INTERFACIAL DEBONDING OF ICE-ASPHALT CONCRETE

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In order to clarify the nature of the bonding mechanism between ice and asphalt concrete and to develop new techniques to reduce debonding resistance, a series of experimental investigation was conducted. Surface energy was varied by using various water repellents, and stiffness of asphalt concrete was varied by mixing crushed rubber particles with the asphalt. Correlations between these variables were investigated and the following conclusion was obtained. Reducing surface energy and/ or increasing deformability of the asphalt concrete is an effective way to decrease interfacial bonding between ice and asphalt concrete. In this regard, use of water repellents or replacement of aggregate with rubber particles is a promising method to facilitate debonding of ice and asphalt concrete.

Keywords : *debonding, interface, ice, asphalt, repellent*

1. INTRODUCTION

In order to clarify bonding mechanism between ice and asphalt concrete and to develop new debonding technique, series of experimental investigations were conducted. Results of these investigation will provide useful informations on developing a new type of asphalt concrete or designing a new mechanism for ice removal machine.

Interfacial debonding resistance were measured by three different methods. One is single plane shear test which is originally contrived for soil test, the second is pure tension test in which tensile stress field is generated at the interface as a reflected wave induced by impact of drop hammer, and the third method is local compression test prosecuted under static or dynamic condition. In the second test, number of repeated cycle until debonding was measured and total energy spent for debonding was taken as a measure. Surface energy and surface roughness of asphalt concrete were measured by roughness tester and contact angle tester provided with optical microscope respectively. Various materials, which might change the debonding characteristics in a surface chemical or mechanical manner, were incorporated with asphalt concrete. As the former method, various types of water repellent agent were coated on asphalt concrete surface by brush-painting or mixed with asphalt. As the latter method, partial replacement of aggregate with rubber particles was adopted.

Table 1 Marshall Test

Asphalt content (%)	6.2
Porosity (%)	3.7
Degree of saturation (%)	79.4
Density (g/cm ³)	2.373
Flow (cm)	3.1
Stability (kg)	900

In order to clarify the debonding characteristics of ice, influences of these variables were experimentally studied and effective methods to facilitate debonding of ice-asphalt concrete interface were investigated.

2. EXPERIMENTAL PROCEDURES

(1) Materials used for series 1

a) Asphalt concrete

Two types of asphalt plate were prepared. One was asphalt concrete that was mixed with quite popular mix proportion using straight asphalt 60/80 (penetration : 69, softening point : 49.0°C).

Results of Marshall test of this mix is shown in **Table 1**. The other is mortar plate that contains no coarse aggregate.

b) BL asphalt emulsion

Properties of BL asphalt emulsion used for flattening the specimen surface is shown in **Table 2**. Nonionic surfactant of higher alcohol ether was used as emulsifier. Toyoura silica sand prescribed in Japanese standard and normal Portland cement were also used for flattening treatment.

c) Water repellent agents

In order to reduce surface tension of asphalt concrete, various materials shown in **Table 3** were selected from commercial products. One of these

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Table 2 Properties of BL Emulsion

Engler degree (25 °C)		5 ~15
Plus sieve (1190 μ m)		% <0.3
Evaporated residue	Residue	% >57
	Penetration (25 °C)	60~150
	Ductility (15 °C) cm	>100
	Solubility in trichloro-ethane	% >97.0

Table 3 Water Repellent Agent

1	organic polysiloxane bonded with special metal
2	dimethyl polysiloxane
3	denatured polysiloxane
4	silicone water repellent agent (polysiloxane group)
5	silicone water repellent agent (polysiloxane group)
6	silane ($\text{Si}, \text{H}_{2n+2}$)
7	fluorine contained resin (solvent:xylene)
8	fluorine contained resin (solvent/acetone/ethyl acetate 50/50)
9	oleic acid
10	surface active agent of nonionic type (sorbitan ester)
11	mixture of higher fatty acid, zinc naphthenate, polyvinyl resin ester, penetration promoter, solvent and diluent
12	pulverized silicone polyper (powder)
13	treated hydrophobic silica powder

materials was applied on surface of asphalt concrete or mixed with asphalt.

d) Aggregate

Crushed pelitic hornfels was used as coarse aggregate by blending two different sizes (No.6 and No.7 by Japanese Standard). Sea sand was used as fine aggregate. Lime stone powder and screenings were also used. Same types of aggregate were used for series 2 except that screenings was not used for series 2.

