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

Study SD2001-13
Final Report

Purdue University
School of Civil Engineering
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EXECUTIVE SUMMARY

This report outlines the research approach and findings from a thorough and systematic examination of the possibility of hot mix contamination due to the use of various fuel types and varying burner conditions in a hot mix asphalt plant. This is the most complete examination of the potential for mix contamination to date. The study differs from some previous studies because the burner was deliberately misfired (fired with excess and insufficient oxygen) in order to evaluate what might happen if a hot mix plant is operated outside the normal ranges. This allowed looking at the “worst case” scenario to an extent never attempted before.

The study was conceived of and initiated by the South Dakota Department of Transportation in 2001. The research was conducted by Purdue University and the North Central Superpave Center in West Lafayette, Indiana, with the assistance of Heritage Research Group in Indianapolis and Western Research Institute in Laramie, Wyoming.

The study involved evaluation of the chemical and physical properties of a single hot mix asphalt produced in one hot mix plant using 11 different burner fuels and operating under three different burner conditions. The research approach and findings are summarized here.

Problem Description

Environmental and economic concerns have lead to many changes in the hot mix asphalt (HMA) industry over the past few decades. Beginning in the late 1960's, growing environmental concerns helped to encourage the use of pollution control devices (bag houses being among the most popular) and new plant designs (such as drum dryers) to reduce emissions from asphalt plants.

In recent years, high energy costs have prompted many contractors to investigate the possibilities of replacing their traditional fuel supplies with less expensive options, including recycled fuel oils. South Dakota reportedly started to allow the use of No. 5 grade fuels in about 1997. Prior to that they had used No. 2 fuel. Requests to use other grades of fuel increased after the requirement was initially loosened.

While there have been a few research projects evaluating the effects of plant type and burner fuel on emissions, binder properties and mixture properties, there has not been a definitive study establishing the effects of fuel type and burner efficiency. The research reported here addresses the need for a thorough and systematic evaluation of differing burner fuel types under varying combustion conditions to determine if there is any effect on binder or mixture properties and any resulting impact on pavement life and performance.

The question was addressed by producing asphalt concrete in one hot mix plant using 11 different burner fuels at three combustion conditions over a five-day period from October 1 to 5, 2001. The heated aggregates, asphalt binders and asphalt mixtures produced under these conditions were tested in a wide variety of ways to detect the presence of any contaminant and to assess the performance impacts due to that contamination. The underlying hypothesis tested in this project is whether the materials produced with different burner fuels and combustion conditions are the same or whether the fuel-burner combination changes the materials in some way.

Contamination of the hot mix could lead to a variety of problems, depending on the nature and amount of contaminant, as discussed in Findings and Conclusions section. Unburned fuel could soften the binder and mix, which could in turn lead to instability, rutting, tenderness and asphalt drain down. Char, ash or

other combustion byproducts could lead to stripping, excessive aging, stiffening of the binder and mix, or increased cracking.

While there have been some studies in the past evaluating the effects of different plant types and fuels on hot mix asphalt properties, this appears to be the first time the burner was deliberately misfired to evaluate the effects of excess or insufficient oxygen. A qualified burner technician was hired by the South Dakota Department of Transportation (SDDOT) to guide the plant operations and adjust the damper and pressure to produce optimum, insufficient oxygen and excess oxygen conditions. For each burner fuel-combustion condition combination, bare aggregates were heated in the plant (without the addition of asphalt binder) and hot mix was produced (with the addition of asphalt binder). Samples of the heated aggregates and hot mix were collected and stored in sealed cans for later testing. Some samples of the plant-produced hot mix were compacted in the plant laboratory in a Superpave Gyratory Compactor for later mixture testing. This was done to avoid the need to reheat the mixture before compacting, which could possibly change the mix properties. These samples were stored in sealed plastic bags. Retained samples of the fuels, asphalt binder, and mixtures were tested using a variety of physical and chemical analysis techniques to examine whether any contamination of the materials had occurred during production.

The tests included:

- Standard fuel quality tests for flash point, water content and solids content.
- Analysis of the residue extracted from heated aggregates to determine their nature, chemical composition and possible effects on binder and mix using gravimetric analysis (weight of residue), chromatography and binder testing of laboratory-contaminated specimens. Attempts were also made to analyze extracted asphalt binder using chromatography to detect the presence of any contaminant.
- Binder testing of recovered binders from plant produced mix using the 11 different burner fuels. The dynamic shear rheometer was used to assess high temperature stiffness and the bending beam rheometer and direct tension test were used to analyze low temperature cracking behavior of the binder; contamination could affect either stiffness or cracking resistance depending on the nature of the contaminant.
- Mixture testing of plant-produced mixes. The Superpave Shear tester was used to perform Frequency Sweep, Simple Shear and Repeated Shear at Constant Height testing on gyratory compacted specimens. These three tests involve different types of shear loading at specified frequencies and stresses. They essentially measure the stiffness of the mix and its resistance to rutting, which could be affected by mix contamination. The dynamic modulus test, which is another stiffness test under axial compressive loading rather than shear, was also performed. This test is one of the candidate Superpave performance tests under development by Dr. Matt Witczak and will be the basis for pavement structural design under the *Mechanistic-Empirical Pavement Design Guide*. Mixes were also analyzed for resistance to stripping, resistance to rutting in a loaded wheel test and compaction characteristics, which could all be influenced by contamination.

Objectives

The research objectives were to:

- Determine the effects of fuel type, fuel quality and combustion conditions on the physical and chemical properties of asphalt concrete produced in Hot Mix Asphalt (HMA) plant.
- Assess the potential effects of the physical and chemical properties induced by fuel type, fuel quality and combustion conditions on field performance and constructability of asphalt concrete.
- Recommend specifications for fuel type, fuel quality and combustion conditions that ensure acceptable asphalt concrete performance.
- Develop or recommend test methods that field personnel can easily use to ensure compliance with the recommended specifications.

Findings and Conclusions

The results of this research effort indicate the following specific findings:

- A survey of state practices showed that few states control the types of fuel that are burned in hot mix plants within their jurisdictions. Some states limit the fuel types, particularly disallowing waste fuels; others have indirect limits through emissions testing.
- Most states have not observed apparent mix contamination problems. Those that have observed occasional problems identified particular problem fuels or plants. Due to the relatively rare occurrence of contamination problems, there has been little research on the topic.
- Industry representatives also reported few instances of contamination. They identified ways to determine if the plant is properly firing and what might signal plant problems.
- Gravimetric analysis of aggregates heated in the plant without the addition of asphalt binder did detect the presence of a minute amount of residue from aggregates heated with the No. 6 fuel at insufficient oxygen conditions and even smaller amounts of residue from the other fuels.
- Chromatographic and FTIR analysis of the residue identified it as a high molecular weight material representative of partially decomposed tars and fuel residues. The residue concentration was found to be less than 35 parts per billion by weight of the aggregate.
- Extracted binders from the plant produced hot mix were analyzed using a variety of binder tests. Neither dynamic shear rheometer testing at high temperatures, nor bending beam rheometer and direct tension testing at low temperatures detected any effect of the residue.
- Binder samples deliberately contaminated with the residue from the heated aggregates were tested in the DSR and no changes in the binder properties were detected.
- Samples of the hot mix asphalt produced in the hot mix plant with different fuels under differing burner conditions were tested in a variety of ways, including Superpave shear tests, dynamic modulus, gyratory compaction parameters, stripping susceptibility and loaded wheel testing. No significant differences were noted in any of the mixture tests, adding more compelling evidence that no detrimental contamination occurred.
- Based on the chemical and physical tests conducted in this research, no performance differences would be expected due to the use of different fuel types or varying combustion conditions.

- Initial cost savings are possible through allowing the use of alternate fuels. The actual savings is highly dependent on fuel prices and availability, but could be in the range of one to two dollars per ton of hot mix.
- Specification changes were recommended to allow use of alternate fuel types and grades while still maintaining the quality of the hot mix and asphalt concrete pavements.
- Simple methods to ensure proper atomization and combustion of burner fuels and proper plant operations were suggested. A monitoring period at start up when fuels heavier than No. 2 are used was recommended. If problems are observed and are persistent, exhaust gas analysis should be required to continue using that particular fuel at that particular plant.
- The results of this research strongly suggest that mixture contamination is not a likely occurrence if burner fuels are properly preheated and the plant is operating reasonably well. This should give the DOT and industry confidence to use alternate fuels while implementing simple controls and checks to ascertain that the burner and plant are operating properly.

In light of these findings, the following specific recommendations are made.

- This research shows that SDDOT should relax its specifications regarding allowable fuel types to include fuels through No. 5 (L and H) and reprocessed fuel oils.
- Waste fuel oils should not be allowed.
- This research shows no detrimental effect of No. 6 fuel despite the observed discoloration of aggregates heated with that fuel. SDDOT should allow the use of No. 6 fuel on pilot projects and evaluate its performance to determine if it is reasonable to allow the widespread use of this fuel in the future.
- This research clearly shows no negative impact of using the alternate fuels, so elaborate and expensive test or monitoring procedures are not recommended for routine implementation.

The research findings support a staged implementation process including the following steps:

- Providing training to plant and field personnel to recognize signs of potential burner problems.
- Checking fuel viscosity for fuels heavier than No. 2.
- Implementing a monitoring period at start-up with a heavy fuel.
- Requiring flame eyes or combustion gas monitoring only for problem cases (plants or fuel types).
- Re-evaluating the changes after implementation.

As an overall summary, then, of the major findings of this study related to the primary objectives of the work:

- The fuel type, quality and burner combustion conditions evaluated in this study were found to have no detrimental effects on the physical or chemical properties of the hot mix produced.
- There was no evidence of any effects of fuel type, quality or combustion conditions on HMA performance or combustion.

- Based on the research testing results, supplemented with information from other states and industry, recommended specification changes were developed.
- Training and monitoring procedures were recommended for field and plant personnel to ensure adequate combustion is achieved.

Implementation Recommendations

The results of this research clearly show that hot mix asphalt contamination is unlikely to occur in a plant operating within normal parameters and is even unlikely if the plant is somewhat outside normal parameters. This does not mean that any and all fuels should be used or that it is not necessary to exercise care in operating a plant properly. Contamination could still result if fuels are not properly preheated, if the atomizer and other parts of the burner or exhaust system malfunction, or if other problems exist. It does show, however, that under reasonably normal conditions, contamination is not likely to be a problem and pavement performance will not be compromised.

Based on these findings, wholesale changes in the specifications and test procedures are not recommended, but relaxing of the specifications to allow more fuel types is possible. The use of alternate fuels, including recycled fuel oils and No. 5L and 5H fuels, may allow contractors to use an economical fuel with high BTU's without sacrificing hot mix or asphalt pavement performance. The use of No. 6 fuel may also be feasible, but should be evaluated further through pilot projects before implementing. Simple changes in the specifications and monitoring procedures are recommended for consideration by the DOT. Following changes in the specifications, the SDDOT should review hot mix production for at least one construction season to observe the effects of the specification changes. Based on this review, the specifications and monitoring procedures can be relaxed, strengthened or allowed to stand accordingly.

PROBLEM DESCRIPTION

Environmental and economic concerns have led to many changes in the hot mix asphalt (HMA) industry over the past few decades. Beginning in the late 1960's, growing environmental concerns helped to encourage the use of pollution control devices (bag houses being among the most popular) and new plant designs (such as drum dryers) to reduce emissions from asphalt plants. Early evaluations of some of these innovations noted greatly reduced visual emissions as more combustion products were caught either in the bag house or in the hot mix asphalt (1-3).

