Application of Automated Non-contact Resonance Testing for Low Temperature Behavior of Asphalt Concrete

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Abstract

Impact resonance testing is a well-documented non-destructive testing method and its applications on asphalt concrete have also been implemented successfully. The test is carried out manually by inducing an impact in order to excite the test specimen and taking measurements of the vibrational response. In an effort to improve the manual procedure of impact resonance testing, an automated non-contact methodology is developed and its applicability with regards to low temperature behaviors of asphalt concrete is investigated. Results from this work show that repeatable fundamental resonance frequency measurements can be performed on a disc shaped specimen in an automated manner without the need to open the thermal chamber. The measurements obtained from the new method have been verified by taking similar resonance frequency measurements using an instrumented impact hammer. It has also been shown in this work that the proposed method is suitable to investigate the lone effects of cyclic thermal conditioning on asphalt concrete without any other possible biasing effects associated with contact in the conventional testing. A hysteretic behavior of stiffness modulus is obtained on three different asphalt concrete specimens subjected to repeated low temperature cyclic conditioning. Reduced modulus values at each temperature are obtained in all the tested specimens after a low temperature stepwise conditioning at temperatures from 0°C to -40 °C. This observed behavior shows that the dynamic modulus of the tested specimens is affected by low temperature conditioning. The norm of the complex modulus decreases and the phase angle or damping ratio increases after low temperature conditioning. Hence, valuable and practical low temperature characteristics of different asphalt concrete mixtures can possibly be obtained by using the proposed methodology.

Keywords: Resonance testing, stiffness modulus, asphalt concrete, Non-contact excitation, Resonance frequency

Sammanfattning

Resonansfrekvensmätningar är en väl dokumenterad oförstörande provningsmetod och dess tillämpningar på asfaltbetong har börjat implementeras i branschen. Metoden utförs vanligtvis manuellt genom att excitera en provkropp med en liten hammare och mäta upp den dynamiska responsen med en accelerometer. I ett försök att förbättra och automatisera det manuella förfarandet för resonansfrekvensmätningar har inom detta projekt en kontaktlös metod utvecklats. Tillämpbarheten för dessa automatiserade mätningar vid låga temperaturer har undersökts. Resultat från arbetet visar att repeterbara resonansfrekvensmätningar kan utföras på cylindriska diskformade provkroppar inne i ett klimatskåp utan att öppna dörren till skåpet. Metoden har verifierats genom att utföra liknande resonansfrekvensmätningar med hjälp av en instrumenterad hammare. Detta arbete har också visat att den föreslagna automatiserade metoden är lämplig för att undersöka den renodlade effekten av temperaturvariationer på styvhetsmodulen i asfaltbetong utan några andra möjliga effekter från konventionell cyklisk belastning. Styvhetsmodulen på tre olika asfaltprovkroppar mättes upp under stegvis temperaturkonditionering från 0° C till -40° C och tillbaka till 0° C under flera upprepade temperaturcykler. Uppmätt styvhetsmodul minskade från cykel till cykel och dämpningen ökade. En hysteresis effekt mellan nerkylning och uppvärmning i respektive temperaturcykel kunde också påvisas. Detta observerade beteende visar att den dynamiska modulen för de undersökta provkropparna påverkas av låg temperaturkonditionering. Det är därför troligt att den föreslagna metoden kan vara värdefull för att studera lågtemperaturegenskaper för olika asfaltrecept.

Nyckelord: Resonanstestning, styvhetsmodul, asfaltbetong, kontaktlös excitation, resonansfrekvens

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Stockholm, January, 2019

List of Acronyms

AC	Asphalt concrete
IRT	Impact resonance testing
NDT	Non-destructive testing
RAS	Resonant Acoustic Spectroscopy
RUS	Resonant Ultrasound Spectroscopy
TL	Thermal Loading
TU	Thermal Unloading

List of Appended Papers

This thesis is based on the following two manuscripts submitted to Journals

Paper I.

Bekele Abiy, Nils Ryden, Anders Gudmarsson and Björn Birgisson, "*Automated Non-contact Resonance Excitation Method for Low Temperature Behavior of Asphalt Concrete* " (submitted manuscript to journal of Non-destructive Evaluation and under review)

Paper II

Bekele Abiy, Nils Ryden, Anders Gudmarsson and Björn Birgisson, "*Effect of cyclic low temperature conditioning on Stiffness Modulus of Asphalt Concrete based on Non-contact Resonance testing method* " (Submitted manuscript to Construction and Building materials and under review)

Contribution of authors to the papers

Paper I. Bekele A. carried out all the experimental work, data analysis and writing the manuscript. All supervision, guidance on methodology and proof reading was done by Nils Ryden. Gudmarsson A. helped with providing samples, proof reading and co-supervision. Birgisson B. helped with proof reading.

Paper II. Bekele A. carried out all the experimental work, data analysis and writing the manuscript. All supervision, guidance on methodology and proof reading was done by Nils Ryden. Gudmarsson A. helped with providing samples, proof reading and co-supervision. Birgisson B. helped with proof reading.

Contents

Chapter 1 Introduction

1.1 Background

Asphalt concrete is a composite viscoelastic material whose behavior is highly dependent on temperature and frequency of loading. It is composed of aggregates, air voids and bitumen, from which its viscoelastic behavior is acquired. When asphalt concrete is cooled down to low temperatures, its mechanical behavior changes due to an increase in its elastic component and a decrease in its viscous component (Witczak M. W and R. E. Root, 1974). Complex dynamic modulus (E*) is considered as one of the main parameters for studying and characterizing these changes associated with decrease in temperature. It is also an important input to the AASHTO mechanistic empirical pavement design (NCHRP Synthesis 457, 2014). Cyclic tension or compression tests are carried out at a reference temperature and shift factors are used to calculate dynamic moduli at lower temperatures and/or higher loading frequencies (Charles E. Dougan et al., 2003). However, conventional cyclic testing methods to determine dynamic modulus of asphalt concrete are generally limited to a loading frequency range of 0.01Hz to 25Hz (Brown et al., 2009). In addition, they are also associated with high costs and are affected by different biasing effects including thermal contaminations. Hence, master curves constructed using different predictive models are commonly used to estimate dynamic modulus values at low temperatures and/or high loading frequencies. The predicted moduli based on master curves are not always in agreement with measured values since they depend on the models and the shift factors used for the prediction and extrapolating could result in unrealistic values (Silvia Angelone et al., 2018). Therefore, it is considered beneficial to develop an alternative testing method that can mitigate these problems.

