Effects of Hot Plant Fuel Characteristics and Combustion on Asphalt Concrete Quality

Study SD2001-13
Appendices

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16. Abstract

This report summarizes the results of an extensive and comprehensive study to evaluate the possibility of contaminating hot mix asphalt due to the use of alternate fuel types and through poor combustion of the fuel. Eleven different fuels were used, and the plant burner was adjusted to optimum, insufficient oxygen and excess oxygen conditions.

Samples of aggregates and of hot mix produced under these combinations of fuel and combustion conditions were collected and tested using a variety of chemical and physical tests. Gravimetric analysis of the heated aggregates did reveal the presence of minute traces of residue at less than 35 ppb by weight of aggregate. This residue was then analyzed using gas chromatography and FTIR, and was shown to be composed of partially decomposed tars and fuel residues. The dynamic shear rheometer, bending beam rheometer and direct tension tests were used to assess whether the residue caused any changes in binder properties; none were detected. Samples of the hot mix produced in the plant were evaluated using gyratory compaction parameters, Superpave shear tests, dynamic modulus, loaded wheel and moisture sensitivity tests. Again, no significant changes in mix properties were observed.

Based on these findings, it was recommended that SDDOT expand the list of allowable fuels to include recycled fuel oils and fuels up to No. 6, allowing the use of economical alternates. No. 6 fuel should be evaluated in pilot field projects for possible inclusion in future specifications. Other specification changes and inspection techniques to ensure combustion adequacy and mix performance were recommended.

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Table 1: Glossary

Term	Meaning
Air voids (V_a)	T the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as percent of the bulk volume of the compacted paving mixture.
Analysis of Variance (ANOVA)	A common statistical technique used to compare groups of observations. The technique was used in this project to determine if the materials produced using different fuels were significantly different from each other, that is whether their means were significantly different.
Asphalt cement	A naturally occurring material or byproduct of petroleum processing that is dark brown to black in color, cementitious, and composed primarily of bitumens.
Asphalt concrete	A mixture of asphalt cement or binder with aggregates compacted into a mass, usually a pavement.
Asphalt content (P_b)	The percent by mass of asphalt binder in the total mixture.
Binder	asphalt cement with or without the addition of modifiers
Bulk Specific Gravity ($G_{1,2,n}$; G_{sb}, G_{mb})	The specific gravity of a porous solid, when the volume of the solid as used in the calculation includes both the permeable and impermeable voids.
Combustion products	The products resulting from the burning of any kind of material containing carbon and hydrogen, typically including carbon dioxide, carbon monoxide, nitrogen, nitrogen oxides, oxygen, sulfur oxides and water vapor.
Complex shear modulus (G^*)	The modulus of elasticity of a material tested in shear. G^* is used in the SST as a factor related to pavement rutting at high temperatures.
Critical Temperatures	The temperature at which a binder just meets the performance grading specification limit.
Dynamic modulus ($|E^*|$)	The norm of the complex modulus E^*, which is the ratio of stress to strain in a linear viscoelastic material. Dynamic modulus is measured by applying a sinusoidal axial compressive load to a specimen and determining the applied stress and resulting strain.
Excess air	Typically refers to the additional air, over and above the stoichiometric air, that is provided to a burner to ensure complete combustion. As used in this report, however, excess air is in excess of the amount typically used for combustion.
Exhaust gases	The combination of combustion products, excess air, water vapor, leakage air, etc.
Extraction	The process of removing asphalt binder from a sample of hot mix asphalt leaving the aggregate behind.
Gravimetric analysis	An analysis technique used to determine relative amounts of different types of chemical constituents based on weight.
Hot Mix Asphalt (HMA)	A mixture of aggregate and asphalt cement, sometimes including modifiers, that is produced by mixing hot, dried aggregate with heated asphalt in a plant designed for the process.
Inorganic carbon	At very high temperatures in the gravimetric analysis, inorganic carbon present in the minerals of the aggregates, such as carbonates, and interstitial water could be driven off. The change in weight, then at high temperatures represents this inorganic carbon and interstitial water, which are components of the aggregate.
Insoluble organic carbon	As measured in gravimetric analysis of residue in this research, insoluble organic carbon represents char
Plastic strain	As used in this report, plastic strain is the accumulated, permanent strain that builds up in a sample subjected to repeated shear in the repeated shear at constant height test in the SST.
Recovery	The process of separating asphalt binder from the solvent used to extract the binder from a sample of hot mix asphalt.
Reclaimed Asphalt Pavement (RAP)	Asphalt paving material milled or scraped off an existing bituminous pavement, consisting of aggregate and asphalt binder.
Soluble organic carbon	The soluble organic carbon measured in the gravimetric analysis represents organic carbon residue from the fuel.
Specific Gravity	The ratio of the mass in air of a unit volume of a material to the mass of an equal volume of water at a stated temperature.
Stoichiometric air	The amount of air needed to provide enough oxygen atoms to react with each carbon and hydrogen atom in a fuel to completely combust the fuel without any oxygen, carbon or hydrogen remaining.

Table 2: Acronyms

Acronymn	Meaning
AASHTO	American Association of State Highway and Transportation Officials
BBR	Bending Beam Rheometer
D/A	Dust to Asphalt Ratio
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Tester
E*	Dynamic Modulus ("E-Star")
EPA-UOF	Environmental Protection Agency Used Oil Fuel
FID	Flame Ionization Device, Used in Chromatography
FS	Frequency Sweep Test in the Superpave Shear Tester
FTIR	Fourier Transform Infrared Analysis
$G^*/\sin \delta$	High Temperature Binder Stiffness ("G-Star Sine Delta")
GC	Gas Chromatography
GPC	Gel Permeation Chromatography
HMA	Hot Mix Asphalt, Asphalt Concrete
HRG	Heritage Research Group
LVDT	Linear Variable Differential Transducer
MS	Mass Spectrometer
NCSC	North Central Superpave Center
N_{ini}	N-Initial
PAV	Pressure Aging Vessel
PG	Performance Graded Binder
RFO	Recycled Fuel Oil
RTFO	Rolling Thin Film Oven
SCF	Standard Cubic Feet, Volume At Standard Conditions (70°F And 760 Mm/Hg Pressure)
SGC	Superpave Gyratory Compactor
SS	Simple Shear Test in the Superpave Shear Tester
SST	Superpave Shear Tester
ssu	Saybolt Seconds Universal
T283	AASHTO Moisture Sensitivity Test
WRI	Western Research Institute

APPENDIX B. EXHAUST GAS DATA

Table 3: Exhaust Gas Composition for #2 Fuel

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	608	11.93	0.05	6.64	84	138.0
	Optimum O_2	320	15.56	0.04	3.92	46	301.9
	Excess O_2	222	17.32	0.03	2.61	28	502.4
AC Added	Insufficient O_2	205	10.30	0.02	7.88	92	100.7
	Optimum O_2	215	16.13	0.04	3.56	44	345.0
	Excess O_2	182	17.20	0.04	2.70	31	482.8

Table 4: Exhaust Gas Composition for #5H Fuel

Conditions		CO (ppm)	O2 (%)	CxHx (%)	CO2 (ppm)	NOx (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	2670	10.82	0.10	7.48	119	111.4
	Optimum O_2	338	16.42	0.03	3.28	50	379.9
	Excess O_2	218	17.61	0.02	2.40	37	555.7
AC Added	Insufficient O_2	4000	9.38	0.15	8.58	149	84.4
	Optimum O_2	845	14.55	0.06	4.67	74	237.4
	Excess O_2	664	16.06	0.04	3.57	60	345.4

Table 5: Exhaust Gas Composition for #5L Fuel

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	398	12.12	0.06	6.49	135	143.2
	Optimum O_2	300	16.56	0.06	3.18	57	396.0
	Excess O_2	294	16.94	0.06	2.89	55	444.0
AC Added	Insufficient O_2	203	10.53	0.05	7.7	161	105.2
	Optimum O_2	316	15.48	0.08	3.98	80	298.5
	Excess O_2	275	16.42	0.06	3.28	67	379.9

Table 6: Exhaust Gas Composition for #6 Fuel

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	2213	9.08	0.82	8.81	133	79.7
	Optimum O_2	1770	12.44	0.35	6.26	77	152.4
	Excess O_2	510	15.24	0.27	4.15	44	280.6
AC Added	Insufficient O_2	330	11.40	2.10	5.40	83	108.0
	Optimum O_2	2915	12.60	0.23	5.95	91	161.0
	Excess O_2	N/A	N/A	N/A	N/A	N/A	N/A

Table 7: Exhaust Gas Composition for RFO #4 Fuel

Conditions		CO (ppm)	O₂ (%)	CₓHₓ (%)	CO₂ (ppm)	NOₓ (ppm)	Excess Air (%)
AC Not Added	Insufficient O₂	149	12.60	0.02	6.13	101	157.3
	Optimum O₂	272	16.50	0.03	3.22	48	388.9
	Excess O₂	150	16.92	0.03	2.91	48	441.2
AC Added	Insufficient O₂	193	13.12	0.01	5.74	97	175.0
	Optimum O₂	134	16.90	0.00	2.90	50	442.6
	Excess O₂	111	18.35	0.00	1.86	34	614.4

Table 8: Exhaust Gas Composition for RFO #5H Fuel

Conditions		CO (ppm)	O₂ (%)	CₓHₓ (%)	CO₂ (ppm)	NOₓ (ppm)	Excess Air (%)
AC Not Added	Insufficient O₂	182	10.15	0.01	7.99	132	97.8
	Optimum O₂	242	17.04	0.03	2.82	50	465.3
	Excess O₂	158	17.88	0.02	2.20	41	614.4
AC Added	Insufficient O₂	4000	8.51	0.18	9.24	143	71.2
	Optimum O₂	275	15.40	0.05	4.07	66	287.9
	Excess O₂	265	17.38	0.03	2.57	39	511.3

Table 9: Exhaust Gas Composition for RFO #5L Fuel

Conditions		CO (ppm)	O₂ (%)	CₓHₓ (%)	CO₂ (ppm)	NOₓ (ppm)	Excess Air (%)
AC Not Added	Insufficient O₂	182	10.94	0.04	7.39	125	113.8
	Optimum O₂	230	16.63	0.05	3.12	41	404.4
	Excess O₂	154	18.41	0.03	1.81	26	614.4
AC Added	Insufficient O₂	4000	10.48	1.07	7.74	121	104.2
	Optimum O₂	139	17.06	0.04	2.81	46	460.2
	Excess O₂	2574	15.90	0.18	3.70	60	336.8

Table 10: Exhaust Gas Composition for Non-spec Waste Fuel #1

Conditions		CO (ppm)	O₂ (%)	CₓHₓ (%)	CO₂ (ppm)	NOₓ (ppm)	Excess Air (%)
AC Not Added	Insufficient O₂	392	13.04	0.04	5.80	100	172.0
	Optimum O₂	238	16.15	0.03	3.48	55	352.7
	Excess O₂	217	16.78	0.05	3.01	46	424.4
AC Added	Insufficient O₂	1623	10.71	0.23	7.56	123	108.9
	Optimum O₂	454	14.51	0.06	4.70	76	245.3
	Excess O₂	338	16.72	0.05	3.06	46	414.4

Table 11: Exhaust Gas Composition for Non-spec Waste Fuel #2

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	174	10.51	0.01	7.72	123	104.8
	Optimum O_2	194	16.93	0.01	2.90	43	442.6
	Excess O_2	121	17.50	0.00	2.48	40	533.7
AC Added	Insufficient O_2	175	12.04	0.01	6.55	118	141.0
	Optimum O_2	265	15.53	0.02	3.94	69	299.6
	Excess O_2	193	17.27	0.01	2.65	47	493.8

Table 12: Exhaust Gas Composition for Non-spec Waste Fuel #3

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	203	13.52	0.04	5.44	105	189.9
	Optimum O_2	151	17.29	0.04	2.63	48	497.2
	Excess O_2	105	18.27	0.04	1.91	35	614.4
AC Added	Insufficient O_2	271	13.78	0.05	5.24	96	200.8
	Optimum O_2	196	16.72	0.04	3.06	56	414.4
	Excess O_2	153	18.02	0.04	2.10	39	614.4

Table 13: Exhaust Gas Composition for Non-spec Waste Fuel #4

Conditions		CO (ppm)	O_2 (%)	C_xH_x (%)	CO_2 (ppm)	NO_x (ppm)	Excess Air (%)
AC Not Added	Insufficient O_2	545	16.91	0.05	2.92	36	439.8
	Optimum O_2	132	17.43	0.03	2.54	36	520.4
	Excess O_2	149	19.23	0.01	1.21	13	614.4
AC Added	Insufficient O_2	333	13.08	0.04	5.77	100	173.6
	Optimum O_2	276	15.94	0.04	3.64	60	333.0
	Excess O_2	270	17.05	0.03	2.82	44	458.7
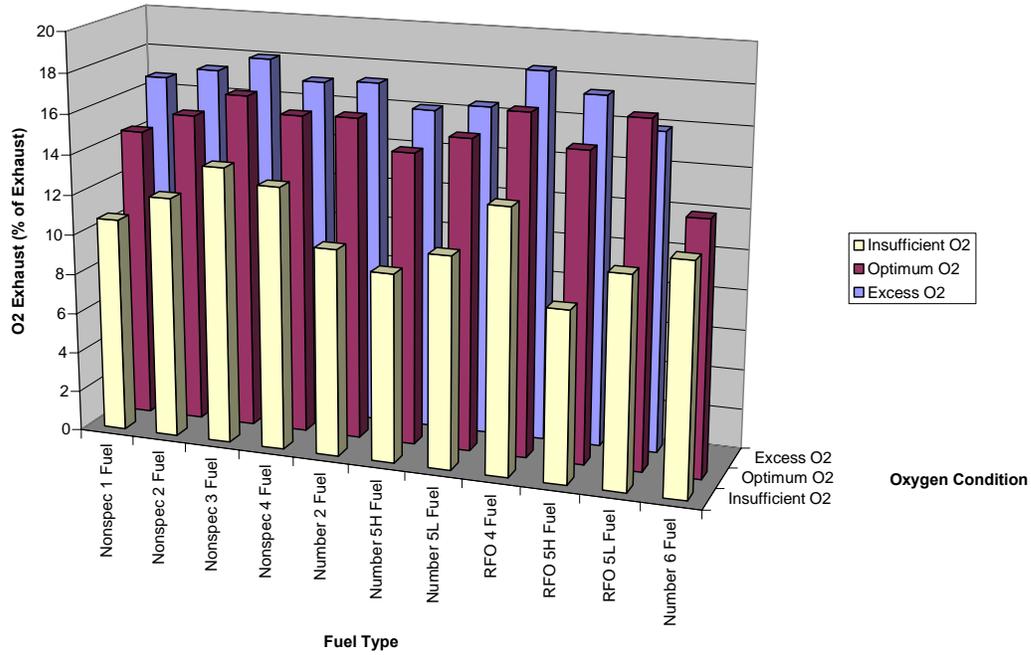
Figure 1: O$_2$ Content vs. Fuel Type and Burner Condition with AC Added
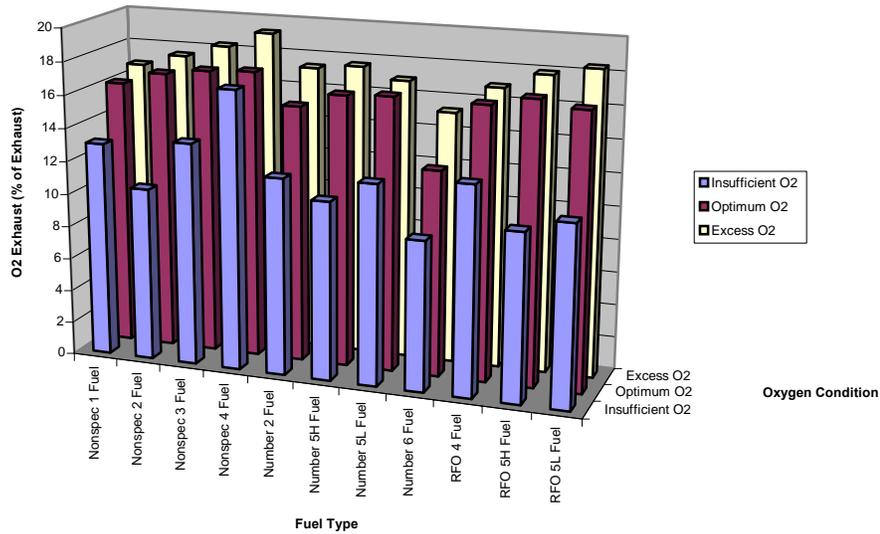
Figure 2: O$_2$ Content vs. Fuel Type and Burner Condition without AC Added
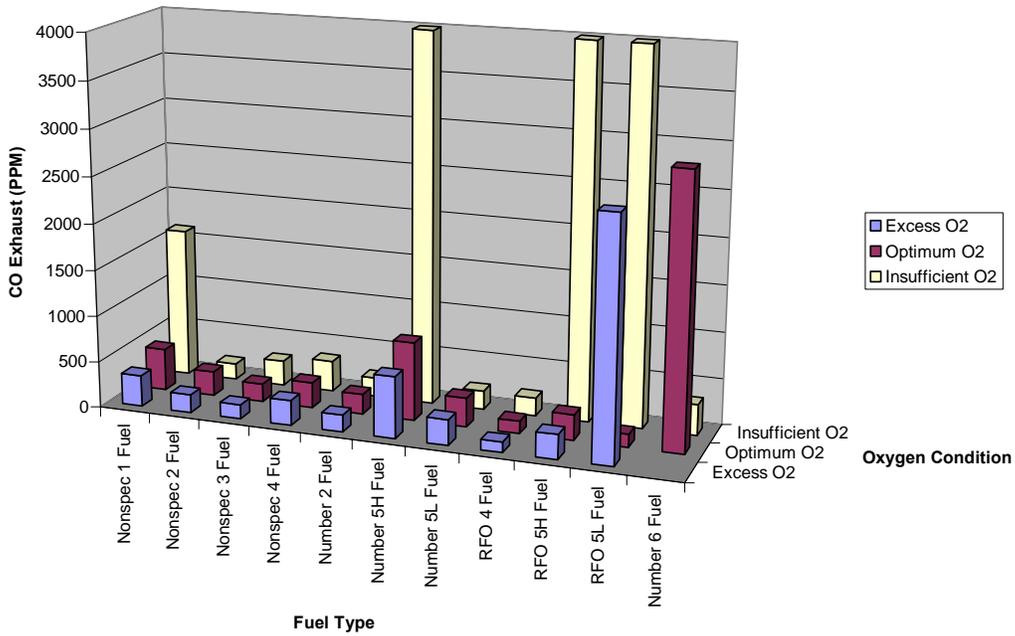
Figure 3: CO Content vs. Fuel Type and Burner Condition with AC Added
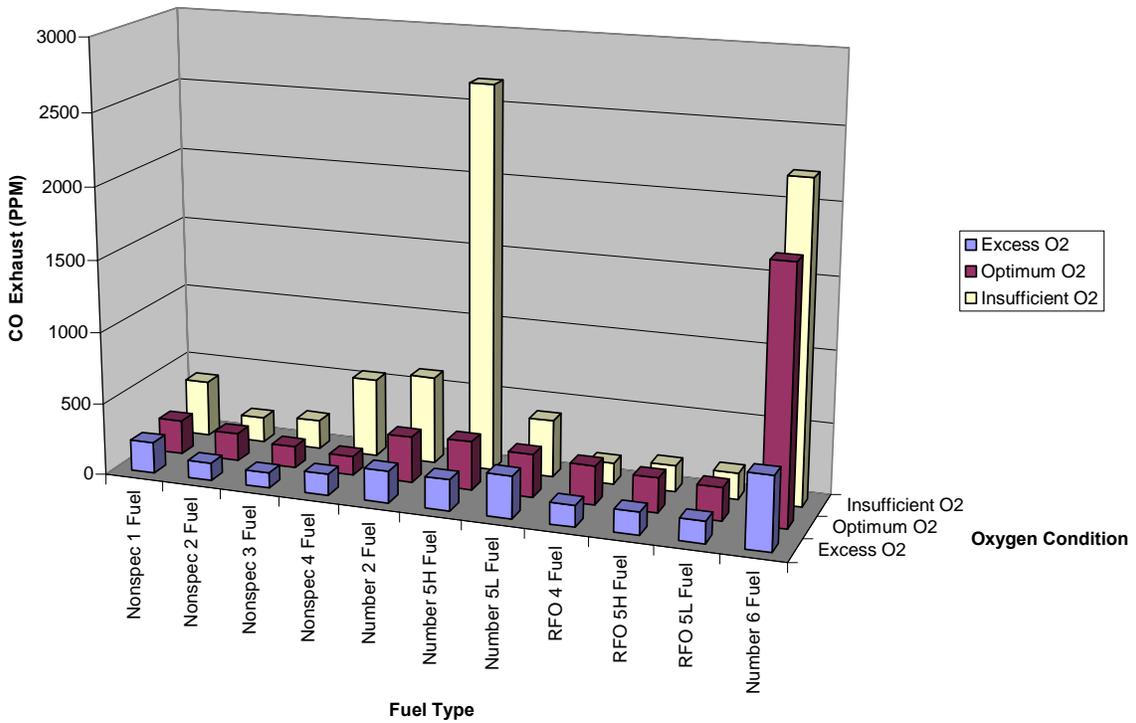
Figure 4: CO Content vs. Fuel Type and Burner Condition with No AC Added
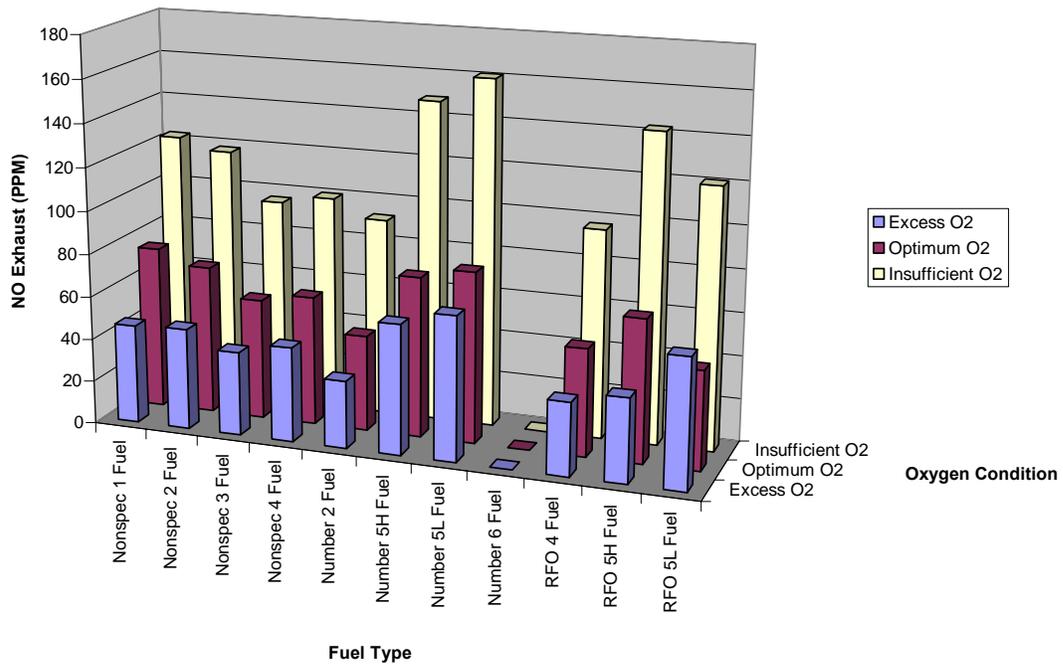
Figure 5: NO Content vs. Fuel Type and Burner Condition with AC Added
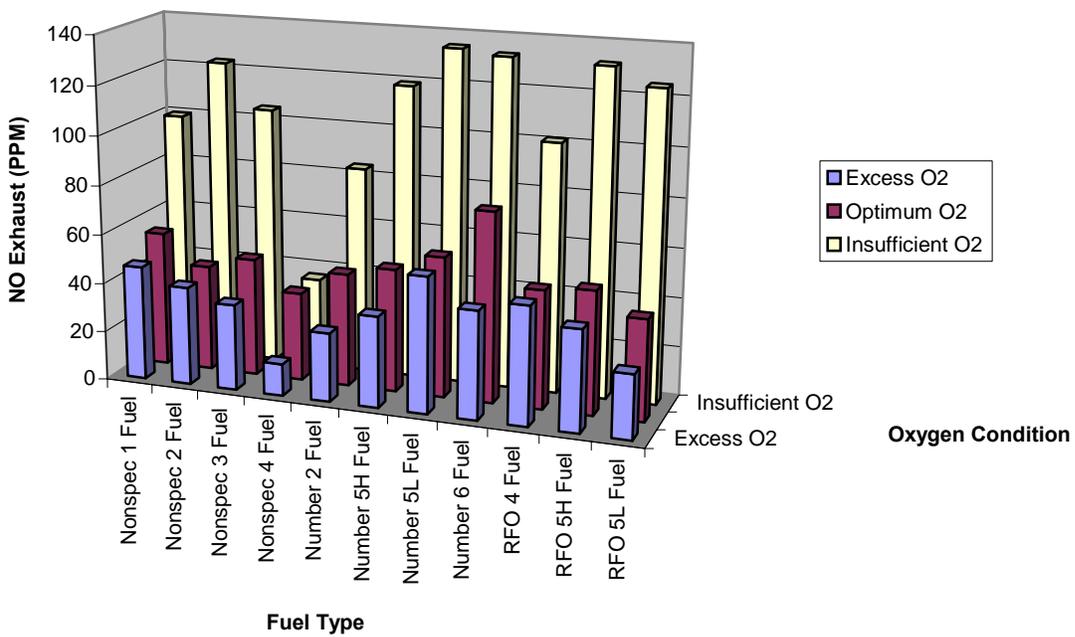
Figure 6: NO Content vs. Fuel Type and Burner Conditions without AC Added

Figure 7: C$_x$H$_x$ Content vs. Fuel Type and Burner Condition with AC Added

(Note different scale on y-axis)

Figure 8: C$_x$H$_x$ Content vs. Fuel Type and Burner Condition without AC Added
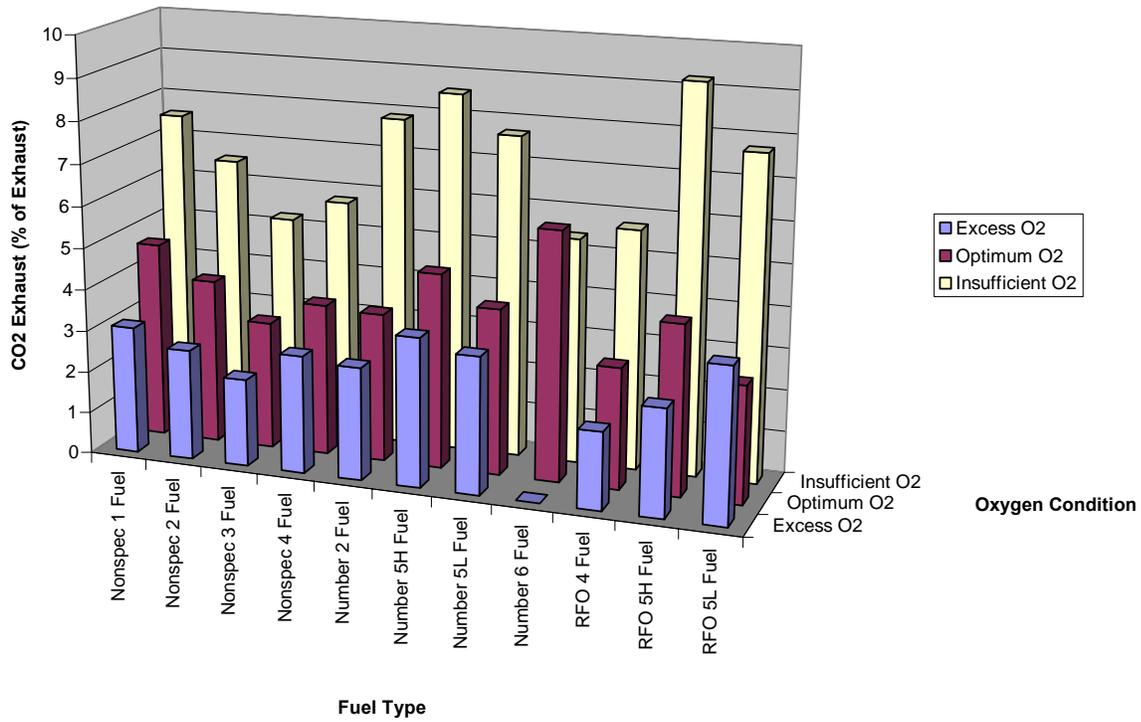
Figure 9: CO_2 Content vs. Fuel Type and Burner Condition with AC Added
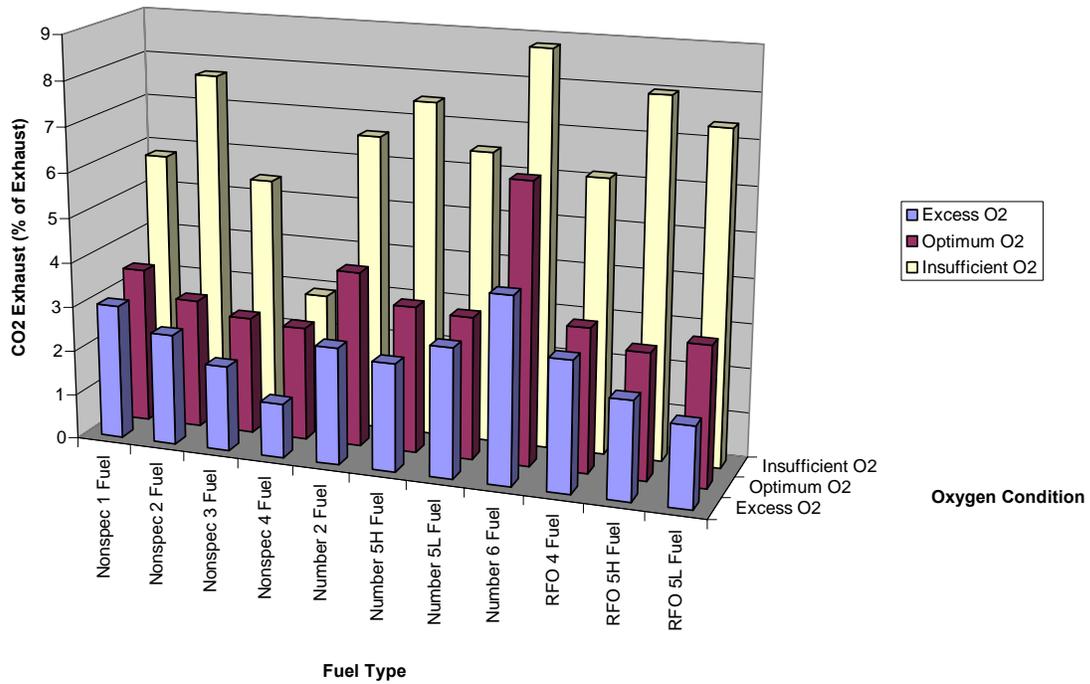
Figure 10: CO_2 Content vs. Fuel Type and Burner Condition without AC Added