In recent years, high energy costs have prompted many contractors to investigate the possibilities of replacing their traditional fuel supplies with less expensive options, including recycled fuel oils. As an example, in 2001 the Rieth-Riley Construction Company in West Lafayette, Indiana, sought approval to convert two plants to recycled fuel oil, generating numerous news stories in the local press and concerns among nearby residents. In a more local example, South Dakota reportedly started to allow the use of No. 5 grade fuels in about 1997. Prior to that the SDDOT had allowed only No. 2 fuel. Requests to use other grades of fuel increased after the requirement was initially loosened.

While there have been a few research projects evaluating the effects of plant type and burner fuel on emissions, binder properties and mixture properties, there has not been a definitive study establishing the effects of fuel type and burner efficiency. The research reported here addresses the need for a thorough and systematic evaluation of differing burner fuel types under varying combustion conditions to determine if there is any effect on binder or mixture properties and any resulting impact on pavement life and performance.

The question was addressed by producing asphalt concrete in one hot mix plant using 11 different burner fuels at three combustion conditions over a five day period from October 1 to 5, 2001. The heated aggregates, asphalt binders and asphalt mixtures produced under these conditions were tested in a wide variety of ways to detect the presence of any contaminant and to assess the performance impacts due to that contamination. It should be noted that the same mix design, aggregates and binder were used in all of the hot mix produced. The underlying hypothesis tested in this project is whether the materials produced with different burner fuels and combustion conditions are the same or whether the fuel-burner combination changes the materials in some way. For that reason and for brevity, this report will refer to different mixtures produced under the varying conditions and will then evaluate whether the materials are different or not using standard, appropriate statistical analysis tools.

Contamination of the hot mix could lead to a variety of problems, depending on the nature and amount of contaminant, as discussed in Findings and Conclusions section. Unburned fuel could soften the binder and mix, which could in turn lead to instability, rutting, tenderness and asphalt drain down. Char, ash or other combustion byproducts could lead to stripping, excessive aging, stiffening of the binder and mix, or increased cracking.

While there have been some studies in the past evaluating the effects of different plant types and fuels on hot mix asphalt properties, this appears to be the first time the burner was deliberately misfired to evaluate the effects of excess or insufficient oxygen. A qualified burner technician was hired by the South Dakota Department of Transportation (SDDOT) to guide the plant operations and adjust the damper and pressure to produce optimum, insufficient oxygen and excess oxygen conditions. For each burner fuel-combustion condition combination, bare aggregates were heated in the plant (without the addition of asphalt binder)

and hot mix was produced (with the addition of asphalt binder). Samples of the heated aggregates and hot mix were collected and stored in sealed cans for later testing. Some samples of the plant-produced hot mix were compacted in the plant laboratory in a Superpave Gyratory Compactor for later mixture testing. This was done to avoid the need to reheat the mixture before compacting, which could possibly change the mix properties. These samples were stored in sealed plastic bags. Retained samples of the fuels, asphalt binder, and mixtures were tested using a variety of physical and chemical analysis techniques to examine whether any contamination of the materials had occurred during production.

OBJECTIVES

The research objectives are to:

- Determine the effects of fuel type, fuel quality and combustion conditions on the physical and chemical properties of asphalt concrete produced in Hot Mix Asphalt (HMA) plant.
- Assess the potential effects of the physical and chemical properties induced by fuel type, fuel quality and combustion conditions on field performance and constructability of asphalt concrete.
- Recommend specifications for fuel type, fuel quality and combustion conditions that ensure acceptable asphalt concrete performance.
- Develop or recommend test methods that field personnel can easily use to ensure compliance with the recommended specifications.

These objectives were addressed through a comprehensive and intensive evaluation of residue on heated aggregate, asphalt binder and mixture properties, and performance testing of plant-produced hot mix asphalt conducted between October 2001 and June 2003. The properties of the mixtures, and their components, heated with different fuels under varying combustion conditions, were evaluated to detect evidence of contamination and to assess the effects of varying fuels and combustion conditions on the properties of the HMA produced.

Objective number one was met by the execution of an extensive evaluation involving tests on aggregates, asphalt binders and HMA mixtures. Aggregates were heated and mixtures were produced using 11 different fuels and three combustion conditions. The fuels included various grades of fuel oil (No. 2, 5L, 5H and 6), various grades of reprocessed fuel oil (RFO4, 5L and 5H), and two non-specification waste oils with two water contents each (Waste Fuels #1 through #4). The three combustion conditions included optimum, insufficient oxygen and excess oxygen (abbreviated O, I and E).

A full factorial experiment would have required testing all 33 cells in the experiment, which would have been excessive considering the number of tests and complexity of the testing. For this reason, a sequential experiment was planned. Tests would be conducted on extreme cases to determine if the test identified any potential problems. Based on the preliminary test results, a decision would then be made as to whether testing additional combinations was justified. If no contamination were detected with a particular test, there would be no benefit in completing the full suite of tests.

The optimum oxygen condition provides somewhat more oxygen than is chemically (stoichiometrically) required to combust the fuel. This additional oxygen is commonly called excess oxygen. As used in this project, however, the excess oxygen condition provides substantially more oxygen than is necessary. Although this would not be expected to cause problems with mix contamination, since there should be more than enough oxygen to support complete combustion, this condition is inefficient and uneconomical. It requires heating more air than is needed and therefore causes excessive fuel consumption. The insufficient oxygen condition would be expected to cause the most problems. Without enough oxygen to support complete combustion, unburned fuel, partially burned fuel and other combustion byproducts could be produced. For this experiment, these oxygen conditions were established

by a burner technician based on analysis of the exhaust gas composition by changing the damper setting and adjusting air and fuel pressures.

The No. 2 fuel at optimum oxygen condition was identified as the control for this experiment, due to fact that this fuel is generally recognized as clean burning under optimum conditions. The No. 6 fuel at insufficient oxygen conditions was taken to be the worst case, due to the observed presence of a brownish tint to the aggregate heated under these conditions. Later testing largely confirmed these assumptions. For example, the aggregates heated with the No. 6 fuel had the highest amounts of residue as determined from the gravimetric analysis.

A wide variety of chemical and physical tests on the fuels, binders, aggregates and mixtures was used in an attempt to detect any contamination and assess its effects on the properties of HMA mixtures. The tests included the following and are discussed in more detail in Task Descriptions section.

Table 1: Tests Used in Study

Category	Tests
Binder Tests	Dynamic Shear Rheometer
	Bending Beam Rheometer
	Direct Tension testing
	Chromatography, using a variety of techniques
Fuel Tests	Chromatography
	Standard fuel quality tests for flash point, water and sediments
Aggregate Tests	Visual examination of residue, if present
	Solvent extraction/recovery and chromatographic analysis
Mixture Tests	Superpave Gyrotory compaction
	Superpave Shear tests
	Dynamic Modulus testing
	Loaded Wheel testing
	AASHTO T283 stripping test

The second objective of determining the effects of fuel type, quality and combustion conditions of the in-service performance and constructability of HMA mixtures was assessed by using the data generated from the mixture tests previously listed. The tests selected for this study included tests to detect the presence of a contaminant, such as chromatography, as well as tests to measure any changes in the binder or mixture due to the presence of that contaminant. The mixture tests in particular included some of the best and most current tests that relate to field performance, such as the shear tests, dynamic modulus and loaded wheel testing. The binder and mixture tests have been shown in previous research to be sensitive to changes in binder or mixture properties as well as being related to ultimate field performance.

The third objective was addressed in light of the findings of the physical and chemical tests conducted as a part of this research and using examples from some other states' specifications. Recommendations were made on how the South Dakota Department of Transportation should revise their specifications to allow the use of economical alternate fuels while maintaining the quality of the hot mix produced.

Lastly, possible inspection and test procedures were recommended considering the findings of the physical and chemical testing in this project and other state and industry practices. Relatively simple techniques are recommended to ensure that adequate combustion is being achieved.

This research project is the most thorough and comprehensive evaluation of the effects of fuel and burner conditions to date. Evaluating 11 fuels in one hot mix plant is unprecedented and marks a great step in resolving the question of fuel contamination.

TASK DESCRIPTIONS

The tasks involved in this effort were identified in the Request for Proposals as shown in italics below. The approach taken to address each task is detailed following the RFP's statement of work. As background information, Appendix A contains a glossary of terms and a listing of acronyms used in this report.

Task 1: Meet with Project Panel

Meet with the project's technical panel to review project scope and work plan.

A meeting with the technical panel was held in Pierre on November 15, 2001, to discuss the proposed conduct of the research plan. The team outlined the possible effects of contamination by unburned fuel or combustion byproducts and their approaches to detecting those contaminants. Due to the urgency of completing production before the end of the 2001 construction season, the time required to establish a contract and the inability of the researchers to obtain airline tickets following the September 11 terrorist attacks, it was not possible to hold the panel meeting prior to construction. The meeting was, however, held prior to the initiation of testing to reach consensus on the tests to be considered. Following the meeting and further review of possible tests, the research team developed the test matrix shown in Table 2. This matrix was used to guide the testing under Tasks 4 through 7. Pending the results of testing the extreme cases, as described in Task 4, additional testing could be done in other cells, as done, for example, with the gravimetric analysis.

Task 2: Review Prior Research

Review previous and ongoing research, conduct a survey of other states' experience and present findings to the technical panel.

This task was addressed through a literature review conducted through the Transportation Research Information Service (TRIS) and the Internet, plus a survey of state experiences through the AASHTO Research Advisory Committee (RAC). The preliminary results of the literature review were presented in the proposal and at the first panel meeting. The survey questions were discussed at the panel meeting and refined through e-mail reviews. Personal contacts were made with some states to solicit and expand on their responses to the survey. Final results of the literature review and survey are presented in Findings and Conclusions.

Task 3: Evaluate Industry Practices

Evaluate the current practices used by the HMA plant manufacturers to determine combustion efficiency, and recommend methods for use in Tasks 4 and 5.

The research team conducted telephone interviews with a number of plant and burner manufacturers as well as NAPA, several contractors and other industry sources. A final summary of the discussions is included here.

Table 2: Planned Test Matrix

Fuel	O2	Qual	Grav	GC	GPC	Ext	Bind	SGC	SST	T283	LWT	E*	Beam
No. 2 (Abbrev. 2)	I	C	C			C	C	C	C				
	O		C	C	D	C	C	C	C	C	C	C	D
	E							C					
Non1 (W1)	I	C	C			C	C	C	C				
	O							C					
	E							C					
Non2 (W2)	I	C	D			C	C	C	C				
	O							C					
	E							C					
Non3 (W3)	I	C	C			C	C	C	C				
	O							C					
	E							C					
Non4 (W4)	I	C	C			C	C	C	C				
	O		C					C					
	E		C					C					
No. 5H (5H)	I	C	C			C	C	C	C				
	O		C					C					
	E		C					C					
No. 5L (5L)	I	C	C			C	C	C	C				
	O							C					
	E							C					
No. 6 (6)	I	C	C	C	D	C	C	C	C	C	C	C	D
	O							C					
	E							C					
RFO4 (R4)	I	C	C			C	C	C	C				
	O							C					
	E							C					
RFO5H (R5H)	I	C	C			C	C	C	C				
	O							C					
	E							C					
RFO5L (R5L)	I	C	C			C	C	C	C				
	O		C					C					
	E		C					C					

Shaded cells were initially planned for testing. C=testing completed, D = testing dropped.

