Table1. Surface energy and its components of test liquids

Property at 20		Liquid			
		n-Hexane	n-Htane	Water	Glycol
Density(kg/m^3)		659	684	998	1113
Viscosity(10^{-3}Pa·s)		0.306	0.401	0.835	21
Surface energy, mJ/m^2	γ^{Total}	18.40	20.30	72.80	48
	γ^{+}	0	0	25.5	1.92
	γ^{-}	0	0	25.5	47
	γ^{LW}	18.4	20.3	21.8	29

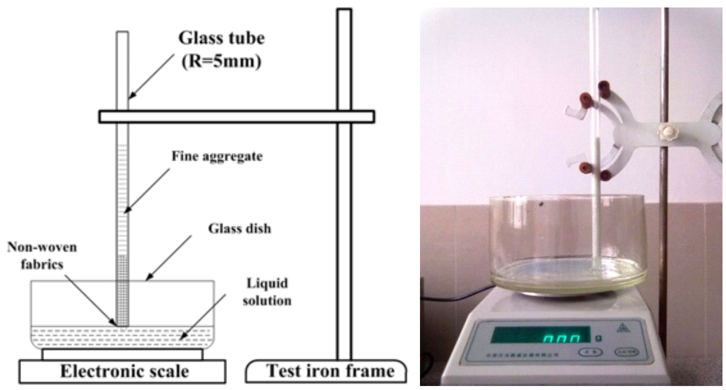

FIG.1. Experimental Set-Up for Capillary Rise Method

$$\begin{cases} \frac{(1+\cos\theta_1)\gamma_{L1}}{2} = \sqrt{\gamma_s^{LW}\gamma_{L1}^{LW}} + \sqrt{\gamma_s^{+}\gamma_{L1}^{-}} + \sqrt{\gamma_s^{-}\gamma_{L1}^{+}} \\ \frac{(1+\cos\theta_2)\gamma_{L2}}{2} = \sqrt{\gamma_s^{LW}\gamma_{L2}^{LW}} + \sqrt{\gamma_s^{+}\gamma_{L2}^{-}} + \sqrt{\gamma_s^{-}\gamma_{L2}^{+}} \\ \frac{(1+\cos\theta_3)\gamma_{L3}}{2} = \sqrt{\gamma_s^{LW}\gamma_{L3}^{LW}} + \sqrt{\gamma_s^{+}\gamma_{L3}^{-}} + \sqrt{\gamma_s^{-}\gamma_{L3}^{+}} \end{cases} \quad (7)$$

Where 'L1', 'L2', and 'L3' represent liquid 1, liquid 2 and liquid 3, respectively. These three equations are translated into 3x3 matrixes. Matlab^{TM} software can be used to determine the solution.

Asphalt Surface Energy Test Method

The Sessile drop method has been adopted in this research because of its simplicity. The method is based on the direct measurement of the contact angle of a drop of liquid of known surface energy properties on the surface of the material being tested. Once the contact angles of three different liquids on the solid surface has been determined, the Young-Dupré equation can be used to form a set of three simultaneous equations whose solution gives the surface energy components of the solid material.

First, the foamed asphalt binder was heated to eliminate bubbles in the asphalt. Hot foamless asphalt cement is coated around a thin glass slide onto which a sessile drop of a probe liquid is dispensed using a syringe. The coated glass plate must be flat and horizontal. During asphalt cooling, a liquid known surface energy drips on the surface of asphalt specimen. Second, the contact angle of liquid on solid surface was measured using digital image processing techniques. The above test process was repeated to measure contact angle for other two specific liquids. After inputting 3 liquid contact angles to Eq.(7), three simultaneous equations can be obtained. Calculation procedure of asphalt surface energy is similar with that of aggregate, which is a numerical method of matrix.

Dataphysics™ OCA20 Video based optical contact angle measuring instrument is employed to determinate contact angle which a specific liquid makes on asphalt film. Optical equipment and image analysis software comprise the instruments for contact angle measurement using Sessile Drop method. In the paper, contact angle pictures are obtained by magnifier and digital camera. Sessile drop method is set-up showed in FIG.2.

