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STUDIES ON ABRASION CHARACTERISTICS OF CONCRETE PAVEMENT


Toshiyasu TOYOFUKU


Hisakatu MIWA


Makoto MURAKUNI


Toshihide TOYOFUKU


Tomio MIYAZAKI


Hiroyuki MURAKI

In regions where snowfall and freezing temperatures occur, concrete pavement suffers abrasion from the tires of vehicles equipped with slip-prevention devices such as chains or studs. The aim of this study is to quantify how various devices and concrete qualities (mix proportions, aggregate, strength, etc.) affect abrasion in experiments using a large rotating test apparatus fitted with common tires such as are typically used on automobiles and trucks.

Relevant factors suggested by these experiments are subjected to multiple regression analysis, and equations for estimating abrasion to concrete pavements are proposed.

Key Words: concrete pavement, tire chains, studded tires, abrasion, concrete quality, mix proportion, aggregate, compressive strength, multiple regression analysis

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Toshiyasu Toyofuku is a Professor of Civil Engineering at Kyushu Sangyo University, Fukuoka, Japan. He obtained his Dr. Eng. from Tokyo University in 1988. His research interests include quality control systems and durability of concrete structures. He is a member of JSCE and JCI.

Hisakatsu Miwa is an Executive Director at Sapporo Road Engineering Co., Ltd., Sapporo, Japan. He is interested in the problem of durability of cement concrete pavements. He is a member of JSCE and JCI.

Makoto Murakuni is a Chief Advisor of Director at Sendai Road Engineer Co., Ltd., Sendai, Japan. He obtained his Dr. Eng. from Nihon University in 1989. His research interests relate to the snow and ice control of highway.

Toshihide Toyofuku is a Professor of Civil Engineering at Kansai University, Suita, Japan. He obtained his Dr. Eng. from Kyoto University in 1986. His research interests include the behavior of prestressed reinforced concrete members. He is a member of JSCE and JCI.

Tomio Miyazaki is a Executive Director at Nitto Co. (Engineering Consultants). His research interests are the design of bridges and durability of concrete. He is a member of JSCE.

Hiroyuki Muraki is an assistant manager at Kakegawa Construction Office of Shizuoka Construction Bureau of Nihon Doro Kodan (Japan Highway Public Corporation). His research interests cover the matter of durability, skid resistance and noise of cement concrete pavements.

1. INTRODUCTION

When various concrete structures are subject to external forces, abrasion damage can become a problem. For instance, floors experience wear from the movement of people and goods;[1] paved road surfaces are worn down by vehicular traffic;[2),3] the aprons and tailraces of dams are worn away by sand, gravel, and rocks present in falling water;[4-8] and coastal structures (bridges, piers) are eroded by sand and rocks present in waves.[9] To date, a large number of studies have been conducted to determine the mechanisms of damage and to suggest possible prevention measures. However, because of the complex circumstances in which abrasion occurs, investigations are being conducted to describe those causes theoretically and to develop new techniques for abrasion testing. Currently, studies have not yet reached the point where quantitative estimation of abrasion resistance or abrasion loss in structures is possible.[10]

To enhance the abrasion resistance of structural concrete, the limits of percentage of abrasion is identified for coarse aggregate in the JSCE's list of standard specifications.[11]

Because the external forces acting on concrete vary depending on the type of structure, a variety of abrasion testing machines have been proposed to reproduce the wear mechanisms of concrete in real-world situations. Examples are: a flooring abrasion tester, rubbing tester, wheel tracking tester, bed-load transport tester, and an impact abrasion tester.

At the Research Institute of Nihon Doro Kodan (Japan Highway Public Corporation), truck tires were run on the traffic simulator machine (a large rotating wheel test apparatus), with an indoor circular track 90 centimeters wide and 6 meters in diameter. This apparatus was used to establish technology for the material and structural design of highway pavement. From 1970 to 1986, laboratory tests were conducted on wear resistance of cement concrete pavement surfaces,[12)-20] wear and skid resistance of cement concrete pavement surfaces,[21)-24] and the performance test of various tires and equipment to prevent skid on snow and ice roads.[25] From the results of these tests, a method was proposed for estimating worn-out wheel tracks (rutting) on concrete pavement.[26)-29] Toshihide Toyofuku also performed studies through basic experiments to elucidate abrasion characteristics.[30),31]

This study consolidates and analyzes the results of these tests to describe the abrasion of concrete pavement in cold climates where such hostile conditions exist that road surfaces suffer damage from non-slip devices (such as chains) and clarifies the correlation between external forces acting on concrete and abrasion.

2. OVERVIEW OF CONCRETE ABRASION TESTS INVOLVING THE TRAFFIC SIMULATOR MACHINE

(1) Outline of tests

The traffic simulator machine was composed of wheels attached to the ends of four frames extending radially at 90° intervals from a rotating support shaft at the center of the apparatus, these wheels traveled on the surface of a circular track composed of various road samples (see Fig. 1 and Photo 1). The primary specifications for this apparatus are as follows: turning radius of 3 m (nominal), variable up to the maximum radius of the track; wheels: tires for passenger cars or trucks, traveling at a maximum speed of 60 km/hr.; maximum axle load: 3 tons; running height tolerance: ±200 mm from nominal height during rotation; traveling torque: the maximum grade ±6% equivalent, to reproduce forces acting on sloped roads when wheels ascend/descend during acceleration/deceleration; and concrete samples: twelve trapezoidal samples, each having 201 cm on the long side, 116 cm on the short side and 160 cm in width, arranged in a circular pattern to form a polygon having 12 sides for use as an abrasion test track.

Tests I through IX were conducted to study the factors influencing abrasion, with the following varied parameters as listed in Table 1: tire conditions (type of non-slip device, type of tire, and tire pressure); traveling conditions (the number of times that the wheels went around the test track, traveling speed,

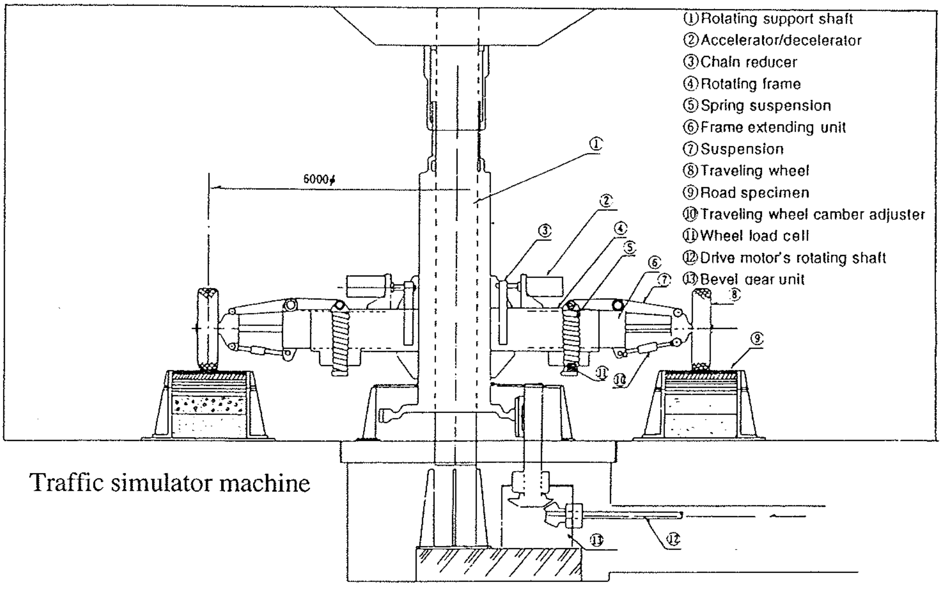


Fig. 1 Traffic simulator machine

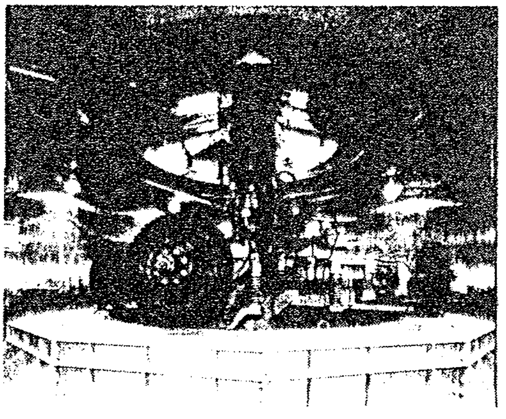


Photo 1 Traffic simulator machine

wheel load, radius of a wheel track, and displacement of a wheel track); concrete sample conditions (material, mix proportion, construction method, surface finishing and strength). Tests were run under wet road conditions, with water sprayed onto the track from the side.

For the non-slip devices; in addition to chained and studded tires, six common non-metal non-slip devices (4 ladder type and 2 net types) were selected from various models for Test I (see Table 2).

(2) Analytical method

From the results of the abrasion tests conducted on the test apparatus, various factors influencing abrasion, such as tire conditions, were arranged as test data (x_1, x_2, x_3, ...) on abrasion (y) measured from each specimen. Abrasion losses were represented as cross sectional areas because the loss depth was affected by the displacement of the track. When tested with 10.00-20-14PR truck tires, the width of the wear-affected area was about 30 cm. Average abrasion loss was obtained by dividing the cross sectional area values by 30 cm.

