TEST SYSTEM DEVELOPMENT FOR THE PERFORMANCE TESTING OF ASPHALT CONTAINING DIFFERENT MINERAL FILLERS

By

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ABSTRACT

This research project identifies the materials and equipment needed to implement Simple Performance Testing (SPT) on Superpave asphalt mixtures. This project can be used as a guide or manual for others who would like to evaluate the performance of Hot Mix Asphalt (HMA) mixtures. This thesis outlines both physical and mechanical SPT requirements and applies them to the performance testing of asphalt mixtures incorporating different types of mineral fillers. Furthermore, this research evaluates the dynamic modulus of asphalt containing various mineral fillers. The results have shown a small increase in dynamic modulus values when 4% fly ash is used as mineral filler when compared to limestone dust (control mix). Portland cement has also shown an increase in dynamic modulus over the control mix although the increase was less than that observed with the use of fly ash. The higher moduli associated with the use of fly ash can be viewed as beneficial in terms of rutting resistance, but require further investigation for fatigue resistance.

ACKNOWLEDGEMENTS

This thesis is mainly based on the work done from September 2005 – to – May 2008, in the TARBA Highway Materials Lab, Department of Civil Engineering at Ryerson University, Canada. This thesis is an analysis of the performance of hot mix asphalt made using various mineral fillers.

I would like to express my sincere gratitude and appreciation to my thesis advisor, Dr. Medhat Shehata, for his guidance, support and patience during the development of this thesis. At every turn, his enthusiastic support played a key role in my successful completion of this thesis.

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Lastly, special gratitude goes to my family & friends who have helped me through this process and who have supported my continued dedication to education. And last but not least a special thank you to my many proof readers who have helped make this thesis what it is today.

DEDICATION

This thesis is dedicated to my family and friends who have helped and supported me through all my years of study.

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CHAPTER 1

INTRODUCTION

1.1 Background

Superpave Mix design and analysis method was developed more than a decade ago under the Strategic Highway Research Program otherwise known as SHRP. Since then many departments of transportation have decided to adopt and follow certain common guidelines which SHRP had set forth. One of the most popular and widely accepted criteria is SUPERPAVE methodology which includes performance grade binder specification and volumetric mix design method. Since its inception SUPERPAVE has been scrutinized and reviewed many times. The main concern with SUPERPAVE or volumetric mix design is that the methodology is all based on volumetric properties of HMA (Hot Mix Asphalt) mixtures and thus does not run any tests to evaluate the true characteristics of a mixture.

Since the late sixties various institutions and government bodies began conducting extensive experimentation and testing on HMA, this testing still continues today. Through the analysis of these extensive studies, namely WesTrack, and National Cooperation Highway Research Program or NCHRP Superpave Project 9-7 (Field Procedures and Equipment to implement SHRP Asphalt Specifications), as well as other experimental projects the main question was whether Superpave volumetric mix design alone would be enough to ensure good performance over a wide range of trouble areas. With the intent to better understand the problems at hand, under the blanket of NCHRP Superpave Project 9-19 (Simple Performance Test for Superpave Mix Design) numerous tests have been developed and adopted over the last couple of decades. After extensive testing the pool of knowledge acquired by US projects such as MnRoad, FHWA-ALF, and WesTrak, most departments of transportation agreed and recommend SPT's for permanent deformation testing as well as dynamic modulus and repeated load resistance.

This research will review and apply simple methodology to a series of HMA samples in attempts to reveal long term performance characteristics. This study will deal primarily with the testing of a series of case specific HMA mixes enhanced by mineral fillers. The mineral fillers used have been implemented in the HMA to increases strength as well as material resilience. If successful this approach would decrease binder consumption through the production of thinner pavements. The minerals used were Fly Ash types F & C (low and high calcium), as well as Portland Cement.

1.2 History of Superpave

Superpave mix design and analysis hit the mainstream research and testing society in the early 1990's under the guidance and support of the Strategic Highway Research Program (SHRP). Originally Superpave design criterion only really outlined three areas, namely material selection, aggregate blending and gradation, and volumetric properties for gyratory compacted specimens. It was the original intention of the scientific community and SHRP to have a fourth step or method which could be used to directly analyze complex mixture properties. The analysis of these properties was performed to determine the potential for long term HMA performance. The problem was that at that point in time no such method existed.

To date most American highway agencies as well as their Canadian counterparts have adopted the volumetric mix design approach. In other words the majority of our asphalt producers are currently using volumetric mix designs. However as mentioned earlier at the time there was still no real performance test to compliment volumetric mix design or Superpave methodology. Comparatively speaking the older tests namely Marshall and Hveem both had comprehensive strength testing programs and capability which did not exist in SUPERPAVE. At the time there was some dispute among the scientific community about the accuracy and effectiveness of the old testing practices, although no one would deny that the old ways did in fact provide useful descriptive information about HMA mixtures. The common argument was that Marshall and Hveem tests were merely empirical but at the end of the day they still did provide many years of mixture quality estimation and can still be used today if needed. Considering the problems at hand and the millions of tones of asphalt that are laid each year something definitely needed to change. Everyone searched for the king of all methods and everyone agreed that the test method selected did not need to be perfect but rather only be available in the near future to assure good mix performance.

Eventually the situation worsened, research from WesTrack NCHRP 9-7 (Field Procedures and Equipment to Improve SHRP Asphalt Specifications) and other experimental construction projects began to show that Superpave volumetric mix design method alone was not sufficient to ensure the production of reliable mixes over a wide range of materials, traffic loading, and environmental conditions. At this point in time there was no avoiding the fact that controlling volumetric properties alone could not sufficiently ensure the long term performance of an HMA mixture. The other conclusion was that a simple performance test was needed to ensure better long term pavement performance.

There were mainly five identifiable distress areas where Superpave fell short; these areas included fatigue cracking, surface friction loss, rutting, thermal or low temperature cracking, as well as moisture susceptibility. All of the mentioned distress mechanisms have been accepted and are known to cause performance degradation over time.

Due to the imminent and immediate need for new evaluation criteria the NCAT board of directors stepped in and provided some vague details on performance testing until something better came along. With the inception of NCHRP 1-37A and 9-19, the wheels were in motion and the train of knowledge seemed to be heading in the right direction. After many years of deliberation and research in the year 2000 NCHRP began a streamlined approach to better the current yet vague guidelines previously set forth. Finally by 2002 NCHRP released a report entitled Simple Performance Test for Superpave Mix Design. This report although riddled with its own problems was still better than anything that had been seen to date. Currently this report in conjunction with ASTM guidelines can be used to gain reasonable approximations about long term performance of a wide variety of HMA mixtures.

1.3 Objectives

The objectives of this research are as follows:

1. Develop a suitable method of finding the dynamic modulus of HMA materials through the modification of a universal test frame under the guidance of ASTM, AASHTO and NCHRP practices.

2. Develop an inexpensive alternative for measuring axial deformations in asphalt specimens at high and low temperatures and frequencies while decreasing negative side effects such as sag attenuation.

3. Test a series of asphaltic specimens with different types of mineral fillers, namely fly ash Type C and Type F as well as Portland cement and limestone dust.

4. Develop a suitable compromise to achieve required compaction and target air voids using only the available compaction equipment.

5. Develop a suitable method for coring HMA specimens with minimal damage to the core while following the strict tolerances set forth by AASHTO, NCHRP, and ASTM.

6. Develop a method of preparing HMA sample ends in accordance with strict surface and squareness tolerances set forth by AASHTO, NCHRP, and ASTM.

7. Evaluate the response of hot mix asphalts made with different mineral fillers when exposed to dynamic loading.

CHAPTER 2

LITERATURE REVIEW

2.0 Complex Dynamic Modulus Test

The complex dynamic modulus test is used to determine various HMA material properties. Dynamic modulus testing is one of the oldest and best documented testing procedures which can be traced back to the 1970's. This test has the ability to relate the stress and strain of almost any visco-elastic material especially asphalt to the materials long term performance. The complex dynamic modulus is unique since it involves both real and imaginary parts. The real and imaginary components of this modulus represent both the viscous and the elastic responses of an HMA mix. The various components of this test are measured and calculated using a series of haversine load applications under stringent data acquisition. The result of dynamic testing yields a waveform similar to that shown in Figure 2.1. (NCHRP Report 513).

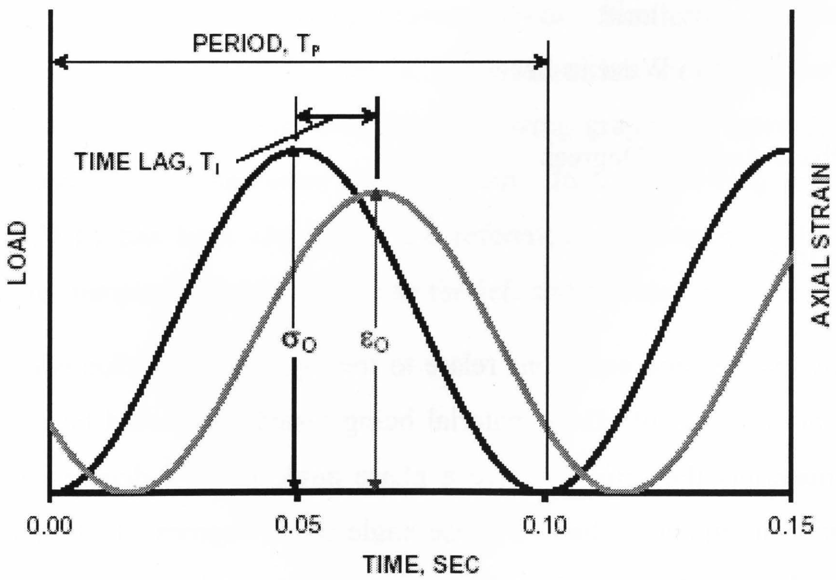


Figure 2.1: Typical Dynamic Modulus Test Waveform (NCHRP Report 513)

The determination of the Complex Modulus requires certain elemental equations. These equations have been depicted below alongside their definitions.

Main Complex Modulus Equations (AASHTO, 2005)

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \qquad \text{(Eq 2.1)}$$

$$\phi = \left(\frac{T_l}{T_p}\right) X360 \qquad \text{(Eq 2.2)}$$

Where,

$|E^*|$ = Dynamic Modulus

ε_0 = Amplitude of Resulting Strain

T_l = Time Lag in Seconds

T_p = Period of Sin Wave in Seconds

ϕ = Phase Angle in Degrees

σ_0 = Stress

The above values and equations relate to the Dynamic Modulus which refers to the overall stiffness of HMA material being tested. It should be noted that all elastic materials theoretically have a phase angle of zero degrees where as all purely viscous materials have a phase angle of 90 degrees. In HMA mixes the phase angle can vary anywhere from five degrees at lower temperatures to 40 degrees at higher temperatures. This is to be expected as HMA exhibits solid characteristics when very cold and more liquid characteristics when very hot.

2.1 Dynamic Modulus in Pavement Design

There are many accepted design guides which are used in Canada and across the continental US. Flexible pavements in general consist of layers which are composed of better material on the surface and weaker materials below. Due to this layering process these systems cannot be analyzed easily as they are neither solid nor liquid nor are they completely homogeneous masses. The first to notice pavement systems are made of layers rather than a single mass and develop a method of analysis was (Burmister, 1945). His research eventually went on to develop the layered theory. Throughout his life Burmister developed a two layer system and eventually a three layer system to explain asphalt pavement systems (Burmister, 1945). Later in history with the inception of computer technology the base theories developed by Burnister were applied to more complex multilayer systems (Huang, 1967). In all these mechanical systems stresses and strains were computed using the linear elastic theory. The strength of the elastic theory lies in the fact that it can be used in conjunction with material dynamic modului and temperature superposition to develop Master Curves. Similarly by knowing the Master Curve and shift factors for a given material the modulus at any temperature can also be determined. The following graph in Figure 2.2 below shows an example of temperature superposition. In the following graph 21°C (shown as 70°F) has been chosen as the reference temperature. The idea is simple, colder temperatures are shifted to the left and warmer ones are shifted to the right.

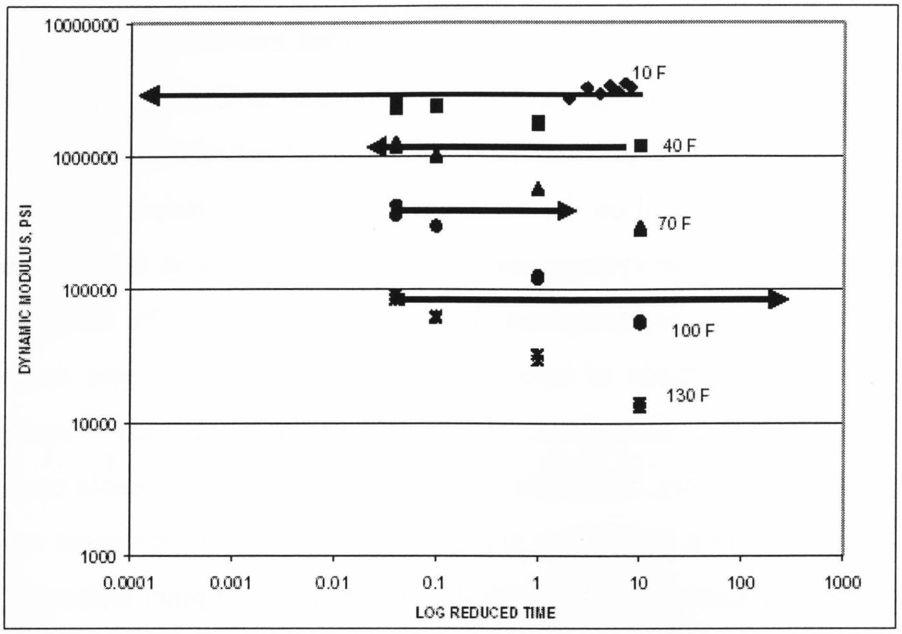


Figure 2.2: Temperature Superposition from Dynamic Values vs. Log Reduced Time (NCAT,01-05)

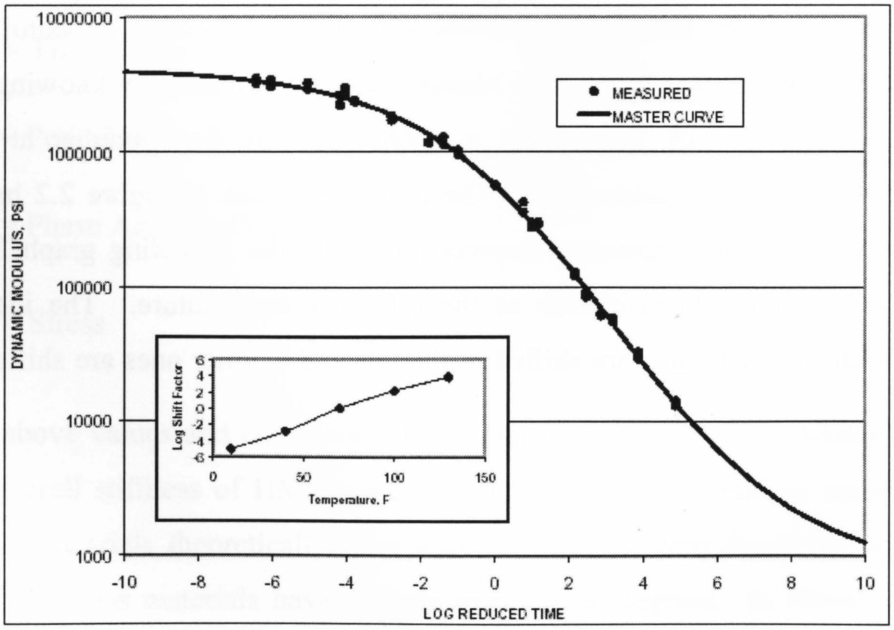


Figure 2.3: Typical Master Curve for a Sample Data Set (NCAT,01-05)

In Figure 2.3 below an example of a typical Master Curve for an arbitrary set of data has been provided. This methodology can be applied to almost any HMA material to gain relatively good results.

This method and a further explanation of the process can be found in almost any design guide for asphalt mixtures. The following equations represent a general Master Curve as well as the shift function used to superimpose the temperatures shown in Eq. 1.

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log tr)}} \qquad \text{(Eq 2.3)}$$

Where:

E* = Dynamic Modulus

tr = time of loading at the reference temperature

δ = minimum dynamic modulus value

δ + α = maximum dynamic modulus value

β,γ,α = parameters describing the shape and the sigmoidal function

$$\log(tr) = \log(t) - c\,[\log(\eta) - \log(\eta\, tr)] \qquad \text{(Eq 2.4)}$$

Where:

tr = time of loading at the reference temperature

t = time of loading at maximum force

η = binder viscosity at temperature of interest

η tr = viscosity at the reference temperature

2.2 Dynamic Modulus as a Performance Test

In NCHRP Project 9-19 samples were tested at 37.8°C and 54.4°C (100°F and 130°F). According to this report a good correlation was noted between dynamic modulus figures and rutting resistance for the sections tested. Figure 2.4 illustrates this relationship. This report also included data for the various experimental sections included in MNRoad, WesTrack as well as FHWA pavement testing facilities. According to this same report as the dynamic modulus at high temperatures increased so did the materials resistance to rutting. To date the ideal test temperatures and minimum dynamic modulus values are still being determined for different materials in order to satisfactorily design mixes which will resist rutting. According to the NCHRP Project 9-19 the research found a fair correlation between cracking observed in each of the experimental sections (Bonaquist et al, 2003).

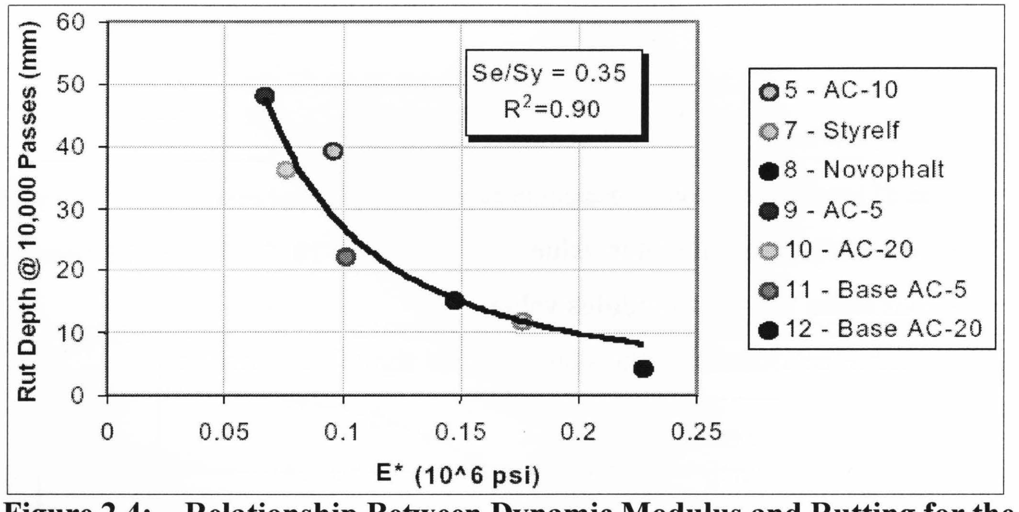


Figure 2.4: Relationship Between Dynamic Modulus and Rutting for the FHWA Pavement Testing Facility (Mehta, 2005)

2.3 Dynamic Test Studies and Protocols

Similar to Project 9-19, project 1-37A had similar achievements. The NCHRP 1-37A Draft Test Method DM-1, Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures was based on the established ASTM D-3497 standards. In this particular test the samples were continuously loaded following a haversine waveform at specific temperatures and loading rates. The measured stresses and strains were used to calculate the dynamic modulus and phase angle for each unique mix. This project used temperatures of 14, 40, 70, 100, 130 °C and frequencies of 0.1, 0.5, 1. 0.5, 10, 25 Hz, respectively. The resulting 30 dynamic modulus values obtained were used along with the principle of superposition to generate Master Curves for each of the mixes tested.

2.4 Dynamic Modulus vs. Master Curves

The main method for using dynamic modulus values as a principle performance test for rutting and fatigue cracking can be found in NCHRP Report 465. The main difference between the dynamic modulus approach and the generation of Master Curves is the number of required measurements. In simple performance testing, the tests are done at specific effective temperatures for rutting and cracking performance which are representative of a pavements location. In this type of testing a specific load rate is used throughout the process which is heavily dependant on the expected traffic speeds in the area of interest.

2.5 Variability in Past Test Studies and Protocols

Variability is a phenomenon that is inherent in all research, especially in the analysis of HMA materials due to the complexity of their visco-elastic behavior. In NCHRP Report 513 two dynamic modulus determination approaches were compared. Tests were conducted on specimens that contained two different maximum aggregate sizes, as well as six different loading frequencies in two different laboratories using three different temperatures. In Report 523 the variability was analyzed and compared using standard deviations, and coefficients of variation. The study also looked at the mean values for specimen dynamic modulus as well as phase angle. In essence this study followed general trends in dynamic modulus data to conclude that both the modulus values and phase shift data were consistent with the materials tested. The overall variability of the dynamic modulus data produced with the two devices was reasonable, with coefficients of variation for various conditions ranging from 5% to 15 %

(Bonaquist et al., 2003). This research and analysis prove that dynamic testing is reproducible in different environments and conditions while still yielding good results. Some may argue that dynamic modulus testing is often one of the most time and cost intensive approaches but past research clearly shows the success of such experimentation in the analysis of HMA material characteristics.

2.5.1 Flow Time Test

This test is simply a compressive creep test. In this test a static load is applied to a specimen and the resulting strains are recorded as a function of time. The flow time test can be run on a variety of machines since it only requires a small load frame and minor data acquisition capability. NCHRP has defined this test in Project 9-19 as the time when the minimum rate of change occurs during a creep test. Furthermore, flow time is determined by the differentiation of the strain versus time curve (NCHRP, 2003). In Project 9-19 the flow time was found to have a close relation to the rutting resistance of certain HMA mixtures, namely the mixtures used in MNRoad, WesTrack, and FHWA Pavement Testing Facility. For tests at a given temperature, axial stress, confining stress, the rutting resistance of the mixture increases as the flow time increases (Bonaquist et al.,2003).

2.5.2 Flow Number Test

In this test haversine axial load is axially applied to HMA specimens. The load is held for 0.1 sec followed by a 0.9 sec rest period. The permanent axial deformation is measured at the end of each rest period during repeated loading and then converted to strain by dividing by the original specimen length. Ultimately, the flow number generated by this test refers to the number of load pulses when a minimum rate of change in permanent deformation occurs. Flow number is similar to Flow Time in that it is determined by differentiating between permanent strain and the number of load cycles. Similar to flow time, flow number is apparently related to the rutting resistance of HMA section tested in WesTrack and FHWA.

2.5.3 Field Shear Test (FST)

This device was initially developed during NCHRP Project 9-7 as a simple device for performing in situ quality control testing on HMA specimens. It was designed to be a replacement for Superpave shear test or SST. The original field shear test had a lot of good qualities. The advantages include small size, ruggedness, and ease of use. The main problem with the device was the fact that it had a lot of variability problems. Unfortunately, measurement variability and quality control are not meant to co-exist and thus this test eventually disappeared into the archives.

2.5.4 Indirect Tensile Test

This test is a very popular test used to determine specific HMA mixture characteristics. Properties measured using indirect tension testing have been successfully used for the evaluation of moisture damage and fracture distress mechanisms in asphalt pavements. Indirect tensile testing of samples requires exposure to a series of sinusoidal loading cycles. This test mainly involves a series of load applications over a 1000 sec period. During the loading horizontal deformation measurements are taken and recorded. It is believed that in some cases creep compliance with respect to a material's ITT results has been strongly correlated to the thermal cracking phenomena. The indirect tensile testing apparatus looks very similar to Figure 2.5.

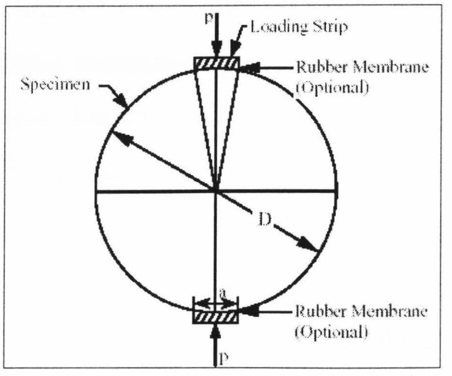


Figure 2.5 Indirect Tensile Testing Apparatus (NCHRP 513)

2.6 Wheel Load Testers

Wheel Load Testers are performance tests on Asphalt concrete primarily used to rank mixtures (Cooley et al, 2000). There are an increasing number of these machines in labs across the US. These systems have seen more than their fare share of scrutiny in the US and in Canada. In the US these testers can be found in many states. For example Georgia has its own unique system called the GLWT. Many US DOT also house many other forms of modified wheel testers, namely the APA or Asphalt Pavement Analyzer as well as Hanburg Wheel Tracking Device otherwise known as the HWTD. Another substantial US investment was the Mobile Load Simulator or the MMLS3 for short. There are many different sizes and types of wheel testers and in this research some of the less significant machines have been disregarded. The following sub sections shall include small definitions of the above mentioned wheel testers.

2.61 Georgia Wheel Load Tester (GWLT)

This piece of equipment was first developed in the 1980's through a cooperative research study between the department of transportation and the Georgia Institute of technology. A full size GWLT wheel tester has been depicted on the next page in Figure 2.6.

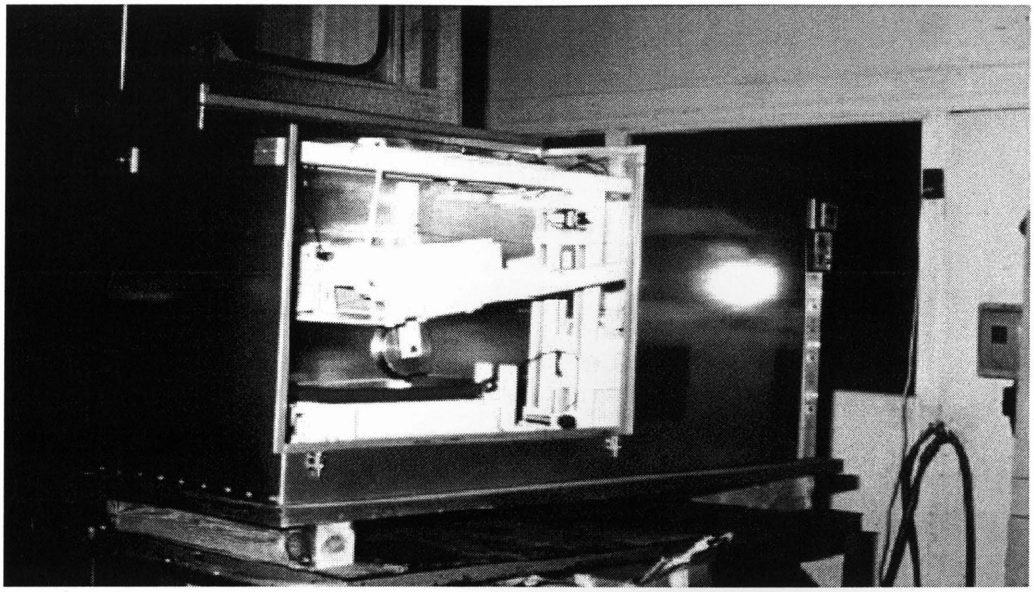


Figure 2.6: Georgia Wheel Tester from the Georgia Institute of Technology

This particular tester is very versatile as it has the ability to test both HMA beams as well as cylinders. This test involves the application of a 100 lb load through a pneumatic hose which is continuously pressurized to 100psi. This test can accommodate a large variety of specimen dimensions. This test has been praised for its adaptability as it can accommodate test specimens ranging from 4 to 7% air voids. The load is applied through a steel wheel which rolls over a hose placed on the surface of the sample being tested. This type of test is usually run for about 8000 loading cycles. One cycle involves the steel roller passing over the sample and then returning to its rest position. The rut depth after testing using this machine has been correlated to the rutting performance of the HMA being tested.

2.6.2 Asphalt Pavement Analyzer (APA)

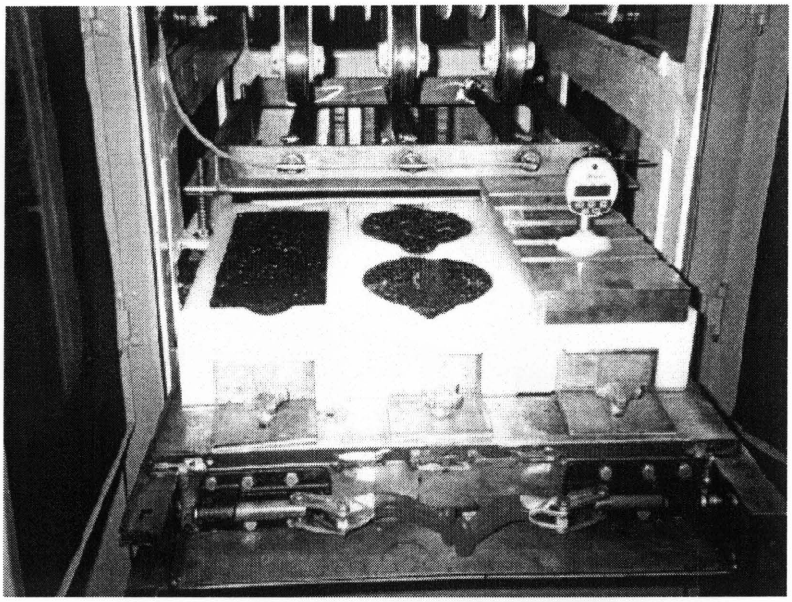


Figure2.7: Full size Asphalt Pavement Analyzer

The APA is basically a modified version of a Georgia Loading Wheel Tester. It was first manufactured in 1996 by Pavement Technology Inc. A full size APA is depicted in Figure 2.7.

This particular machine runs virtually the same test procedure as the GWLT. The main difference between the APA and GWLT is that the APA has the ability to

apply the pneumatic force to samples while they are submersed in water. This test has been thought to vaguely determining rutting, fatigue, as well as moisture resistance in certain HMA mixes.