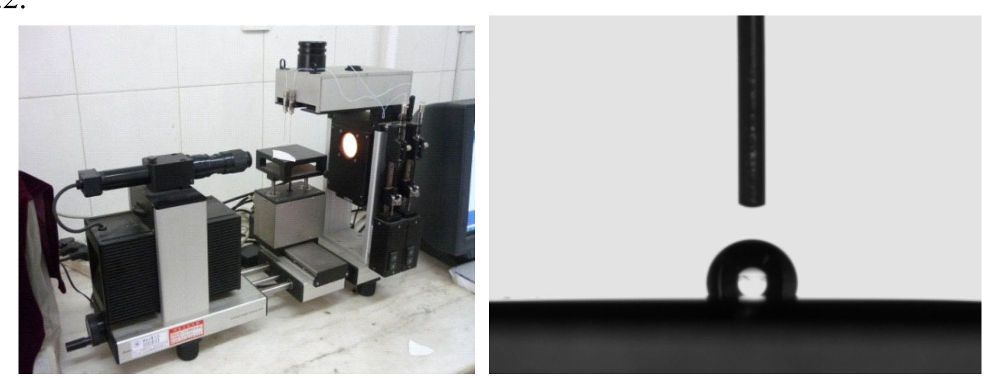

FIG.2. S Set-Up for Eessile Drop Method

TESTS AND RESULTS

Tests Scheme

The test matrix included two aggregates (limestone and sandstone) and two asphalt binders (HXL A-70 and foamed asphalt). The asphalt properties are showed in Table 2. Asphalt foaming condition: asphalt at 150℃ and water content is 1.0%(asphalt weight).

Results and Analysis

Using capillary rise method, contacts angles of four specific liquids (n-Hexane, n-Heptane, water and glycerol) for 2 types aggregates surface are listed in Table 3. Using Sessile Drop method, contact angles of 3 liquid(n-Hexane, n-Heptane, water and glycerol) on two binder(HXL A-70# and foamed asphalt) to are summarized in Table 4. 4 replicates were performed with each aggregate type and each asphalt type. After matrix calculation, surface energy and its components of materials are showed in Table 5.

There is a significant difference in surface energy and its components between limestone and sandstone. Compared to sandstone, limestone was found to have higher Van der Waal components and higher basic force components. The results indicated that Limestone had a higher surface energy compared to sandstone, as expected. Control asphalt and defoamed foamed asphalt have similar Van der Waal components, but foamed asphalt has lower acid-base force than that of control asphalt.

Table2. Properties of control asphalt

Experiment	control asphalt(HXL A-70#)
Penetration(0.1mm)@25℃	70
Ductility(cm) @10℃	>100
Soft point(℃)	46.5

Table3. Summary of test results and calculated liquid-aggregate contact angles

Aggregate type	Liquid	θ(°)
Limestone	Water	40.13
	n-Heptane	17.2
	n-Hexane	0.00/Spreads
	Glycol	54.8
Sandstone	Water	82.56
	n-Heptane	27.39
	n-Hexane	0.00/Spreads
	Glycol	60.45

Table4. Summary of test results and calculated liquid-asphalt contact angles

Asphalt type	liquid	θ(°)
Control asphalt	Glycol	83.6
	Water	104.7
	n-Hexane	0.00/Spreads
Defoamed foamed asphalt	Glycol	82.1
	Water	107.6
	n-Hexane	0.00/Spreads

Table5. Summary of Surface energy

Material	Components of surface energy($mJ \cdot m^{-2}$)				
	γ^{LW}	γ^{-}	γ^{+}	γ^{AB}	γ^{Total}
Limestone	18.52	8.41	5.50	13.60	32.12
Sandstone	14.44	4.59	10.20	13.68	28.12
Control asphalt	18.4	0.074	1.339	0.63	19.03
Foamed asphalt	18.4	0.315	0.249	0.56	18.96

Using equation (1), prediction results of water susceptibility model and retained tensile strength ratio are summarized in Table 6.

