlocking block pavement placed for sidewalks. The concrete flag pavement places 30 × 30-cm flags for a total length of 150m and has been in use for eight years,

Table 1 Minimum Tiptoe Height of Each Test Group

Table 2 Friction Force Ratio of Each Test Group

Test Group	Friction Force Ratio	
	Average	Standard

Test Group		Average (mm)	Standard Deviation (mm)
Elderly	Total	22	6
	Men	22	7
	Women	21	5
Young	Total	30	7
	Men	27	8
	Women	33	4

				Deviation
Stopping	Elderly	Total	0.204	0.025
		Men	0.213	0.023
		Women	0.195	0.023
	Young	Total	0.231	0.015
		Men	0.235	0.018
		Women	0.226	0.008
Pushing	Elderly	Total	0.306	0.038
		Men	0.304	0.036
		Women	0.308	0.040
	Young	Total	0.340	0.028
		Men	0.327	0.022
		Women	0.354	0.026

while the interlocking block pavement uses 10 × 20-cm blocks for a total length of 100m and has been in use for six years.

4.1.3 Measurement Method

To measure the height of fault at joints of each sidewalk, a straight traverse line was set on the road surface, and measurement was made at all points where the joint crossed the line. That is, the interval of measurement was 30 cm for the flag pavement and 10 cm for the block pavement. According to the test method for height of fault of interlocking block pavements, the difference between the heights of adjoining flags or blocks was measured to 0.05 mm, using calipers. Incidentally, along the forward direction of measurement, an increasing height was marked plus and decreasing height minus.

4.1.4 Results and Discussion

The distributions of height of fault at joints of the flag pavement and block pavement are shown in Figure 3 and Figure 4, respectively. Since the plus and minus distributions of each pavement were almost the same and the average value can be considered as 0 mm, these figures average the absolute values of positive and negative height of fault. The standard deviation of the height of fault was 2.30 mm for the flag pavement and 2.46 mm for the block pavement. These results nearly agree with the values of previous studies, and can be regarded as a type of profile of block type pavements.

4.2 Permissible Hight of Fault at Joints

4.2.1 Overview

The authors assumed that, on a walk route having surface irregularities including height of fault at joints, stumbling occurs when the tiptoe height is smaller than an irregularity height and estimated a permissible height of fault at joints that prevents the elderly from stumbling based on the walking characteristic evaluation of elderly people and height measurement of fault.

4.2.2 Tiptoe Locus Curve

As the locus curve of tiptoe during walking has three extreme values as shown in Figure 1, the authors thought it could be approximated by a quartic function, but it turned out not to be expressed by integral power multipliers. However, the important point in studying stumbling during walking is point L, the lowest tiptoe height. Also, in the section between points H and E of the tiptoe locus curve, the speed of tiptoe travel in the going direction is considerably small as shown in Figure 5. It can therefore be considered that tumbling does not occur even when the motion is restricted. Thus, from point S to point H of the tiptoe locus curve is approximated by a cubic curve. For elderly people and young, the average tiptoe locus curves approximated to cubic

