Nondestructive Evaluation of Warm Mix Asphalt through Resonant Column Testing

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16. Abstract

Non-destructive testing has been used for decades to characterize engineering properties of hot-mix asphalt. Among such tests is the resonant column (RC) test, which is commonly used to characterize soil materials. The resonant column device at Penn State was used to determine the modulus and damping of warm-mix asphalt prepared with three different warm-mix technologies: water foaming, a waxy additive, and a chemical additive. Specimens were prepared in a Superpave gyratory compactor and then sawed and drilled to deliver the geometry needed for the RC tests. Hot-mix asphalt specimens were also tested to provide reference data. Testing was completed at 25 ºC. The RC device specimen assembly had to be retrofitted to make it suitable for testing asphalt concrete, which has a higher stiffness than soils at ambient temperatures. The results indicated that the RC test can be successfully used to determine the shear modulus of the asphalt concrete. Different torque levels, therefore inducing different strain levels, could be applied in the RC test to determine the range of linear elastic behavior of the material. This is an important step to ensure the validity of assumptions used for the purpose of modulus calculations. At 25 ºC, it was found that the lowest shear modulus was found for the mix prepared through the water foaming process, and the highest modulus was found for the mix with the waxy additive (Sasobit). The modulus of the mix with the chemical additive and the modulus of the hot-mix asphalt were found to be in between. Use of the RC test to determine the damping properties of asphalt concrete proved to be more challenging and strain dependent, even when maintaining the strain within the linear elastic range.

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Table of Contents

List of Figures

List of Tables

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Introduction and Problem Statement

Flexible pavements comprise more than 93% of the paved highways in the United States [1]. Conventional hot-mix asphalt (HMA) concrete has commonly been used for construction of flexible pavements for decades. The increasing importance of building sustainable infrastructure has caused many agencies to employ new materials and innovative construction techniques. The development of warm-mix asphalt (WMA) technologies has been one of the significant efforts intended to serve this purpose. Such innovative technologies have numerous advantages, including lowering energy consumption, mitigating air pollution problems, and reducing exposure of workers to fumes. As the usage of WMA has gained tremendous popularity in recent years, the need has arisen to choose proper techniques to ensure accurate characterization of WMA and prediction of its performance through accelerated testing in the laboratory. Nondestructive testing of materials for the characterization of engineering properties is one such technique and has been applied for decades. As a commonly used test method for soils and geo-materials, resonant column (RC) testing can nondestructively yield valuable data about dynamic behavior of these materials within the small strain level [2]. Material properties like shear modulus, Young's modulus, and damping in torsion and flexure modes can be measured on cylindrical samples. This method has been commonly used to test soils and geo-materials for more than four decades. However, the use of resonant column testing for characterization of asphalt concrete has been limited. Previously conducted work has presented some common challenges in bringing conventional Resonant Column Apparatus (RCA) devices into use to characterize asphaltic mixtures [3,4,5]. The work presented in this report demonstrates how some of these challenges can be addressed and how this testing system provides a unique way of determining asphalt concrete properties. Specifically, this technique is useful in this research to characterize warm-mix asphalt. This type of asphalt concrete is produced using specific additives that are used to alter binder properties, making it possible for application at lower temperature than conventional hot-mix asphalt.

Scope of Work and Research Approach

As the first step of this study, a literature review was carried out to address the following areas:

a. The state of practice and state of the art in WMA characterization.
b. Background on resonant column testing and its application to geotechnical engineering.
c. Past experience with using RC for testing asphalt concrete mixtures, both hot mix and warm mix.
d. Relevant standards and specifications.
e. Identifying the approach that needs to be taken to address the challenges and issues with using RC for testing specimens stiffer than soil, specifically asphalt concrete.

According to the conclusions drawn from the literature survey, the following plan was devised to study small-strain level mechanical properties of WMA mixtures by means of resonant column testing. The following main objectives were sought during this research:

- Test specimens of both WMA and conventional HMA with resonant column test.
- Upgrade a readily available conventional RCA to be capable of running the RC test on stiffer asphalt concrete samples and maintaining a temperature-controlled environment during test.
- Find a solution for coupling of the RCA drive system and asphalt concrete specimen during torsional resonance test.
- Investigate the effect of strain level on shear modulus and damping ratio of asphalt concrete within the small strain range.

The experimental plan consisted of the following parts to achieve the goals mentioned above.

- Modification of conventional resonant column apparatus to increase the capability of the machine for running the tests on asphalt concrete samples.
- Designing and manufacturing a temperature-controlled chamber appropriate for research uses and conventional RCA.
- Sample preparation including the following steps:
    - Conducting basic tests on aggregate and binder
    - Blending WMA additives and binders and water foaming of binders
    - Batching and mixing aggregate
    - Determination of maximum theoretical specific gravity of loose asphaltic samples and bulk specific gravities of compacted specimens
    - Coring and cutting compacted specimens
    - Gluing specimens to RCA through attachments specifically designed and manufactured for the proposed testing
- Resonant column testing of asphalt concrete samples:

- Torsional mode: Measurements of shear modulus and damping ratio of three WMA mixes and one conventional control HMA mix
- Torsional mode: Measurements of shear modulus and damping ratio under two levels of applied torque

Details of the literature review and experimental activities are presented in the following sections.

Methodology

Literature Survey

Resonant Column Test Basics

First developed by Ishimoto and Iiad in 1937, this test has become popular for studying dynamic response of soils since 1963 [6]. The fixed-free configuration is the most common testing arrangement as a result of the straightforwardness of its mathematical derivation. Basically, a cylindrical specimen is excited in torsion or flexural modes. Motion of the free end is monitored by accelerometers and proximeters that can be used to identify resonant frequency during harmonic excitations and logarithmic decrement during free vibrations, which can then be used to calculate wave velocity, damping, and elastic moduli of the specimen. Many researchers have contributed to improve both the theory and hardware of the resonant column test during the past decades, including Hall and Richart [7], Drnevich, Hall and Richart [8], Hardin and Music [9], Drnevich [10], Hardin and Black [11], Anderson and Stokoe [12], Allen and Stokoe [13], and Porovic [14]. This list is not exhaustive, as covering all of the literature related to the development and applications of resonant column testing is neither feasible nor within the scope of this study. Past research in applying this method to test asphalt concrete will be discussed later in this report.

Young's modulus and shear modulus of a specimen can be measured by running the RC test in flexural and torsional modes, respectively. Damping ratios for each mode can be calculated by running a free vibration test. Having the specimen dimensions (i.e., height and diameter) and also its mass, the mass polar moment of inertia can be calculated from Equation 1, assuming that the specimen is an ideal solid cylinder:

$$I = \frac{md^2}{8} \tag{1}$$

where I is mass polar moment of inertia (kg-m^2), m is mass of the specimen (kg), and d is the outside diameter of the solid specimen (m).

The mass polar moment of inertia of the drive system connected to the specimen I_0 is also needed to reduce data from the RC test. As the drive system geometry is complex, it is not feasible to calculate the mass polar moment of inertia by the simplified formulas; hence, it is generally obtained through calibration tests. Having both I and I_0, the following equations can be used to obtain the shear wave velocity V_s and shear modulus G of a specimen:

$$I/I_o = \beta \tan \beta \tag{2}$$

$$V_s = \frac{2\pi f l}{\beta} \tag{3}$$

$$G = \rho V_s^2 \tag{4}$$

where V_s is the shear wave velocity (m/s), f is the first-mode resonant frequency of the sample as measured through RC test (Hz), l is the sample height (m), G is the shear modulus (kPa), and ρ is the bulk density of the sample (Mg/m^3). Beta values can be found from Table 1 or by solving Equation 2. It should be noted that Table 1, as presented here, is not comprehensive, and similar tables can be found in RC-related references. Shear wave velocity and shear modulus can then be calculated accordingly by Equations 3 and 4.

After determination of the resonance frequency for a specimen, damping ratio can also be obtained by measuring the response of the sample under free-damped vibration at its natural frequency. The damping ratio represented by D can be calculated from Equation 5:

$$D = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}} \tag{5}$$

where δ is the logarithmic decrement of vibration at the top of the specimen.

The use of solid specimens in torsional loading results in shear strain γ that increases in proportion to the radial position. Chen and Stokoe [15] developed the equivalent radius approach to account for the non-uniform distribution of γ in the soil specimen. Kim [16] and Hwang [17] recommended using the equivalent radius varying from 0.82 of specimen radius for γ below 0.001% to 0.79 of specimen radius for γ up to 0.1%. For this study, the equivalent radius was defined as 0.8 of specimen radius and hence the shear strain γ values reported herein are 80% of the maximum shear strain along the outer surface of the specimens, which is consistent with ASTM D4015-07 [18].

The theories presented in this section are a summary of what is of immediate use for the purpose of testing and preliminary data analysis through RC tests. More details are needed in order to upgrade the capacity of conventional apparatuses to conduct the resonant column test on asphalt concrete. A summary of those efforts is presented in a later section of this report, titled "Experimental Plan."

Resonant Column Testing of Asphalt Concrete

One of the first research studies to address the possibility of using a resonant column test to study the mechanical behavior of asphaltic concrete was conducted by Allen and Deen in 1981 [3]. They experimentally investigated the possibility of determining the Young's modulus and damping ratio of asphalt concrete through resonant column testing by changing the temperature and applied strain level. Tests were carried out at three different temperatures, namely 3 °C, 23 °C, and 37 °C. They also studied the effect of applying different strain magnitudes by using three input voltage levels of 100 mV, 200 mV, and 400 mV for exciting the sample. At the time of their publication in 1981, it had been more than two decades since RC tests became commonly used for characterization of geo-materials. The authors had also indicated that its use in studying asphalt concrete had not been widespread or well documented. Allen and Deen reported two major problems with their research: (1) loss of coupling between the apparatus and the specimens, and (2) unreliable measurements when excitations approach the natural frequency of the apparatus for stiff asphalt concrete specimens. Although the only excitation mode covered by their research was longitudinal resonance, the former issue was mentioned as the most important obstacle that prevented them from conducting torsional resonance testing. On the other hand, the capping material that they used to maintain coupling between the specimen and apparatus had a modulus lower than the sample, which was also recognized as one of the main sources of spurious measurements during their tests.