Key:

- O2 = Burner Condition: Insufficient (I), Optimum (O) or Excess (E) Air
- Qual = Standard Fuel Quality Tests
- Grav = Gravimetric Analysis and Total Organic Carbon
- GC = Gas Chromatography, FTIR, etc.
- GPC = Gel Permeation Chromatography (Dropped due to likelihood of no findings – Task Descriptions)
- Ext = Extraction and asphalt content
- Bind = Dynamic Shear Rheometer and Bending Beam Rheometer.

Also Direct Tension on No. 20 and No. 61

- SGC = Gyrotory Compaction and analysis of compaction slopes
- SST = Superpave Shear Tester
- T283 = AASHTO T283 Moisture Sensitivity
- LWT = Purwheel Loaded Wheel Tester
- E* = Dynamic Modulus
- Beam = Beam Fatigue (Dropped due to insufficient material.)

Again, due to the need to complete mix production before the end of the construction season, this task could not be completed before the experimental mixes were produced. However, a burner technician was hired by the SDDOT to guide the plant operations during production, as recommended by the research team in the proposal. The concern was that the research results could be skewed by inconsistencies from one fuel type to another. While it may be possible for a plant operator to determine optimum or near optimum combustion conditions based on experience, intentionally providing excess or insufficient oxygen is more problematic. The burner technician helped to ensure the combustion levels were as consistent as possible from one fuel type to the next.

Task 4: Determine Combustion Residue Content

Using solvent extraction or other appropriate methods, determine the combustion residue content on aggregates heated in an operating HMA plant under conditions of insufficient, optimum and excess oxygen. The aggregates will be heated with no asphalt cement added and fired with propane (if feasible, to establish base line combustion conditions), No. 2, No. 5L, No. 5H, No. 6, (as defined by ASTM D-396) and recycled motor oils RFO4, RFO5L and RFO5H (as defined by ASTM D-6448) and a minimum of four samples of non-specification waste motor oil, which will be identified by the technical panel. Test non-specification waste motor oil to determine deleterious ingredients and quantities.

The plant was fired with 11 different fuels as listed above. It was not feasible to fire the plant with propane, so the No. 2 fuel at optimum oxygen conditions was used as the control for this experiment.

Aggregates heated in the HMA plant without asphalt were evaluated using a methylene chloride solvent extraction. An ultrasonic probe was used to agitate the solvent and separate any residue from the surface of the aggregates. The solute was evaluated using a gravimetric analysis to identify the relative proportions of inorganic, soluble organic, and insoluble organic carbon in the residue. The residues from aggregates heated under insufficient oxygen conditions were tested. In addition, the residues from the No. 2, No. 6, No. 5H, RFO5L, and Non-spec Waste Fuel No. 4 at excess and optimum conditions were also analyzed gravimetrically. The residues from the No. 2 at optimum and No. 6 fuel at insufficient were analyzed using a variety of chromatographic and related procedures to identify the chemical nature or constituents of the residue.

The No. 2 and No. 6 fuels were analyzed chromatographically as well for use in identifying contamination of the aggregates, binders and mixtures. Standard fuel quality tests were conducted on all 11 fuels. These tests included measurements of the flash point and the presence of water or sediments in the fuel.

Summary of Findings. An examination of the data from the combustion residue analyses shows that there is a minute amount of residue present on the heated aggregates. The residue content is generally higher for the insufficient oxygen condition, as expected. Also, the amount of residue observed with the No. 6 fuel, which was assumed to be the worst case based on field observations, was indeed higher than for the other fuels. In all cases, however, the amount of residue was very low. The inorganic carbon content from the aggregate was very low and quite consistent, as would be expected since the same aggregates were used in all of the mixtures. The insoluble organic carbon content, representing carbon char on the heated aggregate, was very low, less than 0.1%, indicating that char was not generated in large quantities with any of the fuels. Soluble organic carbon could be produced by unburned or partially burned fuel residues; the soluble organic carbon content was also very low. The No. 6 fuel at insufficient and “optimum”

conditions yielded the highest amount, but this was still less than 0.1%. There were no correlations between the exhaust gas compositions and the amount of residue, indicating that the CO content, for example, cannot necessarily be used to predict the amount of residue that will be produced.

Task 5: Test Asphalt Cement

Using Gel Permeation Chromatography or other appropriate tests for molecular weight distribution as well as chemical testing for trace elements, test asphalt cement before it is combined with aggregates and when it is extracted from asphalt concrete produced from an operating HMA plant. The plant is to be fired with propane (if feasible), No. 5L, No. 5H, No. 6, (as defined by ASTM D-396) and recycled motor oils RFO4, RFO5L and RFO5H (as defined by ASTM D-6448) and a minimum of four samples of non-specification waste motor oil, which will be identified by the technical panel. Extracted asphalt cement will be obtained for each of the fuels at combustion conditions of insufficient, optimum and excess oxygen.

A variety of chromatographic and related test procedures was conducted to determine which was most appropriate to detect and identify any contaminants in the aggregate residue or recovered asphalt cement. Following these attempts, the asphalt cement was analyzed using Fourier Transform Infrared analysis (FTIR), which appeared to be promising, gas chromatography with flame ionization device (GC-FID) and gas chromatography with mass spectrometer (GC-MS).

Chromatography includes a variety of methods to separate a sample into its various components so that their physical and chemical properties can be determined. Various detectors can be used after the sample is split to analyze different properties of the components. It is analogous, in a way, to performing a sieve analysis of an aggregate blend then analyzing each sieve size for bulk specific gravity, particle shape or other properties. The techniques considered and used in this research are described in detail in Appendix C.

The results were compared to the FTIR traces of the No. 2 and No. 6 fuels and mixtures produced using those fuels at optimum and insufficient oxygen conditions, respectively. This was done to determine if traces of the unburned fuel could be identified in the extracted binder. Additional binder tests on extracted binder were conducted under Task 7 below.

The proposal initially called for using gel permeation chromatography (GPC), as this task identified. During the first meeting with the technical panel, however, one of the panel members, Mr. Thomas Harman of FHWA, suggested that other chromatography methods might be more sensitive and better suited to this study. The panel agreed that the research team should confer with Dr. Anthony Kriech at Heritage Research Group to discuss the best method to use. Dr. Kriech and his staff recommended the chromatographic methods that were eventually used. In addition, Dr. Ray Robertson at Western Research Institute (WRI) agreed to test some of the residue from the heated aggregate using their chromatographic techniques. WRI typically runs GC-MS as a screening tool to determine if GPC will provide any additional information and to guide set-up of the GPC equipment. In their screening, they determined that GPC would not reveal any additional information, so GPC was not run.

Summary of Findings. Gas chromatography revealed that the residue consisted of a high molecular weight hydrocarbon similar to asphalt or partially decomposed tar. The residue was so much like asphalt that it could not be detected in samples of binder recovered from the plant-produced hot mix. Using extremely sensitive gas chromatography, WRI identified traces of the No. 2 and No. 6 fuels in the residue on the

heated aggregates at extremely small concentrations of less than 35 parts per billion. The nature of the residue and its extremely low concentration indicate that it will have no detrimental effect on the hot mix produced. This was confirmed by binder and mixture testing under other tasks. Thus, although there is a residue on the heated aggregates, it is virtually indistinguishable from asphalt and would have no detrimental effect.

Task 6: Evaluate Asphalt Concrete

Evaluate asphalt concrete produced from the fuel combustion conditions of insufficient, optimum and excess oxygen using wheel rutting tests, Tensile Shear Rheometer with freeze thaw, film thickness, Marshall stability, Marshall mix parameters, or other tests as appropriate to determine what impact fuels and combustion residue have on physical and chemical properties of in-place asphalt concrete.

Samples of the mixture produced with different fuels under varying combustion conditions were evaluated through a range of different mixture tests, particularly tests related in some way to field performance. The tests used are described briefly below and in more detail in Appendix D. All of the test results were analyzed using standard statistical methods to determine if statistically valid (or significant) differences existed between any of the fuel-burner combinations, unless noted otherwise. (In some cases, there were not enough replicate tests to allow statistical analysis.) The statistical methods used are described in Appendix L.

First, samples of each mix were compacted in a TestQuip Superpave Gyratory Compactor (SGC) at the plant during mix production. Gyratory parameters at varying numbers of gyrations were recorded and analyzed. If fuel contamination softens the mix to an appreciable extent, it may be revealed through an increase in the density of the mix at low numbers of gyrations (N_{initial}). This parameter was developed in part to identify tender or weak mixtures. Similarly, if a char-like residue stiffened the mixture, this could possibly be detected through a decrease in the density at low numbers of gyrations. The slope of the gyratory compaction curve was analyzed to determine if there were differences in the compaction characteristics of the mixtures, which could be caused by mix contamination.

Gyratory samples compacted in the field were cut for testing in the Superpave Shear Tester (SST) and dynamic modulus. The SST was used to perform three tests on mixes produced with all 11 fuels at insufficient oxygen plus the control (No. 2 at optimum). All SST tests are conducted on disk shaped samples 6 in. (150mm) in diameter and 2 in. (50mm) high cut from gyratory specimens. The Frequency Sweep (FS) test was used to measure the complex shear modulus and phase angle of the mixtures. A repeated horizontal shear load is applied to the specimen at different loading frequencies. The measured stresses and strains are used to determine the complex shear modulus, which relates to the high temperature stiffness, and the phase angle, which relates to the elasticity of the mix. The test is somewhat analogous to the binder dynamic shear rheometer test, with which more people are familiar. The Simple Shear (SS) test was used to measure the shear strain that developed when a specimen was sheared once. The same specimen that is tested in the FS test is tested in the SS test to determine the shear strain under a single load rather than a repeated load. Both the FS and SS tests are related to rutting and are typically conducted on specimens compacted to around 7% air voids, which is similar to the state of a hot mix asphalt pavement after construction. Lastly, the Repeated Shear at Constant Height (RSCH) test was used to measure the accumulated plastic strain in the mixture when repeatedly sheared. The RSCH test is similar to the FS test except that the loading frequency is constant and this test is typically conducted on specimens compacted to about 3% air voids. RSCH is related to plastic or tertiary flow of a mixture late

in its service life when the air void content is low. The test is typically run to 5000 cycles of shear loading and the accumulated plastic (non-recoverable) strain is the parameter of interest. All of these tests have been shown in previous research to be sensitive to changes in binder and mixture properties. For example, HMA mixtures containing varying proportions of RAP were shown in NCHRP 9-12 to exhibit different stiffness due to the presence of varying amounts of hardened RAP binder. (4)

Samples of mixtures produced with the No. 2 at optimum and No. 6 at insufficient oxygen were also analyzed in terms of dynamic modulus and loaded wheel testing. The dynamic modulus is one of the candidate performance tests under development by Dr. Matt Witczak and is the basis for asphalt pavement structural design under the forthcoming *Mechanistic-Empirical Pavement Design Guide*. Dynamic modulus specimens (4 in. diameter by 6 in. high (100mm x 150 mm)) were cored from samples compacted in the SGC at the plant according to the current candidate protocol. The dynamic modulus test is conducted by applying a repeated axial compressive load to the sample and measuring the applied stress and resulting shear strain, which are used to calculate the dynamic modulus of the mixture. The dynamic modulus is another measure of mixture stiffness and is related to rutting.

Samples for testing in the Purwheel loaded wheel tester were compacted in a linear compactor after reheating. The loose plant mix had been stored in sealed cans. The Purwheel device, described later, is essentially a modified Hamburg rut tester able to test wet or dry.