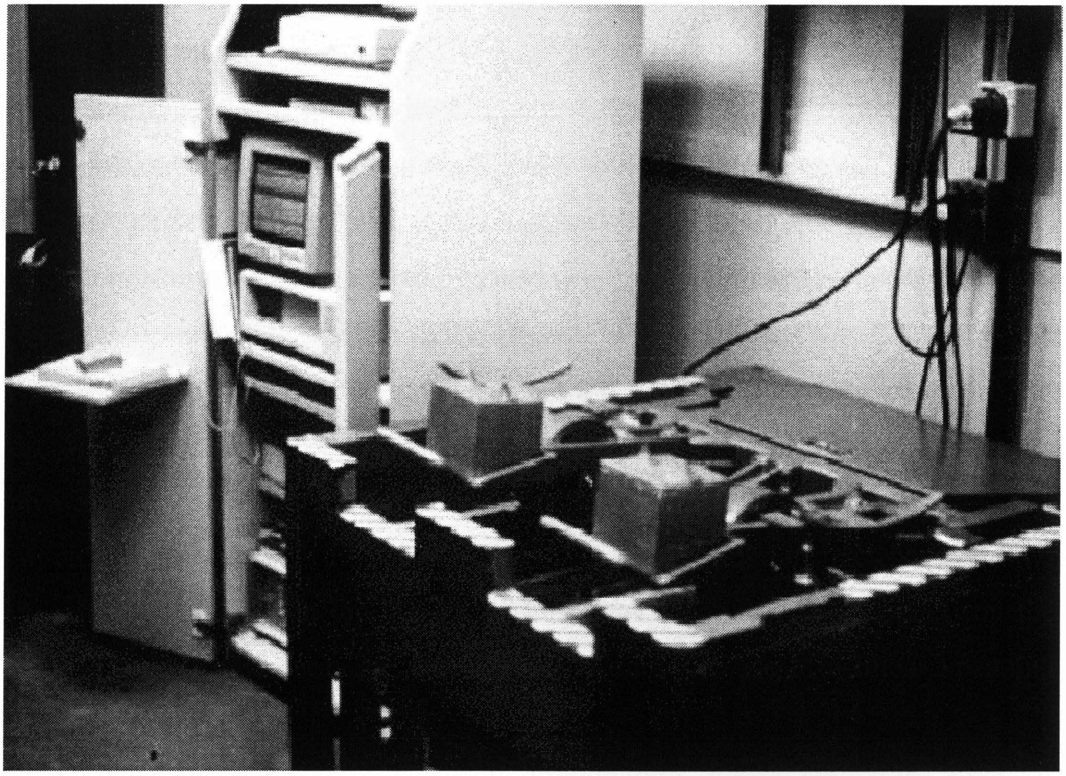


Figure 2.8: Hanburg Wheel Tester and Data Acquisition System

2.6.4 Hamburg Wheel Tracking Device (HWTD)

The Hamburg Wheel Tracking Device was developed by Helmut-Wind Incorporated which is located in Hanburg Germany. It was initially developed for the testing of the heavy traffic roadways across Germany to evaluate rutting and stripping. In Figure 2.8 there is a picture of a Hanburg Wheel Tester in a laboratory aside its data acquisition and control system.

The Hamburg device is a very restrictive apparatus especially in regards to the size of the specimens. In this test the specimen has to be a pre-defined size and have a specific amount of air in order to be tested. The Hamburg device test samples must be 10.2" x 12.6" x 1.6". The target air voids for this test are 7% +/- 1% which can be hit in the lab but is very difficult to obtain accurately in the field. These requirements are usually met through the use of a linear kneading compactor, although some testing has also been done using gyratory compacted specimens. The testing in this device is often done under water between 25 and 70°C (77°F and 158 °F). Most tests are conducted at 50°C under a 705N load for up to 20,000 passes, or until 20 mm of deformation have occurred. The wheel used for loading travels at a fixed rate of about 340 mm/sec and thus sample testing time can vary from sample to sample but is ultimately limited by the samples size

2.7 Simple Performance Testing Procedures

2.7.1 Testing Program Frequencies and Temperatures (ASTM)

The uni-axial Dynamic Modulus test was first standardized in 1979 under the umbrella of ASTM D 3479, "Standard Test for Dynamic Modulus of Asphalt Concrete Mixes" and then later re-approved in 2003 under D 3497-79 and entitled "Standard Test Method for Dynamic Modulus of Asphalt Mixtures".
The test consists of applying a uni-axial sinusoidal or haversine compressive stress to an un-confined cylindrical HMA test specimen. Before its inception in 1979 the basis of this type of testing was presented at the fourth International Conference on the Structural Design of Asphalt Pavements by L.Francken, with his study named "Permanent Deformation Law of Bituminous Road Mixes in Repeated Triaxial Compression". In the early stages of development the accepted practice was simple know as the repeated load test. The main difference in procedure specification is that today's dynamic modulus test is much more difficult to perform and requires a very accurate measuring system.

The current ASTM standardized test calls for certain specific requirements. Namely a testing machine capable of producing sinusoidal loading functions over a range of frequencies from 0.1 to 20 Hz. The load frame in question should be capable of sweeping over a range from 0 to 13.3 kN. This method also calls for an environmental system capable of producing stable temperature controlled atmospheres from -9 to 50 °C +/- 0.5 °C (-48.2°F to 122°F +/- 33°F). Temperature control units should also be capable of holding up to 6 specimens for group conditioning. The loading device should be equipped with a strain measuring device linked to a data acquisition as well as an electronic load cell to verify maximum load points. This test involves laboratory molded specimens which are in accordance with ASTM D3496. The specimens should be produced in house or cored to have a diameter of 100 mm and a minimum height to with ratio of 2:1 (H:DIA). Most samples are made 200 mm x 100 mm. ASTM testing involves the application of haversine loading without impact using loads varying between 0 and 35 psi through each load case for a minimum of 30 seconds and not exceeding 45 seconds at set temperatures of 5, 25, and 40°C (41,77, and 104°F) while being loaded at frequencies of 1, 4, 16 Hz for each temperature. The standard also specifies if field cored specimens are used to test six samples for each temperature and frequency combination, while laboratory prepared specimens only require three samples. The testing is straight forward, to reduce the amount of damage between tests the sample need to be loaded first with the lowest temperatures and highest frequencies. By keeping the samples cold and applying the quicker loads first the samples are conserved and the amount of relative damage to the sample is significantly reduced. The conclusion of this test is to record the resulting recoverable axial strain of each mix and load temperature combination and then compute the average dynamic moduli for each temperature and frequency.

2.7.2 Testing Program Frequencies and Temperatures (NCHRP)

NCHRP otherwise known as the National Co-operative Highway Research Program has been a strong driving force in the attempt to discover the cause and effect of pavement distresses as well as discovering and applying reliable performance testing practice for decades. NCHRP Report 465 actually stemmed from Project 9-19. The experimental plans for these projects were very straight forward. The goal was to use a combination of lab and field projects which covered a diverse range of distress mechanisms to select test methods which had the greatest correlation to both rutting and fatigue cracking. In order to have a pavement stand the test of time it would need to be flexible enough to resist fracture and stiff enough to resist permanent deformation or rutting. Although the goal seems simple, researchers have been struggling to achieve the perfect balance in their mixes for many years. In order to best predict asphalt distresses NCHRP analysis covered a wide range of material, climates as well as pavement structures. This experimentation was designed to quantify the correlation between mixture response and HMA distresses.

The current NCHRP tests call for certain specific requirements. Namely a testing machine capable of producing sinusoidal loading functions over a range of frequencies from 0.1 to 30 Hz. The loading functions should have the ability to sweep over a maximum of 25 kN in some instances. This method also calls for an environmental chamber capable of producing stable temperature controlled atmospheres from -20 to 60 °C +/- 0.5 °C (-68 to 140°F +/- 32.9°F). The temperature control unit should also be capable of holding 6 specimens. The loading device should be equipped with a strain measuring device or LVDT as well as a data acquisition system and electronic load cell to verify maximum load points. According to the report NCHRP 465, this test involves laboratory molded specimens which are short term aged for 4 hours in accordance with AASHTO PP2, "Standard Practice for Short Term Aging of Hot Mix Asphalt". The specimens should be produced in house or cored to have a diameter of 100 mm and a minimum height to diameter ratio of 1.5:1 (H:DIA). Most samples are cored from gyratory compacted pucks which are 4" x 6" to samples that are 150 mm x 100 m in accordance with a study conducted by the Superpave models team.

Similar to ASTM, NCHRP Simple Performance Tests also involve the application of haversine loading without impact using loads which vary between 0 and 100 psi through each load case for a minimum of 30 seconds and not exceeding 45 seconds at set temperatures of 4.4, 9, 21.2, 37.8 and 54.4°C (40, 48, 70, 100 and 130°F) while being loaded at frequencies of 0.1, 0.5, 1, 5, 10, 25 for each temperature. Much like the standard the report also specifies each load, temperature, and frequency combination. The testing is straight forward, to reduce the amount of damage between tests the samples need to be loaded first with the lowest temperatures and highest frequencies while progressing to the hotter temperatures. By keeping the samples cold and applying the quicker loads first the samples are conserved and the amount of relative damage to the samples is significantly reduced. This method of testing requires at least two samples to be made for each mix type. The resulting recoverable axial strain was recorded for each mix as well as the temperatures and frequency combination. The average dynamic modulus was then computed using first principles for each temperature, frequency, and load category.

2.7.3 Similarities and Differences ASTM & NCHRP

The similarities between these two methods of testing are remarkable, as they are both based on the same first principles. Both these tests have deeply rooted elements of material mechanics which have been slightly modified for their application to HMA materials.

Both these methods seem to share the same initial basis, since an HMA material's dynamic modulus is determined by dividing the maximum dynamic stress by the peak recoverable axial strain. Where these tests substantially differ can be seen in the testing procedure. In ASTM the loading frequencies range from 0.1-20 Hz where as in NCHRP the range was increased by 10 to make a range from 0.1-30 Hz. After careful consideration this testing program has omitted all the ranges of measurement between 25 and 30 Hz since they proved to be very difficult to attain. Stable readings at high oscillations were very difficult to capture, even after a long conditioning periods and thus have been avoided. This frequency adoption can be seen in NCHRP report 513. Another difference between these tests can be seen in the maximum load requirements, NCHRP demands a machine capable of 0-25 kN of force where as ASTM only specifies 0-13 kN. In the end though NCHRP only used testing loads within ASTM specifications anyway. High loads were also avoided, since they propagated specimen damage before any good data could be collected. Both NCHRP and ASTM required temperature control for specimens to be tested, ASTM requires 0 to 50°C (32 to 122°F) where as NCHRP specifies a higher range from -20 to 60°C (-68 to 140°F). This action appears justified in the fact that NCHRP specifications cover a wide variety of tests including low temperature cracking which is commonly carried out at temperatures below the freezing mark. Almost all the specified details between these two tests differ in one way or another. Even the specifications used to prepare the samples are different. This is evident since NCHRP follows AASHTO PP2 and ASTM follows ASTM-D3496.

The greatest difference between these two methods is the specimen height to diameter ratios. NCHRP in Report 465 state "The sample preparation was based on the conclusions of an extensive study on sample geometry and aggregate size conducted during NCHRP Project 9-19." where apparently "It was found that a minimum height to diameter ratio of 1.5 was required in order to insure that the response of a sample evaluated in either the dynamic modulus or permanent deformation tests represents a fundamental engineering property". This minimum requirement was very beneficial for the production of asphalt specimens created in gyratory compaction devices since most of them are not capable of producing the ASTM height requirement of 200 mm.

The remaining differences between these two tests lie in the loading frequencies, sample temperatures, number of samples. In ASTM frequencies of 1, 4, 16 Hz were used where as in NCHRP a wider range of frequencies were applied namely 0.1, 0.5,1,5, 10, 25 Hz. Similarly, in ASTM samples were tested at temperatures of 5, 25, and 40°C (41, 77, 104°F) where as in NCHRP samples were tested at temperatures of 4.4,9, 21.2, 37.8°C (40, 48, 70, 100°F). Both of these tests involve numerous samples which raises the demand for time and funds. ASTM recommends 6 field cored samples or 3 laboratory samples where as NCHRP makes it possible to conserve funds by allowing the program to test only two samples per mix design. Furthermore, sample end preparation was also different, in NCHRP certain minimum tolerances were set for cored and sawed samples in terms of smoothness and verticality where as ASTM uses a combination of sulfur mortar capping similar to that of concrete cores following Method C617. ASTM also uses Hardened Steel Disks to transfer load from the actuator to the samples being tested where as NCHRP has no real specification in this area.

2.8 AVAILABLE TESTING USING SPT CRITERIA

2.8.1 Dynamic Modulus for Permanent Deformation

This test method deals with testing asphalt concrete to determine the dynamic modulus of the material as well as its reaction to external stressors which cause permanent deformation. This test was designed to test HMA compliance in terms of dynamic modulus, phase angle, and effective temperature as well as loading frequency. This test has been praised for its usefulness in the characterization of asphalt concrete for use in various pavement projects across the US and Canada. This test yields values which aid designers with thickness design as well as long term performance analysis. It also provides a long term evaluation of permanent deformation phenomena that exist in HMA mixes.

This test is performed by applying a haversine compressive stress in the form of a load directly to the surface of cylindrical specimens. This stress is applied at a set temperature and loading frequency. The applied load and recoverable or elastic strain response of the sample is then measured and recorded. The values obtained are used to calculate the dynamic modulus and phase angle for the sample tested.

The test is significant in that the dynamic modulus obtained through this test at a specific temperature can be used as performance criteria to build permanent deformation resistance in new mixes. According to Project 9-19, dynamic modulus test results at high temperatures correlated very well with test sections at MNRoad, Wes-Track, and FHWA (NCHRP 465, 2002). These reports show that dynamic modulus testing is a unique and powerful tool for the design and analysis of current and future Superpave volumetric mix designs.

In order to perform this test a Dynamic Modulus test system is needed. In this case the test system consists of a load frame with axial loading capability for the sample height being used, as well as an environmental chamber to change the specimen temperature according to the desired test temperature. And lastly, a data acquisition

system is needed to record the results of the testing, namely the horizontal and vertical deformations as well as the temperature at different loads. For more information on the equipment please refer to Appendix B.

2.8.2 Repeated Load and Uni-axial Compression

This test method deals the application of uni-axial compression to cylindrical HMA specimens. This test yields specific hot mix resilience in terms of material compliance as the specimen is subjected to repeated loading conditions. This test has been praised for its increased accuracy and field imitation since it is commonly run in a tri-axial state of compression. This loading represents the true field conditions since the strains incurred by the sample cannot be lost to the environment as the sample is completely restrained from every surface allowing the full extent of the loads to be felt. If the cylindrical test specimen is not restrained the sample has the ability to transfer load effort and strain and convert it to a change in diameter. This change can be visually noted as a bulge or slight increase in cross sectional area near the center of the sample during unrestrained conditions.

This test like the majority of simple performance tests, involves the preparation of at least two cylindrical samples of bituminous paving material. The mixtures are compacted and then subjected to uni-axial load. The procedure uses a total loading cycle of 1 second. The sample is loaded by applying load for a period of 0.1 seconds load, and then allowed to rest for 0.9 seconds. Throughout this cycle both permanent axial and radial strains are recorded. After numerous repetitions under constant volume before shear deformation begins the analyst is able to find the flow number for each mix used. This test is significant because it yields a flow number. The flow number can be used to compare different mixes in terms of their resistance to deformation and shear resistance. The reason for the rest period is to promote the maximum amount of damage to the specimen by allowing the specimen to return to its rest position before the application of the next load.

In order to perform this test a loading frame is needed. In this case the test system consists of a load frame with axial loading capability for the sample height being used which is in most cases between 150 to 200 mm, as well as an environmental chamber to change the specimen temperature according to the desired test requirements. With this particular test it is recommended that a confining pressure device be used to better simulate in situ strains. And lastly a data acquisition system is needed to record the results of the testing, namely the permanent axial and radial strains as well as the temperature at different load intervals.

2.8.3 Static Creep/Flow Time of HMA

This test method deals with testing asphalt concrete to determine its creep and flow time while under tri-axial compression. This test yields an HMA material compliance in terms of creep and flow for a range of set temperatures and stress levels. In this test, asphalt specimens are subjected to static axial loading. While under load, permanent axial and radial strains are captured and recorded. These tests are useful in analyzing creep and flow time in terms of their compliance through various effective temperatures.

This test involves the preparation of cylindrical specimens made of HMA which are compacted using a gyratory compactor and then subjected to static axial load. This test is very versatile as it can be performed with or without confining pressure, but it is much more accurate if the specimen is confined. Confinement increases the quality of this test since the sample would better represent in situ stress conditions. The flow time is known as the estimated time it takes before shear deformation occurs in a constant volume of HMA material. Basically in this test the applied stress and resulting permanent axial strain is measured and used to calculate the flow time.

In order to perform this test a loading frame is needed. In this case the test system consists of a load frame with axial loading capability for the sample height being used, as well as an environmental chamber to change the specimen temperature according to the desired test requirements. With this particular test it is also recommended that a confining pressure device such as a tri-axial cell be used to better simulate in situ conditions. Lastly, a data acquisition system is needed to record the results of the testing, namely the horizontal and vertical deformations as well as the temperature at different loads.

2.9 COMMON HMA DISTRESS MECHANISMS

2.9.1 Permanent Deformation

Permanent deformation in HMA refers to the accumulation of minute amounts of unrecoverable strain in response to repeated loading. Permanent deformation is commonly referred to as rutting due to the visual effects of this distress mechanism on the surface of HMA pavements. Rutting appears as small depressions in asphalt most predominantly visible in the wheel path, these small depressions highly resemble “ruts” or valleys thus the acceptance of the term “rutting”. Rutting occurs as a result of a wide range of environmental and repetitive loading effects which cause small depressions which start between 1 to 3 mm and can continue until the end of the pavements service life. On occasion the rutting progresses can quickly and prematurely produce depressions upward of 4 mm; this degree of degradation is often blamed on material problems rather than just traffic and weather alone. The common misdiagnosis is that rutting only occurs on the road surface, but this is not the case.

Rutting can happen due to HMA problems but also due to sub grade failure as well as unbound base course. In most cases the focus of experimentation and testing is on the HMA. In these cases the sub grades are ignored or considered capable of supporting any applied loads. Permanent deformation which occurs in asphalt is believed to stem from the lateral movement or consolidation of particles due to the applied loads from vehicular traffic. Shear failure of HMA courses generally occurs in the top 100 mm of pavement surfaces (Nevelt et.al 1988). Rutting in asphalt pavement is not usually an instantaneous problem, in most cases the visual and physical signs of deformation appear gradually over time. The degree of rutting which can be visually identified by physical depressions in the wheel paths and sometimes small upheavals to the sides are often worsened as the amount of load and number of repetitions increases. It should be noted that deformation rarely occurs due to volume change or densification but rather by shear deformation in the HMA or unbound materials beneath the HMA. Rutting is mainly caused by deformation flow rather than volume change (Eisman, et.al 1992).

2.9.2 Low Temperature Cracking

Low temperature cracking as the name indicates is a pavement distress which is primarily caused by internally induced unbearable material strains generated by severe temperature gradients. The main cause of damage in this distress mechanism has been severe cold but it can be greatly worsened by repeated heavy traffic loading. Thermal cracking is characterized by intermittent transverse cracks perpendicular to the direction of traffic (McGuiness et al. 1994). In simple terms cold temperature causes HMA to shrink, this shrinkage causes a buildup of tensile strain. At any time during the cold period the tensile stress can exceed past the tensile strength of the material leading to a cracks. This phenomenon can be seen from a single cold spell unlike some other distresses which need many cyclic repetitions. Similar to other pavement distresses low temperature cracking can be worsened by repeated cycles of temperature. Many hot and cold cycles in HMA cause low temperature cracking due to the temperature and cracking in general due to fatigue. It is believed that pavement rigidity or stiffness is the greatest contributor to the low temperature cracking phenomena. HMA is greatly affected by temperature, especially extremes. In essence a stiffer mix will perform better in hot weather and a softer mix will perform better in cold weather. The key is to balance economical design while maintaining acceptable performance in every environment. Recent developments in binder technology in regards to PG ratings for binder have made much advancement in low temperature environment performance in HMA's.

2.9.3 Fatigue Cracking

Repeated loading is the root of many problems associated with material deterioration. Fatigue occurs when a material is stressed beyond its fatigue limit or life due to repeated loading. The visual appearance of fatigue cracking in HMA is very distinctive. Fatigue cracking is sometimes called alligator cracking since it resembles the line pattern on an alligators back. During the design process HMA materials and thickness are specified to support a predefined number of repeated loads of a designated weight. In general, fatigue cracking occurs when the number and degree of load surpasses the design parameters. Asphalt pavement structures are very capable of supporting loads assuming all the systems components are pulling their weight.

Fatigue cracking may be worsened by certain factors. Fatigue can be worsened if there are pre-existing sub grade problems as well as poor quality control both in the plant and in the field. One common problem exists in the drainage of oncoming water. In some cases pavement foundation layers can become saturated and loose strength, this in turn decreases the amount of support available to the surface structure and leads to accelerated damage. The increased stress in the HMA can cause the surface to fail prematurely. Fatigue can also be prematurely seen in pavements which are loaded by the illegal use of overweight trucks. Premature fatigue is also immanent when contractors fail to implement good quality and thickness control measures during construction. In advanced fatigue environments, pavement will crack, ravel, and progressively produce pot holes which lead to a complete loss of surface material as well as complete structural failure.

Fatigue in pavements is a structural integrity problem rather than a material problem. Both structural and material traits heavily affect the development of distress mechanisms. Structurally, poor sub grade and drainage design leads to weak pavement which stems to advanced fatigue deterioration very quickly under vehicular traffic. In early pavement structures experts believed that asphalt failure stems from cracking which would begin at the bottom of the structure and migrate upwards, where in fact, cracking has actually been observed starting at the surface and moving down. Furthermore, for thin pavement structures cracking begins at the bottom of the HMA. Contrarily, in very thick pavements, namely perpetual pavement systems, cracking starts at the surface and migrates downward. Typical fatigue behavior is often misdiagnosed as the sole lack of surface material due to poor quality control where as these properties are only a secondary effect at most.

2.9.4 HMA Friction Properties

Virtually every highway agency across the globe is concerned with the safety of the people who use their roadways. This concern stems from the liability involved when serious accidents occur. When there are major accidents one of the first components tested is the skid resistance of the road surface. Skid resistance is directly correlated to the ease of which a vehicle on a road can loosen or break its frictional bond. In the field certain factors govern how fast a driver can decelerate during an emergency maneuver. Due to the significant correlation between skid resistance and safety we currently have a set of minimum acceptable values for the skid resistance of our highways. Skid resistance is mainly the amount of friction on the surface of the HMA structure in any given weather.

Generally friction can be defined as the relation between both vertical and horizontal force developed by a still tire held by a vehicles brake while a vehicle is still in motion. The friction of pavement is a function of the surface texture which is divided into two components, micro texture and macro texture. (Leu, et al 1978). Regular HMA provides small escape channels which carry water away from the surface, as the water travels away from the wheel path there is less water on the surface to act as a lubricant increasing surface friction as well as skid resistance. In recent studies researches in conjunction with transportation agencies have been looking at SMA materials as well as improved drainage layers to facilitate the movement of water away from the wheel path in attempts to increase skid resistance. Surface friction means better and quicker stops for the driver, which extends to a safer road way for all.

From a design engineer's perspective, friction is a very important HMA surface property which can be facilitated through proper material selection as well as proper design and construction. From a pavement management perspective friction can be seen as measure of serviceability. In other words the longer a road can provide a safe amount of surface friction to the user the less money would be consumed in surface rehabilitation and the lower the life cycle cost for the material.

The following friction characteristics are desirable in a good pavement (NCHRP Synthesis 14, 1972):

1) High friction during weather extremes. Ideally the friction when wet should be as high as possible when compared to that of the dry pavement.
2) Little or no decrease of the friction with increased speed. The friction of dry pavement is nearly independent of speed, but this is not the case for wet pavement.
3) No reduction in friction with time, from polishing or other causes.
4) Resistance to wear by abrasion of aggregate, attrition of binder or mortar, or loss of particles.

As time passes more and more ministries are beginning to see how important the skid resistance is to the safety of the roadway. Hopefully the future will bring pavements that are safer and stronger which last longer.

2.9.5 Moisture Intrusion and Susceptibility

Moisture susceptibility in HMA materials is mainly affected by various environmental factors namely temperature and moisture. Moisture problems in any material are usually propagated by environmental conditions. This distress mechanism can be worsened by the accumulation of other distresses. There are three mechanisms by which moisture can degrade the integrity of a hot mix asphalt matrix:

1) Loss of cohesion of asphalt film that may be due to several mechanisms;

2) Failure of the adhesion between the aggregate and asphalt

3) Degradation or fracture of individual aggregate particles when subjected to freezing (SHRP-A-404, 1994).

Stripping is the main reason for moisture problems. Basically, when the aggregate in the mixture has a high affinity for water the asphalt can be stripped away. Usually asphalt mixes avoid aggregates which tend to absorb great deals of water since stripping leads to a loss in binder to the aggregate. The more binder consumed or absorbed by the aggregate means less binder availability to hold together the materials stone matrix which means less strength and material quality. The loss of HMA material performance can lead to pre-mature rutting, raveling, as well as cracking.

CHAPTER 3

EQUIPMENT AND MATERIAL EXPERIMENTAL DETAILS

3.0 MINERAL FILLERS

3.1 Portland Cement

Portland cements are commonly known as materials composed of hydraulic calcium silicates that set and harden by reacting chemically with water through a process called hydration. A popular material in the HMA area is PCBD otherwise known as Portland cement bypass dust. According to past research PCBD has been know to positively influence the anti-stripping properties of HMA mixes. Asphalt mixes with PCBD filler, has significant improvements on Marshall Properties including stabilities and flow (Aljassar, 2004). Common practice has been to substitute between 2 to 5% of HMA fines with Portland cement. According to Amer, and Ramzi (2002) the optimum percentage of cement should be equal or less than 5% filler by weight.

The problem with using cement as filler is obviously the associated cost. In today's market, asphaltic product costs have been skyrocketing due to the rising crude costs. The reason for adding fillers to HMA is simple; we wish to achieve acceptable performance and reduce cost. For the purposes of this research it is understood that the cost of adding cement to asphalt is a hindrance to the economics of a project. However, there may be a time when the benefits far outweigh the costs, as using cement reduces binder demand.

3.1.2 Fly Ash (Type C and Type F)

Fly ash is mostly made of silicate glass which is composed of silica, alumina, iron and calcium. It also has very small amounts of magnesium, sulfur, sodium, potassium, and carbon as well as some crystalline compounds. Fly ash is a fine powder that looks like cement which is a combustion by-product which is produced when ever coal is used to power industrial processes. In general Type C fly ashes have higher calcium contents (10 to 30% CaO) where as Type F fly ashes are considered low calcium (less than 8% CaO). If recycled fly ash would have a more positive environmental and industrial effect. Unlike fly ash cement requires an enormous amount of energy to produce which makes it very harmful to the environment in terms of Carbon dioxide and ecosystem destruction during the mining process required to claim raw material.

3.1.3 Bag House Dust

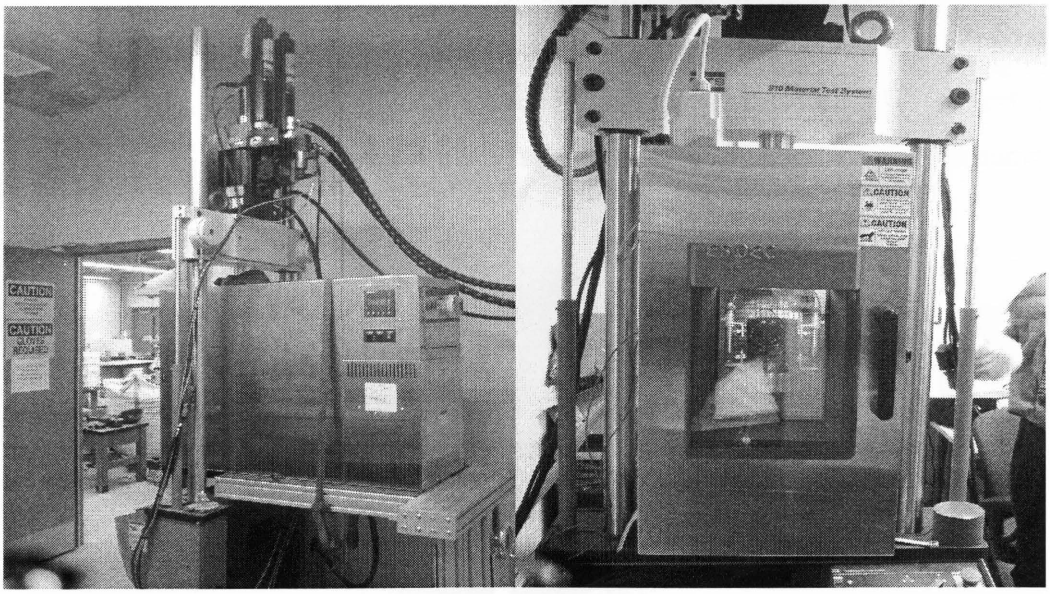
Bag house dust, also known as limestone dust, is plainly as the name implies. This dust is composed of extremely fine limestone particles which are the natural byproduct of aggregate crushing. Bag house dust is generated from the movement and transportation of limestone aggregates during asphalt mix production, as well as the grinding method associated with the crushing process.

3.2 Equipment Requirements

3.2.1 Load Frame

Load frames are the back bone of most axial loading devices, as they provide the essential load needed to perform performance tests. Load frames vary in size and capacity, and can range from one pound to millions of pounds. The development of the asphalt testing system at Ryerson University involved careful equipment selection which was riddled with many tedious tasks. These tasks include space, equipment requirements and hydraulic and electric power supply demands as well as strict safety protocol which push for proper ventilation as well as safe working conditions. The current system set up in the TARBA highway materials laboratory at Ryerson University has a MTS load frame. The MTS load frame is composed of a Model 810 100 ken load system. The maximum load frame requirement for most simple performance testing is 25 kN. From my experience a load cell and frame capable of loading up to 5000 lbs is more than adequate for all HMA testing needs as asphalt is relatively weak, especially at warmer temperatures. Also the load frame should have a long stroke of at least 4" to 6" since simple performance testing changes from standard to standard. For example just changing from NCHRP testing to ASTM can vary the minimum sample height up to 50 mm which can only be accommodated if the load frame has enough stroke height to compensate for the change.

Simple performance testing calls for dynamic loading capability. Simple performance testing commonly involves loading frequencies which range from 0.1 to 30 Hz. The Simple Performance Testing of HMA materials involve frequencial loading as well as confinement and temperature control. It is recommended that the load frame have enough lateral clearance to accommodate both a tri-axial cell as well as a temperature control device. The load frame used for this particular testing is depicted in Figure 3.1. For the specifications of the device used in this project please refer to Appendix B.



3.1: Load Frame

3.2.2 Environmental Chamber

Simple performance testing was designed to accurately and reliably measure mixture response characteristics in a variety of environmental conditions. In a laboratory setting, it is difficult to come up with an accurate method of conditioning samples as well as maintaining set temperature extremes throughout the duration of the testing cycle without an environmental chamber. Simple performance testing is usually conducted between the temperatures of -9 and 37.8°C (-48.2 and 100°F) for NCHRP and 5 to 40.0°C (41 to 104°F) for ASTM. It should be noted that some tests also involve very low temperature extremes which can dive down to -20°C (-68°F). Temperature stability is very important in simple performance testing. Proper testing requires that all temperatures be held within 0.5°C (32.9°F) of their respective targets. The chamber used for the testing was a model 651.34 liquid nitrogen cooled chamber. The decision to purchase a LN2 system was based on unit cost, as a regular compressor based unit would be much more expensive. In the future if another system were to be purchased it would be beneficial to steer away from a liquid nitrogen unit since it is very labor intensive procuring, transporting, and connecting nitrogen to the unit. It should be noted that commercially available liquid nitrogen is bought in containment device called dewers, these devices hold upwards of 200 L of liquid nitrogen. The problem is that the containers actually only last about three weeks whether they are used or not since the gas naturally boils away.