An alternative methodology to the conventional modulus testing of asphalt is the impact resonance testing (IRT). In IRT, an excitation is induced using a manual impacting on a specimen and the vibrational response is consequently measured. A further analysis is carried out to determine the elastic/viscoelastic material properties. This testing technique has been utilized for characterizing asphalt concrete as a non-destructive testing (NDT) method (Gudmarsson et al. 2012). This technique has shown promising results as a convenient, less costly and efficient method. An early contribution regarding its applicability was made by investigating if ASTM C 215, which is utilized for Portland cement concrete, can also produce consistent and precise results for asphalt concrete applications (Whitmoyer and Kim, 1994). IRT has been proposed for the purpose of laboratory quality control of AC and its comparison with field seismic tests has shown good agreement (Nazarian et al., 1999). Thin disc shaped AC specimens have been utilized for IRT and dynamic modulus master curves have been compared against master curves obtained from Witczak's predictive equations (Ryden, 2011). Complex dynamic modulus of a beam shaped asphalt concrete specimen has also been determined by using resonance ultrasound spectroscopy (RUS) technique at multiple resonance frequencies obtained from IRT (Gudmarsson et al., 2012). Indirect tensile strength (IDT) test was utilized to evaluate dynamic modulus master curve of asphalt concrete obtained from IRT considering internal damping with peak transmissibility assessment of input and output accelerometer attached to opposite ends of a rod shaped specimen (Sungho Mun, 2015). Thin disc shaped asphalt concrete specimens were utilized for steel ball dropping approach of IRT to obtain dynamic modulus master curves that are similar to the ones obtained from AASHTO T342-11 tests (D. Kim and Y. R. Kim, 2017). Results of a sensitivity analysis of IRT of asphalt have shown that while variations in specimen geometries have no significant effects, quality of signal is affected by the test temperature and the test can be unreliable at temperatures above 30 ^{o}C (R. Tauste et al., 2017). It has also been shown that Hirsch model can underestimate the limiting maximum modulus at the lower temperature asymptote of dynamic modulus master curve of asphalt concrete and significant improvement is shown by using IRT (Boz et al., 2017). Optimization of measured frequency response functions from impact resonance testing against theoretical frequency functions was carried out to characterize dynamic modulus master curves of beam shaped asphalt concrete (Gudmarsson et al., 2012). Multi modal back analysis based on IRT of asphalt concrete has been investigated in order to compare complex dynamic modulus and Poisson's ratio results with cyclic tension-compression test (Jean-Claude Carret et al., 2018)

In most applications of impact resonance testing, a manual impact is carried out for exciting the test sample. In order to limit potential temperature and operator related disturbances, an automated impact method was developed in a recent project (Gudmarsson and Jakobsson, 2016). This system enables resonance frequency measurements of several specimens inside a closed climate chamber. In another recent study, a solenoid piston programmed with a microcontroller (Arduino UnoR3) was utilized to automate impact resonance testing inside a closed thermal chamber (Jean-Claude Carret et el., 2018). The above mentioned studies indicate the need to develop an automated technique for resonance testing inside a closed thermal chamber.

1.2 Motivation

Impact resonance testing (IRT) using a contact method based on manual excitation has its short comings. In order to perform the manual impacting, the technician needs to keep the thermal chamber open for a certain period since in most cases multiple impacting is necessary to obtain the best possible accuracy. During the period when the thermal chamber is open, variation in the actual measurement temperature is inevitable and can have a pronounced effect on the results at low temperatures. Since asphalt concrete is highly susceptible to changes in temperature due to its viscoelastic behavior, it is important to improve the procedure of the manual impact resonance testing technique for asphalt applications. The study of potential low temperature damage and healing is an interesting and important aspect that can be facilitated by an improved resonance testing method under controlled temperature conditions.

The application of a loud speaker to excite samples of different materials has been successfully illustrated in previous research on material non-linearity studies (T. Sugimoto et al. 2015; Gudmarsson et al. 2015). In this thesis, an automated non-contact system of excitation is developed by using a loud speaker as the source of excitation inside a closed thermal chamber. The fundamental axially symmetric resonance frequency of disc shaped asphalt concrete specimens is measured. It is also verified that this automated non-contact method gives similar results to those obtained through excitation with an impact hammer at the same controlled temperature. The repeatability of the proposed method is also investigated by assembling an automated non-contact experimental set up inside an environmental chamber.

Research on the behavior of asphalt concrete at low temperatures is of major importance in cold regions where pavements are exposed to several months of low temperatures each year. Most of the previous research regarding low temperature behavior of asphalt has focused on the behavior and performance under mechanical loading. However, it is also believed that there is a need to investigate how the asphalt concrete complex modulus is affected by low temperatures without mechanical loading at conventional strain levels (~50 micro strains). Low temperature conditioning may have an effect on the properties of asphalt even without mechanical loading and pavements are repeatedly exposed to low temperature variations under the absence of or in combination with traffic loading. Pavement temperatures are also under cyclic variations during

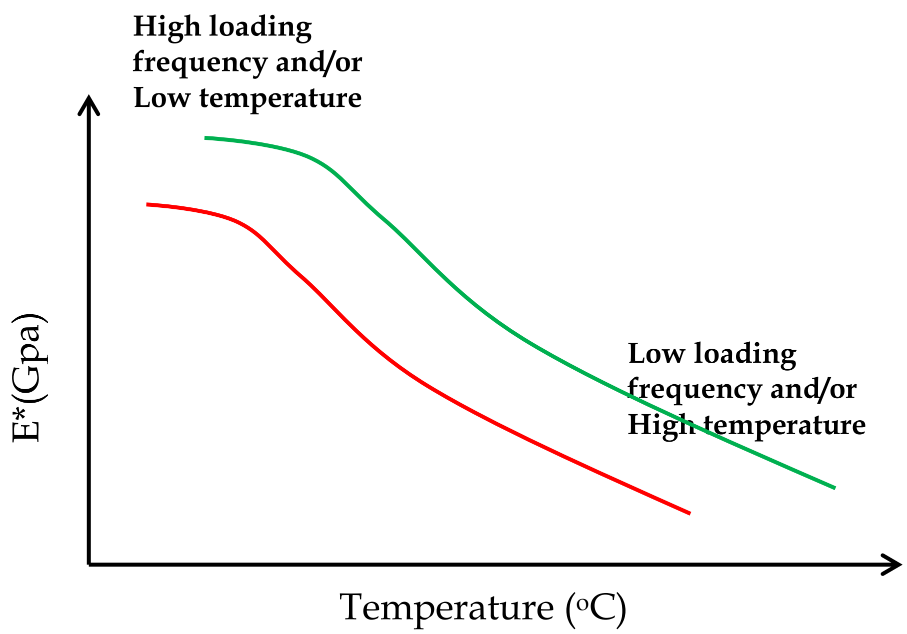

Fig.1 A schematic depiction of the asphalt concrete dynamic modulus with respect to loading frequency and temperature

day and night. This cyclic cooling and heating is believed to induce thermal fatigue distress due to the repeated contractions and relaxations of components of asphalt mixture (MD R. Islam, 2015). Therefore, the sole effect of cyclic cooling and heating is considered to be important and the developed method in this work is considered to be suitable for such a study. Figure 1 shows a typical behavior of the asphalt concrete dynamic modulus as a function of temperature and loading frequency for two different mixes (red and green).