**Oxygen Conditions vs. Fuel Type w/ Respect to NOx Exhaust
With AC Added**
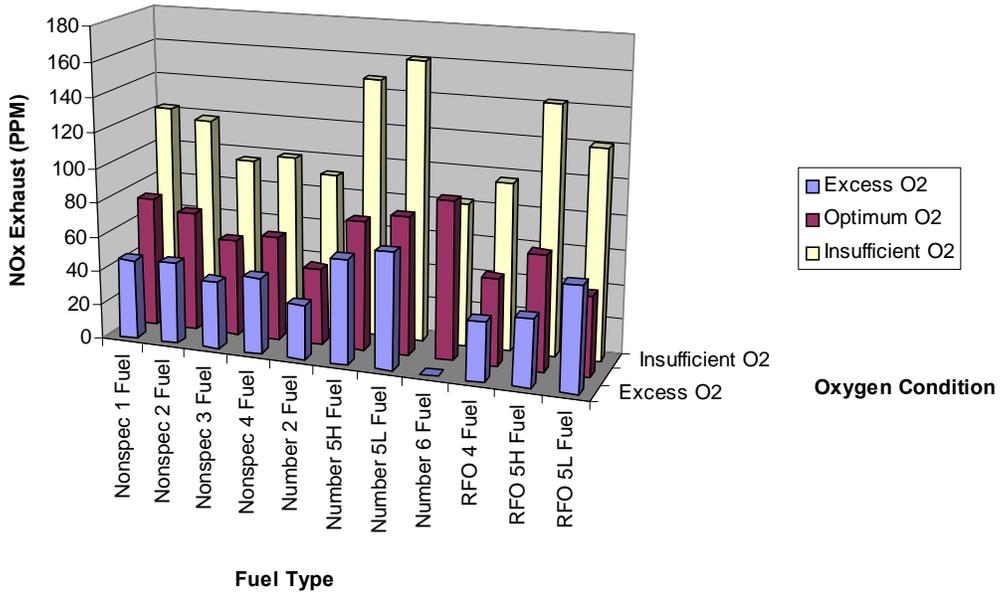
Figure 11: NO$_x$ Content vs. Fuel Type and Burner Condition with AC Added
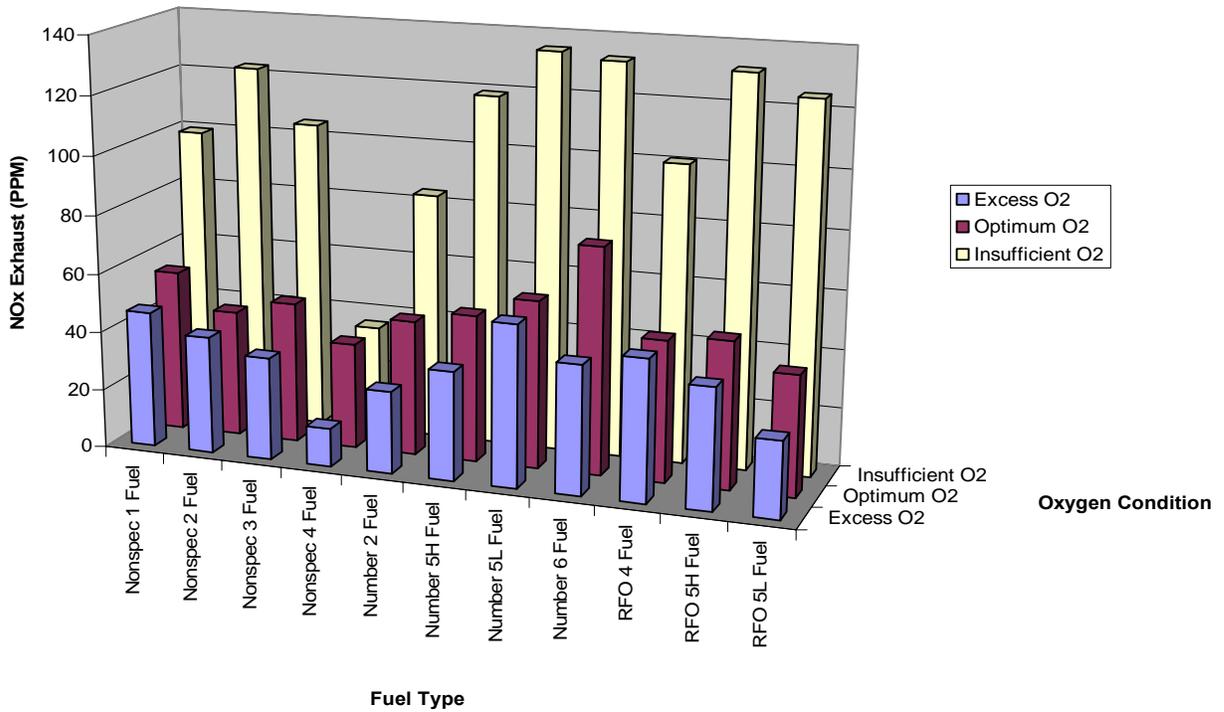
Figure 12: NO$_x$ Content vs. Fuel Type and Burner Condition without AC Added
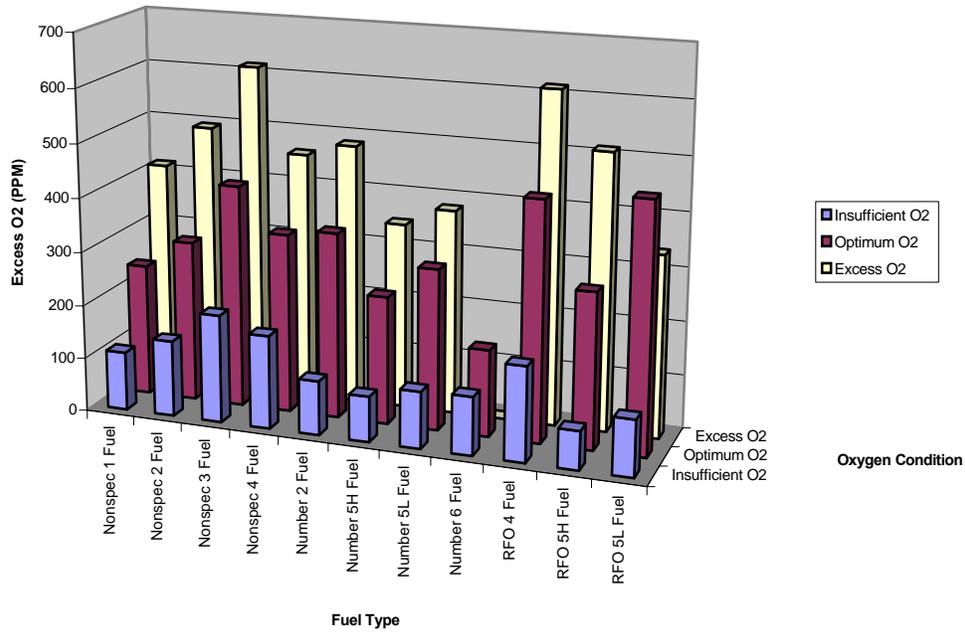
Figure 13: Excess Oxygen Content vs. Fuel Type and Burner Condition with AC Added
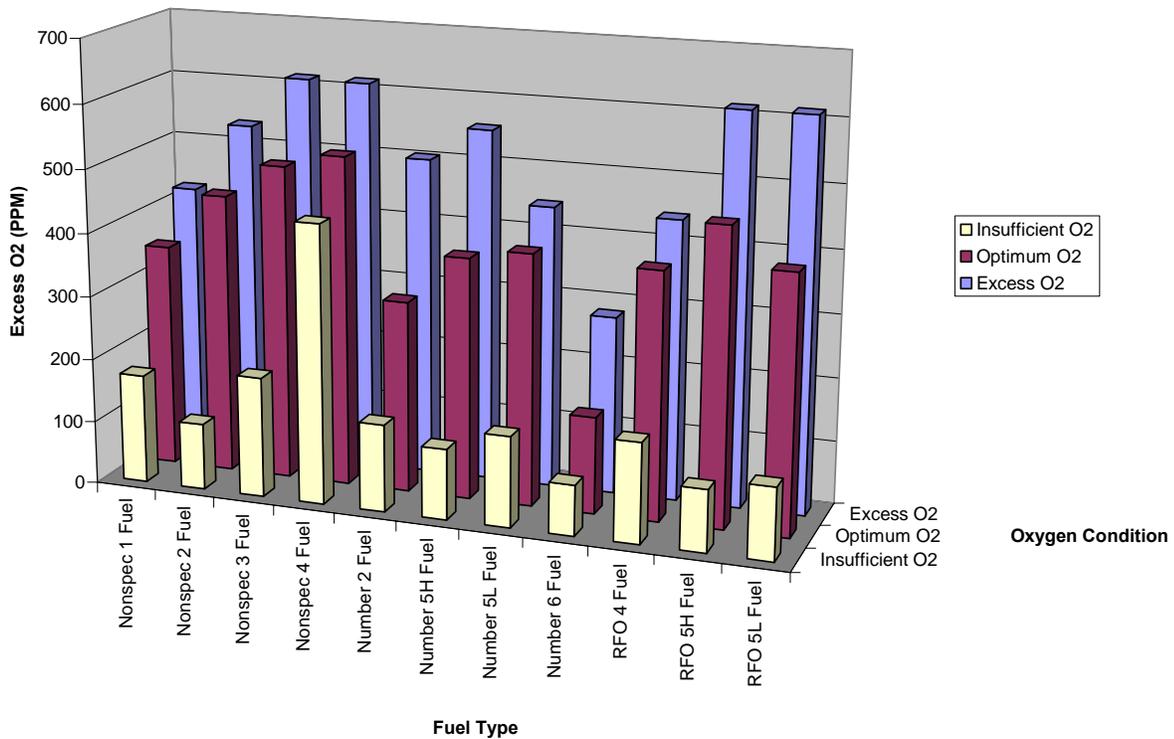
Figure 14: Excess Oxygen Content vs. Fuel Type and Burner Condition without AC Added

APPENDIX C. CHROMATOGRAPHIC AND OTHER ANALYSIS TECHNIQUES

This study used a wide variety of chromatographic and related analysis techniques in an attempt to detect and identify any contamination on the heated aggregates and in mixtures produced using different fuels under varying combustion conditions. This appendix briefly and simply describes some of the techniques considered or used.

Chromatography is method of analyzing a mixture sample that separates the mixture into its various components so that their physical or chemical properties can be determined. There are a wide variety of chromatography techniques that all rely on separating the sample in different ways. There are also a variety of detectors that can be used to analyze the components of the sample, once separated. Figure 15 illustrates the principle of separation used in all types of chromatography. The differences arise from the methods used to separate and analyze the sample.

Separation of a sample is accomplished by passing the sample through a column, or stationary phase. The sample is in the mobile phase, which carries the sample through the stationary phase. Components of the sample take different lengths of time to pass through the stationary phase depending on their properties and are therefore separated from the mixture. Once separated, they can be analyzed based on size, spectra, composition or other property.
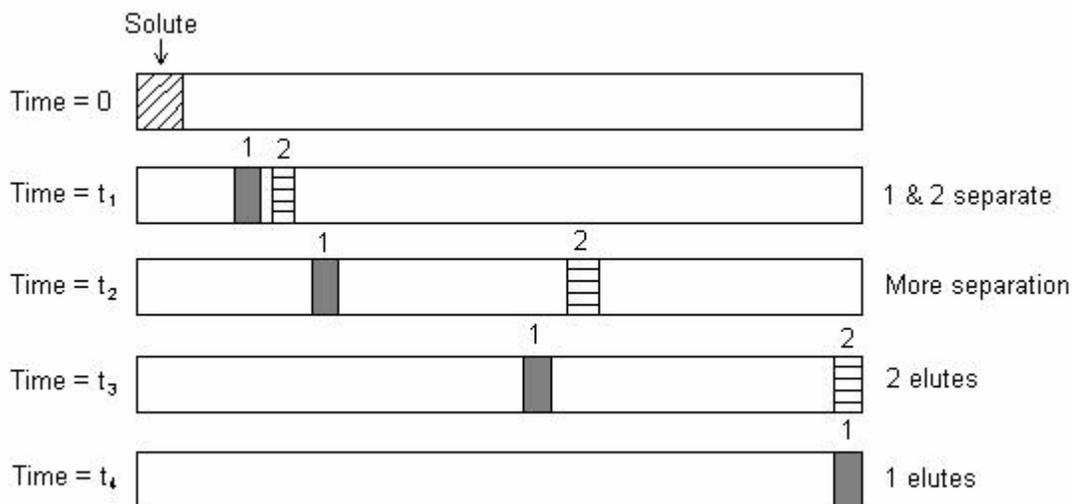
Figure 15: Principle of Chromatographic Separation

Gel Permeation Chromatography

In gel permeation chromatography (GPC), the mobile phase is a liquid solvent with the sample dissolved in it. (GPC is one type of liquid chromatography, since the carrier fluid is in a liquid form.) The stationary phase is a column packed with porous particles. GPC is sometimes called size exclusion chromatography (SEC) because the components are separated based on their molecular sizes. Larger molecules are too big to enter the pores in the column and pass through quickly. Smaller molecules can fit into the pores between the particles in the column and therefore take a longer path through the column. A detector monitors the quantity of material exiting the column as a function of time.

GPC can be used, then, to analyze the molecular size distribution of a sample. It is analogous to running a gradation analysis on an aggregate, only on a molecule size scale. GPC does not identify the chemical composition of the molecules, only their sizes, just as a sieve analysis tells the size of an aggregate, but not whether it is limestone or granite. By comparing the molecular size distribution of different samples, however, it is possible to surmise the composition. For example, if you contaminate an asphalt with a fuel, you may be able to detect the presence of the fuel by comparing the molecular size distribution of the original asphalt and fuel to the contaminated sample. In fact, Nelson and Wood were able to use GPC to detect contamination when they introduced the contaminant in the lab by just such a comparison.

GPC was considered for use in this study, but ultimately was not used for a variety of reasons. One was this inability of the technique to characterize the contaminant. In this study, we did not know if we had unburned fuel, partially burned fuel, carbon char or some other combustion byproduct as a contaminant. In addition, several experts in the field, including chemists at FHWA, Dr. Anthony Kriech at Heritage Research Group and Dr. Ray Robertson at Western Research Institute, advised that gas chromatography techniques were much more sensitive and more likely to be able to identify the chemical composition than GPC. The work done by Nelson and Wood was conducted in the late 1980's and published in 1990. Many advancements in chromatography had occurred in the meantime.

WRI was asked to run GPC, but their standard practice is to run GC as a screening tool first to determine how to set up their GPC equipment. When they ran GC, they found nothing that could be detected using GPC and therefore did not complete the testing. With GC, however, they were able to characterize the residue found on the heated aggregates.

Gas Chromatography

Gas Chromatography (GC) uses an inert gas as the mobile phase. The sample for analysis is vaporized and injected into the gas stream, which carries it through the separation column. The stationary phase is typically a liquid coated onto the walls of the column or onto a support (lining or porous medium) inside the column. If components in the mobile phase have a greater affinity for the stationary phase, they will be retained in the stationary phase for a longer period of time, separating them from those components with less affinity for the stationary phase. The column is usually inside an oven to control the temperature. By increasing the oven temperature, sample components with different boiling points can be driven off (eluted), thus separating the components.

One limitation of GC, then, is that it must be possible to volatilize the sample. Some gas chromatographs can achieve higher temperatures than others and therefore can volatilize different compounds with higher boiling points.

Once the components are separated, they can be analyzed using a variety of detectors, which are sensitive to different types of compounds or different properties. Two different types of detectors were used with GC in this research, the flame ionization device and the mass spectrometer. Both devices are connected to the end of the column so the effluent flows directly into the detector. (In some cases, a system is needed to control the flow of effluent into the detector, particularly with MS.)

Gas Chromatography with Flame Ionization Device

Gas Chromatography with Flame Ionization Device (GC-FID) uses a flame ionization device (FID) to analyze the effluent. The FID is one of the most commonly used GC detectors and is sensitive to most organic compounds, particularly hydrocarbons. It works by mixing the effluent with hydrogen and air, then igniting it, which breaks down the organic compounds and produces ions. The ions are collected and produce an electrical signal. The signal reveals the mass of particles entering the detector (or eluting from the GC column) as a function of time. FID is extremely sensitive. The drawback, for some applications, is that the sample is destroyed in the flame. That was not a concern in this research. WRI used this technique to analyze the residue from the heated aggregates.

Gas Chromatography with Mass Spectrometer

Gas Chromatography with Mass Spectrometer (GC-MS) uses GC to separate the components of a sample, then the components are fed into a mass spectrometer for analysis. The mass spectrometer works by ionizing the sample, separating the ions based on their mass (or more specifically their mass to charge ratio) and measuring the amount of the different ions. In the process of ionization, molecules break down into distinctive fragments and ions that can be used to characterize the compounds.

GC-MS is extremely sensitive and a powerful analytical tool. GC-MS is more complicated and more expensive than GC-FID, but it is more useful for determining the identity and quantity of an unknown material. GC-MS was used in this research and did identify some asphalt-like compounds (high molecular weight, polycyclic aromatic hydrocarbons with four rings and higher) from the heated aggregates.

Fourier Transform Infrared (FTIR) Analysis

In a Fourier Transform Infrared analysis, the infrared spectrum of a sample is measured. The spectrum is recorded as energy versus time. A mathematical process called a Fourier transform is then used to convert the energy vs. time spectrum into an intensity vs. frequency spectrum. This spectrum can be used to identify constituents in a sample, because different materials absorb different frequencies of infrared radiation. FTIR can be used as a detector in a gas chromatograph, but in this case a different analytical technique was used.

For this analysis, Heritage Research Group dissolved samples of the fuels (No. 2 and No. 6), the unheated asphalt binder, the residue from the heated aggregate and samples of the hot mix in tetrachloroethylene solvent. The solvent was centrifuged, placed on a thin potassium bromide (KBr) plate, and allowed to evaporate, leaving any residue behind as a thin film on the plate. The plate was then subjected to infrared radiation and full-scan FTIR spectra ($4000 - 500$ cm^{-1}) were obtained. The scans from the different materials were compared to detect differences that might indicate the presence of fuel, for example, in the hot mix. Despite repeated attempts, this technique was not found to be appropriate for analyzing the residue in this work.

References for Appendix C

Several useful websites were used as references for this appendix, including the following:

1. Thomas G. Chasteen, Sam Houston State University, Chemistry Department, Huntsville, Texas, www.shsu.edu/~chemistry/primers/gcms.html.

2. Rebecca Carrier and Julie Bordonaro, Renssalaer Polytechnic Institute, Troy, New York, www.eng.rpi.edu/dept/chem.-eng/Biotech-Environ/CHROMO/chromintro.html. (Includes the basis for Figure 15.)

3. Brian M. Tissue, Virginia Tech Chemistry Department, Blacksburg, Virginia, www.chem.vt.edu/chem.-ed/sep/sepintro.html.

4. Yuri Kazakevich and H. M. McNair, Seton Hall University, South Orange, New Jersey, http://hplc.chem..shu.edu/NEW/HPLC_Book/Introduction/int_typs.html.

5. Division of Chemistry, Sheffield Hallam University, Sheffield, United Kingdom, www.shu.ac.uk/schools/sci/chem./tutorials/chrom.chrom1.html.

APPENDIX D. BINDER AND MIXTURE TESTS

This appendix describes the tests and procedures used in the conduct of this research project. More detailed descriptions are available in referenced AASHTO and ASTM standards.

Binder Extraction and Recovery

The binder extraction and recovery procedure used for this research project is fully described in AASHTO T319-03 (or TP2-01), *Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*. This method was selected because previous research has shown it changes the physical and chemical properties of the recovered binder less than other, more common techniques like the Abson recovery.

The procedure calls for repeatedly tumbling the hot mix with solvent in a closed vessel with baffles inside to thoroughly mix the solvent and hot mix. The binder-carrying solvent is then pulled from the extraction vessel through a filter into a rotary evaporation device (Rotovapor). The solvent is gently heated by a hot oil bath and is driven off to a condenser tube. The binder remains behind in the flask of the rotary evaporator. A diagram of the set up is shown in Figure 16. It takes about five hours and a $50 single-use filter to extract and recover approximately 50g of binder.
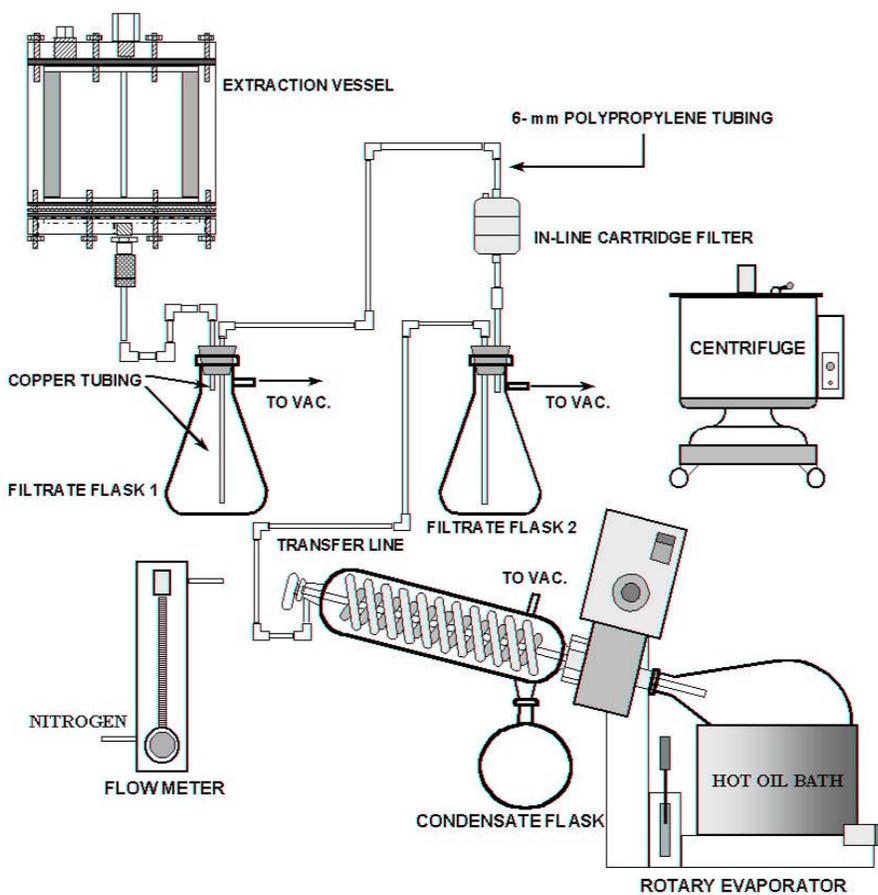
Figure 16: AASHTO T319 Extraction and Recovery Set Up (From AASHTO T391)

Binder Dynamic Shear Rheometer (DSR) Testing

The binder Dynamic Shear Rheometer (DSR) is used in the Performance Graded Binder specifications to assess the high temperature properties of an asphalt binder. The test method is described in AASHTO T315-02, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer*.

Binder Sample

Spindle rotates from A to B to C and back to A repeatedly.

B   C   A
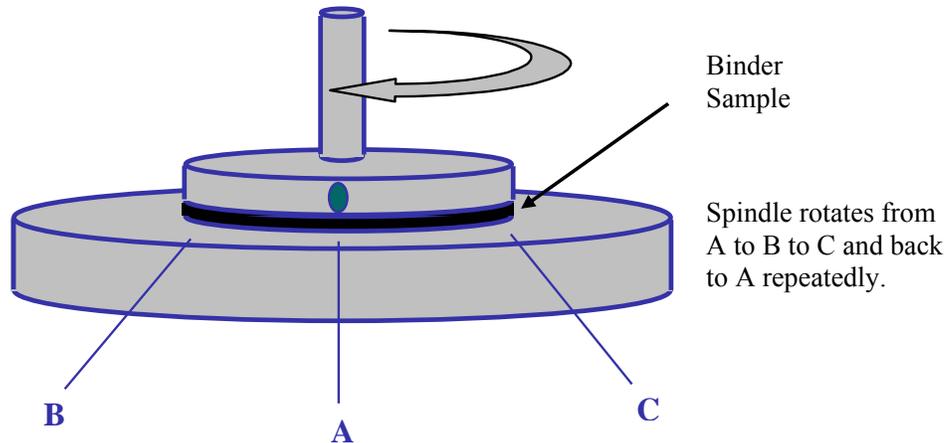
Figure 17: Movement of DSR Platen

In this test, a small disk (25mm diameter by 1mm high) of asphalt binder is sandwiched between two platens and subjected to an oscillatory shear loading in the DSR, as shown in Figure 17.

A photograph of a DSR is shown in Figure 18. Based upon the specimen geometry and the applied shear, it is possible to calculate the shear stress and shear strain in the binder sample. The shear stress divided by the shear strain is the shear modulus, or stiffness. Binder stiffness has been shown to be related to mixture rutting at high temperatures. A stiffer binder (higher modulus) will be more resistant to rutting. The test method has also been shown to be sensitive to changes in the binder.

Since asphalt binder is a viscoelastic material, if you apply a shear stress, there is a time delay (the viscous behavior) before the shear strain reaches its peak. (This is also why the shear modulus determined in this test is termed the complex shear modulus; "complex" signifies that the peak stress and peak strain do not occur at the same time.) This time lag is called the phase angle. This concept is illustrated in Figure 19. The phase angle is an indication of the

Figure 18: The Dynamic Shear Rheometer (DSR)

elasticity of the binder. More elastic binders (lower phase angle) are more resistant to rutting, since they rebound quickly.

Viscoelastic: $0 < \delta < 90°$
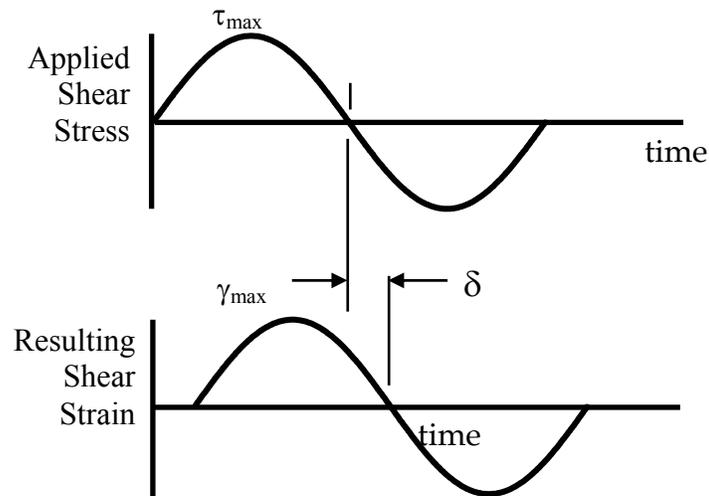
Figure 19: Illustration of Phase Angle Concept

The parameter used for the PG binder specifications at high temperatures is the complex shear modulus divided by the sine of the phase angle, or $G^*/\sin \delta$. Research during the development of the PG specifications under the Strategic Highway Research Program (SHRP) showed that this parameter was fundamentally related to rutting.

A single sample of binder can be tested at up to three temperatures at 6°C increments. The test itself takes only a few seconds and it takes minutes for the temperature to equilibrate. These features make it possible to conduct large numbers of tests in a very short period of time.

Binder Bending Beam Rheometer (BBR) Testing

The bending beam rheometer test is used in the PG specifications to assess the low temperature properties of the binder and is related to the tendency of a binder, and the mixture containing that binder, to crack at low temperatures. Previous research has shown that this parameter is sensitive to changes in the binder properties, so it was used to determine if there were any measurable differences between binders extracted from mixtures produced with the No. 2 fuel at optimum and the No. 6 at insufficient oxygen conditions. The extreme conditions were evaluated first to see if any differences could be detected. If not, no additional BBR testing would be done because of the time consuming process of extracting and recovering enough binder to fabricate the single use beams. After testing, the beam is permanently deformed and must be discarded.

The test, described more fully in AASHTO T313-02, *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, involves applying a small load at the center of a beam of asphalt binder and observing the resulting deflection of the beam. The beam is 6.35 ± 0.05mm wide, 12.7 ± 0.05mm high and 127 ± 2 mm long. It is submerged in a fluid bath maintained at a temperature between 32°F (0°C) and -33°F (-36°C), depending on the binder grade or desired test temperature. After equilibrating to the test temperature, a constant 100g load is applied at the center of the beam and the resulting beam deflection is measured for a period of four minutes. Under a constant load, there is an initial elastic deformation of the beam followed by a slow, gradual increase in the deflection due to a phenomenon called creep, as shown in Figure 20.
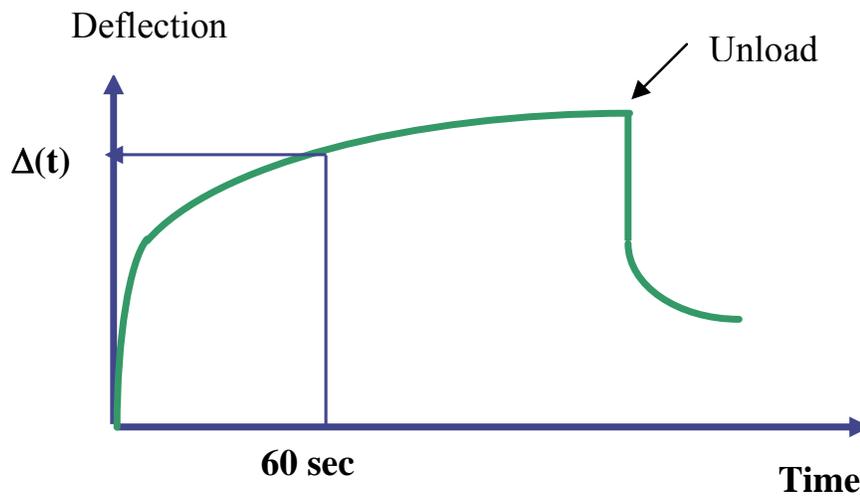
Figure 20: Deflection of the Beam in the BBR Test under Constant Load

The deflection of the beam at 60 seconds is analyzed using classic beam theory to yield an estimate of the binder stiffness, which is related to low temperature cracking. During the development of the test method, the time of 60 seconds was shown to be representative of the binder stiffness after two hours at a temperature 10° cooler. Two hours was determined to be an appropriate approximation of the length of a "cold spell" that causes cracking in the field. By testing at a warmer temperature, the test time could be shortened significantly.

Binder Direct Tension Testing and Estimation of Critical Cracking Temperature

A recent development in binder testing combines the results of stiffness measurements in the BBR with the results of tensile failure testing conducted using a Direct Tension device to predict the critical cracking temperature for a binder and the pavement in which it is incorporated. This technique arose from National Cooperative Highway Research Project 9-10, documented in NCHRP Report 459. The method is also described in AASHTO PP42, *Standard Practice for Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders*. Using this standard, the thermal stresses that build up in a pavement are estimated based on the results of BBR testing at two temperatures. The ultimate tensile strength of the binder is estimated using the results of direct tension testing. The point where the thermal stresses exceed the tensile strength of the binder is the critical cracking temperature, or the temperature at which a thermal crack could be expected to occur. This concept is illustrated in Figure 21.
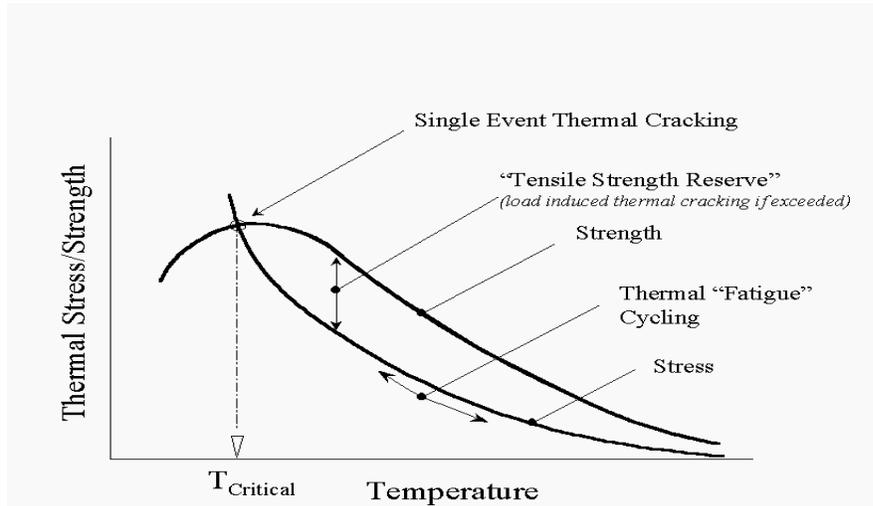
**Figure 21: Prediction of Critical Cracking Temperature from BBR
Stress and DT Strength**

The direct tension test, described in AASHTO T314, *Standard Method of Test for Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT),* involves pulling dog-bone shaped specimens of binder until they break. This test, like the BBR test, is conducted in a fluid filled device at low temperatures, typically 10°C warmer than the low temperature grade of the binder. The elongation of the specimen at the point of failure is the parameter of interest. The greater the elongation a binder can withstand, the less likely it is to crack at low temperatures. The test device is shown in Figure 22 and a specimen is illustrated in Figure 23.
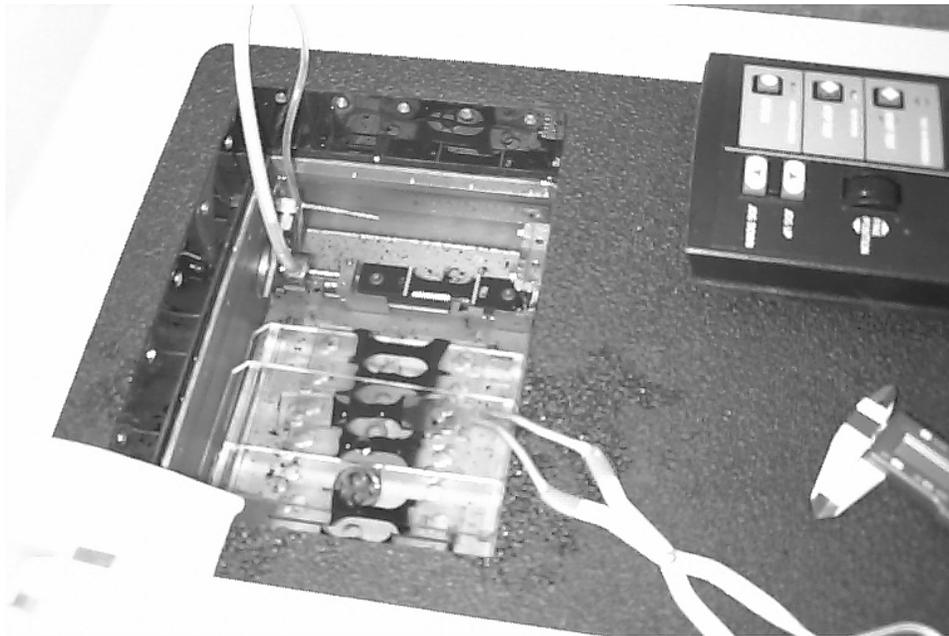
Figure 22: Close-Up of Test Chamber in Direct Tension Tester
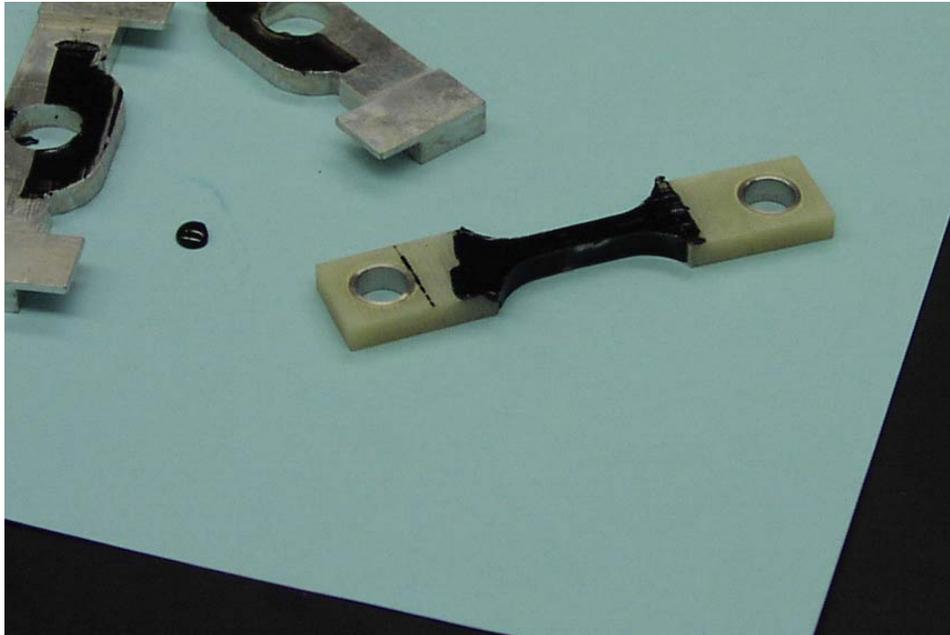
Figure 23: Example of Direction Tension Specimen with Mold Sides in Background

Superpave Gyratory Compactor (SGC)

The Superpave Gyratory Compactor was developed under SHRP to better simulate the compaction of hot mix asphalt in the field in terms of density achieved and the orientation of aggregate particles. Use of the gyratory is now codified in AASHTO T312, *Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor*. The SGC was used in this research to compact specimens in the field for later mixture testing, as described below. Rather than compacting to a fixed number of gyrations, as done during mix design or quality control, the number of gyrations was varied to attempt to reach a target air void content for the particular tests to be run.

The gyratory compactor works by tilting the gyratory mold at a slight angle (1.25° external), then applying a compactive load while the mold slowly gyrates. The tilt, gyrations and loading produce a kneading action on the mixture inside, which compacts it. The compacted specimens are 6 in (150mm) in diameter. The height varies depending on the amount of mix and number of gyrations, but is typically

Figure 24: Gyratory Compactor and Specimen

around 4.5 to 5 in (115 to 125 mm) tall. A photo of the gyratory used on this project with a partially extruded compacted specimen is shown in Figure 24.

