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Determining the Stability of Asphalt Concrete at Varying Temperatures and Exposure Times Using Destructive and Non-Destructive Methods

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Abstract: This study examined the effect of varying temperatures and varying exposure times on the stability of asphalt concrete using destructive and non-destructive methods. The study also looked at the relationship between destructive and non-destructive methods. In order to investigate the stability according to exposure time and environment temperature, exposure times of 1.5, 3, 4.5 and 6 h and temperatures of 30, 40 and 50°C were selected. The results showed that at the environment temperature of 17°C the stability of the asphalt core samples decreased by 40.16% at 30°C after 1.5 h and 62.39% after 6 h. At 40°C the decrease was 74.31% after 1.5 and 78.10% after 6 h. At 50°C the stability of the asphalt decreased by 83.22% after 1.5 h and 88.66% after 6 h. The results also pointed to a moderate negative relationship (R = -0.533) between second ultrasound and stability indicating that non-destructive ultrasound method can be used to predict stability.

Key words: Asphalt concrete, asphalt core, stability, ultrasound, temperature

INTRODUCTION

Damage to highways mostly takes place at the top layer of the highways at the binder and erosion layers as opposed to the foundation and lower layers. Damage to the binder and erosion layers generally comprises surface cracks, deformations, wheel ruts and potholes. Temperature effect is the main cause of the damages to highway pavements and performance. In this study, the effects of varying temperatures and exposure times on the stability of the asphalt concrete were studied. The stability of the asphalt core samples exposed to varying temperatures and varying exposure times were examined by using destructive and non-destructive methods. The data were analyzed statistically to identify the relationships between temperature, exposure time and the stability of asphalt concrete. Stability of asphalt concrete determines the performance of the highway pavement. Low stability in asphalt concrete may lead to various types of distress in asphalt pavements (Tigdemir *et al*., 2002, 2004). The stability of asphalt concrete pavements depends on the stiffness of the mix, bitumen content, softening point of bitumen, viscosity of bitumen, grading of aggregate, construction practice, traffic and climate (Cooper and Pell, 1974). Fatigue cracking due to repeated loading has been recognized as an important distress problem in asphalt concrete pavements (Liang and Zhou, 1997). The measurement of the stability of asphalt concrete samples is done using traditional destructive method and non-destructive ultrasound method. Destructive method is a more commonly used method, which is, although definitive, costly and time consuming. Ultrasonic tests were used on asphalt surface layers frequently and these tests established the usefulness of the ultrasonic method (Sztukiewicz, 1991). Studies demonstrated the relationships between external reactions and the characteristics of longitudinal ultrasonic wave propagation and between the characteristics of longitudinal ultrasonic wave propagation and standard designations of surface qualities (Sztukiewicz, 1993). The influence of bitumen rheology on low temperature behaviour of asphalt mixtures was investigated in laboratory environment (Isacsson and Zeng, 1998). A laboratory investigation of the relationships between bitumen chemistry and low temperature behaviour of asphalt mixtures indicated statistically significant relations between chemical characteristics of bitumen and fracture temperature of asphalt specimens (Isacsson and Huayang, 1997). In literature, the tri-axial and stress relaxation tests conducted by Monismith and Secor are used as benchmarks to delineate the efficacy of the model in predicting the mechanical response characteristics of asphalt concrete over a wide range of temperatures and confining pressures (Krishnan and Rajagopal, 2004). A layered elastic analysis method named MODULUS, which provides consistently reliable and fast results, was developed for microcomputers (Lytton *et al*., 1990).

MATERIALS AND METHODS

Preparation of the samples for experiments: Five specimens taken out of 65 samples randomly and kept at 17°C in the laboratory environment were used as reference samples to compare the stability, depressions and ultrasound values of the other samples exposed to varying temperatures for varying exposure periods. The other 60 samples were separated into three main groups according to temperature. In other words, for each temperature of 30, 40 and 50°C, twenty samples were chosen. Then, each of the twenty samples were divided into four categories according to the exposure times of 1.5, 3, 4.5 and 6 h and five specimens were used for each exposure time. Including the reference group the number of the groups are 13 in total. Separated samples groups were shown in (Fig. 1).

Determination of the physical properties of the samples: Diameter of the specimens was 10.16 cm and they were cut 6.35 cm long with core cutting machine. In this way, specimens were formed according to the specified standards for Marshal Test specimens and they were weighed at 0.01 g sensitivity. After weighing the specimens in the laboratory, specimens were submerged and left in the water for 24 h for saturated surface at 16.2°C. The specimens were weighed after surface saturation at 16.7°C in water and their volumes were calculated using the following equation.

$$V = \frac{m_a - \left[(m_{st} + m_w) - m_{st}\right]}{\rho_w}$$

Where:

V = Specimen volume (cm^3),
m_a = Specimen mass in the air (kg),
m_{st} = In view mass of the wire cage in water (kg),
m_w = Visual mass of the specimen in water (kg),
ρ_w = Density of water at 20°C accepted as 998 kg m^{-3}.