Single or multiple regression analyses were carried out on the test data to obtain the relationship between various influential factors and abrasion loss, as represented by the following equations.[32)]

$$y = a + bx \qquad (1)$$

Table 1 Test parameters

Test type *1		Tire conditions: Tire type *2	Tire conditions: Tire pressure (kgf/cm²)	Tire conditions: Non-slip device type *3	Traveling conditions: Travelling speed (km/hr.)	Traveling conditions: Wheel load (ton)	Traveling conditions: Radius of a track (m) *4	Traveling conditions: Displacement of a track (mm)	Traveling conditions: Torque (kg-m)	Specimen conditions: Specimen type *5	Specimen conditions: Cement type *6	Material: Fine aggregate type	Material: Coarse aggregate type	Material: Max. size of coarse aggregate (mm)	Mix proportion: Slump (cm)	Mix proportion: Air content (%)	Mix proportion: Sand-aggregate ratio, s/a (%)	Mix proportion: Water-cement ratio, W/C (%)	Content per unit volume of concrete (kg/m³): Cement, C	Content per unit volume of concrete (kg/m³): Water, W	Number of vibration and curing type	Surface finishing type	Age when traveling started (day)	Final number of wheel passes
I	CT	165SR13 (normal)	1.7	45181	40	0.4	Outer	±25	5	1	N	1	1	40	1.5±1	4±1	43.8	44.0	300	132	1	Coarse surface	23	3.5
	NT	165SR13 (normal)	〃	Table 2	〃	〃	Inner & outer	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	19~24	6.8
	ST	6.45-13-4PR (bias)	〃	80 pieces	〃	〃	Inner	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	22	10
	〃	165SR13 (radial)	〃	114 pieces	〃	〃	Inner	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	17	10
II	CT	10.00-20-14PR	6.0	89194	40	2.0	2.71	±60	30	6	N	1	1	40	2.5±1	4±1	32.2	36.3	350	127	1	Coarse surface, with abrasion-resistant materials spreaded	28	4
	ST	10.00-20-14PR	6.0	64 pieces	〃	〃	3.18	±60	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃		〃	60
III	CT	10.00-20-14PR	6.5	89194	20, 60	2.0	3.40	±15	30	19	N	3	3	25, 40	2.5±1	4±1	27.1~41.5	36.9~53.8	240~350	127~150	1	Coarse surface, grooved	271	4
	ST	10.00-20-14PR	6.5	78 pieces	60	〃	3.05	±50	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	249	60
IV	CT	6.00-13-6PR	3.0	56180	40	0.5	3.23	±30	30	6	N	1	6	40	2.5±1	4±1	32.0	36.6~38.0	350	128~133	1	Coarse surface	28	5
	〃	10.00-20-14PR	6.0	89194	〃	1.0	2.70	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
	〃	〃	〃	〃	〃	2.0	2.95	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
V	〃	10.00-20-14PR	6.0	89194	20	2.0	2.67	±15	30	5	H	3	3	40	2.5±1	4±1	31.6~35.2	32.5~40.7	300~400	122~132	1	Coarse surface	42~98	5
	〃	〃	〃	〃	40	〃	3.38	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
	〃	〃	〃	〃	50	〃	3.04	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	3
VI	ST	10.00-20-14PR	6.0	64 pieces	40	2.0	3.00	±60	30	12	N	1	6	25, 40	2.5±1	4±1	26.8~40.3	30.0~45.7	340, 400	120~162	1	Coarse surface	28	120
VII	〃	10.00-20-14PR	6.0	64 pieces	40	2.0	3.00	±60	30	12	N	1	1	40	1±1, 5±1	4±1	32.2	31.6~35.4	350	127, 132	12	Coarse surface (surface finishing timing)	28	120
VIII	〃	6.00-13-6PR	3.0	72 pieces	40	0.5	2.96	±30	30	6	N	1	1	40	2.5±1	4±1	34.0	31.6~35.5	350	128~133	1	Coarse surface	7~365	60
	〃	10.00-20-14PR	6.0	78 pieces	〃	1.0	3.23	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
	〃	〃	〃	〃	〃	2.0	2.70	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
IX	〃	10.00-20-14PR	6.0	78 pieces	20	2.0	2.66	±50	30	7	H	3	3	15, 40	2.5±1	4±1	29.9~38.0	32.1~40.7	290~634	115~170	1	Coarse surface, hard facing materials	249~256	60
	〃	〃	〃	〃	40	〃	3.37	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃
	〃	〃	〃	〃	50	〃	3.02	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃	〃

*1 I through IX: test type CT: chained tire NT: tire equipped with non-metallic non-slip device (see Table 2) ST: studded tire
*2 65SR13: normal or snow tires for passenger cars 6.00-13-6PR: normal tires for passenger cars 10.00-20-14PR: snow tires for trucks
*3 CT: chain type under JIS D 4241 ST: number of studs
*4 Inner: 2.61 m or 2.89 m Outer: 3.11 m or 3.39 m
*5 Number of specimens: 4 for Test I, 19 for Test III; 10 for Test V, and 12 for other tests (the number of specimen per specimen type: 1/2, 1 or 2)
*6 N: normal Portland cement H: cement for paving M: moderate-heat Portland cement

Table 2 Non-metal non-slip devices

Type		Tread material	Studded pin or metal: Pin head size (mm) and material	Studded pin or metal: Number of pins*	Studded pin or metal: Total area of pins at the head (cm²)	Side band
Ladder type	LAT	Polyurethane	ϕ 13 pins (made of tungsten cobalt) embedded	32 (1.33)	42.56	Rubber band
	LBT	Special synthetic rubber	ϕ 9 pins (made of abrasion-resistant cemented carbide chips) embedded	44 (0.64)	28.16	Outer rubber ring & inner rope
	LCT	Synthetic rubber (reinforced with steel wire)	ϕ 6.3 pins (made of molybdenum-contained steel) embedded	44 (0.31)	13.64	Rope (made of Teflon)
	LDT	Natural rubber reinforced with polyester fiber	ϕ 5.2 pins (made of tungsten -contained cemented carbide chips) embedded	56 (0.21)	11.76	Outer natural rubber & inner rope (polyester)
Net type	NAT	Rubber cord reinforced with special (Kevlar) fiber	16 x 4.5 metal (made of special metal) fixed to crossed part	255 (0.72)	184.60	Spring
	NBT	Synthetic rubber Nylon 66 reinforced	24 x 6 metal (made of special metal) fixed to crossed part	44 (1.44)	63.36	Outer rubber & inner orange rope

* Data in parentheses indicates the area of a pin or metal at the head in cm²: 0.21 cm² for studded tires.

$$y = 10^a x^b \quad (2)$$

$$y = b_0 x_1^{b1} x_2^{b2} \ldots\ldots x_p^{bp} \quad (3)$$

where a, b are constant (r is single correlation coefficient),
b_0, b_1, b_2 are constant (R is multiple correlation coefficient).

A multiple regression analysis was carried out using a stepwise method on the data obtained from Tests II through IX, where the final number of wheel passes was 30,000-50,000 for chained tires and 600,000-1,200,000 for studded tires, with a variance ratio of F = 2.0 used as a criterion for judgment (see Table 3, hereinafter these items are denoted by the symbols in the table).

Metal component load per unit length of circumference M_L is the total weight borne by the metal (studs for studded tires and cross chains for chained tires) in contact with road surfaces divided by the circumference of the tire, for use as a factor representing the magnitude of external forces induced by non-slip devices.

Table 3 Analytical data (obtained from Tests II to IX)

Item			Division	Symbol	Unit	Analytical data*3 Chained tire (n=601)	Analytical data*3 Studded tire (n=748)
y	Cross sectional area of abrasion*1			A_A	cm^2	0.7-164.0	1.4-81.8
	Depth of abrasion*2			A_D	mm	0.4-50.5	0.7-29.8
x	Tire conditions	Tire pressure		P	kgf/cm^2	3.0-6.5	3.0-6.5
		Metal component load per unit length of circumference		M_L	g/cm	9.01-22.93	1.05-2.34
	Traveling conditions	Number of wheel passes		N	x 10,000	0-5	0-120
		Traveling speed		V	km/hr.	20-60	20-60
		Wheel load		W_L	ton	0.5-2.0	0.5-2.0
		Radius of a track		R_A	m	2.67-340	2.66-3.37
		Displacement of a track		H_E	mm	±15-±60	±30-±60
	Specimen conditions	Cement	Compressive strength (at age of 28 days)	C_{c28}	kgf/cm^2	356-417	367-417
			Flexural strength (at age of 28 days)	C_{b28}	kgf/cm^2	67.3-72.6	67.3-70.2
		Fine aggregate	Fineness modulus	S_{FM}	-	2.58-3.01	2.19-3.41
			Specific gravity	S_H	-	2.56-2.62	2.58-2.63
			Water absorption	S_Q	%	1.3-3.3	1.1-2.9
			Mass of unit volume	S_T	kg/l	1.62-1.83	1.62-1.85
			Solid volume percentage	S_G	%	63.4-71.4	63.4-71.4
		Coarse aggregate	Max. size	G_M	mm	25-40	15-60
			Fineness modulus	G_{FM}	-	6.83-7.54	6.83-7.58
			Specific gravity	G_H	-	2.60-2.81	2.47-3.01
			Water absorption	G_Q	%	0.5-2.0	0.4-4.3
			Mass of unit volume	G_T	kg/l	1.54-1.87	1.54-1.83
			Solid volume percentage	G_G	%	58.1-71.3	58.4-67.6
			Percentage of abrasion	G_S	%	13.5-28.7	10.3-43.1
		Mix proportion	Sand-aggregate ratio	s/a	%	27.1-41.5	26.8-41.5
			Water-cement ratio	W/C	%	32.5-53.8	30.0-53.8
			Cement content per unit volume of concrete	C	kg/m^3	240-400	240-634
			Water content per unit volume of concrete	W	kg/m^3	122-150	115-170
		Concrete	Slump	SL	cm	1.5-3.5	1.0-9.0
			Air content	A	%	3.2-5.5	2.9-6.5
			Compressive strength (at age of 28 days)	f_{c28}	kgf/cm^2	268-448	268-595
			Flexural strength (at age of 28 days)	f_{b28}	kgf/cm^2	42.1-60.9	34.1-71.3
			Age when traveling started	Z_A	day	28-271	7-365

*1 *2, A_{AC}, A_{DC} for chain tires, A_{AS}, A_{DS} for studded tires, A_{AT}, A_{DT} for the total of chained and studded tires.
*3 n: number of data

3. EFFECTS OF MOVING VEHICLES ON ABRASION

(1) Effects of external forces (non-slip devices) on abrasion, based on type

The circumstances under which abrasion occurs in concrete vary greatly in parallel with the characteristics of external forces acting on concrete surfaces, such as the magnitude and pattern of the forces, and the number of times that the forces passed.[33] Therefore, to study the mechanism of abrasion caused by a variety of non-slip devices, a comparison was made of abrasion loss when chained, studded tires or tires equipped with non-metallic non-slip devices ran at a speed of 40 km/hr. The results of this comparison are shown in Fig. 2 (obtained from Test I). Fig. 3 shows typical cross sectional areas of abraded road surfaces after wheels passed 20,000 times.

The displacement of the track was set to ±25 mm for testing ladder type, non-metallic non-slip devices, and studded tires. In areas where tires with stud pins laid out in two rows across their width made contact, road samples showed heavy wear. Furthermore, abrasion in areas which came in contact with outer pins were larger than those in contact with inner pins; due to outer pins traveling on the track faster than inner pins. When chained tires ran on the track, road samples were worn U-shaped.