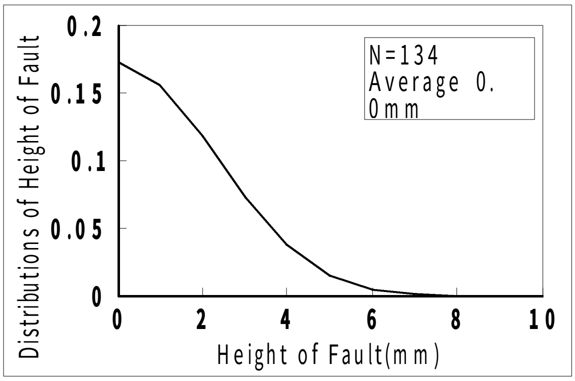


Figure 3 Distributions of Hight of Fault at Joints of Flag Pavement

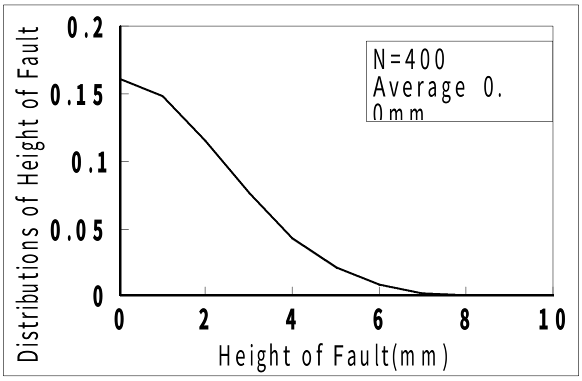


Figure 4 Distributions of Hight of Fault at Joints of Block Pavement

curves are shown respectively in Figure 6 and Figure 7. For both elderly people and young, the approximated curve almost agrees with the tiptoe height between point S and the indicated end line of the tiptoe locus curve, and thus approximation to the cubic curve can be considered acceptable for the study of stumbling.

4.2.3 Probability of Stumbling in a Stride Length

The probability of stumbling (Ps) at fault at joints within a stride length is determined by equation (1). Figure 9 shows the probability of stumbling of both elderly people and young with regard to height of fault at joints determined based on Figures 6 and 7.

$$Ps = \frac{\Delta X_1 + \Delta X_2}{L} \qquad (1)$$

Ps : Probability of stumbling in a stride length

$\Delta X_1, \Delta X_2$: Horizontal distance shown in Figure 8 in which the locus curve of tiptoe is smaller than a certain height of fault at joints (cm)

L : Stride length (cm)

4.2.4 Probability of Stumbling during Walking

With regard to a flag pavement shown in Figure 3, of which the standard deviation of height of fault at joints is 2.30 mm, the probability of stumbling of both elderly people and young at height of fault is calculated in Figure 10. When walking a long distance, the probability of stumbling in a stride length is accumulated. Besides, though with a phase difference, both right and left legs travel. Therefore, Figure 10 is expressed as twice the product of height distribution of fault of