Allen and Deen reported that higher temperature or larger applied force resulted in larger strain amplitudes. They also observed that, as temperature increases, the measured Young's modulus decreases and damping ratio increases (see Figure 1).

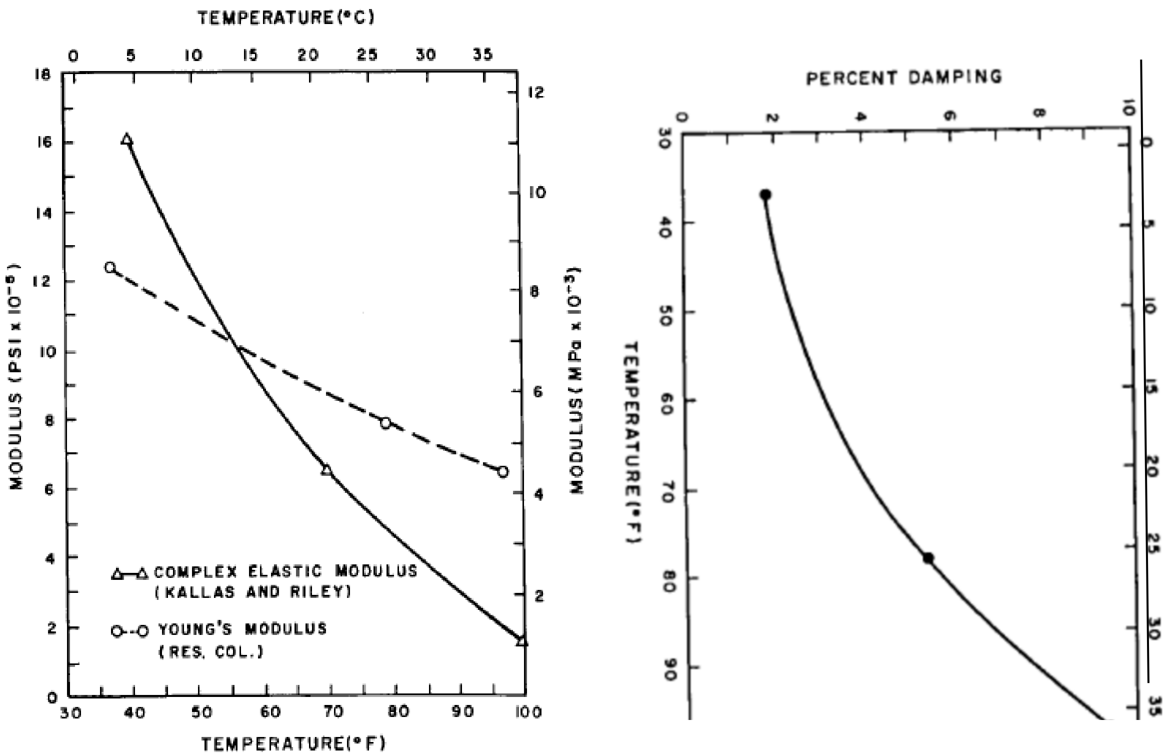

Figure 1 Effect of temperature on modulus and damping ratio from RC test, after Allen 1981 [3]

After the work conducted by Allen and Deen, there was not much research in testing asphalt concrete using RC tests until more recent work by Zhong et al. in 2002 and Wang and Zeng in 2006 [4,5]. These studies were conducted, respectively, at University of Kentucky, and Case Western Reserve University, on shear modulus and damping ratio of rubber modified asphalt concrete. In contrast to the research done by Allen and Deen, Zhong et al. utilized the torsional mode of test to determine shear modulus and damping ratio for rubber-modified asphalt mixes. The research covers a series of tests conducted on different subgrade soil samples and crumb rubber modified asphalt concrete (CRMA) mixes with different rubber contents and types. In their paper, they investigated the potential application of these highly dissipative materials as railroad trackbed foundation. They also used some type of superglue to attach the specimens to the top and bottom plates of their resonant column device. In the case of soil samples, using a grooved/rough plate is often sufficient to transmit the force from the drive system to the specimen. To simulate the field condition under the railroad trackbeds, they applied different confinement levels to the specimens during resonant column testing. Their results are shown in Figure 2. As damping ratio is an important property for railroad applications, simulating the field condition by applying cell pressure was found to be advantageous. However, for asphalt concrete, in contrast to soil samples, it is not necessary to apply confinement pressure to assist with maintaining the stability of samples during tests. They concluded that adding more rubber to the mix would increase the stiffness of the mix. However, the changes in air void should also have been accounted for the purpose of comparison in their work. Based on their experimental study it was found that within small strain range, the level of strain has either no or very slight effect on the shear modulus of crumb rubber modified asphalt mixtures. However, stiffness generally decreases as strain increases. They reported that the trend of changes of damping ratio with confinement pressure was not clear, which was due to the small strain levels in their experiments.

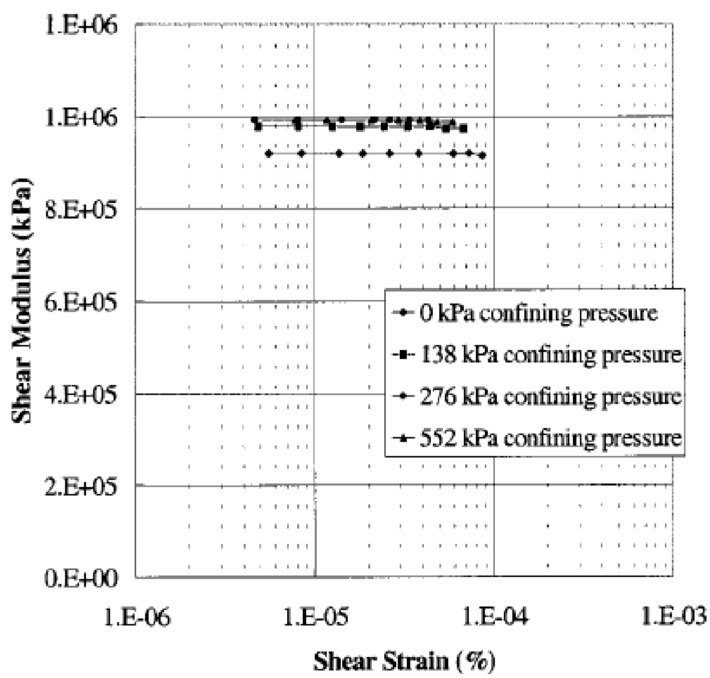

Figure 2 Effect of strain level on shear modulus of CRMA, after Zeng et. al. 2006 [5]

Five years later, Wang and Zeng [5] studied the same mixtures as mentioned in their previous research group publication in 2002. The main purpose of their study was to evaluate application of rubber modified asphalt for use in high speed rails. Therefore, damping ratio was of the most interest for this purpose, followed by shear modulus. They compared shear modulus values for mixtures with two different rubber contents. However, their observation in case of confinement pressure effect seems to be contradictory as compared to the general knowledge in RC testing of soils and also the results obtained by Allen and Deen on asphalt concrete in 1981.

They also reported that for the test temperatures higher than 22 °C, the stiffness of CRMA changes significantly as the temperature increases. Based on their experiments, it was observed that damping ratios of the samples were not affected by changes in rubber content. This fact would also question the problem definition in their research as it was claimed that rubber modified asphalt could be advantageous as a result of its inherently higher damping ratio. Coming up with this conclusion about damping ratio, it would have been worthwhile had they studied the difference between two mixtures, one with rubber modification and the other without rubber. This comparison could have provided valuable results through evaluating rubberized bituminous mixtures as opposed to conventional mixtures. Wang and Zeng have also concluded that increasing the strain level decreases the shear moduli drastically. It should be noted that beyond a certain level of strain which is called linear range threshold, asphalt concrete will not exhibit linear elastic behavior. Thus, by considering the shear moduli measured at range of strains smaller than 10^{-3}% it can be concluded that the shear modulus changes was negligible. However, for the strain levels beyond that threshold it can be seen that the shear modulus decreased slightly. In terms of damping, it was reported that higher temperatures led to higher damping ratios almost for all the samples tested.

Experimental Plan

Required Upgrades to RCA

I) Mass Polar Moment of Inertia of Drive System

One of the most highlighted points based on the literature survey was the fact that the conventional resonant column apparatus needs to be modified to be capable of measuring dynamic properties of stiffer materials like asphalt concrete. This section reports the summary of the efforts made to bring conventional RCA to work with asphalt concrete. One of the concerns is to reach the fundamental mode of vibration frequency of the apparatus during the frequency sweep test in identifying the resonant frequency of a specimen. In the case of GDS RCA, which was used in this study, the manufacturer recommended to keep the upper limit of the frequency sweep span reasonably smaller than 300 Hz. The natural frequency of the RCA itself, however, is believed to be about 450 to 500 Hz. By approaching the apparatus resonance frequency, unwanted vibrations would occur that could lead to spurious measurements. Determination of the modulus of a cylindrical sample through the resonant column test is based on the ratio between mass polar moment of inertia of the drive system and the mass polar moment of inertia of the sample being tested. This can be interpreted by looking at the Equations 1 through 4 presented in the previous section.

For a typical asphalt concrete sample, 60 mm in diameter and 120 mm tall, a typical mass polar moment of inertia of 0.00037636 kg-m^2 can be calculated from Equation 1. As a result of the complex geometry of the drive system of RCA, its mass polar moment of inertia needed to be obtained experimentally through calibration. For torsional mode, as being the main focus of this study, this value was calibrated to be equal to 0.00418 kg-m^2 for the RCA used in this study. This value yields a mass polar moment of inertia ratio of 0.09004, which will result in a resonant frequency in the range of 600 Hz, far beyond the capability of the RCA.

Ways to increase the capability of the machine were sought by adding more mass in a controlled manner to bring down the resonance frequency of the system. Hence, calculations were conducted backwards to determine the required mass polar moment of inertia for the drive system to keep the resonance frequency of the system at 200 Hz or lower. Tables 2, 3, and 4 present the design details and the results of calculations. The designated pieces must have a negligible effect on the electromagnetic field, as is used for driving the system. In other words, the material from which the attachments are being made should have nonmagnetic properties. On the other hand, the material should have a density high enough to provide the desired mass polar moment of inertia while requiring the minimum space due to the space limitations of the RCA. Hence, pieces made of brass and aluminum were designed and manufactured to maintain the requirements in the upgrade plan. Figure 3 shows an overview of the pieces designated to be attached to the original RCA to increase the mass polar moment of inertia of the drive system.