1.3 Objectives

The objective of this study is to develop an automated non-contact resonance testing method with loud speaker as a source of excitation. The applicability of the proposed method is investigated taking into consideration its repeatability and verification with impact resonance testing. The effects of cyclic low temperature variations are also studied on three asphalt concrete specimens.

Chapter 2 Methodology

2.1 Acoustic Resonance Excitation

Seismic waves in a solid object generated by an external excitation source can superpose and create standing waves if the input can provide energy in a frequency that is equal to the object's natural frequency. The instance at which the input wave frequency equals the natural frequency of the object is known as resonance. Every material has its own resonance frequencies depending on its geometry as well as modes of vibrations. The main reasons of measuring the frequency response of civil engineering materials after an excitation include determining the resonance frequencies, relevant damping and elastic or viscoelastic parameters. Measured resonance frequencies depend on elastic or viscoelastic constants, mass density, geometry and boundary conditions of the material. Therefore, elastic/viscoelastic constants of materials can be calculated by measuring resonance frequencies.

Through air coupling, it is possible to obtain resonance of materials for the purpose of frequency response measurement in a non-contact manner. Non-contact method of excitation has been successfully utilized in modal testing that requires small orders of strain magnitudes (M. Luukkala et al. 1971; I. Solodov et al. 2006; M. Brigante et al. 2013). The method facilitates a control of testing temperatures since specimens can be set up in a controlled environment together with the excitation source (loud speaker). It also makes the choice of excitation signal according to required bandwidth. In this work, a loud speaker is used to transmit a sinusoidal signal generated by a MATLAB function. Emitted sound waves cause resonance as a result of the fundamental axially symmetric mode of vibration of a disc shaped asphalt concrete specimens. Air coupling can be applied to this mode where the direct displacement is normal to the specimen's surface. Figure 2 shows a schematic of the mode of vibration considered for this study.

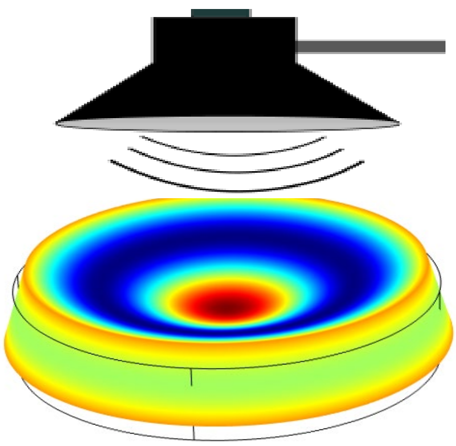

Fig. 2 Illustration of the fundamental axially symmetric mode of vibration under excitation by an acoustic sound wave

2.2 Automated Non-contact Resonance testing set-up

The test setup used in this work has a loudspeaker (Seas Prestige 17TDFC/TV H1210) used for inducing non-contact excitation. A MATLAB function is used to send a 10 s long sinusoidal sweep signal to the loudspeaker. By increasing the frequency of the signal from 8 kHz to 12 kHz, a frequency sweep is applied to the disc shaped asphalt concrete specimen. The test frequency range is selected based on typical results from a similar trial test by using an impact hammer on specimens of similar geometry. A National Instruments data acquisition device (NI USB-6251 M series) is used for recording and sending data input and output. A signal conditioner (PCB model 480B21) is used to amplify the accelerometer signal. The sampling frequency of the sweep is 100 kHz. An accelerometer (PCB model 352B10) with an operating temperature range of -54 °C to 121 °C is attached by wax to the sample and measured data are acquired through the data acquisition device and output to a computer. Figure 3 shows the schematic representation of the experimental setup. The set-up is arranged in such a way that a test sample with the attached accelerometer and loud speaker are placed within the temperature chamber and the excitation is carried out in an automated manner by using a computer.

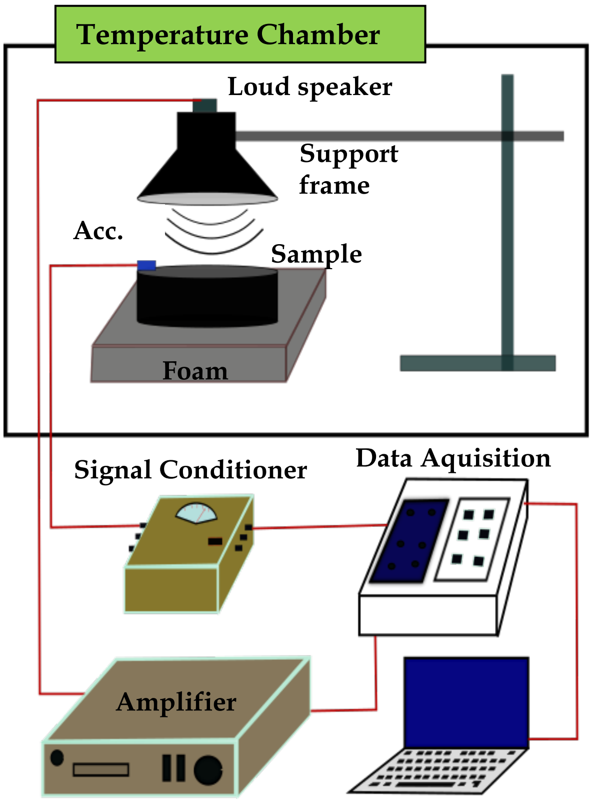

Fig.3 Automated non-contact resonance test set-up

2.3. Materials

Disc shaped asphalt concrete specimens with 100 mm diameters and thicknesses of 20 mm have been used for the testing in this study. Cement concrete of similar geometry is also utilized for the purpose of measurement verifications. Details of the material contents and parameters are included in each of the appended papers.

Chapter 3 Theory of three dimensional vibration for determining dynamic modulus

Free vibration of thin circular plates has been analyzed in multiple previous studies in order to determine elastic material properties (J.So and A.W Leissa 1998; S. Kolluru et al. 2000). A basic theory of elasticity i.e. the dependency of measured fundamental resonance frequency of a circular thin plate on its dynamic modulus and Poisson's ratios has been utilized as a basis for the analysis in the above mentioned studies. According to this method, a dimensionless frequency parameter can be computed for a circular plate from its measured resonance frequencies by taking its diameter, thickness, Poisson's ratio and mass density into consideration. Equation 1 shows how this parameter (Ω_n) is subsequently used to determine shear modulus (G).

$$G = \frac{4\pi^2 {f_n}^2 {R_o}^2 \rho}{\Omega_n^2} \qquad (1)$$

In equation 1, f_n is measured undamped natural resonance frequency, Ro is radius of sample and ρ is its mass density. Dynamic modulus can be determined from shear modulus as in equation 2 by using Poisson's ratio (**ν**).

$$E = 2G(v + 1) \qquad (2)$$

The complex dynamic modulus (E*) is calculated by taking damping into consideration as in equation 3.

$$E^* = E' + iE'' = E'(1 + i\,{}^{\xi}/_{2}) \qquad (3)$$

Where E' and E'' are the storage and loss moduli respectively. Loss modulus is calculated based on the damping ratio (ξ) which is calculated from the measured resonance frequency. The half power band width principle is utilized in order to calculate the damping ratio according to equation 4, where Δf is the frequency bandwidth at 0.707 times the peak amplitude in the resonance curves and f_d is damped resonance frequency.

$$\xi = \frac{\Delta f}{2f_d} \qquad (4)$$

Chapter 4 Summary of appended papers

This thesis is based on two manuscripts which are submitted to journals and are under review. This chapter summarizes briefly the contents of the appended manuscripts.