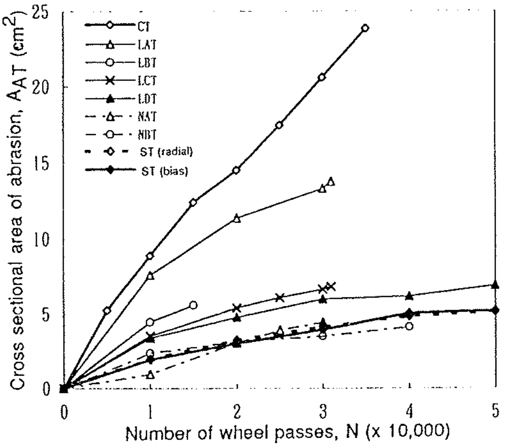


Fig. 2 Comparison of abrasion loss by type of non-slip device (Test I)

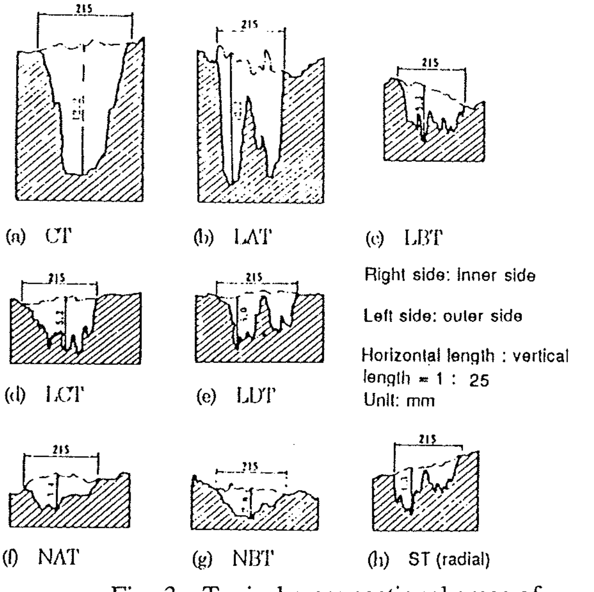


Fig. 3 Typical cross sectional areas of abraded road surfaces (after wheels passed 20,000 times, Test 1)

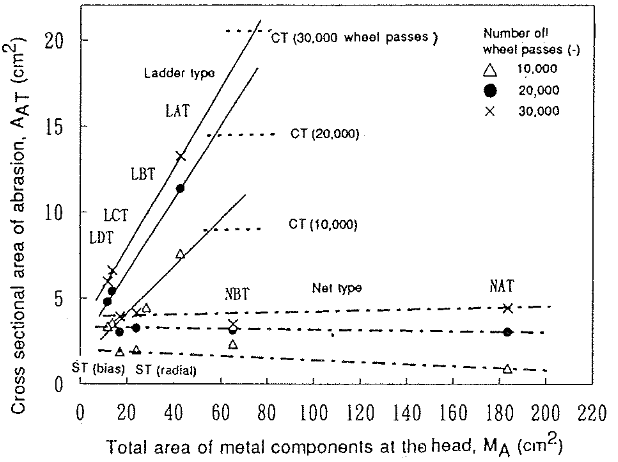


Fig. 4 Relationship between abrasion loss and total area of metal components contacting the pavement

Samples at the outer radius of the track tended to show more wear than those at the inner radius even at the same traveling speeds.

The largest abrasion loss was exhibited from chained tires (about 5 times larger than that from studded tires), followed by tires equipped with non-metallic ladder type non-slip devices. The abrasion loss due to net type non-slip devices was of the same order as that of studded tires. Non-metallic non-slip devices varied greatly in durability, with many breaking at side bands or on the outer sides (which came in contact with road surface corners formed by abrasion).

These tendencies appear affected by such factors as the configuration and material of non-slip devices as well as centrifugal forces acting on tires when running about the center of the test apparatus on a track of about 3 m in radius. Since tires rotate about the axis, or about a frame extending radially from the rotating support shaft at the center of the test apparatus, forces seem to act on the tire to deform it outward in a radial direction, causing the outer side to grow concave. Accordingly, based on the assumption that the effects of studs or other metal on the abrasion of road surfaces can be represented by the total area of metal components contacting the pavement M_A, the relationship between the total area and abrasion loss was obtained, as shown in Fig. 4. Grouping the data in the graph into two types: ladder type (including chained tires) and net type (including studded tires), there is a correlation between the total area of metal components and abrasion loss for each type. Particularly, a good correlation is seen in the group of four ladder type non-slip devices. Although it is difficult to calculate the total area of chain material that contacts the pavement, they can be considered to show almost the same tendencies as the other ladder type devices. As can be seen from the group of four net type non-slip devices, including NAT, NBT, and studded tires (ST), abrasion loss is almost constant without regard to the total area of metal components contacting the pavement.

As mentioned above, the effects of metal components on abrasion loss vary depending on the type of non-slip device, i.e. ladder or net type. The cause of this can be considered as follows. In the former case, since the tread into which stud pins are embedded is linearly cross-shaped (across the width) around the circumference of a tire, the tire becomes convex easily because of small constraints when it rotates at high speeds. As a result, road surfaces are subject to impact loads, and wheel loads act on the surfaces as line loads from the tread. In the latter case, the tread has difficulty becoming convex because of large constraints, impact loads acting on the road surfaces are small and wheel loads act on the surfaces broadly from areas of the tire other than the studded parts. As a consequence, loads acting on studs are reduced.

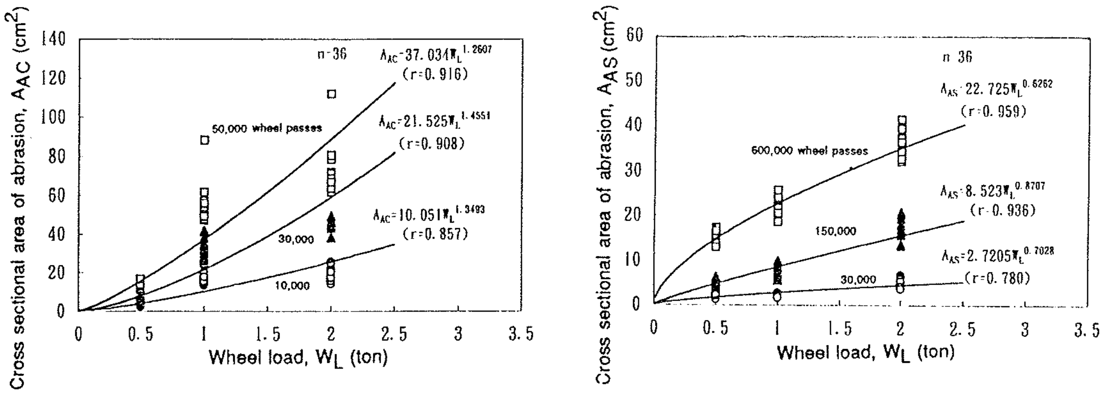
(2) Effects of the magnitude of external forces on abrasion

Fig. 5 shows the relationship between the magnitude of external forces and abrasion loss, with attention paid to wheel loads (obtained from Tests IV and VIII). Assuming actual traffic conditions, the following tire types were used in these tests:

① At a wheel load of 0.5 tons, normal tire 6.00-13-6PR for passenger cars (at a tire pressure of 3.0 kgf/cm^2) equipped with tire chain 56180 (weight: 3.5 kg) specified under JIS D 4241 or with 72 studs;

② At wheel loads of 1.0 and 2.0 tons, snow tires for trucks (at a tire pressure of 6.0 kgf/cm^2) equipped with chain 89194 (weight: 16.9 kg) or with 78 studs.

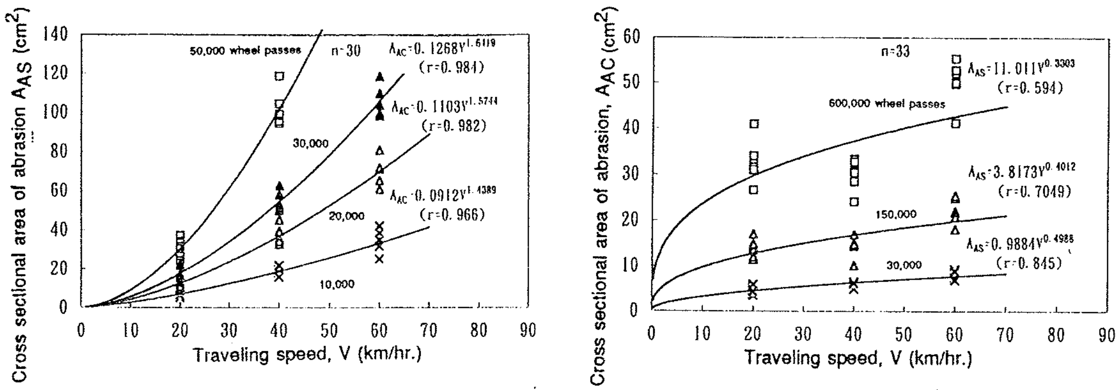
As is evident from the figures, the abrasion loss from studded tires increase in approximate proportion to an increase in wheel load. While the abrasion loss from chained tires at a wheel load of 1.0 ton is about five times larger than that at a wheel load of 0.5 tons, but at a wheel load of 2.0 tons and 1.0 ton, the increase of abrasion loss is smaller than the former case. This appears due to the effects of the weight and dimensions of cross chains predominant over those of wheel loads. When the number of wheels passes reaches 50,000 the data becomes greatly varied, therefore tendencies under loads exceeding the maximum wheel loads of up to 2 tons are unclear. But, the increase in abrasion loss appears to be less than that of the relative equation.



(a) Chained tire (Test IV)

(b) Studded tire (Test VIII)

Fig. 5 Relationship between wheel loads and abrasion loss (at V = 40 km/hr.)



(a) Chained tire (Test V)

(b) Studded tire (Test IX)

Fig. 6 Relationship between traveling speeds and abrasion loss (under W_L = 2.0 tons)

Fig. 6 shows the relationship between traveling speed and abrasion loss (obtained from Tests V and IX). For chained tires, abrasion loss increase almost linearly with traveling speed. Furthermore, the effects of traveling speeds tend to increase with the number of wheel passes. Where the number of passes is 30,000, the abrasion loss at traveling speeds of 40 and 60 km/hr. is about three and six times larger than that at 20 km/hr., respectively. In contrast, for studded tires, there is little difference in the abrasion loss for 40 and 20 km/hr., and the loss at 60 km/hr. is about 1.3-1.8 times larger than that at 20 km/hr. Where the number of passes is 600,000, there is a drop in the correlation between abrasion loss and traveling speed, due to large variations in the abrasion data. The reason that the abrasion loss at 20 km/hr. is greater than that at 40 km/hr. can be considered to be due to the effects of cornering forces: that is, the inner radius of a track is 2.66 m (20 km/hr) and the outer 3.37 m (40 km/hr), i.e. the centrifugal acceleration on the inner side was larger than that on the outer side even at the same traveling speeds.