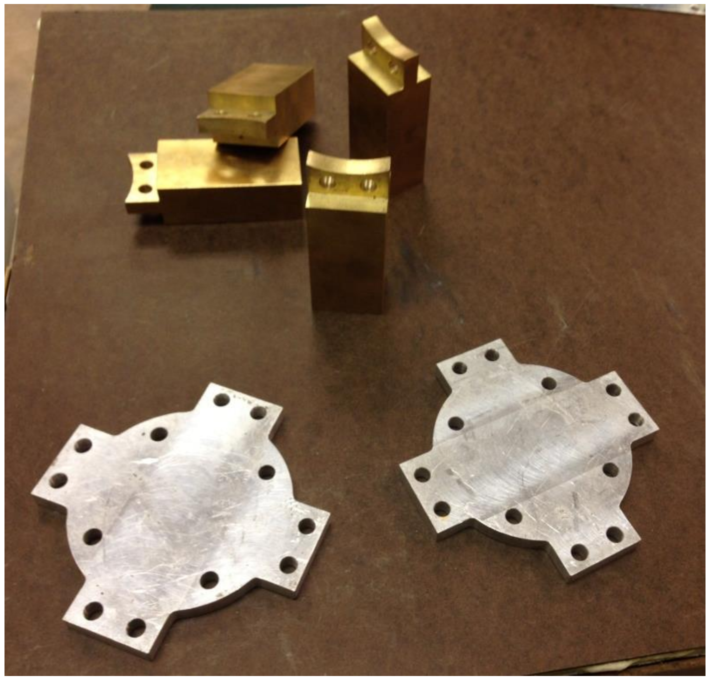

Figure 3 Pieces made to increase mass polar moment of inertia of the drive system include aluminum attaching plates and brass extension wings

The mass polar moment of inertia of the designated pieces should be calculated by adding up the mass polar moment of inertia of each individual piece. Considering the irregular geometry of these pieces, the associated values were calculated. Details of these calculations are presented in the appendix. The holes and bolts were also considered in the calculations. The output of the design was four extruded pieces made of brass, called wings; three thin, disk-shaped connection plates that have four tiny extensions at their perimeter; and one piece of thick disk that will be connected immediately to the original drive system. All of the disks were made of aluminum. The connection between these pieces was maintained via bolts. Based on the data presented in Table 2, the new mass polar moment of inertia for the drive system is 0.044506086 kg-m^2, as opposed to the original one, which was 0.00418 kg-m^2. Hence, the updated ratio for the typical sample used as the reference here will be 0.008456364, as opposed to the old one, 0.09004, which will result in resonant frequencies lower than 200 Hz. Such a design was found to be satisfactory to make torsional resonant column testing on asphalt concrete possible. An advantage of this design is the possibility of attaching and dispatching the pieces at any time without making any permanent alteration to the original device.

II) Connection between the sample and drive system

Another challenge with testing asphalt concrete through torsional resonant column testing has been the coupling between the RCA and the sample. Two problems exist in maintaining reliable fixity between the specimen and the RCA. The first issue comes from the fact that resistance of asphalt concrete specimens to torsion is much higher than that of soil specimens, which leads to a probable slippage of the conventional loading plate (i.e., drive system) on the smooth top face of the sample. In other words, in contrast to soil samples for which the grooved or rough plates might be enough to maintain a fixed boundary condition and transmit the torque to the sample, there should be a more secure connection that would ensure full load transfer from drive system to asphalt concrete samples without slippage. Previous research attempted to use various coupling agents to overcome this concern. Allen and Deen used a sulfur-based capping compound to maintain the connection, which was not satisfactory according to their observation. One of the serious issues with such a compound was the lower stiffness of the glue as compared to the sample stiffness, which may have resulted in some discrepancies in results. However, it had the advantage of being easily removable from the sample. Other researchers used stiffer epoxies. This could solve the relative stiffness problem but could also have some difficulties as, after completion of the test, there would be a need to apply erosive agents to remove the sample from the drive system, or there might be a need to leave the whole assembly in the oven to remove the epoxy.

Based on the common issues mentioned above, during the design of attachments to the original RCA, the connection problem was also considered. A sandwich mechanism was utilized to keep the original pieces of the device away from any manipulation or pollutant agent. Thus, instead of designing only two disk-shaped plates, two pairs of the plates were designed. The very top and very bottom plates were directly attached to the drive system and the pedestal, respectively. The two other plates were placed in a way that had direct contact with the top and bottom surfaces of the sample, and were attached to the drive system by means of 12 bolts per each side. This way, the epoxied plates could be detached from the drive system and undergo any necessary action for extruding the test specimen while the original drive system was left at its original position. Figure 4 shows the top and bottom connections designed and manufactured in this study.

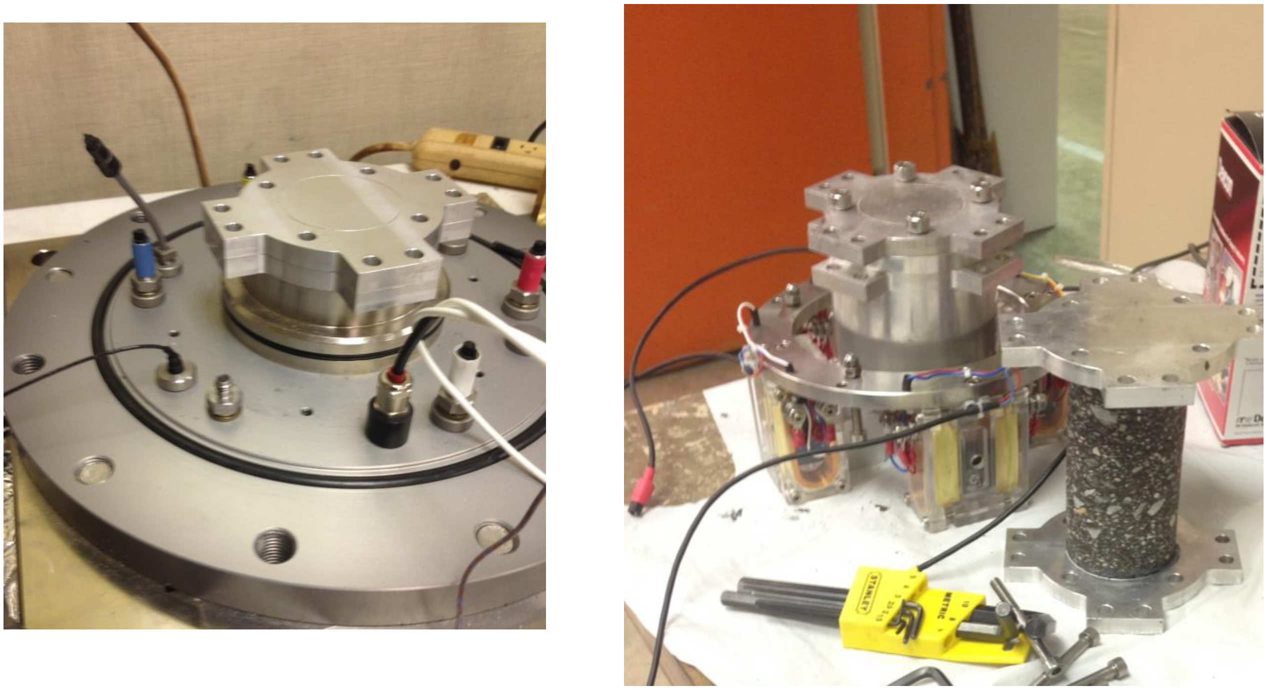

Figure 4 Designed top and bottom connections for gluing asphalt concrete to the drive system

Temperature-Controlled Chamber

An important consideration in testing asphalt concrete is the temperature at which the specimen is tested. Although a slight change in room temperature may be acceptable in testing soil samples, it can have a significant effect on the results when testing asphalt concrete. At the very first step, the temperature of the room at which the RCA was located was monitored for hourly, daily, and weekly changes. Figure 5 shows an example of the temperature log data collected. It should be noted that thermocouple 1 is the built-in thermocouple that provides the reference point for the data logger. The data from the other two thermocouples present the actual measured room temperature. It can be seen from this figure that the temperature fluctuation is considerable for the case of testing asphalt concrete. In other words, assuming that a temperature change of ±0.5 ^{o}C would be acceptable for testing asphalt concrete, the monitored temperature fluctuation seems to be out of this range. More extensive data collection, with 4,000 data points collected over 30 consecutive days, showed that a maximum deviation from the average temperature of about 2.1 ^{o}C exists in thermocouple 1 (i.e., inside the asphalt concrete specimen). However, the average daily room temperature was almost the same over the monitored 30-day period, and there was always a daily fluctuation during each 24-hour time span. This preliminary study indicated that accurate and reliable data could be achieved only through a temperature-controlled chamber surrounding the testing equipment.