Table6. Summary of Gibbs free energy test and AASHTO T283 test

Asphalt mixture	$\Delta G_{bws}(mJ\cdot m^{-2})$	TSR(%)
Control asphalt-Limestone	-42.86	78.6
Foamed asphalt-Limestone	-44.12	82
Control asphalt-Sandstone	-41.02	77.2
Foamed asphalt -Sandstone	-43.78	77.5

It is important to point out that both the sign and magnitude of ΔG_{bws}. The sign would determine whether the interaction (e.g. adsorption) between substances aggregate and asphalt is thermodynamically possible or not. For example, a negative ΔG_{bws} would indicate a feasible adsorption reaction whereas a positive ΔG_{bws} would indicate that no adsorption would be possible. On the other hand, the magnitude of a negative ΔG_{bws} is indicative of the strength of the adsorption interaction; the larger the magnitude, the stronger the interaction.

ΔG_{bws} of all mixture are negative, which means asphalt- aggregate interface is hydrophobic. In other word, all mixtures have good moisture stability. This indicates that moisture invasion into asphalt- aggregate interface will hardly happen. Test results show that limestone has better water/moisture resistant than sandstone when the same binder was used， which is similar with relevant references.

But there are some differences in magnitude of ΔG_{bws} between asphalt mixtures. As aforementioned, ΔG_{bws} absolute value of foamed asphalt mixture is larger than that of control asphalt mixture. When the same aggregate is used, ΔG_{bws} absolute value of foamed asphalt mixture is equal to or larger than that of control asphalt mixture. This may seem to imply that foamed asphalt mixture and control asphalt mixture have the same moisture damage resistance. Compared to limestone, sandstone has more acid component and less basic component. Acidic rock types have a poorer affinity for asphalt than basic rock types. ΔG_{bws} absolute value of mixtures shows the difference. The results show that mixtures with limestone aggregate has substantial water resistance. The study also carried out AASHTO T283 test. 4 replicates were performed with each mixture type. All mixtures were subjected to indirect tensile strength tests. The retained Tensile Strength Ratio (TSR) is calculated. The TSR results confirm Gibbs free energy prediction results. This is mainly due to evaporation of water through heating, mixing and compacting process during specimen preparation. It was also observed that evaporation of water occurred in pavement construction.

CONCLUSIONS

Gibbs free energy equation, based on chemical thermodynamics theory, for a three phase interface, developed by Good, was adopted to study asphalt mixture moisture damage. Contact angle measurements of aggregate and asphalt are conducted using the capillary rise method and the Sessile drop method, respectively. Surface energy parameters are determined utilizing Van Oss equation. It was found that surface energy of foamed asphalt is almost equivalent to that of control asphalt, and limestone has a higher surface energy and a better water resistance compared with granite.

Through the moisture damage thermodynamic prediction model analysis, foamed asphalt-aggregate mixture has almost the same or better water resistance than the control hot mix asphalt. AASHTO T283 test results confirmed the model prediction results. It is believed that the main cause of the reduction of water damage of warm-mix foamed asphalt mixture is the evaporation of the water during the construction process.

ACKNOWLEDGEMENT

The authors appreciate the support of National Natural Science Foundation of China (No. 50908072).

REFERENCES

Cheng Chuan-xuan(1995). "Surface physical chemistry." *Technology and Science Press*. In Chinese.

A W Hefer, Dallas Little(2009). "Adhesion in Asphalt-Aggregate Systems and Quantification of the Effects of Water on the Adhesive Bond". *International Centre for Aggregate Research*.Report No. ICAR 505-1:59-63.

Dennis Sinkonde(2006). "Analysis of Test Methods Used to Evaluate Hot Mix Asphalt Concrete's Susceptibility to Water Damage." *Chang'an University*:33-36.

F L Roberts, P S Kandhal, E R Ray, D Lee, T W Thomas(1996). "Hot Mix Asphalt Materials, Mixture Design and Construction 2nd Edition. " *NAPA Education Foundation*:134-135.

J. D'Angelo, R M Anderson(2002). "Material Production, Mix Design, and Pavement Design Effects on Moisture." *Report for National Seminar on Moisture Sensitivity:*187.