Superpave Shear Tests (SST)

The Superpave Shear Tester (SST) is used to perform a variety of tests on an asphalt mixture in shear mode. The different tests are different combinations of axial and shear loads that may be applied one time or repeatedly, depending on the test. In all cases, specimens consist of 6 in (150mm) diameter cylinders, 2 in (50mm) high. The specimens may be cut from gyratory specimens or field cores. Specimens are affixed to aluminum platens using epoxy steel, and the specimen is mounted in the SST. The SST contains two hydraulic actuators. The top actuator can apply an axial compressive load, which is typically used to keep the specimen height constant during the test (i.e. to control dilation). The bottom actuator can apply a single or repeated shear loading. A photograph of the testing chamber of the NCSC SST and a specimen with platens affixed is shown in Figure 25. A description of the tests used follows.
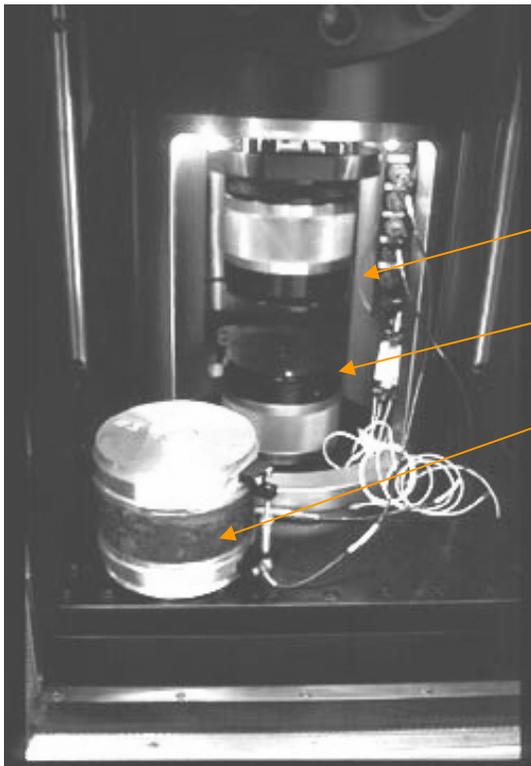
Upper actuator (axial load up and down)

Lower actuator (shear load back and forth)

Specimen with platens and instrumentation (LVDTs) affixed

Figure 25: **SST Test Chamber and Specimen**

Simple Shear at Constant Height (SS)

The Simple Shear at Constant Height (SS) test applies a single, controlled stress to the specimen while an axial load keeps the specimen height constant. The shear load ramps up at 70 kPa/sec to the specified shear load, which varies for different test temperatures. The load is then held constant for ten seconds. After ten seconds, the load ramps down at 25 kPa/sec, as shown in Figure 26. Figure 27 illustrates how the shear and axial loads are applied. The maximum shear deformation is the primary data item of interest (AASHTO TP7-94, *Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device,* Procedure D).
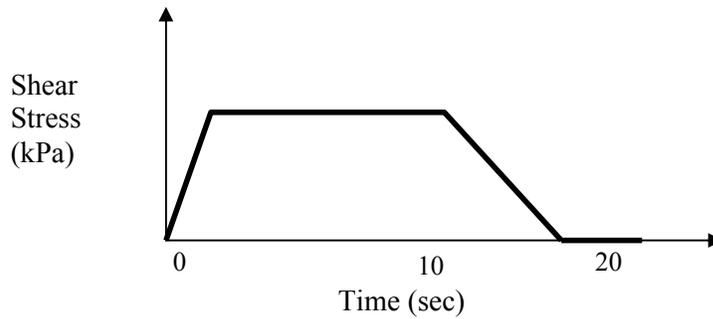
Figure 26: Loading Curve for Simple Shear Test

Axial load to keep height constant
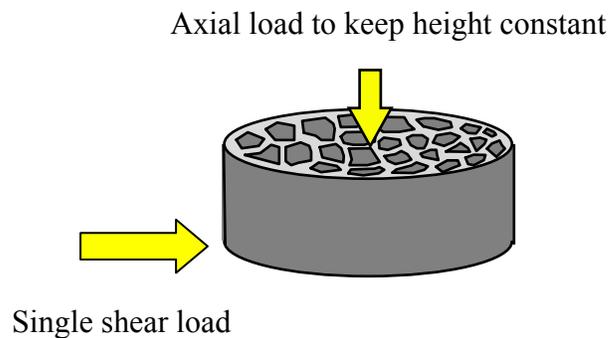
Single shear load

Figure 27: Shear and Axial Load Application in Simple Shear Test

Frequency Sweep (FS)

The Frequency Sweep at Constant Height (FS) test is conducted by applying a repeated shear load producing a strain of 0.005% in a horizontal direction at a wide range of frequencies from 0.01 Hz to 10Hz (Figure 28) while applying an axial stress to keep the specimen height constant (Figure 29). The frequency sweep test allows determination of the complex shear modulus (G*) and phase angle (δ) of a mixture and is typically conducted at 4, 20 and 40°C (AASHTO TP7-94, Procedure E). At 10 Hz and 40°C, a modulus (G*) value of about 35,000 to 50,000 psi or higher generally indicates a good mix while values below about 22,000 psi generally indicate poor performance. Values between 22,000 and 50,000 psi fall in a gray area and could be either good or bad. (These values are used by the Asphalt Institute as rough guidelines and were presented to the Mixture Expert Task Group in September 1997.)
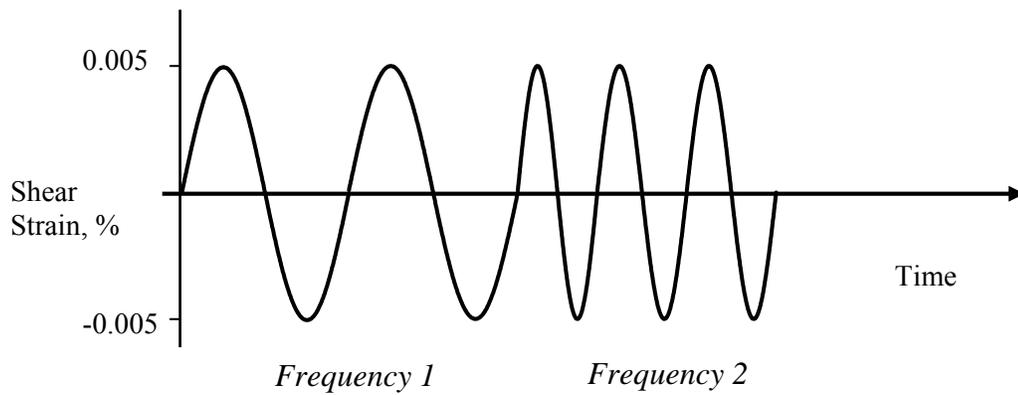
**Figure 28: Illustration of Loading Curve for Frequency Sweep Test Showing Two
of Ten Frequencies**

Axial load to keep height constant

Repeated sinusoidal shear load at
varying frequencies
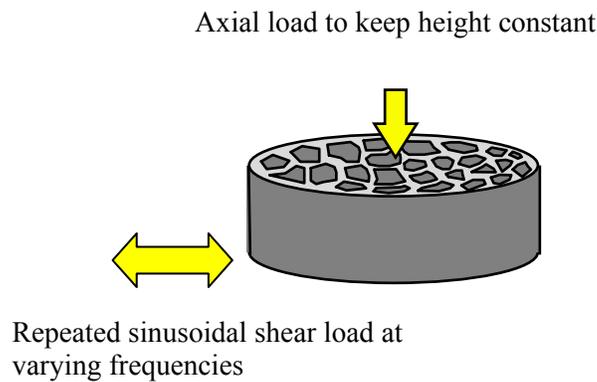
**Figure 29: Shear and Axial Load Application in
Frequency Sweep Test**

Repeated Shear at Constant Height (RSCH)

In the Repeated Shear at Constant Height test (RSCH), a repeated, stress-controlled shear load is applied
to the specimen in haversine pulses as shown in Figure 30. An axial stress is applied to keep the specimen
height constant, as illustrated in Figure 31. The load is applied for 0.1 second followed by a 0.6-second
rest period. The repeated pulses cause the slow accumulation of non-recoverable (permanent or plastic)
shear strain. The test is typically run to 5000 cycles or 5% permanent shear strain. The plastic shear strain
at 5000 cycles is the parameter of interest from this test (AASHTO TP7-94, Procedure C). Permanent
shear strain of less than 1% is generally considered excellent, 1 to 2% is good, 2 to 3% is fair, 3 to 5% is
questionable and more than 5% is poor, according to the guidelines used by the Asphalt Institute and
others.
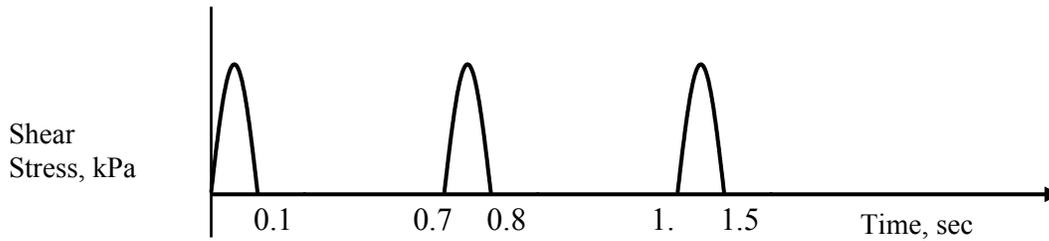
Figure 30: Loading Curve for Repeated Shear Test

Axial load to keep height constant

Repeated haversine shear load
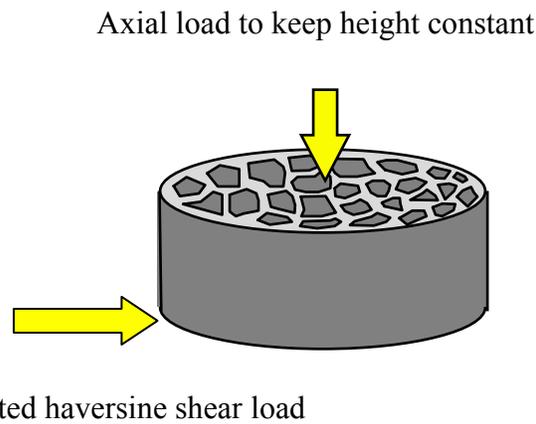
Figure 31: Shear and Axial Load Application in Repeated Shear Test

This test is normally conducted at an effective temperature for rutting based on the climate at the project location or a pre-determined temperature based on the binder grade. In this study, it was decided to conduct the RSCH test at 58°C (136.4°F), a temperature widely used in research.

Dynamic Modulus

The dynamic modulus test is one of the candidate Superpave performance tests being considered by Dr. Matt Witczak and his team under NCHRP 9-19, the Superpave Models contract. The intent of that project is to identify or develop tests and models to predict rutting, thermal cracking and fatigue cracking. Dynamic modulus will be a part of the proposed *Mechanistic-Empirical Pavement Design Guide* for structural design of asphalt pavements.

The test is conducted by applying a sinusoidal compressive load to the axis of a 4 in (100mm) diameter by 6 in (150mm) specimen cut from a larger gyratory specimen. Figure 32 is a photo of a cut specimen and the remains of the gyratory

Figure 32: Cut Specimen for Dynamic Modulus Testing

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specimen from which it was cut. Linear variable differential transducers (LVDTs) are mounted on the sides of the specimen, and it is placed in a test machine, as shown in Figure 33. (Figure 33 shows a confined test with a rubber membrane surrounding the specimen, which is necessary when testing open graded mixes and some other cases. The testing in this project was done without the confining pressure.) The applied stress and resulting strain are measured during the test at a given frequency, typically 5 Hz as used in this project. The loading curve is similar to that shown in Figure 28, but is in axial compression rather than in shear. The modulus is determined from the stresses and strains.

Figure 33: Dynamic Modulus Testing Device

As a rutting test, the dynamic modulus is determined at an effective temperature for the project location, which is a single temperature that is selected to yield the same amount of permanent deformation as would occur if the permanent deformation accumulating over the seasons of the year were summed. The effective temperature for South Dakota is about 99.7°F (37.6°C). For this project, testing was also conducted at 129.9°F (54.4°C) to allow comparison to other test results from other projects.

Purwheel

The Purwheel device is a laboratory wheel tracking device developed by Dr. Thomas D. White and associates at Purdue University. The design of the device was based on the Hamburg Steel Wheel Tester, but it is more flexible. The Purwheel can apply loads through steel wheels, pneumatic tires or rubber-coated wheels). The testing environment can be either wet or dry and the test can be run at temperatures from room temperature up to about 140°F (60°C). Two slabs can be tested simultaneously. Figure 34shows a picture of the Purwheel with two slabs in place. Transducers are used to monitor accumulated plastic deformation (rutting) of the slabs during the test. Figure 35 shows a slab after testing, showing the rutting that developed.

Slabs for testing are compacted in a linear compactor that consists of a rectangular steel mold (12 in by 24.5 in (304.8mm by 622.3mm)), a series of steel plates set on edge, a loading frame with a steel roller and a hydraulic ram. An air cylinder moves the mold back and forth under the roller. The hydraulic ram provides a compressive loading, which is transmitted through the roller to the steel plates. The steel plates are then pressed into the hot mix inside the mold. The plates can move down independently, producing a rolling, kneading action to compact the mix. For this project, loose, plant-produced mix was reheated and compacted in the linear compactor for testing. After compaction and cooling, the slabs are mounted in the Purwheel using Plaster of Paris to grout them in place and prevent rocking.

Figure 34: Purwheel Laboratory Wheel Tracking Device

Figure 35: Slab Tested in the Purwheel Device

Tests were conducted for this project at 99.7°F (37.6°C) with a tire pressure of 115 psi (793 kPa). The measured deflections represent the downward wheel path rutting only. Due to equipment difficulties, upward heave at the sides of the rut was not measured, but visual observations revealed no appreciable heave during this testing.

Fuel Flash Point

The flash points of the fuels were determined according to ASTM D93, *Flash Point by Pensky-Martens Closed Cup Tester*. In this test method, a sample of the fuel (al least 75 mL) is placed in a brass test cup, covered, stirred and heated at a prescribed rate. Periodically, the stirring is stopped and an ignition source is passed over the sample. (The ignition source may be an electric heater or a gas flame from natural or bottled gas.) The flash point is the temperature at which the ignition source ignites the vapors outgassed by the heated sample, producing a flame over the entire surface of the sample. The flash point is an indication of the flammability of the fuel vapors in air. Minimum flashpoint values are specified for the various grades of fuels.

Fuel Water Content

The water content of the fuels was measured according to ASTM D95, *Water in Petroleum Products and Bituminous Mixtures by Distillation*. The method consists of heating a sample of the fuel in a still. This distills the water out of the fuel sample. The water vapor is then condensed and the water is collected in a graduated glass trap, which allows the determination of the amount of water in the fuel in milliliters, which can then be expressed as a percent by volume of the fuel.

The water content is of interest when purchasing fuel so that corrections can be made in the volume of fuel purchased. For this project, however, the primary concern is that a high water content could make a fuel hard to burn or keep burning and could conceivably change the combustion products, perhaps producing more char or other byproducts. Specification limits for various standard grades of fuel have been established to limit the risk of high water contents.

Sediment in Fuel

The amount of sediment and inorganic carbon (insolubles) in the fuels was determined using ASTM D2042, Solubility of Asphalt Materials in Trichloroethylene, based on a recommendation from Heritage Research Group (HRG). HRG, which has extensive experience working with both fuels and asphalts, has found that both D2042 and D473 are solvent extractions that measure the insoluble content in a petroleum product, but that D2042 is more sensitive. D473 uses a heavy ceramic crucible that is too heavy to weigh on the sensitive analytical balance HRG uses. That test is a crude test for No. 6 fuel, but is not sensitive enough for the lighter fuels evaluated in this study.

D2042, then, involves dissolving a sample of the petroleum product in trichloroethylene and filtering the solute. The insoluble material, consisting of sediment and inorganic carbon, is caught in the filter and weighed to determine the percentage by mass.

APPENDIX E. SURVEY AND RESPONSES

A survey of the states was distributed through the Research Advisory Committee of AASHTO. The following questions were asked. A summary of the responses follows in tabular form.

> The South Dakota Department of Transportation is sponsoring a research project entitled *Effects of Hot Plant Fuel Characteristics and Combustion on Asphalt Concrete Quality*. The study is being conducted by the North Central Superpave Center and Purdue University. Your responses to the following questions would be greatly appreciated.

Has your organization observed any problems related to contamination of hot mix asphalt with unburned fuel or combustion products?

Have these problems been related to any particular types or grades of fuel?

Do you limit or control allowable fuel types or grades that may be used for production of hot mix asphalt? If so, how?

Do you determine if proper combustion is being achieved in a hot mix plant? If so, how?

Are you aware of any past or current research related to fuel types and combustion conditions for hot mix asphalt?

Thank you, in advance, for your cooperation.

Please return your responses to Rebecca McDaniel, North Central Superpave Center,

P. O. Box 2382, West Lafayette, IN 47906, phone: 765/463-2317 extension 226,

Fax: 765/497-2402, rsmcdani@purdue.edu by October 26, 2001.

Table 14: Responses to Questionnaire

State	#1	Comment	#2	Grades	Comment	#3	How?	#4	How?	#5	Comment	Contact
AK	N		N			N	AK3	N		N		Newton Bingham
AZ	N		N			N		N		N		Julie Nodes
AR	N		N			N		N		N		Gary.Bennett@ahtd.state.ar.us
CO	N		NA			N		N		N		Donna Harmelink
CT	N		NA			N		N		N		Nicholas Corona
DE	N		N			N		N		N		Jim Pappas
FL	N		N			Y	Spec	N		N		
GA	N		N			Y	GA3	N		N		peter.wu@dot.state.ga.us
HI	N		N			N		N		N		
IL	Y	IL1	Y	Waste oil	Y - IL2	N		N	IL4	N		Jack Davis
IN	Y	IN1	Y			N		N	IN4	N		Ron Walker
IA	N		N			N		N		N		
KS	N		N			N		N		N		Glenn Fager
MA	N		N			N		N		N		Clement Fung
MI	N		N			N		N		N		Frankhousem@michigan.gov
MN	N		N			N		N		Y		
MO	Y	MO1	N			N		N		N		Mark Shelton
MT	N		N			Y	MT3	N		N		R. Scott Barnes
NE	N		N			N		N		N		Laird Weishahn
NV	N	NV1	NA			Y	Spec	N		N		Darin Tedford
NH	N		NA			N		N		N		Alan Perkins
NJ*	N		NA			N		Y	NJ4	N		Joe Merlo
NM	N		NA			N		N		N		
NY	N		NA			N		N		Y	Arkansas DOT?	Zoab Zavery
OH	N		NA			N		N		N		
OK	Y	OK1	N			N		Y	OK4	Y	OK6	Kenneth Hobson
SC	N		N			N		N		N		hawkinscw@dot.state.sc.us
TN	N		N			N	TN3	Y	TN4	N		Brian Egan
TX	Y	TX1	Y	TX2		Y	TX3	N	TX4	N		Darren Hazlett
UT	N		N			N		N		N		handerson@dot.state.ut.us
WA	N		N			Y	WA3	N		N		anderke@wsdot.wa.gov
DC	N		N			Y	Spec	N		N		Wasi Khan
Dakota APA	Y	DA1	N	DA2	Agency			Y	DA4	N		Ken Sweeden
Border States Paving	N	BSP1	N			Y	BSP3	Y		N		Dan Thompson
*Two responses received for NJDOT and combined here.												

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Table 15: Additional Comments Made by State and Industry Representatives

#	Comment
AK3	Dept of Environmental Conservation controls stack emissions and shortly will include CO and possibly NOx and SOx
BSP1	We have experienced occasional poor quality fuel due to water or other contamination (all associated with waste oil). However, we have not experienced any failures and this problem is quickly identified and resolved by returning this product to the supplier at their cost along with any associated down time.
BSP3	Test for BTU Value, water content, ash content, contamination if efficiency is poor.
BSP4	Through experience we can determine with a high confidence level if we are burning a given fuel efficiently simply by the gallons per ton utilized with a given moisture level and aggregate type.
DA1	Very limited examples of performance affected HMA from unburned fuels. Typically, handling and placement issues are the tip-off and corrections made immediately. #2 Problems were related to plant operations, i.e., feed air settings, fuel jets and/or hot tank coils or measurement errors.
DA3	Agency decision; response from producer/contractor association 4 Typically plant settings confirmed by readings and production. Annual or semi-annual combustion tests, air quality and off-season PM
GA3	By Spec and Testing. Typically, #2 burner fuel requirement once was in the specification, but was eliminated about 3 years ago.
IL1	In one case the hot bin aggregates were coated with a black residue at a batch plant. In another case, we had three different parallel flow dryer drum plants mixtures that the liquid asphalt wouldn't adhere to the aggregate when it was being compacted. The mixture had a "brown" appearance behind the rubber-tired roller.
IL2	In all of the instances listed, a waste oil grade of fuel was used. The batch plant example was due to incomplete combustion because of the presence of water in the fuel. The reason for the "browning" was never positively identified, but the presence of anti freeze, synthetic motor oils, and other contaminates was suspected to be the cause.
IL4	While we don't determine if proper combustion is occurring, the Environmental Protection Agency performs periodic stack tests on the baghouses that would detect incomplete combustion.
IN1	During the oil embargo several years ago many plants were using recycled fuel oil in their plants and incomplete combustion did occur on a few occasions. We observed some striping of the binder and there was a distinct odor of fuel oil in the mixture.
IN4	IN4—If there was a problem it would appear in the binder content from the pavement samples and possibly subsequent air void and VMA determinations.
MO1	Rutting and shoving of mixes, tests on recovered asphalts.
MT3	Propane, Butane, Natural Gas, Fuel Oil (grades 1 or 2 only), and coal are permitted. EPA Specification-Used Oil Fuel (EPA-UOF) may be used as well. The following web address is for the used oil specification. The Burner fuel restriction is found as section 401.03.2 on page 137. ftp://ftp.mdt.state.mt.us/contract/stdspec_sup.pdf
NJ4	Visual inspection of aggregates
NV1	We did allow alternate reclaimed waste oil burner fuels for a short time. However, we experienced construction related problems such as pumping, flame blowout and non-uniform products. We discontinued allowing these fuels which seemed to eliminate the problems. (Spec allows: natural gas, liquefied natural gas, fuel oil (ASTM D396, Grades No. 1 and 2), butane, propane, diesel fuel oil (ASTM D975), Grades No. 1-D and 2-D.
OK1	You can generally tell by coating on the aggregates after being processed before addition of binder. The problems on the roadway can be seen as premature "potholing", rutting, uncoated aggregates and a dull dry mixture that doesn't set up well or some combination of these modes. Unusual smoke coming out of smoke stack may indicate a problem.
OK4	Indirectly so by requiring asphalt plants to be inspected early according to AASHTO T156.
OK5	Internet links
TN3	TDOT Specifications state that Dryer shall be operated such that contamination does not occur. Also, have memo stating if fuels other than propane, butane, natural gas, coal, No. 1 or No. 2 fuel oil, then need to check.
TN4	See #3. Take a shovel full of dryer run aggregate and dump into a pail of clean water, look for an oily film to float to the top.

APPENDIX F. BINDER TEST RESULTS

Table 16: Replicate Dynamic Shear Rheometer Data

Fuel/ Burner	Temp. °C	G* kPa	δ deg.	G* kPa	δ deg.	G* kPa	δ deg.	Average G*/sin δ kPa
Original	52	2.763	85.7	2.779	85.7	2.789	85.7	2.78
	58	1.200	86.8	1.219	86.5	1.221	86.6	1.22
	64	0.573	86.7	0.588	85.9	0.601	86.2	0.59
RTFO Aged	52	6.680	82.0	7.267	81.6	7.711	81.9	7.29
	58	2.829	84.1	3.184	83.7	3.286	84.0	3.12
	64	1.290	85.0	1.478	85.3	1.500	85.4	1.43
No.2O	52	10.370	80.0	10.370	80.1	10.630	79.8	10.62
	58	4.484	82.5	4.349	82.7	4.494	82.5	4.48
	64	2.094	84.5	1.989	84.5	2.064	84.4	2.06
No. 2I	52	5.470	83.4	5.648	83.6	5.479	83.7	5.57
	58	2.394	84.7	2.428	85.4	2.380	85.1	2.41
	64	1.118	89.7	1.119	86.3	1.102	86.5	1.11
No. 6I	52	8.175	81.7	8.013	81.5	8.211	81.4	8.22
	58	3.445	83.6	3.434	83.9	3.498	83.8	3.48
	64	1.515	85.2	1.553	85.6	1.578	85.3	1.55
No 5LI	52	6.821	82.4	6.938	82.7	6.751	82.4	6.90
	58	2.979	84.6	2.896	84.5	2.781	84.8	2.90
	64	1.363	86.6	1.323	86.7	1.294	86.7	1.33
No. 5HI	52	8.024	81.8	7.689	82.0	7.250	81.5	7.73
	58	3.521	83.8	3.427	84.1	3.178	83.7	3.39
	64	1.653	86.0	1.567	85.1	1.469	85.8	1.57
RFO5LI	52	8.351	81.9	8.622	82.0	8.448	82.3	8.56
	58	3.523	84.0	3.794	83.8	3.683	84.4	3.69
	64	1.587	86.1	1.704	85.6	1.707	85.7	1.67
RFO5HI	52	7.420	81.7	6.928	82.4	7.709	81.7	7.43
	58	3.156	83.9	3.031	84.6	3.343	84.0	3.19
	64	1.460	86.0	1.374	86.3	1.524	86.2	1.46
RFO4I	52	7.124	82.4	6.876	82.4	6.006	82.3	6.73
	58	3.111	84.4	3.079	84.5	2.559	84.6	2.93
	64	1.435	86.2	1.422	86.6	1.163	86.1	1.34
W1I	52	7.654	81.7	7.696	82.2	8.141	82.1	7.91
	58	3.222	83.2	3.357	84.4	3.517	84.5	3.38
	64	1.430	85.6	1.565	85.9	1.579	86.2	1.53
W2I	52	10.721	82.6	8.155	82.7	8.659	82.3	9.26
	58	4.520	84.8	3.055	84.9	3.792	84.7	3.80
	64	2.090	86.1	1.607	86.2	1.769	86.3	1.83
W3I	52	7.663	82.2	6.863	82.7	7.183	82.3	7.33
	58	3.259	84.3	2.949	84.5	3.219	84.4	3.16
	64	1.652	85.9	1.372	86.2	1.455	85.8	1.50
W4I	52	7.206	82.7	7.188	82.6			7.26
	58	3.092	84.8	3.024	84.1	3.043	84.8	3.07
	64	1.359	86.3	1.436	85.0	1.381	85.9	1.40

Table 17: BBR Results for Recovered Binders (No PAV Aging)

Fuel/ Burner	Temp. °C	S MPa	m .	S MPa	m	Average S MPa	Average m	Critical Temp. °C
PAV Aged	-12	108	0.379	99.7	0.392	104	0.386	-21.6
	-18	266	0.349	256	0.354	261	0.352	
	-24	494	0.270	487	0.262	491	0.266	
RTFO Aged	-18	195	0.409	194	0.415	195	0.412	-23.7
	-24	392	0.294	396	0.296	394	0.295	
No.2O	-18	188	0.373	200	0.384	194	0.379	-24.4
	-24	443	0.310	425	0.300	434	0.305	
No. 2I	-18	160	0.411	153	0.388	157	0.400	-25.6
	-24	388	0.319	332	0.322	360	0.321	
No. 6I	-18	155	0.395	167	0.392	161	0.394	-25.8
	-24	441	0.321	411	0.322	426	0.322	
No 5LI	-18	183	0.409	177	0.409	180	0.409	-23.0
	-24	372	0.275	344	0.283	358	0.279	
No. 5HI	-18	171	0.383	169	0.394	170	0.389	-23.3
	-24	353	0.297	357	0.281	355	0.289	
RFO5LI	-18	197	0.394	180	0.381	189	0.388	-23.9
	-24	405	0.306	402	0.291	404	0.299	
RFO5HI	-18	175	0397	187	0391	181	0.394	-24.8
	-24	391	0.310	381	0.314	396	0.311	
		402	0.308	408	0.313			
RFO4I	-18	186	0.369	192	0.396	189	0.383	-22.3
	-24	414	0.260	383	0.280	402	0.268	
		408	0.264	--	--			
W1I	-18	214	0.380	218	0.381	216	0.381	-22.4
	-24	403	0.277	385	0.263	387	0.270	
		373	0.259	388	0.280			
W2I	-18	162	0.388	175	0.409	169	0.399	-25.7
	-24	406	0.312	412	0.331	409	0.322	
W3I	-18	166	0.408	066	0.406	166	0.407	-25.6
	-24	410	0.317	414	0.329	412	0.323	
W4I	-18	177	0.414	164	0.405	171	0.410	-24.5
	-24	388	0.309	375	0.309	382	0.309	
All results grouped together in one group by Scheffe's comparison of means.								

Table 18: Direct Tension Results for No. 2O at -18C

Replicate No.	Maximum Stress, MPa	Maximum Strain, %
1	2.54*	0.776*
2	3.00	0.965
3	3.02	1.050
4	2.96	1.013
5	2.14*	0.616*
6	3.52	1.257
Mean	*3.12*	*1.071*
C.V., %	*8.4*	*12.0*
*Test dropped according to protocol.		

Table 19: Direct Tension Results for No. 2O at -24C

Replicate No.	Maximum Stress, MPa	Maximum Strain, %
1	2.83*	0.443*
2	2.88*	0.531
3	4.28	0.649
4	3.23	0.523*
5	3.31	0.554
6	3.91	0.671
Mean	*3.60*	*0.601*
C.V., %	*17.3*	*11.5*
*Test dropped according to protocol.		

Table 20: Direct Tension Results for No. 6I at -18C

Replicate No.	Maximum Stress, MPa	Maximum Strain, %
1	1.86*	0.526*
2	4.63	1.829
3	3.45*	1.181*
4	4.73	2.136
5	4.06	1.716
6	3.53	1.394
Mean	*4.22*	*1.715*
C.V., %	*14.0*	*23.2*
*Test dropped according to protocol.		

Table 21: Direct Tension Results for No. 6I at -24C

Replicate No.	Maximum Stress, MPa	Maximum Strain, %
1	2.35	0.378
2	2.29*	0.297*
3	2.15	0.322
4	3.09	0.465
5	1.98	0.320
6	1.91*	0.261*
Mean	*2.40*	*0.372*
C.V., %	*20.3*	*18.3*
*Test dropped according to protocol.		

Table 22: PAV-Aged Bending Beam Rheometer Data for No. 2 Fuel at Optimum

| Temperature | Stiffness, MPa | | m-value |
	Measured	Estimated	
-18 °C	187	189	0.319
	204	204	0.325
-24 °C	372	372	0.267
	397	397	0.273

Table 23: PAV-Aged Bending Beam Rheometer Data for No 6 Fuel at Insufficient Oxygen

| Temperature | Stiffness, MPa | | m-value |
	Measured	Estimated	
-18 °C	210	211	0.341
	213	213	0.336
-24 °C	330	328	0.253
	324	326	0.236

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PAV Fracture Strength & Thermal Stress, MPa
Critical Temperature -29.1 C

South Dakota Recovered Binder -- Fuel Type #20
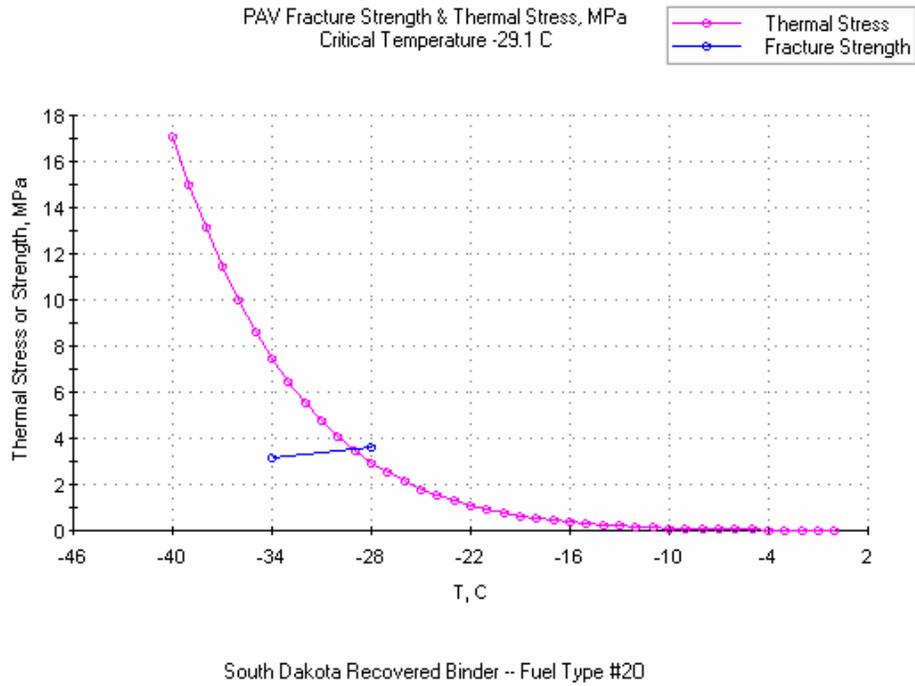
Figure 36: Critical Temperature from AASHTO MP1a for No. 2 Fuel at Optimum

PAV Fracture Strength & Thermal Stress, MPa
Critical Temperature -31.4 C

South Dakota Recovered Binder -- Fuel Type #6I
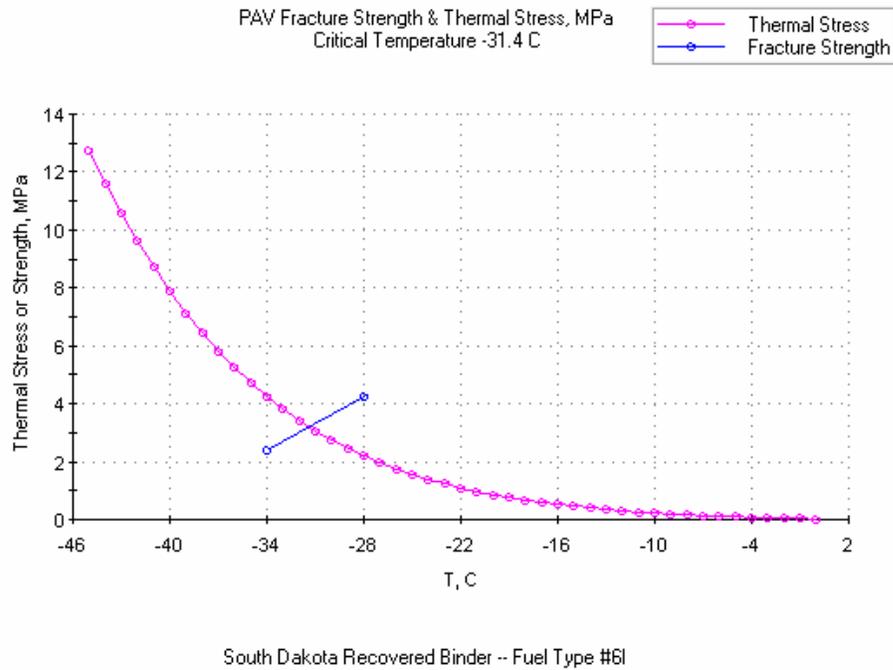
Figure 37: Critical Temperature from AASHTO MP1a for No. 6 Insufficient

APPENDIX G. MIXTURE TESTING RESULTS

Table 24: Summary of Gyratory Compaction Results

Fuel	Burner	Normalized Height Reduction at Gyration # (Standard Deviation)			
		2	4	7	10
No. 2	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
No. 6	Insufficient	0.95 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.95 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.01)	0.90 (0.01)
No. 5L	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
No. 5H	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
RFO4	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.01)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
RFO5L	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.95 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.95 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
RFO5H	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
W1	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
W2	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
W3	Insufficient	0.95 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
W4	Insufficient	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Optimum	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)
	Excess	0.96 (0.00)	0.93 (0.00)	0.91 (0.00)	0.90 (0.00)

Table shows average (standard deviation) of five or six specimens at each combination of fuel and oxygen conditions.