Paper I. *Automated Non-contact Resonance Excitation Method for Low Temperature Behavior of Asphalt Concrete*

The purpose of this paper is to develop an automated non-contact resonance testing technique that can improve the manually applied impact resonance testing method. The newly developed method measures the fundamental axially symmetric resonance frequency of a disc shaped asphalt concrete specimen at low temperatures. An investigation regarding the method's repeatability has been presented in this paper. Verifications by comparing results with the conventional impact resonance testing method have also been carried out. The main benefit of the developed methodology is that repeatable resonance frequency measurements can be taken under a controlled condition inside a closed thermal chamber. Due to this advantage, the method can also be suitable to carry out low temperature studies on asphalt concrete without any biasing effects that may arise due to contact of mechanical loading.

Paper II. *Effect of Cyclic low temperature conditioning on Stiffness Modulus of Asphalt Concrete based on Non-contact Resonance testing method*

This paper presents a study of the effect of cyclic low temperature conditioning on stiffness modulus of asphalt concrete. Three samples of different asphalt mixtures are monitored with a test plan of cyclic temperature variations. A hysteretic behavior is obtained on measured fundamental resonance frequencies of all the three specimens. The complex dynamic moduli of the specimens are calculated based on the measured resonance frequencies. The results show that there is a reduction of dynamic modulus under a thermal unloading (TU) phase with in a complete temperature cycle. Damping of the specimens is also calculated at each measurement temperature from the corresponding resonance frequencies using the half power bandwidth method. The behavior of the damping with respect to the applied cyclic thermal cooling and heating is also monitored and discussed considering potential presence of micro damage. The results obtained in this paper show the relevance of the non-contact resonance method that is developed in paper I, in terms of monitoring the sole effect of low temperature conditioning on stiffness behavior of asphalt concrete.

Chapter 5 Summary of results and discussions

The first objective of developing the new non-contact resonance testing method is to obtain a repeatable measurement that can be verified. A loud speaker has been successfully used to excite the fundamental axially symmetric resonance frequency of a disc-shaped asphalt concrete. Figure 4 shows an example of a time domain response of an excitation and its corresponding frequency spectrum. Hilbert transform is used to obtain amplitudes of the frequency spectrum after the signal is filtered by the Savitszky Golay method. This filtering is carried out for the purpose of smoothing the signal data to improve the signal to noise ratio without affecting the obtained result.

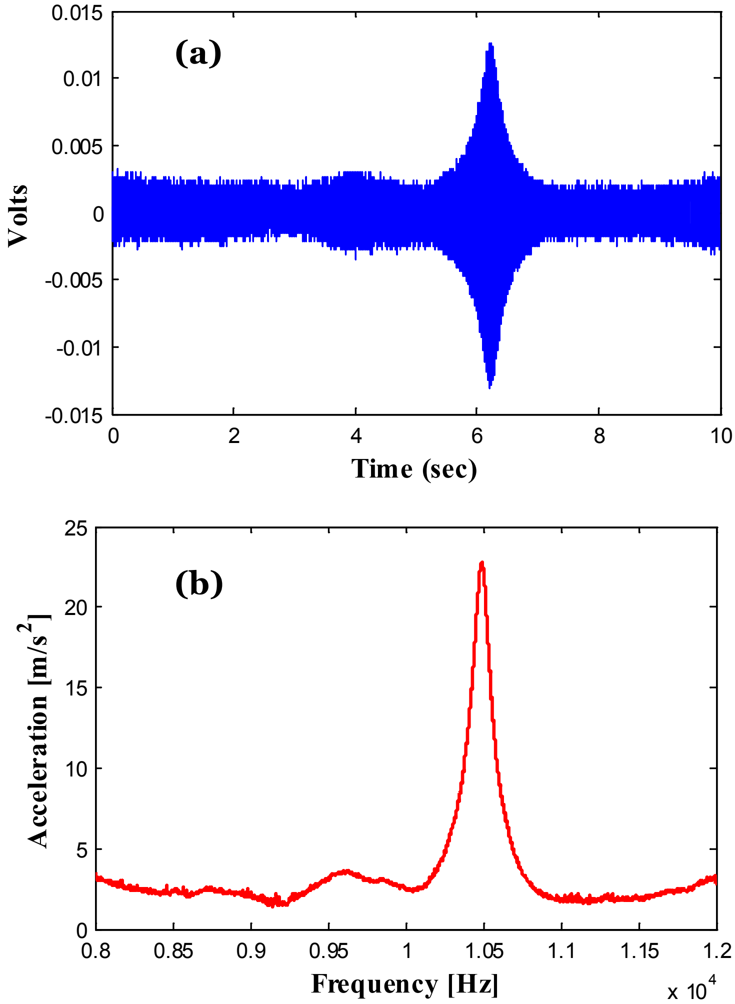

Fig. 4 An example of measured resonance by using loud speaker as an excitation source (a) in time domain and (b) in frequency domain

Repeatability of the method is examined by taking 30 measurements on an asphalt concrete sample of similar geometry as the actual specimen. Results indicate standard deviations of 4.7 Hz and 2.4 Hz at -20 °C and -30 °C respectively. Figure 5 shows an example of repeatability study at -30 °C. In general, the lower the temperature is, the better the repeatability becomes. Standard deviations of 4.9 Hz and 5.1 Hz have also been obtained at temperatures of 0 °C and -10 °C respectively. These deviations in resonance frequencies correspond to approximate modulus deviations of 0.21 %, 0.58 %, 0.62 % and 0.7 % for temperatures of -30 °C, -20 °C, -10 °C and 0 °C respectively.