Van Oss, C.J., and Giese, R.F. (2003). "Surface Modification of clays and related materials". *Journal of Dispersion Science and Technology, 24 (3&4):* 363-376.

Cheng D, D N Little, J Holste, R L Lytton(2003). "Moisture Damage Evaluation of Asphalt Mixture by Considering Both Moisture Diffusion and Repeated Load Conditions". *2003 Annual Meeting of Transportation Research Board*:10-16.

J Liebenberg, D Rossman, E Fletcher(2004). "Asphalt Mix Design and Construction: A Selection of Possible Pitfalls." *Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa*: No 035.

B D Shah(2003). "Evaluation of Moisture Damage Within Asphalt Concrete Mixes." *MSc (Civil Eng.) Dissertation, Texas A&M University*:15.

A R Terrer, Vinay Wagh(1991). "The Effects of the Physical and Chemical Characteristics of the Aggregate on Bonding." *SHRP Contract No.A-003B, Strategic Highway Research Program, National Research Council,* Washington D.C.:2-6.

D N Little, D R Jones(2002). "Chemical and Mechanical Processes of Moisture Damage in Hot Mix Asphalt Pavements". *Report for National Seminar on Moisture Sensitivity, San Diego, C.A*: 40-46, 48-49, 60-63

The Effect of Water and Frost on Fatigue Life of Asphalt Concrete

Piotr Jaskula[1], PhD. and Jozef Judycki[2], Prof. PhD. DSc.

[1]Assistant professor, Highway Engineering Department; Gdansk University of Technology, Narutowicza str. 11, 80-233 Gdansk, Poland; pjask@pg.gda.pl
[2]Professor, Highway Engineering Department; Gdansk University of Technology, Narutowicza str. 11, 80-233 Gdansk, Poland; jojudyck@pg.gda.pl

ABSTRACT: The paper presents testing of fatigue life of asphalt concrete which was subjected to action of water and frost. Simulation of water and frost action was based on the original AASHTO T283 method and its modification. The original method was modified in such a way that instead of a single freeze-thaw cycle 50 and 150 cycles were applied. Fatigue life was measured in the Indirect Tensile Fatigue Test in the NAT apparatus. The asphalt concrete specimens were prepared in laboratory. Some specimens contained liquid adhesive agent, namely fatty amine and others did not. The detrimental effect of water and frost was clearly identified. The testing procedure, the results and the practical conclusions are presented.

1. INTRODUCTION

In the present times fatigue life of asphalt mixtures is the primary criterion used in the design of road pavements. It is a parameter useful at the mixture design stage and promotes awareness of the effect of poor fatigue life on the overall durability of mixture. By allowing for the effect of water and frost on the fatigue life of asphalt mixtures more specific pavement design methods can be obtained.

Fatigue testing was carried out on asphalt concrete specimens subjected to the action of water and frost simulated in laboratory in different ways to obtain different levels of exposure and on the reference specimens. Fatigue testing was carried out according to the Indirect Tensile Fatigue Test (ITFT) method in the Nottingham Asphalt Tester (NAT). The action of water and frost was simulated with the original and modified AASHTO T283 method. In the modified method 50 and 150 freeze-thaw cycles were used respectively instead of a single freeze-thaw cycle.

The objective of testing was to define the detrimental effect of water and frost on the fatigue life of asphalt concrete which was reported before by Poczapskij and Goncharenko (1973), Lottman (1982), Gilmore et al. (1984), Kim et al. (1984), Lottman et al. (1988), Moutier et al. (1988), and the results of fatigue tests were used for separate analyses related to structural design of pavements by Jaskula (2004).

2. MATERIALS

Asphalt concrete mixtures designed for base course, designated further as AC25P, produced with and without the addition of fatty amine as adhesive agent were tested. Asphalt concrete 0/25 mm was made of 35/50 bitumen, 5/8 and 8/11 granite chippings, 2/8 and 12/25 crushed gravel, 0/2 natural (quartzite) sand, 0/2 crushed sand and limestone filler. The content of bitumen was 4.0% by weight. Fatty amine was added at a rate of 0.3% of the weight of bitumen. The mixtures were subjected to short-term ageing according to the SHRP test procedures (Harrigan et al. 1994); a loose, uncompacted mixture was conditioned for 4 hours in a draft oven at 135°C.