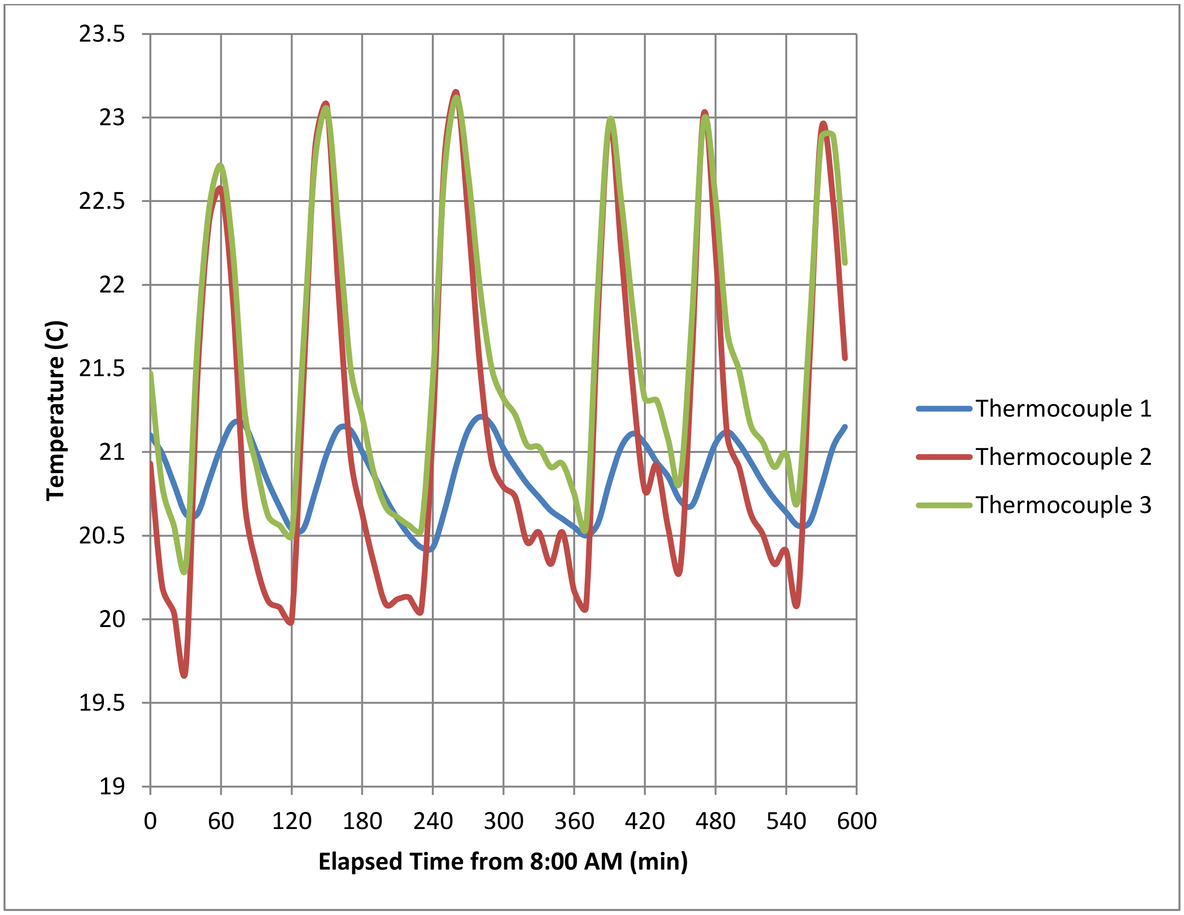

Figure 5 An example of the recorded temperature logs of the room without control chamber

Hence, a closed-loop, temperature control system was designed to keep the temperature constant during the tests. This included a high-precision, liquid-based chiller/heater that can control temperature with 0.01 ^{o}C precision, a rectangular-frame radiator to pass the circulated water, four sets of high-performance computer fans, hoses and valves and connections, wooden box chamber, insulation materials, thermocouples, and computer-equipped data logger. Figure 6 shows the trend of temperature changes after setting up the temperature control system. A dummy asphalt concrete sample was used within the chamber to study the required time for the sample to reach the ambient temperature. In other words, reaching the desired temperature in the chamber does not necessarily mean that the test sample has reached the same temperature. It usually takes longer for the sample to reach the temperature equilibrium. For this purpose, a very tiny hole was drilled into the cylindrical dummy sample in the middle and along its radial plain. The hole was deep enough to provide access to the center of the sample. A thermocouple was then attached to the sample through the drilled hole to monitor the temperature at the core of the dummy sample. To simulate the actual conditions, the dummy specimen was glued to the top and bottom plates in the RCA, and thus it was located in the actual testing position. It can be seen from the figure that it takes about 200 minutes for the dummy sample to reach the chamber temperature. This test was also carried out to 40 °C, as an extreme case scenario, at which the trend was expected to be more vulnerable to heat exchange between the chamber and the surrounding room environment. The results are shown in Figure 6.

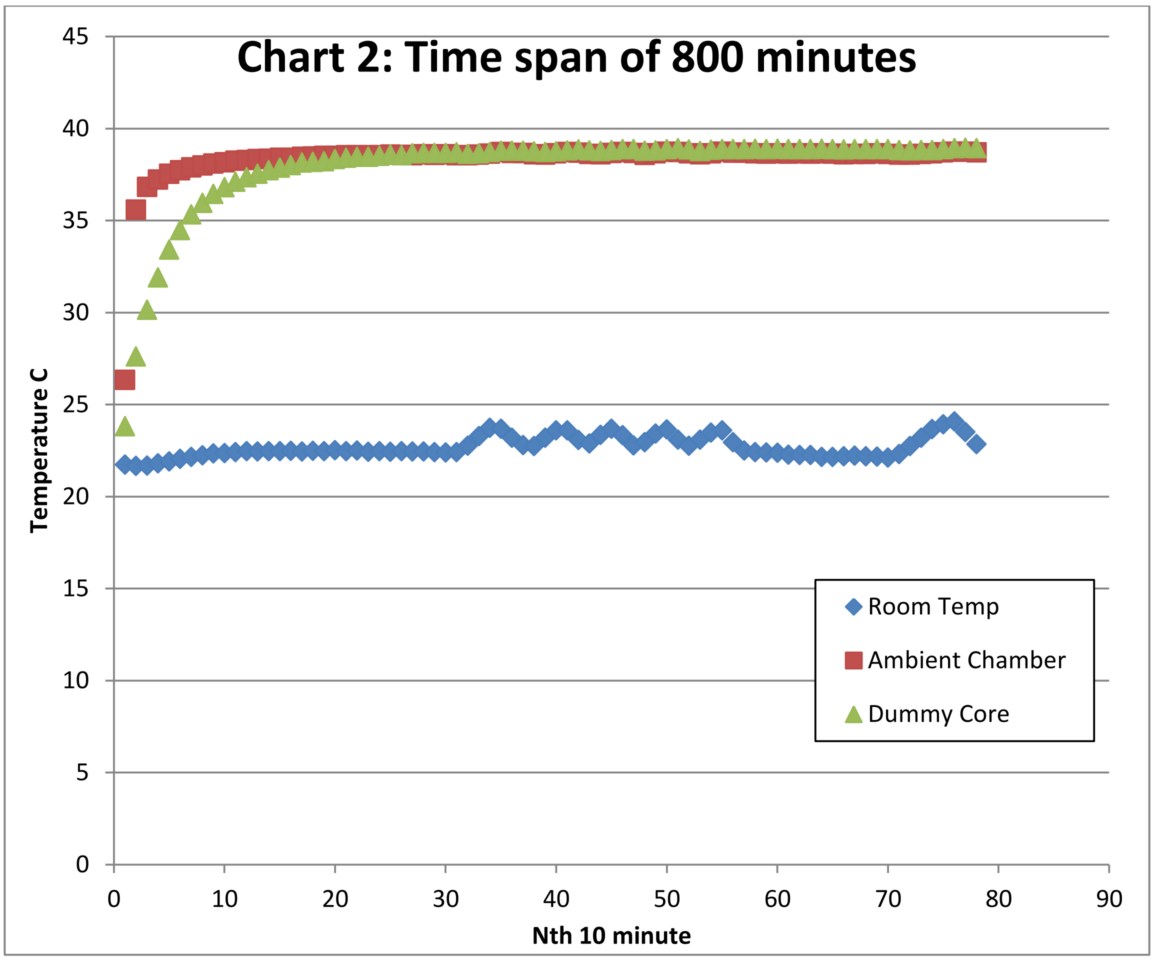

Figure 6 Trend of changes in temperature for the dummy sample and the chamber-enclosed air

Figure 7 shows an overview of the experiment setup, including the temperature control system utilized for testing the asphalt concrete samples. The system is capable of controlling the temperature in the range of -20 °C to 50 °C, but for this research, the results for testing at 25 °C are presented and discussed.

Figure 7 An overview of the experiment setup including the temperature control system developed for this research

Materials (Aggregate, Binder)

Aggregate used in this study was dolomite limestone from the Curtin Gap aggregate quarry of HRI Inc. The gradation is shown in Figure 8 on the 0.45 power scale. The aggregate from A-8 stockpiled material was used for sizes between 9.5 mm and 4.75 mm; the aggregate from B-3 stockpiled material was used for the aggregate sizes ranging from #8 sieve to material passing #200 standard sieve size. The aggregate was 100% crushed. Specific gravities of the fine and coarse portions of the aggregate are shown in Table 1.