Table 25: Purwheel Data

Number of Wheel Passes	Rut Depth (mm)			
	6I (left)	6I (right)	2O (left)	2O (right)
0	0	0	0	0
200	1.08	0.78	0.90	0.80
400	1.38	1.14	1.08	0.96
600	1.56	1.20	1.13	0.98
800	1.74	1.50	1.15	1.05
1000	1.91	1.43	1.34	1.17
1200	2.01	1.52	1.46	1.22
1400	2.06	1.76	1.55	1.24
1600	2.17	1.83	1.60	1.23
1800	2.20	1.62	1.67	1.26
2000	2.30	1.87	1.70	1.32
2200	2.33	2.05	1.73	1.34
2400	2.41	2.2	1.76	1.34
2600	2.68	1.83	1.81	1.44
2800	2.55	2.09	1.90	1.48
3000	2.71	2.36	1.98	1.55
3200	2.80	2.47	1.97	1.52
3400	2.87	2.41	1.94	1.47
3600	3.00	2.47	1.97	1.47
3800	2.99	2.44	2.05	1.52
4000	3.02	2.54	2.11	1.49
4200	3.10	2.63	2.13	1.41
4400	3.20	2.75	2.15	1.35
4600	3.35	2.50	2.27	1.56
4800	3.38	2.85	2.22	1.58
5000	3.34	2.71	2.24	1.75
5200	3.51	2.69	2.25	1.65
5400	3.48	2.88	2.30	1.72
5600	3.60	3.06	2.34	1.76
5800	3.62	3.02	2.37	1.63
6000	3.57	3.08	2.44	1.64
6200	3.75	3.06	2.41	1.71
6400	3.82	2.79	2.50	1.75
6500	3.93	3.01	2.55	1.78
6600	3.99	3.13	2.58	1.83
6700	4.00	3.10	2.58	1.81
6800	4.08	3.18	2.60	1.79
6900	3.99	3.23	2.64	1.78
7000	4.04	3.28	2.67	1.86
7100	4.15	3.25	2.72	1.94
7200	4.17	3.42	2.74	1.89
7300	4.17	3.30	2.79	1.77
7400	4.17	3.15	2.79	1.66
7500	4.24	3.13	2.86	1.91
7600	4.16	3.02	2.87	1.95
7700	4.23	3.20	2.82	1.95
7800	4.33	3.18	2.91	1.81

Table 25: Purwheel Data (continued)

Number of Wheel Passes	Rut Depth (mm)			
	6I (left)	6I (right)	2O (left)	2O (right)
7900	4.36	3.45	2.89	1.73
8000	4.32	3.32	2.90	1.99
8100	4.26	3.27	3.02	1.96
8200	4.38	3.18	3.01	2.04
8300	4.41	3.43	3.08	2.03
8400	4.57	3.50	3.12	2.02
8500	4.49	3.59	3.10	1.92
8600	4.40	3.26	3.17	2.00
8700	4.49	3.51	3.22	2.04
8800	4.55	3.37	3.20	2.06
8900	4.56	3.52	3.26	2.12
9000	4.54	3.91	3.26	2.01
9100	4.25	3.51	3.26	2.08
9200	4.61	3.62	3.32	2.17
9300	4.65	3.65	3.33	1.97
9400	4.60	3.61	3.35	1.99
9500	4.71	3.69	3.36	2.07
9600	4.79	3.49	3.44	2.12
9700	4.83	3.40	3.42	2.26
9800	4.89	3.6	3.45	2.07
9900	4.86	3.79	3.47	2.13
10000	4.90	3.83	3.46	2.18
10100	4.75	3.76	3.54	2.13
10200	4.93	3.8	3.53	1.89
10300	4.91	3.81	3.62	2.14
10400	5.04	3.61	3.60	2.14
10500	5.03	3.80	3.64	2.24
10600	5.04	3.75	3.56	2.17
10700	5.00	3.82	3.55	2.02
10800	5.13	4.36	3.77	2.19
10900	5.28	4.07	3.69	2.30
11000	5.12	4.13	3.73	2.26
11100	5.14	3.99	3.72	2.24
11200	5.17	4.47	3.75	2.30
11300	5.30	3.96	3.78	2.37
11400	5.23	3.83	3.91	2.30
11500	5.34	4.03	3.93	2.37
11600	5.30	4.01	4.02	2.41
11700	5.23	3.99	4.06	2.30
11800	5.47	4.38	4.10	2.21
11900	5.43	3.85	4.13	2.38
12000	5.42	4.27	4.08	2.28
12100	5.47	4.07	4.07	2.39
12200	5.50	4.15	4.02	2.38
12300	5.43	4.23	3.97	2.46
12400	5.50	4.47	4.10	2.23
12500	5.45	4.16	4.08	2.46
12600	5.52	4.26	4.10	2.20

Table 25: Purwheel Data (continued)

Number of Wheel Passes	Rut Depth (mm)			
	6I (left)	6I (right)	2O (left)	2O (right)
12700	5.58	4.30	4.16	2.40
12800	5.54	4.40	4.16	2.50
12900	5.67	4.44	4.21	2.46
13000	5.63	4.27	4.28	2.43
13100	5.74	4.46	4.28	2.32
13200	5.72	4.32	4.30	2.45
13300	5.73	4.15	4.32	2.44
13400	6.02	4.51	4.33	2.47
13500	5.85	4.37	4.34	2.47
13600	5.85	4.29	4.41	2.56
13700	5.89	4.54	4.43	2.42
13800	5.92	4.27	4.42	2.44
13900	5.87	4.64	4.46	2.21
14000	5.98	4.51	4.52	2.48
14100	5.89	4.60	4.15	2.43
14200	5.88	4.64	4.41	2.63
14300	5.96	4.24	4.45	2.55
14400	6.21	4.64	4.57	2.55
14500	6.06	4.34	4.58	2.50
14600	6.07	4.67	4.61	2.41
14700	6.00	4.38	4.59	2.52
14800	6.09	4.69	4.69	2.64
14900	6.01	4.75	4.69	2.56
15000	6.20	4.87	4.76	2.43
15100	6.09	4.84	4.74	2.62
15200	6.24	4.59	4.71	2.61
15300	6.31	4.84	4.70	2.73
15400	6.32	4.74	4.78	2.47
15500	6.31	4.58	4.81	2.47
15600	6.27	4.97	4.69	2.75
15700	6.40	4.78	4.83	2.71
15800	6.39	4.85	4.78	2.70
15900	6.46	4.99	5.07	2.66
16000	6.51	4.68	4.84	2.76
16100	6.42	4.79	4.89	2.73
16200	6.55	5.05	4.93	2.56
16300	6.63	4.81	4.98	2.61
16400	6.64	4.86	5.03	2.60
16500	6.63	5.12	5.05	2.81
16600	6.58	5.35	5.09	2.55
16700	6.57	5.07	5.05	2.74
16800	6.66	5.19	5.07	2.83
16900	6.66	5.08	5.12	2.68
17000	6.66	4.94	5.17	2.83
17100	6.79	5.25	5.18	2.68
17200	6.86	5.44	5.23	2.65
17300	6.82	5.10	5.10	2.91
17400	6.80	5.37	5.23	2.78

Table 25: Purwheel Data (continued)

Number of Wheel Passes	Rut Depth (mm)			
	6I (left)	6I (right)	2O (left)	2O (right)
17500	6.93	5.12	5.21	2.79
17600	7.01	5.29	5.26	2.72
17700	7.00	5.49	5.25	2.67
17800	6.94	5.73	5.32	2.85
17900	6.92	5.50	5.34	2.82
18000	7.02	5.20	5.29	2.64
18100	7.03	5.27	5.33	2.80
18200	7.22	5.42	5.34	3.03
18300	7.03	5.53	5.41	2.82
18400	7.12	5.50	5.48	2.89
18500	7.17	5.63	5.43	2.83
18600		5.53	5.42	2.86
18700		5.38	5.43	2.94
18800		5.81	5.14	2.74
18900		5.57	5.45	2.93
19000		6.08	5.59	2.94
19100		5.50	5.47	2.91
19200		5.84	5.66	2.77
19300		5.46	5.58	2.87
19400		5.41	5.55	2.97
19500		5.72	5.68	2.80
19600		5.64	5.74	2.77
19700		5.87	5.72	2.93
19800			5.70	3.01
19900			5.72	3.00
20000			5.8	2.86

APPENDIX H. FREQUENCY SWEEP TEST RESULTS

Table 26: Summary of Average Frequency Sweep Results

Fuel Type	% Air Voids	Complex Modulus, G*, psi at 10 Hz	
		68°F (20°C)	104°F (40°C)
#2O	6.4	114352	9354
#2I	3.3	379634	14341
#6I	5.0	160214	13006
#5LI	3.6	199480	15739
#5HI	6.2	123543	12270
W1I	4.8	360473	15152
W2I	5.1	182673	17352
W3I	3.9	154758	15125
W4I	5.4	135728	15335
R4I	4.8	298069	12516
RLI	4.5	350248	17548
RHI	4.8	403389	16194

Table 27: FS Test Data for Fuel Type #2O

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	6.3	103531	8962
2	7.1	110360	8435
3	6.1	116431	10135
4	6.0	127087	9883

Table 28: FS Test Data for Fuel Type #2I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	3.3	393200	13407
2	3.2	253731*	14511
3	3.3	366068	15106
* Incomplete test--result discarded			

Table 29: FS Test Data for Fuel Type #6I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	5.5	142352	13181
2	4.9	111690	14397
3	4.8	169645	11273
4	4.6	217171	13171

Table 30: FS Test Data for Fuel Type #5LI

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	3.5	137261	13354
2	3.3	236521	18189
3	4.2	155373	14159
4	3.2	268765	17255

Table 31: FS Test Data for Fuel Type #5HI

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	6.6	123107	14728
2	5.6	125899	11092
3	6.3	131720	13194
4	6.1	113445	10066

Table 32: FS Test Data for Fuel Type W1I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	4.8	291976	14865
2	4.7	428969	15440

Table 33: FS Test Data for Fuel Type W2I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	4.9	226076	19258
2	5.3	164703	15843
3	5.2	157240	16955

Table 34: FS Test Data for Fuel Type W3I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	4.2	168515	14698
2	4.0	147159	16001
3	3.5	134985	15165
4	3.9	168371	14635

Table 35: FS Test Data for Fuel Type W4I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	5.2	143148	15181
2	5.1	143169	16885
3	5.2	129061	13191
4	6.1	127532	16083

Table 36: FS Test Data for Fuel Type R4I

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	5.0	339920	12079
2	4.9	214163	11703
3	5.0	369871	12791
4	4.2	268322	13489

Table 37: FS Test Data for Fuel Type RLI

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	4.3	270194	19098
2	4.7	430301	15997

Table 38: FS Test Data for Fuel Type RHI

Replicate No.	% Air Voids	Complex Modulus, psi	
		@ 20 °C	@ 40 °C
1	4.9	524088	17524
2	4.8	282690	14865
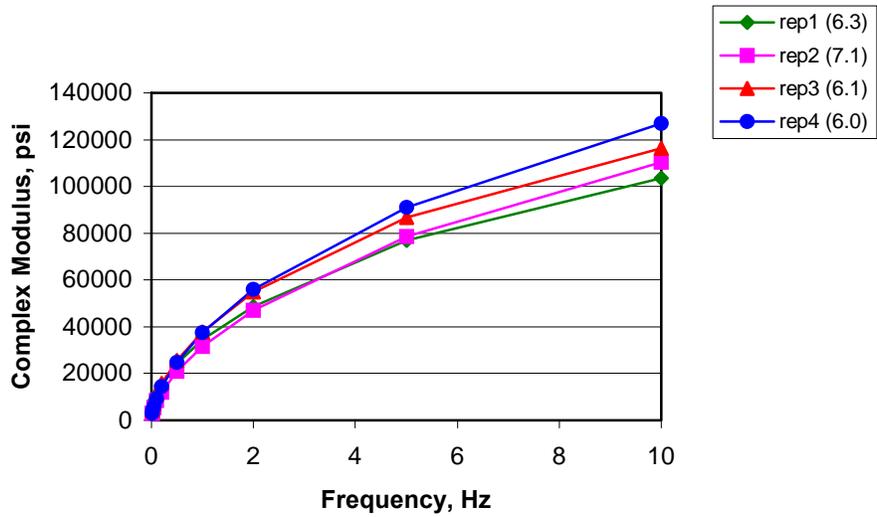
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 38: Frequency Sweep @ 20°C for Fuel #2 Optimum
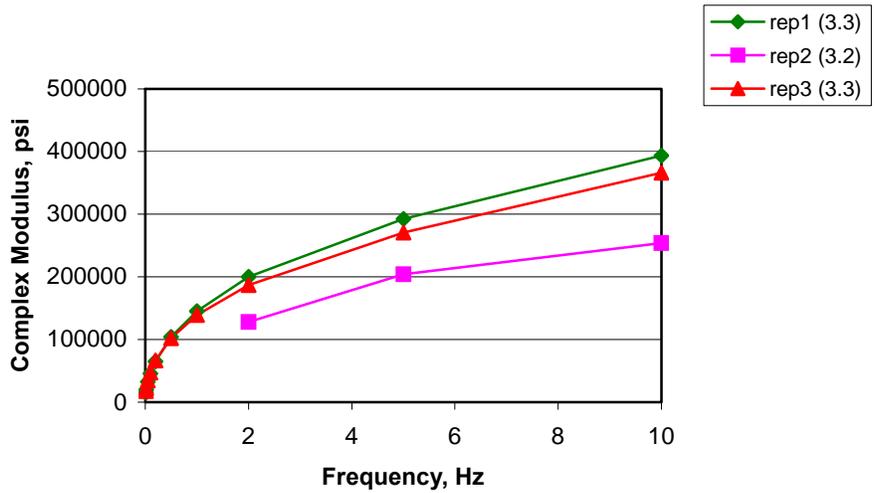
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 39: Frequency Sweep @ 20°C for Fuel #2 Insufficient
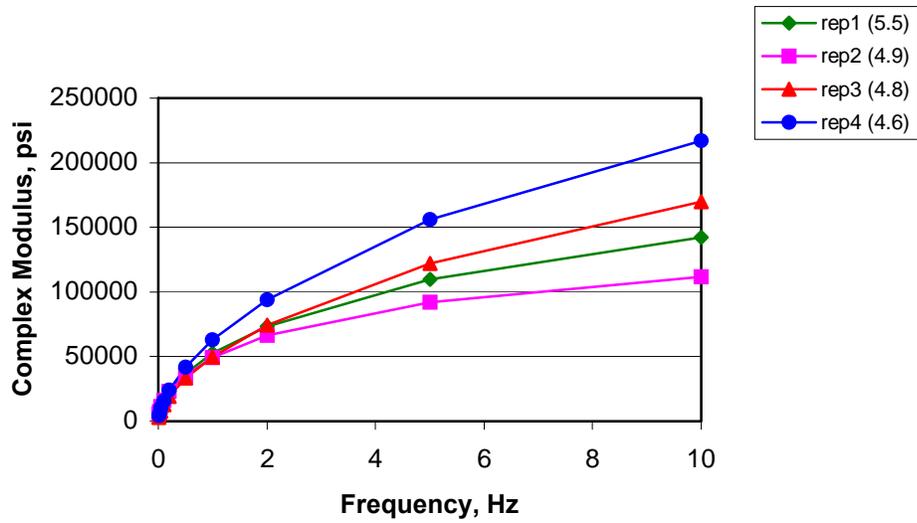
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 40: Frequency Sweep @ 20°C for Fuel #6 Insufficient
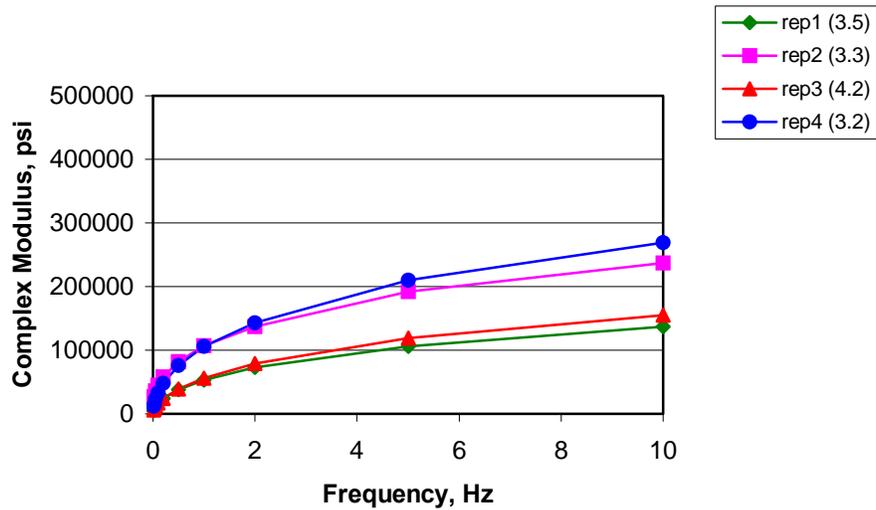
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 41: Frequency Sweep @ 20°C for Fuel 5L Insufficient
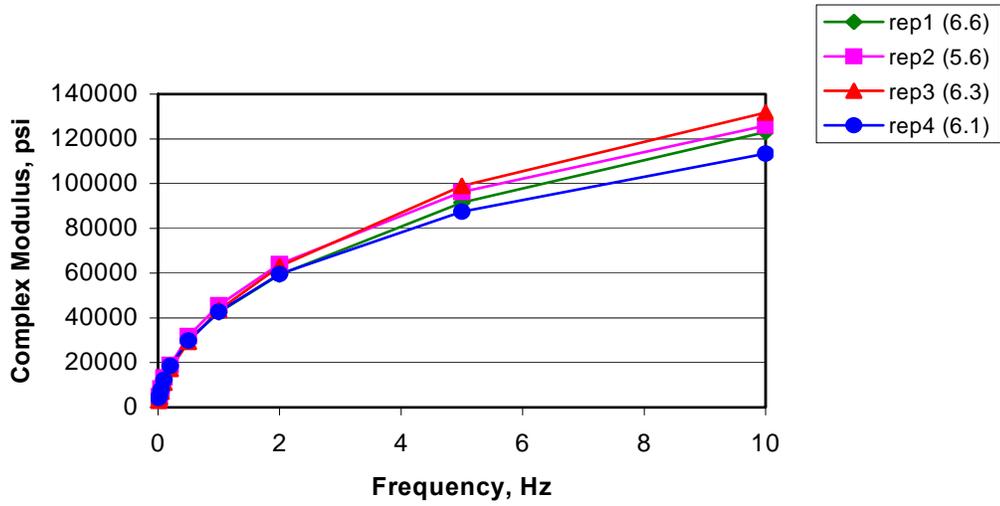
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 42: Frequency Sweep @ 20°C for Fuel 5H Insufficient
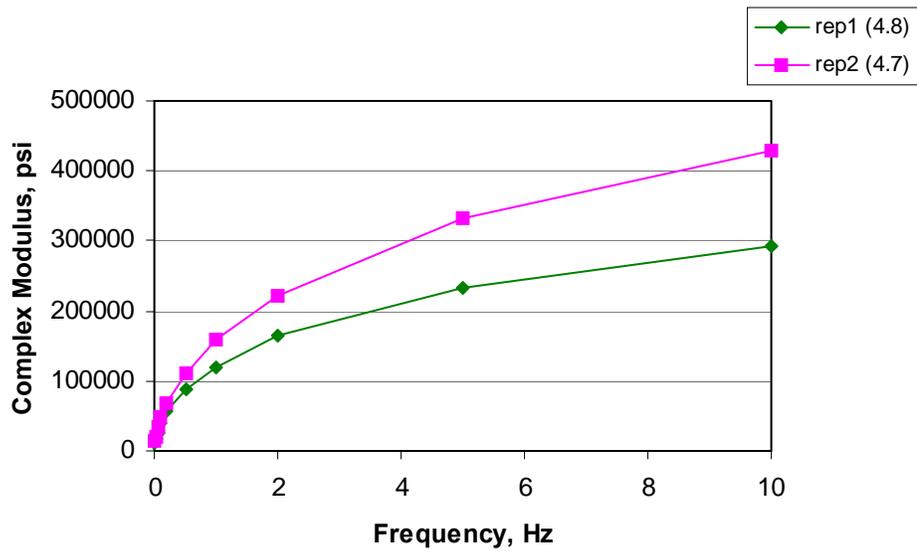
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 43: Frequency Sweep @ 20°C for Waste Fuel #1 Insufficient
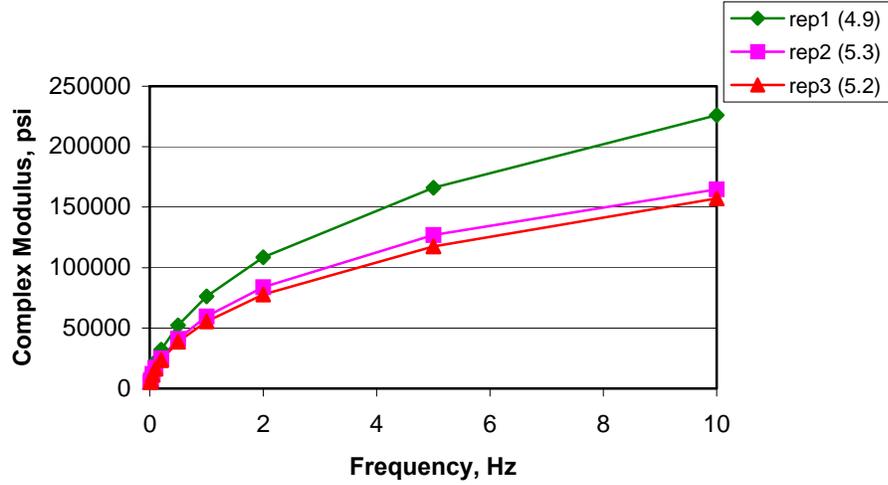
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 44: Frequency Sweep @ 20°C for Waste Fuel #2 Insufficient
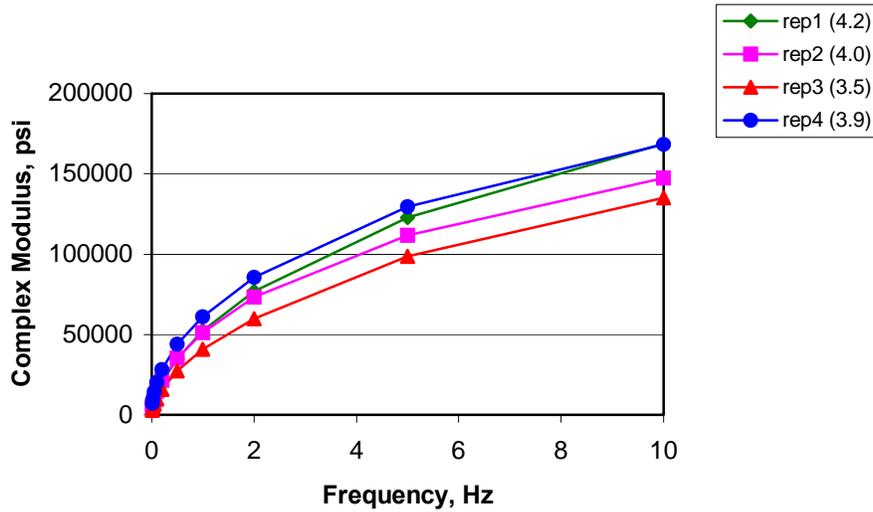
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 45: Frequency Sweep @ 20°C for Waste Fuel #3 Insufficient
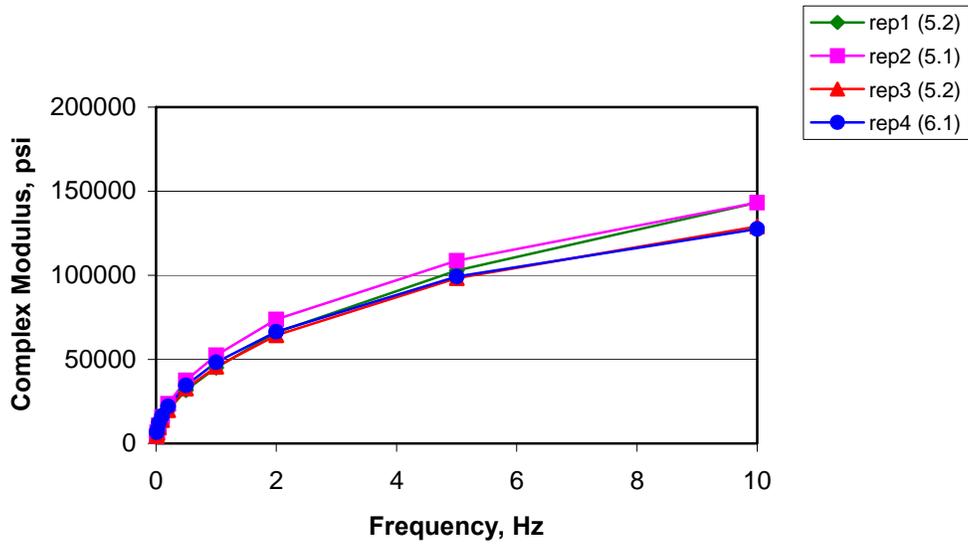
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 46: Frequency Sweep @ 20°C for Waste Fuel #4 Insufficient
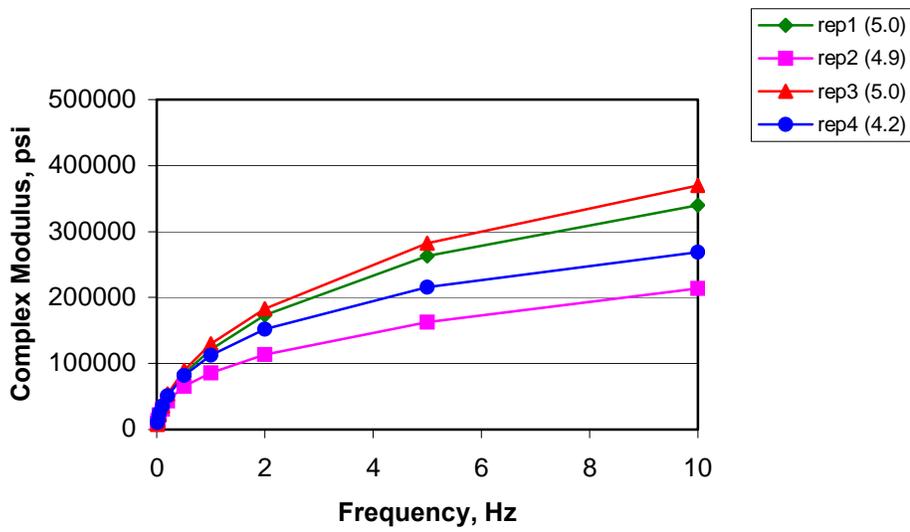
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 47: Frequency Sweep @ 20°C for Fuel RFO4 Insufficient
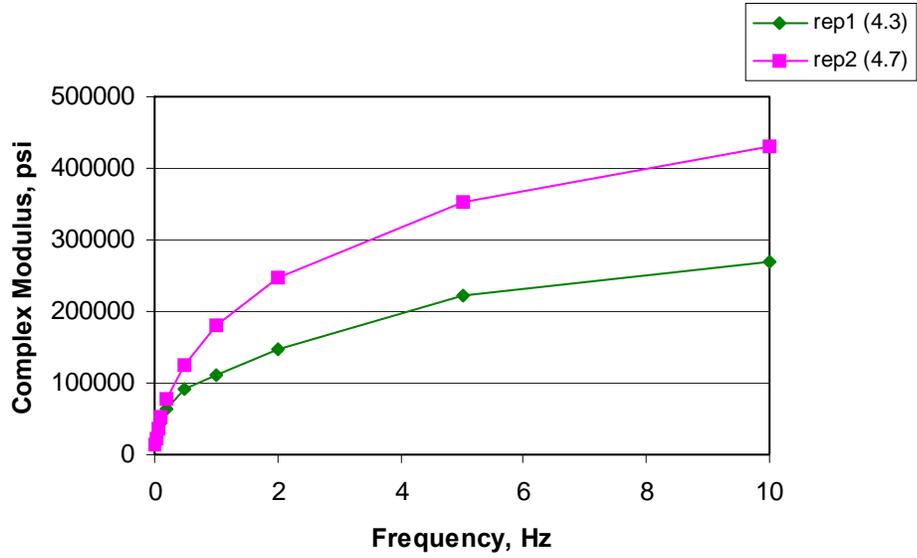
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 48: Frequency Sweep @ 20°C for Fuel RL Insufficient
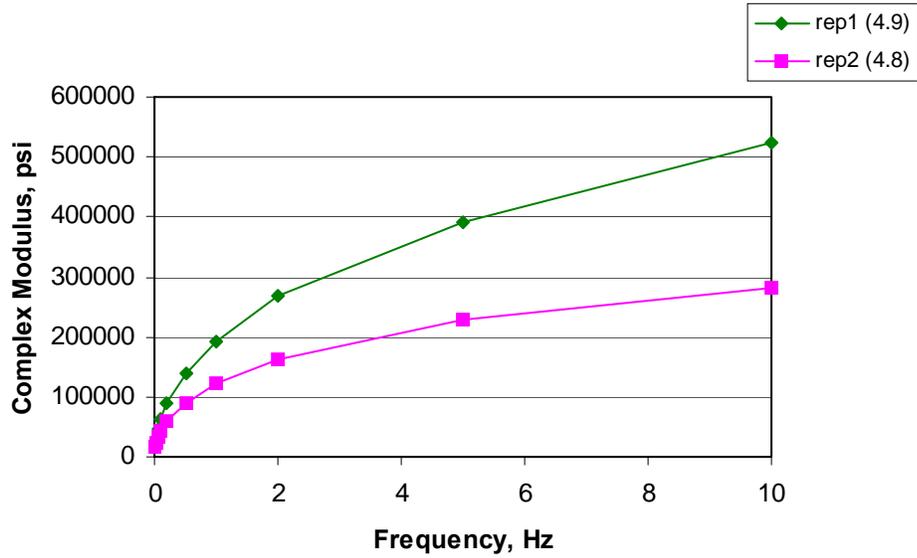
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 49: Frequency Sweep @ 20°C for Fuel RH Insufficient