Figure 3.2: Filling Process

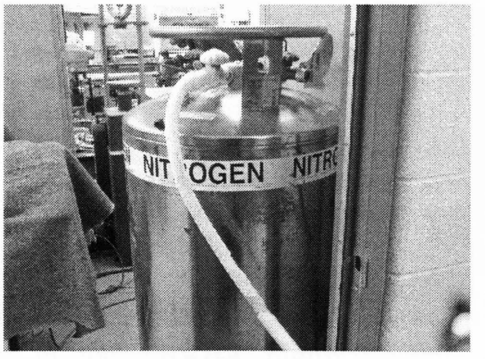


Figure 3.3: Nitrogen Gas Dewer

The tanks cost about $300 CAD and will only last about 3 weeks from the date of delivery. The large dewer as well as the filling process is depicted in Figures 3.2 and 3.3.

3.2.3 Gyratory Compactor

The specimens prepared and tested in this research were all made using a gyratory compaction device. In previous studies some people have chosen to use a California kneading compactor but it is believed that gyratory systems perform much better in terms of representing actual field compaction. One main restriction

with using a gyratory compactor is the final specimen height. If test specimen needed has a height to diameter ration of 1.5 to 1 similar to NCHRP testing then a gyratory can be used. It should be noted that it is very difficult to determine the maximum amount of material that will fit into a gyro so that it can be closed. Also the number of gyrations is usually altered when compacting taller samples. The author would only recommend the use of a gyratory compaction system which follows ASTM D3387 if samples can be made to a maximum height of about 160 mm, anything taller that this would have to be made using a California kneading compactor. The gyratory compactor used for this testing is depicted in Figure 3.4.

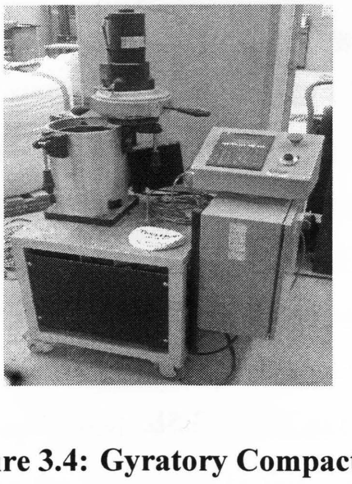


Figure 3.4: Gyratory Compactor

A gyratory compactor is a device which applies two separate compacting efforts to HMA materials. A Gyratory, as the name indicates gyrates during compaction, which applies a shear or kneading force to the contained material to aid in compaction effort. This type of system also applies a continuous force throughout the compaction period of approximately 600 kPa. The combined effort of force and gyration has been thought to better represent in field compaction when compared to other compaction methods such as Marshall and even the California kneading compactor.

All the materials tested in this research were compacted using a Brovold Gyratory compactor, the current owner and distributor of this system is now Pine Instrument Company which is located in Grove City, PA. This particular unit follows SCSC according to AASHTO PP35.

3.2.4 Liner Variable Displacement Transducers (LVDT) and Hardware

The key to most performance tests is precise measurement. It is not enough to be able to apply repeated or static load if the sample response cannot be recorded. In the past, performance testing in asphalt called for disposable strain gauges, which where quite difficult to mount and which were quite costly when used in high and low temperature extremes. Today's performance tests rely on a newer form of technology called a linear variable displacement transducers or transformers which we refer to as LVDT's for short. LVDT's work on a fairly simple premise, they are excited by a set voltage and then depending on their position return a fraction of that voltage which is linearly related to their displacement within a predefined range. LVDT's are produced using numerous combinations of AC and DC input and out put orientations. The internal components of an LVDT look similar to electrical schematic shown in Fig 3.5a. Visually the LVDT's used in this experiment are shown in Figure 3.5b.

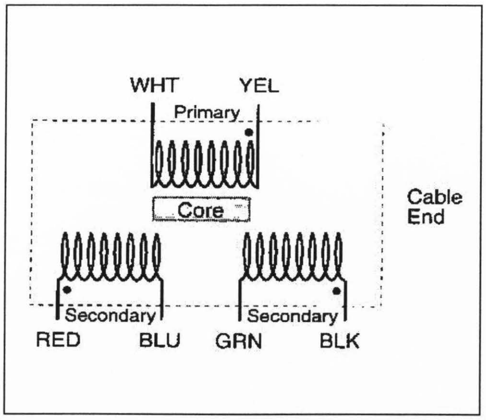


Figure 3.5a: LVDT Schematic (Trans-Tek 2008).

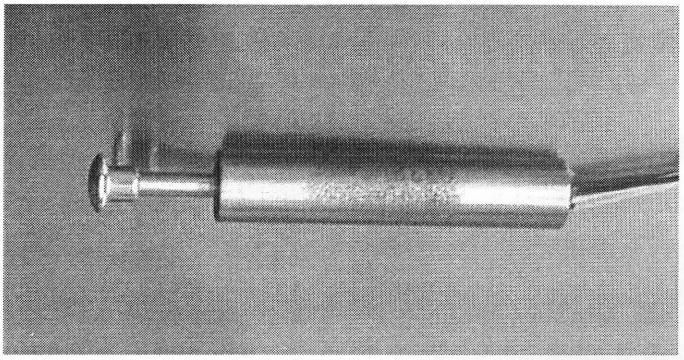


Figure 3.5b: LVDT Used in this study (Manufactured by Trans-Tek Inc.)

The testing of HMA has certain minimum requirements when it comes to LVDT's. Any LVDT used for HMA testing should have a minimum range of 0.02" as well as an inherent non-linearity of 0.25% of full scale (NCHRP 465). It should be noted that signal conditioners are as important as the LVDT's. Signal conditioners provide the excitation voltage to the LVDT's, receive the unit feedback and provide a clean output signal to be connected to a data acquisition system. The samples tested in this report used 2 Tans-Tek 330 series LVDT's for vertical displacement measurements. Through the development of mounting hardware and various testing set ups it should be noted that it is very important to make sure all components are wired correctly and the connections are soldered and tight so as to avoid any signal noise problems during testing. While fabricating mounting hardware for the testing in this report it was found that the hardware used to mount the LVDT's to the specimen should be made of non metallic materials at all costs. If for any reason this is not possible, then ferromagnetic metals should be avoided. All the materials and hardware within an inch of a transducer should be made of non ferrous materials which are poor electrical conductors to avoid directly compromising transducer performance. Any ferromagnetic materials which are within a few mm of the transducer walls can change the shape of the transducers magnetic field. This change in the core field can lead to signal stability problems as well as measurement error. All the components used in this research to hold the LVDT's were made of Aluminum Alloy, Brass and or plastic so as to avoid any interference issues.

3.2.5 Data Acquisition Equipment

Logically, a test can only be validated or rejected if it produces results. The testing of HMA mixtures is no different. In order to understand and predict future performance of a material we need to accurately and efficiently capture and store test data for future review. In most cases a data acquisition system used for conducting a simple performance test should include some form of analog to digital conversion and or digital input storage as well as some form of computational analysis. The system should be capable of measuring and recording very minute changes in material and equipment characteristics during testing. For HMA, the system needs to be capable of measuring and recording repeated applied loads, as well as axial and radial deformations versus time, through a variety of channels. The system used for this testing is shown below in Figure 3.6. The detailed specifications for the system used to test the specimens created for this thesis can be found in Appendix B.

Figure 3.6: Data Acquisition System (Refer to Appendix B for Specs.)

The main advantage to computerized data acquisition is that it has far surpassed the days of the pen and paper approach. Data acquisition systems are capable of recording data points thousands of times a second whereas human capability can hardly record single data point once every few seconds. During the set up of the system used for this testing it has been found that a data acquisition device which combines load, temperature control and data storage is the best option. When the original universal system was purchased for this testing the bare bone software package was not capable of fulfilling the testing program needs. For example, in its original condition the user would have to start and stop the testing process many times in order to achieve certain testing criteria. For example if a user wants to apply a load for 0.1 seconds and then remove it for 0.9 seconds repeatedly this would be almost impossible unless the control software for the load frame had this ability. Since the bare bone software shipped with the universal test frame was not adequate for the testing program it was updated to a more powerful version called MPT (Multi Purpose Test ware). The details for this software can be found on the MTS website which can be easily located through the World Wide Web.

3.2.6 Coring Rig and Accessories

There are many different commercially available coring devices from a wide range of suppliers across the Canada and the US. A decent coring rig can be purchased for about $2500-$3500 CAD. There are few minor but important details which should be addressed when selecting a coring rig for asphalt coring, they have been listed below:

3.2.61 Strength of Rig

The drilling rig should have the power to turn the desired coring bit at a constant rate for the entire coring period without slowing down or overheating. This is assured by buying a device which has a power rating high enough for your project. For this particular project a 20Amp Milwaukee clutch model drilling unit was used and proved to perform very well.

3.2.62 Depth and Diameter of Coring Bit

Simple Performance Testing requires a minimum height to diameter ratio of 1.5:1 and ASTM specifies 2:1 so the coring bit should fulfill both of these requirements in case further research negates one of the two standards in the future. The coring bit should be about 4" in diameter and have a minimum cut depth of 8". The coring in this project was made using standard 4" Wet Diamondcore asphalt coring bit and collar. This combination performed very well for this project. Although the depth of most standard coring bits is a little long which emphasizes the eccentricity of the drill at times. This eccentricity can cause small score marks on the sample wall surfaces if special care is not taken. A custom bit can be used which is closer to the maximum sample height to minimize this phenomena.

3.2.63 Longevity of Product or Warranty

The coring rig used for this research was a Milwaukee product which housed a 20A motor mounted on a 14" x 16" base. It is shown here in Figure 3.7.

The challenge in the coring process was not the commercially available rig but rather the device used to hold the gyratory compacted puck while it was being cored. To facilitate the coring of the 4" x 6" puck a small holding device had to be designed and manufactured. This device is shown below in Figures 3.8a and 3.8b.

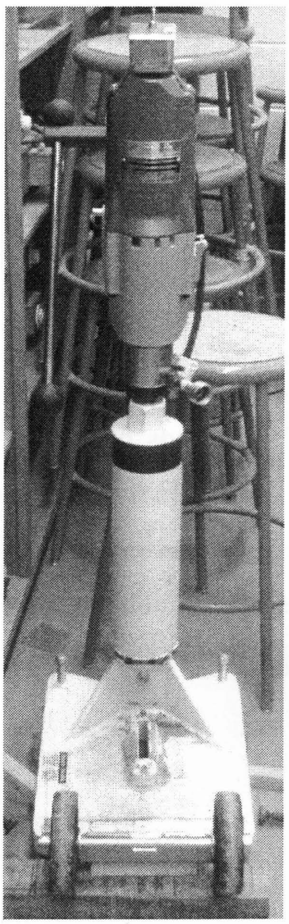


Figure 3.7: Coring Rig

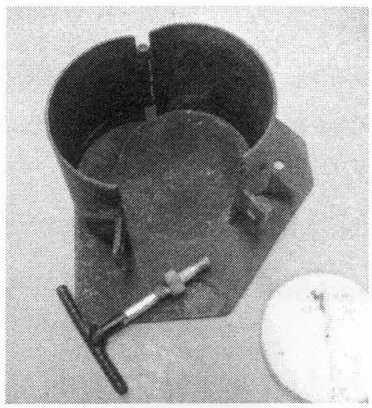


Figure 3.8a: Puck Holder Device (side view)

Figure 3.8b: Puck Holder Device (top view)

The puck holders were made of mild steel which were rolled to the exact sample curvature and retrofitted with a hinge and tightening mechanism which would distribute the holding force around the circumference of the sample being cored. The rig was designed to be strong enough to firmly hold the sample while causing virtually no damage to the original puck; this insures that the sample being extracted remained safe throughout the coring cycle. Small wooden disks were also made and placed below the HMA pucks so as to act as an end indicator for coring. The wooden disks are vital for the protection of diamond coring bit.

The disks were composed of circular plates cut from 3/4" plywood. These disks would suffer mild score marks as the drill bit proceeded to break through the bottom of each sample, however a single disk could be reused repeatedly before replacement was necessary. The purpose of these disks was to insure that the coring bit never hit the steel base of the puck holder where it would be damaged.

3.2.7 Diamond Saw

A machine used for sawing the ends of the cylindrical specimens is necessary for the HMA testing procedure followed in this project. The ends of the samples used in this project were cut to insure the surfaces in contact with the platens were square and smooth. In some cases researchers have used double bladed saws separated by spacers to insure parallel top and bottom surfaces. This testing used a single bladed setup which proved satisfactory for the purpose of this project. The saw used can be seen below in the Figure 3.9.

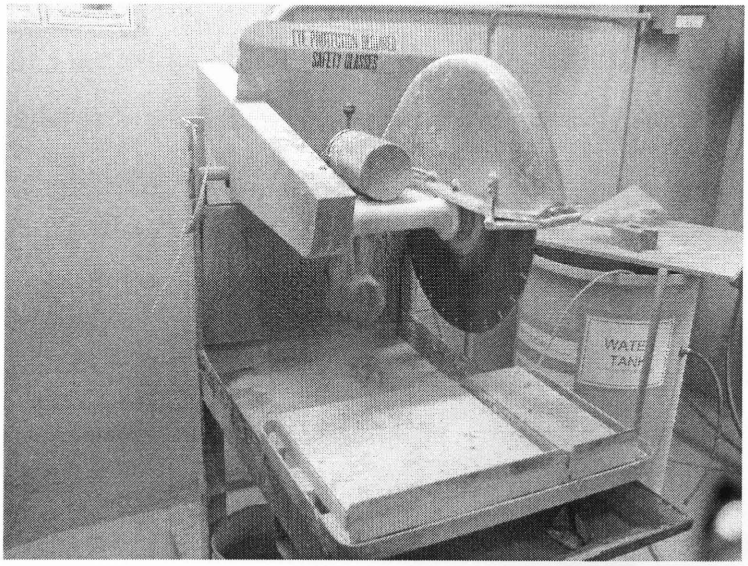


Figure 3.9: Diamond Blade Cutting Saw

The main criteria for a saw or cutting device which can be used for this testing has been listed below:

3.2.71 Blade Diameter

The cutting capacity of the blade has to be at least a few inches larger than the maximum specimen diameter to be cut. For example if you are cutting a 4 inch specimen the diameter of the blade would be 4" + 2" (clearance) x 2 = 12". Therefore, the clear cutting capability of a 12" blade is about +/- 4".

3.2.72 Blade Type

A high grade diamond blade with notched sections is recommended for this type of specimen cutting. The key to cutting asphalt specimens is to keep them as cool as possible throughout the cutting process. A notched blade allows for a cooler cut as the blade will draw more air and water during the cutting process. As an overheated blade would promote premature aging of the binder at the loading interfaces of the sample, the cooling capability of the blade allows for the reduction of this occurrence.

3.2.73 Cutting Process

A wet cutting process should be used. The samples should be cut with a diamond saw which is water cooled. The specimen should also be cut in a slow steady motion so as to avoid the excessive scoring of the sample ends. In some cases, samples that have uneven surfaces at their cut ends can be end-faced using a diamond grinder if necessary to obtain a smoother finish. Another approach to obtaining an even surface would be to cap the samples using a sulfur capping compound similar to that used for concrete specimens. It should be noted that when cutting a sample from a specimen, a tolerance greater than 3-4 mm from the extreme ends of the sample should be considered. This tolerance will reduce the presence of blade wash and reduce the chances of the sample being cut at an angle.

3.2.8 Aluminum Cylinder for Phase Angle Verification

The determination of the dynamic modulus and phase angle for any material relies heavily on the instrumentation used. In this research an MTS based system was used which is powered hydro-mechanically. Basically, a series of electrically controlled valves regulate the movement of high pressure hydraulic oil into and out of an actuator to apply the required force necessary to run a test. The accuracy and control of new hydraulic test systems is very good when compared to the older mechanical devices. For example, when the controller electrically tells the actuator to apply a force the actuator responds with virtually no lag. In other words when it is told the actuator responds almost instantly, in order for this to happen though the actuator needs to be calibrated. New test frames have many pieces of software to aid in calibration and set up. For example the MTS has a function called a PVC or peak valley compensator, this function puts the coarse peaks and valleys of the load and displacement in phase by using the load cell and the LVDT built into the frame.

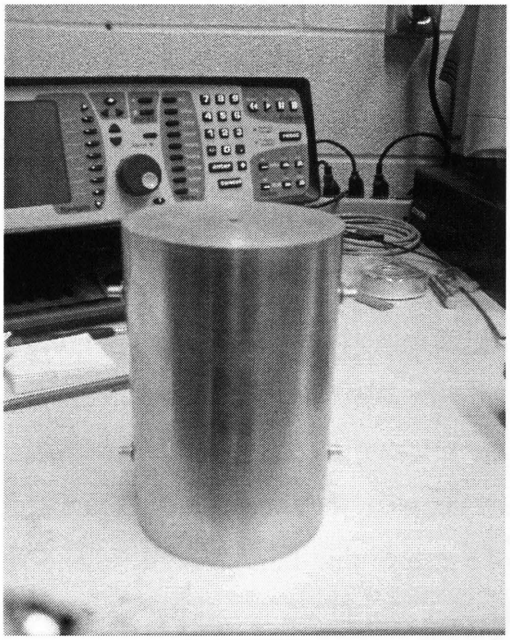


Figure 3.91: Aluminum Alloy Round for Phase Shift Calibration

The problem in this testing system lies in the fine tuning, as there is no real way to tune the device in terms of load and displacement in units smaller than those controlled by the built in LVDTs. To address this issue an aluminum alloy cylinder was fabricated and fitted with LVDT's just like its asphalt counterpart. This aluminum cylinder can be seen in Fig 3.91. Aluminum alloy was used for four main reasons as listed below:

1. Aluminum alloy is lightweight and easier to machine than brass or steel
2. Aluminum alloy is non-ferrous so it will not interfere with the magnetic field generated by the LVDT's used to determine displacement

3. Solid aluminum alloy is a metal which is very homogeneous when compared to other materials such as concrete or asphalt
4. Aluminum Alloy also has published values for its coefficients of thermal expansion as well as its moduli of rigidity and elasticity which are the base numbers used in the dynamic modulus & phase angle calibration of the test frame
5. At room temperature the T6-6061 aluminum alloy used in this research acts purely elastic which is essential in the calibration of the displacement and load sinusoidal waves

Unlike asphalt, at room temperature aluminum alloy is purely elastic as it has no known liquid characteristics at such a low temperature. The aluminum is tested just like the asphalt, it is put through a series of frequencial loads and the displacements are read by the LVDT's. The displacements are then verified from first principles using the selected metals natural properties. In asphalt there is a visible phase difference between the load and the axial strain vs. temperature as shown in Fig 3.91a. To assure that this phase difference is all attributed to the asphalts fluid characteristics aluminum is used to generate a similar graph shown in Fig 3.91b. The ideal difference can be seen in the phase shift. Theoretically aluminum alloy has a phase shift of zero where as asphalt has a shift greater than zero. If this is not the case of any reason then a calibration problem exists in the testing system which needs to be addressed before the next test.

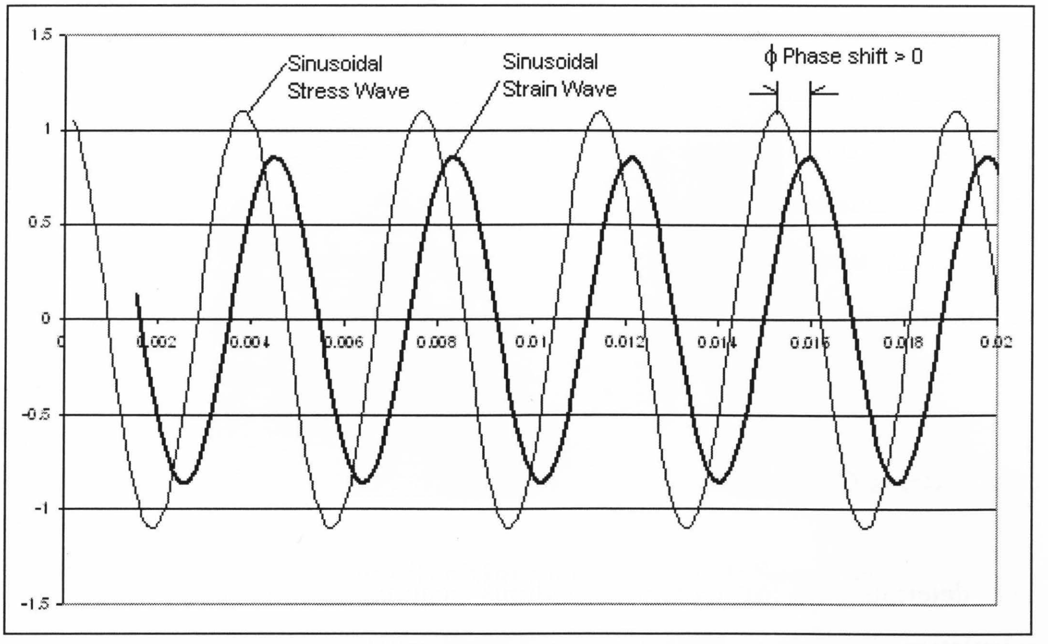


Figure 3.91a: Obtained Sinusoidal Stress and Strain Waves vs. Time in Asphalt (phase shift > 0)

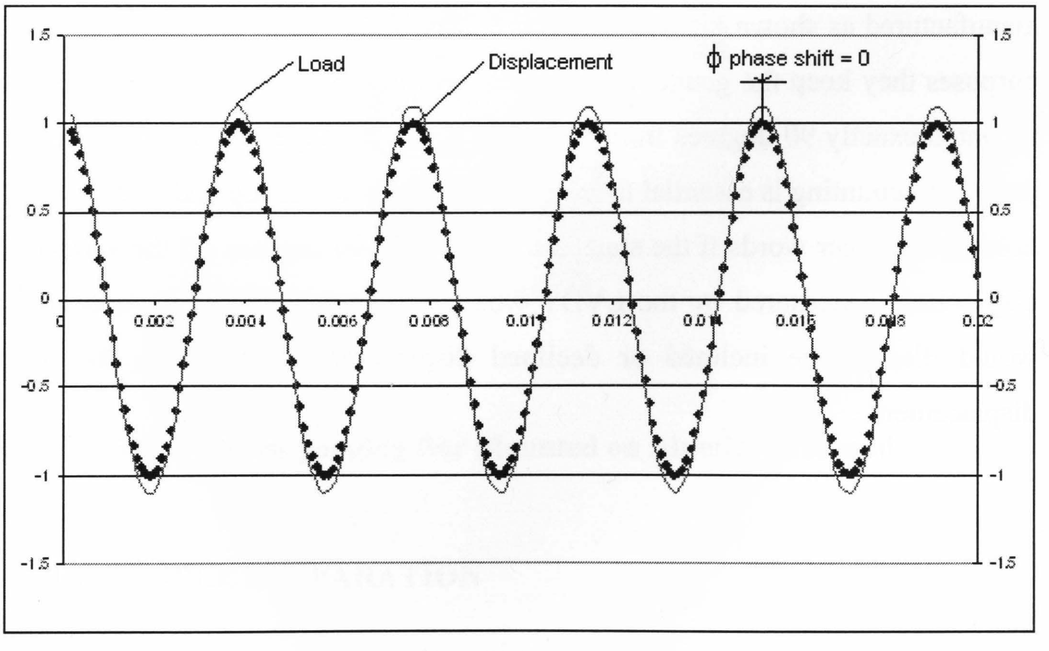
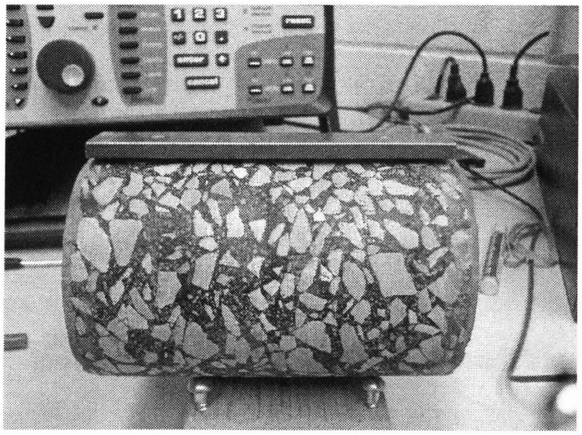


Figure 3.91b: Obtained Sinusoidal Stress and Strain Waves vs. Time in T6-6061 Aluminum Alloy (phase shift = 0)

This procedure was followed so that any phase shift noticed in the asphalt could be correlated to the materials characteristics rather than equipment error. The initial validation of the approximate linearity of a new LVDT can also be done using the aluminum round, as it provides a stable base for any needed adjustments, as well as rough base line figures to check the functionality of all the instruments.

3.2.9 Brass Gauging Bars

The determination of dynamic modulus requires certain calculations, these calculations include a constant value known as the gauge length. The gauge length is denoted as GL in the calculation tables in Appendix A and it refers to the distance between the two LVDT mounting studs. In this testing the gauge length is kept constant on all the samples tested. To achieve this, brass gauge bars were manufactured as shown in Fig 3.92a and 3.92b. These brass bars serve two main purposes they keep the gauge length constant while insuring the LVDT studs are mounted exactly 90 degrees from the surface. Both gauge length combined with precision mounting is essential to insure the linearity of the top and bottom LVDT holders. In other words if the studs are not exactly 90 degrees off the surface the displacement measured by the LVDT would not be accurate as the eccentricity would display the inclined or declined displacement rather than the actual displacement.



3.92a: Brass gauging Bar Mounted on Asphalt Specimen

3.92b: Brass gauging Bar Mounted on Aluminum Round

3.3 SPT SAMPLE PREPARATION

3.3.1 Size

Samples shall have a height to diameter ratio of a minimum of 1.5:1. Samples are usually 100 mm in diameter with a height of 150 mm. The samples used in this testing were +/- 94 mm in diameter and 141 mm in height since standard 4" coring bits yield an internal diameter between 93 mm and 95 mm not 100 mm like one would expect.

3.3.2 Aging

All samples were short term aged prior to compaction in a convection oven in accordance with the short term aging procedure outlined in AASHTO PP2. The samples were aged in a large capacity 27cu.ft chamber as shown in Figure 3.10 below.

Figure 3.10: Convection Oven used for aging

3.3.3 Compaction

All specimens were made using a gyratory compaction device and compacted at the compaction temperatures listed under ASTM D1561 using a device which conforms to ASTM D3387. The compaction device used was not a listed device which could produce samples which were 200 mm in height. For this reason the sample height recommended by NCHRP was used. The gyratory compaction device used for this testing was only capable of achieving suitable sample height with the help of some minor manual tamping. The HMA material was slowly tamped as it was loaded into the gyro to allow for the cover of the apparatus to close. The small manual effort applied has been assumed to be negligible as it is was only enough to insure the material is all level before the gyratory head is closed onto the sample. The gyratory compactor used was a Brovold and it is depicted in Figure 3.11. It has been assumed for the purpose of this project that the energy exerted during the manual tamping is very small when compared to the total compaction effort and thus has been considered negligible.

Figure 3.11: Brovold Gyratory Compactor

3.3.4 Freezing

All samples were produced and then allowed to cool to room temperature for one day before being placed in a freezer. The samples were kept in the freezer for a minimum of three hours before they were cored and end cut. This method was used to achieve higher quality cores, and better end cuts. It is understood for the purposes of this paper and has been accepted that by freezing the samples they should be treated as if they had undergone a single winter freeze thaw cycle. To minimize the damage to the samples during the freezing period the samples have been cooled to room temperature in desiccators and were kept away from any water before they were frozen. The samples were all frozen to -15°C and then cored and cut immediately to achieve the greatest benefit from the stiffness gained through the low temperature. The low temperature was achieved using an ordinary commercial freezer as shown in Figure 3.12.

Figure 3.12: Commercial Freezer

3.3.5 Diameter

The diameter of the specimens tested was measured along the mid height to insure they had a maximum run out of 1mm or less. Any specimens that had a run out of 2.5 mm or more were discarded. The diameter of the specimens are very important as they are the attachment surfaces for the LVDT holders, these surfaces can be kept smooth and unscarred by merely freezing the samples and reducing the feed rate of the coring and cutting process.

3.3.6 End Preparation

The ends of the samples were cut using a diamond saw while frozen to ensure very smooth surfaces. The samples were then capped using the conventional sulfur capping compound used for concrete applications. This compound was then sanded and burnished to a smooth finish using a belt sander. The specimens were then checked for specific tolerances. The height and waviness of the specimens was measured and kept within 0.5mm from the allotted measurement. The best way to check the surface tolerance is through the use of a dial gauge and stand or through the use of a machinists square and feeler gauges.

3.3.7 Air Void Content

The specimens were tested for air void content in accordance with AASHTO T296. A great deal of work was done to check the variation in the amount of air in the cored specimens. Any specimens which differed more that 0.5% were not tested. It should be noted for future reference that the amount of air voids in a core can be 1 to 1.5 % higher when compared to the amount of air voids in an entire puck.

3.3.8 Duplicates

Three samples were made for each test. In accordance with ASTM, one sample was used as a check for air void content, and two samples were used for dynamic testing purposes as outlined by NCHRP.

3.3.9 Sample Storage Before Testing

The samples were produced in various batches. As the samples were made they were cored, cut, capped and affixed with LVDT mounting hardware. The samples were then wrapped with cellophane and placed under vacuum until the time of testing. These precautions were implemented to avoid any premature aging problems. This process was used to protect the samples in the event they could not immediately be tested. This process would make it possible to keep a sample in a fresh state for up to two weeks after production.

3.4 SAMPLE PREPARATION AND ACCESSORIES

3.4.1 Sample Accessories (LVDT mounting hardware)

There are many types and shapes of hardware that have been used in past studies. The hardware used in this test was specially fabricated for this project. The mounting hardware consists of 4 LVDT holders which were machined out of ¼'' wall aluminum angle. These devices were modified two times through out this testing program due to their re-design. The first set of holders was made from steel which proved to be too heavy to accommodate high temperature testing. The second set was made from aluminum alloy which was very light, but generated far too much moment at the surface of the sample under testing conditions due to the distance of the LVDT from the surface of the sample. The conventional mounting method involved mounting a brass stud on the asphalt and then mounting the LVDT holders to that brass stud. Previous testing displayed the female end of the fastener or the nut mounted on the specimen. This set up started by mounting bolts to the specimen rather than brass studs, eventually when the brackets were redesigned a new aluminum low profile fastener was designed and implemented to insure that the LVDT's were mounted within 5mm of the surface of the sample. This was found to be less expensive and easier to replicate. Figure 3.13 shows the fasteners as they were produced. The LVDT holders shown in Fig 3.13 are very small and lightweight. The holders incorporate four brass set screws (two per fixture) used to affix the LVDT to the holder, and two machined adjustment screws (one per fixture) to perform necessary LVDT zero adjustments before calibration.