As described above, paved road surfaces are worn down as chained tires travel on the surfaces. From another aspect, tire chains that act on the road surfaces as external forces are also subject to abrasion. Fig. 7 shows the relationship between traveling speeds and the abrasion loss of tire chains, C_A (percentage of cumulative abrasion loss as measured in weight). As can be seen from the figure, the abrasion loss of tire chains increases as traveling speeds increase, or as the effects of concrete to wear down tire chains increases.

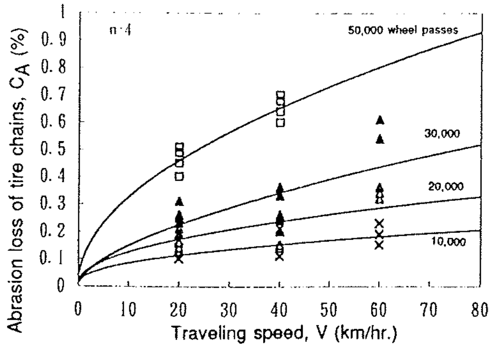


Fig. 7 Relationship between traveling speeds and abrasion loss of tire chains (under $W_L = 2.0$ tons, Test V)

4. EFFECTS OF CONCRETE QUALITY ON ABRASION

(1) Mechanism of road surface abrasion

a) Abrasion by tires

Figs. 8 and 9 show the results of Test III, with attention focused on tire type and the quality of aggregate and concrete (at traveling speeds of 60 km/hr). The effects of these factors on abrasion can be interpreted as follows:

① For normal truck tires, road surfaces show little wear because tire wear is substantial; heat generated by friction softens the tire's rubber and deposits it on the road surface.

② For studded tires, an increase in abrasion loss is almost linear with the number of times that wheels circled the track to a depth about 2 mm, or the depth equivalent to mortar thickness. At a depth of about 2 to 5 mm, the gradient of the straight line becomes mild gradually and a difference between easy-to-wear and hard-to-wear tires becomes apparent. At a depth over 5 mm, the gradient becomes linear again, and a difference in the loss due to concrete quality noticeable. That is, the effects of the quality of mortar in concrete are dominant during the initial abrasion stage, and those of the quality of concrete become apparent when coarse aggregate is exposed.

③ For chained tires, as is the case where an increase in the percentage of abrasion of coarse aggregate is linear to an increase in the number of revolutions using a Los Angeles Abrasion Machine, [34] the abrasion loss increases linearly with the number of times the tire circles the track. The abrasion loss of surfaces induced by chained tires is about ten times larger than that of studded tires (up to about 30,000 times) because of the large impact load of chains.

④ Abrasion loss vary depending on aggregate type used, particularly large losses are the case where river sand F is used as fine aggregate. In the case where studded tires run on concrete type E, after the surfaces have been worn down sharply to a depth of about 2 mm, the depth increases linearly with the number of passes made by the tire. In contrast, for concrete type A, the surfaces have been worn down steeply to a depth of about 7 mm, and the depth increases linearly at the same gradient of concrete type E. In the case where chained tires travel on concrete type E, the depth increases almost linearly to the number of passes made by the tire. For concrete type A, the depth increases sharply up to about 8 mm and at the gradient slightly larger than that of type E at depths exceeding 8 mm.

b) Fundamental mechanism of abrasion

To grasp the effects of external forces and concrete quality on abrasion loss, tests were conducted using an impact abrasion testing apparatus as shown in Fig. 10. Figs. 11 and 12 show the relationship between the number of times that steel balls were dropped and abrasion loss as measured in volume;

Symbol		Coarse aggregate: Type	Solid volume percentage (%)	Percentage of abrasion (%)	Percentage of soft stone (%)	Fine aggregate: Type	Fineness modulus	Mass of unit volume (kg/l)	Mix proportion: Sand aggregate ratio (%)	Water content per unit volume (kg/m³)	Compressive strength (at age of 28 days) (kgf/cm²)
△	A	Crushed stone	58.3	21.4	0	River sand F	2.75	1.620	38.1	142	268
▲	B					Crushed sand	2.66	1.680	37.5	145	369
○	C	River gravel F	61.6	16.1	1.8	River sand F	2.75	1.620	32.7	128	404
●	D					Crushed sand	2.66	1.680	34.0	132	383
×	E	River gravel K	62.5	16.0	4.2	River sand K	2.78	1.666	31.1	123	391

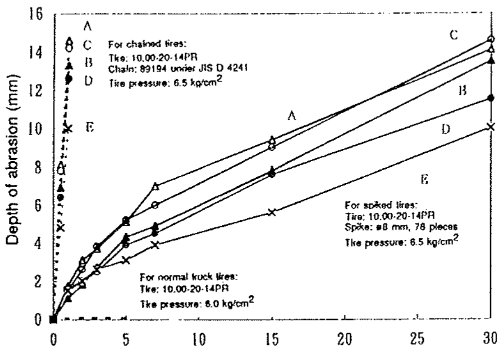


Fig. 8 Relationship between the number of wheel passes and depth of abrasion (Test III, V = 60 km/hr., W_L = 2.0 tons, C = 320 kg/m³)

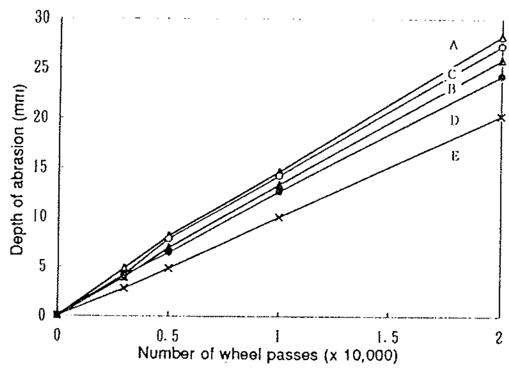


Fig. 9 Relationship between the number of wheel passes and depth of abrasion (Test III, V = 60 km/hr., W_L = 2.0 tons)

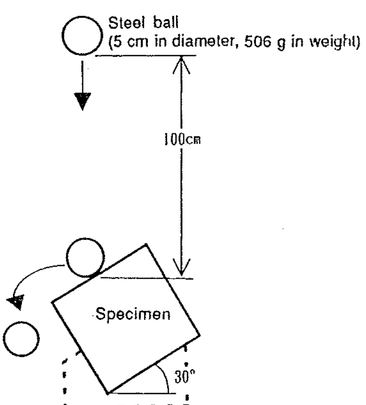


Fig. 10 Impact abrasion testing apparatus

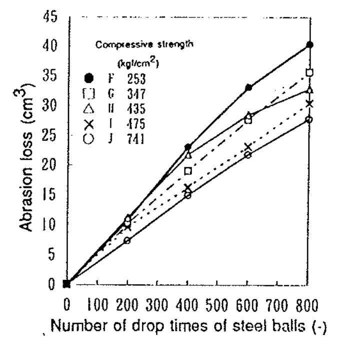


Fig. 11 Relationship between the number of drop times of steel balls and abrasion loss

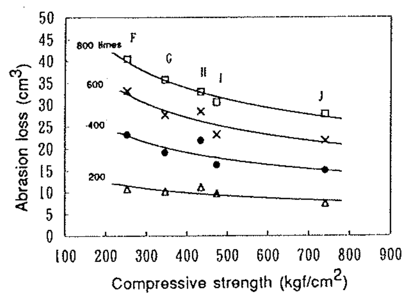


Fig. 12 Relationship between the compressive strength of concrete and abrasion loss

so shown is the relationship between the compressive strength of concrete and abrasion loss, respectively. For specimen J with high mortar strength (compressive strength of concrete = 741 kgf/cm², and W/C = 25%), an increase in abrasion loss is approximately linear. On the other hand, for specimen F with low mortar strength (compressive strength of concrete = 253 kgf/cm², and W/C = 70%), abrasion loss increases linearly up to an abrasion loss of 20 cm³ which is equivalent to a depth of 10 mm (up to 400 passes), then at a mild pace as coarse aggregate is exposed, and at almost the same gradient as specimen J after 600 passes. The abrasion loss drops as the compressive strength of

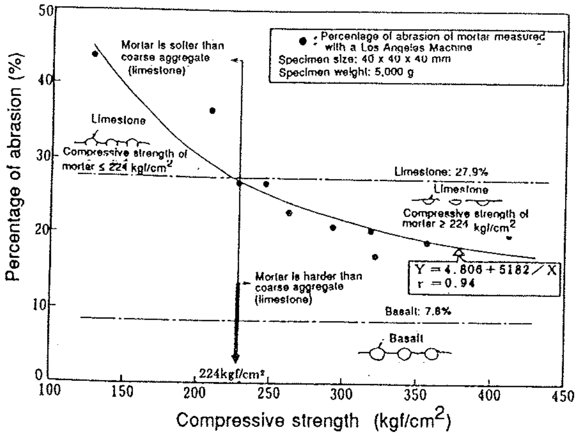


Fig. 13 Relationship between the compressive strength of mortar and the percentage of abrasion

concrete increases. The gradient of the increase in abrasion loss tends to become almost constant for specimens of about 600 kgf/cm^2 or more in compressive strength. It was also verified experimentally that abrasion loss saw a greater increase as steel balls were dropped from higher positions, or at higher speeds.[35)]

Fig. 13 shows the relationship between the compressive strength of mortar and the percentage of abrasion. As is obvious from the curve in the graph, there is a good correlation: that is, the larger the compressive strength, the lesser the percentage of abrasion. In the figure, the percentage of abrasion of limestone and basalt is also shown. Basalt has a low percentage of abrasion, which does not intersect the curve of mortar. Because of a large difference in the strength and abrasion loss between mortar and coarse aggregate, pits and projections are apt to be formed between coarse aggregates. In contrast, because limestone, having a high percentage of abrasion, is apt to be worn away when the compressive strength of mortar is 224 kgf/cm^2 or more, pits and projections have difficulty forming between coarse aggregates.