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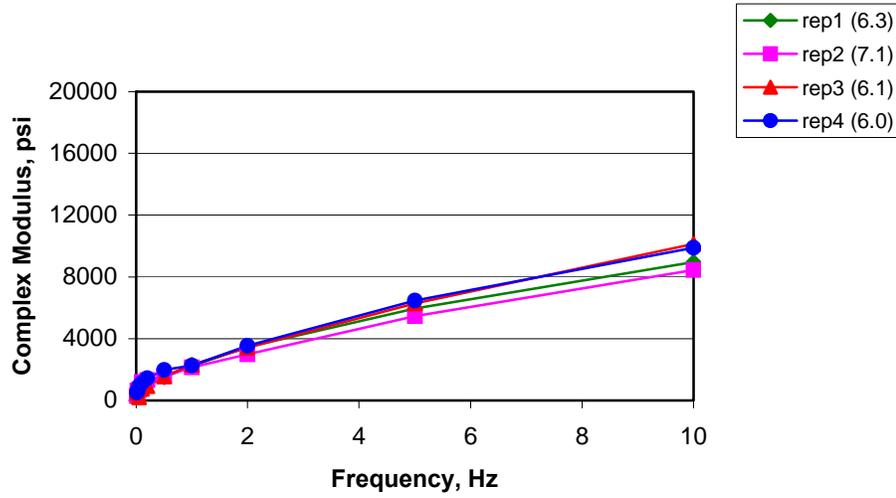
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 50: Frequency Sweep @ 40°C for Fuel #2 Optimum
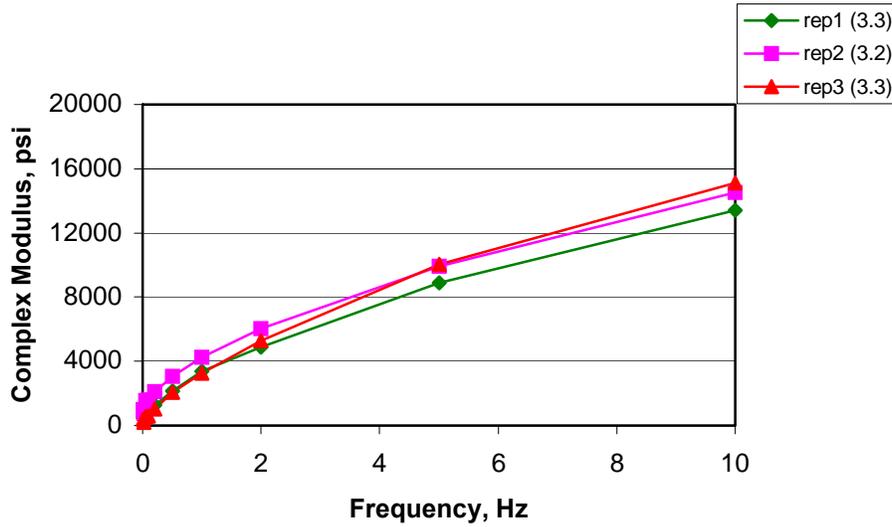
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 51: Frequency Sweep @ 40°C for Fuel #2 Insufficient
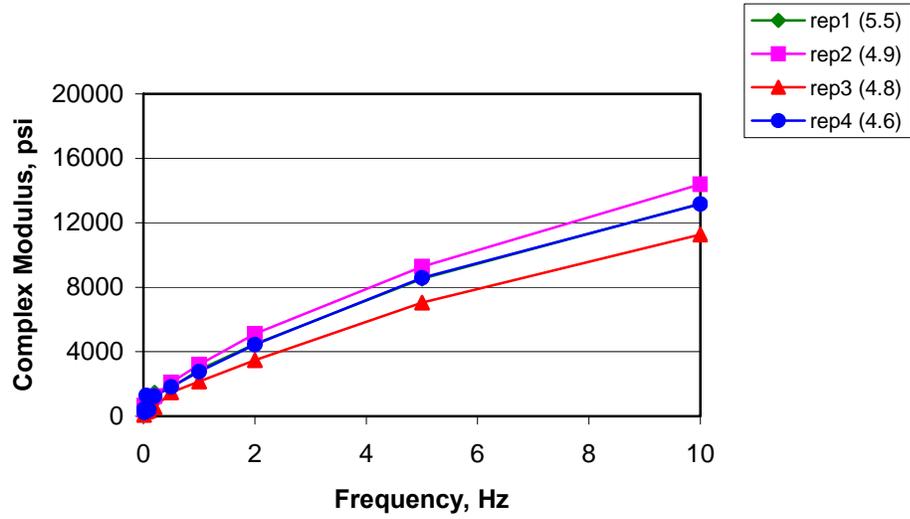
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 52: Frequency Sweep @ 40°C for Fuel #6 Insufficient
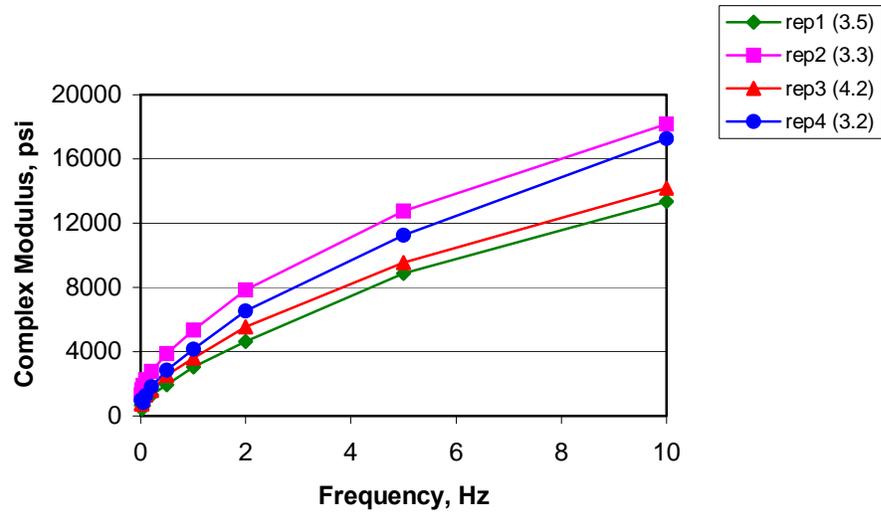
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 53: Frequency Sweep @ 40°C for Fuel 5L Insufficient
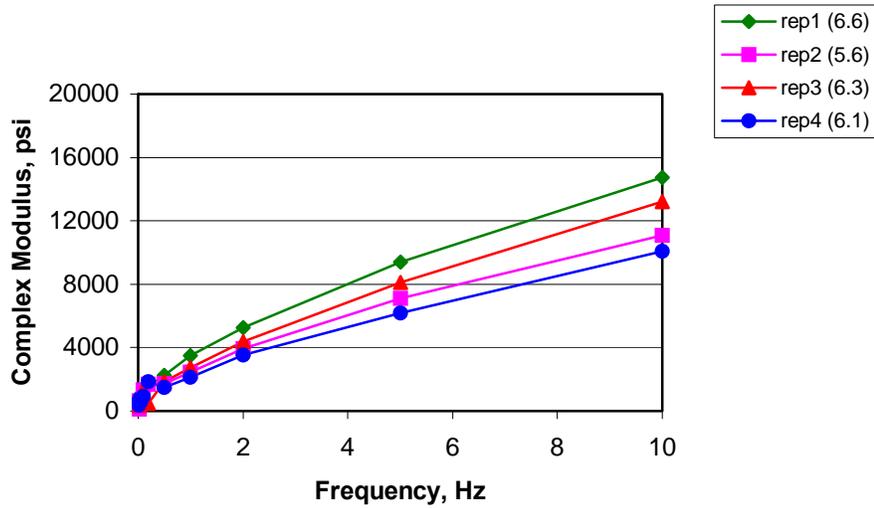
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 54: Frequency Sweep @ 40°C for Fuel 5H Insufficient
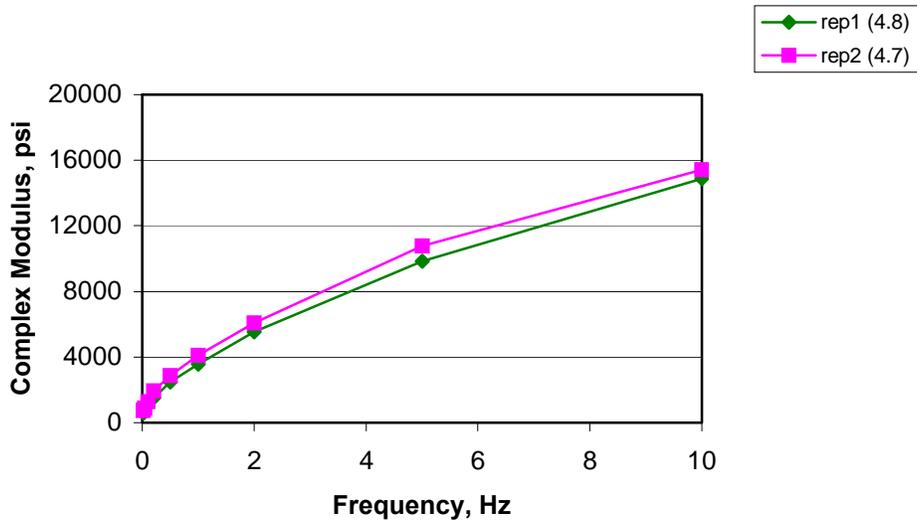
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 55: Frequency Sweep @ 40°C for Waste Fuel #1 Insufficient
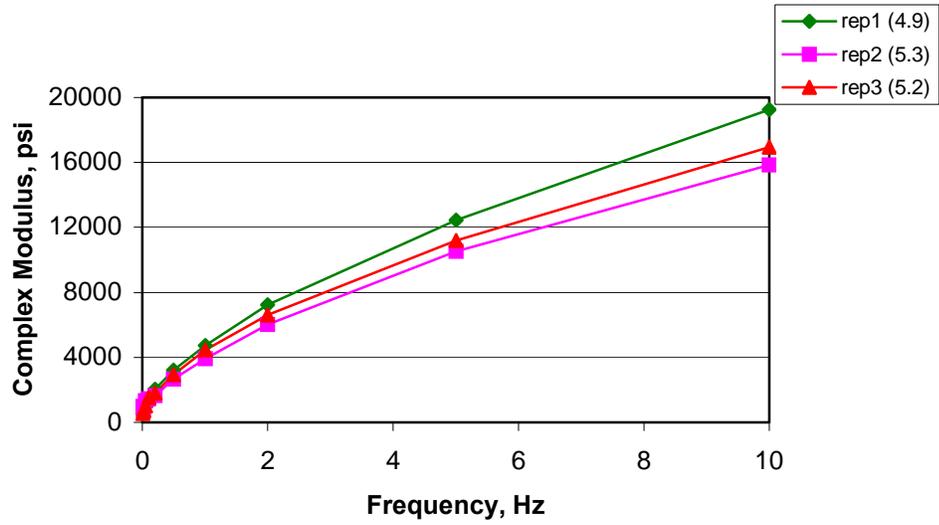
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 56: Frequency Sweep @ 40°C for Waste Fuel #2 Insufficient
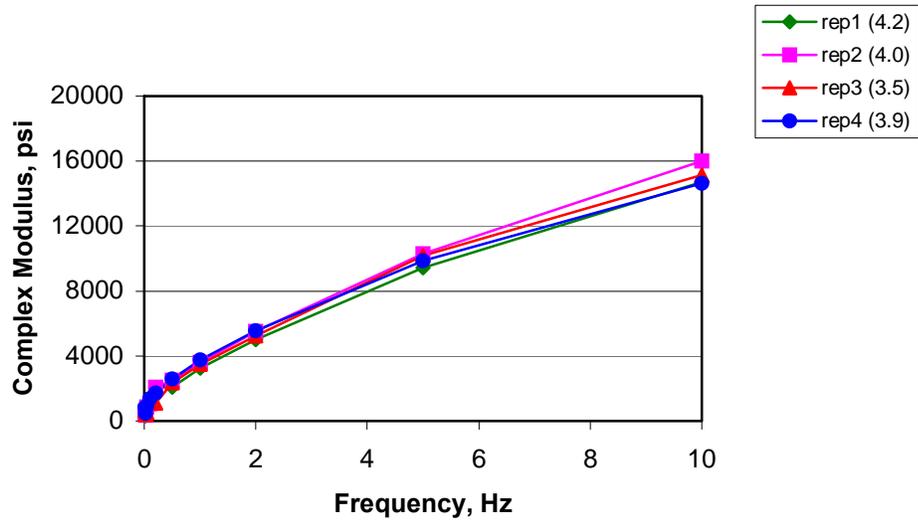
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 57: Frequency Sweep @ 40°C for Waste Fuel #3 Insufficient
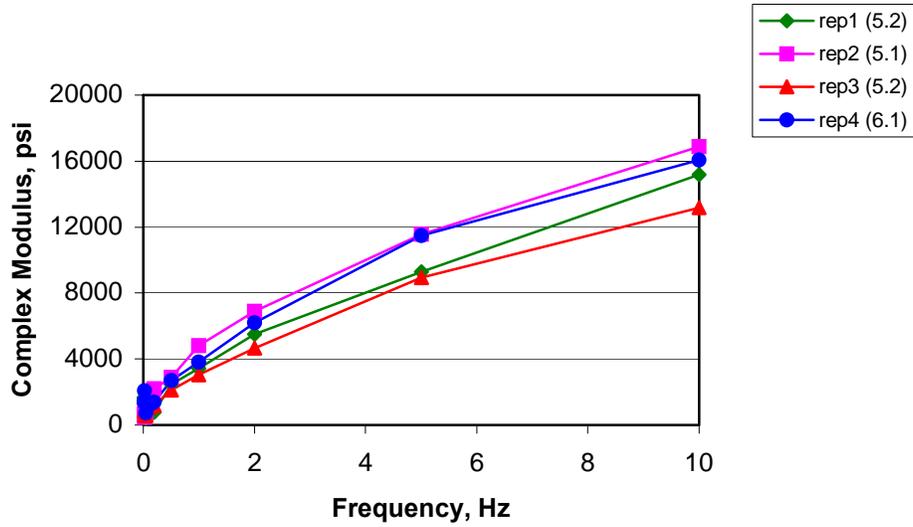
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 58: Frequency Sweep @ 40°C for Waste Fuel #4 Insufficient
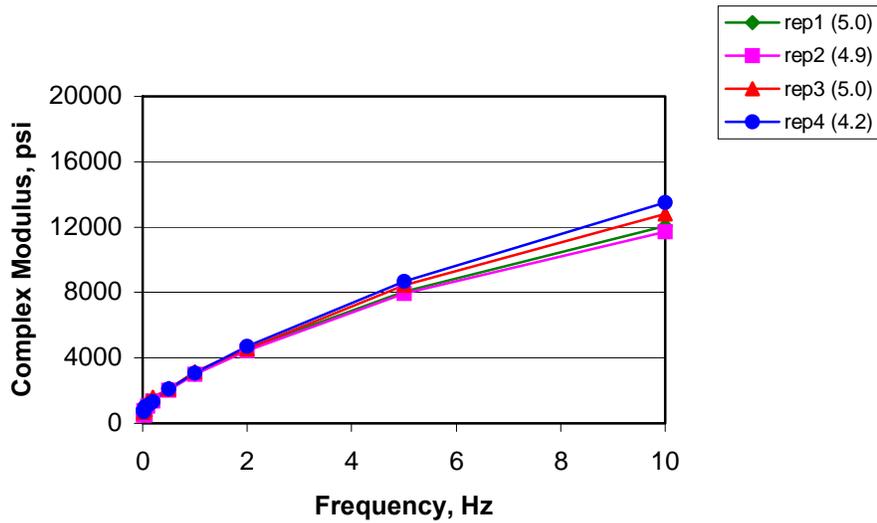
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 59: Frequency Sweep @ 40°C for Fuel RF04 Insufficient
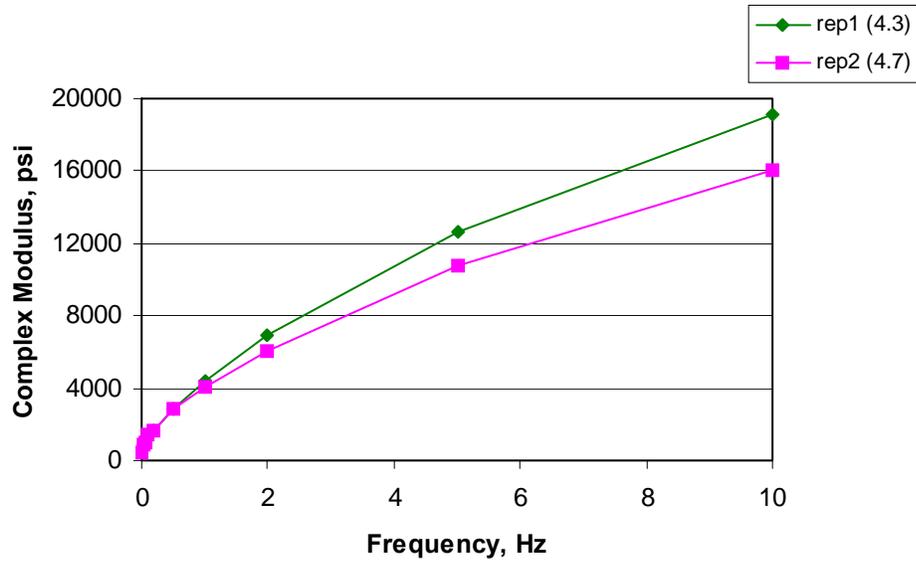
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 60: Frequency Sweep @ 40°C for Fuel RL Insufficient
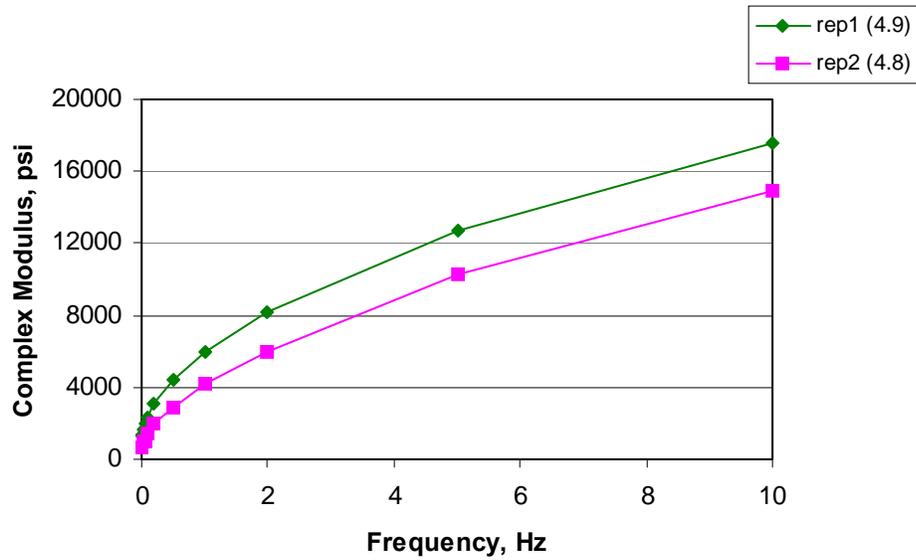
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 61: Frequency Sweep @ 40°C for Fuel RH Insufficient

APPENDIX I. SIMPLE SHEAR TEST RESULTS

Table 39 Average Simple Shear Data

Fuel Type	% Air Voids	Maximum Shear Deformation, in.	
		20 °C	40 °C
#2O	6.4	0.00362*	0.00338*
#2I	3.3	0.00335	0.00261*
#6I	5.0	0.00359*	0.00222*
#5LI	3.6	0.00378*	0.00299*
#5HI	6.2	0.00340*	0.00318*
W1I	4.8	0.00348	0.00276*
W2I	5.1	0.00366*	0.00306*
W3I	3.9	0.00352*	0.00251*
W4I	5.4	0.00356*	0.00298*
R4I	4.7	0.00366*	0.00252*
RLI	4.9	0.00312*	0.00277*
RHI	4.5	0.00290*	0.00294*
*LVDT measurement capacity exceeded.			

Table 40: SS Test Data for Fuel Type #2O

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	6.3	0.00370*	0.00328*
2	7.1	0.00342*	0.00342*
3	6.1	0.00379*	0.00346*
4	6.0	0.00359*	0.00334*
*LVDT measurement capacity exceeded.			

Table 41: SS Test Data for Fuel Type #2I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	3.3	0.00361	0.00260*
2	3.2	debonded	0.00236*
3	3.3	0.00309	0.00287*
*LVDT measurement capacity exceeded.			

Table 42: SS Test Data for Fuel Type #6I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	5.5	0.00371*	0.00178*
2	4.9	0.00346*	0.00197*
3	4.8	0.00340*	0.00232*
4	4.6	0.00380*	0.00283*
*LVDT measurement capacity exceeded.			

Table 43: SS Test Data for Fuel Type #5LI

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	3.5	0.00371*	0.00268*
2	3.3	0.00394*	0.00341*
3	4.2	0.00368*	0.00288*
4	3.2		0.00298*
*LVDT measurement capacity exceeded.			

Table 44: SS Test Data for Fuel Type #5HI

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	6.6	0.00359*	0.00310*
2	5.6	0.00332*	0.00372*
3	6.3	0.00358*	0.00246*
4	6.1	0.00313*	0.00345*
*LVDT measurement capacity exceeded.			

Table 45: SS Test Data for Fuel Type W1I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	4.8	0.00339	0.00244*
2	4.7	0.00358*	0.00309*
*LVDT measurement capacity exceeded.			

Table 46: SS Test Data for Fuel Type W2I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	4.9	0.00373	0.00306
2	5.3	0.00372	0.00307
3	5.2	0.00352	0.00304

Table 47: SS Test Data for Fuel Type W3I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	4.2	0.00342*	0.00263*
2	4.0	0.00361*	0.00223*
3	3.5	0.00358*	0.00277*
4	3.9	0.00346*	0.00242*
*LVDT measurement capacity exceeded.			

Table 48: SS Test Data for Fuel Type W4I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	5.2	0.00375*	0.00319*
2	5.1	0.00348*	0.00259*
3	5.2	0.00348*	0.00290*
4	6.1	0.00353*	0.00324*
*LVDT measurement capacity exceeded.			

Table 49: SS Test Data for Fuel Type R4I

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	5.0		0.00220*
2	4.9	0.00374*	0.00235*
3	5.0	0.00357*	0.00298*
4	4.2	0.00367*	0.00256*
*LVDT measurement capacity exceeded.			

Table 50: SS Test Data for Fuel Type RLI

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	4.3	0.00316	0.00271*
2	4.7	0.00308	0.00283*
*LVDT measurement capacity exceeded.			

Table 51: SS Test Data for Fuel Type RHI

Replicate No.	% Air Voids	Shear Deformation, in.	
		@ 20 °C	@ 40 °C
1	4.9	0.00264	0.00289*
2	4.8	0.00317	0.00299*
*LVDT measurement capacity exceeded.			

APPENDIX J. REPEATED SHEAR TEST RESULTS AT 46°C

Table 52 Repeated Shear Test Results

Fuel Type	Average Air Voids, %	Average Cumulative Strain or Cycles to Failure @ 46°C (No. of specimens averaged)
#2O	2.6 3.7	0.0391 (3) failed at 4200 cycles (1)
#2I	3.3	failed @ 1497 cycles (2)
#6I	2.3 2.2	failed @ 3373 cycles (2) 0.0398 (1)
	4.7	failed @ 1500 cycles (2)
#5LI	3.6	failed @ 1374 cycles (4)
#5HI	3.0 3.0	failed @ 3282 cycles (3) 0.0371 (1)
W1I	1.7	0.0360 (2)
W2I	2.0	0.0401 (3)
W3I	1.8	failed @ 1498 cycles (3)
	3.9	failed @ 1574 cycles (4)
W4I	2.1 1.9	failed @ 3667 cycles (3) 0.0433 (1)
R4I	1.9	0.0370 (3)
	4.2	failed @ 1000 cycles (1)
RLI	4.2	failed @ 1874 cycles (4)
RHI	4.9 4.8	failed @ 2748 cycles (1) 0.0411 (1)

Note: Because so many of these samples failed before 5000 cycles, the results of those failing and those completing the full 5000 cycles were averaged separately. Samples fail when they reach 5% strain, so for those samples, the average number of cycles to 5% strain is shown. Samples that completed 5000 cycles are averaged based on the strain at 5000 cycles.

Table 53: RS Test Data for Fuel Type #2O

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	2.6	0.0390*
2	2.6	0.0375*
3	2.5	0.0408*
4	3.7	0.0421 (4200)
* indicates that these samples were tested to 5000 cycles		

Table 54: RS Test Data for Fuel Type #2I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	3.3	0.0435 (1247)
2	3.3	0.0429 (1747)

Table 55: RS Test Data for Fuel Type #6I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	1.9	0.0435 (3997)
2	2.2	0.0398*
3	2.7	0.0439 (2748)
4	4.8	0.0445 (1500)
5	4.6	0.0441 (1500)
*indicates that these samples were tested to 5000 cycles		
Note: Due to the wide variation in air voids in compacted specimens, the results in Table 1 were averaged for the low air voids and high air voids separately.		

Table 56: RS Test Data for Fuel Type #5LI

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	3.5	0.0423 (1500)
2	3.3	0.0411 (1247)
3	4.2	0.0445 (1247)
4	3.2	0.0422 (1500)

Table 57: RS Test Data for Fuel Type #5HI

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	3.1	0.0447(4200)
2	2.7	0.0401 (2247)
3	3.0	0.0371*
4	3.3	0.0429 (3400)
* indicates that these samples were tested to 5000 cycles		

Table 58: RS Test Data for Fuel Type W1I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	1.7	0.0386*
2	1.7	0.0393*
* indicates that these samples were tested to 5000 cycles		

Table 59: RS Test Data for Fuel Type W2I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	1.9	0.0434*
2	2.0	0.0426*
3	2.1	0.0343*
* indicates that these samples were tested to 5000 cycles		

Table 60: RS Test Data for Fuel Type W3I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	2.0	0.0388 (1000)
2	1.7	0.0396 (1247)
3	1.8	0.0435 (2247)
4	4.2	0.0419 (1500)
5	4.0	0.0421 (1247)
6	3.5	0.0438 (2748)
7	3.9	0.0420 (800)
Note: Due to the wide variation in air voids in compacted specimens, the results in Table 1 were averaged for the low air voids and high air voids separately.		

Table 61: RS Test Data for Fuel Type W4I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	2.6	0.0438 (3400)
2	2.0	0.0438 (3800)
3	1.7	0.0410 (3800)
4	1.9	0.0433

Table 62: RS Test Data for Fuel Type R4I

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	1.7	0.0367*
2	1.8	0.0390*
3	2.1	0.0355*
4	4.2	0.0413 (1000)
* indicates that these samples were tested to 5000 cycles		
Note: Due to the wide variation in air voids in compacted specimens, the results in Table 1 were averaged for the low air voids and high air voids separately.		

Table 63: RS Test Data for Fuel Type RLI

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	4.3	0.0443 (1500)
2	4.7	0.0386 (1000)
3	3.9	0.0448 (2247)
4	4.0	0.0429 (2748)

Table 64: RS Test Data for Fuel Type RHI

Replicate No.	% Air Voids	Permanent strain (no. of cycles to allowable strain limit)
1	4.9	0.0434 (2748)
2	4.8	0.0411*
* indicates that these samples were tested to 5000 cycles		
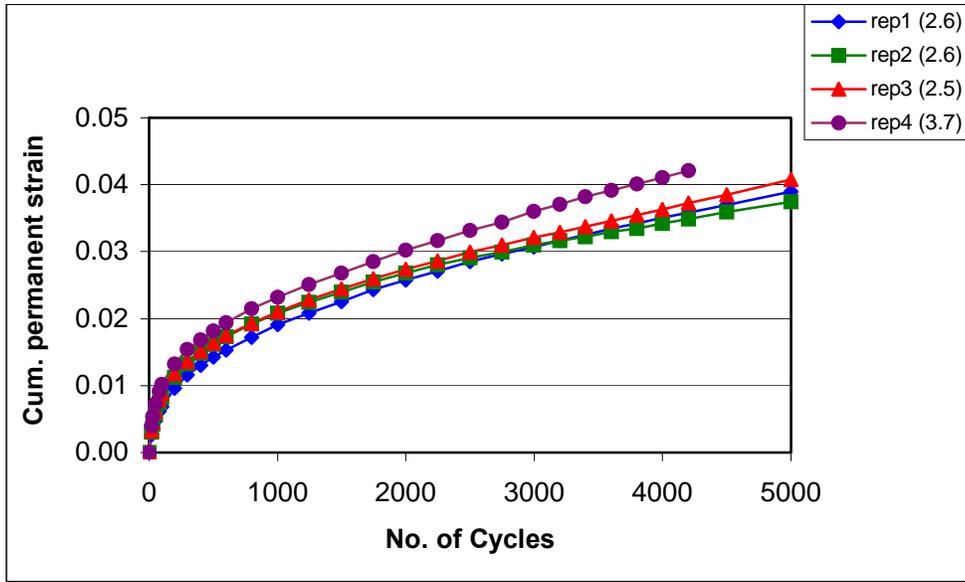
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 62: Repeated Shear @ 46°C for Fuel #2 Optimum
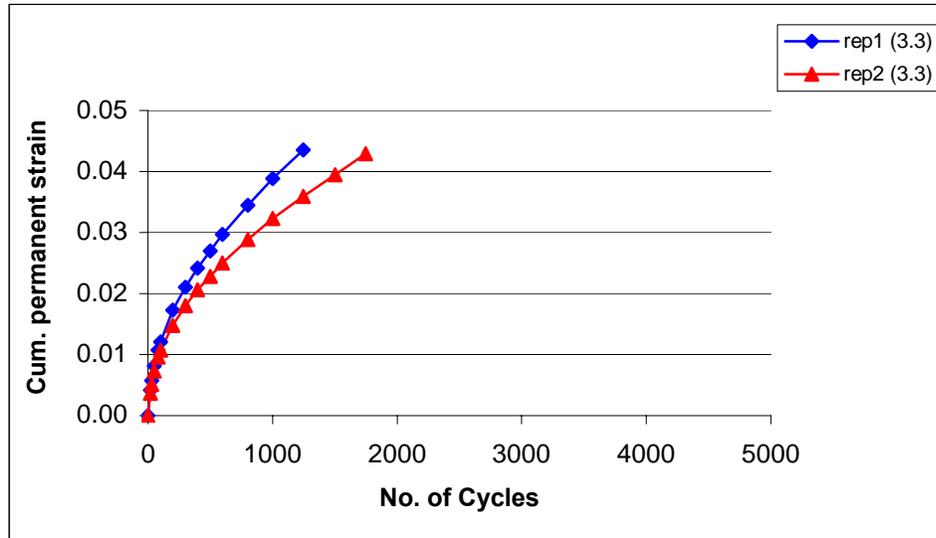
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 63: Repeated Shear @ 46°C for Fuel #2 Insufficient
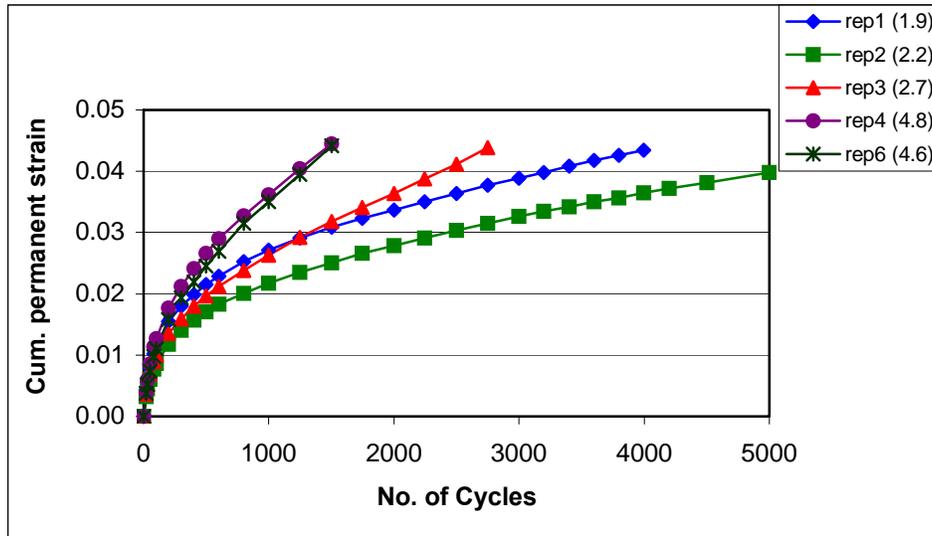
Note: Air void contents of each replicate are shown in parentheses in legends.

**Figure 64: Repeated Shear @ 46°C for Fuel #6 Insufficient**
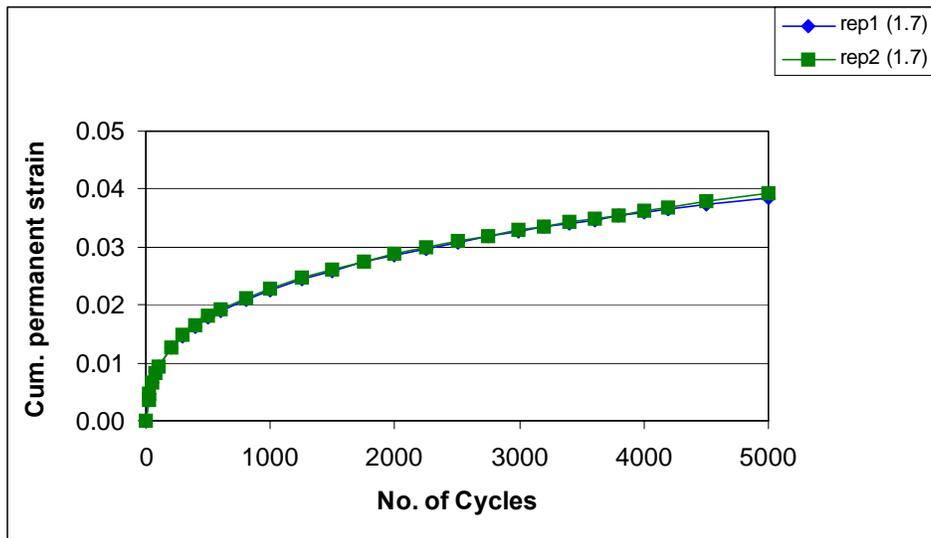
Note: Air void contents of each replicate are shown in parentheses in legends.