A stripping test was also conducted on the mixes produced with No. 2 at optimum and No. 6 at insufficient oxygen. AASHTO T283, *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*, was used to compare the resistance to moisture damage in these two mixes. As this test is prone to significant variability, attempts were made during testing to keep the test parameters, particularly compaction and percent saturation, as consistent as possible.

In the original proposal, the above mixture tests were recommended by the research team. Other tests were considered, but were not selected due to a low probability of success or a shortage of material. The tests described above were felt to be the most likely to detect changes in the mixtures, based on the research team's past experience and published literature. For example, Nelson and Wood (5) found Marshall stability and flow to be unable to identify contaminated samples. Marshall stability is widely recognized as an empirical test method and is being superseded as a research tool by more performance-related tests like the SST, dynamic modulus and other less common tests. Indirect tensile testing and beam fatigue testing were considered, but take quite a large quantity of material. Insufficient material was available for this testing. These tests would not have been likely to provide new information over and above that from the tests that were conducted.

Summary of Findings. The mixture tests included a variety of tests that have been shown in past research to be sensitive to changes in mixture properties and that are related to field performance. None of the tests conducted on the mixtures produced with different burner fuels under differing burner conditions revealed any significant differences in mixture behavior. (See Appendix M for a discussion of the statistical analyses and interpretation.) There were no changes in the compaction properties, complex shear modulus (stiffness), permanent shear strain, dynamic modulus, loaded wheel test rutting or stripping tendencies between any of the fuels or combustion conditions. As noted before, the presence of a harmful contaminant could be expected to affect the stiffness of a mixture, which would affect moduli, strain, rutting and possibly compaction characteristics, or the stripping potential of a mix. Since no changes were

observed in any of the mixture properties, that adds compelling evidence that the amount and the nature of the minute traces of residue found on the heated aggregates are not detrimental to the properties of the hot mix produced.

Task 7: Evaluate Extracted Asphalt Cement

Evaluate asphalt cement extracted from the same sample lots to determine what effects the different fuels and combustion conditions have on ductility, viscosity, penetration and other significant physical properties of the asphalt cement.

In the original proposal, the research team recommended using the newer Performance Graded (PG) binder tests in lieu of ductility, viscosity and penetration. The PG tests were developed for Superpave to be related to fundamental engineering properties of binder that are directly related to performance. Other tests were considered at the proposal development stage but were not included in the work plan since they are not considered as sensitive as the tests used here. Penetration, ductility and viscosity have been superseded by the tests required under AASHTO MP1, *Standard Specification for Performance Graded Binder*, now adopted in most of the country, including South Dakota. The PG tests have also been shown in previous research, such as NCHRP 9-12, to be sensitive to changes in binder stiffness. In addition, research on fuel contamination by Nelson and Wood (5), described in detail in section 5.1.1, showed that penetration and viscosity did not reliably detect the presence of contamination. The tests used are described more fully in Appendix D.

Dynamic Shear Rheometer (DSR) tests were performed on original binder and binder extracted and recovered from plant-produced mix under the varying combustion conditions. This test is the high temperature binder test related to rutting. It applies a repeated oscillatory load to a small disk of binder and measures the stresses and strains in the binder. These are used to calculate the complex shear modulus, which is related to high temperature stiffness, and the phase angle, which is related to the elasticity of the binder. To resist rutting, a binder with high stiffness and elasticity at high temperatures will perform better.

Recovered binders were evaluated as Rolling Thin Film Oven (RTFO)-aged binders, since they had aged during production in the hot mix plant. RTFO aging is intended to simulate plant and construction aging, but it is only an approximation. In plant-produced mix, the binder has undergone construction aging, so would be expected to be stiffer. The DSR test is sensitive to changes in the stiffness of the binder at high and intermediate temperatures and would likely be affected by fuel contamination.

Bending Beam Rheometer (BBR) tests were conducted on original and recovered binders at low temperatures. The BBR is the low temperature cracking test in the PG specifications. A beam of asphalt binder is loaded in the middle of the beam and the deflection of the beam is monitored. Classic engineering beam theory is used to determine the stiffness of the beam and the relaxation of the binder under stress. At low temperatures, a binder with lower stiffness and greater relaxation will be better able to withstand cracking. The BBR is used to evaluate the cracking tendencies of a binder later in its service life. Therefore, the PAV is typically used to simulate long-term service aging in the field after construction. The BBR test is sensitive to changes in low temperature binder stiffness. Conventional wisdom suggests that fuel contaminated binders could exhibit lower stiffness at low temperatures. Contamination by a char-like residue, however, could increase the low temperature stiffness by acting like a very fine mineral filler.

Direct tension (DT) testing was also conducted on the binders recovered from mixes produced with the No. 2 at optimum and No. 6 at insufficient oxygen. The direct tension test involves pulling a “dog bone-shaped” sample of asphalt binder until it fractures at low temperatures. This test, like the BBR, also relates to low temperature cracking. When a pavement cracks at low temperatures, it is the binder film that is stretched due to thermal contraction of the mix, and that is where cracks initiate. A higher tensile strength or ductility will provide increased cracking resistance.

The extraction and recovery procedure developed under NCHRP 9-12 (4) was used to extract and recover the asphalt binder from the hot mix since it was shown in that research to change the recovered binder properties less than other extraction/recovery techniques, such as the Abson process. That procedure has been adopted as AASHTO T319(03), *Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt (HMA)*. Under T319 a sample of aggregate is mixed with a solvent and revolved in a drum with baffles to help agitate the materials and aid in removal of the asphalt film. The solvent is then removed using a Rotovapor device to gently heat and evaporate the solvent, leaving the binder behind. NCHRP 9-12 was a study of Reclaimed Asphalt Pavement (RAP); this study led to the development of the extraction method, demonstrated that this extraction and recovery method produced minimal changes in binder properties compared to other extraction and recovery processes, and showed that the PG binder tests described above were sensitive to changes in binder stiffness such as might occur due to contamination.

Due to the time consuming nature of the extraction process and amount of extracted material needed for BBR and DT testing, these tests were performed on the extreme cases (No. 2 at optimum and No. 6 at insufficient). BBR tests on all fuels at insufficient oxygen were conducted on recovered binders without PAV aging to compare the binders. There were several reasons for not PAV aging the recovered binders including the excessive time and expense involved in recovering enough binder to PAV age, the slight potential that PAV aging could drive off any volatile combustion products that might remain in the binder after recovery, and the fact that these tests were conducted for comparative, not specification purposes. These results are compared to the virgin asphalt after RTFO aging, which simulates typical binder aging during plant production. (BBR tests to verify the binder grade were conducted after PAV aging, as required by the specifications.)

Summary. The binder test results consistently demonstrated that the fuels used to heat the asphalt mixture under different burner conditions did not change the properties of the recovered asphalt binders. No clear differentiation between the recovered binders could be identified when tested in the dynamic shear rheometer at high temperatures or the bending beam rheometer and direct tension tester at low temperatures. The critical cracking temperatures determined according to AASHTO MP1a specifications did not change. All of these test methods have been demonstrated in past research to be sensitive to changes in binder stiffness, either softening or stiffening, so the fact that they did not reveal any differences between the binders heated with different fuels adds more compelling evidence that no detrimental contamination occurred.

Even when the binder was deliberately contaminated with the residue from the heated aggregates, there was no change in the binder properties. This clearly demonstrates that the residue is not detrimental to the binder properties, as suggested by the “asphalt-like” nature of the residue determined by chromatography.

Task 8: Determine Effects on Asphalt Concret

Based on analysis of test results determine what implications, with respect to pavement performance and life cycle costs, that the different fuels and combustion conditions have on asphalt concrete.

The Superpave binder and mixture tests were specifically developed to be related to performance. They measure fundamental physical properties that are performance-related. Loaded wheel tests and moisture sensitivity tests are also somewhat related to performance, though they are more empirical. The chemical tests showed that minute amounts of residue could be detected in the heated aggregates, so the binder and mixture tests were analyzed to determine if this material would affect field performance. That is, based on the test results, would a mixture produced with a given fuel or under certain combustion conditions be more likely to exhibit rutting, cracking or other distress than the same mix produced with a different fuel or better combustion conditions? None of the performance test results gave any evidence of effects of fuel type or combustion condition on performance of the binder or mixtures. Although trace amounts of residue were found in Tasks 4 and 5, they were determined using chromatography to be very similar in nature to asphalt. Binder testing in Task 7 and mixture testing in Task 6 showed there was no detrimental effect of the residue on binder or mixture properties. Therefore, there is no reason to expect that a mixture produced using the fuels and combustion conditions tested in this study would exhibit any difference in performance due to the fuels and/or combustion conditions. Thus, there would be no impact on performance or the service life cycle of the pavement. The only cost differences would be due to initial fuel cost savings.

This analysis of the data was done and the results are presented in Findings and Conclusions section.

Task 9: Develop Specifications for Fuels and Combustion Conditions

Develop specifications for fuels and combustion conditions that will ensure production of acceptable asphalt concrete.

Based on the findings of this research project, recommended specification changes are outlined to ensure that mixture contamination due to plant fuel or burner conditions does not occur. The recommendations are presented in detail in Findings and Conclusions section.

Although the test results from this project did not reveal negative impacts on binder or mixture properties, or on expected performance, using the fuels under the combustion conditions tested here, the literature review, consultations with industry experts and isolated reports of problems from other states show that contamination problems are possible, though rare. The remote possibility of mixture contamination was considered in developing recommended specification changes, recommended test methods and warrants for testing, implementation of training and a monitoring period, and recommended tracking of projects after implementing the specification changes.

Task 10: Determine Test Methods and Frequency

Determine test method(s) and frequency of tests necessary for field personnel to easily determine when HMA combustion conditions are in compliance with the recommended specifications.

Based on a review of all of the findings of this research, including the absence of significant binder or mixture degradation and the experiences of other states and industry, it is recommended that the SDDOT take a staged approach to implementing tests and changes in field procedures. These suggested steps are described in more detail in the Recommended Test Methods section.

Provide training. The first step is to provide a memorandum or other brief instructional document to train field and plant personnel on potential signs of burner and combustion problems.

Check fuel viscosity. The fuel viscosity should be verified at the plant with a viscosity kit, especially with heavy fuels.

Implement monitoring period. Another step that should be taken concurrently with relaxing the specifications as outlined in 5.9 is to implement a monitoring period at start up when a fuel heavier than No. 2 is used.

Require more elaborate testing only for problem fuels or plants.

A flame eye monitoring device could be installed to monitor the color of the flame and detect changes in the combustion efficiency.

Require gas analysis for problem cases.

Reevaluate after implementation. The SDDOT should follow mix production for at least one construction season following the implementation of the specification changes to determine if any problems are noted and if there are any patterns to these problems.

Based on the results of this research, which strongly and consistently demonstrate that mix contamination is not a significant or prevalent problem, no routine testing by field personnel is justified other than checking fuel viscosity and monitoring plant operations at start up and occasionally during production. That is, there is no need to require exhaust gas analysis at every plant or with certain fuels. There are simpler steps to ensure that adequate combustion is being achieved. If problems are observed, more elaborate testing can be required on a case-by-case basis.

Task 11: Prepare Final Report

Prepare a final report and executive summary of the research methodology, findings, conclusions and recommendations.

The research methods, results, findings, conclusions and recommendations are documented in this final report.

Task 12: Make Executive Presentation

Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project.