(2) Effects of concrete quality on abrasion

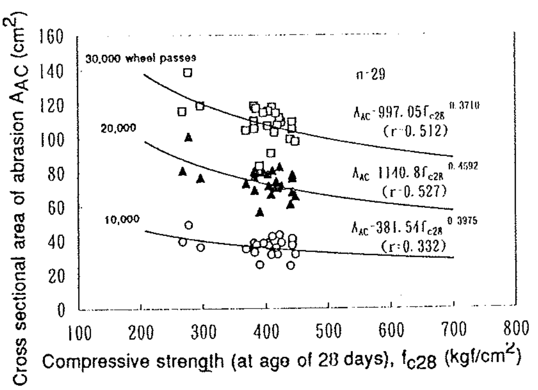
It has been verified through a great number of studies that there is a strong correlation between the compressive or flexural strength of concrete and abrasion loss.[2),6),9)] Figs. 14 and 15 show the relationship between the compressive strength of concrete (at an age of 28 days) and abrasion loss and that between the flexural strength and abrasion loss, respectively (obtained from Test III, V, and IX). As is evident from the figures, the higher the strength, the lesser the abrasion loss and the increase rate of abrasion loss.

The strength of concrete increases with age. As shown in Fig. 16, although younger concrete tends to show more wear, the difference in abrasion loss between 7 days and 1 year of age is very small, about 1 mm (obtained from Test VIII).

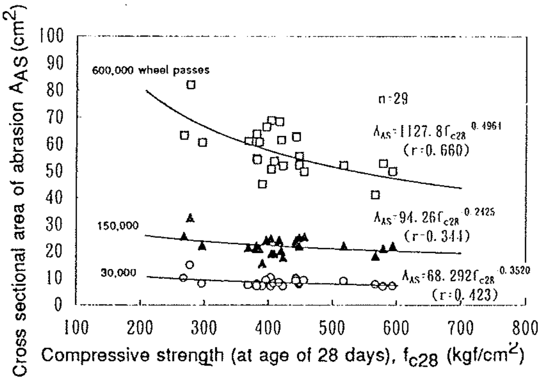
Incidentally, the design flexural strength of concrete for paved concrete roads is generally set to 45 kg/cm^2. It is necessary to take into account a drop in the skid resistance of road when increasing the design strength to reduce abrasion loss.

(3) Effects of concrete mix proportion on abrasion

In general, as the cement content per unit volume of concrete C increases and the water content per unit volume W decreases (i.e. a smaller water-cement ratio W/C), the optimum sand-aggregate ratio also decreases and a higher compressive strength can be obtained.[32), 36)] Figs. 17 through 19 show the relationship between these conditions of concrete mix proportion and abrasion loss (obtained from Test

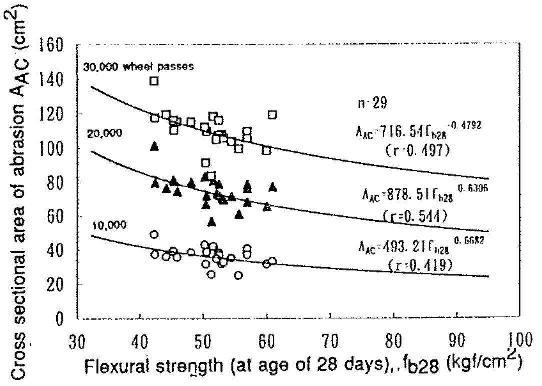


(a) Chained tire (Tests III and V)

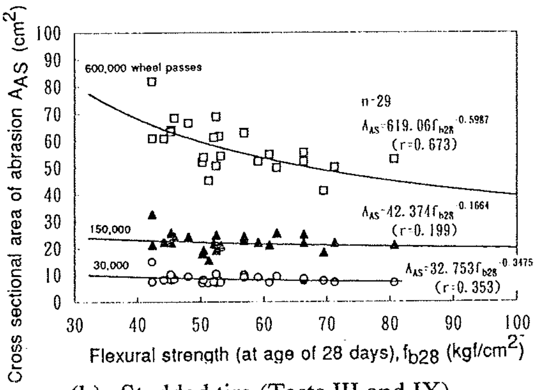


(b) Studded tire (Tests III and IX)

Fig. 14 Relationship between the compressive strength of concrete and abrasion loss ($V = 60$ km/hr., $W_L = 2.0$ tons)



(a) Chained tire (Tests III and V)



(b) Studded tire (Tests III and IX)

Fig. 15 Relationship between the flexural strength of concrete and abrasion loss ($V = 60$ km/hr., $W_L = 2.0$ tons)

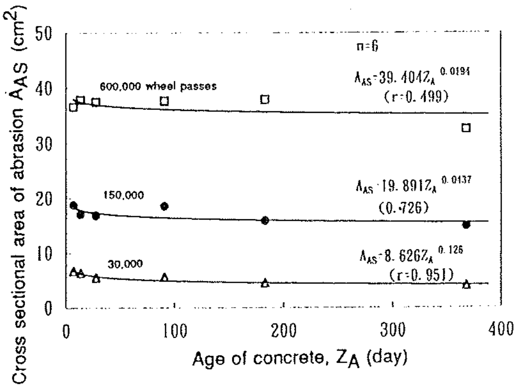


Fig. 16 Relationship between the age of concrete and abrasion loss (ST, Test VIII, $V = 40$ km/hr., $W_L = 2.0$ tons)

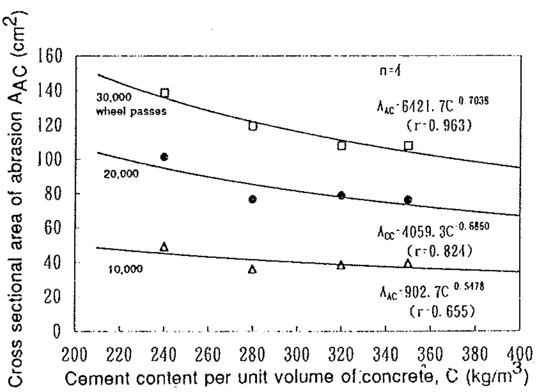


Fig. 17 Relationship between cement content per unit volume of concrete and abrasion loss (CT, Test III, $V = 60$ km/hr., $W_L = 2.0$ tons)

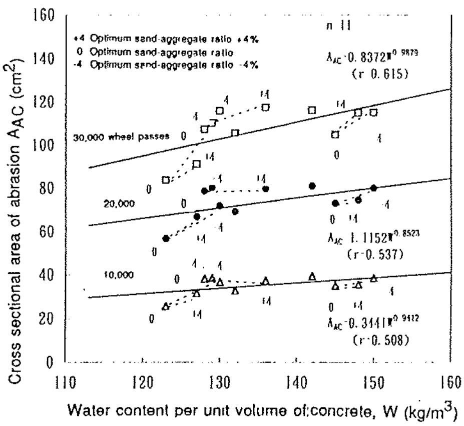


Fig. 18 Relationship between water content per unit volume of concrete and abrasion loss (CT, Test III, V = 60 km/hr., W_L = 2.0 tons)

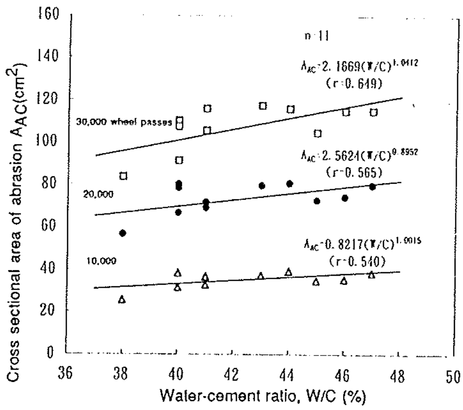


Fig. 19 Relationship between water-cement ratio and abrasion loss (CT, Test III, V = 60 km/hr., W_L = 2.0 tons)

III). Abrasion loss decreases with an increase in cement content per unit volume of concrete, but as is the case in the relationship between the strength of concrete and abrasion loss, the higher the strength, the lesser the abrasion loss and the increase rate of abrasion loss.

As is obvious from the relationship between water content per unit volume of concrete and abrasion loss, at the same workability (at a slump of 2.5±1 cm) and cement content per unit volume of concrete, the abrasion loss increases as the water content increases due to a difference in aggregate quality. When the sand-aggregate ratio is increased by ±4% from the optimum sand-aggregate ratio at which the water content per unit volume of concrete becomes smaller, the water content tends to increase by 1-8 kg/m^3 and the abrasion loss also increases. As shown in the figure, abrasion loss increases with the number of times that wheels pass, which seems due to the fact that coarse aggregate is exposed and the effects of concrete quality become predominant as abrasion develops. Accordingly, to improve the resistance of concrete to abrasion, one approach of decreasing the sand-aggregate ratio, or increasing the weight of coarse aggregate per unit volume of concrete can be considered. However, this tendency cannot be seen from Fig. 18. Another approach to make concrete dense with less water content per unit volume of concrete is considered more effective.

As is the case with the relationship between concrete strength and abrasion loss, there is a good correlation between water-cement ratio and abrasion loss; the less the water-cement content, the less the abrasion loss without regard to cement content per unit volume of concrete, sand-aggregate ratio, and aggregate type.