Measurement of the stability: In this study, ultrasound method used as non-destructive method in order to determine the stability of the asphalt core samples. As destructive method, Marshall Stability test method was used. Whereas the results of the Marshall Stability test method are definitive, the results of the ultrasound method are not. The results of the ultrasound method could be used for only prediction of the stability of the asphalt concrete samples.

Pulse velocity measurement method: The ultrasonic pulse velocity method has been used successfully to evaluate the quality of concrete for more than 60 years. This method can be used for detecting internal cracking and other defects as well as changes in concrete such as deterioration due to aggressive chemical environment and freezing and thawing. By using the pulse velocity method it is also possible to estimate the strength of concrete test specimens and in-place concrete. The pulse velocity method is a truly non-destructive method, as the technique uses mechanical waves resulting in no damage to the concrete element being tested. A test specimen can be tested again and again at the same location, which is useful for monitoring concrete undergoing internal structural changes over a long period of time (Tarun *et al*., 2004).

Concrete technologists have been interested in determining the properties of concrete by non-destructive tests for decades. Many test methods have been proposed for laboratory test specimens using vibrational methods beginning in the 1930s. Powers (1938), Obert (1939), Hornibrook (1939) and Thomson (1940) were the first to conduct extensive research using vibrational techniques such as the resonant frequency method. World War II accelerated research regarding non-destructive testing using stress wave propagation methods. The development of the pulse velocity method began in Canada and England at about the same time. In

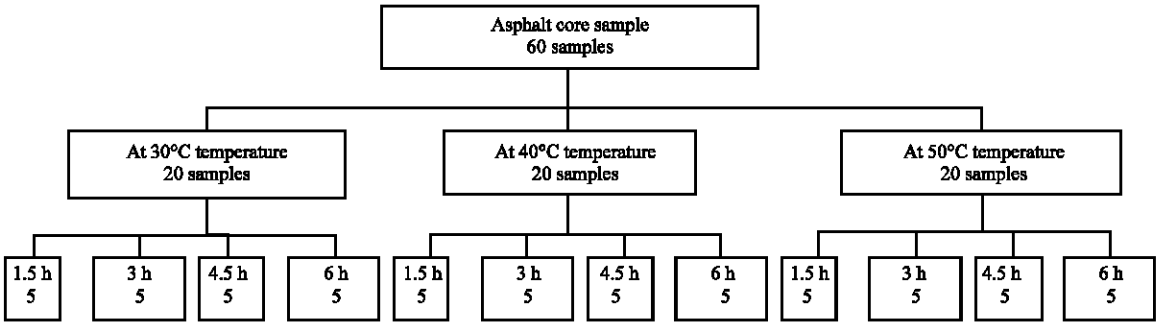

Fig. 1: Grouping samples for three different temperatures and four different exposure times