The principal investigator presented the findings and conclusions of the research project to the SDDOT Research Review Board at the February 13, 2003, meeting.

FINDINGS AND CONCLUSIONS

This section summarizes and analyzes the findings and presents the conclusions of the study based on the descriptions provided in Task Descriptions section. Following the discussion of the literature review and survey (Task 2) and the review of current industry practices (Task 3), the production of the hot mix and collection of samples and exhaust gas data are described. The section then continues with discussion of the findings of tasks 4 through 10.

Literature Review (Task 2)

A review of the available literature indicates that relatively little work has been documented in the area of mix contamination or test methods to detect or identify contamination. Several sources discuss plant operations and the need to maintain a proper balance of combustion air and fuel (1, 3, 6-8).

The burner system in a drum mix plant is used to heat and dry the aggregate. The system is described more fully (and troubleshooting advice is offered) in Appendix K. Air is used to atomize the fuel into droplets then draft air is used for combustion. If there is not enough air or fuel, the burner efficiency will decrease. Most burners are designed to burn many types of fuel such as natural gas, liquid petroleum gas, propane, butane, No. 2 fuel oil, heavy fuel oil, and recycled oil. If the fuel is not sufficiently fluid, it will not be completely atomized and will not be properly combusted. Heavy oils like a No. 5 or 6 fuel oil must be preheated to reduce their viscosity below 100 ssu in order to obtain proper atomization. (7, 8) This can be accomplished by means of an indirect heating source (preheater) installed in the fuel feed line before the burner.

Fuel is pumped from the storage tank, through the feed lines, which may have a preheater, and into the burner. Positive displacement pumps are best for heavy fuels, while centrifugal or turbine pumps can be used for lighter fuels. (16) In the burner, the fuel is forced through a nozzle that sprays out the fuel. It then hits the diffuser plate (also sometimes called the atomizer plate or shear plate), which shatters the stream of fuel into droplets. (The shear plate from the plant used in this research is shown in Appendix K, Figure 82. This atomization is critical to efficient, clean burning of the fuel. Since combustion is initiated at the surface of the droplet, the higher surface area of small droplets leads to better combustion. Large droplets can cause soot formation (16) or could possibly be carried into the veil of aggregate and impinge on the aggregate surface.

Combustion of fuel is a chemical process that requires oxygen. Just as a burning candle will die out if deprived of oxygen, the burner will not ignite the fuel or will not stay lit if there is not enough oxygen. The minimum amount of oxygen needed to burn the fuel based on its chemical make-up is called the stoichiometric air. If only the stoichiometric air content is provided, complete combustion can only occur if there is enough mixing of fuel and air to make oxygen atoms available to combine with each carbon and hydrogen atom in the fuel. Since such perfect mixing is unlikely, burners are typically operated with excess air provided to ensure enough oxygen is available. This level is termed optimum air or combustion air.

There are two basic types of burner air systems. In an induced draft burner, shown in Figure 1, roughly 30% of the combustion air is forced through the burner and the rest is drawn in around the burner opening. In a total air burner, the opening is sealed and all of the combustion air must be forced through the burner. (See Appendix K for more information.)

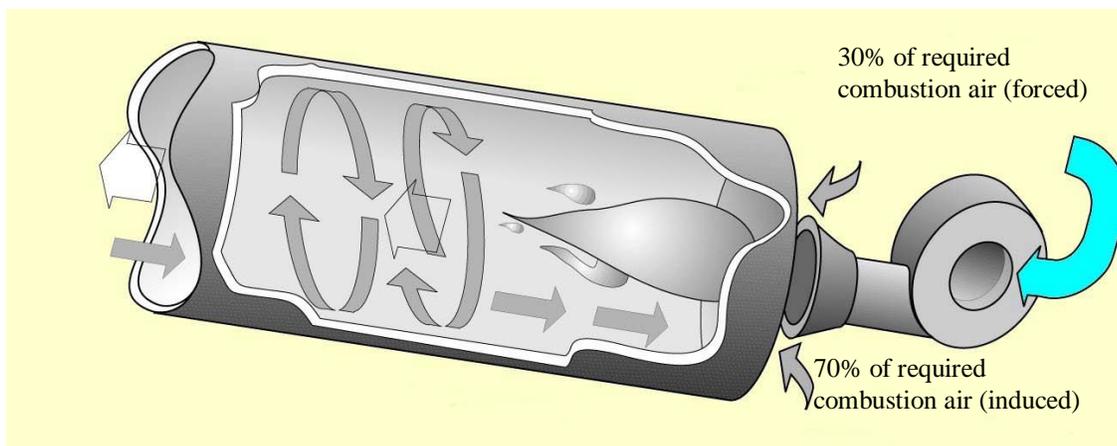


Figure 1: Combustion Air Flow into Burner

Burner combustion can be monitored in many ways, from the very simple to the more complex. The simplest way is to listen to the burner. If it is not properly firing, it may cough, sputter or spit. A properly fired burner will produce a constant roar. Fuel consumption can also be monitored easily. Higher than normal fuel consumption for a given plant, fuel, aggregate moisture content and other factors, can indicate too much excess air is being introduced into the plant, resulting in lowered efficiency. (8)

If less than the optimum amount of air is provided for combustion, not all of the fuel will be consumed. It may form soot that can coat the inside of the plant or the aggregate, or it may pass into the veil of aggregate and coat the aggregate particle surfaces. Incomplete combustion may also produce a brown coloration on the coarse aggregate particles in the mix. (1, 7) Incomplete combustion products could also be carried through the aggregate veil and out with the exhaust gases up the stack or into the emission control devices. If complete combustion is not occurring, unburned fuel can condense on the filter bags in the bag house, causing an increase in the pressure drop across the bag house and fuel staining of the bags, which could lead to a bag house fire. (7)

A more technical way to assess proper combustion is through the use of a flame eye to monitor the color of the flame, which is related to the amount of oxygen and combustion. (7) Just as the flames in a fireplace display different colors depending on the temperature of the fire, the flame of a burner will change color as well. Some of these changes will occur in the infrared or ultraviolet frequency ranges, outside the visible spectrum. The flame eye is a device that monitors the color of the flame. If the amount of oxygen available for combustion changes, so will the flame color. Exhaust gases can also be monitored, as done in this project, to check oxygen, carbon monoxide or total hydrocarbon contents.

Incomplete combustion products caused by improper balance in the burner can result in numerous problems with the burner itself, the plant, plant emissions and the mixture produced (6, 7). The focus of this research, however, is on the effects on the mix and its components. More discussion of possible burner and exhaust system problems is provided in Appendix K.

Contamination of the aggregate or mixture with incomplete combustion products can result in several potentially detrimental effects. For example, if the fuel is not completely burned, droplets can be carried into the mixing zone where they can impinge on the surface of the aggregates, coating the aggregate particles with an oily residue, which can interfere with the bond between the asphalt binder and aggregate and even reduce the binder film thickness on the coated aggregates. Eventually, this may lead to increased moisture sensitivity or raveling of the mixture (1).

Incorporation of incomplete combustion products within the binder can also lead to problems, if unburned fuel particles are caught in the binder film. Burner fuel may act as a solvent for asphalt since fuel is a petroleum product. Its presence in the binder can soften the binder (9) and change its aging characteristics. The binder may age less than usual going through the plant, resulting in a soft, tender mix (10-11).

Under different combustion conditions it may also be possible to over-oxidize the binder, though this has not been definitively reported in the literature. Reports have been made that excessive binder aging was sometimes seen in drum plants, but the causes have not been identified (10). In this research, binders and mixtures were evaluated not only for softening due to the presence of unburned fuel contaminants, but also stiffening or other detrimental effects that may have been caused by poor combustion.

Mixture distresses that may sometimes be attributable to mix contamination with fuel oil or combustion byproducts, and possible mechanisms for the distress, may include (1, 2, 7, 9-11):

- Tenderness, due to softened binder and/or reduced aging;
- Moisture sensitivity, due to reduced adhesion of binder to the aggregate;
- Raveling, due to reduced cohesion of the mix or adhesion of the binder;
- Drain down, due to reduced adhesion of the binder to the aggregate;
- Rutting, due to softening of the binder, reduced cohesion and reduced aging;
- Cracking, due to changes in the age hardening characteristics of the binder, over-oxidation or reduced fatigue resistance;

These possible distresses were considered in selecting tests to perform on the mixtures in this study.

There are, of course, many other causes for the distresses above. Determining if poor combustion was the primary cause in a given case is difficult. There may be clues that the burner is not firing properly, such as increased emissions, difficulty in keeping the burner lit, fuel clogging the filter bags, etc. (7)

The detrimental effects of poor combustion have not been well documented. Von Quintus and Kennedy (11) reported on experiences in Oregon and California where less binder hardening was observed in a drum plant compared to a batch plant. Contamination with unburned fuel was one explanation offered. The type of fuel used also seemed to influence the amount of hardening observed. Lower mixing temperatures with some fuel types may also have affected the hardening rate.

Wilson and Hicks (12) also reported on pavement distress in Oregon and investigated possible causes for this distress in the 1970's. Many elements of the asphalt paving industry were changing in this time period, which may have contributed to the perceived increase in tender mixes, slow-setting mixes, flushing, blue smoke, and raveling or stripping. Possible causes included changes in the asphalt cements;

changes in aggregate quality and control; and changes in construction practices, including increased use of drum mix plants and vibratory rollers. Field evaluations were conducted on 14 projects. On three projects, there was some evidence of reduced aging of the asphalts during construction. This could have been caused by changes in the asphalt cement aging behavior or contamination, though the exact cause could not be identified.

The most useful reference found to address the questions raised by South Dakota is Nelson and Wood (5). They addressed very similar questions for the Indiana Department of Transportation in 1990, so their work will be reported here in some detail. Their research utilized high pressure-gel permeation chromatography (HP-GPC) to characterize binders used in Indiana, building a database of binder chromatograms for later reference. They also examined binders extracted from plant-produced mixes in comparison to original binders to investigate age hardening. Lastly, they developed HP-GPC techniques to identify mix contamination and evaluated resulting binder and mixture properties.

Nelson and Wood found that size exclusion chromatography could be used to identify changes in the binders brought about by aging or deliberate mix contamination with fuel oil. Plant-produced mixtures evaluated in their study, however, did not exhibit any detectable contamination. Deliberately misfiring the burner was not attempted in this research, so it may be that there was not an appreciable amount of contamination in the mixtures tested. Further details on their work follow.

When Nelson and Wood compared samples of the original binders to laboratory-contaminated samples, HP-GPC was able to detect the contamination. Binder samples extracted from plant-produced mix were deliberately contaminated with 1.0 percent burner fuel. A 1.0 percent contamination level was selected based on typical plant efficiency. In order to meet air quality standards, plants need to operate at a minimum of 95 percent efficiency. Assuming a production rate of 300 tons per hour, 6 percent binder content, and a fuel consumption rate of 2 gallons per ton of mix, the authors arrived at 1.0 percent fuel contamination by weight of mix.

The burner fuels evaluated by Nelson and Wood included natural gas, No. 2 fuel oil, No. 4 fuel oil and reclaimed oil. Mix samples produced using natural gas were evaluated, but natural gas samples were not collected and chromatography was not run on the natural gas since procedures to test a gas were not available.

Retained samples of the original materials used in construction were tested for penetration, kinematic and absolute viscosity, specific gravity and HP-GPC. The original materials were then aged in the thin film oven and evaluated for loss on heating, penetration, viscosity and HP-GPC.