(2) Materials used for series 2

a) Rubber tips

Rubber particles manufactured by cryogenic pulverization of waste tires were classified into four different grain sizes, namely 5~3 mm, 3~1 mm, 1~0 mm and 0.6~0 mm. Three types of rubber aggregate, that is, 5~3 mm, 0.6~0 mm and blended type were used. In the last rubber aggregate, equal amounts of the four different sizes were blended.

b) Asphalt

Straight asphalt 60/80 (penetration : 66, softening point : 48°C, ductility : >150 cm) was used.

(3) Methods of experiments for series 1

a) Surface roughness of asphalt concrete

Roughness tester shown in **Photo 1** was used to record the magnified profile of asphalt concrete surface. Tracing of the surface was made by ball type of stylus. As a roughness index, average

Photo 1 Roughness Tester **Photo 2** Single Plane Shear Apparatus

deviation from center line (Ra) defined by equation-(1) for measurement length L was used, where x is distance along the center line and y is deviation from center line in micrometer. In this study L was 16 mm.

$$Ra = \frac{1}{L} \int_0^L |y(x)| dx \dots \dots \dots (1)$$

b) Debonding strength by single plane shear

Single plane shear tester that is originally contrived for soil test (**Photo 2**) was used. Shear plane was carefully adjusted so that the ice-asphalt concrete interface coincides with the plane. Applied load and shear displacement was measured by proving ring and dial gauge (1/1000 mm scale) respectively. Thickness of ice and asphalt concrete was 13.5 mm respectively and ice was prepared by placing a specimen overnight in a refrigerator.

c) Debonding strength by impact tension

As is shown in **Fig.1**, tensile stress wave is generated at the ice-asphalt concrete interface by impact of drop hammer (**Fig.2**). Weight of 1kg was freely dropped from different heights. Specimen, 60 mm in diameter, was screwed to the downmost end of the apparatus. Number of repeated cycles of drop up to debonding was measured.

Fig.1 Impact Tension Test

Fig.2 Principle of Impact Tensile Stress Generation

d) Contact angle and surface tension

Contact angle was measured by sessile drop method using contact angle tester provided with microscope (Photo 3). Surface tension was measured by capillary rise using 0.0408 cm tube. Correction for meniscus was made in accordance with Rayleigh's equation. Contamination of inner surface of tube was eliminated by sodium dichromate solution and the result was checked by comparing two measurements taken for opposite wetting direction.

e) Debonding test by impact blow

Impact energy of N type Schmidt Hammer (impact energy : 0.255 kgf·m) was applied on thin layer of ice bonded to asphalt concrete. Failure aspect was visually observed.

(4) Methods of experiments for series 2

a) Uni-axial compression test of asphalt concrete

Cylindrical specimen 60 mm in diameter was cut from 30×30×5 cm asphalt concrete plate and both ends were finished by gypsum capping. Compressive load was applied by constant crosshead speed 1 mm/min and stress-strain curve was obtained. Test temperature was 20°C and -15°C.

Photo 3 Contact Angle Tester

Table 4 Roughness of Asphalt Concrete

Specimen Number	Average deviation from center line R_a	Maximum height R_{max}	Average roughness from ten summits R_z
i	42.6	503.5	295.8
ii	27.8	396.9	163.6
iii	24.9	307.5	142.4
iv	22.7	252.2	119.0
v	10.1	162.7	45.0
vi	5.0	56.7	31.2

(measurement length=16.0mm, unit: μm)

b) Uni-axial compression test of ice-bonded asphalt concrete

Seventy ml of deionized water was poured on top of cylindrical asphalt concrete specimen (ϕ 100.0 mm×63.5 mm) and was frozen at -10°C. Local compressive load was statically applied at -15°C. Diameter of pressing plunger was 35 mm and crosshead speed was 2 mm/min. Mix proportion of asphalt concrete was optimized in advance for each type of rubber aggregate by Marshall test and porosity measurement. In addition to stress-strain curve, the failure load of bonded ice was measured.