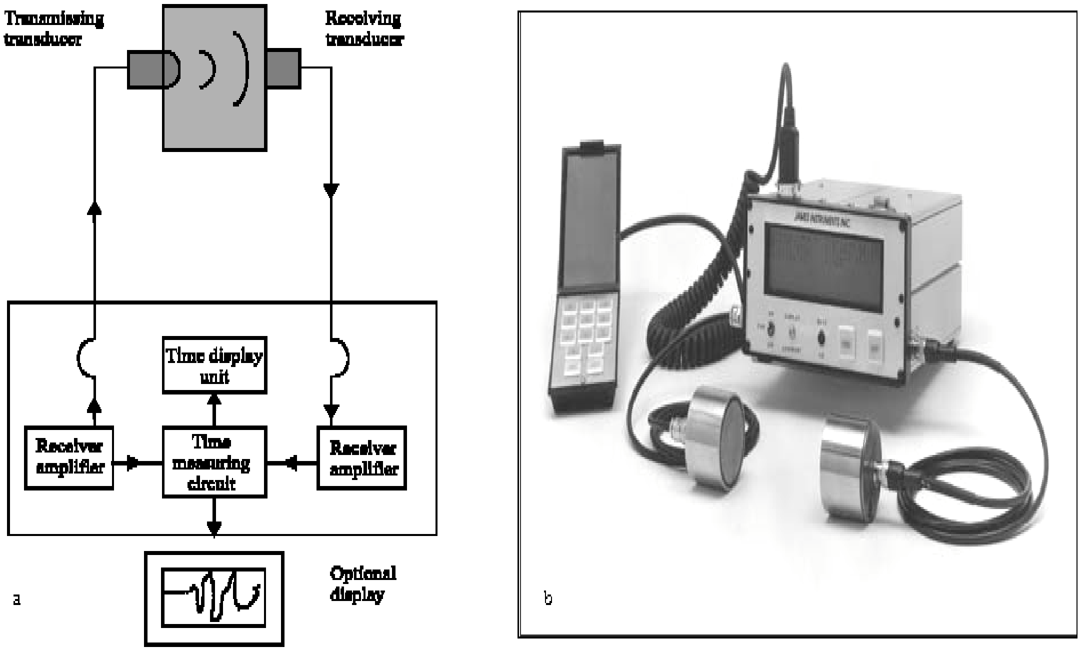

Fig. 2: Schematic diagram of the pulse velocity test circuit and its figure. (a) Schematic diagram of pulse velocity test circuit and (b) Pulse velocity test circuit

Canada, (Leslie and Cheesman, 1949) developed an instrument called the soniscope. While in England, (Jones, 1962) developed an instrument called ultrasonic tester. In principle, both the soniscope and the ultrasonic tester were quite similar, with only minor differences in detail. Since the 1960s, pulse velocity methods have moved out of laboratories and to construction sites (Whitehurst, 1966). Malhotra (1976) has compiled an extensive list of papers published on this subject.

The basic idea on which the pulse velocity method is established is that the velocity of a pulse of compress ional waves through a medium depends on the elastic properties and density of the medium. Schematic diagram and figure of pulse velocity test circuit were shown according to ASTM C597-02 (2003) (Fig. 2a, b).

Three types of propagating mechanical waves (also called stress waves) are created when the surface of a large solid elastic medium is disturbed by a dynamic or vibratory load: (1) compressional waves (also called longitudinal or P-waves), (2) shear waves (also called transverse or S-waves), (3) and surface waves (also called Rayleigh waves). The compressional waves propagate through the solid medium in a fashion analogous to sound waves propagating through air. Each wave type propagates with its characteristic velocity. For a given solid, compressional waves have the highest velocity and surface waves the lowest. In concrete, the velocities of the shear and surface waves are typically 60 and 55%, respectively, of the compressional wave velocity. The particular velocity of a wave depends on the elastic properties and density of the medium (ACI Committee, 228, 1998).

In this study, ultrasound velocity method was used to determine the probable relationship between pulse velocity and the Marshall stability of the asphalt core specimens. For pulse velocity measurement, a pulse velocity device with a digital screen was used. The machine used in the test was suitable for both BS 1881-203 and ASTM C597-02. It could measure from 0.1 to 999.9 µsec and its measurement sensitivity was ±0.1 µsec. It had a 1.2 kV, 500 V wavelengths. Since ultrasound method is based on the passing time of the velocity through the specimen, it is expected that with small cavity samples the stability will be high and with larger cavity samples the stability will be low. Pulse velocities were measured at laboratory temperature (17°C) and these values were recorded as first ultrasound pulse velocity. Then, space volumes of the samples, unit volume weight for saturated surface and air-dry unit volume weight were determined. Descriptive statistics of the first ultrasound velocity and basic physical properties for all samples were given below (Fig. 3, 4 and Table 1).

Table 1: Descriptive statistics for physical properties and first ultrasound velocities for samples

Physically properties	N	Changing range	Min.	Max.	Average	Std. error	Std. deviation	Variance
Space volume (cm^3)	65	49.44	0.74	50.18	11.81	1.4000	11.346	128.750
1st ultrasound velocity (µs)	65	7.30	17.40	24.70	19.77	0.1900	1.559	2.430
Unit volume weight for saturated surface (g cm^{-3})	65	0.27	2.40	2.67	2.52	0.0067	0.054	0.003
Unit volume weight for dry air (g cm^{-3})	65	0.28	2.38	2.66	2.52	0.0070	0.056	0.003