Different conditioning methods were used to simulate the action of water and frost at the laboratory, as presented in Table 1. Two methods of compaction (Marshall and rolling) were used due to some organizational reasons. The average voids content was similar for both compaction methods, and equal in average 5.4% for all prepared samples.

Table 1. Preparation and conditioning of specimens and testing methods

No.	Compaction method	Conditioning methods according to AASHTO T283 and their modifications				Test methods
1.	Roller compacted and cut out	Non-conditioned		With 1 freeze-thaw cycle		Indirect Stiffness Modulus and Indirect Fatigue Test for 7 levels of applied stress
2.	Marshall compaction	Non-conditioned	With 1 freeze-thaw cycle	With 50 freeze-thaw cycles	With 150 freeze-thaw cycles	Indirect Stiffness Modulus and Indirect Fatigue Test for one level of applied stress

The test material compacted by rolling comprised 36 cylindrical specimens of 102 mm in diameter and 50 mm in height which were cut out from 750x870 mm slabs compacted with roller. The test material compacted with the Marshall method comprised 30 cylindrical specimens of 102 mm in diameter and 50-60 mm in height.

To determine the Indirect Tensile Stiffness Modulus (ITSM) at least 3 samples were tested in a uniform series. To determine fatigue life of each mixture for the roller compaction method 7-9 samples were tested and for the Marshall compaction method 3 samples were tested.

3. TESTING

3.1. Indirect Tensile Stiffness Modulus

The following two general methods were used to simulate the action of water and frost: (a) AASHTO T283 method with 1 freeze-thaw cycle with the SHRP short-term oven aging included, as describe by Jaskula and Judycki (2008), (b) modified AASHTO T283 method with 50 and 150 freeze-thaw cycles instead of the single cycle applied in the original procedure. The one freeze-thaw cycle consisted of 4 hours of freezing at -18°C and 2 hours of thawing in water at +20°C. After all prescribed freeze-thaw cycles (1, 50 and 150) the specimens were placed in a water bath at +60°C for 24 hours. The specimens were not wrapped in a foil. After the water bath the specimens were dried up with a cloth and kept for 4 hours at a testing temperature.

The ITSM tests were carried out at +20°C and +25°C on both conditioned and non-conditioned specimens. The measures of resistance to the action of water and frost were the values of Indirect Tensile Stiffness Modulus Ratios (ITSMR) obtained by dividing the value of modulus for conditioned specimens by the value for non-conditioned specimens.

3.2. Fatigue life of asphalt concrete mixtures

The mixtures were subjected to the stress-controlled Indirect Tension Fatigue Test (ITFT) in NAT apparatus presented earlier by Said (1989), Read et al. (1997) andJudycki et al. (2002). In this test horizontal tensile stresses are generated along the vertical diameter of the specimen. Repeated loading results in failure of the specimen which cracks along the vertical diameter and sometimes a specimen is completely split. In the ITFT the limit of fatigue life is defined arbitrarily either as the point of critical vertical deformation or complete failure of the specimen (NAT Manual 1994). In this research it was assumed that the limit of the fatigue life was the complete failure.

The used Indirect Tensile Fatigue Test (ITFT) is rather simple and practical but it should be remembered that the premature failure in ITFT can be affected not only by horizontal tensile stresses but also by accumulation of permanent deformations especially at high temperatures, where nonlinear and viscoelastic material behavior is more pronounced. It is a certain disadvantage of this testing method.