**Figure 65: Repeated Shear @ 46°C for Waste Fuel #1 Insufficient**
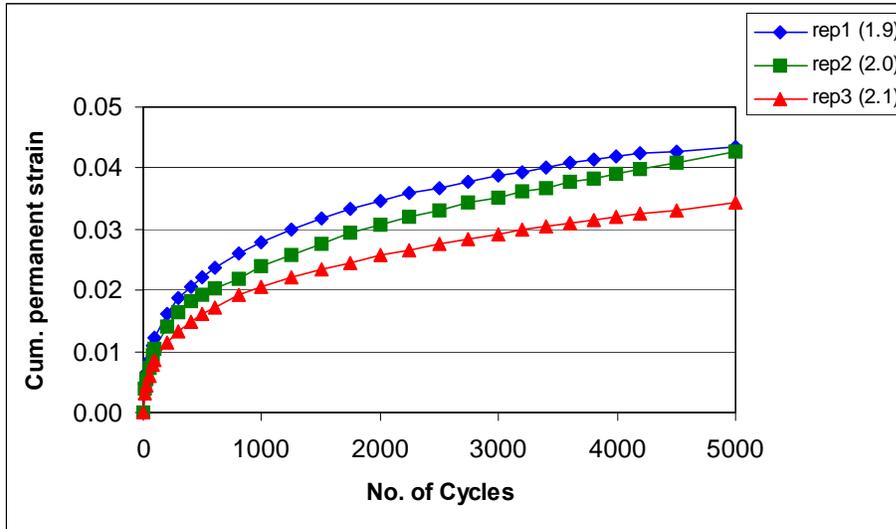
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 66: Repeated Shear @ 46°C for Waste Fuel #2 Insufficient
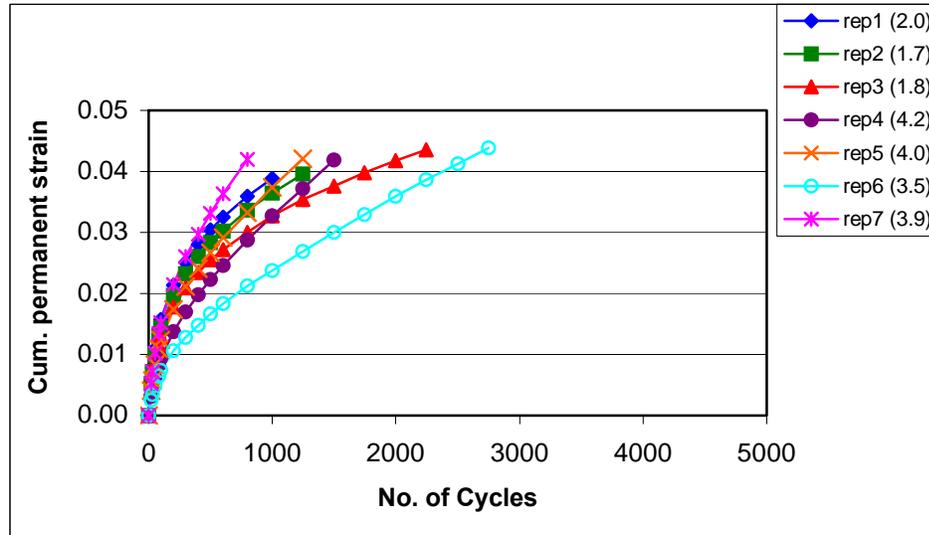
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 67: Repeated Shear @ 46°C for Waste Fuel #3 Insufficient
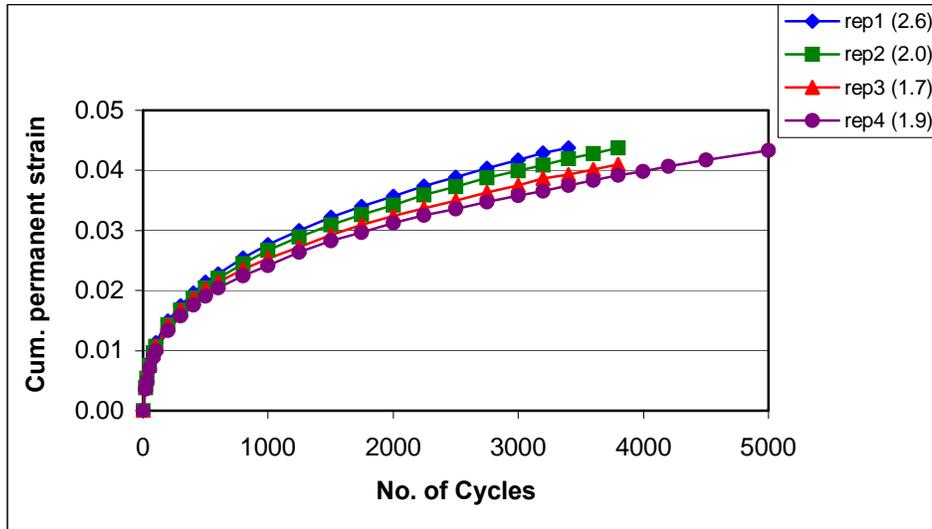
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 68: Repeated Shear @ 46°C for Waste Fuel #4 Insufficient
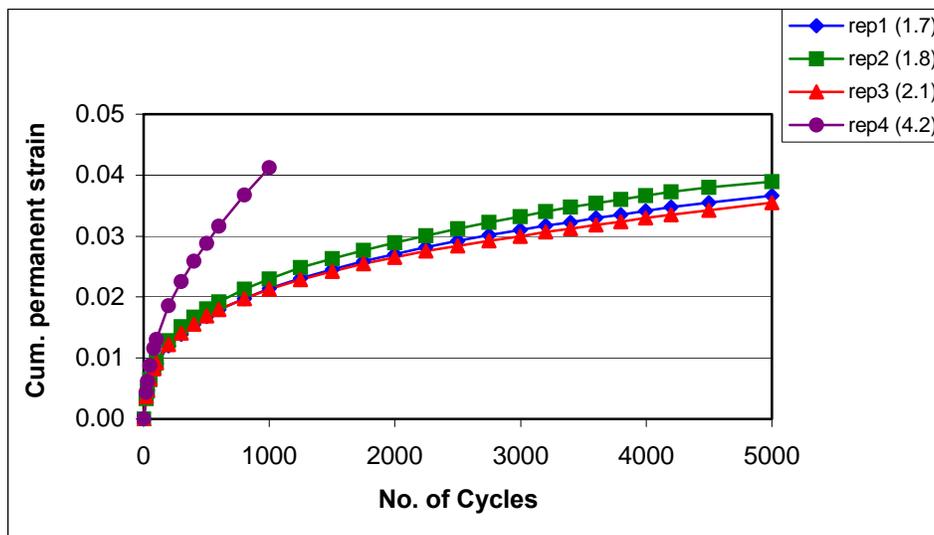
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 69: Repeated Shear @ 46°C for Fuel RF04 Insufficient
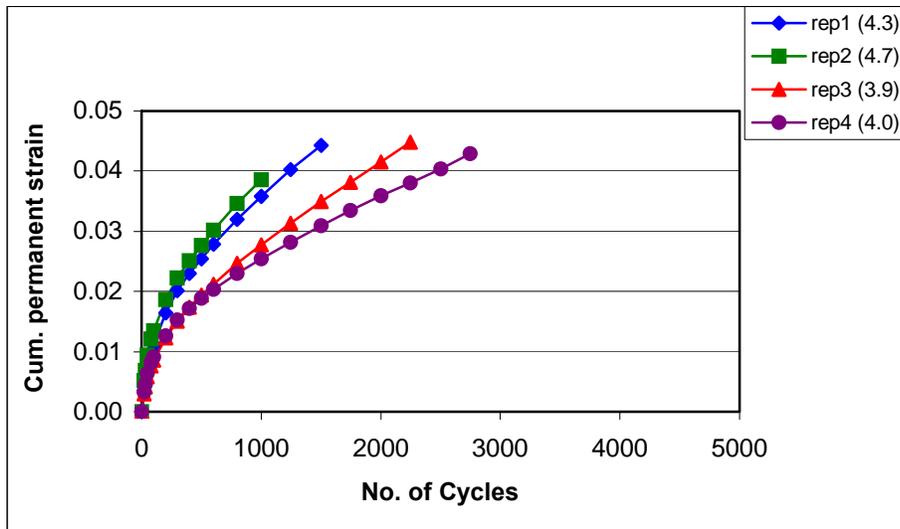
Note: Air void contents of each replicate are shown in parentheses in legends.

Figure 70: Repeated Shear @ 46°C for Fuel RL Insufficient
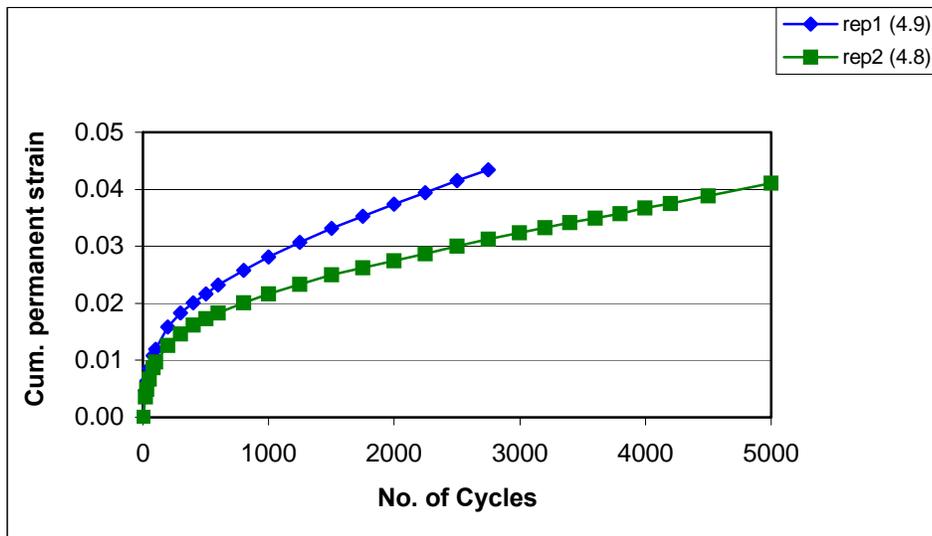
Note: Air void contents of each replicate are shown in parentheses in legends.

**Figure 71: Repeated Shear @ 46°C for Fuel RH Insufficient**
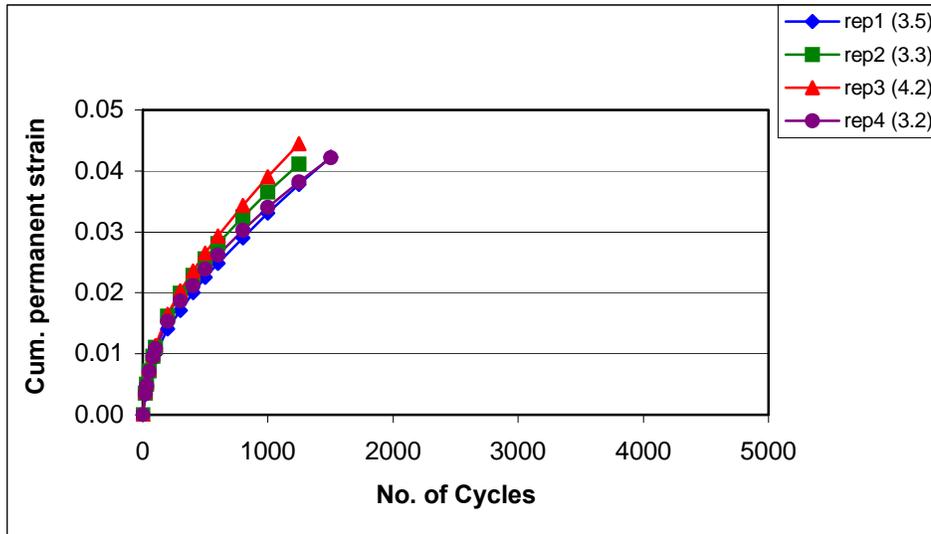
Note: Air void contents of each replicate are shown in parentheses in legends.

**Figure 72: Repeated Shear @ 46°C for Fuel 5L Insufficient**
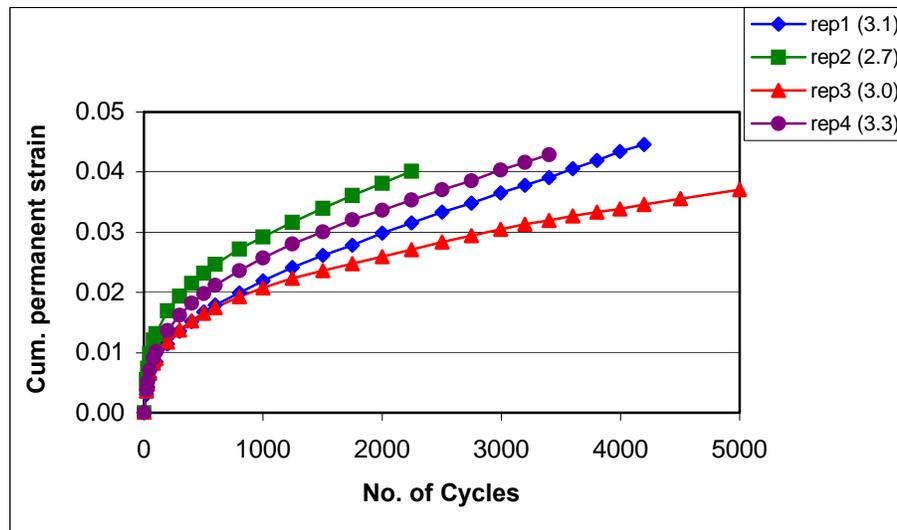
Note: Air void contents of each replicate are shown in parentheses in legends.

**Figure 73: Repeated Shear @ 46°C for Fuel 5H Insufficient**

APPENDIX K. BURNER PRIMER

This document provides a short, simplified overview of the purpose and operation of a hot mix asphalt plant burner and exhaust system, focusing on those issues that may affect proper combustion. Discussion is also provided on fuel types and how to handle them. A troubleshooting guide is provided to help identify and correct problems with the burner and exhaust system. It is intended for field personnel to use to develop an understanding of the importance of the burner and exhaust system and to recognize when a burner is or is not functioning properly.

The information in this document was compiled from a number of sources, including the references cited at the end. These references provide additional details and are excellent sources of information on plant and burner operations.

Introduction

Production of hot mix asphalt requires that aggregates be dried and heated to an appropriate temperature to allow mixing with asphalt binder and compaction on the roadway. This is accomplished by burning a fuel to produce a flame and heated gases (air and combustion products). These gases are drawn through the drum of a dryer, raising the aggregate temperature and driving off moisture in the form of steam.

This primer briefly describes typical fuels used, the combustion process, the HMA plant burner, the exhaust system, how to recognize if the system is working correctly and what to do if there are problems. Proper, efficient combustion is important for a number of reasons. For example, inefficient combustion may require the use of additional fuel to heat the aggregates to the proper temperature, which is wasteful and increases fuel costs. Also, incomplete or improper combustion may cause problems with the quality of the mix produced. Incomplete combustion may:

- allow unburned fuel to coat the heated aggregate particles and cause stripping of the mix;
- soften the asphalt binder;
- cause clogging of the burner nozzle;
- lead to coating (blinding) of the baghouse filters and associated fire risk; or
- other problems. (*7*)

Typical Burner Fuels

Almost all HMA plants use a liquid or gaseous hydrocarbon fuel to fire the burner to heat the aggregates. A few plants use solid fuels like pulverized coal or wood. (This discussion will focus on using liquid and gaseous fuels, since so few plants use solid fuels.)

The combustion process works by burning a fuel in the presence of oxygen to produce heat. Oxygen from the air is necessary for combustion to occur in a hot mix plant, just as a candle needs oxygen to burn. With hydrocarbon-based fuels, also called fossil fuels, the hydrogen in the fuel chemically combines with oxygen in the air to produce water (H_2O), and the carbon combines with oxygen to produce carbon dioxide (CO_2). Heat is liberated in the process.

In order for combustion to occur efficiently, there must be enough oxygen available to combine with the hydrogen and carbon at the moment of combustion. Also, the fuel must be available in small droplets so that the oxygen can react with the hydrogen and carbon at the surface of the droplet. In large droplets, the oxygen has a harder time getting to the hydrocarbons on the interior of the droplet to combine and so the

fuel may not burn completely. This can lead to higher fuel costs, since unburned fuel does not produce heat. It can also cause problems with mix quality if the unburned fuel contaminates the hot mix produced.

In general, gaseous fuels, like propane, are relatively easy to burn, and they burn cleanly and completely. Liquid fuels can be a little more difficult to handle, depending on how heavy or viscous they are. No. 2 fuel oil and LP (liquid propane) fuel are relatively light and can be burned fairly easily; this is one reason they are widely used as home heating oils. Heavier fuels are more viscous and are harder to break into small droplets, or to atomize, for burning. The rest of this discussion focuses on liquid fuels.

Petroleum products fall along a range or spectrum of viscosity from very light, flammable gases through liquid fuels like gasoline and kerosene, to heavier distilled liquid fuels, to the residue left after distilling all the lighter fractions off. The residue also grades from lighter fuel oil residues all the way to asphalt. This is illustrated in Figure 74. The American Society for Testing and Materials (ASTM) has published standards for various grades and types of fuel. In general, lighter fuels burn more easily. However, lighter fuels are also typically more expensive.

| Gasoline |
| Kerosene |
| Diesel Oil |
| Lube Oil |
| Asphalt |

| No. 2 Fuel |
| No. 4 |
| No. 5L |
| No. 5H |
| No. 6 |

Heavier
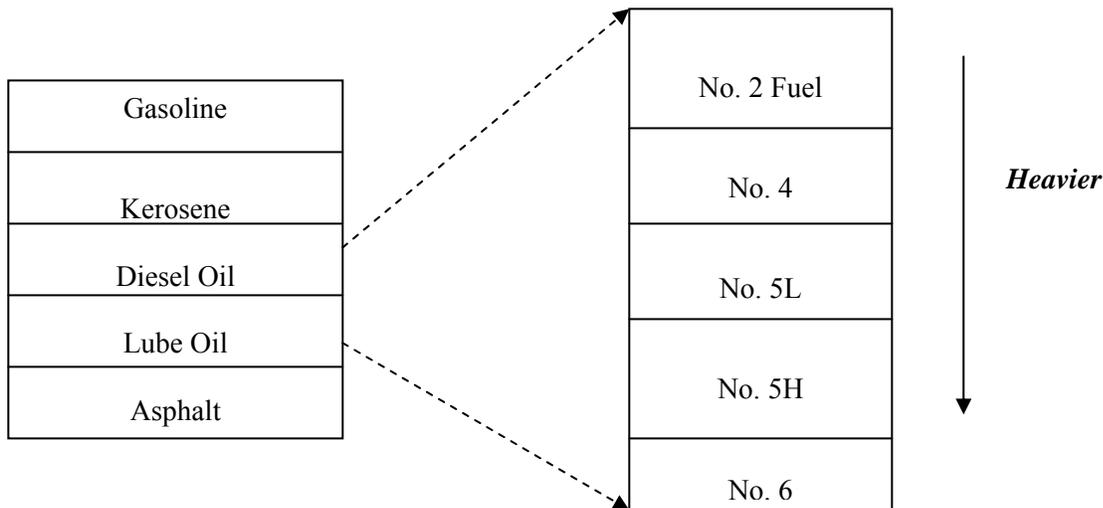
Figure 74: Range of Petroleum Products

ASTM D396, *Standard Specification for Fuel Oils*, sets standards for distilled or residual fuel oils. A distilled fuel is a lighter fuel created by a distillation process from crude oil. No.1 and No. 2 fuel oils are typically distilled fuels. (No. 1 fuel is rarely used for HMA applications.) Fuel oils with higher numbers, like No. 4, No. 5 and No. 6, are typically residual fuels, or essentially the bottoms or byproducts left after distilling the crude oil. (No. 4 grades can also be distilled or blends of distilled and residual fuels, but are most often residual.) The No. 4 and No. 5 grades are subdivided into light (L) and heavy (H) grades.

Fuel can also be produced by recycling other oils, like used lubricating oils. ASTM D6448, *Standard Specification for Industrial Burner Fuels from Used Lubricating Oils*, sets the standards for reprocessed fuel oils (RFO). Like distilled/residual fuels, the reprocessed fuels are graded based on viscosity into RFO4, 5L, 5H and 6 grades.

The ASTM standards set limits on a number of properties of the fuels, including viscosity, gross heating value (BTUs per gallon), flash point, water and sediment content and some chemical properties. The viscosity is important because it influences the pumpability of the fuel and the need to preheat. The heating value is an important economic consideration when balancing the cost of the fuel, the cost of using the fuel (preheating, etc.) and the amount of heat the fuel will produce. Too much water in a fuel can interfere with burning and can lead to increased maintenance problems with burner nozzles. It can also cause increased storage tank corrosion. Sediment can clog supply lines and filters as well as cause problems with fouling of the burner.

The heavier fuel oils typically need to be preheated to make them more fluid (less viscous) so that they can be atomized. No. 2 fuel can be atomized for burning at ambient temperature, but the other fuels are usually too thick and viscous to atomize properly without preheating. A viscosity of less than 90 or 100 Saybolt seconds universal (ssu) is generally recognized as the required viscosity to allow formation of small droplets for efficient, complete combustion. (The viscosity of a fuel can be verified in the field with a simple handheld viscometer kit.) Preheating is typically accomplished by an in-line, indirect heater that is controlled with a thermocouple to maintain the proper temperature. The fuel is heated as it flows once through a shell surrounding an oil-filled and heated core. The fuel oil can also be preheated by an outflow heater where the fuel leaves the storage tank. The fuel can be circulated back into the storage tank and through the outflow heater repeatedly to maintain a stable temperature. In this case, the in-line heater can be adjusted to give a little boost in temperature if needed to fine-tune the viscosity.

The Burner

All hot mix asphalt (HMA) plants require a dryer of some sort to heat and dry the aggregates for hot mix. In a batch plant, the process of drying and heating the aggregates takes place in a separate dryer before the heated aggregates are screened into the hot bins for batching. In a drum mix plant, the aggregates are heated, dried and mixed with asphalt, and sometimes RAP and other additives, in different parts of the same drum.

The major components of the dryer are shown in Figure 75. The burner, dryer and exhaust fan will be briefly discussed here.
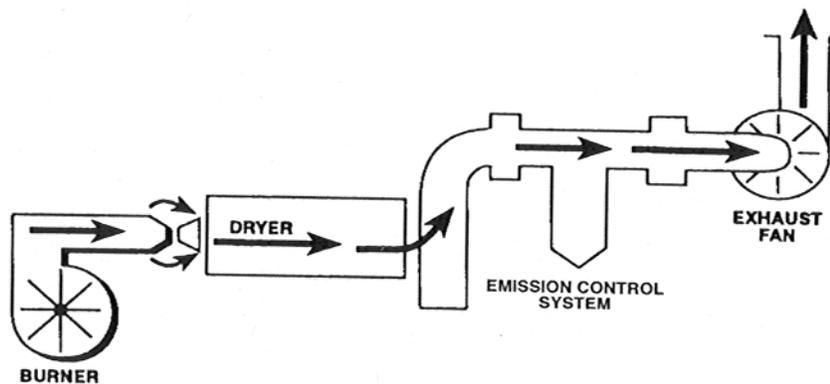
Figure 75: Major Components of Burner/Exhaust System *(3)*

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Dryers

There are two basic types of dryers: counter-flow and parallel-flow. In a counter-flow dryer, the aggregate moves from the cold end of the drum towards the burner, or in a direction opposite to that of the heated gas stream. This type of dryer is typical of most batch plant set-ups and some newer drum plants. In a parallel-flow dryer, the aggregate enters the drum at the same end as the burner and moves in the same direction as the combustion exhaust gases. Counter-flow and parallel-flow dryers are illustrated in Figure 76 and Figure 77. Regardless of the type of dryer, the principle of operation of the burner is essentially the same.

The burner is needed to provide heat energy to dry the aggregates to an acceptable moisture content (typically less than 0.5% by weight) and to heat the aggregates to mixing temperature. The burner fires directly into the drum of the dryer and the exhaust system (discussed later) pulls the heated gases through the drum. Flights in the drum lift the aggregates and drop them in a veil through the gas stream so that heat can be transferred from the hot gases to the aggregate, driving off moisture and raising the temperature of the aggregate.
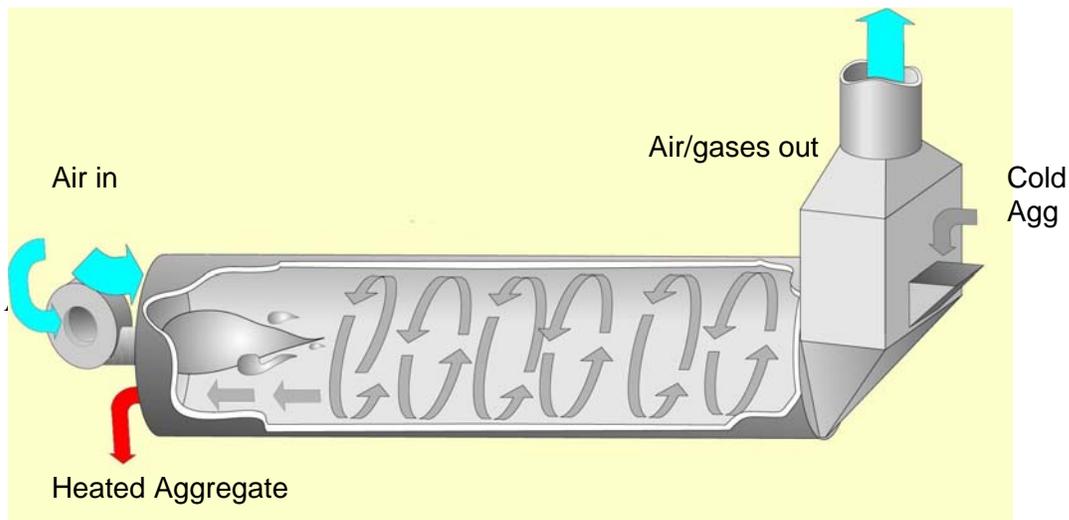
Figure 76: Counter Flow Dryer *(5)*
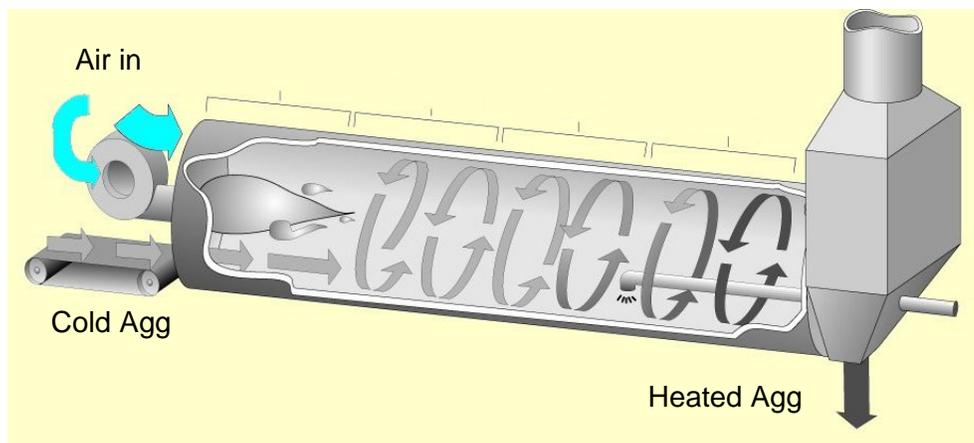
Figure 77: Parallel Flow Dryer *(5)*

Burner Types

The burner itself consists of a burner blower that forces air into the combustion area; a means to introduce the fuel into the combustion area, atomize it and mix it with air; and a pilot light to ignite the fuel-oxygen mixture. The burner blower is illustrated in Figures K5 and K6. The atomization of fuel and mixing with air will be discussed in the next section.

There are two basic types of burners: total air and induced draft burners. In a total air burner, all of the oxygen required for the combustion process is forced by the burner blower into the drum through the burner itself as illustrated in Figure 78. In an induced draft burner, roughly 30% of the air needed for combustion (called primary air) is forced through the burner and the rest of the air required (secondary air) is pulled into the drum by the exhaust fan through an opening around the burner, as shown in Figure 79.

100% of required combustion air (forced)

This area sealed
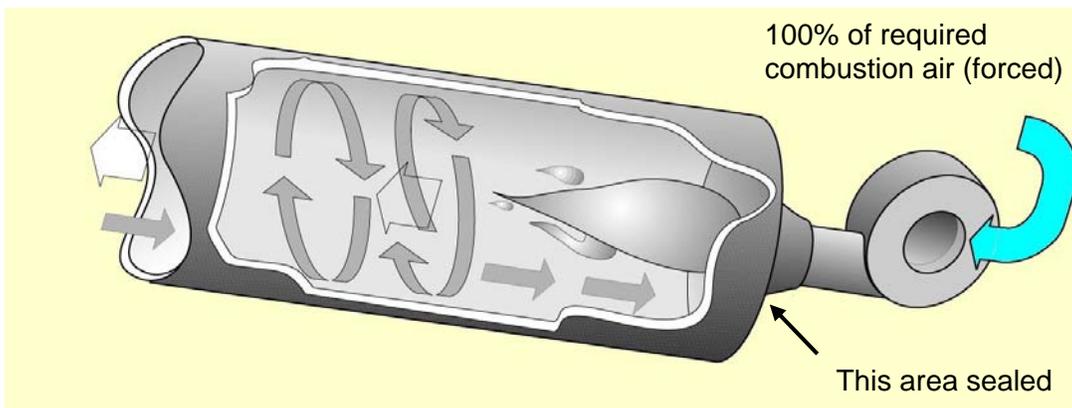
Figure 78: Total Air Burner (*5*)

30% of required combustion air (forced)

70% of required combustion air (induced)
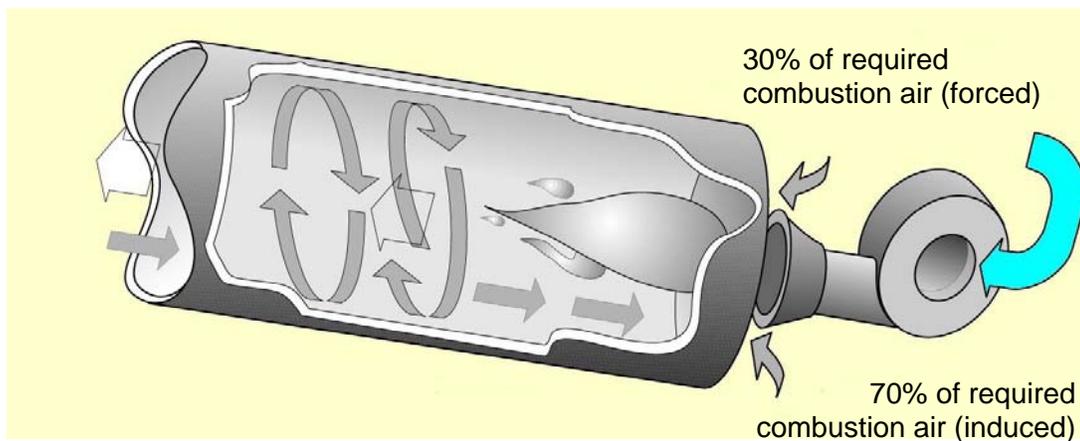
Figure 79: Induced Draft Burner (*5*)

Fuel Atomization and Combustion

It was noted previously that combustion occurs at the surface of a fuel droplet where the fuel can react with oxygen in the air. Therefore, the more surface area the fuel has, the more readily it can react with oxygen, or burn. The surface area of the fuel is increased by dispersing the fuel into small droplets through a process called atomization.

A perfume or cologne bottle, especially the old-fashioned kind shown in Figure 80, is often called an atomizer. It is a good, simplified illustration of how fuel is atomized. In the perfume atomizer, the liquid perfume is held in the bottle. When the bulb is squeezed, some of the perfume is pumped through a tube, mixed with air from the bulb and sprayed through a nozzle in a fine mist.

Figure 80: Perfume Atomizer

The same sort of process occurs in the burner of a hot mix plant, though it is more complicated. Fuel oil is heavier than perfume, so it takes more effort to atomize it, even after preheating. Plus, once the fuel is atomized into a mist, it is ignited. Nonetheless, the basic principle is the same. Fuel is forced, under pressure, through a pressure tip into the nozzle, as illustrated in Figure 81 *(4)*. Compressed air is also forced through the nozzle of the burner, spraying the fuel out in relatively large droplets. The droplets then hit a head, called the atomizer or shearing plate, which shatters the fuel into microscopic droplets (less than 50 microns in diameter). A photo of a shearing plate is shown in Figure 82. The pressurized air carries the droplets out of the nozzle where the fuel/oxygen mixture is ignited by the pilot light.
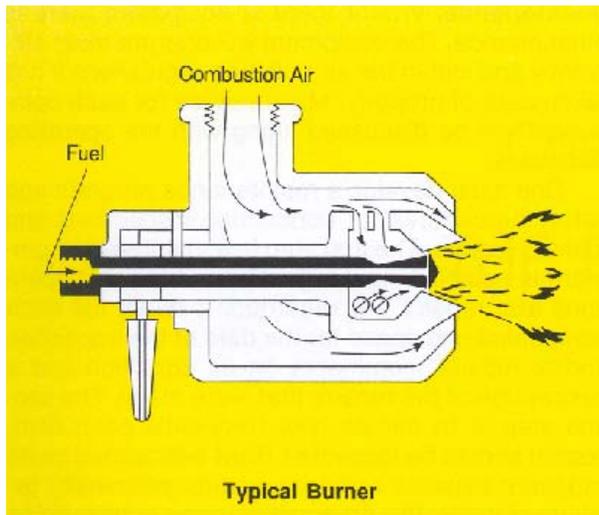
Figure 81: Atomization in a Hot Mix Plant Burner *(4)*

Atomization of the fuel is critical to the efficiency and completeness of the combustion process. Poor atomization can be caused by:

- too high a fuel viscosity (inadequate preheating),
- low fuel pressure,
- low air pressure, or
- worn, clogged or improperly sized nozzles.

More information is provided in the troubleshooting section at the end of this document.
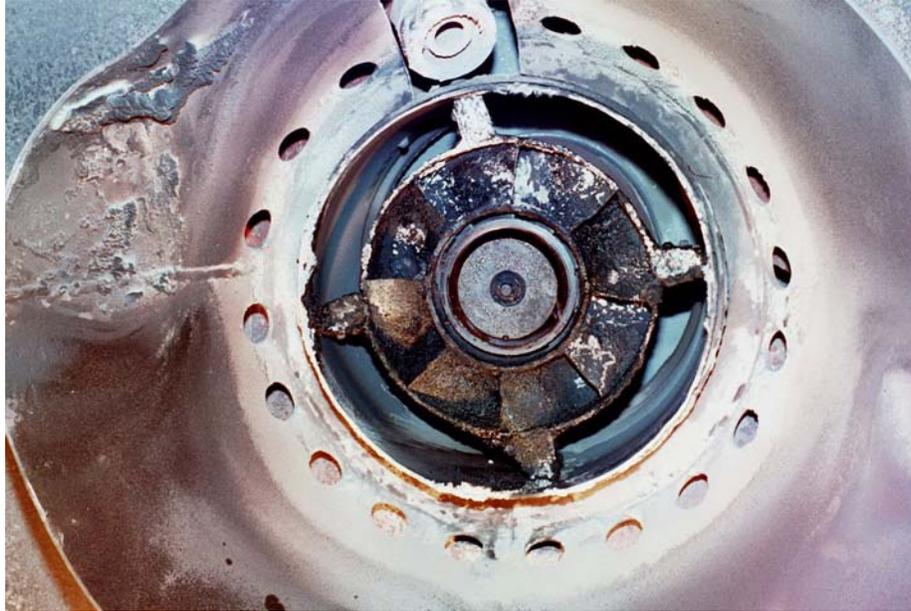
Figure 82: Shearing or Atomizer Plate in a Burner

The Exhaust System

The last major component of the dryer is the exhaust system. The exhaust fan pulls combustion air into the burner, pulls the heated combustion gases through the drum, pulls out moisture (steam) from the drying aggregates, and provides the suction to pull dust through the emission control devices. In induced draft burners, the exhaust fan provides most of the air required for combustion (approximately 70%). Depending on the moisture content of the aggregate, steam can occupy as much as 50% of the exhaust volume. (*4*) The exhaust fan must be properly sized for the particular plant.

The exhaust fan pulls a constant volume of gas through the plant at all times. If the production rate in the plant is decreased, the volume of combustion gases and steam is also decreased. Less fuel is used, which means a lower volume of combustion gases is produced, and less steam is produced when less aggregate is heated (assuming the aggregate moisture content does not change). Since the exhaust volume is constant, this means more air will be pulled in around or through the burner blower. This additional air must be heated even though it is not needed to heat the smaller volume of aggregates, thus wasting fuel.

Fuel efficiency can be improved by use of a damper system on the exhaust fan. The damper serves to reduce the cross-sectional area of the exhaust and therefore the amount of exhaust pulled through the plant. This allows the operator to be able to adjust the capacity of the exhaust system to take production changes into account. In fact, most damper systems are automatic and will adjust as the production rate changes after the initial setting. Dampers are very important for improved efficiency and lower costs. They are also an important tool that can be used to optimize the amount of air flowing through the dryer, as discussed later.