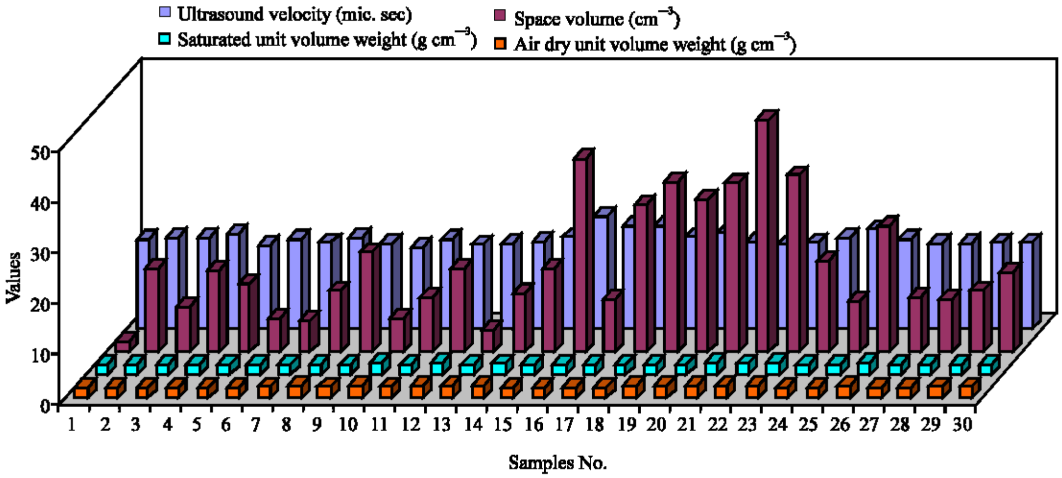

Fig. 3: Physical properties and first ultrasound velocities for samples in laboratory temperature

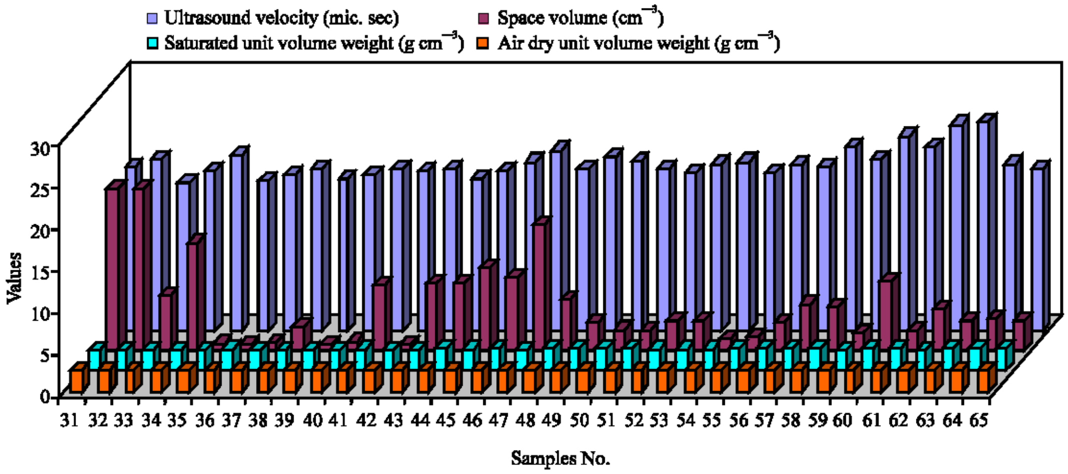

Fig. 4: Physical properties and 1th ultrasound velocities in laboratory temperature

Marshall stability test: The Marshall Test device had a digital screen and was suitable for BS 598-107. It had the dimensions of 550×400×870 mm and load capacity of 50.8 mm min^{-1}. It could measure at 0.1 kg sensitivity. It had a dial gauge with a sensitivity of 0.01 mm and capacity of 25 mm. Five specimens were selected randomly from the total of 65 specimens for reference groups in order to observe the random stability, resistance to the plastic flow and ultrasound velocity under different exposure times and temperature. As soon as the exposure time finished, ultrasound velocity was measured for samples, which were exposed to various temperatures. After the ultrasound velocity measurement, the specimens were immediately placed in Marshall Stability test machine and their stability and resistance to plastic flow was measured (Fig. 5 and Table 2).

Analysis of test results: The relationship between stability, resistance to plastic flow, ultrasound velocity, temperature, exposure time and physical properties for asphalt core samples was determined using SPSS statistical program.

Table 2: Descriptive statistics for the stability, resistance to plastic flow and 2nd ultrasound velocity

Properties	N	Changing range	Min.	Max.	Average	Std. error	Std. deviation	Variance
2nd ultrasound velocity (μ sec)	65	11.30	17.90	29.20	21.92	0.36	2.960	8.80
Resistance to plastic flow (mm)	65	4.93	4.06	8.99	5.90	0.13	1.059	1.12
Stability (kg)	65	4666.00	326.00	4992.00	1570.46	130.74	1054.040	1111008.53
Temperature (°C)	65	33.00	17.00	50.00	38.23	1.24	10.030	100.64
Exposure time (h)	60	4.50	1.50	6.00	3.75	0.22	1.690	2.86