The parameters monitored during the ITFT were: vertical deformation Δp measured with LVDT sensors and the amplitude of the horizontal stress in the specimens which was kept constant (σ=const) until failure of the specimen took place. In this research, the relevant literature was studied, which included Said (1989), NAT Manual (1994), Read et al. (1997), Judycki et al. (2002), and on this basis the test conditions were established. The tests were carried out at the following test parameters: temperature of +25°C, load rise time of 0.124 s, cycle duration of 1.5 s, 40-50 mm specimen height and 102 mm specimen diameter, amplitude of the horizontal stress values in the range from 220 kPa to 520 kPa in 60 kPa increments.

The ITFT fatigue curves $\sigma=f(N_f)$ and the number of cycles until crack initiation represented by the peak of $f(N_f)=N_f/\Delta p$ curve were determined with the method based on the dispersed energy concept described by Read et al. (1997) which assumes that stiffness is inversely proportional to the vertical deformation Δp, as described in details by Jaskula (2004).

4. TEST RESULTS

4.1. Results of testing of asphalt concrete compacted by rolling

Table 2 presents the values of the Indirect Tensile Stiffness Modulus Ratios (ITSMR). The Indirect Tensile Fatigue Test (ITFT) results are presented in Fig 1.

Table 2. Indirect Tensile Stiffness Modulus Ratios (ITSMR) for AC25P asphalt concrete according to AASHTO T283 with 1 cycle of freeze-thaw, compaction by rolling, (mean values of minimum 8 specimens).

ITSMR (%)			
AC25P with adhesive agent		AC25P without adhesive agent	
20°C	25°C	20°C	25°C
83.7	81.9	86.8	92.6

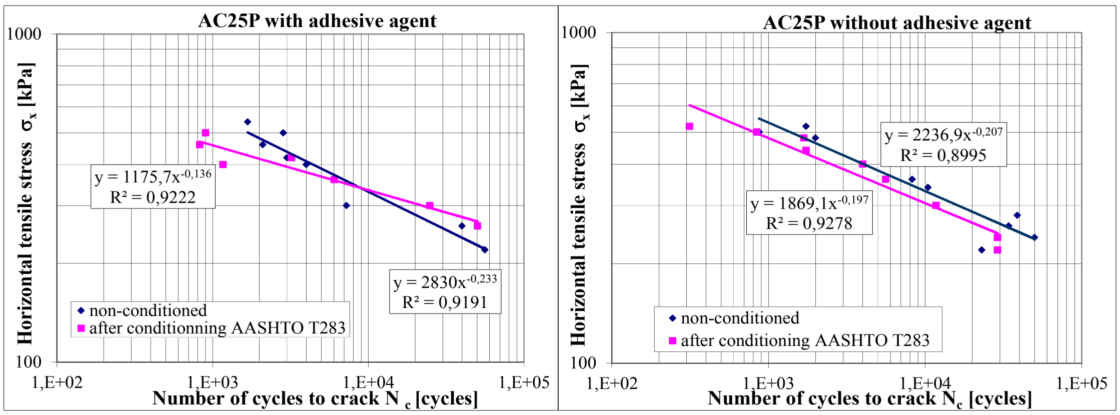

FIG 1. Fatigue curves of asphalt concrete conditioned according to AASHTO T283 with 1 freeze-thaw cycle and non-conditioned, compaction by rolling.

4.2. Results of testing of asphalt concrete compacted by Marshall method

Table 3 presents average values of the Indirect Tensile Stiffness Modulus Ratios of AC25P asphalt concrete in relation to the number of the freeze-thaw cycles. The specimens were compacted according to the Marshall method.

Table 3. Indirect Tensile Stiffness Modulus Ratios (ITSMR), compaction by Marshall method, (mean values of 3 specimens).

Number of freeze-thaw cycles	ITSMR (%)			
	AC25P with adhesive agent		AC25P without adhesive agent	
	20°C	25°C	20°C	25°C
1	90.7	78.7	94.6	77.9
50	54.9	35.5	32.4	17.4
150	34.4	32.9	16.0	18.0

Figure 2 presents a comparison of the results obtained in the ITFT fatigue testing on specimens made of AC25P asphalt concrete with and without adhesive agent, non-conditioned and conditioned in different ways. Results presented in this figure were obtained as mean values from 3 specimens tested at one level of horizontal tensile stress in the fatigue test (ITFT).