(5) Factors varied

a) Series 1

Four types of asphalt concrete surface were studied.

- Asphalt concrete surface
- Asphalt mortar surface
- Finished surface of asphalt concrete
- Cut surface of asphalt concrete

No coarse aggregate was used to get b) surface, for c) surface asphalt concrete was finished with BL asphalt emulsion containing silica sand and cement (weight ratio 1:2:1) and asphalt concrete was cut by diamond cutter to get d) surface. In order to control roughness of pavement, a) surface and d) surface described above were polished by sand paper in different degree, and six steps of roughness shown in Table 4 were obtained, where rank i) to iv) were obtained from surface a) and

Fig.3 Single Plane Shear Test of Ice (-20°C) Fig.4 Single Plane Shear Test of Compressed Artificial Snow (-20°C)

rank v) and vi) from surface d). Rank i) corresponds to original asphalt concrete surface just after finished. For every type of surface, liquid type water repellent agents listed in Table 3 were coated, and some types of agents were mixed with asphalt. Single plane shear test was carried out for all surfaces bonded with ice or compressed artificial snow ($\rho=0.8$) and impact tension test was carried out for the specimens with different surface roughness. Normally, tests were done at temperatures -12.5 , -15.0 and -17.5°C , but some tests were done at -10°C and -20°C .

Artificial snow was prepared by compressing crashed ice particles in a steel pipe 60 mm in diameter until its bulk specific gravity becomes 0.8.

3. TEST RESULTS OF SERIES 1

(1) Single plane shear test of ice and compressed artificial snow

Shear stress and shear displacement curves for both cases are shown in Fig.3, and 4. More or less linear relationship was obtained. The slope of the latter was approximately one third of the former. Average shear strength of ice was 5.0 kgf/cm^2 and that of compressed artificial snow was 2.8 kgf/cm^2 .

Type A

Type B

Type C

Type D

Photo 4 Types of Failure Surface

(2) Type of failure of ice bonded asphalt concrete

Failure could be classified into four groups. (photo 4)

Type A : complete debonding at ice-asphalt interface

Type B : interfacial debonding with local failure of ice at indent spots

Type C : some area failed in ice and the other area failed like type A or B

Type D : failure of ice (Ice in this list means ice or compressed artificial snow.)

(3) Shear debonding test of ice-asphalt concrete interface

Influence of types of pavement and roughness of asphalt concrete are shown in Fig.5, and 6 for untreated surface. Shear strength and shear displacement of interface were smaller than those of ice or compressed artificial snow. Effect of water repellent coating (No.3 agent) is shown in Fig.7 for different roughness of pavement. Water repellent

Fig.5 Single Plane Shear Test of Ice-asphalt concrete Interface

Fig.6 Single Plane Shear Test of Ice-asphalt concrete Interface

Fig.7 Single Plane Shear Test of Ice-Treated asphalt concrete Interface (No.3)

agent can reduce the shear strength of interface more effectively for smooth surface than for rough surface.

(4) Impact tension test of ice-asphalt concrete interface

Typical results are shown in Fig.8 and Table 5. Roughness of pavement exhibits great influence on debonding energy of treated and untreated interface. It is clear that water repellent agent is very effective. Type of failure for repellent coated surface was only type A for all test cases.

Fig.8 Results of Impact Tension Test (-15°C)

(5) Adhesional energy of water-asphalt interface

Adhesional energy W_a should be corrected by the amount of π_c that is reduction in free energy due to adsorption of saturated vapour of liquid. Adhesional energy obtained by sessile drop method corresponding to $W_a - \pi_c$ is shown in