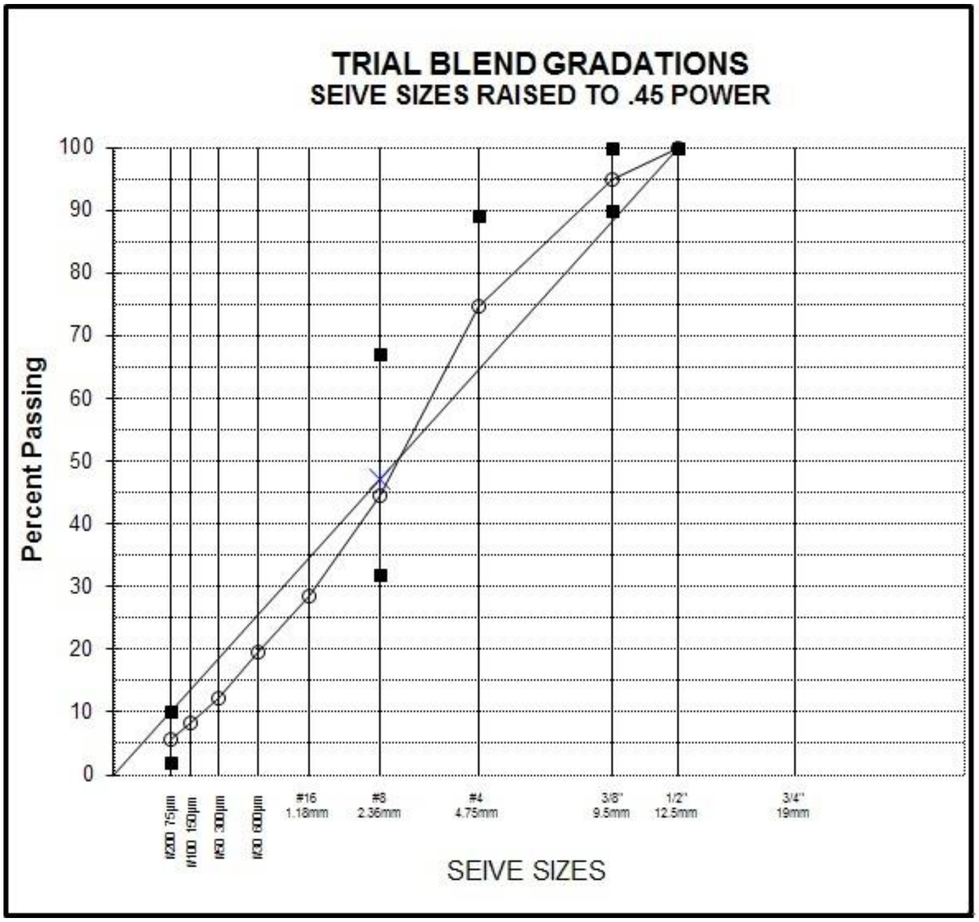

Figure 8 Aggregate gradation used for asphalt concrete sample preparation

Table 1 Specific gravities for the fine and coarse aggregates used in this study

AASHTO T85	Bulk Specific Gravity (G_{sb})	2.753
	Apparent Specific Gravity (G_{sa})	2.820
AASHTO T84	Bulk Specific Gravity (G_{sb})	2.735
	Apparent Specific Gravity (G_{sa})	2.821

The asphalt binder was a PG 58-22 obtained from United Refinery. Mix design for the same aggregate source was previously conducted during a project at the Thomas D. Larson Pennsylvania Transportation Institute (Larson Institute), from which the results were used in this study. However, the purpose of this research was not to develop the best mix design for the utilized aggregate and binder sources, but to study the mechanical properties of a control mix through resonant column testing. The binder content used to prepare HMA samples here was chosen to be 5.4%, as calculated through the mix design process.

WMA Technologies

As mentioned before, three different warm-mix asphalt technologies were used in this study. These technologies are:

- Water foaming
- Incorporation of a chemical additive (Evotherm^{TM})
- Incorporation of a waxy additive (Sasobit^{TM})

Water was used to foam the asphalt during the foaming process. Penn State acquired water foaming equipment from Pavement Technology Incorporated. This piece of equipment was used in this research to prepare the foamed specimens. Evotherm™, from MeadWestvaco Corporation, is a chemical additive, while Sasobit™ is an organic (waxy) additive from Sasol Wax North America Corporation. Both of these additives were blended into asphalt binder prior to introducing the heated aggregate for sample preparation. The binder was originally obtained in 5-gallon buckets and was split into smaller, quart-size cans for easier handling. The 5-gallon bucket was placed in an oven at 135 ^{o}C for 5 hours, at which point the viscosity of the binder was low enough for the binder to be pourable into the quart cans. The cans were then labeled with the proper identification of their contents. For this purpose, a high-shear blender was used at the appropriate rpm and temperatures according to the manufacturer's recommendations and the prior knowledge on dealing with WMA additives at the Northeast Center of Excellence for Pavement Technology (NECEPT). Table 2 presents the blending conditions used to prepare binder for WMA technologies.

Table 2 Details of WMA additives blending by high-shear blender

WMA Agent	Application Rate (%)	RPM	Temperature (^{o}C)	Duration (minutes)
Evotherm™	0.4	500	135	30
Sasobit™	1.5	1000	135	30

To blend the Evotherm™ and Sasobit™ into the original binder, each can was weighed, and the weight was recorded. Then, the proper amount of additive was added to each can. Cans were placed into oven at 135 ^{o}C for 45 minutes prior to introducing the additive. This could ensure that the binder was fluid enough to be modified by WMA additives. A confining, opentop heater was used to keep the temperature of the binder both constant and at the desired level during the blending process. After adding the proper amount of additive, the shaft of the high-shear blender was lowered into the hot binder. The binder was blended for a total of 30 minutes at 500 rpm for Evotherm™ and 1,000 rpm for Sasobit™. The application rate for Evotherm™ and Sasobit™ was 0.4% and 1.5%, respectively. Each of the cans was then labeled with the appropriate identification of their content according to the type and rate of additive. The Sasobit™ and Evotherm™ additives are shown in Figure 9. Figure 10 shows a view of the high-shear blender used in this study.

Figure 9 Evotherm^{TM} (top left); Sasobit^{TM} (top-right); and modified binder cans (bottom)

Figure 10 A view of the high-shear blender used for blending WMA additives into binder

Sample Preparation

Evotherm™ and Sasobit™ Samples

Sample preparation for Evotherm™ and Sasobit™ was almost the same, while for foaming technology additional steps were needed, as will be discussed later. Aggregate was batched for preparation of each of the samples. The batches were then placed in an oven at the mixing temperature, as mentioned in Table 3, for 24 hours. The binder cans were also placed into the oven approximately 1 hour prior to the mixing process. A rotary bucket mixer was used to mix the aggregate and the binder. The blade and the bucket were placed in an oven in advance to reach the mixing temperature. For Evotherm™ and Sasobit™, the aggregate and binder were heated up to 132 ^{o}C and then were mixed using the bucket mixer. The loose mixtures were then spread into a tray as a thin lift and were conditioned for two hours in an oven that was previously set to the temperature of 121 ^{o}C. After two hours of conditioning, the preheated gyratory compactor molds were filled with the mixture and weighed prior to set up the gyrations. The weight of the mixture was used to determine the most appropriate height needed to be set into the gyratory compactor to reach the desired level of air voids. The compactions were targeted to provide an air void level of 7.5% ±0.5%. For this purpose, hypothetical height-mass relationships were developed to adjust the target height for the amount of mixtures being compacted. Figure 11 illustrates the gyratory compactor at NECEPT that was used for preparing the 6-inch samples in this study.

Figure 11 A view of the sample preparation by means of gyratory compactor at NECEPT

The samples were extruded by means of the hydraulic jack after compaction and were left in the room temperature to cure for 24 hours. Afterwards, the bulk specific gravity of each 6-inch specimen was determined prior to coring and cutting.

Samples Prepared through Foaming

In the case of foaming technology, water was used at the rate of 2% to foam the standard binder. Binder was first heated in the oven at a temperature of 135 °C (275 °F) for 45 minutes. Parallel to heating the binder, the foamer was started. The reservoir and exit temperatures were set at 138 °C (280 °F) and 141 °C (285 °F), respectively. The reservoir bag was placed and the corresponding thermocouples of the bag were attached to the foaming equipment. Air pressure was supplied by means of a hose that was attached to the air regulator and the pressure was adjusted to the manufacturer's recommended level. The water application rate for foaming, 2%, was set to the foamer. The desired amount of foamed binder was selected. To avoid falling short with the quantity of foamed binder, the desired amount of exhausted binder was always selected to be 80 grams more than what really was needed. At this point, the heated fluid binder was poured into the plastic bag residing inside the reservoir of the foamer and approximately 15 minutes was allowed for the temperature of the binder and the reservoir to establish at the target level. This amount of time was found to be sufficient for the stated procedure and the binder used in this study. The water and air pressure were kept at 30 and 40 Pa, respectively. Once the temperature of the binder and reservoir were converged and stabilized, the foaming process began. A hot container was used to collect the foamed asphalt. The foamed asphalt was immediately transported and added to the batched material on scale to prepare the asphalt mix. The same binder content was used to prepare the WMA samples with this technology as well. An average expansion factor of 440% was achieved in the laboratory. Figure 12 shows a view of the foamer equipment available at NECEPT.

Table 3 Different technologies and details of sample preparation

Technology	Application Rate (%)	Mixing Temperature ^{o}C (^{o}F)	Compaction Temperature ^{o}C (^{o}F)
Evotherm™	0.4	132 (270)	121 (250)
Sasobit™	1.5	132 (270)	121 (250)
Foaming (water)	2.0	138 (280)	128 (262)
HMA	0.0	147 (297)	138 (280)

Figure 12 PTI Foaming equipment

For preparing HMA samples, the appropriate amount of asphalt binder was added to the heated aggregate at 148 °C to result in a binder content of 5.4%. Afterwards, the mix was compacted by means of gyratory compactor available at NECEPT laboratories. Calibrations and adjustments were made in a way that the compacted sample of a height of 150 mm would yield an air void level of 7.5%. The samples were then left at room temperature for 24 hours to cool down.

Sample Dimensions

The resonant column apparatus available at the Civil Infrastructure Testing and Evaluation Laboratory (CITEL) is capable of testing sample dimensions of either 100 mm in diameter by 200 mm tall or 60 mm in diameter and 120 mm tall. First, 6-inch-diameter cylindrical samples of asphalt concrete were compacted. Afterwards, 60 mm diameter by 120 mm tall samples were cored and sawed from the compacted specimens as shown in Figure 13 to fit into the RCA. Figure 14 also shows the 6-inch compacted sample as compared to small specimens obtained for RC testing. Besides the coring, in order to shorten the sample height from 150 mm to 120 mm, a rotating blade saw was used to produce smooth parallel faces. Three replicates were prepared to be tested at four different temperatures and two different torque levels.

Figure 13 Coring and saw cutting process to obtain the appropriate specimen dimensions

Figure 14 Original 6-inch-diameter sample and small RC test specimen

As mentioned in the literature review section, one of the challenges with using the resonant column apparatus for asphalt concrete is maintaining a rigid connection between the driving system and the sample [3]. Loss of bond between the driving plate and sample can lead to spurious measurements. To overcome this obstacle, a specific type of glue was determined to be the most appropriate. A 5-minute curing epoxy produced by Devcon, SF Grade 10240, was used to bind the sample to the top and bottom plates of RCA. This epoxy is generally used for the case of emergency repair purposes; it can have an initial setting time of 5 minutes and achieve final hardening in less than 1 hour for attaching plastic to steel. The high modulus of the hardened epoxy as compared to the HMA sample eliminates discrepancies as a result of induced deformation in the thin binding layer. Figure 15 shows a specimen after being glued to the plates. It should be noted that the specimen is attached to the plates while the assembly is connected to RCA; this picture is only intended to demonstrate the schematics of the connection between specimen and samples into the RCA.