Table 3: Significance levels for relationship among all of the data

Data	Space volume	1st Ultrasound velocity	Saturated unit volume weight	Unit volume weight for air dry	2nd Ultrasound velocity	Resistance to plastic flow	Stability	Temperature	Exposure time
Space volume	1.00	0.110	-0.120	-0.119	-0.353**	-0.107	0.302*	-0.481**	0.073
1st Ultrasound velocity	0.110	1.00	0.028	-0.012	0.465**	0.020	-0.064	0.153	0.226
Saturated unit volume weight	-0.120	0.028	1.00	0.993**	0.290*	0.199	-0.522**	0.579**	0.301*
Unit volume weight for air dry	-0.119	-0.012	0.993**	1.00	0.238	0.203	-0.515**	0.549**	0.295*
2nd Ultrasound velocity	-0.353**	0.465**	0.290*	0.238	1.00	0.224	-0.533**	0.665**	0.051
Resistance to plastic flow	-0.107	0.020	0.199	0.203	0.224	1.00	-0.218	0.201	-0.093
Stability	0.302*	-0.064	-0.522**	-0.515**	-0.533**	-0.218	1.00	-0.887**	-0.482**
Temperature	-0.481**	0.153	0.579**	0.549**	0.665**	0.201	-0.887**	1.00	0.324**
Exposure time	0.073	0.226	0.301*	0.295*	0.051	-0.093	-0.482**	0.324**	1.00

**: Correlation is significant at the 0.01 level. *: Correlation is significant at the 0.05 level

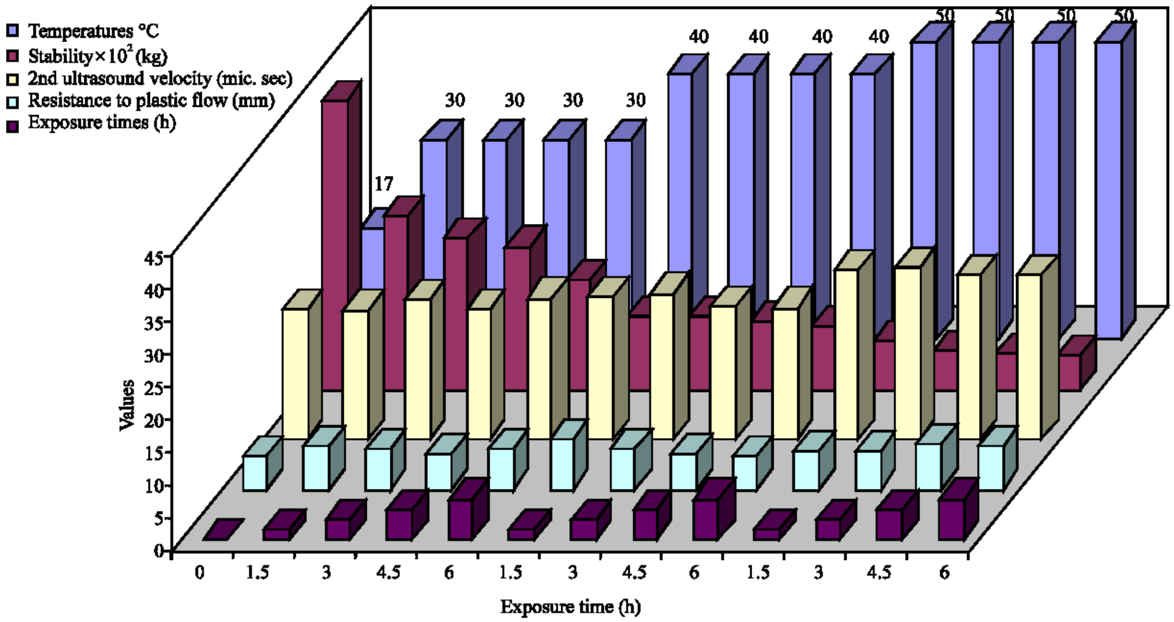

Fig. 5: Stability, resistance to plastic flow and ultrasound velocity in different temperature and exposure times

The relationship between stability, physical properties, environment temperature and exposure time: The correlation analysis was conducted to determine the significance level and the relationship between all variables was presented (Table 3).

The results regarding the relationship between stability and other variables were as follows: temperature -0.887, second ultrasound -0.533, saturated unit volume weight -0.522, air dry unit volume weight -0.515, exposure time -0.482, resistance to flow -0.218, first ultrasound velocity -0.064 and space volume is 0.302.