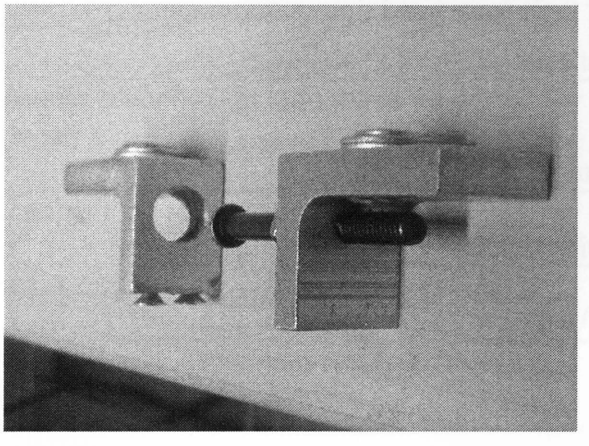


Figure 3.13: LVDT Fasteners

3.4.2 Time requirements

Simple performance testing is not as simple as the name would imply as all forms of testing require a great deal of time and precision. In fact simple performance testing actually takes longer that many other conventional testing procedures due to all the inherent precision tasks involved in the process. It is believed that unlike Marshall testing SUPERPAVE simple performance testing requires the use of expensive machines which need to be operated by properly trained personnel to ensure successful results. The time requirements for SPT can be broken down into three primary groups. These groups include, sample preparation, test preparation, and physical testing.

3.4.2.1 Sample Preparation

Sample preparation is among the longest and most tedious tasks associated with the testing of materials. A great deal of sample preparation time is consumed making samples which are never performance tested. For example numerous samples are produced for the determination and convergence toward the targeted number of air voids. These samples never make it to the load frame as they are melted down to find MRD & BRD. Table 1 lists the actions involved in sample preparation and their associated time requirements.

Table 1: Sample Activity Time Requirements

Lab Activities for Sample Preparation		Estimated Time Required
1	Acquire aggregates namely HL3 and HL8 and ship to downtown location	3-5 Days depending on season
2	Dry Aggregate (heavily dependant of facility)	3-5 Days
3	Sieve aggregate stockpile to desired sieve sizes for all mixes	4 Days
4	Batching approximately 7100g samples	30 min/each
5	Heat batched aggregate	6h+ to Overnight
6	Heating Binder (depends on amount of binder and oven type)	about 2h – 4h
7	Mixing (2stages)	10min
8	Short Term Aging	2h +/- 5min
9	Compaction (heavily dependant on specimen height and number of gyrations)	20-30min
10	Cool down for extraction (depends on lab temp)	1-2h
11	Cooling to room temp	6h+ to Overnight
12	Freezing (-5°F) or (-15°C)	3-5h to Overnight
13	Sawing and Coring	35-40min
14	Getting wet SSD weight	5 min
15	Drying Core	Overnight
16	Dry weight	2 min
17	Obtain MRD	25 min

3.4.2.2 Testing preparation

Testing preparation refers to the time consumed preparing the physical cored specimens for testing. Ideally once the samples are prepared they are ready for final simple performance testing. The steps involved in testing preparation have been summarized below in Table 2:

Table 2: Testing Activity Time Requirements

Lab Activities for Testing Preparation		Estimated Time Required
1	Glue on female type LVDT holder stud	5min per side
2	Curing Epoxy resin to 75% strength to insure stability	1h-4h
3	Mounting LVDT brackets	10min
4	Installing LVDT's in brackets	10min
5	Zeroing LVDT using an oscilloscope	20 min/ LVDT
6	Calibrating new zeroed range using feeler gauges (set max range to 0.022")	20 min/ LVDT
7	Purging nitrogen dewer and starting chamber	20min
8	Pre heating or cooling specimens and chamber	2-5h
9	Writing testing program for machine control	20min-1h
10	Powering up the hydraulic power unit and chiller	15min
11	Checking for specimen contact in chamber	5min

3.4.23 SPT Procedures

Simple Performance Testing covers a wide range of tests and applications. Table 3 illustrates three tests and their estimated time requirements. These tests do not have a total time frame as they can range from days to weeks.

Table 3: SPT Procedure Time Requirements

Simple Performance Testing Procedures		Estimated Time Required
1	Dynamic Modulus Testing for one temperature all frequencies	30min
2	Dynamic Modulus Testing for five temperatures all frequencies	3-5 days
3	Verification of Accuracy in Dynamic Response Using Aluminum Cylinder	30-180min

3.4.3 Pre-Test Sample Conditioning

In most testing environments samples need to be conditioned. Samples are conditioned for many reasons. The two main reasons for conditioning a sample are to achieve stable temperature throughout the specimen, as well as to ensuring the specimen is capable of producing a good response wave to frequencial loading. The amount of time it takes to achieve temperature stability has many controlling variables. These variables include specimen size, chamber heating and coolong capacity as well as sample surface area. It is important in sample testing that a sample be the same temperature through out, this can be assured through the use of an internal temperature probe placed in a dummy sample. In the testing involved in this paper samples were brought to their desired set points in 2 to 5 hours. In general the larger the temperature gradient between the desired specimen temperature and room temperature the longer the conditioning would take. It should also be noted that cooling samples often takes longer than heating. In the research presented samples were cooled using liquid nitrogen, although this is a significantly more expensive operating experience, liquid nitrogen is capable of cooling samples much quicker than conventional refrigeration devices. The specimens in this paper were conditioned by applying a small repeated load at the highest testing frequency selected for each testing category for a minimum of 200 cycles before testing.

3.4.4 Sample Preparation Weigh Cards

The samples prepared for this paper have been made to strictly conform to the following weigh cards which have been generated with the help of past research and optimization from (Fung 2007.). The samples were prepared by sieving all the materials to each of their respective sizes rather than generally scooping materials in the fine spectrum during the weighing process. All materials were precisely sieved and weighed to ensure reproducibility as well as to insure that any material performance differences discovered between each of the mineral fillers was caused by the fillers and not by any mix variability. The specific values can be found for each of the five mixes in the weigh cards shown in Tables 4 - 7.

Table 4: Control Mix Weigh Card

Filler Type	Control						
Aggregates:	HL3&8						
Sieve (mm)	**25.4**	**19**	**12.7**	**9.5**	**4.75**		
% passing	100	97.8	89.1	72.8	47.9		
% of total AGG mass	0	2.2	8.7	16.3	24.9		
Mass Used(g)	0	149.5	591.1	1107.5	1691.9		
			HL3&8	52.1	%		
Aggregates:	Trap rock						
Sieve (mm)	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**	**PAN**
% passing	43.1	30.7	20	10.6	5.2	4	
%of tot AGG mass	4.8	12.4	10.7	9.4	5.4	1.2	4.0
Mass Used (g)	326.1	842.5	727.0	638.7	366.9	81.5	271.8
			Trap rock		43.9	%	Dust 4 %

Materials in (g)			
7100	Total for all materials		
305.3	AC	% AC of total	4.3
6794.7	AGG		
271.8	DUST	%Dust of Agg	4

Table 5: Fly Ash Type C Mix Weigh Card

Filler Type	Fly Ash Type C						
Aggregates:	HL3&8						
Sieve (mm)	**25.4**	**19**	**12.7**	**9.5**	**4.75**		
% passing	100	97.8	89.1	72.8	47.9		
% of total AGG mass	0	2.2	8.7	16.3	24.9		
Mass Used(g)	0	150.0	593.0	1111.0	1697.2		
			HL3&8	52.1	%		
Aggregates:	Trap rock						
Sieve (mm)	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**	**PAN**
% passing	43.1	30.7	20	10.6	5.2	4	
%of tot AGG mass	4.8	12.4	10.7	9.4	5.4	1.2	4.0
Mass Used (g)	327.2	845.2	729.3	640.7	368.1	81.8	272.6
			Trap rock		43.9	%	Dust 4 %

Materials in (g)			
7100	Total for all materials		
284	AC	% AC of total	4
6816	AGG		
272.6	DUST	%Dust of Agg	4

Table 6: Fly Ash Type F Mix Weigh Card

Filler Type	Fly Ash Type(F)					
Aggregates:	HL3&8					
Sieve (mm)	**25.4**	**19**	**12.7**	**9.5**	**4.75**	
% passing	100	97.8	89.1	72.8	47.9	
% of total AGG mass	0	2.2	8.7	16.3	24.9	
Mass Used(g)	0	150.0	593.0	1111.0	1697.2	
			HL3&8	52.1	%	

Aggregates:	Trap rock						
Sieve (mm)	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**	**PAN**
% passing	43.1	30.7	20	10.6	5.2	4	
%of tot AGG mass	4.8	12.4	10.7	9.4	5.4	1.2	4.0
Mass Used (g)	327.2	845.2	729.3	640.7	368.1	81.8	272.6
			Trap rock		43.9	%	Dust 4 %

Materials in (g)			
7100	Total for all materials		
284	AC	% AC of total	4
6816	AGG		
272.6	DUST	%Dust of Agg	4

Table 7: Portland Cement Mix Weigh Card

Mineral Filler: Portland Cement

Aggregates:	HL3&8				
Sieve (mm)	**25.4**	**19**	**12.7**	**9.5**	**4.75**
% passing	100	97.8	89.1	72.8	47.9
% of total AGG mass	0	2.2	8.7	16.3	24.9
Mass Used(g)	0	149.2	589.9	1105.2	1688.3
			HL3&8	52.1	%

Aggregates:	Trap rock						
Sieve (mm)	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**	**PAN**
% passing	43.1	30.7	20	10.6	5.2	4	
%of tot AGG mass	4.8	12.4	10.7	9.4	5.4	1.2	4.0
Mass Used (g)	325.5	840.8	725.5	637.4	366.1	81.4	271.2
			Trap rock		43.9	%	Dust 4 %

Materials in (g)

7100	Total for all materials		
319.5	AC	% AC of total	4.5
6780.5	AGG		
271.2	DUST	%Dust of Agg	4

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Mix Properties

In this program three specimens were made for each mix, one was used to assure compliance in terms of air void content and the other two were tested to determine dynamic modulus values. Table 8 shows the specific mix characteristics of the samples tested in terms of MRD, BRD and Air Voids. The values listed in Table 8 are the average of two specimens. The test variation between the two test samples was small.

Table 8 Mix Properties

	AC (%)	BRD	MRD	Average Air Void (%)	Puck Reference	ACCEPATBLE RANGE (4.0 %+/- 0.5)
Control	4.5	2.477	2.584	4.14	3CON	ACCEPTABLE
Portland Cement	4.7	2.481	2.582	3.92	3PC	ACCEPTABLE
Fly Ash (Type C)	4.2	2.483	2.588	4.05	3FAC	ACCEPTABLE
Fly Ash (Type F)	4.2	2.471	2.578	4.15	3FAF	ACCEPTABLE

4.1.1 Results from SPT Testing

The experimental results are listed in Tables 9 through 12. These tables depict the test temperatures as well as the corresponding mixture performance as observed through each materials unique dynamic moduli. Mixture performance and dynamic moduli were correlated as the hardness of an HMA mixture relates to its integrity regarding fatigue and rutting. High dynamic modulus values were obtained from the testing of harder mixes at lower temperatures. These results imply that the sample may be less capable of resisting fatigue. Where as, lower dynamic moduli from soft mixes portrays an HMA sample that may be more inclined to resist fatigue.

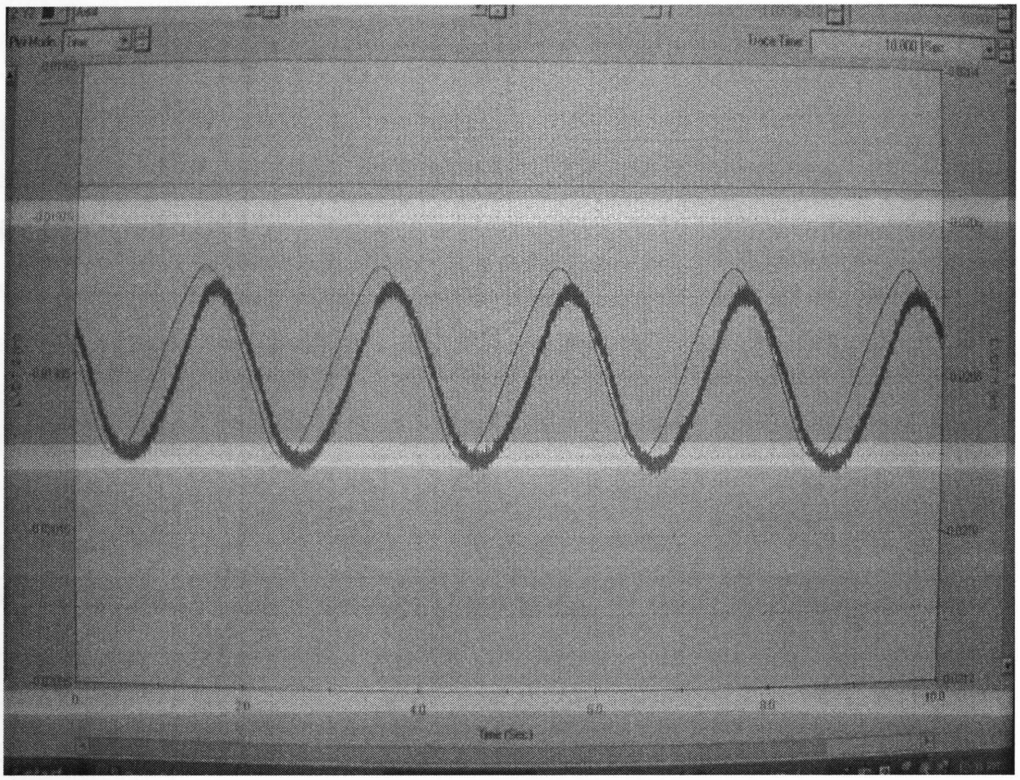
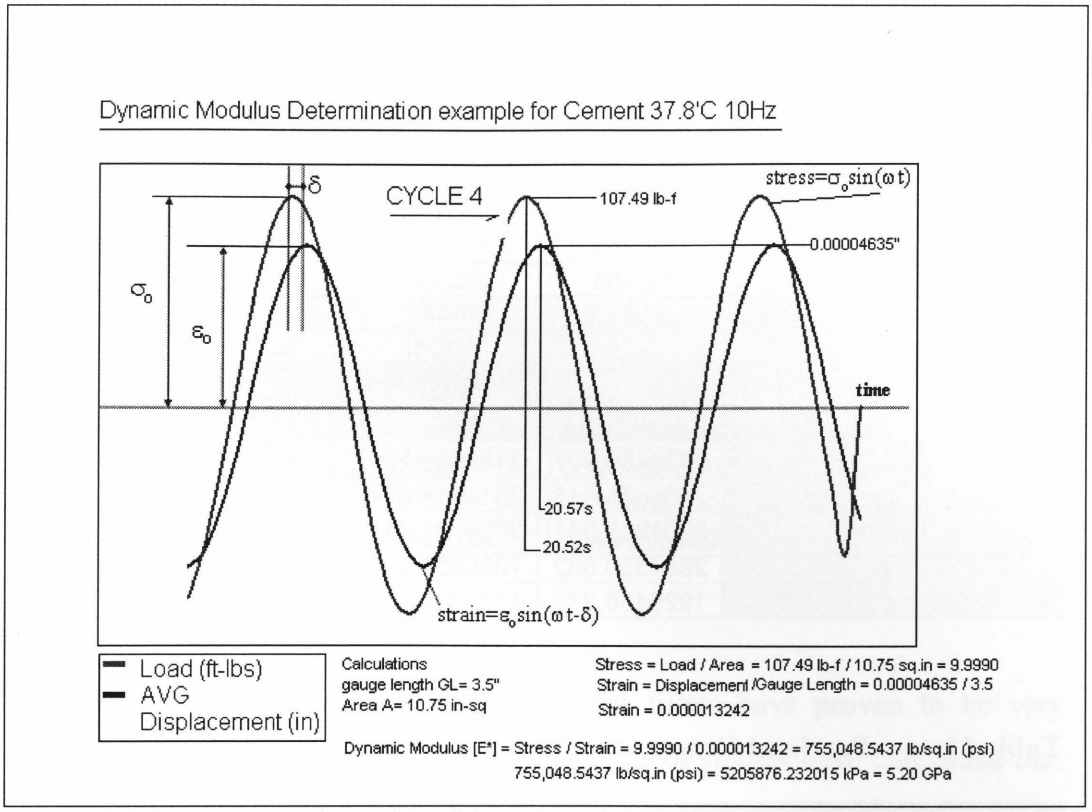


Figure 4.1: Load vs. AVG displacement

The testing pursued for the purposes of this paper has produced a waveform very similar to the ideal wave shown in Figure 4.2. This figure depicts the load and the average LVDT displacement reading for one of the test specimens. Fig 4.1 depicts the actual monitor showing the impulse generated during an actual test. The load is shown as the thin red line in lb-ft and the displacement is the thicker red line displayed in inches. The scales have been adjusted to yield adequate visual demonstrative performance.



*Please refer to Appendix A for a bigger version of these calculations.

Figure 4.2 Solved Example for One Data Set

Table 9: Control Mix Dynamic Moduli

Mineral Filler Type (CONTROL)	Frequency (Hz)	Dynamic Modulus (GPa) -9°C	4.4°C	21.1°C	37.8°C
Bypass Dust Passing 0.75µm Sieve	10	20.029	16.047	4.914	3.108
	5	18.428	14.404	4.197	2.665
	1	15.075	13.019	3.722	2.336
	0.5	13.791	12.360	3.311	2.100
	0.1	9.694	9.454	2.637	1.852
	Frequency (Hz)	Dynamic Modulus (psi) -9°C	4.4°C	21.1°C	37.8°C
	10	2906936.497	2328977.323	713185.343	451155.959
	5	2674561.577	2090555.982	609160.059	386792.304
	1	2188015.216	1889555.410	540223.912	339042.859
	0.5	2001580.476	1793928.569	480571.126	304771.270
	0.1	1406962.565	1372123.033	382676.606	268770.750

Table 10: Fly Ash Type F Mix Dynamic Moduli

Mineral Filler Type	Frequency (Hz)	Dynamic Modulus (GPa)			
		-9°C	4.4°C	21.1°C	37.8°C
Fly Ash Type F Passing 0.75µm Sieve	*10*	27.784	21.913	9.620	5.302
	5	25.263	18.009	7.985	3.597
	1	22.401	14.261	5.750	2.445
	0.5	19.873	11.683	4.192	1.454
	0.1	13.294	7.104	3.216	1.091
	Frequency (Hz)	**Dynamic Modulus (psi)**			
		-9°C	4.4°C	21.1°C	37.8°C
	10	4032459.987	3180358.226	1396204.977	769482.410
	5	3666675.646	2613814.074	1158937.761	522002.237
	1	3251219.047	2069781.419	834599.460	354847.937
	0.5	2884350.532	1695657.410	608424.895	211007.903
	0.1	1929488.270	1031080.949	466713.241	158390.423

Table 11: Portland Cement Mix Dynamic Moduli

Mineral Filler Type	Frequency (Hz)	Dynamic Modulus (GPa)			
		-9°C	4.4°C	21.1°C	37.8°C
Type 10 Portland Cement Passing 0.75µm Sieve	*10*	28.790	20.561	7.835	5.184
	5	25.981	18.130	7.217	3.865
	1	23.460	15.938	6.763	2.564
	0.5	20.408	12.872	5.943	2.026
	0.1	17.203	11.897	5.080	1.459
	Frequency (Hz)	**Dynamic Modulus (psi)**			
		-9°C	4.4°C	21.1°C	37.8°C
	10	4178488.680	2984111.662	1137220.524	752410.043
	5	3770880.060	2631404.692	1047510.190	560936.651
	1	3404929.107	2313151.461	981532.766	372170.634
	0.5	2961906.303	1868275.394	862540.683	294029.333
	0.1	2496859.461	1726699.117	737368.436	211778.071

Table 12: Fly Ash Type C Mix Dynamic Moduli

Mineral Filler Type	Frequency (Hz)	Dynamic Modulus (GPa)			
		-9°C	4.4°C	21.1°C	37.8°C
FLY ASH Type C Passing 0.75µm sieve	*10*	27.6260	19.7936	9.0136	4.5133
	5	25.7096	17.6230	5.4624	3.6109
	1	22.5342	14.5115	4.5668	3.3752
	0.5	19.8363	11.8134	3.7999	2.2324
	0.1	13.0399	10.6785	2.5297	1.6485
	Frequency (Hz)	**Dynamic Modulus (psi)**			
		-9°C	4.4°C	21.1°C	37.8°C
	10	4009574.504	2872794.762	1308213.167	655046.539
	5	3731436.285	2557757.652	792796.779	524076.554
	1	3270571.138	2106162.336	662812.282	489865.994
	0.5	2878992.185	1714575.900	551505.418	324010.112
	0.1	1892576.338	1549851.782	367152.115	239263.603

According to earlier research, certain mineral fillers have proven to be very beneficial in particular environments. A number of studies have concluded that fly ash makes a very good "asphalt extender", in particular according to (Suheihani 1986). Tables 11 and 13 show an increased modulus through a variety of temperatures. Unfortunately, the high dynamic values associated with the cooler temperatures imply the possibility of the material having fatigue problems. Generally, the more rigid the material at high temperature, the better it will resist rutting; and the more flexible at low temperature, the better it would resist fatigue. In this case, the two fly ash mixes show high modulus values in the cold side of the spectrum and thus would mean they may have low performance in terms of fatigue.

Tables 9 through 12 shows the results for the entire range of mineral fillers used. It appears that Type F Fly ash demonstrated higher dynamic modulus values when compared to Type C in colder temperatures and Type C yields higher dynamic modulus values in warmer temperatures. This phenomenon would lead to the belief that Type C fly ash will perform better in HMA in terms of rutting resistance. Higher dynamic modulus values at high frequency low temperature were observed in Type F when compared to Type C. This leads to believe that Type C fly ash may be a better option than Class F in terms of fatigue.

4.1.3 Mix Properties

The results of this report were consistent with those done earlier at Ryerson. According to (Fung, 2008) the material performance displayed through the dynamic modulus testing conducted here appears to be in harmony of the TSR values performed by (Fung, 2008). According to Fig 4.4 below the substitution of fly ash leads in terms of tensile strength followed by Portland cement and tailed by the control mix. This increase in tensile strength can be seen through the increase present in the dynamic modulus values shown in Tables 10 to 13.

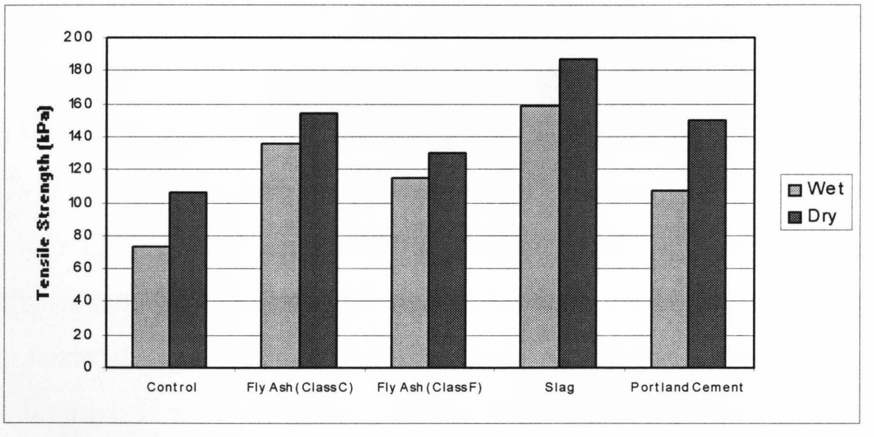


Figure 4.3 Indirect Tensile Strength Test Results (Fung, 2008).

Similar to the indirect tensile strengths shown in Fig 4.3 the TSR values shown here in Fig 4.4 also show an increase in performance when fly ash is used over both the control sample as well as the Portland cement sample. It appears that the TSR values indicate a slightly higher strength in Type F fly ash, where as in the dynamic modulus values it appears Type F fly ash yields slightly lower values in colder temperatures. However the results showed Fly Ash enhances the moisture susceptibility as well as the dynamic modulus of the mixtures tested when compared to bag house dust.

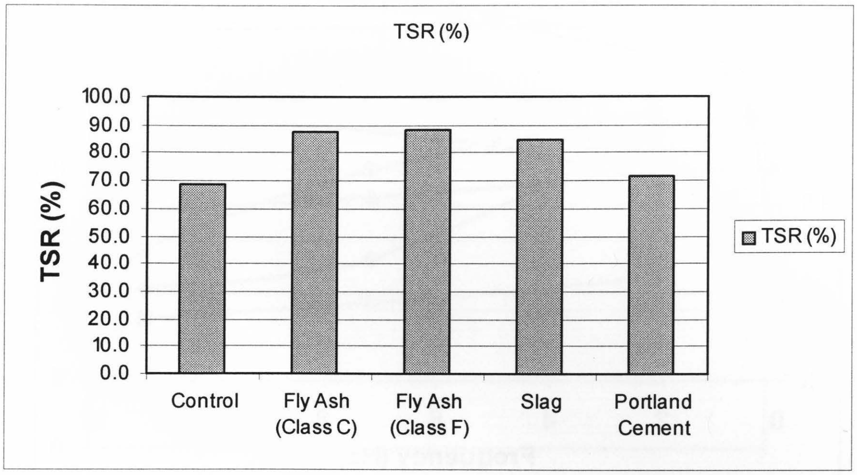


Figure 4.4: Tensile Strength Ratio Test Results (Fung,2008).

4.1.4 Temperature and Frequency Effects on Filler Type

Visco-elastic materials can be greatly affected by variations in temperature. As asphalt is visco-elastic it follows certain trends. For example, the warmer an HMA material the softer it is and the colder the stiffer. This phenomenon is visible in the following graphs. The graphs show the affect of mineral fillers on the performance of each unique specimen under temperature change. Figures 4.5 to 4.9 show the individual performance of each mix in different temperatures in terms of their dynamic moduli.

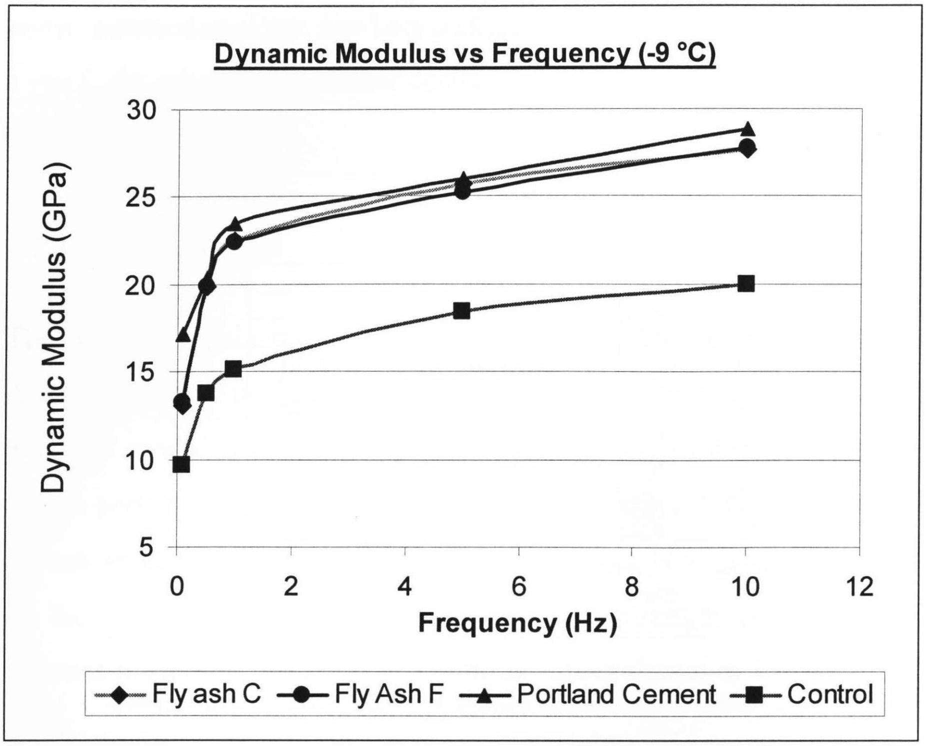


Fig 4.5: Dynamic Modulus vs. Frequency (-9°C)

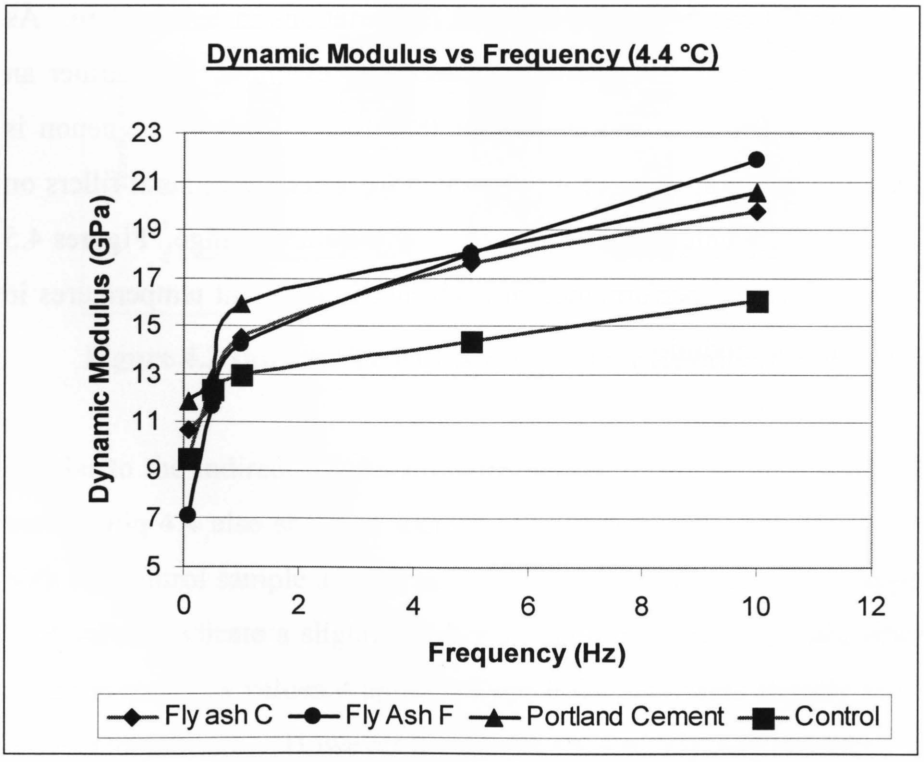


Fig 4.6: Dynamic Modulus vs. Frequency (4.4°C)