(4) Effects of aggregate quality on abrasion

a) Coarse aggregate

Regarding the requirements for aggregate quality in order to improve the resistance of roads to abrasion, it is specified that the limits of percentage of abrasion of coarse aggregate is to be 35% or less for concrete pavement, and 25% or less for roads subject to severe abrasive conditions by chained and other tires in cold climates.[11] In addition, the standard limits of percentage of abrasion for dam concrete is to be 40%.[11]
Fig. 20 shows the relationship between percentage of abrasion of coarse aggregate and abrasion loss. As shown in the figure, the abrasion loss tends to increase on a whole with the percentage of abrasion of coarse aggregate, but there is a weak correlation between them. On the other hand, as can be seen from Fig. 21, there is a strong correlation between the solid volume percentage of coarse aggregate and

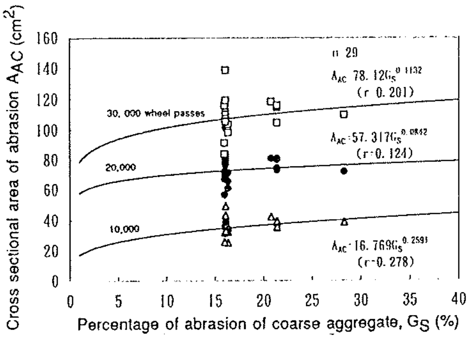


Fig. 20 Relationship between the percentage of abrasion of coarse aggregate and abrasion loss (CT, Test III & V, V = 60 km/hr., W_L = 2.0 tons)

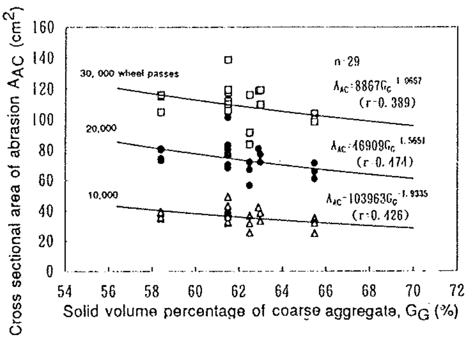


Fig. 21 Relationship between solid volume percentage of coarse agrregate and abrasion loss (CT, Test III & V, V = 60 km/hr., W_L = 2.0 tons)

abrasion loss, i.e. abrasion loss decreases with the large solid volume percentage. It has already been verified through past studies that the abrasion loss of concrete using crushed stone is more than that of concrete using gravel even at the same strength.[9),12)] This seems due to the fact that aggregate having sharp corners or a smaller solid volume percentage is apt to be worn away more than that having round ones because the former undergoes external forces at the sharp corners.

In addition, as to the relationship between the maximum size of coarse aggregate and abrasion loss, it has been verified through steel-ball tests using a Los Angeles Abrasion Machine that abrasion loss decreases as coarse aggregate size increases (from 5 to 60 mm).[34), 37)] On the other hand, abrasion loss tends to increase with the maximum size of coarse aggregate since the mortar content increases between aggregates as their size increases to maximum. Therefore, taking mix proportions into consideration, there is little correlation (positive[20),24)] or negative[22)]) between the maximum size of coarse aggregate and abrasion loss (Tests III, VI, and IX).

b) Fine aggregate

Figs. 22 and 23 show the relationship between the mass of unit volume of fine aggregate and abrasion loss and also that between the fineness modulus of fine aggregate and abrasion loss, respectively. It can be seen from these figures that abrasion loss tends to decrease as either the mass of unit volume, the solid volume percentage, or the fineness modulus of fine aggregate increases. This is due to the data verified earlier, that fine aggregate in large mass of unit volume has good grain shape, therefore decreasing the unit water content in concrete and increasing the compressive strength of concrete.[32),36)] Further, the compressive strength of concrete tends to decrease and the abrasion loss to increase as the water absorption increases.[32)]

Fine aggregate at a large fineness modulus contains a high proportion of large grains. As described earlier, it was verified through a Los Angeles Machine using steel-ball tests that the percentage of abrasion loss tends to decrease as grain size increases. This agrees with the above-mentioned tendency of the abrasion loss to decrease as the fineness modulus of fine aggregate increases.

(5) Construction methods

To investigate the effects of construction methods on abrasion loss, tests were conducted with the following varied parameters:

- number of days under moist curing (zero, 3 and 10 days)
- compaction method (single-layer and double-layer compaction)
- vibrator type (internal and surface vibrators)

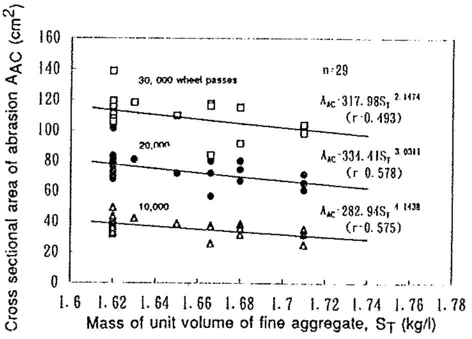


Fig. 22 Relationship between the mass of unit volume of fine aggregate and abrasion loss (CT, Test III, V = 60 km/hr., W_L = 2.0 tons)

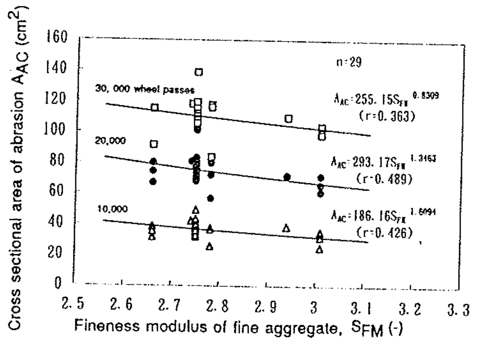
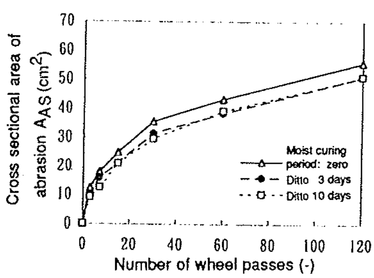
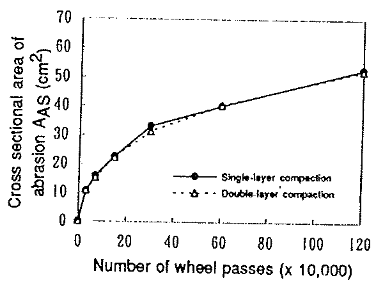


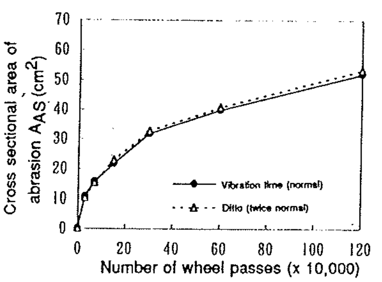
Fig. 23 Relationship between the fineness modulus of fine aggregate and abrasion loss (CT, Test III, V = 60 km/hr., W_L = 2.0 tons)



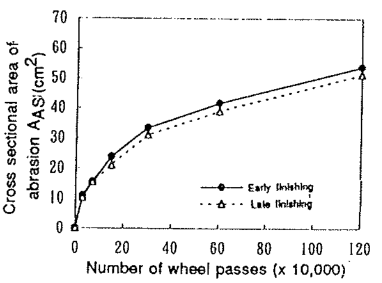
(a) Number of days under moist curing



(b) Compaction methods



(c) Vibration time



(d) Surface finishing timing

Fig. 24 Relationship between construction methods and abrasion loss (ST, Test VII, V = 40 km/hr., W_L = 2.0 tons)

- vibration time (normal and twice normal)
- surface finishing timing (early and late)
- the slump of concrete (zero and 6 cm) (Test VII)

As a result, it was found that the following parameters having some correlation with concrete strength had some correlation with abrasion loss: the number of days under moist curing; the slump of concrete (a difference in water content); and surface finishing timing. Little correlation was found between the other parameters and abrasion loss (see Fig. 24 for typical relationships between construction methods and abrasion loss).

(6) Abrasion-resistant materials

To clarify the effectiveness of abrasion-resistant materials on retarding road abrasion, tests were conducted by spreading five types of abrasion-resistant materials on concrete surfaces, as listed in Table 4 (Test II). From the test results shown in Fig. 25, no improvement in the resistance of concrete to abrasion was recognized. After the tests were complete, core samples were taken from road specimens for observation of cross sections. From these observations it was found that abrasion-resistant materials were distributed from the surface of the sample to a depth of about 5 mm in the top mortar layer of concrete. Accordingly, just as is the case with fine aggregate, abrasion-resistant materials exerted no effect because these materials peeled off and were blown away during the tests.

Table 4 Abrasion-resistant materials

Material	Specific gravity	Mohs' hardness	Remarks
Foreign-made abrasion-resistant material	3.21	9	Primary composition: silicon carbide
Non-natural emery	3.71	8	Percentage of abrasion (D grain size): 17.5%
Natural emery	3.26	8	Percentage of abrasion (D grain size): 14.0%
Iron powder	7.26	8	Microstructure: temper-hardened martensite
Silica sand	2.52	7	Percentage of abrasion (D grain size): 41.9%

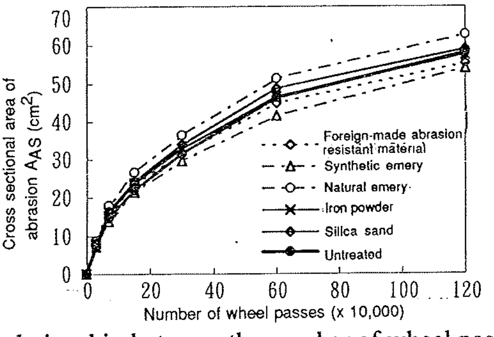


Fig. 25 Relationship between the number of wheel passes and the abrasion loss of concrete sprayed with abrasion-resistant materials

(7) Grooving

The mechanism of abrasion on grooved road surfaces, or road surfaces with depressions artificially provided to improve the skid resistance, is different from that of ordinary road surfaces without grooves. Figs. 26 and 27 show the details of grooves and the relationship between the number of wheel passes and a difference in the abrasion loss of grooved and non-grooved road surfaces, respectively (obtained from Test III). It can be considered that grooved surfaces have already been worn to an equivalent abrasion depth of 0.6 mm (for grooves spaced every 25 mm) and 0.2 mm (for grooves spaced every 50 mm) before testing. The surfaces are worn down sharply to an average abrasion depth of about 2 mm when studded tires travel on the surfaces. As a result, as compared with non-grooved surfaces, grooved ones wear to the average depth in about half the normal number of wheel passes. However, after the groove corners are worn and abrasion develops to a depth of about 2 mm or more, the increase in the abrasion of grooved surfaces is the same as non-grooved surfaces, and the difference in the depth of abrasion between grooved and non-grooved surfaces in the final state is the same as the difference in the depth of abrasion by grooving in the initial state. This occurrence coincides with the finding that the abrasion of crushed stone having more sharp corners (or a smaller solid volume percentage) is more than that of gravel. This tendency is also seen on road surfaces grooved perpendicularly to the direction of travel.[23]

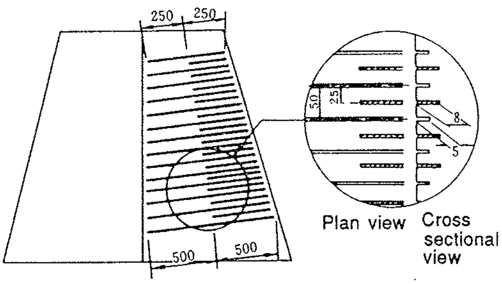


Fig. 26 Details of grooves

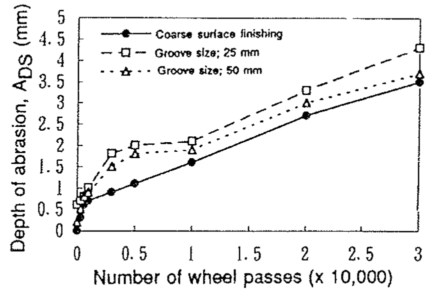


Fig. 27 Relationship between the number of wheel passes and the abrasion loss of grooved and non-grooved road surface (ST, Test III, V=60 km/hr., W_L = 2.0 tons)

5. ESTIMATION OF CONCRETE ABRASION LOSS

(1) Results of multiple regression analysis on abrasion loss

Various factors influencing the abrasion of concrete have been discussed so far. Table 5 and Fig. 28 show typical results of a multiple regression analysis on the relationship between the factors and abrasion loss (refer to Table 3 for the symbols). In Table 5, predictor variables x_1, x_2, ... are arranged in the order that the data was taken by the stepwise method (in the order of decreasing correlation.) Although all data is within the range listed in Table 3, some data was biased. A study was made on the number of items to be adopted (i) by deleting variables in a narrow range and variables that lacked rationality traceable to a correlation between variables (multi-collinearity) so that a strong correlation could be obtained.