Table 5 Result of Impact Tension Test

Type	Roughness	Drop Height (cm)	Average Number of Drop	Standard Deviation of Drop Number	Required Energy (J)	Probability of Type A (%)
Normal Asphalt Concrete	i	30	15.7	7.15	46.31	0
		20	20.3	7.52	39.85	0
	ii	30	11.3	6.38	33.08	0
		20	18.6	7.50	36.40	0
	iii	30	10.6	6.05	31.16	0
		20	19.7	7.00	38.63	0
	iv	30	2.6	2.33	7.64	80
		20	6.8	2.40	13.33	40
	v	30	1.3	0.43	3.68	75
		20	5.8	4.26	11.37	60
	vi	30	1.3	0.43	3.68	100
		20	4.0	2.61	7.84	100
Treated Asphalt Concrete	i	20	12.5	7.43	24.50	100
		10	19.6	7.44	19.18	100
	ii	20	8.8	5.01	17.31	100
		10	18.7	9.41	18.30	100
	iii	20	6.2	3.44	12.09	100
		10	12.8	6.62	12.57	100
	iv	20	3.3	2.49	6.53	100
		10	9.0	5.55	8.82	100
	v	20	2.2	1.46	4.25	100
		10	3.0	1.63	2.94	100
	vi	20	1.3	0.47	2.61	100
		10	1.7	0.74	1.64	100

Table 6 Contact Angle and $W_a - \pi_c$

Type of agent	Glass		Asphalt Concrete	
	Contact Angle (degree)	$W_a - \pi_c$ (erg/cm ²)	Contact Angle (degree)	$W_a - \pi_c$ (erg/cm ²)
BL asphalt emulsion	34.8	—	—	—
0	—	—	83.1	82.7
1	97.8	63.8	103.0	57.2
2	81.1	85.2	102.2	58.2
3	83.0	82.8	103.5	56.6
3 (2% mixed)	93.2	69.7	100.1	60.9
4	69.6	99.5	98.4	63.0
5	67.6	101.9	98.6	62.8
6	100.0	61.0	102.2	58.2
7	90.0	73.8	84.7	80.6
8	90.0	73.8	87.0	77.7
9	106.0	53.5	75.6	53.5
10	89.0	75.1	89.0	75.1
11	98.0	63.5	120.5	36.3
12	90.7	72.9	91.2	72.3
13 (1% mixed)	85.0	80.2	84.5	80.9

Table 6 for various types of treated surfaces. Asphalt concrete surface finished with mixture of BL asphalt emulsion and cement (weight ratio 1 : 1) was used for untreated surface for this measurement.

(6) Critical surface tension of asphalt

For untreated surface described above, Zisman plot was done as shown in Fig.9. Critical surface tension γ_c was obtained as 33.0 dyne/cm.

Fig.9 Zisman Plot for Critical Surface Tension (γ_c)

Fig.10 Relation between $W_a - \pi_c$ and τ_B (water)

(7) Relation between adhesional energy of water and shear debonding strength of ice-asphalt concrete interface

Relation between the data shown in 3.(3) and the data shown in 3.(5) can be plotted as Fig.10. Relation between debonding strength and adhesional energy $W_a - \pi_c$ is not so clear. But in reference to icing force, rather linear relation is reported by Shimada et. al.¹⁾

(8) Effect of roughness of shear debonding strength

For repellent coated surface (No.3) shear debonding strength is linearly decreased with decreasing roughness (Fig.11), but for untreated asphalt concrete shear debonding strength is not influenced by roughness of pavement.

(9) Effect of roughness on debonding energy by impact tension

Fig.11 Relation between Roughness of Asphalt Concrete and Shear Strength of Interface

Fig.12 Relation between Required Energy and Roughness of Asphalt Concrete (Drop Height 20 cm)

For the case of debonding by impact tension, roughness of asphalt concrete influences energy requirement for both treated and untreated surface (Fig.12). This means that, for asphalt concrete, tension type of debonding is more effective than shear type of debonding. Stiking contrast between Fig.11 and 12 could be attributed to the difference in mechanism of interfacial debonding.

Fig.13 Relation between Single Plane Shear Strength and Impact Tensile Strength of Ice-Asphalt Concrete Interface

Photo 5 Surface after One Blow

(10) Relation between shear debonding strength and energy requirement by impact tension

For repellent coated surface, either of these two indices could be used to evaluate debonding resistance of ice-asphalt concrete interface. But for asphalt concrete surface, impact tension test is more effective than shear debonding test (Fig.13).