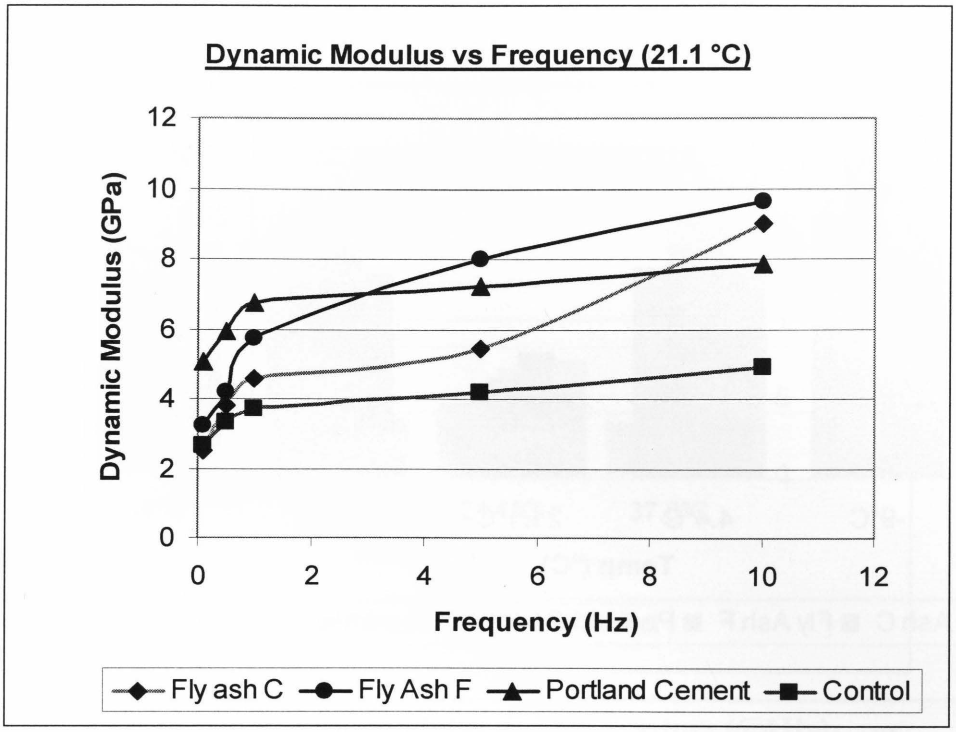


Fig 4.7: Dynamic Modulus vs. Frequency (21.1°C)

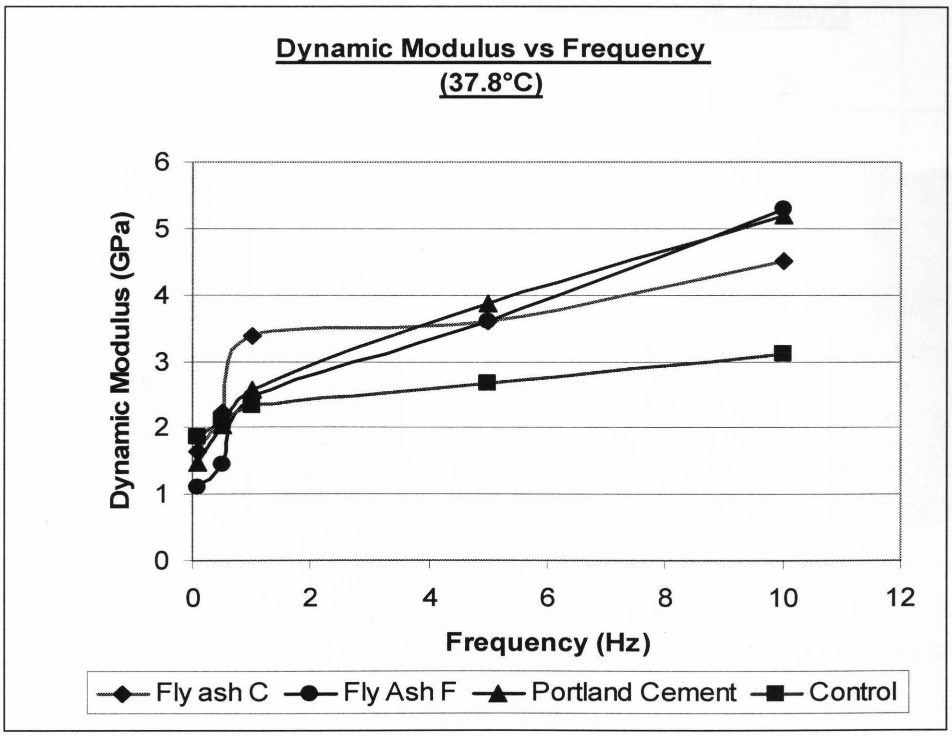


Fig 4.8: Dynamic Modulus vs. Frequency (37.8°C)

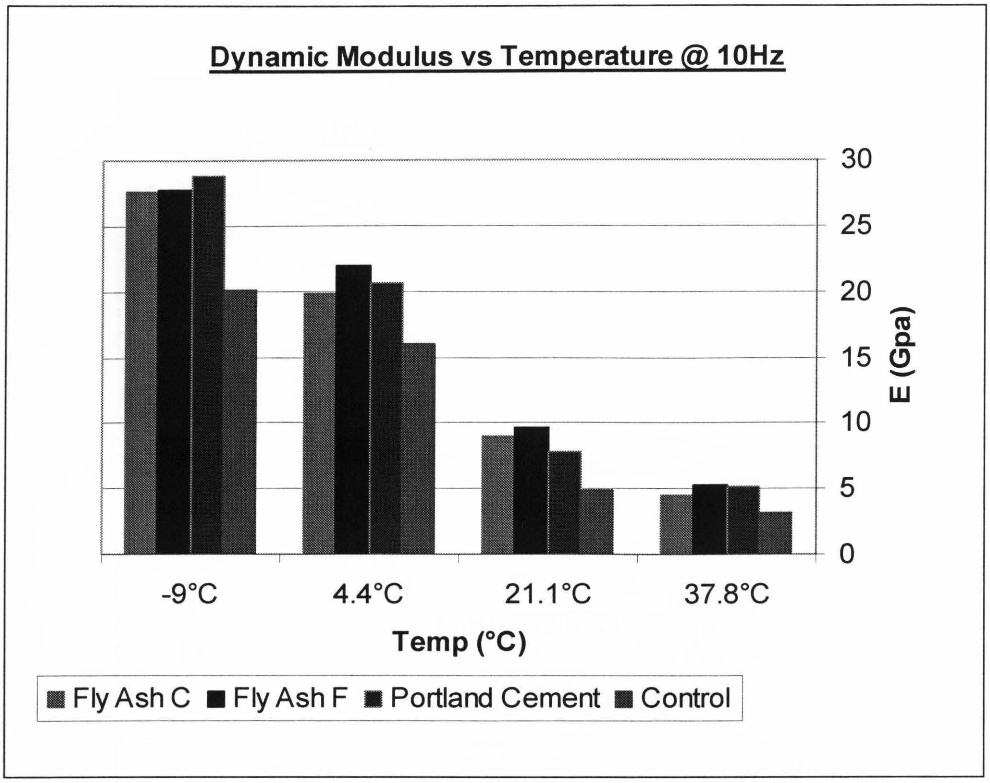


Fig 4.9: Dynamic Modulus vs. Temperature (@10Hz)

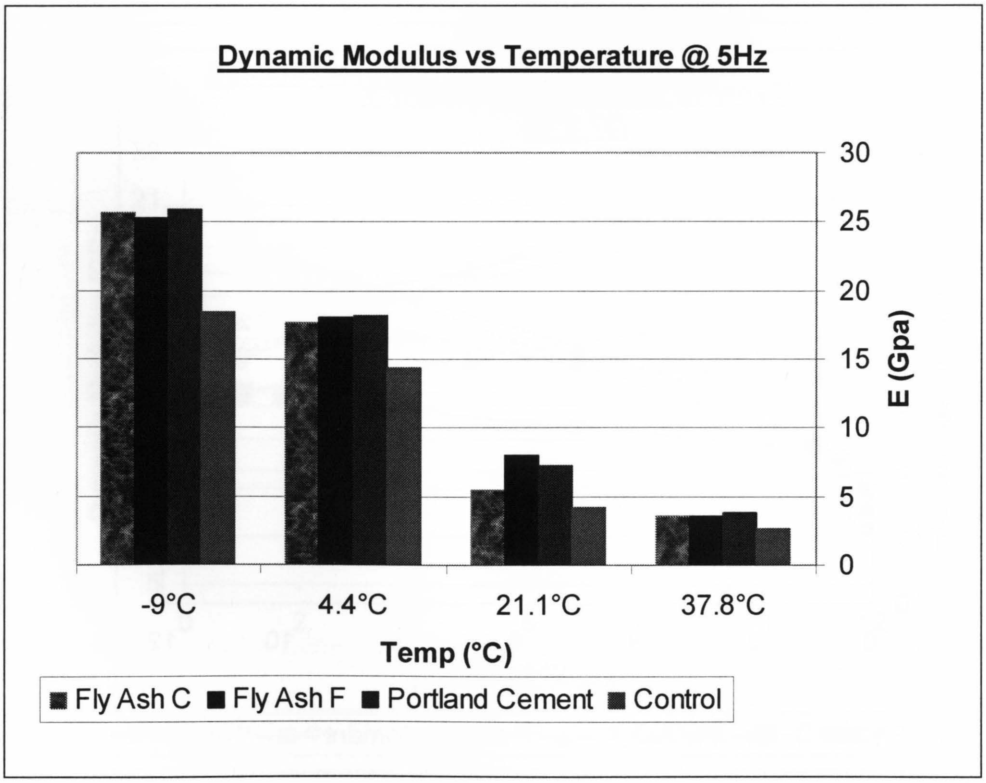


Fig 4.10: Dynamic Modulus vs. Temperature (@5Hz)

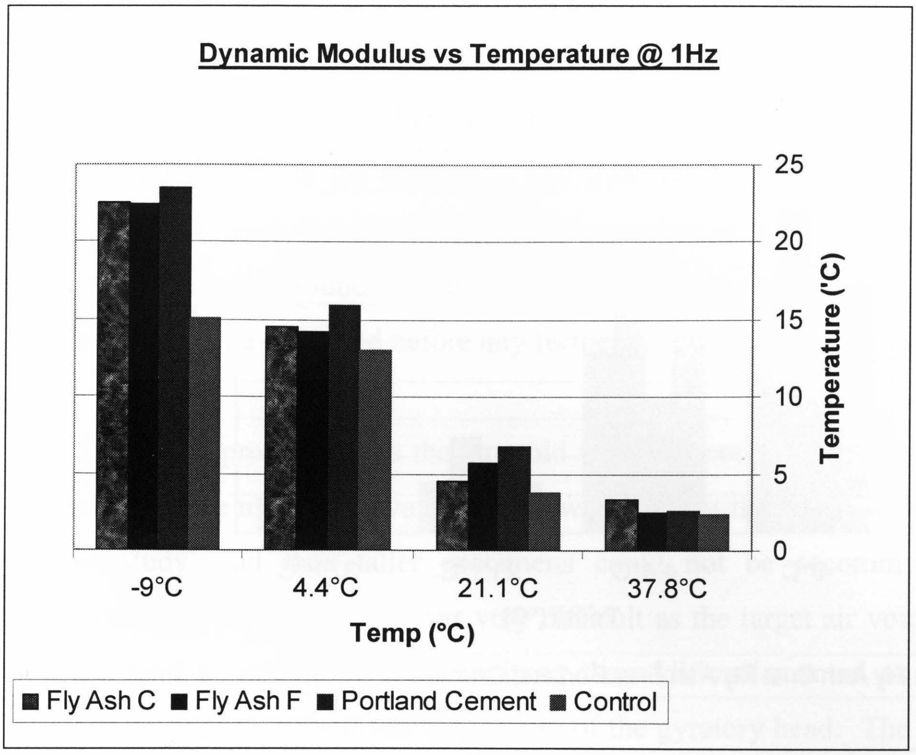


Fig 4.11: Dynamic Modulus vs. Temperature (@1Hz)

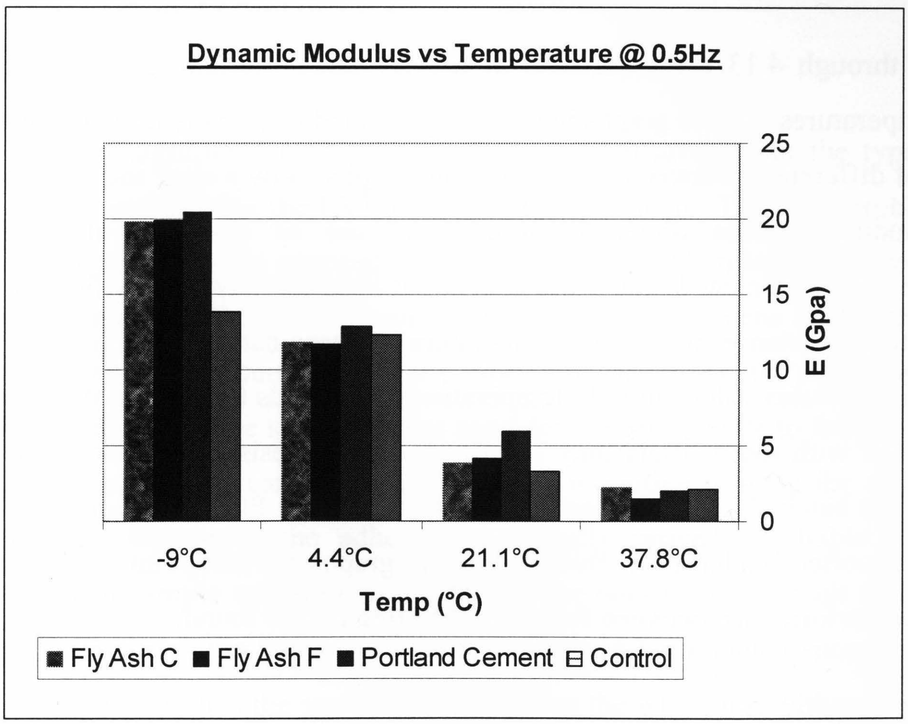


Fig 4.12: Dynamic Modulus vs. Temperature (@0.5Hz)

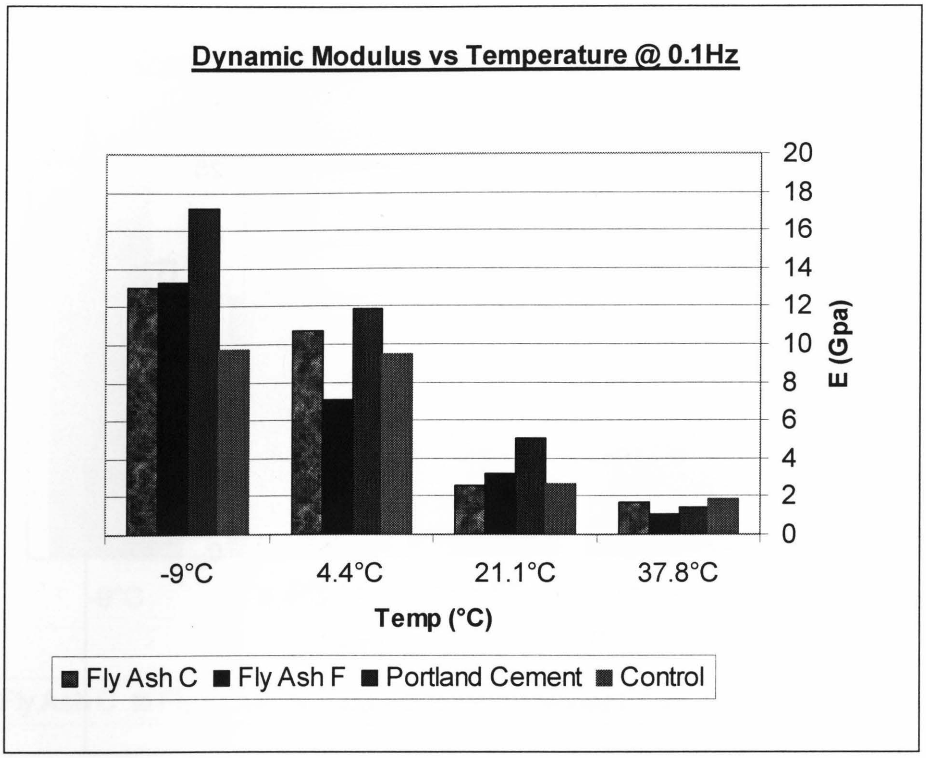


Fig 4.13: Dynamic Modulus vs. Temperature (@0.1Hz)

Figures 4.9 through 4.13 are depictions of the Dynamic Modulus readings at different temperatures. These graphs have been generated to visually demonstrate core material differences between each mix. The graphs show a clear increase in dynamic modulus values obtained through the use of Fly Ash at high temperatures. These elevated values are a sign that Fly Ash may be beneficial in terms of rutting resistance in extreme temperatures. These bar graphs also show high dynamic modulus values in cold temperatures, this lends to the idea that the materials made with these fillers may not be capable of resisting fatigue. The HMA materials batched in this research were all made with PG 58-28 binder, so the use of a softer binder may shift these bar graphs to the point where a compromised performance between fatigue and rutting can be found.

4.2 Limitations of Test Set-up

Dynamic testing is often hindered by many small problems due to the unpredictable nature of the equipment and materials. This testing program and the equipment used for this study have experienced the same material and equipment limitation found by other researchers in the past. In this study many problems had to be corrected before any further research could continue.

The first of the problems was the Brovold Gyratory compaction device used for this testing. Due to limited availability, it was inherent that the system be applied to this study, and thus taller specimens could not be accommodated. The compaction process in general was very difficult as the target air void content of 4% was hard to achieve without applying the additional manual or mechanical compaction needed to facilitate the closure of the gyratory head. The mechanical compaction was performed by only one researcher which removed some variability; however some natural inconsistencies can never be completely eliminated.

Another significant problem with this program arose from the type of glue or epoxy used to affix the LVDT studs to the specimen. The main problem with the epoxy resin was the materials failure rate. The problem initially became apparent when many of the studs began breaking off the specimens before testing. Even when allowed to cure for longer periods than necessary, the adhesive holding the studs affixed to the specimen was considerably susceptible to failure. In addition, regardless of the care applied during the mounting process for ensuring not to damage the studs, the adhesive continually proved unreliable as the bonds between sample and stud would fail. The only positive result from the use of adhesives was the fact that if the LVDT could be mounted successfully without losing a stud, then the sample would survive the whole test without a stud failure.

Comparatively speaking, the dynamic values obtained in this paper were deemed acceptable as they were similar to values obtained from related conducted research. According to the publications presented at the annual conference of the transportation association of Canada in 2006 by Ludomir Uzarowski and his group, the dynamic modulus values obtained therein for SP19 were very similar to the values obtained for the control mix used for this study.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

Based on the investigations conducted in this study, the conclusions are summarized as follows:

1. The test set-up developed to determine dynamic modulus values of HMA materials was successful in attaining dynamic modulus values for the mixtures tested in this program.
2. An inexpensive alternative was found for measuring axial deformations in the HMA specimens through the design and fabrication of specific LVDT holders and mounting hardware.
3. High temperature sag attenuation issues were addressed in this system through the modification of mounting hardware and the LVDT's used.
4. The production of specimens using the available gyratory compaction equipment was successful in attaining the required amount of air voids in each specimen.
5. A suitable method was developed for restraining and coring gyratory compacted HMA pucks to their desired dimension was successful.
6. The development of suitable end cutting process was successfully devised and applied to the specimens tested in this study.
7. The effect mineral fillers on asphalt mixtures was successfully demonstrated through the observed changes in dynamic modulus values obtained herein.
8. There was a noticeable increase in the dynamic modulus values obtained from testing the materials containing fly ash fillers.
9. Similar to the Fly Ash, Portland cement performed well in terms of rutting but it exhibited high dynamic modulus values at low temperature and high frequency which may lead to diminished performance in terms of fatigue.

The test set-up was developed to determine dynamic modulus values of HMA materials. This set-up was successful in attaining dynamic modulus values for each mix design tested as the values obtained are reasonable when compared to values published by NCHRP report 465. An inexpensive alternative was found for the measurement of axial deformations in the HMA specimens through the in house design and fabrication of specific LVDT holders and mounting hardware. Commercially available displacement transducers specified for this test are available but at a much higher cost.

The modification of the linear variable displacement transducers used in this project made it possible to run all necessary testing at low cost. The modifications to the purchased components included the design of new holders which mounted only few mm away from the surface of the sample. The LVDT springs and collars were also removed. These changes were made to negate the effect of the spring force during high temperature displacement measurements. The preparation of asphalt specimens using the current compaction equipment was successful in attaining the required amount of air voids in each specimen as shown in this report. The development of a suitable in house method for coring gyratory compacted HMA pucks to their desired dimension was successful through the design and fabrication of a unique puck holding device. Both end cutting and coring were greatly aided through the freezing of the sample prior to machining.

The effect of each mineral fillers attributes was successfully demonstrated through the observed changes in dynamic modulus values obtained herein. From the graphs it is apparent that fly ash performs best in terms of rutting resistance. Howerever, fly ash's performance in terms of fatigue requires further investigations as it resulted in an increase in the dynamic modulus of the mixtures at low temperature.

5.1 Recommendations for Future Research

In the future, certain key areas not covered here should be analyzed. For example this testing program did not include very high frequencies, namely the 25Hz band. This frequency band was not used as some researchers have experienced stability problems and error due to micro vibration in their samples. Similarly, very high temperatures were not tested. The highest temperature tested here was below 40°C although some believe that the testing should continue up to 54.4 °C. High temperatures were not considered here as they would further complicate the development process by introducing sag attenuation. With the addition of a higher range of temperatures masters curves can be generated to help further distinguish and differentiate each material, as well as allow for temperature superposition to theoretically predict the materials response without having to test it. By performing more tests and generating maters curves there is a possibility that the pavement thickness can be decreased without compromising strength or structural integrity through the use of mineral fillers. Now that all the essential work has been done in establishing a frame and testing its capability many more materials can be tested as fillers. There are now numerous possibilities for testing different materials now that the ground work has been laid. All that remains is the production of samples and the testing using the newly available test set-up.

The main problem with the asphalt mixtures tested in this research was their low resistance to fatigue due to their high rigidity in cold temperatures. This disadvantage may possibly be overcome through the use of softer binders which would soften up the system so that it may perform better in terms of fatigue. Also, it is apparent from the literature review that the fineness of the mineral filler has a large effect on its performance. It would be beneficial in future research to possibly substitute mineral fillers with different gradations to evaluate the effect of fineness on the material performance.

5.2 Possible Program Changes and Improvements

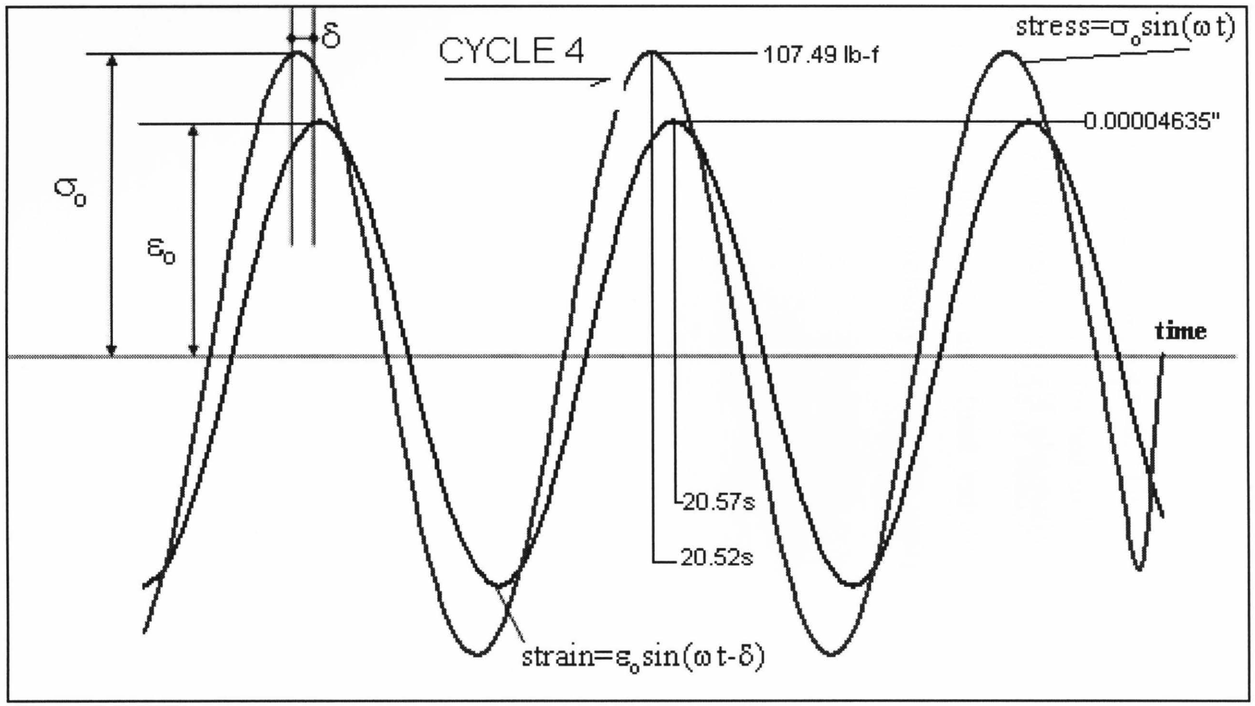
It would be beneficial for future research in this area to obtain a compaction device capable of producing taller specimens. In this report a shorter sample height was used in accordance with NCHRP test protocol. It should be known that to remain versatile a facility should have the ability to create taller specimens which will allow for conformance with ASTM and AASHTO standards as well.

Data analysis was a significant part of this research. The identification of the last five loading cycles as well as the data collection had to be done manually which was very tedious. Dynamic modulus software is readily available to identify, record, as well as plot the data points and final values for each test. The acquisition of such software would probably shorten the analysis time.

Appendix - A

Sample Experimental Results

Dynamic Modulus Determination example for Cement 37.8'C 10Hz



Load (ft-lbs)
AVG Displacement (in)

Calculations
gauge length GL= 3.5"
Area A= 10.75 in-sq

Stress = Load / Area = 107.49 lb-f / 10.75 sq.in = 9.9990
Strain = Displacement /Gauge Length = 0.00004635 / 3.5
Strain = 0.000013242

Dynamic Modulus [E*] = Stress / Strain = 9.9990 / 0.000013242 = 755,048.5437 lb/sq.in (psi)
755,048.5437 lb/sq.in (psi) = 5205876.232015 kPa = 5.20 GPa

Cement
(-9 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00008183	1041.4406	26.57536	26.57308	0.002279	8.11E-05	1038.38
	0.00008091	1038.3851	26.67725	26.67448	0.002768		
	0.00008091	1037.9147	26.77376	26.774904	0.00114		
	0.00008091	1036.0004	26.88298	26.875978	0.006999		
	0.00008091	1038.1372	26.97689	26.947611	0.029278		
5	0.00009121	1042.218	46.13705	46.129395	0.007652	9.12E-05	1056.39
	0.00009121	1040.4429	46.34343	46.32959	0.013836		
	0.00009121	1041.547	46.53272	46.529461	0.003254		
	0.00009121	1040.7267	46.73861	46.730145	0.008464		
	0.00009121	1041.9926	46.93278	46.928062	0.004719		
1	0.00010112	1040.6821	62.55827	62.554203	0.004067	1.01E-04	1057.55
	0.00010112	1046.1841	63.5739	63.538414	0.035481		
	0.00010112	1040.903	64.5739	64.558434	0.015464		
	0.00010112	1043.6071	65.57341	65.549644	0.023766		
	0.00010112	1041.3528	66.57632	66.55682	0.0195		
0.5	0.00011672	1045.7644	88.06543	88.072594	0.007164	1.17E-04	1061.84
	0.00011672	1049.4213	90.10938	90.072594	0.036781		
	0.00011672	1046.3206	92.12451	92.070969	0.053543		
	0.00011672	1047.1211	94.13574	94.074875	0.060867		
	0.00011672	1045.585	96.15609	96.074875	0.081215		
0.1	0.00013891	1050.4585	182.4141	182.14063	0.27343	1.39E-04	1065.29
	0.00013891	1046.9055	192.1908	192.15186	0.03891		
	0.00013891	1051.6189	202.4564	202.12402	0.33237		
	0.00013891	1050.7767	212.4883	212.19678	0.2915		
	0.00013891	1051.6792	222.6141	222.18408	0.43003		

10Hz		
Cycle #	P(lb-f)	A(in2)
1	1041.4406	10.75
2	1038.3851	10.75
3	1037.9147	10.75
4	1036.0004	10.75
5	1038.1372	10.75

Δ	GL
0.00008183	3.5
0.00008091	3.5
0.00008091	3.5
0.00008091	3.5
0.00008091	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	96.8781953	2.3381E-05	4143467	28.548485
2	96.5939628	2.31168E-05	4178527	28.79005
3	96.5502047	2.31168E-05	4176634	28.777008
4	96.3721302	2.31168E-05	4168931	28.723933
5	96.5709023	2.31168E-05	4177529	28.783177

Kpa	log KPa
2.9E+07	7.45558
2.9E+07	7.45924
2.9E+07	7.45905
2.9E+07	7.45824
2.9E+07	7.45914

5Hz		
Cycle #	P(lb-f)	A(in2)
1	1057.218	10.75
2	1055.4429	10.75
3	1056.547	10.75
4	1055.7267	10.75
5	1056.9926	10.75

Δ	GL
0.00009121	3.5
0.00009121	3.5
0.00009121	3.5
0.00009121	3.5
0.00009121	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.3458605	2.60598E-05	3773852	26.00184
2	98.1807349	2.60598E-05	3767516	25.958182
3	98.2834419	2.60598E-05	3771457	25.985337
4	98.2071349	2.60598E-05	3768529	25.965162
5	98.324893	2.60598E-05	3773047	25.996296

E (Kpa)	logE (Kpa)
2.6E+07	7.415
2.6E+07	7.41427
2.6E+07	7.41473
2.6E+07	7.41439
2.6E+07	7.41491

1HZ		
Cycle #	P(lb-f)	A(in2)
1	1055.6821	10.75
2	1061.1841	10.75
3	1055.903	10.75
4	1058.6071	10.75
5	1056.3528	10.75

Δ	GL
0.00010112	3.5
0.00010112	3.5
0.00010112	3.5
0.00010112	3.5
0.00010112	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.202986	2.88923E-05	3398929	23.418618
2	98.7148	2.88923E-05	3416643	23.540671
3	98.2235349	2.88923E-05	3399640	23.423518
4	98.4750791	2.88923E-05	3408346	23.483504
5	98.2653767	2.88923E-05	3401088	23.433496

E (Kpa)	logE (Kpa)
2.3E+07	7.36956
2.4E+07	7.37182
2.3E+07	7.36965
2.3E+07	7.37076
2.3E+07	7.36984

0.5Hz		
Cycle #	P(lb-f)	A(in2)
1	1060.7644	10.75
2	1064.4213	10.75
3	1061.3206	10.75
4	1062.1211	10.75
5	1060.585	10.75

Δ	GL
0.00011672	3.5
0.00011672	3.5
0.00011672	3.5
0.00011672	3.5
0.00011672	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.6757581	3.33488E-05	2958899	20.386815
2	99.0159349	3.33488E-05	2969100	20.457097
3	98.7274977	3.33488E-05	2960451	20.397504
4	98.8019628	3.33488E-05	2962683	20.412889
5	98.6590698	3.33488E-05	2958399	20.383367

E (Kpa)	logE (Kpa)
2E+07	7.30935
2E+07	7.31084
2E+07	7.30958
2E+07	7.3099
2E+07	7.30928