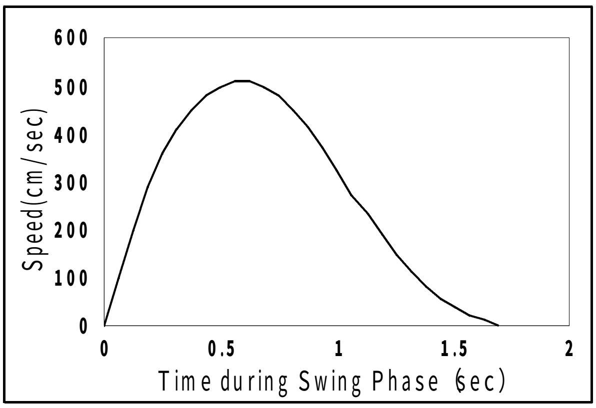


Figure 5 Example of Speed Change during Tiptoe Travel

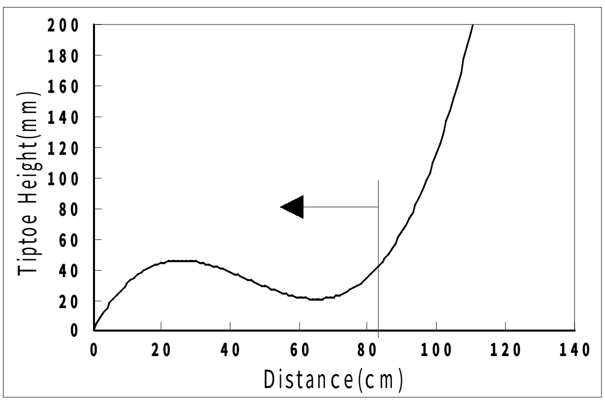


Figure 6 Average Tiptoe Locus Curves of Elderly People

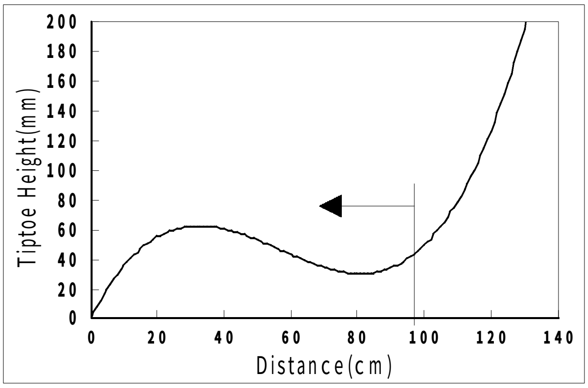


Figure 7 Average Tiptoe Locus Curves of Young People

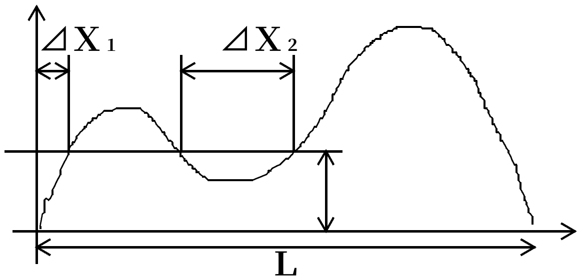


Figure 8 Range of Stumbling in a Stride Length

Figure 3 and the probability of stumbling in a stride length of Figure 9. The probability of stumbling risk of elderly people on a pavement with a standard deviation of fault height of 2.30 mm is 0.0034. That is, elderly people in this experiment are to stumble once while they pass 300 joints. The relationship between the standard deviation of height of fault and the probability of stumbling risk is shown in Figure 11. Figure 11 shows the relationship between the degree of height distribution of fault and the degree of stumbling risk. Assuming that no incident appears within a range where the deviation is 3 σ or larger in the normal distribution and that the risk probability is 0.0013 or less in this range, no stumbling occurs while walking 230m on a flag pavement using 30-cm/side flags (1/0.0013 $\times$ 0.3m). According to a survey about the behavioral characteristics of the elderly in a metropolis center area, the distance of one continuous walk is 248m, and this means stumbling scarcely occurs where the probability of stumbling risk is 0.0013 or less. According to Figure 11, this requires a standard deviation of fault height of 1.2 mm or less. On the other hand, the Japan Road Association proposes σ values of 2.4 mm or less and 4.0 mm or less measured by a 3-m profile meter as standard values for longitudinal irregularity to be applied to the construction and maintenance/repair, respectively, of ordinary roads. Though it is not easily possible to place blocks to attain 1.2 mm or less as the standard deviation of irregularity, 2.4 mm or so can be reached by careful execution.

5. EVALUATION OF SKIDDING

5.1 Properties of Paving Materials

5.1.1 Outline of the Experiment

Skidding during walking outdoors is considered basically to be subject to the influence of the surface geometry of the paving material, in particular the height difference or the steepness of surface roughness. Also, since paving materials are mostly left in a wet and contaminated condition outdoors, it is considered that measurement of the water absorption of such paving materials is important. From these viewpoints, the water absorption and surface geometry of the materials used were measured.

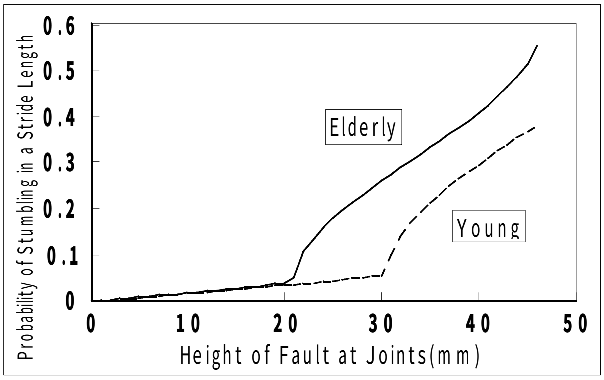
5.1.2 Method of Material Property Test

(1) Materials Used

The paving materials used for tests are materials normally used for sidewalks and a material by test production. The materials normally used for sidewalks include 4 types of cement concrete, 1 asphalt concrete, 2 types of baked earth and 2 types of natural stone: 9 types in total. The test-produced material is concrete. The paving materials used for tests are shown in Table 3.