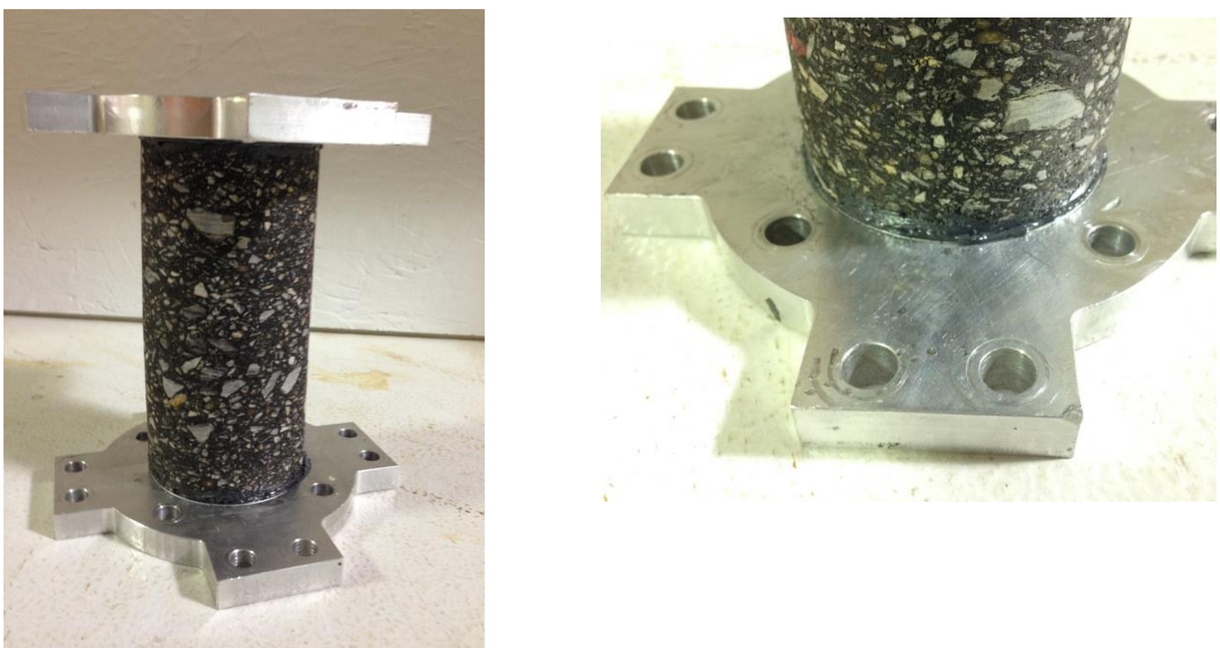

Figure 15 WMA sample glued to the top and bottom plates

One of the advantages of using this type of glue is that after testing it is possible to take the plates off from the specimen by cooling down the whole assembly and using a specific tool to remove the plates. Although it cannot be claimed that removing the sample this way is fully non-destructive, it served to minimize any possible damages induced during the dispatching process.

Determination of Specific Gravities

To ensure that the results of the tests would be comparable, air void level was kept roughly the same for all the replicates and samples prepared in this study. In order to calculate the air void of the prepared samples, maximum theoretical gravities, G_{mm}, and bulk specific gravity of the samples, G_{mb}, were needed to be measured in the lab. AASHTO Standards T166 and T209 were used to determine G_{mb} and G_{mm} values, respectively. Figure 16 and Figure 17 show the bulk specific gravity and maximum theoretical gravity measurement equipment, respectively.

Bulk specific gravity tests were conducted on both 6-inch and small cored specimens according to the AASHTO T166 procedure. All the tests were carried out at the same temperature of 25 °C. Maximum theoretical gravity was conducted on loose asphalt concrete mixtures according to AASHTO T209, method A. Two samples were obtained and tested and the average G_{mm} was used as the representative value for each mix type. The results are presented in Table 4.

Figure 16 G_{mm} measurements according to T209 method at NECEPT

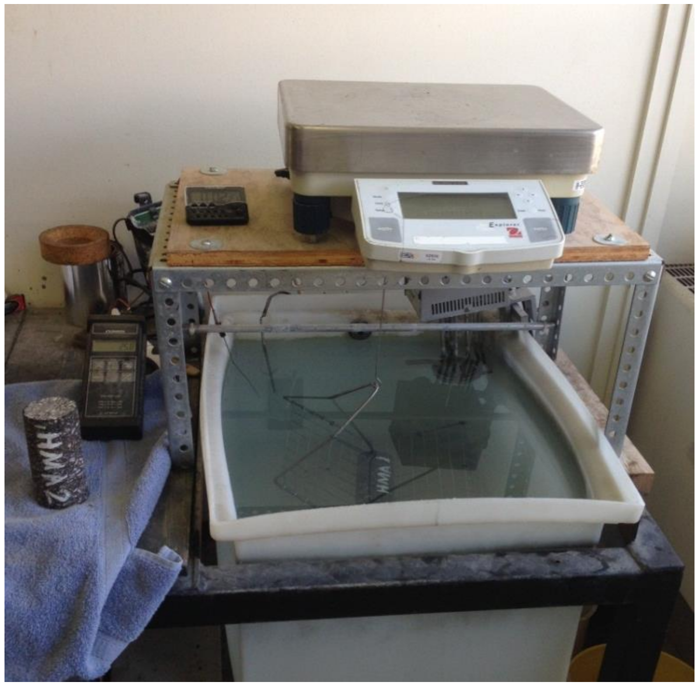

Figure 17 Bulk specific gravity measurement at NECEPT

Table 4 G_{mm}, G_{mb}, and air voids for the samples

Technology \ Sample ID	Gmm	Sample ID	Gmb	Air void (%)
Evotherm™	2.555	Evo-1-1	2.360	7.6
		Evo-2-1	2.355	7.8
		Evo-2-2	2.355	7.8
Sasobit™	2.553	Saso-1-1	2.366	7.3
		Saso-1-2	2.357	7.7
		Saso-2-1	2.359	7.6
Foaming (water)	2.554	Foam-1-2	2.351	7.9
		Foam-2-1	2.347	8.1
		Foam-2-2	2.361	7.6
HMA	2.561	HMA-1-2	2.360	7.8
		HMA-2-1	2.358	7.9
		HMA-2-2	2.363	7.7

Resonant Column Testing of Asphalt Concrete

As mentioned before, the resonant column test can be run mainly in two different modes, i.e., torsional shear mode and flexural/longitudinal mode. This report presents the results from the torsional mode of RC test that was not investigated in Allen's study. After setting up the sample into the RCA, the temperature control chamber was installed and the sample was left for a sufficient amount of time to reach the target temperature of 25 °C. A real-time temperature control system was designed to monitor the changes in temperature during the test along with a data logger that recorded the temperature log continuously. The preliminary stage of the test includes running a coarse band frequency sweep test in order to determine the approximate resonance frequency of the sample. A fine sweep test was subsequently carried out to determine the resonance frequency with precision. The minimum interval for searching the frequency would be 0.1 Hz using a GDS RCA. Figure 18 shows the schematic of the user-interface software panel during running of the test.

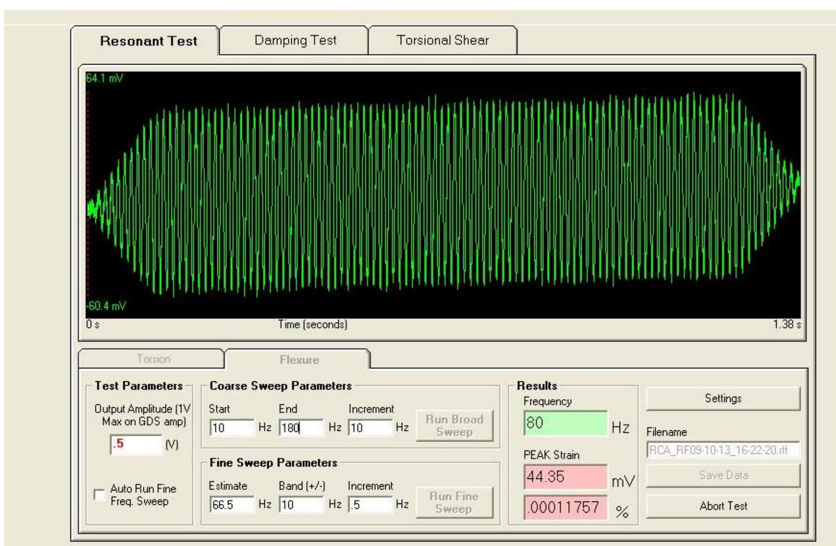

Figure 18 Schematic of the RC software panel during flexural test mode

Findings

Torsional resonant column testing was conducted on three lab-prepared replicates from each of the four mixtures (see Table 4) of interest at 25 °C. For each test, two different levels of load (i.e., shear strain) were applied to the specimens by changing the input excitation voltage level. The following subsections present the experimental results.

Effect of Torque Magnitude

In order to evaluate the effect of applied torque level on the captured material properties, two voltage levels of 0.5 V and 1.0 V were used in this study. One of the benefits of using more than one torque level is the ability to double check the validity of linear-elasticity assumption during the tests. As will be discussed in the following section, the specimens' shear moduli are not sensitive to the changes of torque level within the range of applied strain. Hence, it implies that the material is in the linear elastic range so that the modulus will not change with the change of applied torque.

Table 5 illustrates proportionality between the applied torque and induced strain at the two input voltages at the temperature of 25 °C. By looking at the third and fifth columns of the table it is evident that the ratio of induced strain at 0.5 V to the associated value at 1.0 V is approximately 0.5. This indicates that by doubling the applied force, the strains also doubled, which is further evidence that the specimen is in linear elastic range with constant shear modulus.