0.1Hz		
Cycle #	P(lb-f)	A(in2)
1	1065.4585	10.75
2	1061.9055	10.75
3	1066.6189	10.75
4	1065.7767	10.75
5	1066.6792	10.75

Δ	GL
0.00013891	3.5
0.00013891	3.5
0.00013891	3.5
0.00013891	3.5
0.00013891	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	99.1124186	3.96885E-05	2497260	17.206119
2	98.781907	3.96885E-05	2488932	17.148741
3	99.2203628	3.96885E-05	2499979	17.224858
4	99.1420186	3.96885E-05	2498005	17.211258
5	99.2259721	3.96885E-05	2500121	17.225832

E (Kpa)	logE (Kpa)
1.7E+07	7.23568
1.7E+07	7.23423
1.7E+07	7.23616
1.7E+07	7.23581
1.7E+07	7.23618

Cement
(4.4 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00008566	785.79	22.31779	22.266928	0.050862	8.6E-05	785.136
	0.00008566	785.59	22.42057	22.367676	0.052898		
	0.00008566	785.97	22.52148	22.467123	0.054361		
	0.00008566	783.98	22.61947	22.568523	0.050944		
	0.00008566	784.35	22.7194	22.667645	0.051757		
5	0.00009930	802.5485	41.9266	41.921715	0.004883	9.9E-05	802.5449
	0.00009930	803.2217	42.13135	42.122234	0.009114		
	0.00009930	802.0156	42.32585	42.323406	0.002442		
	0.00009930	802.2455	42.53158	42.522137	0.009441		
	0.00009930	802.693	42.72575	42.721844	0.003906		
1	0.00011322	804.7286	58.4069	58.351074	0.055828	0.00011	804.3579
	0.00011322	803.7513	59.41504	59.351074	0.063965		
	0.00011322	804.1942	60.42611	60.347332	0.078777		
	0.00011322	806.0897	61.41488	61.337078	0.077801		
	0.00011322	803.026	62.42416	62.353844	0.070312		
0.5	0.00014096	809.1213	84.01058	83.86377	0.146812	0.00014	808.8949
	0.00014096	809.0932	86.00603	85.863121	0.142906		
	0.00014096	809.1033	88.01937	87.861984	0.157387		
	0.00014096	808.1333	90.02116	89.977121	0.044043		
	0.00014096	809.0234	92.04607	91.860519	0.185547		
0.1	0.00015334	812.8214	178.8163	177.99577	0.82048	0.00015	813.2234
	0.00015334	812.6185	188.7661	188.02719	0.73892		
	0.00015334	813.3356	198.9063	197.96989	0.93636		
	0.00015334	814.413	208.8467	207.94238	0.9043		
	0.00015334	812.9284	218.9839	218.00163	0.98226		

10Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	785.79	10.75		0.00008566	3.5
2	785.59	10.75		0.00008566	3.5
3	785.97	10.75		0.00008566	3.5
4	783.98	10.75		0.00008566	3.5
5	784.35	10.75		0.00008566	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.096744	2.45E-05	2986597	20.577656
2	73.07814	2.45E-05	2985837	20.572418
3	73.113488	2.45E-05	2987281	20.582369
4	72.928372	2.45E-05	2979718	20.530257
5	72.962791	2.45E-05	2981124	20.539946

Kpa	log KPa
2.1E+07	7.313396
2.1E+07	7.313285
2.1E+07	7.313495
2.1E+07	7.312394
2.1E+07	7.312599

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	802.54846	10.75		0.00009930	3.5
2	803.22174	10.75		0.00009930	3.5
3	802.01563	10.75		0.00009930	3.5
4	802.24554	10.75		0.00009930	3.5
5	802.69299	10.75		0.00009930	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	74.655671	2.84E-05	2631416	18.130459
2	74.718301	2.84E-05	2633624	18.14567
3	74.606105	2.84E-05	2629669	18.118422
4	74.627492	2.84E-05	2630423	18.123616
5	74.669115	2.84E-05	2631890	18.133724

E (Kpa)	logE (Kpa)
1.8E+07	7.258409
1.8E+07	7.258773
1.8E+07	7.25812
1.8E+07	7.258245
1.8E+07	7.258487

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	804.72858	10.75		0.00011322	3.5
2	803.75128	10.75		0.00011322	3.5
3	804.19421	10.75		0.00011322	3.5
4	806.08966	10.75		0.00011322	3.5
5	803.026	10.75		0.00011322	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	74.858473	3.23E-05	2314217	15.944957
2	74.767561	3.23E-05	2311407	15.925593
3	74.808764	3.23E-05	2312681	15.934369
4	74.985085	3.23E-05	2318131	15.971926
5	74.700093	3.23E-05	2309321	15.911222

E (Kpa)	logE (Kpa)
1.6E+07	7.202623
1.6E+07	7.202096
1.6E+07	7.202335
1.6E+07	7.203357
1.6E+07	7.201704

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	809.12134	10.75		0.00014096	3.5
2	809.0932	10.75		0.00014096	3.5
3	809.10327	10.75		0.00014096	3.5
4	808.1333	10.75		0.00014096	3.5
5	809.02338	10.75		0.00014096	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	75.267101	4.03E-05	1868798	12.876021
2	75.264484	4.03E-05	1868733	12.875573
3	75.26542	4.03E-05	1868757	12.875733
4	75.175191	4.03E-05	1866516	12.860298
5	75.257989	4.03E-05	1868572	12.874462

E (Kpa)	logE (Kpa)
1.3E+07	7.109782
1.3E+07	7.109767
1.3E+07	7.109772
1.3E+07	7.109251
1.3E+07	7.109729

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	812.82135	10.75		0.00015334	3.5
2	812.61853	10.75		0.00015334	3.5
3	813.33557	10.75		0.00015334	3.5
4	814.41296	10.75		0.00015334	3.5
5	812.92841	10.75		0.00015334	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	75.611288	4.38E-05	1725846	11.891076
2	75.592421	4.38E-05	1725415	11.888109
3	75.659123	4.38E-05	1726937	11.898598
4	75.759345	4.38E-05	1729225	11.91436
5	75.621247	4.38E-05	1726073	11.892642

E (Kpa)	logE (Kpa)
1.2E+07	7.075221
1.2E+07	7.075113
1.2E+07	7.075496
1.2E+07	7.076071
1.2E+07	7.075278

Cement
(21.1 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00000676	283.2143	20.5197	20.507324	0.012371	6.76E-06	282.6051
	0.00000676	282.4868	20.61816	20.608236	0.009928		
	0.00000676	283.4516	20.71696	20.707684	0.009277		
	0.00000676	282.8185	20.81722	20.807617	0.009604		
	0.00000676	281.0541	20.91732	20.909018	0.0083		
5	0.00000760	283.4243	40.18278	40.164063	0.018718	7.6E-06	293.4526
	0.00000760	282.8526	40.38786	40.367027	0.020832		
	0.00000760	282.4704	40.58561	40.562988	0.022625		
	0.00000760	284.094	40.785	40.761395	0.023601		
	0.00000760	284.4217	40.99138	40.962078	0.029297		
1	0.00000843	284.725	58.67709	58.351074	0.326012	8.43E-06	304.8568
	0.00000843	284.848	59.66602	59.351074	0.314942		
	0.00000843	285.8111	60.69011	60.347332	0.342773		
	0.00000843	284.8592	61.69352	61.337078	0.356445		
	0.00000843	284.0409	62.67871	62.353844	0.324867		
0.5	0.00000973	289.4008	82.30322	82.120445	0.182778	9.73E-06	309.2206
	0.00000973	289.3117	84.29134	84.115562	0.175782		
	0.00000973	290.8142	86.26547	86.094078	0.171387		
	0.00000973	289.1966	88.33529	88.124512	0.210777		
	0.00000973	287.3796	90.31999	90.148277	0.171715		
0.1	0.00001158	295.5146	187.1919	186.22754	0.96435	1.16E-05	314.599
	0.00001158	295.346	197.1797	196.27637	0.90332		
	0.00001158	294.2157	207.225	206.20215	1.02281		
	0.00001158	294.62	217.214	216.257	0.95704		
	0.00001158	293.2988	227.2551	226.36882	0.88623		

10Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	283.21426	10.75		0.00000676	3.5
2	282.48682	10.75		0.00000676	3.5
3	283.4516	10.75		0.00000676	3.5
4	282.81848	10.75		0.00000676	3.5
5	281.05414	10.75		0.00000676	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.34551256	1.93E-06	13644874	94.0131836
2	26.27784372	1.93E-06	13609827	93.7717093
3	26.3675907	1.93E-06	13656309	94.0919688
4	26.30869581	1.93E-06	13625806	93.8818041
5	26.14457116	1.93E-06	13540803	93.2961301

Kpa	log KPa
94013184	7.973189
93771709	7.972072
94091969	7.973553
93881804	7.972581
93296130	7.969864

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	293.42429	10.75		0.00000760	3.5
2	292.85257	10.75		0.00000760	3.5
3	292.47037	10.75		0.00000760	3.5
4	294.09402	10.75		0.00000760	3.5
5	294.42169	10.75		0.00000760	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	27.29528279	2.17E-06	12568910	86.5997907
2	27.24209953	2.17E-06	12544420	86.4310561
3	27.20654605	2.17E-06	12528049	86.3182555
4	27.35758326	2.17E-06	12597598	86.7974515
5	27.38806419	2.17E-06	12611634	86.8941584

E (Kpa)	logE (Kpa)
86599791	7.937517
86431056	7.93667
86318256	7.936103
86797452	7.938507
86894158	7.938991

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	304.72495	10.75		0.00000843	3.5
2	304.84796	10.75		0.00000843	3.5
3	305.81113	10.75		0.00000843	3.5
4	304.85922	10.75		0.00000843	3.5
5	304.04086	10.75		0.00000843	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	28.34650698	2.41E-06	11773298	81.1180241
2	28.35794977	2.41E-06	11778051	81.1507695
3	28.44754698	2.41E-06	11815264	81.4071661
4	28.35899721	2.41E-06	11778486	81.1537669
5	28.2828707	2.41E-06	11746868	80.9359188

E (Kpa)	logE (Kpa)
81118024	7.909117
81150769	7.909293
81407166	7.910663
81153767	7.909309
80935919	7.908141

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	309.40076	10.75		0.00000973	3.5
2	309.31165	10.75		0.00000973	3.5
3	310.81415	10.75		0.00000973	3.5
4	309.19662	10.75		0.00000973	3.5
5	307.37964	10.75		0.00000973	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	28.78146605	2.78E-06	10356520	71.3564219
2	28.77317674	2.78E-06	10353537	71.3358706
3	28.91294419	2.78E-06	10403830	71.6823889
4	28.76247628	2.78E-06	10349687	71.3093415
5	28.59345488	2.78E-06	10288867	70.8902954

E (Kpa)	logE (Kpa)
71356422	7.853433
71335871	7.853308
71682389	7.855412
71309341	7.853146
70890295	7.850587

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	315.51459	10.75		0.00001158	3.5
2	315.34598	10.75		0.00001158	3.5
3	314.21573	10.75		0.00001158	3.5
4	314.62003	10.75		0.00001158	3.5
5	313.29883	10.75		0.00001158	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	29.35019442	3.31E-06	8874172	61.1430467
2	29.33450977	3.31E-06	8869430	61.1103721
3	29.22937023	3.31E-06	8837640	60.8913428
4	29.26697953	3.31E-06	8849012	60.9696914
5	29.14407721	3.31E-06	8811852	60.7136583

E (Kpa)	logE (Kpa)
61143047	7.786347
61110372	7.786115
60891343	7.784556
60969691	7.785114
60713658	7.783286

Cement
(37.8 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00004635	107.49	20.5319	20.521973	0.009929	4.6E-05	107.1218
	0.00004635	107.289	20.63558	20.62435	0.01123		
	0.00004635	106.988	20.73438	20.724936	0.009439		
	0.00004635	107.412	20.83398	20.824545	0.009439		
	0.00004635	106.43	20.93311	20.92627	0.006835		
5	0.00006631	103.985	40.20052	40.178875	0.021648	6.6E-05	114.2454
	0.00006631	104.729	40.39974	40.380371	0.019371		
	0.00006631	104.633	40.59522	40.582848	0.012367		
	0.00006631	104.277	40.80534	40.786133	0.019207		
	0.00006631	103.604	40.99235	40.983398	0.008954		
1	0.00010777	103.272	56.68604	56.626141	0.059894	0.00011	123.1953
	0.00010777	102.99	57.69125	57.63916	0.052086		
	0.00010777	102.883	58.68181	58.616051	0.065754		
	0.00010777	103.102	59.71754	59.631348	0.086192		
	0.00010777	103.73	60.71501	60.61491	0.100098		
0.5	0.00014151	106.517	82.17773	82.288574	0.11084	0.00014	127.7933
	0.00014151	105.23	84.1823	84.255859	0.073562		
	0.00014151	105.985	86.16863	86.306808	0.138183		
	0.00014151	105.31	88.18523	88.290527	0.105301		
	0.00014151	105.924	90.11556	90.274094	0.158532		
0.1	0.00019949	104.848	106.9883	106.3833	0.60498	0.0002	129.7586
	0.00019949	104.018	117.2069	116.54167	0.6652		
	0.00019949	105.494	127.0112	126.65446	0.35677		
	0.00019949	105.721	136.8094	136.48618	0.32324		
	0.00019949	103.712	147.2655	146.60075	0.66472		

10Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	107.48969	10.75		0.00004635	3.5
2	107.28922	10.75		0.00004635	3.5
3	106.98802	10.75		0.00004635	3.5
4	107.41166	10.75		0.00004635	3.5
5	106.43047	10.75		0.00004635	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.99904093	1.3E-05	754994	5.2019085
2	9.98039256	1.3E-05	753585.9	5.1922068
3	9.95237395	1.3E-05	751470.3	5.1776304
4	9.99178233	1.3E-05	754445.9	5.1981322
5	9.90050884	1.3E-05	747554.1	5.1506481

Kpa	log KPa
5201908	6.716163
5192207	6.715352
5177630	6.714131
5198132	6.715847
5150648	6.711862

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	113.98477	10.75		0.00006631	3.5
2	114.72874	10.75		0.00006631	3.5
3	114.63306	10.75		0.00006631	3.5
4	114.27662	10.75		0.00006631	3.5
5	113.60381	10.75		0.00006631	3.5

Cycle #	σ=P/A	ε =Δ/GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	10.6032344	1.9E-05	559657	3.8560366
2	10.6724409	1.9E-05	563309.8	3.8812046
3	10.6635405	1.9E-05	562840	3.8779678
4	10.6303833	1.9E-05	561089.9	3.8659097
5	10.5677963	1.9E-05	557786.5	3.8431489

E (Kpa)	logE (Kpa)
3856037	6.586141
3881205	6.588967
3877968	6.588604
3865910	6.587252
3843149	6.584687

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	123.27248	10.75		0.00010777	3.5
2	122.98989	10.75		0.00010777	3.5
3	122.88288	10.75		0.00010777	3.5
4	123.10165	10.75		0.00010777	3.5
5	123.72961	10.75		0.00010777	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	11.4672074	3.1E-05	372403.8	2.5658621
2	11.44092	3.1E-05	371550.1	2.5599801
3	11.4309656	3.1E-05	371226.8	2.5577527
4	11.4513163	3.1E-05	371887.7	2.5623063
5	11.5097312	3.1E-05	373784.8	2.5753771

E (Kpa)	logE (Kpa)
2565862	6.409233
2559980	6.408237
2557753	6.407859
2562306	6.408631
2575377	6.410841

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	128.51718	10.75		0.00014151	3.5
2	127.22974	10.75		0.00014151	3.5
3	127.98494	10.75		0.00014151	3.5
4	127.31049	10.75		0.00014151	3.5
5	127.92416	10.75		0.00014151	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	11.9550865	4E-05	295694.8	2.0373375
2	11.8353247	4E-05	292732.7	2.0169282
3	11.9055758	4E-05	294470.3	2.0289001
4	11.8428363	4E-05	292918.5	2.0182083
5	11.8999219	4E-05	294330.4	2.0279365

E (Kpa)	logE (Kpa)
2037337	6.309063
2016928	6.30469
2028900	6.307261
2018208	6.304966
2027937	6.307054

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	129.84775	10.75		0.00019949	3.5
2	129.0177	10.75		0.00019949	3.5
3	130.49399	10.75		0.00019949	3.5
4	130.72139	10.75		0.00019949	3.5
5	128.71228	10.75		0.00019949	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	12.0788605	5.7E-05	211923.5	1.4601532
2	12.0016465	5.7E-05	210568.8	1.4508192
3	12.1389758	5.7E-05	212978.3	1.4674202
4	12.1601293	5.7E-05	213349.4	1.4699773
5	11.9732353	5.7E-05	210070.3	1.4473847

E (Kpa)	logE (Kpa)
1460153	6.164398
1450819	6.161613
1467420	6.166554
1469977	6.167311
1447385	6.160584

Fa©
(-9 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-ft)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	8.32E-05	1020.9	20.5928	20.599121	0.00635	8.3E-05	1025.21
	8.32E-05	1027.28	20.6982	20.697592	0.00065		
	8.32E-05	1027.28	20.7988	20.797527	0.0013		
	8.32E-05	1021.88	20.8983	20.898926	0.00065		
	8.32E-05	1028.7	20.9935	20.99707	0.00358		
5	8.97E-05	1024.62	40.2668	40.262695	0.00407	9E-05	1027.47
	8.97E-05	1030.22	40.4614	40.460289	0.00114		
	8.97E-05	1027.04	40.6668	40.661785	0.00505		
	8.97E-05	1031.18	40.8669	40.859539	0.00732		
	8.97E-05	1024.28	41.0674	41.062828	0.00455		
1	0.000102	1026.1	56.6636	56.664391	0.00082	0.0001	1023.79
	0.000102	1026.14	57.6964	57.667809	0.0286		
	0.000102	1020.17	58.7085	58.688805	0.01969		
	0.000102	1020.3	59.7246	59.688805	0.0358		
	0.000102	1026.26	60.7646	60.66618	0.09847		
0.5	0.000116	1021.2	82.2616	82.216309	0.04525	0.00012	1022.38
	0.000116	1021.32	84.2842	84.216965	0.06722		
	0.000116	1027.04	86.279	86.172363	0.10661		
	0.000116	1015.33	88.3063	88.236328	0.06999		
	0.000116	1027	90.3351	90.171715	0.16341		
0.1	0.000176	1027	196.974	196.34392	0.6302	0.00018	1025.46
	0.000176	1021.17	207.779	206.48503	1.29363		
	0.000176	1027	216.627	216.31967	0.30713		
	0.000176	1026.88	218.757	218.2693	0.4875		
	0.000176	1025.24	221.563	220.985	0.578		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1020.905	10.75		0.00008325	3.5
2	1027.278	10.75		0.00008325	3.5
3	1027.284	10.75		0.00008325	3.5
4	1021.879	10.75		0.00008325	3.5
5	1028.698	10.75		0.00008325	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	94.96788	2.4E-05	3992741	27.509986
2	95.56078	2.4E-05	4017669	27.681736
3	95.56134	2.4E-05	4017692	27.681898
4	95.05853	2.4E-05	3996552	27.536246
5	95.69279	2.4E-05	4023219	27.719976

Kpa	log KPa
2.8E+07	7.43949
2.8E+07	7.44219
2.8E+07	7.4422
2.8E+07	7.4399
2.8E+07	7.44279

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1024.617	10.75		0.00008965	3.5
2	1030.222	10.75		0.00008965	3.5
3	1027.044	10.75		0.00008965	3.5
4	1031.18	10.75		0.00008965	3.5
5	1024.285	10.75		0.00008965	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	95.31323	2.6E-05	3721077	25.638221
2	95.83464	2.6E-05	3741433	25.778475
3	95.53901	2.6E-05	3729892	25.698955
4	95.92371	2.6E-05	3744911	25.802434
5	95.28228	2.6E-05	3719869	25.629896

E (Kpa)	logE (Kpa)
2.6E+07	7.40889
2.6E+07	7.41126
2.6E+07	7.40992
2.6E+07	7.41166
2.6E+07	7.40875

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1026.096	10.75		0.00010192	3.5
2	1026.137	10.75		0.00010192	3.5
3	1020.174	10.75		0.00010192	3.5
4	1020.295	10.75		0.00010192	3.5
5	1026.264	10.75		0.00010192	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	95.45078	2.9E-05	3277927	22.584918
2	95.45457	2.9E-05	3278057	22.585814
3	94.89994	2.9E-05	3259011	22.454583
4	94.91116	2.9E-05	3259396	22.457237
5	95.46644	2.9E-05	3278465	22.588623

E (Kpa)	logE (Kpa)
2.3E+07	7.35382
2.3E+07	7.35384
2.2E+07	7.3513
2.2E+07	7.35136
2.3E+07	7.35389

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1021.2	10.75		0.00011562	3.5
2	1021.319	10.75		0.00011562	3.5
3	1027.037	10.75		0.00011562	3.5
4	1015.326	10.75		0.00011562	3.5
5	1027.003	10.75		0.00011562	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	94.99535	3.3E-05	2875678	19.813421
2	95.00638	3.3E-05	2876012	19.815722
3	95.53836	3.3E-05	2892116	19.926678
4	94.44889	3.3E-05	2859136	19.699445
5	95.53518	3.3E-05	2892020	19.926015

E (Kpa)	logE (Kpa)
2E+07	7.29696
2E+07	7.29701
2E+07	7.29943
2E+07	7.29445
2E+07	7.29942

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1026.998	10.75		0.00017641	3.5
2	1021.169	10.75		0.00017641	3.5
3	1026.997	10.75		0.00017641	3.5
4	1026.875	10.75		0.00017641	3.5
5	1025.235	10.75		0.00017641	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	95.53473	5E-05	1895425	13.059477
2	94.99248	5E-05	1884666	12.985352
3	95.53461	5E-05	1895422	13.05946
4	95.52329	5E-05	1895198	13.057913
5	95.3707	5E-05	1892170	13.037053

E (Kpa)	logE (Kpa)
1.3E+07	7.11593
1.3E+07	7.11345
1.3E+07	7.11593
1.3E+07	7.11587
1.3E+07	7.11518

(4.4 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	8.843E-05	782.979	20.63607	20.628256	0.007812	8.84E-05	780.3022
	8.843E-05	781.082	20.73535	20.72933	0.006022		
	8.843E-05	775.438	20.83513	20.831543	0.003582		
	8.843E-05	782.979	20.9349	20.928061	0.006835		
	8.843E-05	779.033	21.03499	21.030437	0.004557		
5	9.964E-05	785.308	40.19157	40.187176	0.004394	9.96E-05	783.2961
	9.964E-05	785.717	40.38623	40.387047	0.000817		
	9.964E-05	786.027	40.5918	40.585289	0.006508		
	9.964E-05	777.924	40.79248	40.790691	0.001789		
	9.964E-05	781.505	40.9917	40.988531	0.003168		
1	0.0001211	779.828	56.6958	56.616051	0.07975	0.000117	782.6533
	0.0001211	781.049	57.68197	57.611328	0.070641		
	0.0001211	783.578	58.66553	58.065145	0.600382		
	0.0001211	785.068	59.68295	59.596355	0.08659		
	0.0001211	783.744	60.69385	60.605309	0.088539		
0.5	0.0001473	779.321	82.37207	82.139	0.23307	0.000142	776.6186
	0.0001473	779.116	84.34197	84.140625	0.20134		
	0.0001473	774.825	86.3532	86.159348	0.193847		
	0.0001473	774.791	88.36572	88.158531	0.207192		
	0.0001473	775.04	90.37614	90.158691	0.217453		
0.1	0.0001647	784.694	177.3254	176.24707	1.07829	0.000161	784.2826
	0.0001647	784.957	187.2585	186.2518	1.00667		
	0.0001647	783.865	197.245	196.27946	0.9655		
	0.0001647	784.551	207.1693	206.1945	0.97478		
	0.0001647	783.347	217.1458	216.29004	0.8558		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	782.97931	10.75		0.00008843	3.5
2	781.08203	10.75		0.00008843	3.5
3	775.43768	10.75		0.00008843	3.5
4	782.97925	10.75		0.00008843	3.5
5	779.03259	10.75		0.00008843	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.835285	2.5E-05	2882651	19.861466
2	72.658793	2.5E-05	2875666	19.813338
3	72.133738	2.5E-05	2854885	19.670161
4	72.835279	2.5E-05	2882651	19.861464
5	72.468148	2.5E-05	2868121	19.761351

Kpa	log KPa
19861466	7.298011
19813338	7.296958
19670161	7.293808
19861464	7.298011
19761351	7.295817

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	785.30774	10.75		0.00009964	3.5
2	785.71698	10.75		0.00009964	3.5
3	786.02667	10.75		0.00009964	3.5
4	777.92383	10.75		0.00009964	3.5
5	781.50531	10.75		0.00009964	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.051883	2.8E-05	2565974	17.67956
2	73.089952	2.8E-05	2567311	17.688773
3	73.11876	2.8E-05	2568323	17.695745
4	72.365007	2.8E-05	2541847	17.513327
5	72.698168	2.8E-05	2553550	17.593956

E (Kpa)	logE (Kpa)
17679560	7.247471
17688773	7.247698
17695745	7.247869
17513327	7.243369
17593956	7.245364

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	779.828	10.75		0.00012110	3.5
2	781.04883	10.75		0.00012110	3.5
3	783.57776	10.75		0.00012110	3.5
4	785.06812	10.75		0.00012110	3.5
5	783.7439	10.75		0.00012110	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.54214	3.5E-05	2096667	14.446036
2	72.655705	3.5E-05	2099949	14.468651
3	72.890954	3.5E-05	2106749	14.515499
4	73.029593	3.5E-05	2110756	14.543107
5	72.906409	3.5E-05	2107195	14.518577

E (Kpa)	logE (Kpa)
14446036	7.159749
14468651	7.160428
14515499	7.161832
14543107	7.162657
14518577	7.161924

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	779.32068	10.75		0.00014734	3.5
2	779.11646	10.75		0.00014734	3.5
3	774.82477	10.75		0.00014734	3.5
4	774.79114	10.75		0.00014734	3.5
5	775.0401	10.75		0.00014734	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.494947	4.2E-05	1722039	11.86485
2	72.47595	4.2E-05	1721588	11.861741
3	72.076723	4.2E-05	1712105	11.796402
4	72.073594	4.2E-05	1712030	11.79589
5	72.096753	4.2E-05	1712581	11.79968

E (Kpa)	logE (Kpa)
11864850	7.074262
11861741	7.074148
11796402	7.07175
11795890	7.071731
11799680	7.07187

	0.1Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	784.69366	10.75		0.00016473	3.5
2	784.95685	10.75		0.00016473	3.5
3	783.86487	10.75		0.00016473	3.5
4	784.55066	10.75		0.00016473	3.5
5	783.34705	10.75		0.00016473	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.994759	4.7E-05	1550867	10.685475
2	73.019242	4.7E-05	1551387	10.689059
3	72.917662	4.7E-05	1549229	10.674189
4	72.981457	4.7E-05	1550585	10.683528
5	72.869493	4.7E-05	1548206	10.667138

E (Kpa)	logE (Kpa)
10685475	7.028794
10689059	7.028939
10674189	7.028335
10683528	7.028715
10667138	7.028048

(21.1 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-ft)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	6.972E-05	280.586	29.34245	29.38916	-0.04671	6.97E-05	280.1274
	6.972E-05	280.551	29.49658	29.489258	0.007324		
	6.972E-05	280.016	29.59912	29.590008	0.009113		
	6.972E-05	279.075	29.69434	29.690918	0.003418		
	6.972E-05	280.409	29.80013	29.789551	0.01058		
5	0.0001152	280.55	48.76318	48.744629	0.018555	0.000115	280.458
	0.0001152	281.34	48.96484	48.41246	-0.55238		
	0.0001152	280.526	49.16309	49.144859	0.018227		
	0.0001152	280.324	49.36165	49.345379	0.016274		
	0.0001152	279.55	49.56201	49.546875	0.015137		
1	0.0001413	287.594	65.45671	65.37175	0.084961	0.000136	287.7216
	0.0001413	287.539	66.45036	66.370605	0.079758		
	0.0001413	287.56	67.44743	67.370934	0.076499		
	0.0001413	288.35	68.47168	68.361008	0.110672		
	0.0001413	287.565	69.47624	69.366539	0.109703		
0.5	0.0001699	287.788	91.10352	90.889816	0.2137	0.000164	287.7919
	0.0001699	286.907	93.0892	92.906578	0.182617		
	0.0001699	288.718	95.10629	94.854172	0.252113		
	0.0001699	287.789	97.09489	96.888184	0.20671		
	0.0001699	287.758	99.04232	98.86882	0.1735		
0.1	0.0002543	287.152	205.9115	205.04851	0.86296	0.000237	286.7488
	0.0002543	286.664	215.8386	215.0498	0.78875		
	0.0002543	287.026	225.8423	224.93864	0.90365		
	0.0002543	285.357	235.8387	235.07114	0.76757		
	0.0002543	287.545	245.6803	245.02866	0.65168		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	280.58624	10.75		0.00006972	3.5
2	280.55148	10.75		0.00006972	3.5
3	280.01596	10.75		0.00006972	3.5
4	279.07468	10.75		0.00006972	3.5
5	280.40851	10.75		0.00006972	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.101046	2E-05	1310356	9.02835354
2	26.097812	2E-05	1310194	9.02723507
3	26.047996	2E-05	1307693	9.01000378
4	25.960435	2E-05	1303297	8.97971645
5	26.084513	2E-05	1309526	9.02263476

Kpa	log KPa
9028354	6.955609
9027235	6.955555
9010004	6.954725
8979716	6.953263
9022635	6.955333

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	280.55035	10.75		0.00011518	3.5
2	281.34003	10.75		0.00011518	3.5
3	280.52609	10.75		0.00011518	3.5
4	280.32376	10.75		0.00011518	3.5
5	279.54974	10.75		0.00011518	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.097707	3.3E-05	793057.8	5.46416859
2	26.171166	3.3E-05	795290.1	5.47954887
3	26.09545	3.3E-05	792989.3	5.46369608
4	26.076629	3.3E-05	792417.3	5.45975538
5	26.004627	3.3E-05	790229.3	5.4446801

E (Kpa)	logE (Kpa)
5464169	6.737524
5479549	6.738745
5463696	6.737487
5459755	6.737173
5444680	6.735972

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	287.59357	10.75		0.00014133	3.5
2	287.53928	10.75		0.00014133	3.5
3	287.55963	10.75		0.00014133	3.5
4	288.3501	10.75		0.00014133	3.5
5	287.5654	10.75		0.00014133	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.75289	4E-05	662517.4	4.56474457
2	26.74784	4E-05	662392.3	4.56388287
3	26.749733	4E-05	662439.2	4.56420587
4	26.823265	4E-05	664260.1	4.57675237
5	26.75027	4E-05	662452.5	4.56429745

E (Kpa)	logE (Kpa)
4564745	6.659416
4563883	6.659334
4564206	6.659365
4576752	6.660557
4564297	6.659374