(2) Method of Water Absorption Test

Surface absorption was measured as a water-absorptive property of paving materials. Surface absorption is the amount of water absorption from the surface per unit area (g/cm ^{2}) measured



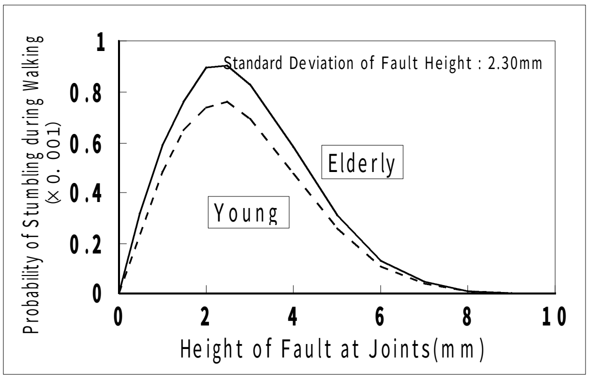


Figure 9 Probability of Stumbling in a Stride Length

Figure 10 Probability of Stumbling during Walking

after applying a 15-cm water head for 24 hours to a 9-cm diameter area of the top surface of a paving material, using a test method devised in the course of this study.

(3) Method of Surface Geometry Measurement

To measure the surface geometry, a laser displacement measurement system was employed. The laser displacement measurement system is a trial production prepared for this study. A laser beam is radiated nearly vertically to the surface of the sample, and the surface roughness of the sample is measured at 0.02-mm pitches and with 0.001 mm of measuring accuracy, and the result is input to a computer.

5.1.3 Results and Discussion

(1) Water Absorption

Results of water absorption tests are shown in Table 4. Incidentally, the trial production material is excluded from the test because it is made of cement concrete and the water absorption is considered similar to that of concrete flags normally used for paving sidewalks.

(2) Expression of Surface Geometry

Two methods are used to express the surface geometry of a road surface: one expressing longitudinal roughness and the other expressing transverse roughness, and each have several specific procedures. Skidding during walking outdoors is considered to be affected by the height difference or the steepness of surface roughness. As a means to express the height difference,

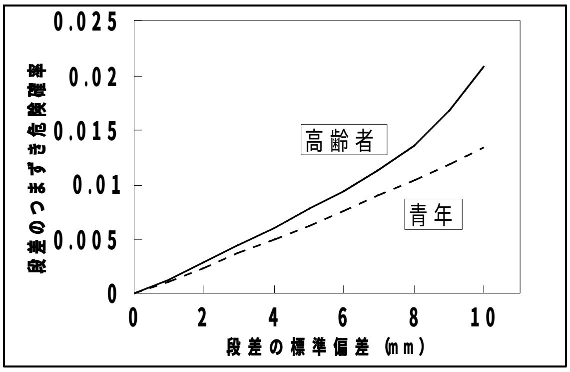


Figure 11 Relationship between the Standard Deviation of Fault Height and the Probability of Stumbling Risk

Table 4 Water Absorption of Paving Materials

Material	Absorption (g/cm^2)	Material	Absorption (g/cm^2)	Material	Absorption (g/cm^2)
CP	0.432	CL	0.626	TP	0.019
CS	0.208	AC	0.134	RN	0.035
CW	0.241	BL	0.053	RA	0.014

Table 3 Paving Materials used for Tests

Type		Mark	Characteristics	Size(mm)
Mater	Cement Concrete	CP	Concrete bolck by normal curing	300 × 300 × 60
		CS	Concrete bolck with chippings of granite	300 × 300 × 60
		CW	Concrete bolck which top aggregate of granite is exposed by washing	300 × 300 × 60

ials Normally Used		CL	Concrete bolck by instant demolding	297 × 197 × 80
	Asphalt Concrete	AC	Asphalt concrete bolck	300 × 300 × 50
	Baked Earth	BL	Brick for pavement	234 × 115 × 60
		TP	Porcelain tile for pavement	300 × 300 × 17
	Natural Stone	RN	Granaite plate which surface is finished by hammer	300 × 300 × 45
		RA	Granaite plate which surface is finished by burning	300 × 300 × 45
Materials by Test Production	Cement Concrete	NF	Concrete bolck which surface is finished by shot blasting at 2 day curing	300 × 300 × 60
		BF	"NF" finished by hammer	
		KF	"NF" finished by 2 hammers	
		SC	Concrete bolck with 1.2 ~ 0.6mm chippings	
		LC	Concrete bolck with 2.5 ~ 1.2mm chippings	

the square average (square root) roughness is adopted in this study and referred to as "standard deviation." 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. 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." Surface roughness is arranged by means of the standard deviation and average gradient in Table 5. The pitch used for calculating the surface gradients is 0.02 mm.