Prediction of the stability based on the physical properties, environment temperature and exposure time: Multi-linear regression and analysis of variances were used to predict the stability based on the physical properties, environment temperature and exposure time. The obtained results from these analyses were given below. For the prediction of the stability (S) based on physical properties (x_1, x_2, x_3), environment temperature (x_4) and exposure time (x_5) a model equation was formed with multi-linear regression analysis. Correlation coefficient (R) was almost perfect at 0.934 and adjusted R square was 0.872.

$$S = -485{,}962 - 14{,}155x_1 + 32989{,}52x_2 - 30452{,}28x_3 - 104{,}604x_4 - 100{,}169x_5$$

Where:

S = Stability (kg),
x_1 = Space volume (cm^3),
x_2 = Saturated unit volume weight (g cm^{-3}),
x_3 = Air dry unit volume weight (g cm^{-3}),
x_4 = Environment temperature (°C),
x_5 = Exposure time (h).

The prediction of stability based on environment temperature and exposure times: Multi linear regression and ANOVA analyses were conducted in order to determine the relationship between environment temperature, exposure time and the stability. For prediction of the stability (S) based on environment temperature (x_4) and exposure time (x_5) a model equation was formed with multi linear regression analysis. Correlation coefficient (R) was almost perfect at 0.91 and adjusted R square was 0.82.

$$S = -5263{,}485 - 85{,}779x_4 - 119{,}497x_5$$

Where:

S = Stability (kg),
x_4 = Environment temperature (°C),
x_5 = Exposure time (h).

To simulate the situation of the asphalt concrete exposed to environment day temperature and to investigate the stability based on exposure time and environment temperature, exposure times of 1.5, 3, 4.5 and 6 h were selected. In laboratory, environment temperature was 17°C and this temperature was selected as reference temperature. The temperatures selected for testing were 30, 40 and 50°C. These temperatures were selected to represent day conditions in summer. It can be seen that the environment temperature had a negative effect on the stability and as the temperature went higher the stability values went lower. Exposure time, compared to the temperature, had little effect on stability. The relationship between average stability and environment temperature for groups as well as the tendency lines and correlation coefficients were presented in figures (Fig. 6-9).

Average stability and missing stability rate for different temperature and different exposure times were calculated and the results were given below (Fig. 10).

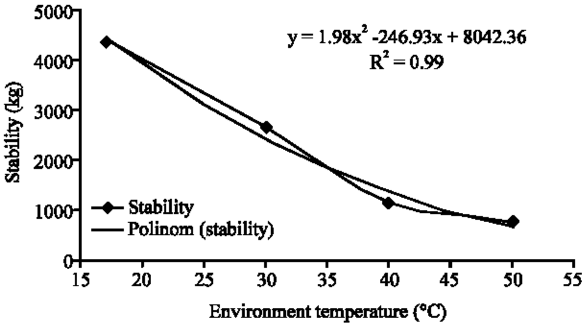

Fig. 6: Average stability for groups based on 1.5 h-exposure time

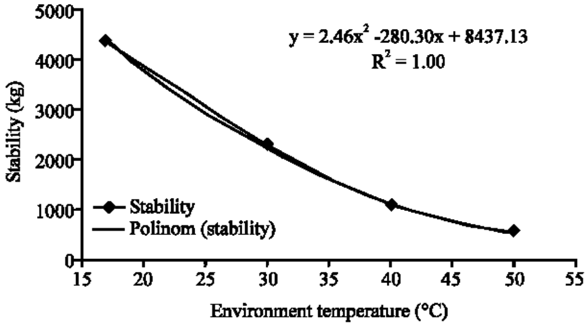

Fig. 7: Average stability for groups based on 3 h-exposure time

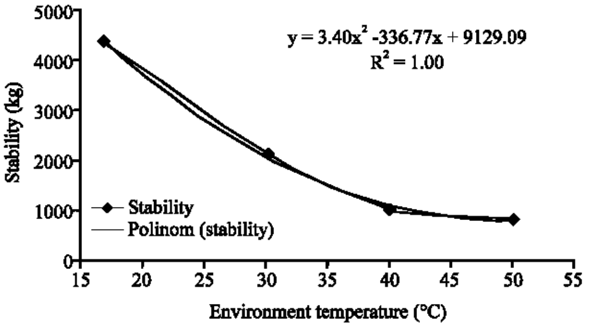

Fig. 8: Average stability for groups based on 4.5 h-exposure time

Relationship between stability and ultrasound velocity: Ultrasound velocity was measured at various environment temperatures at the end of exposure time for 12 groups. Then without losing time, samples were placed on stability test machine and stability tests were carried out. Multi-linear regression and analysis of variance were conducted to determine the relationship between ultrasound velocity and stability. According to the results, the relationship between second ultrasound velocity and stability could be written as follows:

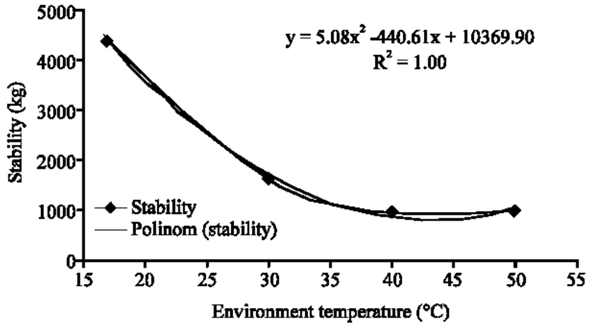

Fig. 9: Average stability for groups based on 6 h-exposure time

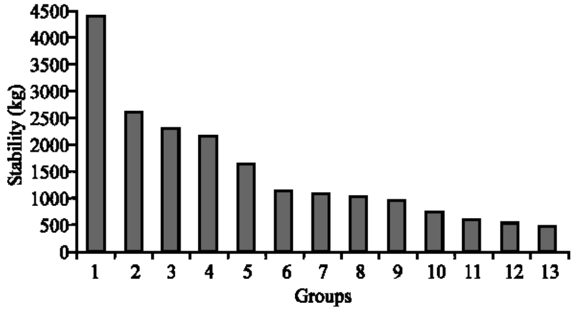

Fig. 10: Average stability values for groups based on environment temperatures and exposure time

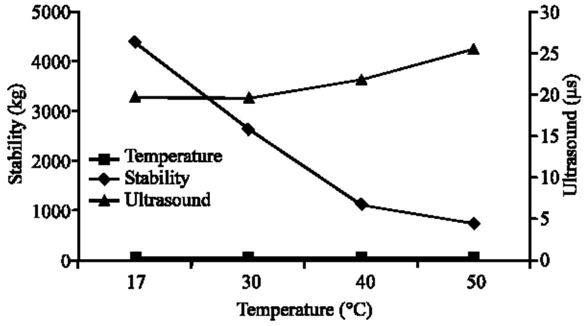

Fig. 11: Group averages for stability and second ultrasound velocity based on temperatures after 1.5 h

$$S = 5717{,}763 - 189{,}175x_5$$

S = Stability (kg).
x_5 = 2nd ultrasound velocity.

According to the group average, stability and second ultrasound velocity values based on exposure times were presented (Fig. 11-14).

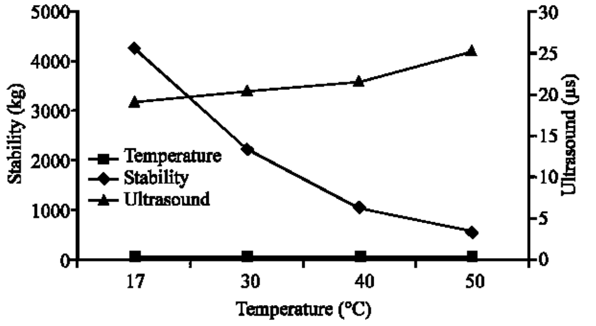

Fig. 12: Group averages for stability and second ultrasound velocity based on temperatures after 3 h

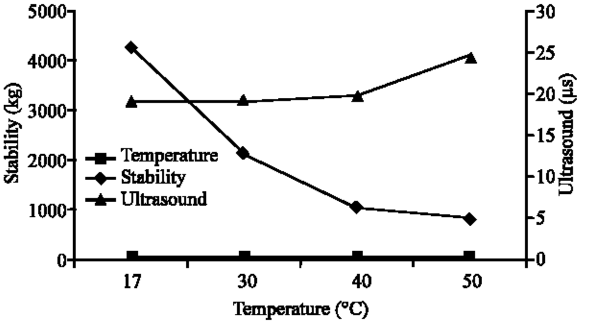

Fig. 13: Group averages for stability and second ultrasound velocity based on temperature after 4.5 h

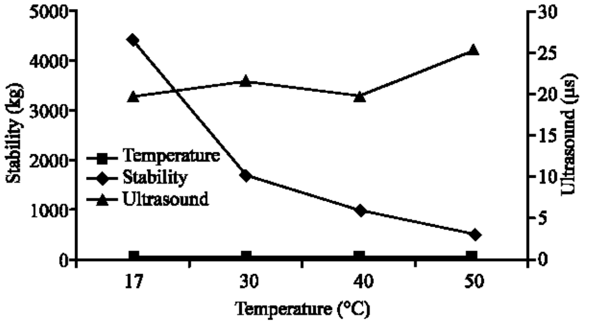

Fig. 14: Group averages for stability and second ultrasound velocity based on temperature after 6 h