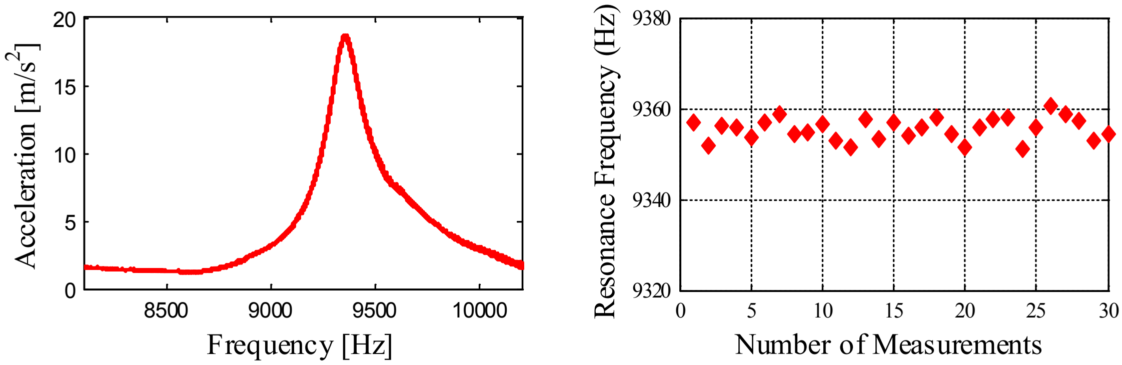

Fig. 5 Example of repeatability of measured resonance frequency of a dummy AC sample at -30 °C using the automated non-contact resonance test method

In order to verify the measured resonance frequencies by the new automated methodology, an instrumented impact hammer is used to trigger the same mode of excitation. Results have shown a good agreement between the impact hammer excitation and the non-contact excitation by a loud speaker on a cement concrete sample of similar geometry (paper I). In this case, measurements are taken at room temperature since cement concrete is not affected by temperature due to its elastic behavior. However, the main objective of this method is to improve the procedure of the testing so that measurements can be carried out under controlled conditions on an asphalt concrete sample at low temperature. Therefore comparison of results from impact resonance and the developed non-contact resonance has to be carried out at low temperatures on asphalt concrete specimens.

In order to observe the differences in results due to different durations of measurement, two impact resonance measurements are carried out at -20 °C and -30 °C at 5 and 10 seconds after the opening of the thermal chamber (paper I). These chosen durations are assumed to be the time required to apply the impact while the thermal chamber is open. Depending on the experience of the operator and how many impacts are required, it could take more time than the assumed periods. These two manual measurements are then compared with the automated non-contact measurement at each temperature. Results indicate that even with these short times considered for the manual measurement, there can be a significant difference due to the temperature contamination caused by opening of thermal chamber. The longer the duration of manual measurement, the more this difference becomes since the measurement temperature becomes more corrupted with a longer period while the climate chamber is open. Figure 6 shows an example of a comparison based on the above mentioned measurement protocol.

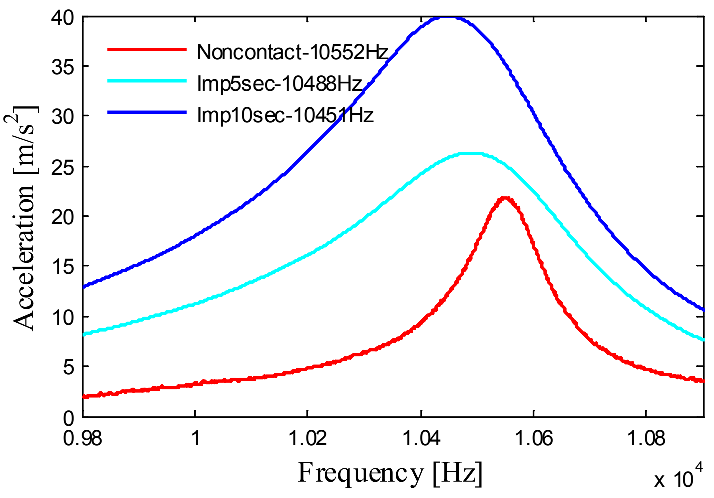

Fig. 6 Examples of variations in resonance frequency measurements at -30 °C caused by manually applied impact while thermal chamber is kept open for 5 and 10 seconds.

In order to show the application of the developed test method on a temperature-dynamic modulus, testing is performed on a ABT-11 70/100 specimen. The details of this mixture's properties are presented in paper I. The conditioning period to obtain constant resonance frequency measurement at one temperature is obtained from a dummy sample and found to be from 3 to 4 hours. Accordingly, the testing was carried out by conditioning the specimen at the required temperature for 4 hours and in a decreasing step wise order from 0 °C to -40 °C. Figure 7 shows the norm of the complex dynamic modulus computed from measured resonance frequencies with decrease in temperature.

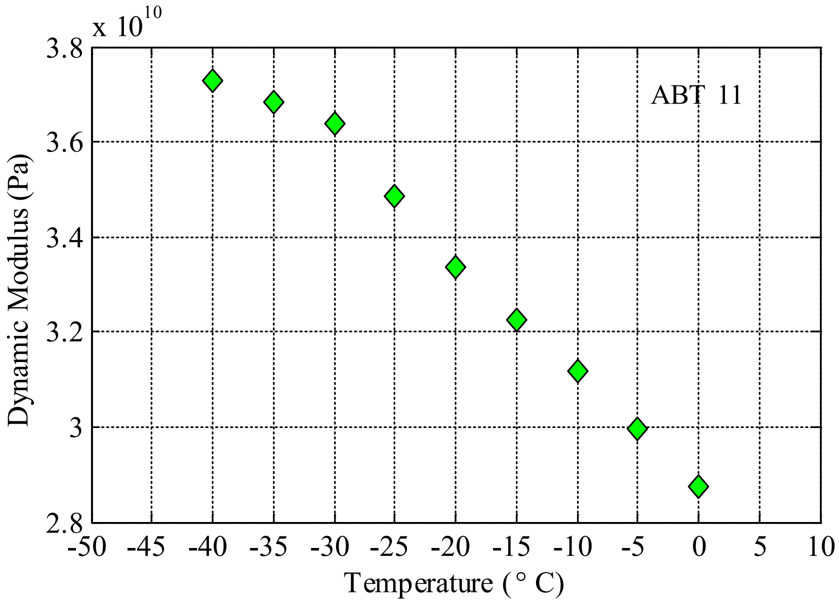

Fig. 7 Dynamic modulus at decreasing order of temperature computed from measured resonance frequencies using the non-contact resonance testing method

Repeated cyclic low temperature measurements of resonance frequencies are performed in Paper II in order to study the effect of cyclic temperature cooling and heating on asphalt concrete. The test was carried out by decreasing and increasing temperatures between 0 °C to -40 °C in a stepwise manner at an interval of 10 °C. Three mixture types were tested with four cooling and heating cycles applied on each specimen. A hysteretic effect is obtained on the behavior of measured resonance frequencies of each specimen. Measured resonance frequencies in the thermal unloading (TU) phase are lower than the corresponding results in the thermal loading (TL) phase (figure 8). Since the measured resonance frequencies are directly proportional to the stiffness modulus, the hysteretic behavior is also applicable to stiffness modulus.