Another important factor related to the exhaust system is leakage or tramp air. There are numerous joints, openings, and holes where air can enter the hot mix plant. Since the exhaust fan pulls a constant volume through the plant at a given damper setting, any leakage air reduces the exhaust volume available to carry combustion gases, steam and fugitive dust. The farther back in the system that the leak occurs (closer to the exhaust fan), the worse it is because the pressure is higher closer to the fan and more air will be pulled into the system.

Leakage air reduces the amount of secondary air that is drawn into the plant. This air is also heated as it moves through the plant, consuming energy but producing no useful product. Leakage air does not aid combustion because usually it is not available in the small area where combustion occurs, but rather is pulled into the dryer after combustion. From a fuel efficiency standpoint, it is important to prevent leakage air from entering the system by sealing joints and openings around discharge points, feed chutes, front and rear drum seals and other openings or holes.

How Much Air is Required?

The previous sections of this document summarize important features of fuels used to heat aggregates for hot mix asphalt; the types of burners that are used to produce heat through combustion of the fuel; and the exhaust system that pulls oxygen into and through the dryer to provide air for fuel atomization and combustion, to evacuate steam from the drying aggregates, to remove combustion by-products and to remove fugitive dust in the plant. The fuel, burner and exhaust must be balanced or adjusted to work together properly.

As noted before, combustion of a hydrocarbon fuel requires one atom of oxygen for each two hydrogen atoms in the fuel to produce water (H_2O) and two atoms of oxygen for each atom of carbon in the fuel to produce CO_2. For each fuel, then, there is a theoretical number of oxygen atoms that is required to provide exactly the right number of oxygen atoms to react with the hydrogen and carbon in that fuel. The amount of air that provides exactly the right amount of oxygen for a given fuel is called stoichiometric air. ("Stoichiometry" refers to an exact chemical balance in a reaction.) Theoretically, then, it is possible to calculate the amount of air to allow for complete combustion as shown in Table 65.

Table 65. Stoichiometric Air for Different Fuel Grades

Fuel Grade	Stoichiometric Air (SCF/gallon of fuel)
No. 2	1,377
No. 4	1,448
No. 6	1,492
LP	883
Natural Gas	1,006

Since it has been pointed out several times that additional air from leakage or a lower production rate in an undampered system is wasteful, one might be inclined to think that only the stoichiometric air should be provided. Practically speaking, however, hot mix plant burners are not perfect or exact. The stoichiometric air calculation assumes that the right amount of oxygen is accessible to the hydrogen and carbon atoms *at the instant of combustion*. In order to make sure there is enough oxygen available at the right time, then, excess air is supplied to the system to increase the chances of oxygen being available when it is needed for combustion. A minimum excess air content of about 25-30% of the stoichiometric

air is recommended for light fuel oils. Heavy fuel oils may require up to 50% excess and natural gas may require only about 10% excess. (*4*)

Plant Set-Up

One common way to initially set up a plant burner to provide enough oxygen for a given fuel is to operate the plant and close the damper until the plant is starved for oxygen. This can be detected by "puffing" of the plant. In an induced draft burner, dust and sometimes a flame will shoot out of the breach around the burner. At this point, there is not enough air for good combustion, so the operator opens the damper until the puffing stops. This process should allow enough oxygen for combustion while keeping the excess air at a minimum to improve fuel efficiency. This damper setting can be marked and returned to when that fuel is used. In automatic damper systems, after this initial set-up, the automatic controls will adjust the damper as production or the aggregate moisture content fluctuates. (*4*)

Flame Eye Monitor

Once the optimum air content is determined, changes in the combustion process can be monitored by use of a flame eye. A flame eye is an electronic sensor that detects the presence of a flame and monitors the "color" of the flame. A change in the color indicates that something has changed the combustion of the fuel. This could be a reduction in the oxygen available, change in the fuel, change in the fuel/oxygen ratio or other variation. The flame eye may not tell you exactly what has changed, but it does alert you to a possible problem.

When a fuel is burned, it emits light and heat. Some of the light emitted is in the visible spectrum and some is infrared (IR) or ultraviolet (UV). The relative amount of infrared or ultraviolet light depends on the type of fuel and how hot it is burning. A flame eye monitors the amount of UV or IR that is emitted. Essentially, the detector consists of a sealed tube containing a gas that is sensitive to light of a certain frequency range. When light of that range hits the tube, it completes a circuit and the amount of current produced is measured. A change in the amount of current indicates a change in the light emitted, which in turn indicates a change in the combustion process. UV detectors are recommended for gaseous fuels and light fuel oil, while IR detectors are generally preferred for fuels heavier than No. 2. (*3*)

The detector is mounted at the burner end of the plant where it can detect the light emitted by the burner flame. These detectors can be used to monitor both the pilot light and the burner flame.

Combustion Analyzers

The optimum amount of air to supply to a plant can also be determined by analyzing the chemical content of the gas stream in the drum using a combustion analyzer. When a hydrocarbon fuel is burned under ideal conditions with oxygen, water (H_2O) and carbon dioxide (CO_2) are produced. When burned with air, nitrogen gas (N_2) from the air is also present, since nitrogen does not burn.

Conditions in a hot mix plant are far from ideal, however, and 100% complete combustion is almost impossible to achieve. Some combustion byproducts are produced under normal operating conditions. The water content of the gas stream is increased as moisture is driven out of the heated aggregates. Unburned oxygen (O_2) from the excess air is also present in the gas stream. Nitrogen (N_2) from the air is present. In addition, various nitrogen compounds (NO_x) can form depending on the availability of oxygen. Carbon monoxide (CO) is also produced when incomplete combustion occurs due to a lack of oxygen at the instant of combustion. Sulfur dioxide (SO_2) can be produced from sulfur in the fuel.

Hydrocarbons can also be detected in the gas stream. In a drum mix plant, these can be produced from the fuel, but they are often due to the asphalt cement added in the drum as well. (*1, 4, 5*)

A combustion analyzer can be used to detect the amount of various compounds in the gas stream. High oxygen levels can indicate high excess air volumes or a large amount of leakage air. Excessive carbon monoxide readings can indicate incomplete combustion. (The CO content will never be zero because the combustion process is never perfect.) Some analyzers (more expensive analyzers) can also measure the hydrocarbon content of the gas stream. High hydrocarbon contents can suggest incomplete combustion of the fuel or vaporization of part of the asphalt binder.

When using a combustion analyzer, the probe should be inserted into the drum of the dryer before the exhaust gas discharge. Leakage air will affect the gas contents measured, so measurements should be taken where leakage air is minimized.

Many factors affect the composition of the gas stream. Combustion analyzers can help to diagnose problems. The interpretation of the gas composition data is complex, however, and training is absolutely essential. Calibration of the analyzer is also critical. For these reasons, use of a combustion analyzer is "best left to qualified, trained professionals – such as burner technicians or plant consultants." (*5*)

What to Watch For/Troubleshooting

If combustion analyzers are tools for trained professionals, what can a regular plant technician or inspector on a project look for to ensure the burner is being fired properly and what can he or she do if there seems to be a problem?

One of the first clues that a burner is firing properly is its sound. The burner should produce a uniform, steady roar. A sputtering, hiccoughing or spitting sound is an indication that the burner is not firing steadily and completely. The burner may be starved for oxygen or the fuel pressure may not be appropriate. (*7*) Puffing of the burner is also a sign of too little oxygen. Puffing is often accompanied by a flame or dust being emitted from the breach around the burner. Increasing the air flow by opening the damper should eliminate puffing. (*5, 6*)

Difficulty in lighting the burner or keeping it lit can signify trouble. The fuel may be too viscous, there may be too much water in the fuel, the nozzles may be fouled or any number of other problems. (*2, 7*) The burner can be quenched by cold, wet aggregate falling through the combustion zone, especially in a parallel flow plant. Flights should be provided for a length of the drum at least equal to the drum diameter to keep the aggregates from falling through the zone where the flame is developing. If these flights become worn, the cold aggregate can quench the developing flame or become contaminated with fuel or combustion products. (*5*)

An increase in fuel consumption may also indicate problems. More fuel will be needed to produce mix at the desired temperature if the fuel is not being burned efficiently to produce the maximum heat output. (*7*)

A discoloration of aggregates heated without the addition of asphalt can also indicate problems with combustion or the combustion flights, if they can be observed. (This can be impossible to observe under normal operating conditions in a drum mix plant since the aggregates are coated with asphalt in the same drum as they are heated in. It may be possible to heat aggregates without asphalt during start-up or a monitoring period.) In severe cases, uncoated or partially coated particles in the hot mix may also be a sign of excessive contamination with unburned fuel. (*7*)

The emission control system on the plant can also help to alert a technician to a possible problem with the burner. With a baghouse, there will be a pressure change across the baghouse under normal conditions. An increase in the pressure drop may indicate that the bags are being blinded or clogged by unburned fuel. This should be investigated immediately, as the presence of fuel in the baghouse could greatly increase the risk of a baghouse fire. With a wet scrubber, the presence of an oily film on the surface of the wastewater pond may also indicate unburned fuel is being carried through the plant. Visible exhaust gases (high opacity) may indicate burner problems and may be in violation of clean air regulations. (*2, 7*)

The following troubleshooting guide may help to identify and correct problems with the fuel supply and burner/exhaust systems at a hot mix plant. The symptom tables *(2)* give clues that may signify various problems with the fuel delivery and burner systems. The action tables *(2)* offer suggestions for correcting the observed problems.

Fuel Supply Problems

Table 66: Fuel Supply Symptom Table (2)

Problem	Symptoms	Possible Causes
No fuel at the burner	Pressure and temperature gauges at burner do not register	No fuel delivery to burner
	Pressure gauge at burner reading incorrect	Fuel pressure incorrect
	Temperature indicator at burner reading incorrect	Fuel temperature/ pressure incorrect

Table 67: Fuel Supply Action Table (2)

Problem	Causes	Corrective Actions
No fuel delivery to burner	Fuel level in tank too low No fuel in day tank Outflow heater faulty Filter blocked by particulates, carbon or wax crystals	Top up fuel Check transfer pump Check and repair heater Clean tank and replace filter Check line temperature
Fuel pressure incorrect	Back pressure valve faulty Filter blocked Circulation pump faulty Line heater carbonized	Reset or repair valve Clean filter Replace blown heater elements and clean filter and heater Raise line temperature Repair/replace pump Clean or replace line heater
Fuel temperature incorrect	Line heater faulty Low fuel flow	Check carbonizing (soot), elements, fuses, breakers, thermostats and switches Check as for fuel pressure above

Burner Problems

Table 68: Burner Symptom Table (2)

Problem	Symptoms	Possible Causes
Burner ignition failure	Burner will not start	No gas flame No fuel ignition No ignition spark
Incorrect burner operation	Black smoke High exhaust temperature White smoke Low heat output Sparklers and klinker buildup	Incorrect burning Lean mixture Non-burner related problem Small flame Excessive air Poor atomization Flame impingement

Table 69: Burner Action Table (2)

Problem	Causes	Corrective Actions
No gas flame (gas ignition burners)	No gas Faulty gas valve No spark Air/gas ratio incorrect Faulty controller Faulty sensor	Change gas bottle Repair/replace valve Check no spark as below Check settings Repair/replace controller and/or sensor
No fuel ignition	Incorrect gas flame Spark ignition failure Inadequate atomization Incorrect air/fuel ratio Fuel temperature wrong Fuel pressure wrong Wrong burner settings Blocked nozzle Burner damage	Check size and position of flame Check transformer, power, points See atomization below Check burner settings for air, fuel temperature, fuel pressure Replace nozzle Replace burner
No spark	Power failure Faulty ignition transformer Faulty flame sensor Point settings incorrect	Check power Repair/replace transformer Repair/replace sensor Correct point setting
Incorrect burning	Excessive fuel/air (rich mixture) Poor atomization Klinker buildup Low air supply High burner pump pressure Oversize burner nozzle	Adjust mixture – more air See atomization below See flame impingement below Check air damper, fan intake blockage, fan failure Set correct pressure Replace with correct nozzle
Lean mixture	Incorrect air settings Fuel starvation	Correct settings Check fuel pressure, dirty nozzles, faulty modulator
Non-burner related temperature problems	Loss of insulation Faulty circulation fans (exhaust system)	Repair insulation to hold heat Check and correct air circulation
Small flame	Dirty nozzles Nozzle too small Too much excess air Fuel starvation	Clean nozzles Replace with large nozzle Adjust air supply and damper Check fuel supply pressure and temperature, dirty nozzle, modulator
Excessive air	Too much excess air introduced to combat black smoke	Adjust air supply and look for other causes for black smoke
Poor atomization	Worn burner nozzle Incorrect fuel temperature Incorrect fuel pressure Klinker buildup on nozzle and shearing plate	Replace nozzle Correct fuel temperature and pressure Clean nozzle and shearing plate
Flame impingement on walls of drum	Poor atomization Burner misalignment Flame too large Flame shape	See poor atomization above Correct burner alignment Reduce flame size Reduce bushy shape of flame

References/Additional Reading

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6. Freddy Roberts, Prithvi S. Kandhal, E. Ray Brown, Dah-Yinn Lee and Thomas W. Kennedy, Hot Mix Asphalt Materials, Mixture Design and Construction, Chapter 6, NAPA Education Foundation, Lanham, MD, 1996.

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APPENDIX L. STATISTICS PRIMER

Introduction

Experiments are normally conducted in order to make some inference or inferences about a population. This is done by sampling the population, testing the samples, and using the results to make conclusions about the population. In hot-mix asphalt (HMA) research, for example, one might sample and test only 20,000 g of material out of a population of 2 Mg. Thus any conclusions drawn about the population are made based on test results from only one percent of the population. Remarkably, this can be done with the aid of proper experimental designs and statistical analysis.

Basic Statistics

In completing experimental research one uses random variables to gather information of interest. The random variables are experimental observations that provide useful data to the researcher and follow a probability distribution. Thus each experimental observation provides one specific value of the random variable. An example of a random variable is the air void content of compacted HMA specimens. If three specimens are compacted from samples taken from the population, then three experimental observations of the air voids are obtained.

Variation and Mean

When experimental observations of random variables are obtained, variation is exhibited. Thus, when specific values of the population are measured, the values will not all be the same. The magnitude of this variation is measured using what is known as the sample variance.

$$S^2 = \frac{1}{n-1} \sum_{i-1}^{n} \left(y_i - \bar{y} \right)^2 \qquad (1)$$

where   n = the number of observations

y_i = the value of each individual observation from i = 1 to i = n.

$\bar{y}$ = the mean of the individual observations (see equation 2)

Variance is simply a measure of how much scatter is in the data. One can visualize data scatter by thinking of shooting arrows at a target. If ten arrows are shot and they all hit the target in a small, confined area, then there is little scatter. If however the arrows are all over the target, the scatter is larger, as illustrated in Figure 83. If one had HMA air void data with values ranging from 1 to 10 percent, the data has much more scatter (variance) than a similar set of data having air voids ranging from 3 to 5 percent.

Although the variation of data is correctly measured by the variance, the standard deviation, s, is often used by engineers to describe the scatter in the data. The standard deviation is calculated by taking the square root of the variance. The reason for the widespread use of standard deviation rather than variance is that the standard deviation has the same units as the variable being measured.
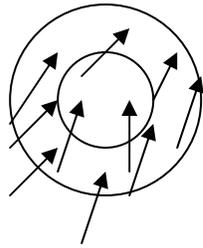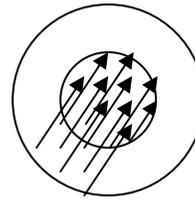
A. High variability   B. Low variability

Figure 83: Illustration of high and low variability or variance.

The $\bar{y}$ value in equation (1) is the sample mean, or average value of the observations and is calculated using equation (2).

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad (2)$$

where the variables are as described for equation 1.

Thus if ten experimental observations are made (n=10) of the air void content in an HMA mixture, the mean is calculated by simply adding the ten individual results together and dividing by ten.

Data Distribution

The most frequently encountered distribution in statistical inference is the normal distribution, often referred to as the bell-shaped distribution because of its well-known form, as shown in

Figure 84. One of the important theorems regarding normal distributions is that the sample mean has the same value as the mean of the population from which the samples are taken and that the population variance is estimated by the sample variance divided by the number of observations. This theorem thus allows for samples to be taken from the population, tested, and the results used to make inferences about the population.

Average
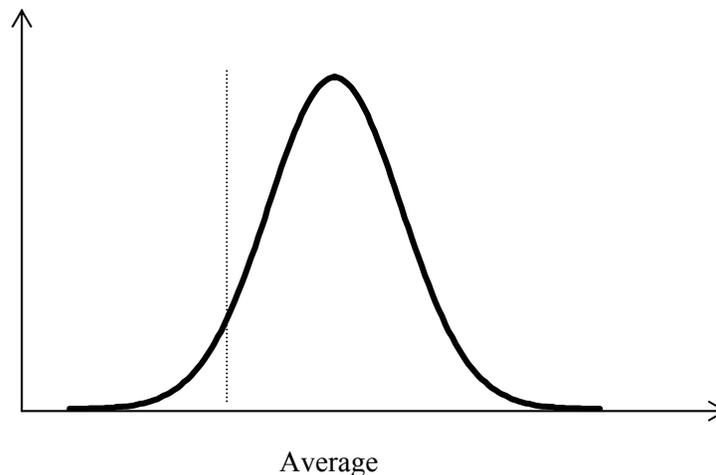
Figure 84: Standard normal distribution

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Statistical Comparisons

Many times the reason for completing an experiment is to determine if different treatments affect the outcome. For example, if one were to compact samples of an HMA mixture with two different compaction devices, say the Marshall hammer and the Superpave Gyratory Compactor (SGC), would the resulting specimens have different densities? In this example, the compactor types are the treatments. In order to answer the question, one might compact three specimens with each device and compare the mean values. Statistical techniques are used to make this comparison.

Mean Comparisons

In order to compare mean values from two different treatments, the mean and variance (standard deviation) must be calculated for each treatment. Once these are known, hypothesis testing or significance testing can be used to determine if the mean values are the same or different. Hypothesis testing gives a definite answer; the means either are or are not the same. The so-called null hypothesis, H_0, is that there is no difference between the means. The alternative hypothesis, H_1, is that the means are different.

Rather than supplying a definite answer, significance testing tells the researcher how probable it is that the means are equivalent. Significance testing is more appropriate when sampling from a population rather than testing the entire population. Significance testing lets you assess whether something is statistically significant or not based on the difference between the means and considering the standard deviations, as illustrated in Figure 85.

No significant difference   Significant difference
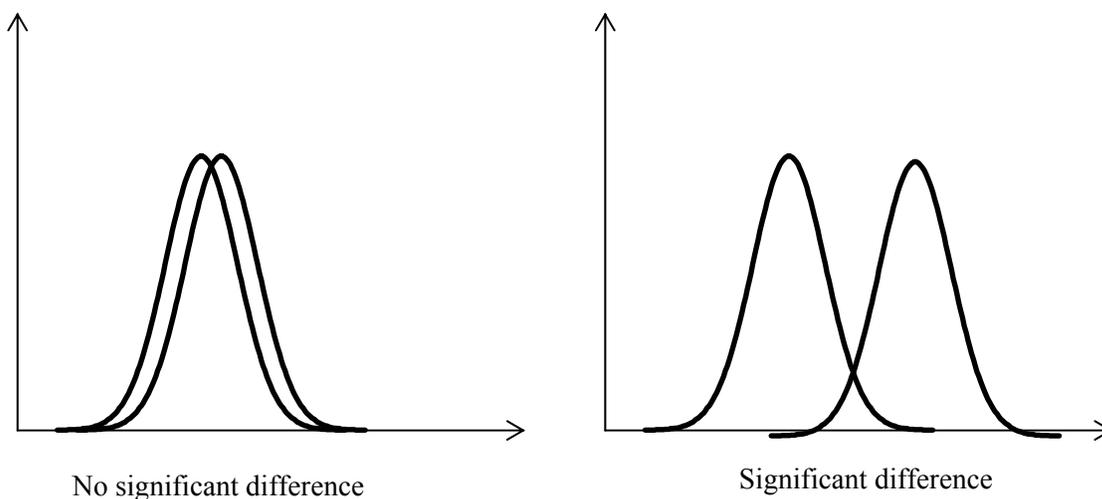
Figure 85: Illustration of significance in comparison of means

In either case, the testing is based on a Type I error, denoted as α. A Type I error is the risk of accepting the alternate hypothesis when, in fact, the null hypothesis is true. In other words, α is the risk of saying the means are different when they are really the same. This Type I error is usually chosen at 0.05. The reverse of this value is commonly referred to as confidence. Thus if the Type I error is chosen as 0.05, one commonly refers to making a statistical decision based on the data with a 95 percent (1-0.05) confidence level. Or, you can say with 95% confidence that the means are or are not different. This is commonly referred to as statistical significance. If you test and find no statistical difference between the means (accept H_0), then you can be 95% confident that the means are the same.

The p-value is a statistic commonly used to draw conclusions from a comparison on means at any given α level. The p-value is the probability that result of a test could have been more extreme than the observed result, if the means are in fact equal (null hypothesis is true). If the p-value is greater than the desired α level, the null hypothesis is accepted. If the p-value is lower than the desired α level, the null hypothesis is rejected and the means are not equal. In other words, if the p-value is higher than the α level (often set at 0.05), it indicates the result is consistent with the null hypothesis. If the p-value is low, it implies that the result is very unlikely (low probability) if the means are equal and so the null hypothesis should be rejected.

Multiple Comparisons

Many times one desires to compare three or more treatments. Special testing techniques must be used to do so. One could compare the means individually, but this may provide erroneous results. For example, if four treatments were to be compared, one could compare the means of treatments 1 and 2, 1 and 3, 1 and 4, 2 and 3, 2 and 4, and 3 and 4. If one specified a Type I error and used it for each of the comparisons, the overall Type I error for the multiple comparisons would be larger than the original value specified. In order to solve this problem, a multiple comparison technique is used. When a multiple comparison technique is employed, the Type I error is set and maintained over the entire set of multiple comparisons.

There are several different techniques for doing multiple comparisons of means. Some examples include Scheffe's method, Bonferroni t-tests, Tukey's Studentized Range and others. Scheffe's method was used in this research because it controls the Type I error across the experiment. Scheffe's method, among others, is pre-programmed in standard statistical software packages. (The methods accomplish the same comparison, but differ in the specifics of how the comparisons are calculated.) SAS, one of the most respected and widely used program was used in this research. When using Scheffe's method, the program compares the means and standard deviations of the data for each treatment, in this case the fuel-burner condition combination. The method categorizes the treatments into groups that are statistically the same; that is, they cannot be differentiated from each other. There can be any number of groups and the groups can overlap a little, a lot or not at all. If groups do not overlap, or only overlap slightly, then one can conclude that real differences exist between the treatments. If the groups overlap a lot, however, one cannot conclude that the treatments are different.

This is illustrated in Table 70. In this table, the letters indicate the groupings of the different fuels based on the modulus values determined in the Frequency Sweep test. The grouping called A indicates that one cannot differentiate between the mixes produced with RFO5H, Waste #1, RFO5L, No. 2 at insufficient, RFO4, No. 5L and Waste #2. Similarly, Group B shows that there is no difference between Waste #1, RFO5L, No. 2 at insufficient, RFO4, No. 5L, Waste #2, No. 6, Waste #3, Waste #4 and No. 5H. Lastly, Group C shows that there is no difference between RFO5L, No. 2 at insufficient, RFO4, No. 5L, Waste #2, No. 6, Waste #3, Waste #4, No. 5H and No. 2 at optimum. Since these groups overlap so completely, there is no clear distinction between any of the groups meaning that none of the means can be identified as being different from the others. One way to visualize this is shown in Figure 86.

Table 70: Scheffe's Comparison of Means for Frequency Sweep Modulus

Fuel	Group A	Group B	Group C
RFO5H	A		
Waste #1	A	B	
RFO5L	A	B	C
No. 2 Insufficient	A	B	C
RFO4	A	B	C
No. 5L	A	B	C
Waste #2	A	B	C
No. 6		B	C
Waste #3		B	C
Waste #4		B	C
No. 5H		B	C
No. 2			C
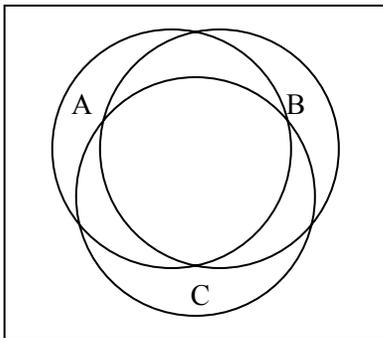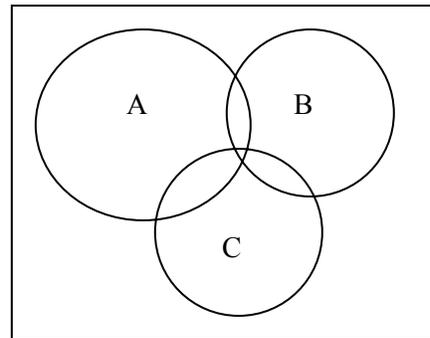
No difference between groups   Difference between groups

Figure 86: Multiple comparison of means

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APPENDIX M. RESULTS OF STATISTICAL ANALYSES

The well-known statistics package SAS was used to analyze the data summarized below. If the p-value is greater than the α risk (0.05 was used here), that indicates the means of the treatments are not significantly different. In some cases, comparisons of means were run even with high p-values for completeness and comparison to other similar data. *Shading highlights potentially different cells.*

Bonferroni, Tukey and Scheffe tests were used as the core tests for all data sets. Some analyses also used Duncan and Student-Newman-Kuels tests for additional comparisons.

Exhaust Gas Data with Asphalt Added

Table 71: Comparison of means— O_2 Emission at Optimum Burner Condition with AC (p<0.0001)

O_2 (%) emission	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
17.06	2	RL	A	A	A	A	A
16.93	1	R4	A	A	A	A	A
16.72	1	W3	A	A	A	A	AB
16.13	11	2	AB	AB	AB	AB	AB
15.94	6	W4	AB	AB	ABC	AB	AB
15.53	1	W2	AB	BC	ABC	AB	ABC
15.48	10	5L	AB	BC	ABC	AB	ABC
15.36	4	RH	AB	BC	ABC	AB	BC
14.55	2	5H	B	C	BC	BC	C
14.51	2	W1	B	C	C	BC	C
12.60	2	6	C	D	D	C	D

Table 72: Comparison of Means—C_xH_x Emission at Optimum Burner Condition with AC (p<0.0001)

C_xH_x (%) emission	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
0.230	2	6	A	A	A	A	A
0.080	10	5L	B	B	B	B	B
0.065	2	W1	BC	BC	BC	BC	BC
0.055	2	5H	BC	BC	BC	BC	BC
0.0475	4	RH	BCD	BCD	BCD	BC	BC
0.045	2	RL	BCD	CD	BCD	BC	BCD
0.040	6	W4	BCD	CD	BCD	BC	BCD
0.040	1	W3	BCD	CD	BCD	BC	BCD
0.03818	11	2	BCD	CD	BCD	BC	BCD
0.020	1	W2	CD	DE	CD	BC	CD
0.000	1	R4	D	E	D	C	D

Table 73: Comparison of Means—CO Emission at Optimum Burner Condition with AC (p<0.0001)

CO (ppm) emission	N replicates	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
2915.0	2	6	A	A	A	A	A
844.5	2	5H	B	B	B	B	B
453.5	2	W1	B	B	B	B	B
315.6	10	5L	B	B	B	B	B
275.5	6	W4	B	B	B	B	B
274.5	4	RH	B	B	B	B	B
265.0	1	W2	B	B	B	B	B
215.3	11	2	B	B	B	B	B
196.0	1	W3	B	B	B	B	B
139.0	2	RL	B	B	B	B	B
134.0	1	R4	B	B	B	B	B

Table 74: Comparison of Means—CO_2 Emission at Optimum Burner Condition with AC (p<0.0001)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
5.95	2	6	A	A	A	A	A
4.70	2	W1	AB	B	B	AB	B
4.67	2	5H	B	B	B	ABC	B
4.07	4	RH	BC	BC	BC	BCD	BC
3.98	10	5L	BC	BC	BC	BCD	BCD
3.94	1	W2	BC	BC	BC	BCD	BCD
3.64	6	W4	BC	CD	BC	BCD	CD
3.56	11	2	BC	CD	BC	BCD	CD
3.06	1	W3	C	D	C	CD	CD
2.81	2	RL	C	D	C	D	D
2.90	1	R4	C	D	C	D	D

Table 75: Comparison of Means—NO_x Emission at Optimum Burner Condition with AC (p<0.0001)

NO_x emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
91.00	2	6O	A	A	A	A	A
79.50	10	5L	AB	AB	AB	AB	AB
75.50	2	W1	ABC	BC	AB	ABC	ABC
74.50	2	5H	ABC	BC	ABC	ABC	ABC
69.00	1	W2	ABCD	BCD	ABCD	ABC	BCD
66.25	4	RH	ABCD	BCD	ABCD	ABC	BCD
60.00	6	W4	BCD	CDE	BCD	ABC	BCDE
56.00	1	W3	BCD	DE	BCD	BC	CDE
50.00	1	R4	CD	E	CD	BC	DE
46.00	1	RL	CD	E	D	C	E
44.46	11	2O	D	E	D	C	E

Table 76: Comparison of Means—Excess Air Emission at Optimum Burner Condition with AC (p<0.0001)

X_{air} emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
460.20	1	RL	A	A	A	A	A
442.60	1	R4	A	A	A	A	A
414.40	1	W3	AB	AB	AB	A	AB
344.96	11	2	ABC	BC	ABC	AB	BC
332.97	6	W4	ABC	C	ABC	AB	BC
299.60	1	W2	BC	CD	BC	ABC	C
298.52	10	5L	BC	CD	BC	ABC	C
287.93	4	RH	BCD	CD	C	ABC	C
245.30	2	W1	CD	D	CD	BC	CD
237.40	2	5H	CD	D	CD	BC	CD
161.00	2	6	D	E	D	C	D

Table 77: Comparison of Means—O_2 emission at Insufficient Burner Condition with AC (p=0.1612)

O_2 emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
13.78	1	W3	A	A	A	A	A
13.12	1	R4	A	AB	A	A	A
13.08	1	W4	A	ABC	A	A	A
12.04	1	W2	A	ABCD	A	A	A
11.40	1	6	A	ABCD	A	A	A
10.71	1	W1	A	BCDE	A	A	A
10.53	1	5L	A	CDE	A	A	A
10.48	1	RL	A	DE	A	A	A
10.30	1	2	A	DE	A	A	A
9.38	1	5H	A	E	A	A	A
8.51	1	RH	A	E	A	A	A

Table 78: Comparison of Means—C_xH_x at Insufficient Oxygen with AC (p=0.7322)

C_xH_x emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
2.1	1	6	A	A	A	A	A
1.07	1	RL	A	A	A	A	A
0.230	1	W1	A	A	A	A	A
0.180	1	RH	A	A	A	A	A
0.150	1	5H	A	A	A	A	A
0.050	1	W3	A	A	A	A	A
0.050	1	5L	A	A	A	A	A
0.040	1	W4	A	A	A	A	A
0.020	1	2	A	A	A	A	A
0.010	1	W2	A	A	A	A	A
0.010	1	R4	A	A	A	A	A

Table 79: Comparison of Means—CO at Insufficient Oxygen with AC (p=0.8896)

CO emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
4000	1	5H	A	A	A	A	A
4000	1	RH	A	A	A	A	A
4000	1	RL	A	A	A	A	A
1623	1	W1	A	A	A	A	A
333	1	W4	A	A	A	A	A
330	1	6	A	A	A	A	A
271	1	W3	A	A	A	A	A
205	1	2	A	A	A	A	A
203	1	5L	A	A	A	A	A
193	1	R4	A	A	A	A	A
175	1	W2	A	A	A	A	A

Table 80: Comparison of Means CO_2 at Insufficient Oxygen with AC (p=0.1479)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
9.24	1	RH	A	A	A	A	A
8.58	1	5H	A	A	A	A	A
7.88	1	2	A	AB	A	A	A
7.74	1	RL	A	ABC	A	A	A
7.70	1	5L	A	ABCD	A	A	A
7.56	1	W1	A	ABCDE	A	A	A
6.55	1	W2	A	BCDEF	A	A	A
5.77	1	W4	A	CDEF	A	A	A
5.74	1	R4	A	DEF	A	A	A
5.40	1	6	A	EF	A	A	A
5.24	1	W3	A	F	A	A	A

Table 81: Comparison of Means—NO_x at Insufficient Oxygen with AC (p=0.0925)

NO_x emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
161	1	5L	A	A	A	A	A
149	1	5H	A	AB			
143	1	RH	A	ABC	A	A	A
123	1	W1	A	ABC	A	A	A
121	1	RL	A	BCDE	A	A	A
118	1	W2	A	BCDEF	A	A	A
100	1	W4	A	CDEFG	A	A	A
97	1	R4	A	DEFG	A	A	A
96	1	W3	A	EFG	A	A	A
92	1	2	A	FG	A	A	A
83	1	6	A	G	A	A	A

Table 82: Comparison of Means—Excess Air at Insufficient Oxygen with AC (p=0.1305)

X_{air} emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
200.8	1	W3	A	A	A	A	A
175.0	1	R4	A	AB	A	A	A
173.6	1	W4	A	ABC	A	A	A
141.0	1	W2	A	ABCD	A	A	A
108.9	1	W1	A	CDE	A	A	A
108.0	1	6	A	DE	A	A	A
105.2	1	5L	A	DE	A	A	A
104.2	1	RL	A	DE	A	A	A
100.7	1	2	A	DE	A	A	A
84.4	1	5H	A	E	A	A	A
71.2	1	RH	A	E	A	A	A

Table 83: Comparison of Means—O_2 at Excess Oxygen with AC (p=0.9725)

O_2 emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
18.350	1	R4	A	A	A	A	A
18.020	1	W3	A	A	A	A	A
17.380	1	RH	A	A	A	A	A
17.270	1	W2	A	A	A	A	A
17.203	7	2	A	A	A	A	A
17.050	1	W4	A	A	A	A	A
16.720	1	W1	A	A	A	A	A
16.420	1	5L	A	A	A	A	A
16.057	3	5H	A	A	A	A	A
15.900	2	RL	A	A	A	A	A

Table 84: Comparison of Means—C_xH_x at Excess Oxygen with AC (p=0.5749)

C_xH_x emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
0.1767	3	RL	A	A	A	A	A
0.0600	1	5L	A	A	A	A	A
0.0500	1	W1	A	A	A	A	A
0.0400	3	5H	A	A	A	A	A
0.0400	7	2	A	A	A	A	A
0.0400	1	W3	A	A	A	A	A
0.0300	1	W4	A	A	A	A	A
0.0300	1	RH	A	A	A	A	A
0.0100	1	W2	A	A	A	A	A
0.000	1	R4	A	A	A	A	A

Table 85: Comparison of Means—CO at Excess Oxygen with AC (p=0.6118)

CO emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
2514	2	RL	A	A	A	A	A
664	3	5H	A	A	A	A	A
338	1	W1	A	A	A	A	A
275	1	5L	A	A	A	A	A
270	1	W4	A	A	A	A	A
265	1	RH	A	A	A	A	A
193	1	W2	A	A	A	A	A
182	7	2	A	A	A	A	A
153	1	W3	A	A	A	A	A
111	1	R4	A	A	A	A	A

Table 86: Comparison of Means CO_2 at Excess Oxygen with AC (p=0.9762)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
3.695	2	5H	A	A	A	A	A
3.280	1	5L	A	A	A	A	A
3.067	2	RL	A	A	A	A	A
3.060	1	W1	A	A	A	A	A
2.820	1	W4	A	A	A	A	A
2.700	7	2	A	A	A	A	A
2.650	1	W2	A	A	A	A	A
2.570	1	RH	A	A	A	A	A
2.100	1	W3	A	A	A	A	A
1.860	1	R4	A	A	A	A	A

Table 87: Comparison of Means—NO_X at Excess Oxygen with AC (p=0.7272)

NO_X emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
67.00	1	5L	A	A	A	A	A
60.33	3	5H	A	A	A	A	A
60.00	2	RL	A	A	A	A	A
47.00	1	W2	A	A	A	A	A
46.00	1	W1	A	A	A	A	A
44.00	1	W4	A	A	A	A	A
39.00	1	W3	A	A	A	A	A
39.00	1	RH	A	A	A	A	A
34.00	1	R4	A	A	A	A	A
31.43	7	2	A	A	A	A	A

Table 88: Comparison of Means—X_{air} at Excess Oxygen with AC (p=0.7038)

X_{air} emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
614.4	1	W3	A	A	A	A	A
614.4	1	R4	A	A	A	A	A
511.3	1	RH	A	A	A	A	A
493.8	1	W2	A	A	A	A	A
482.8	7	2	A	A	A	A	A
458.7	1	W4	A	A	A	A	A
414.4	1	W1	A	A	A	A	A
379.9	1	5L	A	A	A	A	A
345.4	3	5H	A	A	A	A	A
336.8	2	RL	A	A	A	A	A

Table 89: Summary of p-values for Comparison on Means Tests (with AC Added)

Variable	p-values		
	Optimum	Insufficient	Excess
Oxygen	< 0.0001	0.1612	0.9728
Hydrocarbons	< 0.0001	0.7322	0.5749
Carbon monoxide	< 0.0001	0.8896	0.6118
Carbon dioxide	< 0.0001	0.1476	0.9762
Nitric oxides	< 0.0001	0.0925	0.7272
Excess air	< 0.0001	0.1305	0.7038
Shading indicates possible significance.			