A comparison was made on a correlation between the factors and abrasion loss from each type tire in the following three cases, with the compressive and flexural strength of concrete taken as variables.

Case 1: where the number of items is 15, consisting of primary factors
Case 2: where the number of items is 7-11
Case 3: where the number of items is limited to 4 or 5

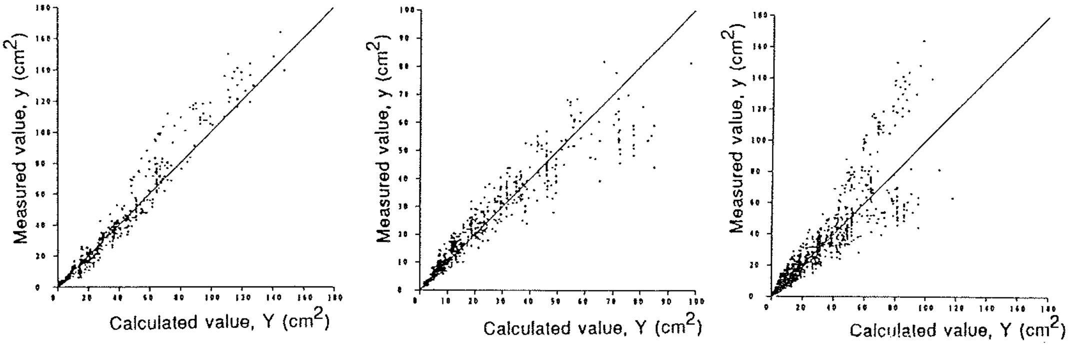
As can be seen from Table 3, for chained tires, the abrasion loss as measured in cross sectional area A_{AC} covers a wide range, up to 164 cm^2 (with a mean abrasion depth of about 55 mm), and with a multiple correlation coefficient R of 0.97-0.99, indicating a strong correlation. The abrasion loss is largely affected by tire and traveling conditions, with specimen conditions having relatively little affect. Factors are arranged in order of decreasing correlation as follows:

The number of wheel passes N, metal component load per unit length of circumference M_L, and traveling speed V are predominant, followed by the radius of track R_A, the mass of unit volume of fine aggregate S_T, displacement of a track H_E, wheel load W_L, the solid volume percentage of coarse aggregate G_G, the fineness modulus of fine aggregate S_{FM}, the compressive strength of concrete f_{c28}, the flexural strength of concrete f_{b28}, and age of concrete when traveling started Z_A. Of the traveling conditions, a positive correlation is seen between R_A and abrasion loss. This indicates that the larger the radius of a track, the smaller centrifugal and cornering forces act on the tire and the larger component of chain loads act on the road surface. Therefore, a positive correlation is also seen between H_E and abrasion loss.

Table 5 Results of multiple regression analysis on abrasion loss

Tire	Case	Regression equation	No.
Chained tire	Case 1	$A_{AC}=10^{-7.7427}\cdot N^{0.8375}\cdot M_L^{2.1936}\cdot V^{0.9266}\cdot R_A^{1.8887}\cdot S_T^{-4.5006}\cdot H_E^{0.3175}\cdot f_{c28}^{-0.3417}\cdot G_S^{0.2900}\cdot G_G^{2.3292}\cdot S_{FM}^{-0.5622}\cdot G_M^{0.4271}\cdot Z_A^{0.0865}$ (3.3) (85.7) (50.5) (27.9) (11.4) (-9.0) (5.0) (-3.5) (4.4) (4.2) (-2.2) (2.6) (1.7) [n=601, i=15, p=12 (F_{OUT}: W_L, S_Q, G_Q), R=0.987, K=0.975, e_s=8.5cm², z_s=0.229]	(4)
		$A_{AC}=10^{-5.6679}\cdot N^{0.8350}\cdot M_L^{2.1996}\cdot V^{0.9304}\cdot R_A^{1.9475}\cdot S_T^{-4.5911}\cdot H_E^{0.2056}\cdot f_{b28}^{-0.4359}\cdot G_G^{1.7822}\cdot S_{FM}^{-0.7245}\cdot G_S^{0.1471}$ (7.0) (86.8) (51.0) (27.9) (12.2) (-9.6) (7.4) (-3.8) (4.2) (-3.1) (2.7) [n=601, i=15, p=10 (F_{OUT}: W_L, Z_A, S_Q, G_M, G_Q), R=0.987, K=0.974, e_s=8.5cm², z_s=0.230]	(5)
	Case 2	$A_{AC}=10^{-0.0668}\cdot N^{0.8077}\cdot M_L^{1.5860}\cdot V^{1.1425}\cdot S_T^{-3.5519}\cdot S_{FM}^{-1.5024}\cdot W_L^{0.29744}\cdot f_{c28}^{-0.4628}$ (9.5) (85.6) (19.8) (38.8) (-11.0) (-5.8) (4.8) (-4.5) [n=601, i=11, p=7 (F_{OUT}: Z_A, G_M, G_G, G_S), R=0.984, K=0.969, e_s=8.8cm², z_s=0.258]	(6)
		$A_{AC}=10^{2.8689}\cdot N^{0.7968}\cdot M_L^{1.5113}\cdot V^{1.1624}\cdot G_G^{-2.1330}\cdot f_{c28}^{-0.5621}\cdot W_L^{0.39804}\cdot S_{FM}^{-0.5929}$ (4.8) (80.5) (18.2) (37.6) (-7.7) (-5.2) (6.2) (-2.3) [n=601, i=7, p=7 (F_{OUT}: None), R=0.983, K=0.966, e_s=9.6cm², z_s=0.272]	(7)
	Case 3	$A_{AC}=10^{-1.2312}\cdot N^{0.7625}\cdot M_L^{1.4219}\cdot V^{1.2447}\cdot W_L^{0.5185}\cdot f_{c28}^{-0.5833}$ (4.1) (81.5) (17.1) (40.9) (9.3) (-5.9) [n=601, i=5, p=5 (F_{OUT}: None), R=0.981, K=0.963, e_s=10.7cm², z_s=0.286]	(8)
		$A_{AC}=10^{-2.7908}\cdot N^{0.7418}\cdot M_L^{2.1023}\cdot V^{1.2681}\cdot f_{c28}^{-0.2996}$ (10.5) (76.2) (49.0) (39.1) (-3.0) [n=601, i=4, p=4 (F_{OUT}: None), R=0.978, K=0.957, e_s=12.7cm², z_s=0.298]	(9)
		$A_{AC}=10^{1.1694}\cdot N^{0.7812}\cdot W_L^{1.3505}\cdot V^{1.2235}\cdot f_{c28}^{-0.8405}$ (3.6) (68.9) (41.3) (33.0) (-7.0) [n=601, i=4, p=4 (F_{OUT}: None), R=0.972, K=0.944, e_s=11.1cm², z_s=0.367]	(10)
		$A_{AC}=10^{0.5480}\cdot N^{0.7780}\cdot W_L^{1.3272}\cdot V^{1.2340}\cdot f_{b28}^{-0.9193}$ (2.2) (68.6) (41.6) (33.3) (-6.6) [n=601, i=4, p=4 (F_{OUT}: None), R=0.972, K=0.944, e_s=11.0cm², z_s=0.373]	(11)
Spiked tire	Case1	$A_{AS}=10^{1.8483}\cdot N^{0.6466}\cdot M_L^{0.7602}\cdot V^{0.3861}\cdot f_{c28}^{-0.3172}\cdot S_T^{-3.7683}\cdot S_{FM}^{-0.6243}\cdot R_A^{-0.8305}\cdot G_S^{0.1797}\cdot Z_A^{-0.0334}$ (5.5) (36.2) (9.4) (3.8) (-1.9) (-5.3) (-2.3) (-1.9) (1.6) (-1.6) [n=748, i=15, p=9 (F_{OUT}: $M_L, H_E, S_Q, G_M, G_G, G_Q$), R=0.836, K=0.699, e_s=6.4cm², z_s=0.226]	(12)
		$A_{AS}=10^{0.5265}\cdot N^{0.6436}\cdot M_L^{0.9842}\cdot V^{0.3368}\cdot S_T^{-3.0098}\cdot S_{FM}^{-0.8968}\cdot M_L^{-0.3428}\cdot G_S^{0.2755}\cdot G_Q^{-0.1180}$ (3.8) (36.2) (7.9) (3.8) (-3.9) (-3.6) (-1.9) (2.4) (-1.6) [n=748, i=15, p=8 (F_{OUT}: $R_A, H_E, f_{b28}, Z_A, S_Q, G_M, G_G$), R=0.835, K=0.697, e_s=6.6cm², z_s=0.237]	(13)
	Case2	$A_{AS}=10^{1.7383}\cdot N^{0.6492}\cdot M_L^{0.8081}\cdot V^{0.2737}\cdot f_{c28}^{-0.4145}\cdot S_T^{-3.3072}\cdot S_{FM}^{-0.6664}\cdot G_S^{0.1666}$ (5.1) (37.2) (10.5) (3.1) (-2.6) (-4.8) (-2.5) (1.5) [n=748, i=12, p=7 (F_{OUT}: Z_A, S_Q, G_M, G_G, G_Q), R=0.835, K=0.698, e_s=6.3cm², z_s=0.239]	(14)
		$A_{AS}=10^{1.1267}\cdot N^{0.6366}\cdot M_L^{0.8384}\cdot V^{0.3792}\cdot f_{c28}^{-0.4849}\cdot S_Q^{0.3864}\cdot S_{FM}^{-0.7601}$ (2.6) (36.1) (11.1) (4.4) (-3.1) (4.3) (-2.7) [n=748, i=8, p=6 (F_{OUT}: G_G, G_S), R=0.834, K=0.695, e_s=6.8cm², z_s=0.229]	(15)
		$A_{AS}=10^{4.6499}\cdot N^{0.6498}\cdot M_L^{0.9424}\cdot V^{0.2637}\cdot f_{c28}^{-0.3936}\cdot G_G^{-2.0070}\cdot S_{FM}^{-0.4662}$ (3.8) (36.9) (14.0) (2.9) (-2.5) (-3.2) (-1.7) [n=748, i=6, p=6 (F_{OUT}: None), R=0.831, K=0.695, e_s=5.9cm², z_s=0.244]	(16)
	Case3	$A_{AS}=10^{0.0982}\cdot N^{0.6637}\cdot M_L^{1.2072}\cdot V^{0.4423}\cdot f_{c28}^{-0.2998}$ (0.2) (33.4) (9.9) (4.5) (-1.9) [n=748, i=4, p=4 (F_{OUT}: None), R=0.780, K=0.609, e_s=7.5cm², z_s=0.424]	(17)
		$A_{AS}=10^{1.0583}\cdot N^{0.6452}\cdot W_L^{1.0169}\cdot V^{0.3686}\cdot f_{c28}^{-0.5568}$ (2.4) (36.5) (17.5) (4.2) (-3.9) [n=748, i=4, p=4 (F_{OUT}: None), R=0.828, K=0.686, e_s=5.9cm², z_s=0.255]	(18)
		$A_{AS}=10^{0.2784}\cdot N^{0.6418}\cdot W_L^{0.9722}\cdot V^{0.4052}\cdot f_{b28}^{-0.4189}$ (0.9) (36.0 (17.1) (4.7) (-2.8) [n=748, i=4, p=4 (F_{OUT}: None), R=0.827, K=0.683, e_s=5.9cm², z_s=0.252]	(19)
Chained + spiked tire	Case1	$A_{AT}=10^{-0.1013}\cdot N^{0.7298}\cdot M_L^{0.9023}\cdot V^{0.9319}\cdot W_L^{0.5272}\cdot S_T^{-2.6858}\cdot f_{c28}^{-0.3005}\cdot Z_A^{-0.0525}\cdot S_{FM}^{-0.6247}\cdot G_S^{0.2113}\cdot S_Q^{0.1531}\cdot G_Q^{-0.0765}$ (4.1) (59.5) (51.6) (20.2) (11.0) (-4.6) (-2.6) (-3.0) (-2.9) (2.7) (1.9) (-1.9) [n=1349, i=15, p=11 (F_{OUT}: R_A, H_E, G_M, G_G), R=0.904, K=0.817, e_s=12.5cm², z_s=0.352]	(20)
		$A_{AT}=10^{-0.7978}\cdot N^{0.7268}\cdot M_L^{0.9055}\cdot V^{0.9508}\cdot W_L^{0.5177}\cdot S_T^{-2.8400}\cdot Z_A^{-0.0597}\cdot S_{FM}^{-0.8367}\cdot G_S^{0.2369}\cdot G_Q^{-0.0948}\cdot S_Q^{0.1402}$ (4.0) (59.4) (51.8) (20.9) (10.8) (-4.9) (-3.4) (-4.1) (3.0) (-1.9) (1.7) [n=1349, i=15, p=10 (F_{OUT}: $R_A, H_E, f_{b28}, G_M, G_G$), R=0.903, K=0.816, e_s=12.5cm², z_s=0.355]	(21)
	Case2	$A_{AT}=10^{0.0643}\cdot N^{0.7298}\cdot M_L^{0.9047}\cdot V^{0.9375}\cdot W_L^{0.5201}\cdot S_T^{-2.7346}\cdot f_{c28}^{-0.3256}\cdot Z_A^{-0.0574}\cdot S_{FM}^{-0.6537}\cdot G_S^{0.1575}\cdot S_Q^{0.1169}$ (4.3) (59.5) (51.9) (20.4) (10.9) (-4.7) (-2.8) (-3.3) (-3.0) (2.2) (1.5) [n=1349, i=12, p=10 (F_{OUT}: G_M, G_G), R=0.904, K=0.817, e_s=12.4cm², z_s=0.352]	(22)
		$A_{AT}=10^{1.2209}\cdot N^{0.7251}\cdot M_L^{0.8976}\cdot V^{0.9397}\cdot W_L^{0.5722}\cdot S_Q^{0.3008}\cdot f_{c28}^{-0.3259}\cdot S_{FM}^{-0.5693}\cdot G_G^{-1.1695}\cdot Z_A^{-0.0308}\cdot G_S^{0.1173}\cdot G_M^{0.1400}$ (1.5) (58.4) (51.1) (20.0) (12.4) (4.8) (-2.8) (-2.6) (-2.8) (-1.9) (1.6) (1.5) [n=1349, i=11, p=11 (F_{OUT}: None), R=0.903, K=0.815, e_s=12.6cm², z_s=0.356]	(23)
	Case3	$A_{AT}=10^{-0.3919}\cdot N^{0.7303}\cdot M_L^{0.9065}\cdot V^{0.9486}\cdot W_L^{0.6764}\cdot f_{c28}^{-0.4781}$ (1.3) (64.0) (53.2) (21.0) (18.4) (-4.6) [n=1349, i=5, p=5 (F_{OUT}: None), R=0.898, K=0.807, e_s=12.2cm², z_s=0.377]	(24)
		$A_{AT}=10^{-0.8031}\cdot N^{0.7276}\cdot M_L^{0.9067}\cdot V^{0.9584}\cdot W_L^{0.6517}\cdot f_{b28}^{-0.4911}$ (3.7) (63.9) (53.1) (21.4) (18.4) (-4.4) [n=1349, i=5, p=5 (F_{OUT}: None), R=0.898, K=0.807, e_s=12.2cm², z_s=0.372]	(25)