Asphalt concrete is expected to become stiffer at low temperatures due to its viscoelastic behavior. As a thermo-rheologically simple material, it is believed to change its properties with temperature due to changes in free volume which decreases when the temperature is decreased (H. U. Bahia and D.A. Anderson, 1992).The normal expectation is that the stiffness modulus decreases and would return to its previous value when the temperature is increased back to its corresponding previous value. However, the results of this work show that even though the modulus decreases as temperature increases, a reduction is also apparent as compared to the values at the same temperatures in the TU phase. Figure 8 shows an example of the observed hysteretic behavior on the ABS 11 70/100 sample.

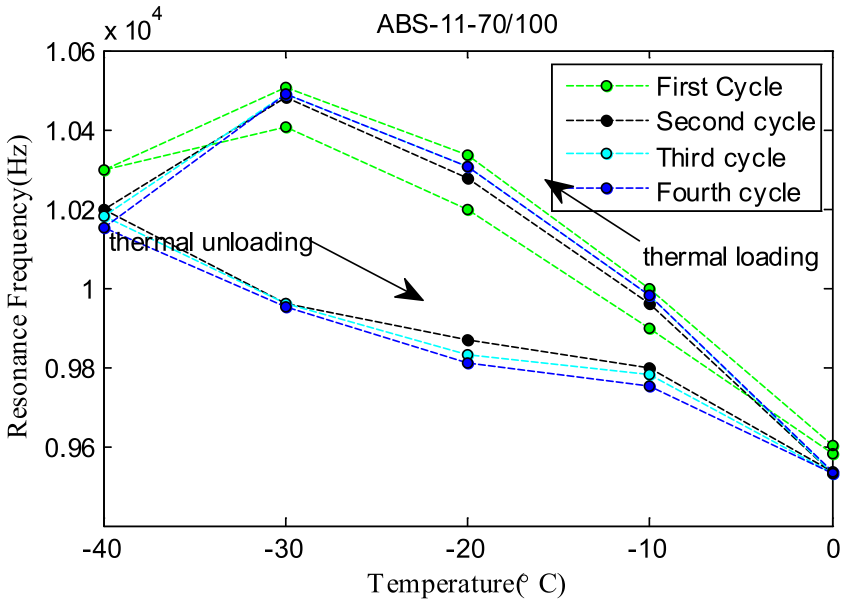

Figure 8. Hysteretic behavior of measured resonance frequencies with cooling and heating cycles on sample ABS-11-70/100

In addition to the observed hysteretic effect, a decrease in stiffness modulus is also obtained on ABS 11-70/100 at -40 °C. In all the tested specimens, as the number of cycles increases, a tendency of decreasing stiffness modulus is manifested.

The reduction in modulus is calculated based on the measurements by assuming Poisson's ratio values of 0.2 and 0.25 for temperatures below -20 °C and above -20 °C respectively. This calculation is carried out in order to show the relative changes in modulus due to the effect of the applied cyclic cooling. Figure 9 shows these reductions of all the three specimens at each temperature within the cooling and heating cycles.

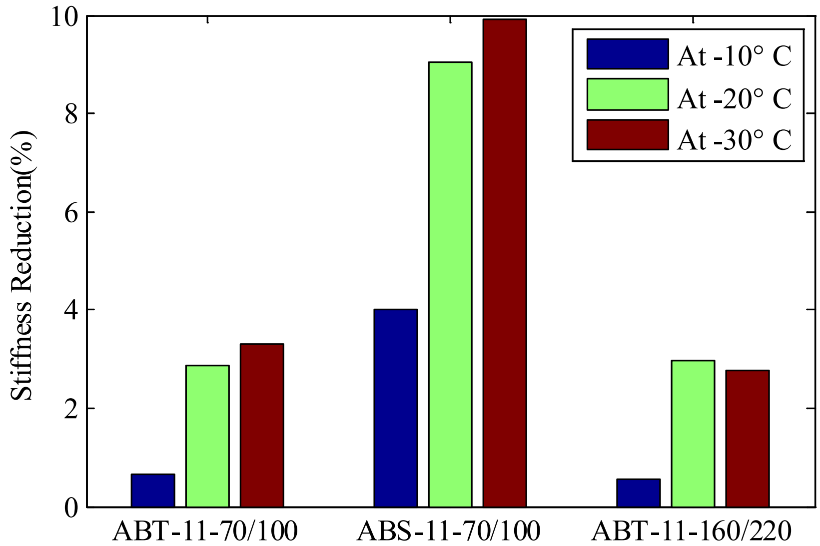

Figure 9. Reduction in stiffness modulus of tested specimens due to cooling and heating cycles

Measured resonance frequencies are used to compute damping ratios of the specimens tested within the temperature cycles. Results from these calculations show an expected decrease of damping ratios as temperature decreases in the thermal loading phase up to -30 °C in the first applied cycles. On the contrary, results calculated at -40 °C are less than those at -30 °C in the fourth cycles for all the specimens tested. ABS-11 70/100 shows this specified reduction in damping in the first cycle as well as the last one. In addition to these, a hysteretic effect is also observed on damping ratios of ABT 11 70/100 and ABS 11-70/100 specimens. Recent studies regarding early damage detecting in different materials have shown that damping is a more reliable and sensitive parameter than stiffness (D. Montalvão et al. 2006; M S Cao et al. 2017). Higher damping ratio suggests the existence of more dissipated energy than expected, indicating the presence of micro damage which may be caused by thermal stresses developed due to differential contraction with in asphalt concrete. Figure 10 shows the damping ratios of ABS 11-70/100 with the application of temperature cycles. It can also be observed that after the specimen is heated to 40°C and kept at room temperature, the first cycle has no such effect of increasing damping ratio at -40 °C.

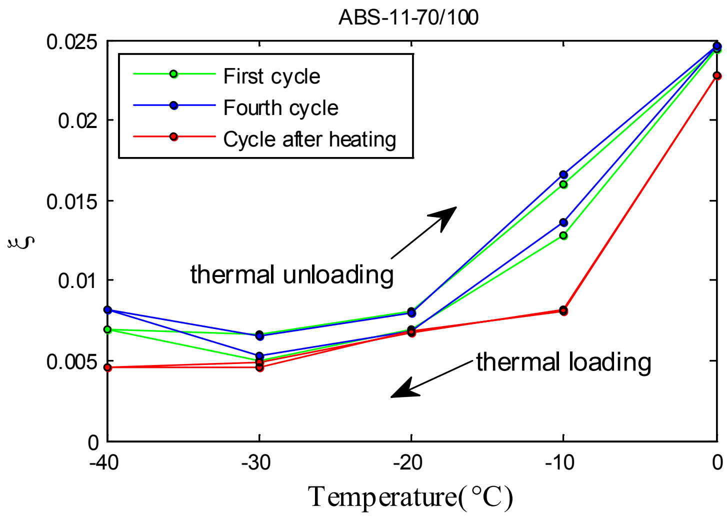

Figure 10. Damping ratios from measured resonance frequencies with application of cyclic cooling on ABS 11-70/100

Chapter 6 Conclusions

The focus of the present study is to develop an automated non-contact resonance testing method that can improve the manually applied impact resonance testing.method The newly developed method enables automatic measurements of the fundamental axially symmetric mode resonance frequency of a disc shaped asphalt concrete specimen. It has been shown in this thesis that the test can be carried out in a controlled environment as the excitation is triggered remotely by a computer. Results of the study have also shown good repeatability of the developed method. The adaptability of the measurement set-up is also studied by varying the air gap between the specimen and the loud speaker. A comparison with the impact resonance method has revealed the method's advantage regarding control of measurement temperatures, particularly for asphalt concrete. The proposed technique has a significant relevance for studying the sole effects of low temperature conditioning on asphalt by avoiding possible thermal contamination, which is associated with opening of the thermal chamber.