Table 5 Ratio of strain at 500 mV to the strain at 1,000 mV

Temperature (°C)	Specimen ID	γ(500 mV)/ γ(1,000 mV)	Specimen ID	γ(500 mV)/ γ(1,000 mV)
25	HMA 1-2	0.50	Evo 2-1	0.51
25	HMA 2-2	0.49	Evo 2-2	0.51
25	Foam 1-2	0.52	Saso 2-1	0.53
25	Foam 2-1	0.51	Saso 1-2	0.53

Comparing the WMA Technologies through RC

A summary of the measured shear moduli is shown in Figure 19 that can facilitate comparing different asphaltic mixtures of interest. As can be seen from this figure, the samples prepared by foaming technology have the lowest shear modulus as compared to the regular hot mix asphalt and the other WMA technologies. Tests were conducted on three replicates of each of the mixtures and the average results are presented here. For the tests carried out at 25 °C, a standard deviation of 6.7% was observed for the shear modulus. The results were consistent and all of the measurements were distributed reasonably around the mean value for foamed samples. Similar to what was presented for foaming technology, small strain shear moduli of WMA samples prepared by Evotherm™ technology were measured. It can be seen from the figure that Evotherm™ did not significantly affect the shear modus of the asphalt mixture. However, the effect of these WMA additives should also be investigated at higher temperatures. More elaborate studies need to be carried out to make definitive conclusions. In the case of Sasobit™ technology, it was observed that the samples generally showed higher shear modulus as compared to the control HMA mix. This observation is in agreement with the general knowledge about the properties of Sasobit™ WMA as compared to regular HMA.

Three different WMA technologies were investigated in this study, along with one conventional HMA mixture, which was used as the control mixture. Figure 19 presents a general overview of the results of four mix types. It can be concluded that Sasobit™ technology exhibits the highest stiffness among the technologies investigated in this research. Foaming results in the lowest stiffness.

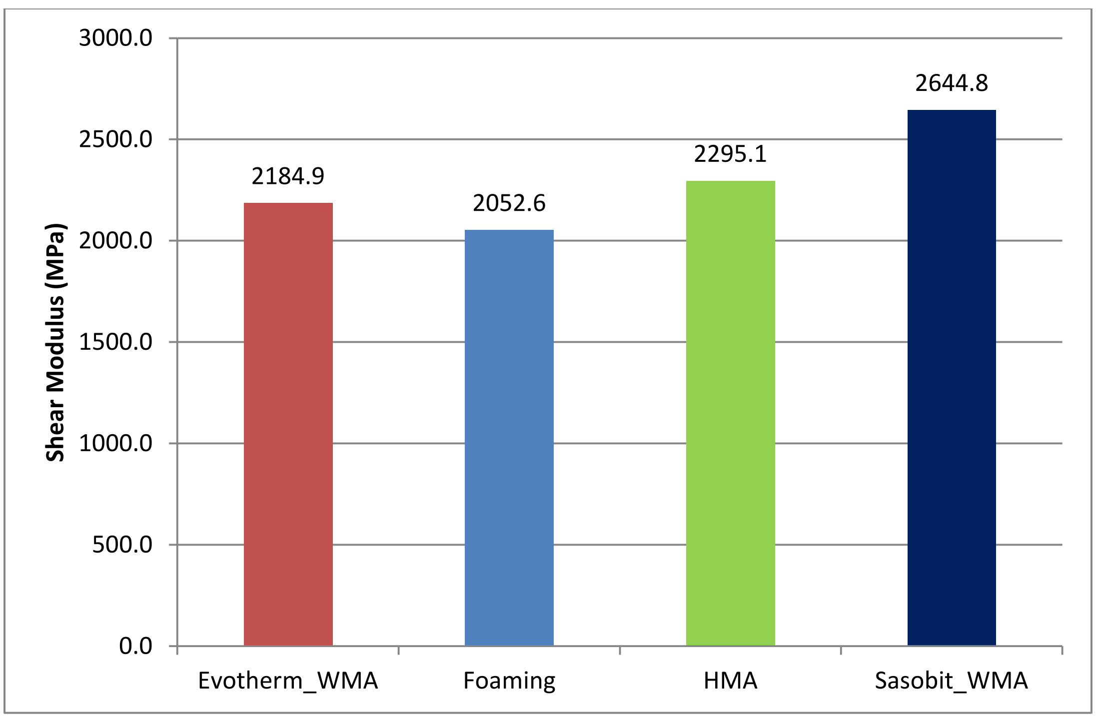

Figure 19 Comparing the stiffness of different technologies

Torsional Damping Ratio

Logarithmic decay method was used in this study to measure damping ratios of the asphalt concrete specimens. In this method, power supply to the coils is cut off after steady-state resonation of a specimen and the free vibration response of the specimen is monitored. The logarithmic decay and damping ratio can be calculated based on the monitored free-vibration response. Logarithmic decay, δ, can be defined as the slope of the best fit line when plotting the logarithm of peak amplitudes against the cycle number during free vibration. Having the logarithmic decrement, δ, the damping ratio can be calculated using Equation 6.

$$D = \sqrt{\frac{\delta^2}{4\pi^2+\delta^2}} \qquad (6)$$

The number of cycles used for the purpose of damping calculations in this study was 5 cycles. Based on the results of the damping tests at two different strain levels, it can be concluded that damping is sensitive to the applied level of stress in a way that larger torque magnitudes lead to higher damping ratios. The phenomenon is, however, complicated and several factors such as the viscoelastic nature of asphalt concrete and binder-aggregate interaction need to be taken into account to interpret the damping behavior.

Evaluating the damping behavior of the four investigated mixtures at 25 ^{o}C, it can be concluded that regular HMA, Evotherm™ technology, and Sasobit™ technology all yield approximately the same level of damping. This is illustrated by Figure 20, which presents the mean value of the damping ratio for all the different mix types measured at 25 ^{o}C. The average values for torsional damping ratio were measured as 5.2% for HMA, 5.6 for Evotherm™, 5.1% for Sasobit™. However, the foaming technology exhibits a slightly higher damping ratio of 6.4%. Although the average damping ratio was found to be close for all three technologies other than foaming, it follows the expected behavior, as the stiffer mixtures were expected to show lower damping while the softer materials were supposed to have higher damping ratios. These results were based on the tests at 1,000 mV level of torque.

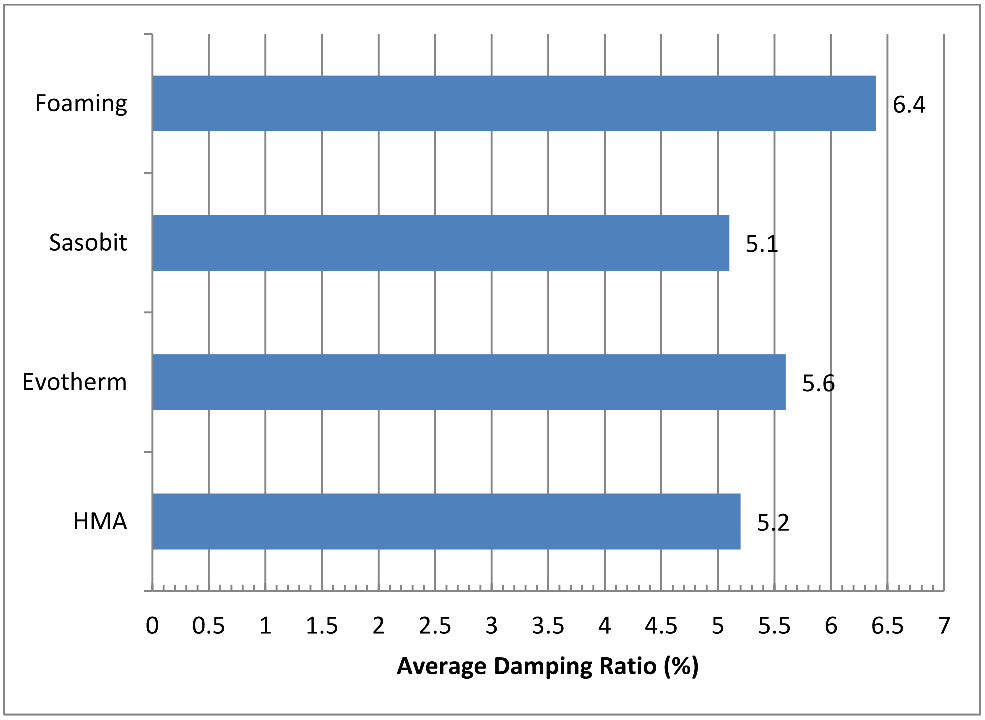

Figure 20 Average damping ratio of different mix types at 25 °C

Repeatability of the Tests

Repeatability of the tests conducted for this research was investigated from two different angles. One considered investigating the repeatability of the same test on the same sample for multiple times. The other dealt with the repeatability of the test on different replicates of the same mixture type. The former could be easily investigated during the test, because the test by its nature is assumed to be non-destructive.

The results obtained in the current research showed that almost for all of the mix types investigated here, the coefficient of variation of frequencies captured for the same mixture at 25 °C was smaller than 1%. However, this is not the case with damping ratio. Dealing with damping ratio, it was observed that the repeatability of the torsional damping test was not as good as the resonance test. For instance, for the Sasobit™ mix tested at 25 °C, the scattering of multiple measurements on the same sample ranged from 5% up to 19%. The minimum dispersion with respect to the mean observed for all the tests was calculated to be approximately 2.2%.

Investigating the repeatability of the tests between replicates, it was observed that the standard deviation of the test results was typically in the range of 2% to 17%. As an example, at 25 °C the standard deviation was calculated as 8.7%, 2.9%, 9.8%, and 6.7%, respectively, for the

Sasobit™ mix, the Evotherm™ mix, HMA, and the mix produced through foaming. With regard to the inherent variability of the materials and the difference between air void levels of the replicates, such a level of variability seems to be acceptable.