Note: Data in parentheses in the lower column indicates t-value. n: number of data, i: number of items, p: degree of freedom, F_{Out}: items taken out, R: multiple correlation coefficient, K: coefficient of determination,
e_S: standard deviation of residual, e, z_S: standard deviation of measured values divided by calculated values,
$\overline{e}$, i.e. mean value of e, and $\overline{z}$, i.e. mean value of z, is 0 and 1.0, respectively.



(a) Eq. (6) (b) Eq. (14) (c) Eq. (22)

Fig. 28 Typical relationships between calculated value and measured value of abrasion loss

For studded tires, the abrasion loss as measured in cross sectional area A_{AS} covers a range of 82 cm^2 (or a mean abrasion depth of about 30 mm), with a multiple correlation coefficient R of 0.82-0.84,indicating a lesser correlation than that of chained tires. Factors are arranged in order of decreasing correlation as follows: N, W_L, V, f_{c28}, S_T, S_{FM}, G_G, S_Q, G_M, and R_A. Tendencies different from those of chained tires are as follows: although there is a strong correlation between N and W_L, there is little correlation with M_L, and a weak correlation with V. Further, a negative correlation is seen with R_A, indicating that large cornering forces act on road surfaces due to the side-skid of tires as the radius of a track becomes smaller.

For chained and studded tires, cross sectional area of abrasion A_{AT} shows tendencies on the average of both tires. The difference in external forces are represented by M_L and W_L. Factors are arranged in order of decreasing correlation as follows: N, M_L, V, W_L, S_T, S_Q, f_{c28}, f_{b28}, Z_A, S_{FM}, G_G, and G_S. Of the concrete quality factors, the correlation with f_{c28} is better that with f_{b28}.

(2) Equations for estimating abrasiones

The abrasion of road surfaces is greatly influenced when (large) trucks having large M_L (for chained tires) and W_L (for studded tires) travel on the surfaces, and the abrasion loss is governed by the number of times that trucks passed. From Table 5, the following typical equations of estimating depth of abrasion, A_{DC}, A_{DS} and A_{DT} (mm), can be derived by dividing cross sectional area of abrasion, A_{AC}, A_{AS} and A_{AT} (cm^2), by the width of the tire tread for trucks, 30 cm.

$$A_{DC} = A_{AC} / 3 \tag{26}$$

$$A_{DS} = A_{AS} / 3 \tag{27}$$

$$A_{DT} = A_{AT} / 3 \tag{28}$$

To estimate the depth of abrasion on actual road surfaces, it is necessary to first make an investigation of the following factors, and then substitute this data into the equations: the number of wheel passes by vehicle type, the percentage of tires equipped with non-slip devices by non-slip device type, the distribution of wheel loads, the distribution of vehicles across the traffic lanes, and the concrete quality. An important point to note when substituting data into these equations is that factors having strong correlation should be taken as variables, and that the data, from which the equations are derived, should be within the range listed in Table 3.

6. CONCLUSIONS

The results of this study can be summarized as follows.

(1) The magnitude of external forces acting on road surfaces and the effects of non-slip devices on abrasion loss vary depending on ladder type (inclusive of chained tires) or net type (inclusive of studded tires).

(2) The abrasion of road surfaces is affected by the mutual magnitude of external forces acting on road surfaces and the quality of mortar and coarse aggregate in concrete.

(3) The abrasion of surfaces caused by chained tires is greatly affected by the number of times that wheels pass over the pavement, metal component load per unit length of circumference, traveling speed, and wheel load. And that abrasion also varies depending on concrete quality.

(4) The abrasion of surfaces caused by studded tires is greatly affected by the number of times the wheels pass over the pavement and wheel load. And that abrasion also varies depending on traveling speed and concrete quality.

(5) Selecting a fine aggregate with large mass of unit volume, large finess modulus, and small water absorption, plus a coarse aggregate with small percentage of abrasion and large solid volume percentage, and using a low water-cement ratio to get high compressive and flexural strength, will increase concrete's resistance to surface abrasion.

(6) As listed above, the authors propose Eqs. (26) through (28) for estimating both the depth of abrasion and the useful life of concrete pavement surfaces. These proposed equations show good consistency with multiple regression Eq. (3).

(7) The differences in external forces between various non-slip devices can be represented by the metal component load per unit length of tire circumference, traveling speed, and wheel load.

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