Samples of plant-produced mix were also tested. Mixes were tested for Marshall stability and flow and indirect tensile strength, with and without fuel contamination. Binder was extracted and recovered using the Abson process, then penetration, viscosity and HP-GPC tests were conducted on the binder. After deliberate contamination with 1.0 percent burner fuel, the binder samples were again tested for penetration, viscosity and HP-GPC analysis. The burner fuels used, with the exception of natural gas as noted previously, were also analyzed using HP-GPC.

When comparing the contaminated and uncontaminated binders, Nelson and Wood found no consistent trends in penetration, kinematic or absolute viscosities, viscosity-temperature susceptibility (VTS) or penetration viscosity number (PVN). Similarly, there were no consistent trends in changes in stability, flow or indirect tensile strength. HP-GPC analysis, however, did detect the presence of contamination

when contamination was introduced in the lab. No evidence of contamination was found in plant-produced mix.

Chromatograms of the contaminated binder show increases in the large and medium molecular sizes (LMS and MMS) and decreases in the small molecular sizes (SMS) compared to uncontaminated samples. Other parameters showed similar significant changes due to contamination. While chromatography could be used to detect contamination, it could not be used to identify the type of contaminant. All of the fuels evaluated were hydrocarbons with similar molecular sizes and were present in such small amounts that they could not be conclusively identified.

Jennings and Pribanic also used HP-GPC to analyze asphalt binders in the 1980's (several papers including 13, 14). In their work, they used HP-GPC to analyze the molecular size distribution of various asphalt cements, including asphalts from 15 states in one study. (14) Pavement performance characteristics were compared with the HP-GPC data. Asphalt pavements with a large amount of large molecular size material did not perform as well as those with a smaller amount of large molecular size material in terms of crack resistance. Larger amounts of large molecular size material work better in warmer climates than in colder climates. These reports do not address impacts due to the type of burner fuel used or combustion efficiency. Pribanic, Emmelin and King also reported in 1989 on the use of HP-GPC to categorize 19 asphalts based on the shape of their chromatogram and related to temperature sensitivity, as measured by the penetration-viscosity number (PVN) and aging index. They suggested HP-GPC could be a useful tool for refiners. (15)

One last report related to testing procedures should be noted. Under NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System* (4), the North Central Superpave Center and the Asphalt Institute evaluated, among other things, the best extraction/recovery techniques to use to minimize changes in the binder properties and evaluated the ability of Superpave binder and mixture tests to detect changes in properties brought about by the addition of reclaimed asphalt pavement (RAP). This research led to changes in AASHTO TP2, *Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*, now adopted as AASHTO T319(03). The improved method was demonstrated to mitigate problems with incomplete removal of the extraction solvent and did not change the binder properties to the extent that a conventional Abson recovery can. Based on these findings, the new AASHTO T319 protocol was followed when extracting and recovering asphalt binder from the plant-produced mixtures for binder testing in this study.

Another important conclusion from the NCHRP 9-12 study was that the Superpave binder specifications were applicable to recovered RAP binders and blended binders. The PG binder tests were demonstrated to be sensitive to changes in the binder stiffness. (4) Nelson and Wood (5) had already established that penetration and viscosity were not able to differentiate between contaminated and uncontaminated binders. These two findings together suggested that the Superpave Performance Grading specification tests may be a more appropriate set of tests to evaluate fuel contamination.

Similarly, NCHRP 9-12 determined that some Superpave Shear tests (SST) were able to differentiate between RAP and virgin mixtures; these tests were sensitive to changes in binder and mixture stiffness. (4) Poor adhesion between the aggregate and binder could also affect these tests. Nelson and Wood had determined that Marshall stability and flow could not detect contamination. (5) Therefore, the SST tests were used to compare the plant-produced mixtures under varying combustion conditions.

Summary. The literature does acknowledge that there is a possibility of contaminating an asphalt mix due to improper combustion in the hot mix plant. Several possible detrimental effects are noted, including softening of the binder and mix, increased moisture sensitivity, poor fuel efficiency, reduced film thickness, tenderness of the mix, reduced or excessive binder aging, and others. These possible effects were considered and explored in this testing program. Few specific cases of mixture contamination have been reported in the literature, however.

The literature also revealed some binder and mixture tests that are sensitive to changes in binder or mixture stiffness, such as might be produced by contamination, and others that are not. This information was considered in selecting test procedures to be used in this experiment. HP-GPC was used successfully in the 1980's to identify laboratory-induced contamination and to analyze variations in the molecular size distribution of different asphalts.

Survey of State Experiences (Task 2)

A survey was prepared in consultation with the project panel and distributed through the AASHTO RAC listserv. Responses were eventually received from 35 respondents, representing 31 states, the District of Columbia, the Dakota Asphalt Pavement Association and Border States Paving. A listing of the survey questions and summary of the responses is provided in Appendix E. This section summarizes the responses.

Of 35 respondents to the survey, only six reported having seen any problems related to hot mix asphalt contamination with unburned fuel or combustion byproducts. Illinois reported one case where the hot bin aggregates were coated with a black residue at a batch plant; this was concluded to be due to incomplete combustion because of high water content in the fuel. Illinois also reported three different parallel flow plants where the asphalt binder would not adhere to the aggregate; the cause was never determined, but was suspected to be due to antifreeze, synthetic motor oils or other contaminant in the fuel. In all cases, they said, a waste grade of oil was used.

Indiana reported having a few problems with incomplete combustion in some plants using recycled oils during the oil embargo. This manifested itself in stripping and a distinct odor of fuel oil in the mixture.

Missouri noted some cases of rutting and shoving that they attributed to contamination, which they detected through testing the recovered binders.

Oklahoma has observed a dark coating on heated aggregates, rutting, uncoated aggregates and a dull, dry mixture that is slow to set. They have attributed some of these problems to contamination, but not to any particular fuel type. They also noted that usually smoke from a plant during production indicates a problem.

Texas indicated seeing some problems with soft asphalts related to the use of fuels heavier than No. 2 and with waste oils. They have not had these problems in recent years, which they attribute to changes in their specifications. Texas now requires that burners produce complete combustion and that waste oils and fuels heavier than No. 2 be preheated to a viscosity of 100 ssu or less, unless the burner manufacturer allows a higher viscosity.

Illinois, Indiana, Missouri and Oklahoma do not limit the types of fuel allowed even though they have seen some problems in the past. The District of Columbia, Georgia, Montana, Nevada, Tennessee and Washington State reported controlling the allowable fuel types or grades used. Georgia limited the fuel to

No. 2 until about three years ago when they removed the requirement. They did not report seeing an increase in problems since then. Montana specifies that only propane, butane, natural gas, fuel oil grades No. 1 or 2, coal or EPA Specification-Used Oil Fuel (EPA-UOF) are permitted. Washington State allows the same fuels except for the EPA-UOF, but also permits “other acceptable burner fuel as determined by the engineer.” Tennessee requires that combustion be checked if fuels other than propane, butane, natural gas, fuel oil grades No. 1 or 2, or coal are used. Combustion is checked by taking a shovel of heated aggregate, dumping it in a pail of water and checking for an oily film. Nevada used to allow reclaimed waste oil for a short time, but they discontinued that after noticing construction related problems including pumping difficulties, flame blow-out and non-uniform products. Eliminating the reclaimed waste oils seemed to eliminate the construction problems as well.

Only New Jersey, Oklahoma and Tennessee determine if proper combustion is being achieved. New Jersey uses a visual inspection of the heated aggregate as a check on combustion. Tennessee drops the heated aggregate in water to check for an oily residue. Oklahoma indirectly checks combustion by requiring that plants be inspected yearly according to AASHTO M156, *Requirements for Mixing Plants for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures*.

Three states indicated they thought some research had been done previously. Oregon, Florida and Arkansas were cited as the sources. The work in Oregon and Florida was known to the researchers. One state thought perhaps Arkansas had done some work, but Arkansas said they had not.

Judging by the responses to the survey, most states did not believe there was a significant problem with hot mix contamination due to burner fuel types or combustion conditions and had not taken steps to control or investigate the potential problems. Most states were, however, interested in hearing the results of this investigation.

The two responses from industry representatives were particularly interesting as they may indicate how contractors control their own operations. Informal discussions with a number of contractors around the country supported the observations made by these two industry representatives. DAPA indicated that plant settings are typically confirmed by checking readings and production. They also indicated contractors implement annual or semi-annual combustion tests, air quality tests and off-season periodic maintenance to keep their plants operating properly. Oklahoma requires annual plant inspections, as noted above. Border States Paving noted that they check the fuel for BTU value, water content, ash content and contamination if they note poor combustion efficiency. They also commented that their experience allows them to determine that they are burning a fuel efficiently based on the gallons of fuel consumed per ton of hot mix produced for a given moisture content and aggregate type.

Summary. The survey of state practices and experiences revealed that few problems attributable to fuel contamination had been observed. In those few cases where contamination was suspected, it was usually related to particular fuels or plants. Few states have implemented stringent restrictions on fuel types or burner operations due to problems related to contamination. Several state specifications have features that were considered in developing the recommendations for specification changes based on the results of this research. Most states have no tests or procedures to evaluate burner operation.

Current Industry Practices (Task 3)

Telephone interviews were conducted with five representatives of hot mix plant and burner manufacturers as shown in Table 3. These experts were asked the following questions:

- What combustion efficiency is normal?
- Have they have ever encountered a case of lowered burner efficiency and, if so, did that cause aggregate or mix contamination?
- What are some methods to measure burner efficiency?
- Would any single gas, such as CO or CO₂, be indicative of burner efficiency?
- What type of instrumentation could be used to monitor combustion efficiency?
- Have they ever heard of a mix plant causing contamination of hot mix?

Additional discussion elucidated a few other points during the conversations.

The following summarizes the opinions expressed by these burner and plant manufacturers. They indicated that a burner running at reduced efficiency would increase the amount of fuel used, thereby decreasing the cost effectiveness of the plant. These problems would likely be noticed by the producer and remedied immediately to avoid excess expense. This was supported by the comments made by Border States Paving in response to the survey described earlier. Border States indicated they check the amount of fuel used per ton of hot mix to monitor combustion efficiency. However, there may be some mix producers who do not monitor their production that closely.

The industry experts recommended that combustion at the burner could be monitored or regularly checked with a combustion analyzer, though they noted that it is very difficult to get an exact reading of the burner or plant efficiency because drum and batch mix plants are open systems. Measuring the exhaust gases is one way to get a good idea of what is going on inside the drum. A rise in the CO or THC (total hydrocarbon) levels can indicate lowered burner efficiency. Lowered burner efficiency, however, does not necessarily mean that the fuel has not been consumed. Consequently, the lowered burner efficiency would not necessarily signify the contamination of the asphalt or hot mix.

The experts indicated that the first sign that a burner is malfunctioning would be a sharp rise in the production of CO, though they did not identify a specific level that would be a cause for concern. The actual values would depend on the particular plant, environmental and operating conditions. Smoke would likely follow the rising CO levels. The experts' opinions, based on their years of experience, were that only after these first two signs would contamination of the materials begin to occur. For a burner to be malfunctioning to this degree something would have to be broken or clogged, according to the industry representatives. They also expressed their opinions that the burner would probably have to be fixed to comply with Federal Clean Air Act emissions standards before getting to the point where contamination would occur.