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	287.7876	10.75		0.00016990	3.5
2	286.90668	10.75		0.00016990	3.5
3	288.71835	10.75		0.00016990	3.5
4	287.789	10.75		0.00016990	3.5
5	287.75769	10.75		0.00016990	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.77094	4.9E-05	551497.2	3.79981603
2	26.688993	4.9E-05	549809.1	3.78818476
3	26.857521	4.9E-05	553280.9	3.81210523
4	26.77107	4.9E-05	551499.9	3.79983451
5	26.768157	4.9E-05	551439.9	3.79942111

E (Kpa)	logE (Kpa)
3799816	6.579763
3788185	6.578431
3812105	6.581165
3799835	6.579765
3799421	6.579717

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	287.15192	10.75		0.00025428	3.5
2	286.66422	10.75		0.00025428	3.5
3	287.02618	10.75		0.00025428	3.5
4	285.35727	10.75		0.00025428	3.5
5	287.54453	10.75		0.00025428	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.711807	7.3E-05	367668.2	2.53323415
2	26.666439	7.3E-05	367043.8	2.5289317
3	26.70011	7.3E-05	367507.2	2.53212489
4	26.544862	7.3E-05	365370.4	2.51740188
5	26.748328	7.3E-05	368170.9	2.53669773

E (Kpa)	logE (Kpa)
2533234	6.403675
2528932	6.402937
2532125	6.403485
2517402	6.400953
2536698	6.404269

(37.8 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-ft)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	5.367E-05	108.025	28.84131	28.82601	0.015299	5.37E-05	107.9819
	5.367E-05	108.561	28.93148	28.926434	0.005045		
	5.367E-05	107.893	29.03728	29.026367	0.010912		
	5.367E-05	107.713	29.13962	29.127441	0.012182		
	5.367E-05	107.717	29.23161	29.227051	0.004558		
5	7.178E-05	115.827	48.19369	48.18441	0.009277	7.18E-05	115.5454
	7.178E-05	115.568	48.39909	48.368883	-0.03021		
	7.178E-05	115.471	48.60433	48.584801	0.019531		
	7.178E-05	115.448	48.8099	48.785156	0.024742		
	7.178E-05	115.413	48.99886	48.984539	0.014324		
1	8.247E-05	124.17	64.90837	64.820641	0.08773	8.03E-05	124.0835
	8.247E-05	124.034	65.88461	65.829269	0.055336		
	8.247E-05	124.349	66.89372	66.818039	0.075684		
	8.247E-05	123.762	67.90804	67.842125	0.065918		
	8.247E-05	124.102	68.9082	68.818848	0.089355		
0.5	0.0001288	128.794	90.49512	90.32959	0.165527	0.00012	128.159
	0.0001288	128.247	92.50033	92.323242	0.177086		
	0.0001288	127.755	94.52279	94.345055	0.177734		
	0.0001288	127.729	96.46322	96.394371	0.068848		
	0.0001288	128.269	98.49577	98.335617	0.160156		
0.1	0.0001764	129.732	195.2235	194.57275	0.65073	0.000167	129.6283
	0.0001764	130.732	205.2121	204.62549	0.58659		
	0.0001764	129.724	215.035	214.72412	0.31088		
	0.0001764	128.801	225.2738	224.57358	0.70019		
	0.0001764	129.152	235.2333	234.7507	0.48255		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	108.02493	10.75		0.00005367	3.5
2	108.56139	10.75		0.00005367	3.5
3	107.89334	10.75		0.00005367	3.5
4	107.71287	10.75		0.00005367	3.5
5	107.71674	10.75		0.00005367	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	10.048831	1.5E-05	655307.8	4.51507108
2	10.098734	1.5E-05	658562.2	4.53749327
3	10.03659	1.5E-05	654509.6	4.50957107
4	10.019802	1.5E-05	653414.8	4.50202805
5	10.020162	1.5E-05	653438.3	4.5021898

Kpa	log KPa
4515071	6.654665
4537493	6.656816
4509571	6.654135
4502028	6.653408
4502190	6.653424

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	115.82689	10.75		0.00007178	3.5
2	115.56783	10.75		0.00007178	3.5
3	115.47129	10.75		0.00007178	3.5
4	115.44812	10.75		0.00007178	3.5
5	115.4127	10.75		0.00007178	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	10.774594	2.1E-05	525353.5	3.61968531
2	10.750496	2.1E-05	524178.4	3.61158947
3	10.741515	2.1E-05	523740.6	3.60857252
4	10.73936	2.1E-05	523635.5	3.60784844
5	10.736065	2.1E-05	523474.8	3.60674153

E (Kpa)	logE (Kpa)
3619685	6.558671
3611589	6.557698
3608573	6.557335
3607848	6.557248
3606742	6.557115

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	124.17049	10.75		0.00008247	3.5
2	124.03366	10.75		0.00008247	3.5
3	124.34949	10.75		0.00008247	3.5
4	123.76157	10.75		0.00008247	3.5
5	124.10216	10.75		0.00008247	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	11.550743	2.4E-05	490209.5	3.37754361
2	11.538015	2.4E-05	489669.3	3.37382172
3	11.567394	2.4E-05	490916.2	3.38241256
4	11.512704	2.4E-05	488595.2	3.36642064
5	11.544387	2.4E-05	489939.8	3.37568497

E (Kpa)	logE (Kpa)
3377544	6.528601
3373822	6.528122
3382413	6.529227
3366421	6.527168
3375685	6.528362

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	128.7943	10.75		0.00012878	3.5
2	128.24724	10.75		0.00012878	3.5
3	127.75493	10.75		0.00012878	3.5
4	127.72888	10.75		0.00012878	3.5
5	128.26949	10.75		0.00012878	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	11.980865	3.7E-05	325616.4	2.24349666
2	11.929976	3.7E-05	324233.3	2.2339673
3	11.88418	3.7E-05	322988.6	2.22539165
4	11.881756	3.7E-05	322922.8	2.22493787
5	11.932046	3.7E-05	324289.5	2.23435488

E (Kpa)	logE (Kpa)
2243497	6.350925
2233967	6.349077
2225392	6.347406
2224938	6.347318
2234355	6.349152

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	129.73183	10.75		0.00017639	3.5
2	130.73183	10.75		0.00017639	3.5
3	129.72412	10.75		0.00017639	3.5
4	128.80125	10.75		0.00017639	3.5
5	129.15231	10.75		0.00017639	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	12.068077	5E-05	239454.8	1.64984326
2	12.1611	5E-05	241300.5	1.66256059
3	12.06736	5E-05	239440.5	1.64974521
4	11.981512	5E-05	237737.1	1.63800876
5	12.014168	5E-05	238385.1	1.64247331

E (Kpa)	logE (Kpa)
1649843	6.217443
1662561	6.220777
1649745	6.217417
1638009	6.214316
1642473	6.215498

LC
(-9 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00008393	1041.97	224.3924	224.33627	0.05616	8.39E-05	1039.506
	0.00008393	1038.64	224.4924	224.43491	0.05745		
	0.00008393	1041.57	224.5869	224.53598	0.05093		
	0.00008393	1035.75	224.6917	224.63412	0.05762		
	0.00008393	1039.61	224.793	224.7352	0.05777		
5	0.00009267	1045.86	243.9875	243.79053	0.19694	9.27E-05	1043.59
	0.00009267	1043.89	244.2041	243.98828	0.21582		
	0.00009267	1041.34	244.3928	244.18718	0.20557		
	0.00009267	1043.1	244.6047	244.38818	0.21648		
	0.00009267	1043.76	244.7808	244.58855	0.19221		
1	0.000104763	1052.38	260.4152	259.38446	1.03076	0.000105	1046.148
	0.000104763	1046.04	261.3921	260.36899	1.0231		
	0.000104763	1046.23	262.4251	261.36835	1.05679		
	0.000104763	1042.74	263.3636	262.36298	1.00064		
	0.000104763	1043.35	264.3861	263.36362	1.02246		
0.5	0.000118223	1046.05	285.9455	285.84277	0.10273	0.000118	1047.346
	0.000118223	1045.97	287.8615	287.8436	0.01791		
	0.000118223	1049.33	289.9378	289.85712	0.08072		
	0.000118223	1049.48	291.9549	291.8576	0.09733		
	0.000118223	1045.91	293.8758	293.84262	0.0332		
0.1	0.00017641	1047	196.9741	196.34392	0.6302	0.000176	1045.455
	0.00017641	1041.17	207.7787	206.48503	1.29363		
	0.00017641	1047	216.6268	216.31967	0.30713		
	0.00017641	1046.88	218.7568	218.2693	0.4875		
	0.00017641	1045.24	221.563	220.985	0.578		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1041.967	10.75		0.00008393	3.5
2	1038.6353	10.75		0.00008393	3.5
3	1041.5702	10.75		0.00008393	3.5
4	1035.7476	10.75		0.00008393	3.5
5	1039.6091	10.75		0.00008393	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	96.92716279	2.4E-05	4042007	27.849431
2	96.61723721	2.4E-05	4029083	27.760382
3	96.89025116	2.4E-05	4040468	27.838825
4	96.34861395	2.4E-05	4017881	27.6832
5	96.70782326	2.4E-05	4032861	27.786409

Kpa	log KPa
27849431	7.444816
27760382	7.443425
27838825	7.444651
27683200	7.442216
27786409	7.443832

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1045.8628	10.75		0.00009267	3.5
2	1043.8903	10.75		0.00009267	3.5
3	1041.3416	10.75		0.00009267	3.5
4	1043.0994	10.75		0.00009267	3.5
5	1043.7556	10.75		0.00009267	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.28956279	2.6E-05	3674661	25.318417
2	97.10607442	2.6E-05	3667731	25.270666
3	96.86898605	2.6E-05	3658776	25.208967
4	97.03250233	2.6E-05	3664952	25.25152
5	97.09354419	2.6E-05	3667258	25.267406

E (Kpa)	logE (Kpa)
25318417	7.403437
25270666	7.402617
25208967	7.401555
25251520	7.402288
25267406	7.402561

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1052.38446	10.75		0.00010476	3.5
2	1046.0364	10.75		0.00010476	3.5
3	1046.2294	10.75		0.00010476	3.5
4	1042.7382	10.75		0.00010476	3.5
5	1043.353	10.75		0.00010476	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.89622884	3E-05	3270600	22.534433
2	97.30571163	3E-05	3250871	22.398503
3	97.32366512	3E-05	3251471	22.402636
4	96.99890233	3E-05	3240621	22.32788
5	97.05609302	3E-05	3242532	22.341044

E (Kpa)	logE (Kpa)
22534433	7.352847
22398503	7.350219
22402636	7.350299
22327880	7.348847
22341044	7.349103

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1046.046	10.75		0.00011822	3.5
2	1045.968	10.75		0.00011822	3.5
3	1049.3273	10.75		0.00011822	3.5
4	1049.4825	10.75		0.00011822	3.5
5	1045.9067	10.75		0.00011822	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.30660465	3.4E-05	2880770	19.848506
2	97.29934884	3.4E-05	2880555	19.847026
3	97.61184186	3.4E-05	2889807	19.910768
4	97.62627907	3.4E-05	2890234	19.913713
5	97.29364651	3.4E-05	2880386	19.845863

E (Kpa)	logE (Kpa)
19848506	7.297728
19847026	7.297695
19910768	7.299088
19913713	7.299152
19845863	7.29767

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1046.9984	10.75		0.00017641	3.5
2	1041.1692	10.75		0.00017641	3.5
3	1046.9971	10.75		0.00017641	3.5
4	1046.8754	10.75		0.00017641	3.5
5	1045.235	10.75		0.00017641	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.3952	5E-05	1932337	13.3138
2	96.85294884	5E-05	1921578	13.239675
3	97.39507907	5E-05	1932334	13.313784
4	97.38375814	5E-05	1932110	13.312236
5	97.23116279	5E-05	1929082	13.291376

E (Kpa)	logE (Kpa)
13313800	7.124302
13239675	7.121877
13313784	7.124301
13312236	7.124251
13291376	7.12357

LC
(4.4 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00007994	778.28	20.62549	20.62435	0.001138	7.99E-05	780.8427
	0.00007994	780.27	20.73519	20.724773	0.010416		
	0.00007994	784.66	20.82699	20.82601	0.000976		
	0.00007994	775.01	20.92464	20.923666	0.000977		
	0.00007994	785.99	21.0319	21.026855	0.005047		
5	0.00009706	780.52	40.17855	40.179039	0.000488	9.71E-05	779.2075
	0.00009706	777.88	40.38965	40.376793	0.012855		
	0.00009706	778.8	40.58952	40.577637	0.011883		
	0.00009706	779.5	40.79525	40.77816	0.01709		
	0.00009706	779.33	40.98975	40.977867	0.011879		
1	0.00012201	773.91	56.6084	56.785809	0.177411	0.000122	775.6498
	0.00012201	775.38	57.59782	57.788574	0.190754		
	0.00012201	776.8	58.63151	58.794598	0.163086		
	0.00012201	775.38	59.61426	59.778648	0.16439		
	0.00012201	776.79	60.61491	60.784996	0.170086		
0.5	0.00015246	782.05	82.16162	82.04541	0.116211	0.000152	794.0515
	0.00015246	784.06	84.25586	84.061363	0.194496		
	0.00015246	796.06	86.2124	86.05504	0.157362		
	0.00015246	788.05	88.23406	88.046387	0.187668		
	0.00015246	820.05	90.15039	90.048668	0.101723		
0.1	0.00025027	802.05	201.2606	200.98721	0.27338	0.00025	792.573
	0.00025027	799.23	207.0625	206.37109	0.69141		
	0.00025027	800.5	216.57	216.32858	0.24141		
	0.00025027	801.32	225.9873	225.76549	0.22183		
	0.00025027	759.77	231.9876	230.98761	1.00001		

10Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	778.28052	10.75		0.00007994	3.5
2	780.27496	10.75		0.00007994	3.5
3	784.65747	10.75		0.00007994	3.5
4	775.00946	10.75		0.00007994	3.5
5	785.99133	10.75		0.00007994	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.398188	2E-05	3169922	21.8407648
2	72.583717	2E-05	3178046	21.8967344
3	72.991393	2E-05	3195896	22.0197201
4	72.093903	2E-05	3156599	21.7489695
5	73.115473	2E-05	3201328	22.057152

Kpa	log KPa
21840765	7.339268
21896734	7.340379
22019720	7.342812
21748970	7.337439
22057152	7.343549

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	780.52203	10.75		0.00009706	3.5
2	777.88422	10.75		0.00009706	3.5
3	778.79706	10.75		0.00009706	3.5
4	779.50446	10.75		0.00009706	3.5
5	779.3299	10.75		0.00009706	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.6067	3E-05	2618223	18.0395598
2	72.361323	3E-05	2609375	17.9785943
3	72.446238	3E-05	2612437	17.999692
4	72.512043	3E-05	2614810	18.0160416
5	72.495805	3E-05	2614225	18.0120071

E (Kpa)	logE (Kpa)
18039560	7.256226
17978594	7.254756
17999692	7.255265
18016042	7.255659
18012007	7.255562

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	773.90918	10.75		0.00012201	3.5
2	775.3764	10.75		0.00012201	3.5
3	776.79767	10.75		0.00012201	3.5
4	775.37524	10.75		0.00012201	3.5
5	776.79059	10.75		0.00012201	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	71.991552	3E-05	2065137	14.2287913
2	72.128037	3E-05	2069052	14.2557671
3	72.260248	3E-05	2072844	14.281898
4	72.127929	3E-05	2069049	14.2557457
5	72.25959	3E-05	2072826	14.2817678

E (Kpa)	logE (Kpa)
14228791	7.153168
14255767	7.153991
14281898	7.154786
14255746	7.15399
14281768	7.154782

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	782.04541	10.75		0.00015246	3.5
2	784.06136	10.75		0.00015246	3.5
3	796.0555	10.75		0.00015246	3.5
4	788.04639	10.75		0.00015246	3.5
5	820.04867	10.75		0.00015246	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	72.74841	4E-05	1670019	11.5064314
2	72.935941	4E-05	1674324	11.5360926
3	74.051675	4E-05	1699937	11.7125655
4	73.306641	4E-05	1682834	11.5947253
5	76.283597	4E-05	1751173	12.0655829

E (Kpa)	logE (Kpa)
11506431	7.060941
11536093	7.062059
11712565	7.068652
11594725	7.06426
12065583	7.081548

	0.1Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	802.04657	10.75		0.00025027	3.5
2	799.22986	10.75		0.00025027	3.5
3	800.50153	10.75		0.00025027	3.5
4	801.32189	10.75		0.00025027	3.5
5	759.76532	10.75		0.00025027	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	74.608983	7E-05	1043405	7.18906281
2	74.346964	7E-05	1039741	7.16381552
3	74.465259	7E-05	1041395	7.175214
4	74.541571	7E-05	1042463	7.18256722
5	70.675844	7E-05	988400.5	6.81007913

E (Kpa)	logE (Kpa)
7189063	6.856672
7163816	6.855144
7175214	6.855835
7182567	6.85628
6810079	6.833152

(21.1 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00006479	277.77	158.506	158.49629	0.00974	6.48E-05	277.8493
	0.00006479	277.89	158.6012	158.59653	0.00471		
	0.00006479	277.4	158.7012	158.69548	0.00569		
	0.00006479	278.34	158.8013	158.79688	0.00439		
	0.00006479	277.84	158.9022	158.89648	0.00571		
5	0.0009239	274.67	178.0711	178.04883	0.02231	7.7E-05	274.0589
	0.00007699	275.13	178.2822	178.25	0.03223		
	0.00007699	274.05	178.472	178.44824	0.02378		
	0.00007699	274.04	178.6712	178.64941	0.02182		
	0.00007699	272.4	178.8698	178.84538	0.02442		
1	0.0012934	276.5	194.5609	194.48698	0.0739	0.000345	276.2922
	0.00010778	276.74	195.5607	195.43295	0.12776		
	0.00010778	276.57	196.5228	196.43962	0.08318		
	0.00010778	278.06	197.5228	197.44434	0.07846		
	0.00010778	273.58	198.5111	198.41391	0.09717		
0.5	0.00177792	276.65	220.1296	219.93034	0.19922	0.000474	276.8723
	0.00014816	276.69	222.1354	221.93864	0.19678		
	0.00014816	277.2	224.1183	223.94321	0.17512		
	0.00014816	277.2	226.141	225.94321	0.19775		
	0.00014816	276.62	228.1577	227.93945	0.21826		
0.1	0.00296576	276.92	335.1252	334.19385	0.93133	0.000791	276.0462
	0.00024715	275.21	344.9676	344.33774	0.62988		
	0.00024715	275.6	355.1631	354.29492	0.86817		
	0.00024715	275.92	365.1882	364.30731	0.88086		
	0.00024715	276.58	375.0314	374.26123	0.7702		

	10Hz				
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	277.76794	10.75		0.00006479	3.5
2	277.89304	10.75		0.00006479	3.5
3	277.40433	10.75		0.00006479	3.5
4	278.34048	10.75		0.00006479	3.5
5	277.84094	10.75		0.00006479	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	25.8388781	2E-05	1395796	9.61703381
2	25.8505153	2E-05	1396425	9.62136509
3	25.805054	2E-05	1393969	9.6044447
4	25.8921377	2E-05	1398673	9.6368566
5	25.8456688	2E-05	1396163	9.61956125

Kpa	log KPa
9617034	6.983041
9621365	6.983237
9604445	6.982472
9636857	6.983935
9619561	6.983155

5Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	274.67377	10.75		7.6992E-05	3.5
2	275.13055	10.75		0.00007699	3.5
3	274.04565	10.75		0.00007699	3.5
4	274.04117	10.75		0.00007699	3.5
5	272.40326	10.75		0.00007699	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	25.5510484	2E-05	1161538	8.00299684
2	25.5935395	2E-05	1163470	8.01630575
3	25.4926186	2E-05	1158882	7.9846957
4	25.4922019	2E-05	1158863	7.98456517
5	25.3398381	2E-05	1151936	7.93684242

E (Kpa)	logE (Kpa)
8002997	6.903253
8016306	6.903974
7984696	6.902258
7984565	6.902251
7936842	6.899648

1HZ					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	276.50229	10.75		0.00034491	3.5
2	276.74387	10.75		0.00010778	3.5
3	276.57056	10.75		0.00010778	3.5
4	278.0592	10.75		0.00010778	3.5
5	273.58487	10.75		0.00010778	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	25.7211433	1E-04	261010.7	1.79836366
2	25.7436158	3E-05	835964	5.75979163
3	25.727494	3E-05	835440.4	5.75618458
4	25.8659721	3E-05	839937.2	5.78716722
5	25.4497553	3E-05	826421.5	5.69404426

E (Kpa)	logE (Kpa)
1798364	6.254878
5759792	6.760407
5756185	6.760135
5787167	6.762466
5694044	6.755421

0.5Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	276.64624	10.75		0.00047411	3.5
2	276.68979	10.75		0.00014816	3.5
3	277.20328	10.75		0.00014816	3.5
4	277.19769	10.75		0.00014816	3.5
5	276.62436	10.75		0.00014816	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	25.734534	0.0001	189977.6	1.30894539
2	25.7385851	4E-05	608023.9	4.18928462
3	25.7863516	4E-05	609152.3	4.19705923
4	25.7858316	4E-05	609140	4.19697459
5	25.7324986	4E-05	607880.1	4.18829396

E (Kpa)	logE (Kpa)
1308945	6.116922
4189285	6.62214
4197059	6.622945
4196975	6.622936
4188294	6.622037

0.1Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	334.19385	10.75		0.00079087	3.5
2	344.33774	10.75		0.00024715	3.5
3	354.29492	10.75		0.00024715	3.5
4	364.30731	10.75		0.00024715	3.5
5	374.26123	10.75		0.00024715	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	31.0878	0.0002	137579.3	0.94792155
2	32.0314177	7E-05	453617	3.12542115
3	32.957667	7E-05	466734.2	3.21579864
4	33.8890521	7E-05	479924.1	3.30667725
5	34.8149981	7E-05	493037	3.39702515

E (Kpa)	logE (Kpa)
947921.6	5.976772
3125421	6.494909
3215799	6.507289
3306677	6.519392
3397025	6.531099

(37.8 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00004295	101.833	30.60433	30.597494	0.00684	4.3E-05	101.5088
	0.00004295	101.289	30.69841	30.700521	0.00211		
	0.00004295	101.619	30.80984	30.799807	0.01003		
	0.00004295	101.377	30.09993	30.0898928	0.01004		
	0.00004295	101.426	30.09935	30.087561	0.01179		
5	0.0007746	103.979	50.16765	50.149578	0.01807	6.46E-05	103.4975
	0.00006455	103.562	50.36768	50.348797	0.01888		
	0.00006455	103.996	50.56852	50.548668	0.01985		
	0.00006455	102.495	50.76791	50.747398	0.02051		
	0.00006455	103.456	50.96761	50.946129	0.02148		
1	0.0011748	107.758	66.65414	66.592285	0.06185	0.000313	106.7013
	0.00009790	107.157	67.63754	67.592125	0.04541		
	0.00009790	107.035	68.62045	68.594079	0.02637		
	0.00009790	106.122	69.65463	69.612793	0.04183		
	0.00009790	105.434	70.65398	70.610519	0.04346		
0.5	0.0019752	107.976	92.27409	92.131676	0.14242	0.000527	106.6774
	0.00016460	106.892	94.24007	94.182785	0.05729		
	0.00016460	106.138	96.32471	96.191574	0.13313		
	0.00016460	105.452	98.25798	98.193527	0.06445		
	0.00016460	106.929	100.2747	100.18083	0.09391		
0.1	0.0024766	96.9263	187.4185	187.00017	0.41829	0.00066	100.4018
	0.00020638	102.908	197.1528	196.68034	0.47249		
	0.00020638	103.272	207.0355	206.75684	0.27865		
	0.00020638	96.678	227.5015	226.9904	0.51106		
	0.00020638	102.225	237.2862	237.04623	0.23992		

	10Hz				
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	101.83311	10.75		0.00004295	3.5
2	101.28863	10.75		0.00004295	3.5
3	101.61946	10.75		0.00004295	3.5
4	101.37658	10.75		0.00004295	3.5
5	101.42605	10.75		0.00004295	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.4728474	1.2E-05	771941.1	5.31867407
2	9.4221981	1.2E-05	767813.7	5.29023625
3	9.452973	1.2E-05	770321.5	5.30751527
4	9.4303795	1.2E-05	768480.4	5.29482982
5	9.4349814	1.2E-05	768855.4	5.2974136

Kpa	log KPa
5318674	6.725803
5290236	6.723475
5307515	6.724891
5294830	6.723852
5297414	6.724064

5Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	103.97933	10.75		6.4553E-05	3.5
2	103.5618	10.75		0.00006455	3.5
3	103.99595	10.75		0.00006455	3.5
4	102.49497	10.75		0.00006455	3.5
5	103.45555	10.75		0.00006455	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.6724958	1.8E-05	524432.3	3.61333858
2	9.6336558	1.8E-05	522326.4	3.59882918
3	9.6740419	1.8E-05	524516.1	3.61391613
4	9.5344158	1.8E-05	516945.8	3.56175625
5	9.6237721	1.8E-05	521790.6	3.59513693

E (Kpa)	logE (Kpa)
3613339	6.557909
3598829	6.556161
3613916	6.557978
3561756	6.551664
3595137	6.555715

1HZ					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	107.7582	10.75		0.00031328	3.5
2	107.15746	10.75		0.00009790	3.5
3	107.03481	10.75		0.00009790	3.5
4	106.12226	10.75		0.00009790	3.5
5	105.43392	10.75		0.00009790	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	10.024019	9E-05	111988.3	0.77159965
2	9.9681358	2.8E-05	356364.9	2.45535383
3	9.9567265	2.8E-05	355957	2.45254349
4	9.8718381	2.8E-05	352922.2	2.43163376
5	9.8078065	2.8E-05	350633	2.41586147

E (Kpa)	logE (Kpa)
771599.7	5.887392
2455354	6.390114
2452543	6.389617
2431634	6.385898
2415861	6.383072

0.5Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	107.97568	10.75		0.00052672	3.5
2	106.89169	10.75		0.00016460	3.5
3	106.13837	10.75		0.00016460	3.5
4	105.45222	10.75		0.00016460	3.5
5	106.92915	10.75		0.00016460	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	10.044249	0.00015	66742.46	0.45985552
2	9.943413	4.7E-05	211431.7	1.45676458
3	9.8733367	4.7E-05	209941.7	1.44649802
4	9.8095088	4.7E-05	208584.5	1.43714689
5	9.9468977	4.7E-05	211505.8	1.4572751

E (Kpa)	logE (Kpa)
459855.5	5.662621
1456765	6.163389
1446498	6.160318
1437147	6.157501
1457275	6.163542

0.1Hz					
Cycle #	P(lb-f)	A(in2)	P(inch)	Δ	GL
1	96.92628	10.75		0.00066042	3.5
2	102.90831	10.75		0.00020638	3.5
3	103.27161	10.75		0.00020638	3.5
4	96.67797	10.75		0.00020638	3.5
5	102.22502	10.75		0.00020638	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.0163981	0.00019	47783.6	0.32922897
2	9.572866	5.9E-05	162344.5	1.11855392
3	9.6066614	5.9E-05	162917.7	1.12250278
4	8.9932995	5.9E-05	152515.8	1.05083372
5	9.5093042	5.9E-05	161266.6	1.11112695

E (Kpa)	logE (Kpa)
329229	5.517498
1118554	6.048657
1122503	6.050187
1050834	6.021534
1111127	6.045764

Control
(-9 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-ft)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00011788	1052.76	39.98145	39.97396	0.00749	0.000118	1052.464
	0.00011788	1052.9	40.17253	40.17153	0.001		
	0.00011788	1052.64	40.38298	40.37484	0.00814		
	0.00011788	1053.44	40.57813	40.57438	0.00375		
	0.00011788	1050.58	40.77767	40.77474	0.00293		
5	0.00012826	1055.863	39.5822	39.5765	0.0057	0.000128	1053.59
	0.00012826	1053.89	39.7806	39.77767	0.00293		
	0.00012826	1051.342	39.97966	39.97461	0.00505		
	0.00012826	1053.099	40.1792	40.17757	0.00163		
	0.00012826	1053.756	40.38216	40.37533	0.00683		
1	0.00015696	1056.68	56.63477	56.606285	0.028481	0.000157	1054.798
	0.00015696	1053.064	57.62875	57.611656	0.01709		
	0.00015696	1052.973	58.63981	58.614258	0.025554		
	0.00015696	1055.63	59.65186	59.605309	0.046546		
	0.00015696	1055.645	60.65186	60.606445	0.04541		
0.5	0.00017112	1053.739	82.18832	82.120773	0.067543	0.000171	1052.011
	0.00017112	1053.631	84.19971	84.120605	0.079102		
	0.00017112	1049.898	86.17253	86.140625	0.031906		
	0.00017112	1052.121	88.18864	88.130371	0.058273		
	0.00017112	1050.667	90.20622	90.137535	0.068688		
0.1	0.00024293	1048.211	96.75732	96.244629	0.512695	0.000243	1049.785
	0.00024293	1051.138	106.7196	106.18359	0.53598		
	0.00024293	1050.457	116.8281	116.2041	0.62403		
	0.00024293	1048.338	126.8573	126.30095	0.55631		
	0.00024293	1050.779	136.7487	136.257	0.4917		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1052.76	10.75		0.00011788	3.5
2	1052.9	10.75		0.00011788	3.5
3	1052.64	10.75		0.00011788	3.5
4	1053.44	10.75		0.00011788	3.5
5	1050.58	10.75		0.00011788	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.931163	3.37E-05	2907754	20.0344255
2	97.944186	3.37E-05	2908141	20.0370897
3	97.92	3.37E-05	2907423	20.0321418
4	97.994419	3.37E-05	2909632	20.0473661
5	97.728372	3.37E-05	2901733	19.9929392

Kpa	log KPa
20034425	7.301777
20037090	7.301835
20032142	7.301727
20047366	7.302057
19992939	7.300877

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1055.8628	10.75		0.00012826	3.5
2	1053.8903	10.75		0.00012826	3.5
3	1051.3416	10.75		0.00012826	3.5
4	1053.0994	10.75		0.00012826	3.5
5	1053.7556	10.75		0.00012826	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.219795	3.66E-05	2680331	18.4674825
2	98.036307	3.66E-05	2675324	18.4329827
3	97.799219	3.66E-05	2668854	18.3884049
4	97.962735	3.66E-05	2673316	18.4191495
5	98.023777	3.66E-05	2674982	18.4306267

E (Kpa)	logE (Kpa)
18467483	7.266408
18432983	7.265596
18388405	7.264544
18419150	7.26527
18430627	7.26554

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1056.6803	10.75		0.00015696	3.5
2	1053.0635	10.75		0.00015696	3.5
3	1052.9727	10.75		0.00015696	3.5
4	1055.6296	10.75		0.00015696	3.5
5	1055.6448	10.75		0.00015696	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.295842	4.48E-05	2191919	15.1023245
2	97.959395	4.48E-05	2184417	15.0506324
3	97.950949	4.48E-05	2184229	15.0493346
4	98.198102	4.48E-05	2189740	15.0873077
5	98.199516	4.48E-05	2189771	15.0875249