(11) Visual observation of ice debonding

By single impact blow of Schmidt Hammer, no crack or debonding was observed for 5 mm ice on asphalt concrete (10 × 10 cm), but many radial cracks were observed in ice for the case of repellent coated (No.3) surface (Photo 5). After five blows all ice bonded to repellent coated surface was gone, while most part of ice remained on non-coated surface without cracking (Photo 6).

Photo 6 Surface after Five Blows

Fig.14 Stress-strain Curve of Asphalt Concrete Containing Different Amount of Rubber Particles (-15°C)

Fig.15 Stress-strain Curve of Asphalt Concrete Containing Different Amount of Rubber Particles (20°C)

4. TEST RESULTS OF SERIES 2

(1) Stress-strain curve of rubber mixed asphalt (-15°C)

At temperature -15°C , addition of rubber particles always reduces the maximum stress and stiffness of asphalt concrete (Fig.14). Effect of grain size distribution is clearly recognized. For 5~3 mm rubber aggregate, the maximum reduction in stiffness was obtained.

(2) Stress-strain curve of rubber mixed asphalt (20°C)

At temperature 20°C , initial stiffness is increased only for 3% of rubber content (Fig.15).

Fig.16 Stress-strain Curve (Effect of Size Rubber Particles, 20°C)

This increase is more pronounced for smaller size of rubber particle. The maximum stress is also increased with increase in stiffness (Fig.16).

(3) Ice failure by plunger load

For asphalt concrete containing different amount of rubber particles, failure load of ice bonded to the surface of asphalt concrete by static local compression of plunger is shown in Table 7.

Maximum load of ice failure can be reduced by 30% by mixing 3% of rubber 5~3 mm in particle size.

5. CONCLUSIONS

(1) Reducing surface energy and/or increasing deformability of asphalt concrete is an effective way to decrease interfacial bonding resistance between ice and asphalt concrete. In this regard, use of water repellent agent or replacement of aggregate with rubber particles is a promising method to facilitate debonding of ice and asphalt concrete pavement.

(2) For repellent coated surface shear debonding strength is linearly related to the energy required for debonding by dynamic tension. But for uncoated surface, no direct relation was found between these two types of strength.

(3) For uncoated surface, shear debonding strength is not influenced by roughness of pavement. But for coated surface, shear debonding strength is linearly decreased with decrease in roughness of pavement.

(4) The energy required for tensile debonding is linearly related to the roughness of pavement both for repellent-coated and non-coated surface.

Table 7 Local Plunger Load (kgf) of Ice Failure

Grain Rubber content(%)	size 5~3mm	0.6~0mm	Blended	Normal Asphalt Concrete
5	1690 (0.72)	1728 (0.74)	2080 (0.89)	2347 (1.0)
3	1695 (0.72)	1898 (0.81)	2157 (0.92)	
1	2365 (1.01)	2060 (0.88)	2278 (0.97)	

(5) When bonding between ice and asphalt concrete pavement is weakened either by a surface chemical or mechanical method, radial cracks starting from the spot where dynamic or static load was applied, were formed in ice by local compression and ice pieces were easily taken off.

(6) Shear debonding strength can be related to bonding energy between water and asphalt concrete surface at 20 degree centigrade which is experimentally determined by contact angle measurement.

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アスファルト—氷界面の付着低減法

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氷とアスファルト舗装の付着機構を明らかにし、新しい付着抵抗の低減法を開発するために、一連の実験的検討を行った。界面の付着抵抗を3つの方法で測定した。表面エネルギー、表面粗さ、アスファルトの剛性を主な変数とした。表面エネルギーは撈水剤の使用により変化させ、アスファルトの剛性はゴム粒子の混入により変化させた。3変数の関係を検討し以下の結論が得られた。表面エネルギーの低減およびアスファルトの変形性能の向上は氷とアスファルトの付着を低減する有効な方法である。この点で、撈水剤の使用およびゴム粒子の骨材への置き換えは、舗装面への氷付着低減法として期待できる。