RESULTS AND DISCUSSION

It was found that environment temperature has reduced the stability of the asphalt concrete considerably. Temperature increases both viscosity and ductility on asphalt cements. Because of the viscosity-temperature dependency (Ukwuoma and Ademodi, 1999; Gardiner and Brown, 2000; Bahia *et al.*, 2001; Petersen *et al.*, 1994;

Coplantz *et al*., 1993) of asphalt materials, some experts (Sousa *et al*., 1994; Kandhal *et al*., 1995; Huner and Brown, 2001; West, 2005; McDaniel *et al*., 2000) believe that the relevant performance of hot mix asphalt mixture has a strong relationship with mixing temperatures in the central plant and compaction temperatures in the field. This has been widely implemented to determine the mixing and compaction temperature both in laboratory and field construction (Gudimettla *et al*., 2003). It was determined that both exposure times and environmental temperature increases the ductility of asphalt cements (Özgan and Kap, 2005). Increasing viscosity and ductility decreases the stability of asphalt concrete and as a result; some problems, such as segregation, high air void, content resulting in inadequate mixing and compaction temperature, are considered to be the major contributors to early or premature distresses of asphalt pavement (Gardiner and Brown, 2000; Krishnan and Rao, 2001; Epps *et al*., 2000, 2002; Rauhut *et al*., 1994).

The results showed that at 30°C, the stability of the asphalt core samples decreased by 40.16, 47.47, 50.4 and 62.39% after 1.5, 3, 4.5 and 6 h, respectively. At 40°C, the results indicated that the stability of the asphalt core samples decreased by 74, 31, 74.99, 76.73, 78.10% after 1.5, 3, 4.5 and 6 h, respectively. Finally, at 50°C the stability of the asphalt core samples decreased by 83.22, 86.22, 87.19, 88.66% after 1.5, 3, 4.5 and 6 h, respectively. The test results indicate that there exists a negative relationship between environmental temperature where the samples are stored and their stability. The significance level for the relationship between environmental temperature and the stability of the asphalt core specimens was 0,887. It was observed that as the temperature increased, the stability of the asphalt concrete decreased and this decrease was greatest by 88.66% at 50°C after six hours of exposure time. This finding can be explained by the increase in ductility and the decrease in the viscosity of the bitumen leading to increased fluidity due to increasing the high temperature.

The overall results concerning the effect of exposure times on the stability of the asphalt core samples showed that increase in exposure time reduced the stability of the asphalt core samples but this effect was not as strong as the effect of the temperature. The results showed that when the exposure time was short, the temperature affected the surface of the samples and inside the samples the bitumen was not affected much by the temperature. However, as the exposure time increased the temperature inside the samples increased too and as a result the bitumen is heated. The fluidity of the bitumen increases when the bitumen is heated, as a result of the increasing ductility and decreasing viscosity. In terms of the stability of the samples and ultrasound measurements, the results showed that the relationship between stability and first ultrasound passing time measured at 17°C in laboratory environment was -0,064. This indicates that there was no relationship between the stability of the samples and first ultrasound passing time.

The relationship between stability and second ultrasound, on the other hand, was found to be -0,533. This shows that when the stability of the samples was high, the ultrasound passing time was short and when the stability was low, ultrasound-passing time was longer. This could clearly be observed with the samples exposed to 50°C temperature because with these samples when the stability of the samples was lowest at 50°C, the ultrasound passing time was longest. The interaction of ultrasound passing time and the volume of the cavities in the samples can account for this. The fluidity of the bitumen increases when the samples are exposed to high temperature and fills in the cavities in the samples and with the samples with fewer cavities ultrasound passing time increases. For samples that were not exposed to high temperature, the bitumen does not exhibit fluidity and fill in the cavities and with the samples with more cavities ultrasound passing time decreases. In other words, since the cavities in the samples the speed of ultrasound passing slow down, with samples having greater cavities ultrasound passing time increases. However, in this study, the influence of high temperature on the speed of ultrasound was not taken into consideration.

The stability of the asphalt concrete was found to decrease significantly when it was exposed to high temperature for longer periods when the load applied to the pavement kept constant. It is clear that vehicles with the same weight will have a varying negative impact on the asphalt pavement depending on the time of the different times of the day they are using the highway. The greatest negative impact will be incurred on the pavement at the time of the day when the asphalt concrete gets heated the most. However, it should be noted that in this study the samples were exposed to varying temperatures form all sides, which is not the case with highways. On highways only the surface of the asphalt concrete was exposed to heat. Therefore, in order to understand the actual impact of the temperature on highways, the effect of the heat during the day on the lower layers of the asphalt needs to be determined. This finding could inform the decisions with regards to the optimal thickness of the binder and erosion layers and as a result, the stability of the asphalt concrete can be improved and certain undesirable outcomes, such as rutting, cracking and depressions could be avoided.

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