5.2 Evaluation of Skid Resistance

5.2.1 Outline of the Experiment

By the selected three methods of skid measurement, skid resistance of typical sidewalk paving materials was evaluated, and skid-free paving materials were examined from the relationship with material properties. The effects of wetness and contamination of the pavement surface on skid resistance were studied as well.

5.2.2 Test Methods

(1) Skid Resistance Test
To measure skidding, the following three methods were used in this study.
1) British Portable Skid Resistance Tester: BPST
BPST is intended to determine the skid resistance value from the loss of energy due to friction between a prescribed rubber slider attached at the end of a pendulum and the test surface, and the skid resistance value is expressed in BPN. The speed of the rubber slider of the pendulum immediately before touching the test surface corresponds to 50 km/h.
2) Dynamic Friction Tester: DFT
DFT is a rotary skid tester having a disk to which a prescribed tire rubber is attached. It rotates under a prescribed vertical load and determines the friction coefficient at running speeds between 0 and 80 km/h from the friction force and the speed of rotation of the disk. In this study, values at 8 km/h were used.

Table 5 Standard Deviation 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

Table 6 Correlation of Skid Measurements with Surface Roughness (14 Paving Materials)

Surface Conditions	Skid \ Surface Roughness	Correlation with Laser Roughness: Standard Deviation	Correlation with Laser Roughness: Average Gradient
Air Dry	BPN	0．54	0．42
	μvalue	0．56	0．38
	CSR	0．70	0．72

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

Surface Dry	BPN	0.30	0.14
	μvalue	0.11	0.15
	CSR	0.59	0.64
Wet	BPN	0.49	0.41
	μvalue	0.22	0.25
	CSR	0.67	0.72
Dry Mud	BPN	0.86	0.90
	μvalue	0.80	0.70
	CSR	0.74	0.76
Wet Mud	BPN	0.89	0.87
	μvalue	0.78	0.71
	CSR	0.83	0.87
Oil	BPN	0.73	0.85
	μvalue	0.30	0.24
	CSR	0.42	0.54

3) O-Y Pull Slip Meter: O-Y PSM
O-Y PSM measures the tensile load-time curve of a 7 × 8-cm sliding piece cut out of a shoe sole by pulling it on 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 the tensile load measured by O-Y PSM by 80 kgf. When the testing machine was developed, function tests were conducted with respect to various combinations of different floor sole materials, and favorable CSR ranges have been determined.

(2) Test Conditions
It is necessary to consider the effect of contamination by rain and mud in order to evaluate slip of outdoor pavement materials. The following six surface conditions of test samples were chosen.
1) Air dry : Samples are naturally dried indoors. Samples have any water neither on the surface nor inside.
2) Surface dry : Samples are dried after 24-hour immersion. Samples have not any water on the surface but have water inside.
3) Wet : Water is sprinkled on the surface of a sample after it is immersed for 24 hours. Samples have water both on the surface and inside.
4) Dry mud : Dry powder of loam is scattered at 10 g/m^2 on the surface of a sample.
5) Wet mud : Wet mud is spread at 400 g/m^2 on the surface of a sample. Wet mud is composed of 67 % water, 30 % sand and 3 % dry loam.
6) Oil contaminated : Cooking oil is spread at 40 g/m^2 on the surface of a sample.

5.2.3 Results and Discussion

(1) Evaluation of Test Methods
Surface roughness was measured by the laser displacement measuring system and its correlation with the three types of skid measurements in terms of the standard deviation and the average gradient of the surface roughness are tabulated in Table 6. According to Table 6, the correlation of three types of skid measurements with laser roughness shows, for both the standard deviation and the average gradient, a tendency of high CSR in all the surface conditions, indicating that CSR reflects the surface geometry on average more than other skid measurements. Also, Table 6 reveals that the coefficients of correlation of the standard deviation are nearly the same as those of the average gradient by all three methods. It may be because the correlation of the standard deviation and the average gradient of surface roughness are relatively strong, as the samples used for the tests were prepared on the assumption of outdoor use with skid in mind, resulting in a tendency that samples with larger height differences had steeper gradients. In the discussion below, the average gradient is used as an index to the surface geometry. In Table 6, the correlation of the average gradient and skid measurements suggests that the BPN and friction coefficient values (μ) are scarcely related to the average gradient under air dry, surface dry and wet conditions, while the relationship is strong under conditions contaminated with dry mud, wet mud and oil. CSR is strongly related to the average gradient except for oil contamination.
(2) Relationship of Surface Water Absorption and Surface Geometry with Skid Resistance
Using 9 samples of conventional paving materials, Table 7 compares the single correlation of the