Discussion: Based on p-values, only the measurements at optimum show significant differences in the means for exhaust gases with different fuels. Comparison of means tests show that Fuel 6 is the source of these differences. Since the optimum conditions were never achieved with Fuel 6, this is to be expected. The other fuels are virtually indistinguishable (substantial overlap in groups with no clear separations).

Exhaust Gas Data with No Asphalt Added

Table 90: Comparison of Means O_2 Emission at Optimum Burner Condition without AC (p=0.3351)

O_2 emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
17.43	1	W4	A	A	A	A	A
17.29	1	W3	A	A	A	A	A
17.04	2	RH	A	A	A	A	A
16.93	1	W2	A	A	A	A	A
16.63	1	RL	A	AB	A	A	A
16.56	1	5L	A	AB	A	A	A
16.50	1	R4	A	AB	A	A	A
16.42	1	5H	A	AB	A	A	A
16.15	1	W1	A	AB	A	A	A
15.56	1	2	A	AB	A	A	A
12.44	1	6	A	B	A	A	A

Table 91: Comparison of Means—C_xH_x Emission at Optimum Burner Condition without AC (p=0.1137)

C_xH_x emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
0.35	1	6	A	A	A	A	A
0.060	1	5L	A	B	A	A	A
0.050	1	RL	A	B	A	A	A
0.040	1	W3	A	B	A	A	A
0.040	1	2	A	B	A	A	A
0.030	1	W1	A	B	A	A	A
0.030	1	W4	A	B	A	A	A
0.030	1	5H	A	B	A	A	A
0.030	1	R4	A	B	A	A	A
0.030	2	RH	A	B	A	A	A
0.010	1	W2	A	B	A	A	A

Table 92: Comparison of Means—CO Emission at Optimum Burner Condition without AC (p=0.0998)

CO emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
1770	1	6	A	A*	A	A	A
338	1	5H	A	B	A	A	A
320	1	2	A	B	A	A	A
300	1	5L	A	B	A	A	A
272	1	R4	A	B	A	A	A
242.5	2	RH	A	B	A	A	A
238	1	W1	A	B	A	A	A
230	1	RL	A	B	A	A	A
194	1	W2	A	B	A	A	A
151	1	W3	A	B	A	A	A
132	1	W4	A	B	A	A	A
*Although Duncan test identified this as different, p-value indicates it is not significant.							

Table 93: Comparison of Means—CO_2 Emission at Optimum Burner Condition without AC (p=0.3268)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
6.26	1	6	A	A	A	A	A
3.92	1	2	A	AB	A	A	A
3.48	1	W1	A	AB	A	A	A
3.28	1	5H	A	AB	A	A	A
3.22	1	R4	A	AB	A	A	A
3.18	1	5L	A	AB	A	A	A
3.12	1	RL	A	AB	A	A	A
2.90	1	W2	A	B	A	A	A
2.82	2	RH	A	B	A	A	A
2.63	1	W3	A	B	A	A	A
2.54	1	W4	A	B	A	A	A

Table 94: Comparison of Means—NO$_x$ Emission at Optimum Burner Condition without AC (p=0.6217)

NO$_x$ emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
77.0	1	6	A	A	A	A	A
57.0	1	5L	A	A	A	A	A
55.0	1	W1	A	A	A	A	A
50.0	2	RH	A	A	A	A	A
50.0	1	5H	A	A	A	A	A
48.0	1	W3	A	A	A	A	A
48.0	1	R4	A	A	A	A	A
46.0	1	2	A	A	A	A	A
43.0	1	W2	A	A	A	A	A
41.0	1	RL	A	A	A	A	A
36.0	1	W4	A	A	A	A	A

Table 95: Comparison of Means—Excess Air Emission at Optimum Burner Condition without AC (p=0.6000)

X$_{air}$ emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
520.4	1	W4	A	A	A	A	A
497.2	1	W3	A	A	A	A	A
465.3	2	RH	A	A	A	A	A
442.6	1	W2	A	A	A	A	A
404.4	1	RL	A	A	A	A	A
396.0	1	5L	A	A	A	A	A
388.9	1	R4	A	A	A	A	A
379.9	1	5H	A	A	A	A	A
352.7	1	W1	A	A	A	A	A
301.9	1	2	A	A	A	A	A
152.4	1	6	A	A	A	A	A

Table 96: Comparison of Means—O$_2$ Emission at Insufficient Burner Condition without AC (p=0.0052)

O$_2$ emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
16.91	1	W4	A	A	A	A	A
13.52	1	W3	AB	B	B	AB	B
13.04	2	W1	AB	BC	BC	ABC	BC
12.60	1	R4	AB	BC	BC	ABC	BC
12.12	1	5L	AB	BCD	BCD	BC	BC
11.93	1	2	AB	CDE	BCD	BC	BC
10.94	1	RL	B	DEF	BCD	BC	BC
10.82	2	5H	B	DEF	BCD	BC	BCD
10.51	1	W2	B	EFG	BCD	BC	CD
10.15	1	RH	B	FG	CD	BC	CD
9.08	2	6	B	G	D	C	D

Table 97: Comparison of Means—C_xH_x Emission at Insufficient Burner Condition without AC (p=0.0115)

C_xH_x emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
0.82	2	6	A	A	A	A	A
0.10	2	5H	A	B	B	AB	B
0.06	1	5L	A	B	B	AB	B
0.05	1	W4	A	B	B	AB	B
0.05	1	2	A	B	B	AB	B
0.045	2	W1	A	B	B	AB	B
0.04	1	W3	A	B	B	AB	B
0.04	1	RL	A	B	B	AB	B
0.02	1	R4	A	B	B	B	B
0.01	1	W2	A	B	B	B	B
0.01	1	RH	A	B	B	B	B

Table 98: Comparison of Means—CO Emission at Insufficient Burner Condition without AC (p=0.8590)

CO emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
2670	2	5H	A	A	A	A	A
2213	2	6	A	A	A	A	A
608	1	2	A	A	A	A	A
545	1	W4	A	A	A	A	A
398	1	5L	A	A	A	A	A
392	2	W1	A	A	A	A	A
203	1	W3	A	A	A	A	A
182	1	RH	A	A	A	A	A
182	1	RL	A	A	A	A	A
174	1	W2	A	A	A	A	A
149	1	R4	A	A	A	A	A

Table 99: Comparison of Means—CO_2 Emission at Insufficient Burner Condition without AC (p=0.0053)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
8.81	2	6	A	A	A	A	A
7.99	1	RH	A	AB	AB	AB	AB
7.72	1	W2	A	ABC	ABC	AB	AB
7.485	2	5H	AB	BCD	ABC	AB	ABC
7.39	1	RL	AB	CDE	ABC	AB	BC
6.64	1	2	AB	DE	ABC	AB	BC
6.49	1	5L	AB	EF	ABC	AB	BC
6.13	1	R4	AB	EF	BC	ABC	BC
5.805	2	W1	AB	EF	BC	ABC	BC
5.44	1	W3	AB	F	C	BC	C
2.92	1	W4	B	G	D	C	D

Table 100: Comparison of Means—NO$_x$ Emission at Insufficient Burner Condition without AC (p=0.0193)

NO$_x$ emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
135	1	5L	A	A	A	A	A
133	2	6	A	A	A	A	A
132	1	RH	A	A	A	A	A
125	1	RL	A	A	A	AB	A
123	1	W2	A	AB	A	AB	A
119	2	5H	A	AB	A	AB	A
105	1	W3	A	ABC	A	AB	A
101	1	R4	A	BC	AB	AB	A
99.5	2	W1	A	BC	AB	AB	A
84	1	2	A	C	AB	AB	A
36	1	W4	A	D	B	B	B

Table 101: Comparison of Means—Excess Air at Insufficient Burner Condition without AC (p=0.0005)

X$_{air}$ emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
439.8	1	W4	A	A	A	A	A
189.9	1	W3	B	B	B	B	B
171.95	2	W1	B	BC	BC	BC	BC
157.3	1	R4	B	CD	BCD	BCD	BC
143.2	1	5L	B	CD	BCD	BCD	CD
138.0	1	2	B	DE	BCD	BCD	CD
113.8	1	RL	B	DEF	CDE	BCD	D
111.35	2	5H	B	EF	CDE	BCD	DE
104.8	1	W2	B	FG	DE	CD	DE
97.8	1	RH	B	FG	DE	CD	DE
79.65	2	6	B	G	E	D	E

Table 102: Comparison of Means—O$_2$ Emission at Excess Burner Condition without AC (p=0.0050)

O$_2$ emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
19.23	1	W4	A	A	A	A	A
18.41	1	RL	AB	AB	AB	AB	AB
18.27	1	W3	AB	AB	AB	AB	AB
17.88	1	RH	AB	BC	AB	AB	AB
17.61	1	5H	AB	BC	AB	AB	AB
17.50	1	W2	AB	BC	AB	AB	AB
17.32	1	2	AB	BC	AB	AB	AB
16.94	1	5L	AB	C	AB	AB	ABC
16.92	1	R4	AB	C	AB	AB	ABC
16.785	2	W1	AB	C	AB	AB	BC
15.24	4	6	B	D	B	B	C

Table 103: Comparison of Means—C_xH_x Emission at Excess Burner Condition without AC (p=0.0005)

C_xH_x emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
0.27	4	6	A	A	A	A	A
0.06	1	5L	B	B	B	B	B
0.04	1	W3	B	BC	B	B	B
0.035	2	W1	B	BC	B	B	B
0.03	1	2	B	BC	B	B	B
0.03	1	R4	B	BC	B	B	B
0.03	1	RL	B	BC	B	B	B
0.02	1	5H	B	BC	B	B	B
0.02	1	RH	B	BC	B	B	B
0.01	1	W4	B	BC	B	B	B
0.00	1	W2	B	C	B	B	B

Table 104: Comparison of Means—CO Emission at Excess Burner Condition without AC (p=0.5179)

CO emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
510.0	4	6	A	A	A	A	A
294.0	1	5L	A	A	A	A	A
222.0	1	2	A	A	A	A	A
218.0	1	5H	A	A	A	A	A
217.0	2	W1	A	A	A	A	A
158.0	1	RH	A	A	A	A	A
154.0	1	RL	A	A	A	A	A
150.0	1	R4	A	A	A	A	A
149.0	1	W4	A	A	A	A	A
121.0	1	W2	A	A	A	A	A
105.0	1	W3	A	A	A	A	A

Table 105: Comparison of Means—CO_2 Emission at Excess Burner Condition without AC (p=0.0051)

CO_2 emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
4.1525	4	6	A	A	A	A	A
3.01	2	W1	AB	B	AB	AB	AB
2.91	1	R4	AB	B	AB	AB	ABC
2.89	1	5L	AB	B	AB	AB	ABC
2.61	1	2	AB	BC	AB	AB	BC
2.48	1	W2	AB	BC	AB	AB	BC
2.40	1	5H	AB	BC	AB	AB	BC
2.20	1	RH	AB	BC	B	AB	BC
1.91	1	W3	AB	CD	B	AB	BC
1.81	1	RL	AB	CD	B	AB	BC
1.21	1	W4	B	D	B	B	C

Table 106: Comparison of Means—NO$_x$ Emission at Excess Burner Condition without AC (p=0.0166)

NO$_x$ emission (ppm)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
55	1	5L	A	A	A	A	A
48	1	R4	A	AB	AB	AB	AB
46.5	2	W1	A	AB	AB	AB	AB
43.75	4	6	A	AB	AB	AB	AB
41	1	RH	A	ABC	ABC	AB	AB
40	1	W2	A	BCD	ABC	AB	AB
37	1	5H	A	BCD	ABC	AB	AB
35	1	W3	A	BCD	ABC	AB	AB
28	1	2	A	CD	ABC	AB	BC
26	1	RL	A	DE	BC	AB	BC
13	1	W4	A	E	C	B	C

Table 107: Comparison of Means—Excess Air Emission at Excess Burner Condition without AC (p=0.0015)

X$_{air}$ emission (%)	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
614.4	1	W3	A	A	A	A	A
614.4	1	W4	A	A	A	A	A
614.4	1	RH	A	A	A	A	A
614.4	1	RL	A	A	A	A	A
555.7	1	5H	AB	AB	AB	A	AB
533.7	1	W2	AB	ABC	AB	AB	AB
502.4	1	2	AB	BCD	AB	AB	AB
444.0	1	5L	AB	CD	ABC	AB	AB
441.2	2	R4	AB	CD	ABC	AB	AB
424.4	1	W1	AB	D	BC	AB	B
280.6	4	6	B	E	C	B	C

Table 108: p-values for Comparison of Means Tests (without AC added)

Variable	p-values		
	Optimum	Insufficient	Excess
Oxygen	0.3351	0.0052	0.0050
Hydrocarbons	0.1137	0.0115	0.0005
Carbon monoxide	0.0998	0.8590	0.5179
Carbon dioxide	0.3268	0.0053	0.0051
Nitric oxides	0.6217	0.0193	0.0166
Excess air	0.6000	0.0005	0.0015
Shading indicates possible significance.			

Discussion: When no asphalt was added and aggregates alone were heated in the hot mix plant, the p-values indicate possible significant differences in the means of the oxygen, hydrocarbons, carbon dioxide, nitric oxides and excess air content under insufficient and excess oxygen conditions. These conditions were examined using comparison of means tests to see where the differences were. It is not clear why the carbon monoxide content does not vary along the same lines as the other exhaust gases, but the p-values indicate no significant differences. Since a rise in carbon monoxide may signal poor combustion, according to the industry experts, this may suggest that the combustion levels with the different fuels are comparable.

At insufficient oxygen, three of the five tests identified the oxygen level with Waste Fuel 1 as different from (higher than) the other fuels. The same three tests identified this fuel as having a significantly different CO_2 content (lower) than all of the others. Two tests suggested this fuel produced a significantly lower NO_x content at insufficient oxygen. All five tests differentiated this fuel as having a significantly higher excess air content. The excess air content for W4 was very high (439.8% based on one reading), in the range of the optimum and excess air conditions rather than insufficient. This would explain the high O_2 and low CO_2 and NO_x contents as well. Other than the W4 for these exhaust gases, the other fuels are indistinguishable. The only other p-value that shows a significant difference exists in the insufficient oxygen case is for the total hydrocarbons. This is clearly caused by the No. 6 fuel, which is indicated by three tests as being significantly different from the other fuels, which cannot be distinguished from each other. The No. 6 fuel does indeed have a high C_xH_x content. Because of the start-up problems experienced with the No. 6 fuel, it is not absolutely certain that the plant conditions were exactly what was desired. The No. 6 fuel at insufficient does have one of the very lowest excess oxygen conditions, exactly opposite the W4 case discussed above. As discussed in the text of the report, however, this case is when staining of the aggregate was observed, so the high C_xH_x content appears reasonable. This case was examined as the worst case when looking at the gravimetric analysis and other tests.

At excess oxygen conditions, the No. 6 fuel is again the cause for the low p-values. For these oxygen conditions, the No. 6 fuel exhibited the lowest O_2 content, highest C_xH_x, highest CO_2 content and lowest excess air content. The excess air content here is more comparable to those observed on the low side of optimum and high side of insufficient. This low excess air content suggests that perhaps the excess oxygen condition was not achieved with this fuel, which may be related to the start-up problems. Again, however, this fuel also exhibited high C_xH_x, which could indicate a problem. This condition was examined further through the gravimetric analysis.

Attempts to Correlate Gravimetric Analysis Data with Exhaust Gas Data

At the sponsor's suggestion, attempts were made to correlate the gravimetric analysis data with the exhaust gas data. Table 109 shows the data used to examine possible correlations between the soluble organic residue, insoluble organic residue and inorganic carbon residue. Table 110 shows the resulting correlation coefficients (R^2). An R^2 value of 1.00 indicates a perfect correlation. Values around 0.500 and lower indicate essentially that no relationship exists. The higher the R^2, the more confidence one can have in the correlation.

Table 109: Organic and Inorganic Residue Data and Exhaust Gas Data

Fuel	Soluble Organic Residue per 100 g Aggregate	Insoluble Organic Residue* (%)	Inorganic Carbon Residue* (%)	CO (ppm)	NOx (ppm)	CO2 (ppm)	CxHx (%)
2O	14.50	0.0383	0.0015	320	46	3.92	0.04
2I	23.01	0.0717	0.0053	608	84	6.64	0.05
2E	29.42	0.0551	0.0065	222	28	2.61	0.03
W1I	13.61	0.0962	0.0039	392	99.5	5.805	0.045
W3I	21.46	0.0615	0.0031	203	105	5.44	0.04
W4O	9.60	--	--	132	36	2.54	0.03
W4I	10.98	0.0688	0.0036	545	36	2.92	0.05
W4E	6.89	--	--	149	13	1.21	0.01
R4I	29.85	0.0577	0.0107	149	101	6.13	0.02
5LI	27.03	0.0686	0.0035	398	135	6.49	0.06
5HO	16.38	--	--	338	50	3.28	0.03
5HI	29.04	0.0866	0.0042	2670	119	7.485	0.10
5HE	46.84	--	--	218	37	2.4	0.02
RHI	19.74	0.0709	0.0036	182	132	7.99	0.01
RLO	2.51	--	--	230	41	3.12	0.05
RLI	9.49	0.0763	0.0036	182	125	7.39	0.04
RLE	4.25	--	--	154	26	0.8	0.03
6O	94.76	0.0531	0.0039	1770	77	6.3	0.35
6I	70.79	0.0696	0.0056	2213	133	8.8	0.82
6E	39.88	0.0373	0.0042	510	43.8	4.2	0.27
* % reduction based on original weight of aggregate							
-- data not available, not tested							

Table 110: Correlation Coefficients for Exhaust Gases vs. Gravimetric Analysis Results

Exhaust Gas	Soluble Organic Residue per 100g of Agg	Insoluble Organic Residue, %	Inorganic Carbon Residue, %
CO	0.393	0.056	0.001
NO	0.070	0.341	0.001
CO2	0.078	0.247	0.005
CxHx	0.526	0.011	0.086

Discussion: The correlation coefficients are, for the most part, very low. The correlation of exhaust gases with inorganic carbon residue would be expected to be extremely low, because the inorganic carbon comes from the aggregates, not the fuels. The R^2 values for the soluble and insoluble organic residues, which could come from the fuels used, were higher, but still too low to suggest any sort of relationship. The highest R^2 value is observed for the total hydrocarbons versus the soluble organic residue, but it is still too low to show that a reliable relationship exists. The No. 6 fuel shows the highest soluble residues and highest hydrocarbon content. So, although there is not a good predictive relationship between soluble residue and total hydrocarbons, this does again appear to be the worst fuel. The nature and effects of this residue are examined further in other tests, including deliberate contamination of the binder with residue, binder testing and mixture testing.

Attempts to Correlate Gravimetric Analysis Data with Fuel Quality Data

The fuel quality tests were primarily intended to help pinpoint the presence of deleterious materials in the fuels. Since the data was available, however, attempts were made to correlate the fuel quality test results with the gravimetric analysis data, as shown in Table 111. For those fuel tests where the results could only be given as greater than a given number, such as flash point greater than 220ºC, the value that it was greater than was used for the linear regression. The R^2 values are shown at the bottom of Table 111.

Table 111: Data and Correlation Coefficients for Gravimetric Analysis Results vs. Fuel Quality Tests

Fuel	Soluble Organic Residue per 100g agg	Insoluble Organic Residue *	Inorganic Carbon *	Flash Point, ºC	Water, %	Solids, %
2OA1	14.50	0.0383	0.0015	160	0.1	0.04
2IA1	23.01	0.0717	0.0053	160	0.1	0.04
2EA1	29.42	0.0551	0.0065	160	0.1	0.04
W1IA1	13.61	0.0962	0.0039	210	2	0.32
W3IA1	21.46	0.0615	0.0031	200	3	1.03
W4IA1	10.98	0.0688	0.0036	190	12	0.49
R4IA1	29.85	0.0577	0.0107	180	1.25	0.22
5LIA1	27.03	0.0686	0.0035	230	0.1	0.08
5HIA1	29.04	0.0866	0.0042	240	0.1	0.08
RHIA1	19.74	0.0709	0.0036	210	2	0.4
RLIA1	9.49	0.0763	0.0036	210	2	0.36
6OA1	94.76	0.0531	0.0039	265	0.1	0.14
6EA1	39.88	0.0373	0.0042	265	0.1	0.14
6IA1	70.79	0.0696	0.0056	265	0.1	0.14
R^2 vs. soluble organic				0.431	0.136	0.078
R^2 vs. insoluble organic				0.003	0.030	0.030
R_2 vs. inorganic				0.024	0.020	0.042

Discussion: These low R^2 values indicate no correlations exist between the fuel quality data and the gravimetric analysis results. That is, a higher water content, for example, cannot be determined to relate to a high residue content. This is not unexpected since all of the fuels met the fuel quality requirements for their grades except that the waste fuels had high water contents.

Dynamic Shear Rheometer Testing

Table 112: Comparison of Means—Binder DSR Storage Modulus at 52°C (p-value≤0.0001)

Binder Stiffness at 52°C, kPa	N (replicates)	Fuel Type	Bonferroni	Tukey	Scheffe
10.6193	3	2O	A	A	A
9.257	3	W2I	AB	AB	AB
8.5553	3	RLI	BC	BC	ABC
8.2223	3	6I	BCD	BCD	BC
7.9073	3	W1I	BCD	BCDE	BC
7.7340	3	5HI	BCD	CDE	BC
7.4260	3	RHI	CD	CDE	BCD
7.3003	3	W3I	CD	CDE	BCVD
7.2933	3	RTFO*	CD	CDE	BCD
7.2560	2	W4I	CD	CDE	BCD
6.8960	3	5LI	DE	DEF	CD
6.7287	3	R4I	DE	EF	CD
5.5673	3	2I	E	F	D
2.7850	3	Unaged	F	G	E

*RTFO signifies binder that was aged in the RTFO oven in the laboratory. Unaged is binder sampled from the tank with no laboratory aging.

Table 113: Comparison of Means Binder DSR Storage Modulus at 58°C (p-value≤0.0001)

Binder Stiffness at 58°C, kPa	N (replicates)	Fuel Type	Bonferroni	Tukey	Scheffe
4.48	3	2O	A	A	A
3.8043	3	W2I	AB	AB	AB
3.6867	3	RLI	BC	BC	AB
3.4793	3	6I	BCD	BCD	AB
3.3837	3	W1I	BCD	BCD	BC
3.3647	3	5HI	BCD	BCD	BC
3.1933	3	RHI	BCD	BCD	BC
3.1570	3	W3I	BCDE	BCD	BC
3.1170	3	RTFO	BCDE	BCDE	BC
3.0667	3	W4I	BCDE	CDE	BC
2.9300	3	R4I	CDE	DE	BC
2.8977	3	5LI	DE	DE	BC
2.4093	3	2I	E	E	C
1.2157	3	Unaged	F	F	D

*RTFO signifies binder that was aged in the RTFO oven in the laboratory. Unaged is binder sampled from the tank with no laboratory aging.

Table 114: Comparison of Means Binder DSR Storage Modulus at 64°C (p-value≤0.0001)

Binder Stiffness at 64°C, kPa	N (replicates)	Fuel Type	Bonferroni	Tukey	Scheffe
2.05867	3	2O	A	A	A
1.82600	3	W2I	AB	AB	AB
1.67000	3	RLI	BC	BC	ABC
1.56767	3	5HI	BCD	BCD	BC
1.55433	3	6I	BCD	BCD	BCD
1.52833	3	W1I	BCD	BCD	BCD
1.49667	3	W3I	BCD	CD	BCD
1.45600	3	RHI	CD	CD	BCD
1.42767	3	RTFO	CDE	CD	BCD
1.39600	3	W4I	CDE	CDE	BCD
1.34300	3	R4I	CDE	DE	CD
1.32900	3	5LI	DE	DE	CD
1.11433	3	2I	E	E	D
0.58867	3	Unaged	F	F	E
*RTFO signifies binder that was aged in the RTFO oven in the laboratory. Unaged is binder sampled from the tank with no laboratory aging.					

Discussion: The results of analyzing the high temperature stiffness of the extracted and recovered binders, compared to laboratory aged binder and unaged binders, shows that the binders are not distinguishable, except for the unaged binder that is clearly softer. This is to be expected since aging is known to increase the binder stiffness. Had the unaged binder not been significantly different from the others, it would have raised concerns about the validity of the data. Removing the unaged binder from the comparisons did not appreciably affect the p-value or the grouping of the data. The p-value suggests there are differences between the binders, but the comparisons show that the binder groupings overlap too much to differentiate between groups.

DSR Testing after Deliberate Contamination

In an attempt to examine the nature of the residue removed from the heated aggregates through the gravimetric analysis, Heritage Research Group contaminated the virgin binder with residues recovered from unheated aggregate (aggregate blank) and evaporated methylene chloride solvent (MeCl$_2$ blank) and from aggregates heated with the No. 6 fuel at insufficient oxygen and No. 2 fuel at optimum, as described in the report. They then performed DSR testing on the residues and on the uncontaminated virgin binder. The results are shown in Table 115.

Table 115: DSR Test Results after Deliberate Contamination (p-value=0.1344)

Material	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Average (SD)	Grouping*
Neat PG58-22	1.23	1.19	1.21	1.22	1.21 (0.02)	A
MeCl$_2$ blank	1.19	1.19	1.22	1.27	1.22 (0.04)	A
Agg blank	1.21	1.25	1.25	1.26	1.24 (0.02)	A
6I residue	1.24	1.25	1.22	1.26	1.24 (0.02)	A
2O residue	1.25	1.25	1.24	1.25	1.25 (0.00)	A
*SNK, Tukey, Bonferroni, Duncan and Scheffe comparisons yielded the same grouping – no difference.						

Discussion: This testing was done to examine the nature of the residues recovered in the gravimetric analysis and in consideration of the chromatography analysis, which indicated the residue from the heated aggregates was similar to asphalt. Depending on the nature of the residue, it could either soften the binder

(if fuel-like) or stiffen the binder (if char-like) or have no effect (if asphalt-like). This deliberate contamination shows that the residue did not affect the binder stiffness, i.e., it did not soften or stiffen the binder.

Bending Beam Rheometer Testing

Table 116: Comparison of Means—Binder Creep Stiffness at -18ºC (p-value=0.0001)

Creep Stiffness at -18°C, MPa	N (replicates)	Fuel Type	Bonferroni	Tukey	Scheffe
216.0	2	W1I	A	A	A
194.5	2	RTFO	AB	AB	AB
194.0	2	2O	AB	AB	ABC
189.0	2	R4I	ABC	ABC	ABC
188.5	2	RLI	ABC	BC	ABC
181.0	2	RHI	BCD	BC	ABC
180.0	2	5LI	BCD	BCD	ABC
170.5	2	W4	BCD	BCD	BC
170.0	2	5HI	BCD	BCD	BC
168.5	2	W2	BCD	BCD	BC
166.0	2	W3	BCD	CD	BC
161.0	2	6I	CD	D	BC
156.5	2	2I	D	D	C
*RTFO signifies binder that was aged in the RTFO oven in the laboratory.					

Table 117: Comparison of Means—Binder Creep Stiffness at -24ºC (p-value=0.0017)

Creep Stiffness at -24°C, MPa	N (replicates)	Fuel Type	Bonferroni	Tukey	Scheffe
434.0	2	2O	A	A	A
426.0	2	6I	AB	A	A
412.0	2	W3I	ABC	AB	A
409.0	2	W2I	ABC	AB	A
407.5	2	R4I	ABC	AB	A
403.5	2	RLI	ABC	AB	A
394.0	2	RTFO	ABC	AB	A
386.0	2	RHI	ABC	AB	A
381.5	2	W4I	ABC	AB	A
379.0	2	W1I	ABC	AB	A
360.0	2	2I	BC	B	A
358.0	2	5LI	C	B	A
355.0	2	5HI	C	B	A
*RTFO signifies binder that was aged in the RTFO oven in the laboratory.					

Discussion: Again, the p-values indicate the potential for significant differences but when comparison of means tests are used to further analyze the data, no clear differentiation is observed. The groupings overlap so much that it is not possible to separate them. The fuel used to heat the mixtures had no effect on the binder low temperature properties.

Direct Tension Testing

Table 118: Summary of Direct Tension Test Results and Analysis at -18°C

Failure Strain		Failure Stress	
6I	2O	6I	2O
1.829	0.965	4.63	3.00
1.181	1.050	3.45	3.02
2.136	1.013	4.73	2.96
1.716	1.257	4.06	3.52
0.526	0.776	1.86	2.54
0.388	0.477	1.42	2.02
1.394	0.616	3.53	2.14
p-value = 0.135 No significant difference in means		p-value = 0.250 No significant difference in means	

Discussion: Direct tension testing is another low temperature binder test. Comparisons based on both failure strain and failure stress show no significant differences in the low temperature properties of the binders from mixtures heated with No. 2 fuel at optimum or No. 6 at insufficient oxygen. No comparison of means tests were run since the p-values show no significant differences exist.

Superpave Shear Test Results

Table 119: Comparison of Mean—Frequency Sweep Shear Modulus |G*| at 20°C (p-value=0.0001)

FS Shear Modulus at 20°C, psi	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
403389	2	RHI	A	A	A	A	A
379634	2	2I	AB	A	AB	AB	A
355423	2	W1I	AB	A	ABC	ABC	A
350248	2	RLI	ABC	A	ABC	ABC	A
298069	4	R4I	ABCD	AB	ABCD	ABC	AB
199480	4	5LI	BCDE	BC	BCDE	ABC	BC
182672	3	W2I	BCDE	C	CDE	ABC	BC
160215	4	6I	CDE	C	DE	BC	C
154758	4	W3I	CDE	C	DE	BC	C
135728	4	W4I	DE	C	DE	BC	C
123543	4	5HI	DE	C	E	BC	C
114352	4	2O	E	C	E	C	C

Table 120: Comparison of Means—Frequency Sweep Shear Modulus |G*| at 40°C (p-value=0.0001)

FS Shear Modulus at 40°C, psi	N (replicates)	Fuel Type	Bonferroni	Duncan	Tukey	Scheffe	SNK
17548	2	RLI	A	A	A	A	A
17352	3	W2I	A	A	A	A	A
16195	2	RHI	AB	AB	AB	A	AB
15739	4	5LI	AB	ABC	AB	A	AB
15335	4	W4I	AB	ABC	AB	A	AB
15153	2	W1I	AB	ABCD	AB	AB	AB
15125	4	W3I	AB	ABCD	AB	AB	AB
14341	3	2I	AB	BCDE	AB	AB	AB
13006	4	6I	ABC	CDE	BC	AB	B
12516	4	R4I	BC	DE	BC	AB	B
12270	4	5HI	BC	E	BC	AB	B
9354	4	2O	C	E	C	B	B

Discussion: The p-values for the frequency sweep shear moduli at 68°F (20°C) and 104°F (40°C) suggest that differences exist in the means. Comparison of means tests yield up to five different groups, but again there is so much overlap between the groups that no clear differentiation between the groups exists.

No statistical analysis was done on the simple or repeated shear test results due to the high number of failures or tests that could not be completed because all of the mixtures were so soft that the measurement capacity of the instrumentation was exceeded. Statistical analysis would be meaningless.

Mixture Dynamic Modulus Testing

Table 121: Dynamic Modulus Test Results and Analysis

Temperature, °C (°F)	Mean Dynamic Modulus, |E*|, MPa*		p-value
	No. 2 O	No. 6I	
37.6C (99.7F)	973.3	858.3	0.64
54.4C (129F)	287.8	284.3	0.93
*Four replicates for each case.			

Discussion: The p-values indicate clearly that no significant differences exist between the dynamic moduli of the mixes heated with No. 2 fuel at optimum (the control) vs. the No. 6 fuel at insufficient oxygen (worst case). No comparison of means tests were done since the p-values are so high.