Summary and Recommendations

Non-destructive testing has been used for decades to characterize engineering properties of hot-mix asphalt. Among such tests is the resonant column test, which is commonly used to characterize soil materials. The resonant column device at Penn State was used to determine the modulus and damping of warm-mix asphalt prepared with three different warm-mix technologies: water foaming, a waxy additive, and a chemical additive. Specimens were prepared in a Superpave gyratory compactor and then sawed and drilled to deliver the geometry needed for the RC tests. Hot-mix asphalt specimens were also tested to provide reference data. Testing was completed at 25 ºC. The RC device specimen assembly had to be retrofitted to make it suitable for testing asphalt concrete, which has a higher stiffness than soils at ambient temperatures. The results indicated that the RC test can be successfully used to determine the shear modulus of the asphalt concrete. Different torque levels, and therefore inducing different strain levels, could be applied in RC test to determine the range of linear elastic behavior of the material. This is an important step to ensure the validity of assumptions used for the purpose of modulus calculations. At 25 ºC, it was found that the lowest shear modulus was found for the mix prepared through the water foaming process, and the highest modulus was found for the mix with the waxy additive (Sasobit™). The modulus of the mix with the chemical additive and the modulus of the hot-mix asphalt were found to be in between. Use of the RC test to determine the damping properties of asphalt concrete proved to be more challenging and strain dependent, even when maintaining the strain within the linear elastic range.

This study is a significant step forward on how to use the resonant column test to determine asphalt concrete engineering properties. Further work is needed to include other types of asphalt mixes, including those with finer and coarser gradations, with special modifiers such as polymers and crumb rubber, and different performance-grade binders. It is also important to investigate the asphalt concrete behavior at a range of temperatures, with the idea of developing the modulus master curve for comparison with results obtained from commonly used tests such as dynamic modulus. Finally, further work is needed to validate the results obtained for damping ratio, or ensure that reliable results are achievable for damping ratio using RC for asphalt concrete.

References

1. U.S. Department of Transportation, *National Transportation Statistics Report*, 2012.

2. Hoyos, L., Puppala, A., and Ordonez, C. (2011). "Characterization of Cement-Fiber-Treated Reclaimed Asphalt Pavement Aggregates: Preliminary Investigation," *J. of Materials in Civil Engineering*, Vol. 23, pp. 977-989.

3. Allen, D. L., and Deen, R. C. (1981). " Modulus and Damping of Asphaltic Concrete Using the Resonant Column," *Geotechnical Testing Journal (GTJ) ASTM*, Vol. 3(4), pp. 167-171.

4. Zhong, X. G., Zeng, X., and Rose, J. G. (2002). "Shear Modulus and Damping Ratio of Rubber Modified Asphalt Mixes and Unsaturated Subgrade Soils," *J. of Materials in Civil Engineering*, Vol. 14, pp. 496-502.

5. Wang, C., and Zeng, X. (2006). "Influence of Temperature and Pressure on the dynamic Properties of Rubber-Modified Asphalt Concrete," *J. of Materials in Civil Engineering*, Vol. 18, pp. 125-131.

6. GDS Instruments, *Resonant Column System Handbook*, 2010.

7. Hall, J. R. Jr., and Richart, F. E., Jr. (1963), "Dissipation of Elastic Wave Energy in Granular Soils," *Journal of Soil Mechanics and Foundations Division,* ASCE, Vol. 89(6), pp. 603-624.

8. Drnevich, V. P., Hall, J. R., Jr. and Richart, F. E., Jr. (1987). "Effects of Amplitude of Vibration on the Shear Modulus of Sand," Proc. International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, Albuquerque, N.M. Aug.

9. Hardin, B. O., and Music, J. (1965). "Apparatus for Vibration of Soil Specimens During Triaxial Test," *Instruments and Apparatus for Soil and Rock Mechanics*, ASTM STP 392, American Society for Testing and Materials, West Conshohocken, PA, pp. 55–74.

10. Drnevich, V. P. (1985). "Recent Developments in Resonant Column Testing," *Richart Commemorative Lectures*, ASCE Detroit Convention, October 24, R. D. Woods, Editor, pp. 79-107.

11. Hardin, B. O., and Black, W. L. (1968). "Vibration modulus of normally consolidated clay," *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 94(2), pp. 353–379.

12. Anderson, D., and Stokoe, K. (1987). "Shear Modulus: A Time-Dependent Soil Property," American Society for Testing and Materials, *Dynamic Geotechnical Testing*, SPT 654, 1987.

13. Allen, J. C., and Stokoe, K. H. (1982). *Development of Resonant Column Apparatus with Anisotropic Loading*, Civil Engineering Department University of Texas at Austin, Tex., Report GR82-28.

14. Porovic, E. (1995). "Investigations of Soil Behavior Using a Resonant-column Torsional-shear Hollow-cylinder Apparatus," University of London.

15. Chen, A. T. F., and Stokoe, K. H., II. (1979). *Interpretation of strain dependent modulus and damping from torsional soil tests*. Report No. USGS-GD-79-002, NTIS No. PB-298479, U.S. Geological Survey, Washington, D.C.

16. Kim, D.S. (1991). "Deformational characteristics of soils at small strains from cyclic tests." Ph.D. Dissertation, Univ. of Texas at Austin, Austin, TX.

17. Hwang, S.K. (1997). "Investigation of the dynamic properties of natural soils." Ph.D. Dissertation, Univ. of Texas at Austin, Austin, TX.

18. ASTM. (2007). "Standard test methods for modulus and damping of soils by the resonant column method." D4015-07, ASTM, West Conshohocken, PA.

APPENDIX

Details of Calculations for Mass Polar Moment of Inertia after Retrofitting of the Resonant Column Tester through Adding Pieces to Increase the Mass

	Diameter (m)	Radii	Distance centroid (m)	thickness	Density (kg/m3)	Volume (m3)	Mass (kg)	I (Basic) kg-m2	Parallel axis Theorem	Total Inertia	+/-	Quantity	Total	Total Added mass (kg)
Circular Plate 1 (Thick- Top)	0.1	0.05	0	0.05	2700	0.000392699	1.060287521	0.001325359	0	0.001325359	1	1	0.001325359	1.060287521
Holes Drilled half way (1)	0.0084	0.0042	0.04	0.025	2700	1.38544E-06	0.003740694	3.29929E-08	5.98511E-06	6.0181E-06	-1	4	-2.40724E-05	-0.014962777
Houses available (1) (counter Sunk area)	0.01	0.005	0.0165	0.03	2700	2.35619E-06	0.006361725	7.95216E-08	1.73198E-06	1.8115E-06	-1	3	-5.4345E-06	-0.019085175
Houses available (1) (Deep part)	0.0084	0.0042	0.0165	0.02	2700	1.10835E-06	0.002992555	2.63943E-08	8.14723E-07	8.41118E-07	-1	3	-2.52335E-06	-0.008977666
Extensions (1)/ (a*b)	0.04	0.0148	0.0574	0.01	2700	0.00000592	0.015984	2.42296E-06	5.26634E-05	6.62358E-05	1	4	0.000264943	0.063936
Holes in the extensions (1)	0.0084	0.0042	0.0562	0.01	2700	5.54177E-07	0.001496278	1.31972E-08	4.7259E-06	4.7391E-06	-1	8	-3.79128E-05	-0.011970222
													0.001520359	1.069227679
Plate (2) (to be glued to the Sample)	0.1	0.05	0	0.01	2700	7.85398E-05	0.212057504	0.000265072	0	0.000265072	1	1	0.000265072	0.212057504
Holes Drilled for connection to Plate 1	0.0084	0.0042	0.04	0.01	2700	5.54177E-07	0.001496278	1.31972E-08	2.39404E-06	2.40724E-06	-1	4	-9.62897E-06	-0.005985111
Houses available (2)	0	0	0	0.01	2700	0	0	0	0	0	0	0	0	0
Extensions (2)	0.04	0.0148	0.0574	0.01	2700	0.00000592	0.015984	2.42296E-06	5.26634E-05	6.62358E-05	1	4	0.000264943	0.063936
Holes in the extensions (2)	0	0	0.0562	0.01	2700	0	0	0	0	0	-1	4	0	0
													0.000520386	0.270008393
Arm conection part (sandwich)	0.04	0.0148	0.0574	0.01	8400	0.00000592	0.049728	7.5381E-06	0.000163842	0.000206499	1	4	0.000825997	0.198912
Arm Main part	0.04	0.05	0.0898	0.03	8400	0.00006	0.504	0.0001722	0.004064276	0.004236476	1	4	0.016945905	2.016
Lumped mass	0.04	0.03	0.1298	0.03	8400	0.000036	0.3024	0.000063	0.005094847	0.005157847	1	4	0.020631389	1.2096
hole in sandwich part of Arm	0.0084	0.0042	0.0562	0.01	8400	5.54177E-07	0.004655086	4.10579E-08	1.47028E-05	1.47439E-05	-1	8	-0.000117951	-0.037240691
													0.03828534	3.387271309

It (new with plates)= 0.044506086

I0 (current drivesys.) = 0.00418

I (sample) = 0.00037636

I/It = 0.008456364

Total Mass Added = 4.726507382

For the ***Aluminum*** made part

Parameters for	Quadrant	r	alpha (rad)	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
	Triangles	b	h	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
	Rectangle	Height	Width	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
Shape	Rectangle	0.0648258	0.04	0	0.0324129	0.070011864	3.3853E-05	0.0324129	7.35542E-05	0.000107407	1	1	0.000107407
	triangles	0.02	0.0458258	0.015275267	0.013333333	0.012372966	8.59235E-07	0.020275886	5.08667E-06	5.9459E-06	-1	2	-1.18918E-05
	Quadrant	0.05	0.4101525	0	0.032406579	0.027685294	2.04885E-07	0.032406579	2.90747E-05	2.92796E-05	-1	1	-2.92796E-05
													6.62358E-05

For the ***Brass*** made part

Parameters for	Quadrant	r	alpha (rad)	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
	Triangles	b	h	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
	Rectangle	Height	Width	Xc	Yc	M	Izc	Distance	Parallel Axis Theorem	Itotal	-/+	Qnty.	total
Shape	Rectangle	0.0648258	0.04	0	0.0324129	0.217814688	0.00010532	0.0324129	0.000228835	0.000334156	1	1	0.000334156
	triangles	0.02	0.0458258	0.015275267	0.013333333	0.038493672	2.67318E-06	0.020275886	1.58252E-05	1.84984E-05	-1	2	-3.69967E-05
	Quadrant	0.05	0.4101525	0	0.032406579	0.086132025	2.04885E-07	0.032406579	9.04547E-05	9.06596E-05	-1	1	-9.06596E-05
													0.000206499