In an effort to study the effect of cyclic low temperature conditioning on asphalt concrete stiffness, repeated cooling and heating cycles are applied on three asphalt concrete samples. A hysteretic behavior is observed on the measured resonance frequencies of all the three specimens with the applications of the cooling and heating cycles. Measured resonance frequencies are used to calculate stiffness moduli of the specimens for the purpose of studying the effect of the cooling and heating cycles and comparing reductions in thermal unloading phase of the cycles at each measurement temperature. In addition to the hysteretic behavior, the ABS 11-70/100 specimens' stiffness modulus has shown a decrease at -40 ^{o}C compared to its value at -30 ^{o}C in all the four cycles applied to it. As the number of applied cycles increases, stiffness moduli of all the specimens at -40 ^{o}C become lower and lower. ABT 11-160/220 shows a relatively less pronounced hysteretic effect until the fourth cycle as compared to the other two samples. This can be attributed to its resistance to thermal fatigue due to the softer bitumen used for the mix.

Damping ratios that are calculated based on the measured resonance frequencies of the specimens are also studied with respect to the applied cooling and heating cycles. Results show that damping of the specimens decrease with decrease in temperature until -30 ^{o}C and increased values are obtained at -40 ^{o}C. A combination of reduction in stiffness and increase in damping is considered as a potential indication of a presence of micro damage.

It should be noted that further studies need to be carried out in order to include the effects of more number of cycles, longer periods under low temperature and more mixture types. This study is limited to showing the observed behaviors and the applicability of a non-contact method of studying these behaviors.

References

A. Gudmarsson, N. Ryden, and B. Birgisson, “Application of resonant acoustic spectroscopy to asphalt concrete beams for determination of the dynamic modulus,” Mater. Struct., vol. 45, no. 12, pp. 1903–1913, 2012.

A. Gudmarsson, N. Ryden, and B. Birgisson, “Characterizing the low strain complex modulus of asphalt concrete specimens through optimization of frequency response functions,” J. Acoust. Soc. Am., vol. 132, no. 4, pp. 2304–2312, 2012.

A. Gudmarsson, N. Ryden, B. Birgisson, H. D. I. Benedetto, and C. Sauzéat, “Characterizing the Complex Modulus and Poisson ’ s Ratio of Asphalt Concrete Specimens through Modal Testing,”Int. Symp. Non-Dest Testing in Civil Engineering , 2015.

A. Gudmarsson, N. Ryden, and B. Birgisson, “Non-contact excitation of fundamental resonance frequencies of an asphalt concrete specimen,” AIP Conf. Proc., vol. 1650, no. 2015, pp. 1401–1408, 2015.

A. Gudmarsson, N. Ryden, H. Di Benedetto, C. Sauzéat, N. Tapsoba, and B. Birgisson, “Comparing Linear Viscoelastic Properties of Asphalt Concrete Measured by Laboratory Seismic and Tension-Compression Tests,” J. Nondestruct. Eval., vol. 33, no. 4, pp. 571–582, 2014.

A. Gudmarsson and M. Jakobsson, ‘automatiserad mätning av asfaltprovkroppars resonansfrekvenser,'' SBUF stödjer forskning and utveckling, 2016

ASTM: C215-08, ''Standard Test Method for Fundamental Transverse,Longitudinal and Torsional Frequencies of Concrete Specimens,'' ASCE, West Conshoshocken, 2008.

Brown, E.R., Kandhal, P.S., Roberts, F.L., Kim, Y.R., Lee, D.Y., and Kennedy, T. W., “Hot Mix Asphalt Materials, Mixture Design and Construction (NAPA Research and Education Foundation) ,” 2009.

B. Behnia and W. G. Buttlar, “Cooling cycle effects on low temperature cracking characteristics of asphalt concrete mixture,” Materials and Structures, 2014.

Charles E. Dougan, Jack E. Stephens, J. Mahoney and Gilbert H.,''E* - Dynamic Modulus Test Protocol – Problems and Solutions,'' 2003

D. Kim and Y. R. Kim, “Determination of Dynamic Modulus Values of Asphalt Mixtures Using Impact Resonance Testing of Thin Disk Specimens,” J. Test. Eval., vol. 45, no. 2, p. 20150076, 2015.

D. Dollimore, “Physical aging in amorphous polymers and other materials,” Thermochim. Acta, vol. 54, no. 1–2, pp. 242–243, 1982.

D. Montalvão, N.M.M. Maia and A.M.R. Ribeiro, “A Review of Vibration-based Structural Health Monitoring with Special Emphasis on Composite Materials,” The Shock and Vibration Digest 2006

G. Martinček, “The determination of poisson’s ratio and the dynamic modulus of elasticity from the frequencies of natural vibration in thick circular plates,” J. Sound Vib., vol. 2, no. 2, pp. 116–127, 1965

G. Martinček, “The determination of poisson’s ratio and the dynamic modulus of elasticity from the frequencies of natural vibration in thick circular plates,” J. Sound Vib., vol. 2, no. 2, pp. 116–127, 1965

H. U. Bahia and D. A. Anderson, “Physical Hardening of Paving Grade Asphalts As Related To Compositional Characteristics,” Prepr. ACS, Div. Fuel ..., vol. 37, no. 3, pp. 1397–1407, 1992.

H. M. El Hussein, K. W. Kim and J. Ponniah,“Asphalt concrete damage associated with extreme low temperatures,” 1999.

H. M. Hussein and A. Halim, “Differential thermal expansion and contraction: a mechanistic approach to adhesion in asphalt concrete,” Can. J. Civ. Eng., vol. 20, no. 3, pp. 366–373, 1993.

I. Boz, P. Tavassoti-Kheiry and M. Solaimanian, “The advantages of using impact resonance test in dynamic modulus master curve construction through the abbreviated test protocol,” Mater. Struct., vol. 50, no. 3, pp. 1–12, 2017.