The probability of mix contamination with unburned fuel is somewhat dependent on the style of the drum mix plant (parallel flow and counter flow). In the parallel flow drum mix plant the aggregate travels away from the burner flame and could have small deposits of fuel oil remain without being vaporized. This is more possible with the heavier oils and waste oils, but is still not very likely. This is virtually impossible in counter flow systems. In the counter flow system, the aggregate moves towards the flame, getting hotter and vaporizing all of the oil as the aggregate moves through the drum. The aggregate dryer in a batch mix plant is typically a counter flow system. (See Appendix K.)

None of the experts consulted reported observing any char or ash residue as a byproduct of poor combustion.

Table 3: Manufacturers' Representatives Interviewed

Name	Position	Company
Malcolm Swanson	Chief Engineer	Astec, Inc.
Bruce Erwin	Engineer	Astec, Inc.
Joe Meusil	Engineer	Cedarapids
Ray Baum	Engineer	Hauck Manufacturing
Al Hammer	Assistant Service Manager	Hauck Manufacturing

Summary. The manufacturers indicated their experience shows that mix contamination would be preceded by a number of problems, including trouble keeping the burner lit, excessive fuel consumption, visible exhaust gases, a rise in carbon monoxide or total hydrocarbon production. They were unanimous in maintaining that mix contamination would be a very rare event and would only result in case of a malfunction in the plant or burner. They recommended checking the exhaust gas composition, monitoring fuel consumption and observing the performance of the burner to ascertain that the burner is properly combusting the fuel. These suggestions were considered in the development of recommendations based on the findings of this research.

Mixture Production

The hot mix asphalt evaluated in this project was produced by W. Hodgman and Sons in Mitchell, South Dakota, between October 1 and October 5, 2001. The plant, shown in Figure 2, was a Barber Green Thermodrum with a Hauck burner (induced draft) and a Protectaire bag house. This section describes the mixture, combustion levels and production. (Figure 82 in Appendix K shows the atomizer plate from this plant.)

During production, each fuel was used to heat aggregates without added asphalt binder and hot mix was also produced. In some cases the aggregates were heated first, then hot mix was produced. In other cases, hot mix was produced first, then aggregates were heated. The burner conditions were varied so that the three cases, optimum, insufficient and excess were all produced (except with the first fuel, the No. 6, as described later). After all three conditions were used to produce hot mix and heated aggregate, the fuel was changed. This means that the experiment was not randomized. That is, the fuel and burner conditions were not randomly selected, so there is the possibility of unmeasurable systematic variation due to plant, atmospheric or other conditions outside of the control of the contractor, DOT or research team. From a practical standpoint, randomizing a project of this scope and complexity would be nearly impossible. Switching from one fuel to another to produce one burner condition and then changing again for the next random fuel-burner combination would have had an extremely negative impact on production. It would be very hard to justify the difficulty, time and expense of totally randomizing this experiment. Nonetheless, there is a chance of some systematic effect, which should be realized. This may have an impact on the level of variability observed in some of the testing. For example, on a windy day, there may have been more fluctuation in the amount of leakage air than on a calm day; this could affect the exhaust gas readings.



Figure 2: W. Hodgman and Sons Plant

Mixture Composition

The mixture evaluated in this study was an asphalt concrete mix for shoulders designed by the SDDOT. The mixture was placed on the shoulders of Highway 37 from Ethan, South Dakota, south 17.579 miles.

The different fuels used were preheated as needed to make them fluid enough to atomize so that complete combustion could be achieved, if enough oxygen were present to support combustion. The fuel viscosity was checked after heating.

The job mix formula is shown in Table 4. The aggregates were from the Fisher Quarry alongside the James River. The aggregates were quartzite and included $\frac{3}{4}$ in. rock, crusher fines and chips. A PG58-28 binder from Jebro was used in the mixture. The mix was a 50-blow Marshall design.

Combustion Levels During Production

Brian Prigge, president of Electromatics Inc., was the burner technician who measured the exhaust gas composition at the plant and instructed the plant operator on how to adjust the plant to produce the optimum, insufficient oxygen and excess oxygen conditions. Mr. Prigge monitored the oxygen and carbon monoxide levels, among other parameters, and usually adjusted the burner conditions by adjusting the damper controlling the flow of air into the drum (secondary air). In some cases, however, other operating parameters, such as the fuel pressure, were adjusted to bring the burner to the desired condition.

At the beginning of mix production with the No. 6 fuel, the exhaust gas readings were taken in the drum, but the line kept plugging up so the instrumentation was moved to the bottom of the fan housing in the bag house. Taking readings in the drum is preferred. Hot mix plants are typically not closed systems, and air leaks will allow changes in the gas composition from the drum to the bag house. This additional air will increase the observed oxygen content and decrease the concentration of CO and other gases. Moving

Table 4: Mixture Design Parameters

Sieve Size/Parameter	Composite % Passing	Job Mix Formula	JMF Tolerances
1 in.	100.0		100
¾ in.	99.4	100	97-100
5/8 in.	95.7		
½ in.	87.6	88	81-95
3/8 in.	76.8		
#4	64.3	65	60-70
#8	48.8	50	45-55
#16	40.2	37	32-42
#40	24.9	23	18-28
#200	4.9	5.0	4.0-8.0
Binder Content, %		6.5	
Bulk Specific Gravity		2.309	
Rice Specific Gravity		2.403	
Air Voids, %		3.9	
VMA, %		17.0	
D/A		0.8	

the probe to the bag house resulted in an increase in the oxygen content of about 6-8%, which was verified by comparing readings in the drum to the bottom of the bag house. Moving the probe, while not ideal, was necessary in order for the contractor to continue with production.

The amounts of CO, O₂, NO, C_xH_x, CO₂, NO_x and excess air were all monitored. These values are shown in Appendix B for each individual fuel type. (The NO and NO_x readings were identical, except for the No. 6 fuel where no measurements were recorded for the NO, therefore only the NO_x data is used in subsequent analyses.) The values shown in Appendix B are the averages of all readings taken at a given set of conditions (fuel type and combustion condition). The number of readings taken at each set of conditions varied from one or two in most cases, to as many as 11 for the No. 2 fuel at optimum. (The number of replicates and statistical analysis of this data is summarized in Appendix M, Tables 71 to 108.) This same data is shown graphically for each exhaust gas, with and without asphalt added to the aggregate, in Appendix B. These values are compared to gravimetric data in section 5.4.

The CO monitor had an upper limit of 4000 ppm, so when the CO content exceeded this, the monitor could not record the very high CO content.

Because the exhaust gas probe had to be moved out of the drum and into the bag house because of clogging of the probe, the data must be treated with some caution. Air leakage within the plant could affect the readings to varying degrees depending on a great number of factors, including pressure within the plant, gas flow volumes, temperature, how much leakage air was pulled in, and more. It is impossible to determine if conditions were constant within the plant, particularly from one day to the next despite the care exercised during construction to keep conditions as consistent as possible. There were simply too many variables that could not be controlled. The statistical analysis must also be taken cautiously due to the fact that only one or two readings were taken in most cases. The data is still useful to indicate general trends, but is not reliable enough to be used in any sort of predictive relationships.

Some trends are obvious in this data despite its limitations. First, as the excess air increased, the oxygen content increased, as expected, producing the insufficient, optimum and excess oxygen conditions desired. Also, as the oxygen level increased the quantities of the other gases (CO, NO, C_xH_x and NO_x) decreased in most cases.

The technical literature shows that incomplete combustion may be signaled by a marked rise in CO and total hydrocarbon contents. There was a large spike in the CO content with the No. 5H and No. 6 fuels at insufficient oxygen conditions when no asphalt was added; this is when samples of the heated aggregates were collected for analysis of the residue. The No. 6 fuel was the first one used and start-up issues were more severe with this fuel than the others. In fact, the optimum condition was not achieved for the No. 6 fuel, as indicated in part by the high CO content. The exhaust gas data for the No. 6 fuel reflects these start-up problems; no readings at all were obtained for the excess air conditions with asphalt added.

For the total hydrocarbons when no asphalt was added, most of the readings were less than 0.05%. The No. 6 fuel did have higher values, less than 1%, but it is unclear if this is due to the start up problems or not; the excess air reading is quite low compared to the other fuels, which may indicate that start-up problems were a factor. The No. 5L and No. 5H fuels also showed higher contents than the other fuels though lower than the No. 6; these readings were less than 0.1%. All of these values are very low and are not likely significant, except perhaps for the No. 6 and 5H. These combinations will be analyzed further in terms of residue content in the next section.

Statistical analysis of the exhaust gas data without asphalt added did not conclusively show any significant differences, as summarized in Appendix M. For the optimum air conditions, the p-values were all greater than 0.10, indicating no significant differences exist between the treatments (fuels). At insufficient oxygen, the p-values suggest possible differences in all of the exhaust gases except the carbon monoxide. Further examination through comparison of means testing shows that higher than normal excess air with Waste fuel 4 likely explains most of the differences noted. The exception is that the No. 6 fuel at insufficient also shows a high C_xH_x content; three of the five comparisons run show this value as being significantly different from the others, two do not. This verifies that the No. 6 at insufficient is the worst case and should be examined further through other tests to determine the effects of this fuel on binder and mixture properties.

Similar analyses were also performed on the exhaust gases when asphalt was added, as shown in Appendix M. With asphalt added, only the optimum air conditions show significant differences in the treatment means. In every case this is due solely to the No. 6 fuel. This is not an unexpected result since the optimum conditions were not achieved with this fuel. The exhaust gases produced with the other fuels at optimum and with all fuels at insufficient were indistinguishable. No readings were obtained for the No. 6 fuel at excess oxygen with asphalt.

When asphalt binder was added, the total hydrocarbons increased slightly or stayed about the same in most cases. In a few cases, the total hydrocarbon content seemed to increase more, especially in the insufficient oxygen cases. Total hydrocarbons were up to 0.2% for the RFO5H and Non-Spec Waste #1, 1.07% for the RFO5L and as high as 2.1% for the No. 6, under insufficient oxygen conditions. At other oxygen conditions and with other fuels, the readings were similar with and without asphalt. The problems with the No. 6 fuel have been noted before. The No. 6 fuel with asphalt at insufficient conditions was the first setting attempted and clogging of the probe occurred. This condition (No. 6 at insufficient oxygen)

will be taken as the worst case in subsequent analysis. The RFO5L fuel produced about 0.2% total hydrocarbons at the excess oxygen condition with asphalt; and only 0.03% without asphalt. The reason for the spike in the C_xH_x for the RFO5L with AC is unknown. It does not seem to correlate to unusual readings for any other gases and is far in excess of any of the other fuels. (This fuel also does not correspond to a high gravimetric residue, as shown in the next section.) This is one of the cases where only a single reading was recorded, so the spike may have been caused by a minute droplet of asphalt or fuel being detected. It does not appear to be related to the fuel combustion since the C_xH_x content without asphalt is not excessive.

Since asphalt is itself a hydrocarbon, it is not surprising for the content to increase when asphalt is added to the aggregate. The fact that it does not increase slightly in all cases may be a reflection of the variability in conditions, particularly the unknown amount of leakage air. None of these values are *sure* signs of poor combustion, however, the highest readings could be *potential* signs of contamination that will be contrasted with residue contents in the next section.