E (Kpa)	logE (Kpa)
15102325	7.179044
15050632	7.177555
15049335	7.177517
15087308	7.178612
15087525	7.178618

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1053.739	10.75		0.00017112	3.5
2	1053.6309	10.75		0.00017112	3.5
3	1049.8977	10.75		0.00017112	3.5
4	1052.1211	10.75		0.00017112	3.5
5	1050.667	10.75		0.00017112	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	98.022233	4.89E-05	2004868	13.8135401
2	98.012177	4.89E-05	2004662	13.812123
3	97.664902	4.89E-05	1997559	13.7631842
4	97.87173	4.89E-05	2001790	13.792331
5	97.736465	4.89E-05	1999023	13.7732691

E (Kpa)	logE (Kpa)
13813540	7.140305
13812123	7.14026
13763184	7.138719
13792331	7.139638
13773269	7.139037

	0.1Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	1048.2113	10.75		0.00024293	3.5
2	1051.1384	10.75		0.00024293	3.5
3	1050.4565	10.75		0.00024293	3.5
4	1048.3381	10.75		0.00024293	3.5
5	1050.7792	10.75		0.00024293	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	97.508028	6.94E-05	1404854	9.67944291
2	97.780316	6.94E-05	1408777	9.70647247
3	97.716884	6.94E-05	1407863	9.70017564
4	97.519823	6.94E-05	1405024	9.68061381
5	97.746902	6.94E-05	1408295	9.70315553

E (Kpa)	logE (Kpa)
9679443	6.98585
9706472	6.987061
9700176	6.98678
9680614	6.985903
9703156	6.986913

(4.4 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.001312	786.018	23.68799	23.683496	0.004492	0.001318	785.6944
	0.001312	785.807	23.88613	23.783725	0.102408		
	0.001318	785.934	23.88835	23.883789	0.004559		
	0.001321	784.624	23.98975	23.884506	0.10524		
	0.001328	786.09	24.58398	23.683432	0.900552		
5	0.001457	789.01	43.44541	43.241051	0.204359	0.001476	789.9646
	0.001467	790.879	43.44756	43.419453	0.028106		
	0.001478	789.092	43.64746	43.641113	0.006348		
	0.001483	791.136	43.85352	43.839031	0.014485		
	0.001478	789.708	44.04883	44.040691	0.008137		
1	0.0016	787.836	59.7277	59.667156	0.060547	0.001632	789.1913
	0.001621	789.945	60.7341	60.661133	0.072965		
	0.001632	789.07	61.72738	61.66325	0.064129		
	0.001651	789.442	62.72266	62.665039	0.057617		
	0.001655	789.664	63.73926	63.663414	0.075844		
0.5	0.001624	787.673	130.1714	129.25864	0.91275	0.001718	788.637
	0.001673	788.667	140.243	139.28027	0.96274		
	0.001718	789.232	150.1538	149.24219	0.91162		
	0.001765	789.452	160.2148	159.27197	0.94287		
	0.001808	788.162	169.5858	169.3143	0.271478		
0.1	0.002158	789.339	180.1994	179.27409	0.9253	0.002245	788.4817
	0.002201	787.215	190.4751	189.34912	1.12598		
	0.002246	789.297	200.18	199.27116	0.90886		
	0.002293	788.67	210.12	209.29868	0.82128		
	0.002327	787.888	220.0776	219.30112	0.77652		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	786.0178	10.75		0.00010984	3.5
2	785.807	10.75		0.00010984	3.5
3	785.9337	10.75		0.00010984	3.5
4	784.6235	10.75		0.00010984	3.5
5	786.0903	10.75		0.00010984	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.11793	3.1E-05	2329936	16.05325697
2	73.09833	3.1E-05	2329311	16.04895271
3	73.11011	3.1E-05	2329686	16.05153914
4	72.98824	3.1E-05	2325803	16.02478207
5	73.12468	3.1E-05	2330151	16.05473788

Kpa	log KPa
16053257	7.205563
16048953	7.205447
16051539	7.205517
16024782	7.204792
16054738	7.205603

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	789.0098	10.75		0.00012303	3.5
2	790.8788	10.75		0.00012303	3.5
3	789.0916	10.75		0.00012303	3.5
4	791.1356	10.75		0.00012303	3.5
5	789.7075	10.75		0.00012303	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.39626	3.5E-05	2088029	14.38652091
2	73.57012	3.5E-05	2092975	14.42059867
3	73.40387	3.5E-05	2088245	14.38801096
4	73.59401	3.5E-05	2093655	14.4252807
5	73.46116	3.5E-05	2089876	14.39924233

E (Kpa)	logE (Kpa)
14386521	7.157956
14420599	7.158983
14388011	7.158001
14425281	7.159124
14399242	7.15834

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	787.8361	10.75		0.00013598	3.5
2	789.9454	10.75		0.00013598	3.5
3	789.0696	10.75		0.00013598	3.5
4	789.4418	10.75		0.00013598	3.5
5	789.6637	10.75		0.00013598	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.28708	3.9E-05	1886311	12.99668028
2	73.4833	3.9E-05	1891361	13.03147689
3	73.40183	3.9E-05	1889264	13.01702926
4	73.43644	3.9E-05	1890155	13.02316817
5	73.45709	3.9E-05	1890686	13.02682928

E (Kpa)	logE (Kpa)
12996680	7.113832
13031477	7.114994
13017029	7.114512
13023168	7.114717
13026829	7.114839

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	787.6733	10.75		0.00014313	3.5
2	788.6665	10.75		0.00014313	3.5
3	789.2318	10.75		0.00014313	3.5
4	789.4517	10.75		0.00014313	3.5
5	788.1617	10.75		0.00014313	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.27193	4.1E-05	1791736	12.34506366
2	73.36433	4.1E-05	1793996	12.36063022
3	73.41691	4.1E-05	1795281	12.36948928
4	73.43737	4.1E-05	1795782	12.37293683
5	73.31737	4.1E-05	1792847	12.3527192

E (Kpa)	logE (Kpa)
12345064	7.091493
12360630	7.092041
12369489	7.092352
12372937	7.092473
12352719	7.091763

0.1Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	789.3389	10.75		0.00018709	3.5
2	787.2152	10.75		0.00018709	3.5
3	789.2972	10.75		0.00018709	3.5
4	788.6696	10.75		0.00018709	3.5
5	787.8879	10.75		0.00018709	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	73.42687	5.3E-05	1373615	9.464204722
2	73.22932	5.3E-05	1369919	9.438741953
3	73.42299	5.3E-05	1373542	9.463704857
4	73.36461	5.3E-05	1372450	9.456179668
5	73.2919	5.3E-05	1371090	9.446807293

E (Kpa)	logE (Kpa)
9464205	6.976084
9438742	6.974914
9463705	6.976061
9456180	6.975716
9446807	6.975285

(21.1 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-ft)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.001546	283.3735	20.6154	20.609213	0.006185	0.00155	282.89
	0.001548	282.5074	20.7207	20.710938	0.009765		
	0.00155	283.1159	20.81999	20.809246	0.010742		
	0.00155	281.9168	20.91911	20.911133	0.007976		
	0.001554	283.5365	21.02035	21.009604	0.010742		
5	0.0019	297.8737	40.18766	40.166016	0.021648	0.001912	298.0922
	0.001907	298.5156	40.39014	40.365887	0.02425		
	0.001911	298.6231	40.58447	40.565918	0.018555		
	0.001916	297.5448	40.7889	40.766766	0.022136		
	0.001914	297.904	40.99007	40.967773	0.022301		
1	0.002199	307.7705	56.66667	56.57943	0.087238	0.002225	307.695
	0.002212	307.6576	57.6958	57.588379	0.107422		
	0.00223	307.6782	58.68473	58.586754	0.09798		
	0.002236	307.7156	59.70036	59.585777	0.114582		
	0.002249	307.653	60.68425	60.584637	0.099609		
0.5	0.002507	313.5395	82.31332	82.071945	0.241371	0.002544	312.9323
	0.002529	312.816	84.31609	84.117676	0.19841		
	0.002544	311.9343	86.30518	86.111816	0.19336		
	0.002561	313.5313	88.32195	88.078293	0.243652		
	0.00258	312.8406	90.3073	90.094727	0.21257		
0.1	0.003142	316.324	177.1301	176.18864	0.94141	0.003228	316.2052
	0.003185	316.3703	187.1123	186.2225	0.8898		
	0.003216	316.0776	197.1899	196.30014	0.8898		
	0.003287	316.2885	217.1776	216.2308	0.94678		
	0.003312	315.9654	227.1455	226.33073	0.81478		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	283.3735	10.75		0.00012914	3.5
2	282.5074	10.75		0.00012914	3.5
3	283.1159	10.75		0.00012914	3.5
4	281.9168	10.75		0.00012914	3.5
5	283.5365	10.75		0.00012914	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	26.36033	3.69E-05	714404.3	4.92224587
2	26.27976	3.69E-05	712220.7	4.9072007
3	26.33636	3.69E-05	713754.8	4.91777027
4	26.22481	3.69E-05	710731.7	4.89694118
5	26.37549	3.69E-05	714815.2	4.92507703

Kpa	log KPa
4922246	6.692163
4907201	6.690834
4917770	6.691768
4896941	6.689925
4925077	6.692413

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	297.8737	10.75		0.00015932	3.5
2	298.5156	10.75		0.00015932	3.5
3	298.6231	10.75		0.00015932	3.5
4	297.5448	10.75		0.00015932	3.5
5	297.904	10.75		0.00015932	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	27.70918	4.55E-05	608713.4	4.19403536
2	27.76889	4.55E-05	610025.2	4.20307368
3	27.77889	4.55E-05	610244.9	4.20458713
4	27.67859	4.55E-05	608041.4	4.18940546
5	27.712	4.55E-05	608775.4	4.1944624

E (Kpa)	logE (Kpa)
4194035	6.622632
4203074	6.623567
4204587	6.623723
4189405	6.622152
4194462	6.622676

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	307.7705	10.75		0.00018544	3.5
2	307.6576	10.75		0.00018544	3.5
3	307.6782	10.75		0.00018544	3.5
4	307.7156	10.75		0.00018544	3.5
5	307.653	10.75		0.00018544	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	28.62982	5.3E-05	540356.6	3.72305677
2	28.61931	5.3E-05	540158.3	3.72169079
3	28.62122	5.3E-05	540194.4	3.72193926
4	28.62471	5.3E-05	540260.2	3.72239265
5	28.61888	5.3E-05	540150.1	3.7216343

E (Kpa)	logE (Kpa)
3723057	6.5709
3721691	6.57074
3721939	6.570769
3722393	6.570822
3721634	6.570734

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	313.5395	10.75		0.00021201	3.5
2	312.816	10.75		0.00021201	3.5
3	311.9343	10.75		0.00021201	3.5
4	313.5313	10.75		0.00021201	3.5
5	312.8406	10.75		0.00021201	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	29.16647	6.06E-05	481503.6	3.31755965
2	29.09916	6.06E-05	480392.5	3.30990419
3	29.01714	6.06E-05	479038.4	3.30057451
4	29.1657	6.06E-05	481490.9	3.31747214
5	29.10145	6.06E-05	480430.3	3.3101648

E (Kpa)	logE (Kpa)
3317560	6.520819
3309904	6.519815
3300575	6.51859
3317472	6.520807
3310165	6.51985

	0.1Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	316.324	10.75		0.00026903	3.5
2	316.3703	10.75		0.00026903	3.5
3	316.0776	10.75		0.00026903	3.5
4	316.2885	10.75		0.00026903	3.5
5	315.9654	10.75		0.00026903	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	29.42549	7.69E-05	382820.4	2.63763275
2	29.42979	7.69E-05	382876.4	2.63801848
3	29.40257	7.69E-05	382522.3	2.63557842
4	29.42219	7.69E-05	382777.5	2.63733699
5	29.39213	7.69E-05	382386.4	2.63464244

E (Kpa)	logE (Kpa)
2637633	6.421214
2638018	6.421278
2635578	6.420876
2637337	6.421166
2634642	6.420722

(37.8 degrees)

Freq (Hz)	Peak Displ. Values (in)	Peak Load Values (lb-f)	Peak Displ. Time (secs)	Peak Load Time (secs)	Phase Shift Values (secs)	Average Displ. (in)	Average Load (lb)
10	0.00093	107.36	22.27588	22.27002	0.005859	0.000931	107.5403
	0.000929	107.47	22.38119	22.370117	0.011069		
	0.000932	107.6	22.46654	22.469238	0.002698		
	0.000929	107.57	22.58057	22.569012	0.011554		
	0.000936	107.7	22.68636	22.669434	0.016927		
5	0.001069	105.48	41.8527	41.830078	0.022625	0.001071	105.9952
	0.001069	105.54	42.03662	42.029949	0.006672		
	0.00107	106.49	42.23568	42.225586	0.010094		
	0.001072	106.43	42.45297	42.423016	0.029949		
	0.001072	106.04	42.65283	42.62484	0.027992		
1	0.001209	105.8	58.34001	58.262207	0.077801	0.001218	105.7351
	0.001209	106.42	59.35107	59.234703	0.116371		
	0.001222	105.42	60.50914	60.255859	0.253281		
	0.001222	105.55	61.35059	61.261395	0.089191		
	0.001229	105.5	62.35612	62.260742	0.095379		
0.5	0.001332	104.46	83.9292	83.819992	0.109207	0.001345	104.8966
	0.001341	105.15	85.979	85.801109	0.177895		
	0.001346	104.59	87.92806	87.814941	0.113121		
	0.001348	105.17	89.9624	89.756187	0.206215		
	0.001357	105.12	91.91179	91.764816	0.146973		
0.1	0.00151	104.49	188.6564	188.229	0.42742	0.001524	104.86
	0.00152	105.53	198.722	198.09473	0.62729		
	0.001522	104.4	208.6729	208.17693	0.49592		
	0.001531	105.45	218.7902	218.13933	0.65088		
	0.001538	104.44	228.6856	228.18994	0.49561		

	10Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	107.355	10.75		0.00007761	3.5
2	107.4738	10.75		0.00007761	3.5
3	107.6021	10.75		0.00007761	3.5
4	107.5662	10.75		0.00007761	3.5
5	107.7044	10.75		0.00007761	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.986513	2E-05	450378.7	3.10310902
2	9.997567	2E-05	450877.2	3.10654381
3	10.00949	2E-05	451415.1	3.11024974
4	10.00616	2E-05	451264.7	3.10921349
5	10.01901	2E-05	451844.2	3.11320673

Kpa	log KPa
3103109	6.491797
3106544	6.492277
3110250	6.492795
3109213	6.492651
3113207	6.493208

5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	105.4805	10.75		0.00008922	3.5
2	105.5351	10.75		0.00008922	3.5
3	106.4927	10.75		0.00008922	3.5
4	106.4314	10.75		0.00008922	3.5
5	106.0365	10.75		0.00008922	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.812135	3E-05	384913.7	2.6520556
2	9.81722	3E-05	385113.2	2.65342989
3	9.906301	3E-05	388607.7	2.67750723
4	9.900599	3E-05	388384	2.67596599
5	9.86386	3E-05	386942.8	2.66603616

E (Kpa)	logE (Kpa)
2652056	6.423583
2653430	6.423808
2677507	6.427731
2675966	6.427481
2666036	6.425866

1HZ					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	105.7992	10.75		0.00010154	3.5
2	106.4179	10.75		0.00010154	3.5
3	105.4159	10.75		0.00010154	3.5
4	105.5471	10.75		0.00010154	3.5
5	105.4956	10.75		0.00010154	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.84179	3E-05	339248.4	2.33742155
2	9.899335	3E-05	341232	2.35108849
3	9.806127	3E-05	338019.1	2.32895176
4	9.818333	3E-05	338439.9	2.33185058
5	9.813548	3E-05	338274.9	2.33071412

E (Kpa)	logE (Kpa)
2337422	6.368737
2351088	6.371269
2328952	6.36716
2331851	6.367701
2330714	6.367489

0.5Hz					
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	104.4571	10.75		0.00011206	3.5
2	105.1452	10.75		0.00011206	3.5
3	104.5892	10.75		0.00011206	3.5
4	105.1671	10.75		0.00011206	3.5
5	105.1244	10.75		0.00011206	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.716936	3E-05	303494.3	2.09107563
2	9.780945	3E-05	305493.5	2.10485038
3	9.72923	3E-05	303878.3	2.09372128
4	9.782983	3E-05	305557.2	2.10528898
5	9.77901	3E-05	305433.1	2.10443399

E (Kpa)	logE (Kpa)
2091076	6.32037
2104850	6.323221
2093721	6.320919
2105289	6.323312
2104434	6.323135

	0.1Hz				
Cycle #	P(lb-f)	A(in2)		Δ	GL
1	104.4894	10.75		0.00012702	3.5
2	105.5274	10.75		0.00012702	3.5
3	104.4014	10.75		0.00012702	3.5
4	105.4458	10.75		0.00012702	3.5
5	104.4363	10.75		0.00012702	3.5

Cycle #	σ=P/A	ε =Δ-GL	[E*]=σ/ε (psi)	[E*]=σ/ε (GPa)
1	9.719942	4E-05	267820.7	1.8452846
2	9.816499	4E-05	270481.2	1.86361535
3	9.711755	4E-05	267595.1	1.84373034
4	9.808912	4E-05	270272.1	1.862175
5	9.715004	4E-05	267684.6	1.84434703

E (Kpa)	logE (Kpa)
1845285	6.266063
1863615	6.270356
1843730	6.265697
1862175	6.27002
1844347	6.265843

Appendix - B

Material Test System (MTS) 810 Load Frame & Environmental Chamber Specifications

1 810 System

1.1 318.10B-01 Model 318.10B-01, 100 kN (22,000 lbs) Load Unit 1

Nominal dynamic load rating: +/-100 kN (+/-22,000 lbs).
Test space:
- Width: 533 mm (21 inches).
- Height (with standard columns): 146 mm (5.75 inches) to 1308 mm (51.5 inches).

Overall height (with standard columns): 2540 mm (100 inches).
Base dimensions:
- Width: 844 mm (33.25 inches).
- Depth: 610 mm (24 inches).

1.1.1 22,000 lbs Actuator, 6 inch Stroke, 1 inch -14 Mounting Threads 1
1.1.2 Position Transducer, 150mm (6 inch) 1
1.1.3 Hydraulic Lifts (22 Kip 65 in) 1
1.1.4 Hydraulic Crosshead Locks (22 Kip 65 in) 1
1.1.5 Emergency Stop and Hydraulic Lift / Lock Controls 1
1.1.6 298.12 298.12 Hydraulic Service Manifold with Off/Low/On Control 1
Close-coupled accumulators allowing maximum high frequency response of servovalve(s).
Maximum operating pressure: 21 MPa (3000 psi).
Off/Low/High pressure control.
Slow pressure turn on.
Fast emergency unload for system depressurization.
1.1.7 Hydraulic Service Manifold Adapter 1
1.1.8 318.10 Crosshead 1
1.1.9 Columns for Standard Test Space 1
1.1.10 252.24G-04 252.24G-04, 10 gpm (37 lpm) 5 port High Response Servovalve 1
1.1.11 493.25 Calibration performed at MTS. Full Range for 493.25. 1
English units of measure.

1.2 FlexTest SE Controller - PLUS 1
1.2.1 493.02 MTS Model 493.02 FlexTest SE 1-Channel Chassis 1
The MTS FlexTest SE digital controller is a flexible and easy-to-use servo-controller for general testing applications.

FlexTest SE hardware is VME-based including an MVME processor to provide real-time closed-loop control. The controller includes one analog input for high level data signal or external program, three analog outputs, and four digital inputs and four digital outputs (one pair dedicated for interlock).
The Basic model can operate stand-alone (without PC) or with PC automation. A dedicated PC is included as a standard feature with the Plus model. The Plus model also features a higher performance controller processor, capable of update rates up to 6KHz
The higher performance processor is available as an option on the Basic model controller. If a stand-alone controller is desired for low-cost initial use, and TestWorks 4 or other application software is anticipated in the future, the Basic model should be ordered with the 6KHz processor.
Capabilities include:
- Function generation of monotonic ramps and cyclic waveforms using sine, square and triangular shapes can be generated.
- Graphic color display with optional general purpose scope; meters, which provide digital displays of specified measurements.
- Auto zero, bumpless start, hydraulics on mode-switching.
- Ability to save and restore PID tuning settings.
- Adaptive controls compensation; Peak-Valley and Null Pacing.

1.2.2 Multi-position Handle 1

1.2.3 493.25 MTS Model 493.25 Universal Conditioner 3

Provides transducer conditioning for AC or DC transducers.
Normalized with an on board reference for easy portability of calibrations.
Low noise, low drift, high accuracy signal conditioning.
Computer control of range, transducer zero, excitation, filter.
Designed for full range calibrations.
Shunt calibration for 100% range.
Supports strain gage bridge completion.
Excitation loss detection.
Computer controlled limit detection.
Excitation frequency: 9.83 kHz.

1.2.4 493.45 Analog input package for 493 1

Provides set of 6 auxiliary input channels for high level (+/- 10V) analog signals which can be used for control and data acquisition.
Includes adapter supporting BNC connectors on six 'pig-tail' leads.
Limit of 1 module per controller.

1.2.5 493.14 493.14 Two Stage Valve Driver 1

Provides servovalve drive signal for 2-stage servovalves.
- Supports single or dual MTS Model 252 style servovalves.

- Digitally controlled fault protection logic.
- 16 bit resolution on valve D/A.

1.2.6 E-Stop Cable, 25ft / 7.5m 1
1.2.7 Load Transducer ID Cable, PT, 5ft / 1.5m 1
1.2.8 Transducer Cable, 25ft / 7.5m 2
1.2.9 HSM Cable, 298.12, 25ft / 7.5m 1
1.2.10 Single Servovalve Cable, 25ft / 7.5m 1
1.2.11 Ground Cable, 25ft / 7.5m 1
1.2.12 LVDT Transducer ID Cable, 5ft / 1.5m 1
1.2.13 FlexTest SE PC Automation Kit 1

This kit includes the MTS computer referenced elsewhere in this quote. Installed on the computer is Model 793.00 Software and 100MBPS Ethernet network card / cable.
Enables use of Basic TestWare to setup and run cyclic and monotonic tests, and acquire and store test data.

1.3 Compaq Pentium IV / 3.2 GHz 1

Compaq/HP Pentium IV/3.2 GHz
512MB SDRAM Memory, 512KB L2 CACHE Memory.
40GB SMART III Ultra ATA/100 Hard Drive, 1.44MB Diskette Drive.
CD/RW, X48
Windows XP.

1.3.1 17 inch Compaq Monitor SVGA 1

1.4 793.00 793.00 FlexTest SE Automation (PC) System Software Key 1

MTS 793 System Software including:
- Station Builder Software -- Provides a software interface for reconfiguring the controller.
- Station Manager Software -- Provides the main user interface to the test station.
- Basic TestWare -- Basic TestWare (BTW) is a software application that allows the user to define, save and execute simple test procedures.
- Null Pacing -- Ensures that desired levels are achieved on initial pass without over-programming. Can be used to optimize performance to reproduce waveshape or to maximize test speed.
- Peak Valley Control (PVC) -- Corrects for peaks and mean levels in cyclic waveforms. PVC is our most popular and widely used compensation tool.

1.4.1 FlexTest SE Maintenance, Enhancement, and Support (ME&S)
1

The FlexTest SE Maintenance, Enhancement, and Support (ME&S) makes it easy and cost effective to keep pace with rapidly changing technologies.
ME&S owners receive all software Updates (maintenance) and software Upgrades (enhancement) that become available after your initial purchase. During the life of the contract, ME&S owners are authorized to contact MTS for live technical support.
Enhancements may include upgrades for previously purchased software options (e.g. improved editing and plotting for the Profile Editor option).
The ME&S only covers new features that are included in the base system.
New features that are sold as options with a new release are not included, but are available for an additional charge.
Coverage includes FlexTest SE and all applications and options delivered on the System Software Media (e.g. MPT). Coverage for additional applications is available at an additional charge.

1.5 Service 1

1.5.1 MTS Installation and Commissioning 1

MTS Installation and Commissioning Plan.
This items covers installation and commissioning per the MTS Installation and Commissioning Plan. See plan for details.

1.6 Vented In-vessel Load Cell 25 kN (5.5 Kip) 1

25 kN (5.5 Kip) force rating.
Air or silicon oil confining fluid use only.
Uses load channel signal conditioner from the Uniaxial Testing System
Requires (1) load calibration.
Cable, 7.6 m (25 ft.)

1.7 Model 651.34S LN2 Cooled Chamber Assembly 1

MTS Model 651.34 Liquid Nitrogen cooled, mechanically heated chamber
Temperature control from -70° C up to +100° C for asphalt testing. Please contact MTS for extended temperature range option.
Inside dimensions adequate for all Uniaxial Test Packages and the Model 655.04 Triaxial Cell: 305 mm wide x 610 mm high x 508 mm deep
Temperature controller with PID control algorithms for manual or software command of temperature set point. Stability, ±0.2° C with control and readout RTD on the specimen surface.
"U" Plugs for easy removal from load frame test space
Sight window in front door with interior lighting

Solenoid controlled LN2 regulator and flexible hose for connection to customer-supplied LN2 container
Cart for 810 Load Unit
Electrical power requirements: 220 VAC, 30A, 60 Hz, 1 Phase

1.8 Feed trough cables for triaxial cell 5
complete with limo connectors on one end and PT connectors on the other end. Length is 15 feet or more. Specifically designed to work with feed throughs of a triaxial cell.

Fair market value of all above items (1.1 1.9)............................ Call for Quote.

2 Options for 810 System
2.1.1 661.20E-03 661.20E-03 Axial Load Cell 1
2.1.2 1 inch -14 Load Cell Mounting Hardware 1
2.1.3 493.25 Calibration performed at MTS. Full Range for 493.25. 1

3 Options for Spare Parts and Consumables
3.1 Actuator Seal Kit, 318.10 Load Frame, 100 kN (22 kip) 1
Actuator Seal Kit, 318.10 Load Frame, 100 kN (22 kip)
- Non-Hydrostatic bearing

NOTE: The prices quoted above are expressed in Canadian dollars, unless otherwise noted. Prices do not include any local, state, or federal taxes, if applicable.

Standard Project Engineering and Services

Documentation
MTS supplies one set of documentation. Documentation is supplied on CD; paper copies are also provided for some items. Depending on the system configuration, documentation consists of some or all of the following:

Software Information
Includes descriptions of some or all of the following, as appropriate for the system: System Controller software, Test Definition software, Data Analysis software and other software tools.

Operation Information
Includes system operating instructions and information.

Reference Information
Pertinent system drawings, parts lists, and product information manuals. **Note: For MTS Minneapolis based servocontrolled systems, the documentation is supplied in pdf format on a browser-based CD. Paper copies of the System Reference manual are available on request for an additional fee.**

Vendor Manuals
As received by MTS for equipment such as personal computers.

Customer Responsibilities

Facility Requirements
The customer should perform a detailed review of the machine specifications to assure that the facility where the machine will be installed has an appropriate sized dock to accommodate the dimensions of the MTS system being purchased. The path that the system will take to it's final destination should be measured to verify that the entry into the building, any doorways, elevators, or stairways that the machine must travel through, will accommodate the dimensions of the purchased MTS system. The customer should have appropriate moving equipment available to position the machine. Please pay close attention to the fork-lift handling instructions that accompany the shipment.

Equipment & Personnel

The customer will provide suitable equipment and personnel to unload and set in place all items in the contract, prior to the arrival of the MTS installation engineer. It is the customer's responsibility to ensure the system is handled and manipulated per the packing instructions.

Power

Electrical power for MTS supplied equipment will be provided by the customer. This electrical supply should be free from power transients caused by other equipment on the circuit. This includes appropriate electrical power for the hydraulic power supply (HPS) as well as a fused disconnect when an HPS is purchased. The desired HPS voltage must be specified at the time of the order.

Water

If a hydraulic power supply with a water to oil heat exchanger or water-cooled accessories are purchased, a cooling water supply and drain of sufficient capacity are required. The cooling water lines shall be provided and connected by the customer.

Environment

Environmental requirements are indicated in the associated product literature. If purchased, the hydraulic power supply will require a room with adequate ventilation to ensure the maximum temperature for the room does not exceed 104 degree F (40 degree C). The electronic components and computer equipment should be located in a suitable environment with respect to temperature, humidity, and dust.

Specimens

For installation, demonstration, and training, the customer will provide suitable specimens and other materials appropriate for use with the equipment described in this quotation.

Accreditation

MTS North American Field Service is accredited by the American Association of Laboratory Accreditation (A2LA) to deliver on-site calibrations in conformance to ISO/IEC 17025. Our Certificate number is 1145.01. The accreditation covers the specific calibrations listed on the agreed Scope of Accreditation, available on the A2LA website, www.a2la.org. Our calibration service meets the requirements of ISO/IEC 17025, ANSI/NCSL Z540-1, and ISO 10012-1. All systems used for accredited testing must be calibrated on site at the time of installation by an accredited calibration entity.

For systems installed outside North America, please contact the local MTS Field Service office for information concerning accredited calibration services.

Warranty

MTS warrants equipment of its manufacture to be free of defects in materials and workmanship for a period of 12 months after **shipment** from its plant or 12 months from completion of commissioning at your site if MTS installs the equipment. MTS allows a maximum of 3 months for transit; the warranty shall not exceed 15 months from shipment in any case. MTS shall, at its option, repair or replace free of charge within the warranty period any components or assemblies supplied by MTS which prove to be defective in workmanship or materials, subject to the following:

MTS reserves the right to request the prepaid return of such defective items to its plant for inspection and evaluation.

Expendable items (oil, lamps, seals, filters, etc.) and items subject to normal wear and/or replacement, will not be covered under warranty if their failure is the result of normal wear. Re-calibration of transducers is not covered by this warranty.

MTS reserves the right to reject those claims for warranty where it is determined that failure is caused by Buyer made modifications, improper maintenance, misuse or abuse of the equipment.

This warranty is extended only to the original Buyer of the equipment.

Items supplied by MTS but not of its manufacture (computers, oscilloscopes, commercial software packages, etc.) carry the original manufacturer's warranty which is passed on to the customer who is responsible to deal directly with the manufacturer on warranty issues.

MTS Integrated Software, MTS will provide telephone consultation and strive to correct errors brought to its attention for the period of the warranty.

This warranty is expressly in lieu of all other warranties expressed or implied, statutory or otherwise, including any implied warranty of merchantability or fitness or suitability for a particular purpose. No warranties are expressed or implied which extend beyond the description of the face hereof. In no event shall MTS be liable to the Buyer for collateral, indirect, incidental or consequential damages of any kind.

MTS assumes no liability for damages arising from the use of the equipment by the buyer or any third party. By purchasing MTS equipment, the Buyer assumes all liability for any damages of any kind which may result from its use or misuse by the Buyer, Buyer's employees, agents, contractors or any other third party unknown to MTS or the Buyer, including damages due to failure of the equipment.

MTS *Limited Warranties* is the over-ruling document in the event of a conflict or misunderstanding and is incorporated by this reference.

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