I. Solodov, K. Pfleiderer, H. Gerhard, S. Predak, and G. Busse, “New opportunities for NDE with air-coupled ultrasound,” NDT E Int., vol. 39, no. 3, pp. 176–183, 2006.

J.E. Kliewer, H. Zeng and Vinson T.S., “Aging and Low-Temperature Cracking of Asphalt Concrete Mixtures,” Jour. Cold Regions Eng. 1996J. So and A. W. Leissa, “Three-Dimensional Vibrations

of Thick Circular and Annular Plates," J. Sound Vib., vol. 209, no. 1, pp. 15–41, 1998.
J. So and A. Leissa, "Free Vibrations of Thick Hollow Circular Cylinders FromThree-Dimensional Analysis," J. Vib. Acoust., vol. 119, pp. 89–95, 1997
J. C. Carret. H. D. Benedetto and C. Suarez,"Multi Modal Dynamic Linear Viscoelastic Back Analysis for Asphalt Mixes",JONE, 2018
Jean-Claude Carret,AlvaroPedraza,HervéDi Benedetto and CédricSauzeat,"Comparison of the 3-dim linear viscoelastic behavior of asphalt mixes determined with tension-compression and dynamic tests," Construction and Building materials, 2018
Kweon and Kim, "Determination of Asphalt Concrete Complex Modulus with Impact Resonance Test," *J. Transp. Res. Board ,Natl. Acad.*, pp. 151–160, 2014.
K. E. Van Den Abeele, A. Sutin, J. Carmeliet, and P. a. Johnson, "Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS)," *NDT E Int.*, vol. 34, no. 4, pp. 239–248, 2001.
LaCroix A., Kim Y.R., Sakhaei Far M., "Constructing the dynamic modulus mastercurve using impact resonance testing," Association of Asphalt Paving Technologists (AAPT) Journal, vol. p. 61-9278, 2009.
M.W Witczak and R.E. Root,"Summary of Complex Modulus Laboratory Test Procedures and Results," ASTM,1974.
L. Zhang, T. S. Li, and Y. Q. Tan, "The potential of using impact resonance test method evaluating the anti-freeze-thaw performance of asphalt mixture," *Constr. Build. Mater.*, vol. 115, pp. 54–61, 2016.
M. Akentuna, S.Soo Kim,M. Nazzal, A.R.Abbas and M. S. Arefin"Study of thermal stress development of asphalt mixtures using the Asphalt Concrete Cracking Device(ACCD),"Constructon and Building Materials, April 2016.
Md. R. Islam, "Thermal Fatigue damage of asphalt pavement," PhD Thesis, University of New Mexico, 2015.
M. Luukkala, P. Heikkila, and J. Surakka, "Plate wave resonance - a contactless test method," *Ultrasonics*, vol. 9, no. 4, pp. 201–208, 1971.
M. Brigante and M. A. Sumbatyan, "Acoustic methods in nondestructive testing of concrete: Review of foreign publications in the field of theoretical studies," *Russ. J. Nondestruct. Test.*, vol. 49, no. 4, pp. 185–195, 2013.
M. Kaczmarek, B. Piwakowski, and R. Drelich, "Noncontact Ultrasonic Nondestructive Techniques: State of the Art and Their Use in Civil Engineering," *J. Infrastruct. Syst.*, vol. 23, no. 1, p. B4016003, 2016.
Moses Akentuna1 and Sang-Soo Kim, "Effects of Aggregate Thermal Contraction Properties on Asphalt Mixture's Thermal Properties and Low Temperature Performance," ASCE Congress on Technical Adv.,2017
M S Cao, G G Sha, Y F Ga and W Ostachowicz, "Structural damage identification using damping: a compendium of uses and features," Smart Mater. Struct. 26, 2017
N. M. Jackson and T.S. Vinson, "Analysis of Thermal Fatigue Distress of Asphalt Concrete Pavements,"Jour. of the Transportation Res. Board., 2014.
NCHRP synthesis 457,"Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide and Software ," 2014
O. Paul Togunde and S. A. M. Hesp, "Physical hardening in asphalt mixtures," *Int. J. Pavement Res. Technol.*, vol. 5, no. 1, pp. 46–53, 2012.
P. Kriz, J. Stastna, L. Zanzotto, and B. Materials, "Temperature Dependence and Thermo-Reversibility of Physical Hardening of Asphalt Binders," EAPA, 2008.
R. Taustea,F. Moreno-Navarroa, R. Gallegob, M.C. Rubio-Gámeza,"Analysis of the sensitivity of the impact resonance frequency test as a tool to determine the elastic properties of bituminous materials," Materiales de Construcción,Vol 67, No 327 2017
Ryden, N."Resonant frequency testing of cylindrical asphalt samples,". European Journal of Environmental and Civil Engineering, 15, 587-600, 2011.
Ryden N., "Determining the asphalt mastercurve from free-free resonant testing on cylindrical samples", Proc. of the 7th Int. Symp. on Non-Destructive Testing in Civil

Engineering(NDTCE'09), Ed by A. Odile and D. Xavier, Nantes, France, June 30th-July 3rd 2009.

S. Mun, "Determining the Dynamic Modulus of a Viscoelastic Asphalt Mixture Using an Impact Resonance Test With Damping Effect," *Res. Nondestruct. Eval.*, vol. 26, no. 4, pp. 189–207, 2015.

S. Kolluru, J. Popovics, and S. Shah, "Determining Elastic Properties of Concrete Using Vibrational Resonance Frequencies of Standard Test Cylinders," *Cem. Concr. Aggregates*, vol. 22, no. November 2016, pp. 81–89, 2000.

T. Sugimoto, K. Sugimoto, and N. Utagawa, "Study on the Long Distance Non-Contact Acoustic Inspection Method using a Strong Ultrasonic Sound Source,"World Conference on Non-Destructive Testing, pp. 1–8, 2016.

T. Sugimoto, I. Uechi, K. Sugimoto, N. Utagawa, and K. Katakura, "Study on the Non-contact Acoustic Inspection Method for Concrete Structures by using Strong Ultrasonic Sound source," *Phys. Procedia*, vol. 70, pp. 398–401, 2015.

T.H. Wang,Li-jun Su and Ju-yun Z., "A case study on diurnal and seasonal variation in pavement temperature," Int. Jour. Pav. Eng, 2014.

U. Isacsson and H.Zen, "Cracking of asphalt at low temperature as related to bitumen rheology," Jour. Materials Science,1998.

Vinson, T. S., V. C. Janoo, and R. C. G. Haas., "Low Temperature and Thermal Fatigue Cracking," Summary Report SR-OSU-A-003A-89-1. Strategic Highway Research Program, June 1989.

Whitmoyer, S.L., Kim, Y.R., "Determining asphalt concrete properties via the impact resonant method. Journal of Testing Evaluation", 22(2), 139-148, 1994.