Table 7 Single Correlation of Average Gradient and CSR, Multiple Correlation of Surface Water Absorption, Average Gradient and CSR (14 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

Table 8 Average Skid Test Values under 6 Surface Conditions

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

average gradient and CSR, and the multiple correlation of the surface water absorption, average gradient and CSR. Table 7 reveals that, under surface dry and oil contaminated conditions, the coefficients of single correlation are small but coefficients of multiple correlation are large, indicating that the effect of surface absorption is large compared with other conditions.

(3) Effects of Samples' Surface Conditions on Skid Resistance

Table 8 gives the average skid test values of conventional paving materials under 6 sample surface conditions. The effects of surface conditions on the skid resistance are discussed below.

1) Table 8 exhibits that BPN and friction coefficient values (μ) indicate smaller values under surface dry and wet conditions than the air dry condition. On the other hand, CSR indicates nearly the same values under air dry, surface dry and wet conditions. This may be because water exists between the sample surface and the rubber sliding piece of BPST and DFT, reducing the skid resistance when the sliding piece touches the sample surface at a certain speed, whereas water sprayed over the sample surface is removed when the sliding piece of O-Y PSM is left on the test surface, resulting in no difference in the skid resistance. According to past studies, it is preferable that BPN be 40 or more, the friction coefficient 0.5 or more and CSR be 0.5 to 0.8 for the elderly. Since BPN, friction coefficient values (μ) and CSR of the tested materials comfortably satisfy these requirements under air dry, surface dry and wet conditions, it is considered that skidding is not a problem. Incidentally, BPN and friction coefficient values (μ) of porcelain tile are nearly desirable or slightly lower under surface dry and wet conditions, but its CSR values are above the desirable level.

2) Table 8 exhibits that BPN, friction coefficient values (μ) and CSR measurements are significantly lower under wet mud and oil contaminated conditions than under other conditions, because the wet mud and oil work as a lubricant. The CSR values of flat-surface paving materials such as concrete flags, paving bricks, porcelain tile, natural stone flags (smoothened) are reduced to below 0.5 under wet mud and oil contaminated conditions. These materials can cause skidding when contaminated with wet mud or oil. Such measures as surface treatment may therefore be necessary for these materials where such contamination is expected.

6. CONCLUSION

(1) Changes in tiptoe height during the swing phase of walking forms a quartic curve having two maximum values and one minimum value. The authors defined a minimum value as the minimum tiptoe height. The average minimum tiptoe height was 22 mm for elderly people, and 30 mm for young. The average minimum tiptoe height minus 2 σ was 10 mm for elderly people, and 16 mm for young.

(2) The friction coefficient, when applying the average plus 3 σ for safety, is required to be 0.42 or larger for elderly people. In this connection, the value is 0.43 or larger for young, and the friction coefficient of a skid-free road surface is approximately 0.45.

(3) The authors proposed the method to obtain the probability of stumbling risk of elderly people on the flag pavement and block pavement based on the relationship between the probability of stumbling and the standard deviation of height of fault at joints.

(4) Taking into consideration the behavioral characteristics of the elderly in a metropolis center

area, a standard deviation of fault height of 1.2 mm or less is required for the flag pavement and block pavement. Though it is not easily possible to place blocks to attain 1.2 mm or less as the standard deviation of fault height, 2.4 mm or so can be reached by careful execution.

(5) Surface absorption and the surface geometry of paving materials have a strong relationship with skid resistance. Under surface dry and oil contaminated conditions, surface absorption has a stronger relationship. Under the other conditions, the surface geometry has a stronger relationship.

(6) To evaluate surface geometry of paving materials for skid on the pavement, it is desirable to obtain the standard deviation and the average gradient of the surface roughness measured by the laser displacement measuring system.

(7) Such measures as surface treatment may be necessary for flat-surface paving materials such as concrete flags, paving bricks, porcelain tile, natural stone flags (smoothened) where the contamination with wet mud or oil is expected.

Table 8 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