Summary. In summary, the exhaust gas composition generally varied as expected. That is, as the oxygen available for combustion decreased, the amount of CO and total hydrocarbons increased. The quantities of NO_x also tended to increase as available oxygen decreased. The No. 2 fuel generally showed the most favorable exhaust gas composition, especially at optimum oxygen, as expected. The No. 5H fuel at insufficient oxygen and No. 6 fuel at insufficient and “optimum” oxygen showed spikes in the CO content, potentially signifying contamination could result. Based on total hydrocarbons, the No. 5H, RFO5H, RFO5L and Non-Spec #1 fuels had the highest contents, which could indicate the possibility of contamination. The presence and effects of contamination will be evaluated in other tasks. The exhaust gas data confirms the observation during construction that the optimum oxygen condition was not obtained with the No. 6 fuel, which was the first one attempted. Statistical analyses of the exhaust gas contents for the various fuels at different oxygen levels did not show any conclusive differences based on fuel type.

Combustion Residue (Task 4)

Samples of heated aggregates (ten at insufficient oxygen plus five at optimum and excess oxygen conditions) and of the unheated aggregate (blank) were provided to Heritage Research Group (HRG) in Indianapolis, Indiana, for analysis of any residue on the surface. (The aggregate heated with Waste Fuel 2 was not analyzed since the fuel quality tests showed no difference between Waste 1 and 2.) HRG used a modified EPA Method 3550B ultrasonic probe extraction with methylene chloride to extract the residue from approximately 3.5 oz (100 g) of each aggregate. Each aggregate sample was agitated with the ultrasonic probe (sonicated) in 1.7-2.5 oz (50-75 ml) of methylene chloride for three minutes. This was repeated twice, then the aggregate was sonicated again for one minute in 1.7 oz (50 ml) of solvent to remove all traces of the residue. The solvent was decanted into a beaker and centrifuged for 10 to 20 minutes and rinsed several times with more solvent. The extract was then analyzed using a variety of chromatographic and related tests plus a gravimetric analysis. The results are discussed below.

Gravimetric Analysis

Samples of the solvent recovered from the heated and blank aggregates were analyzed using a gravimetric analysis. In this technique, the solvent collected through the ultrasonic extraction was heated in a muffle furnace to drive off the solvent and measure residue remaining.

This analysis of soluble organic residue, summarized in Table 5, did reveal minute traces of organic material that had been deposited on the aggregates. The heated aggregates showed more residue than the unheated, blank aggregates, as expected. The worst case was with the No. 6 fuel at “optimum” which had up to 0.1% residue in the aggregate. This was expected due to the noticeable brown tint to the aggregates observed during production. Also, remember that this was the first fuel used and there were difficulties in getting the burner adjusted and the probe working properly. The optimum burner condition was not actually obtained for this fuel. At insufficient oxygen conditions, the No. 6 fuel produced about 0.07% residue and at excess oxygen only about 0.04%. None of the other fuels produced residues over 0.03-0.04%.

Table 5: Soluble Organic Residue from Gravimetric Analysis

Fuel	Burner	Residue per 100 g Aggregate	% Residue in Aggregate
Blank Aggregate	None	1.067 mg	0.001%
		1.703 mg	0.002%
		2.25 mg	0.002%
No. 2 Fuel	Optimum	14.01 mg	0.014%
		14.98 mg	0.015%
	Insufficient	22.67 mg	0.023%
		23.34 mg	0.023%
	Excess	31.66 mg	0.032%
		27.18 mg	0.027%
Non-spec Waste #1 (W1)	Insufficient	13.61 mg	0.014%
Non-Spec Waste #3 (W3)	Insufficient	21.46 mg	0.021%
Non-Spec Waste #4 (W4)	Optimum	9.61 mg	0.010%
	Insufficient	10.98 mg	0.011%
	Excess	6.89 mg	0.007%
RF04 Fuel Oil (R4)	Insufficient	29.85 mg	0.030%
5L Fuel Oil (5L)	Insufficient	27.03 mg	0.027%
5H Fuel Oil (5H)	Optimum	16.38 mg	0.016%
	Insufficient	29.04 mg	0.029%
	Excess	46.84 mg	0.047%
RFO5H Fuel Oil (RH)	Insufficient	19.74 mg	0.020%
RFO5L Fuel Oil (RL)	Optimum	2.51 mg	0.003%
	Insufficient	9.49 mg	0.009%
	Excess	4.25 mg	0.004%
No. 6 Fuel Oil	Optimum*	107.21 mg	0.107%
		82.31 mg	0.082%
		74.70mg	0.075%
	Insufficient	71.58 mg	0.072%
		66.10 mg	0.066%
	Excess	43.29 mg	0.043%
36.46 mg		0.036%	

*Optimum conditions were not actually achieved for this fuel as explained previously.

For the residues at insufficient oxygen, the total organic carbon analysis using the muffle furnace was conducted to determine the insoluble organic and inorganic content of the residue. By increasing the temperature of the muffle furnace, different types of residue were burned off and the gravimetric loss was determined at each temperature. At 428°F (220°C), the solvent and moisture were driven off. At 1472°F

(800°C), insoluble organic carbon was driven off. Organic carbon could be introduced from the fuel. Lastly, at 1742°F (950°C) inorganic carbon from the aggregate or interstitial water would be removed. These results are summarized in Figure 3. The inorganic carbon content is very low and fairly constant. This would be expected due to the quartzite composition of the aggregate. There is some variability in the data, which may be due to the aggregate absorbing carbon dioxide (CO₂) as a sequesterant during combustion. That absorbed CO₂ could later be released when heated to a very high temperature. According to HRG, this is known to happen with some materials, such as the mineral olivine. Another possible explanation is that the act of heating the aggregates may make the interstitial water more accessible so that it can be driven off in the muffle furnace. In any case, the contents are very low, less than 0.01% by weight of the aggregate.

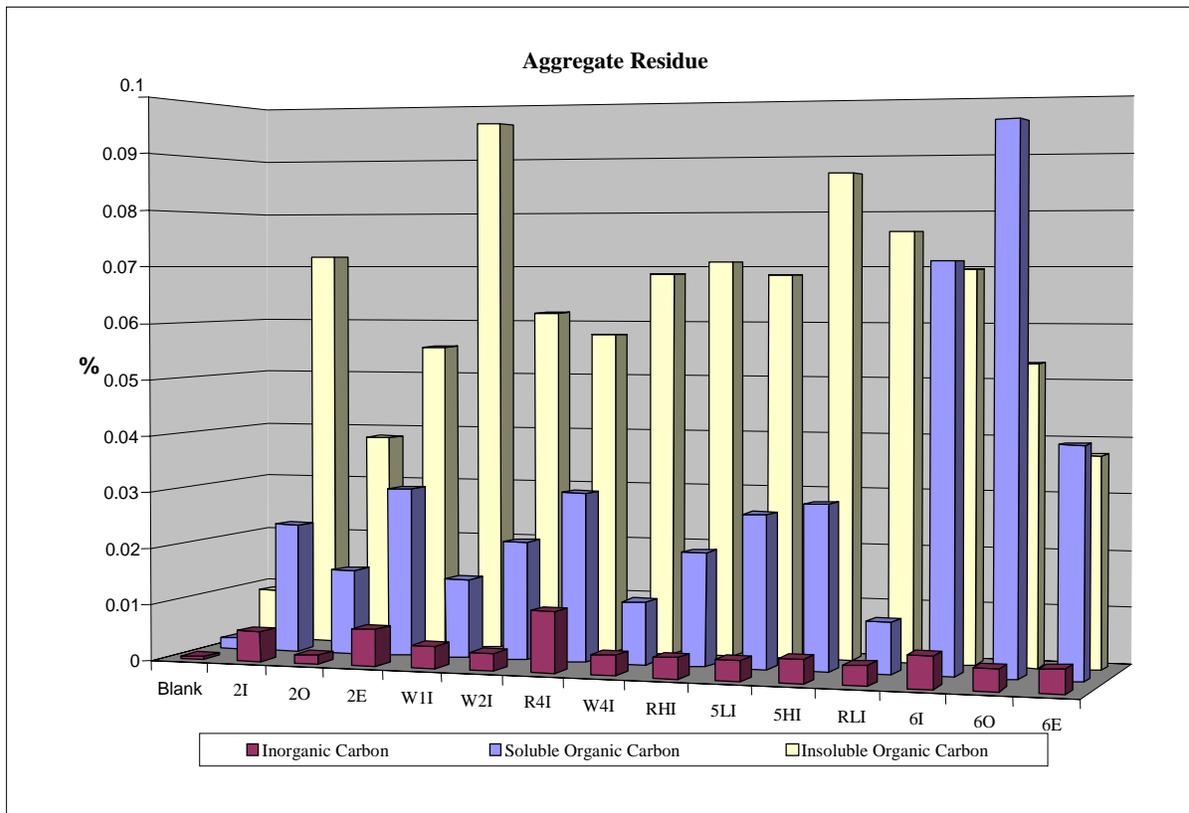


Figure 3: Inorganic and Organic Residues

The insoluble organic carbon represents carbon char on the aggregate. This would be expected to decrease as the oxygen content increases, as it does for the No. 2 fuel going from insufficient to optimum oxygen. The insoluble organic carbon appeared to increase as the oxygen increased further to excess, however. This would not be expected and may be an artifact of the variability in sampling and testing. The content is very small, less than 0.1%. With such very low amounts of residue, it would take only a tiny smudge of material on one or two pieces of aggregate to cause variability in the test results. For example, aggregates may have picked up minute traces of asphalt binder or char from the plant walls and baffles during production. Variability is to be expected in these results and in the chromatographic analysis of the residue described in the next section.

Table 6: Insoluble Organic and Inorganic Carbon Residue

Description	Weight of Original Sample grams	% Reduction Based on Original Weight		
		Water Vapor at 220 °C	of Aggregate	
			Insoluble Organic Residue at 800 °C	Inorganic Carbon at 950 °C
Blank Aggregate	100.6577 g	0.0009	0.0091	0.0005
No. 2 Fuel Oil				
Optimum Burn (2O)	99.951 g	0.0067	0.0383	0.0015
No. 2 Fuel Oil	100.9134 g	0.0089	0.0761	0.0039
Insufficient Burn (2I)	101.2308 g	0.0057	0.0673	0.0067
No. 2 Fuel Oil				
Excess Burn (2E)	100.7429 g	0.0049	0.0551	0.0065
Non-Spec Waste Oil #1				
Insufficient Burn (W1I)	100.6265 g	0.0085	0.0962	0.0039
Non-Spec Waste Oil #3				
Insufficient Burn (W3I)	99.7079 g	0.0062	0.0615	0.0031
Non-Spec Waste Oil #4				
Insufficient Burn (W4I)	99.7873 g	0.0039	0.0688	0.0036
No. RF04 Fuel Oil				
Insufficient Burn (R4I)	100.2213 g	0.0034	0.0577	0.0107
No. 5L Fuel Oil				
Insufficient Burn (5LI)	99.1273 g	0.0036	0.0686	0.0035
No. 5H Fuel Oil				
Insufficient Burn(5HI)	100.4396 g	0.0047	0.0866	0.0042
No. RFO5H Fuel Oil				
Insufficient Burn (RHI)	100.1589 g	0.0031	0.0709	0.0036
No. RFO5L Fuel Oil				
Insufficient Burn (RLI)	100.7443 g	0.0055	0.0763	0.0036
No. 6 Fuel Oil				
Optimum* Burn (6O)	101.2523 g	0.0027	0.0531	0.0039
No. 6 Fuel Oil				
Excess Burn (6E)	101.8625 g	0.0020	0.0373	0.0042
No. 6 Fuel Oil	100.6575 g	0.0147	0.0706	0.0037
Insufficient Burn (6I)	100.7492 g	0.0139	0.0686	0.0074
*Optimum conditions were not actually achieved for this fuel as explained previously.				

The soluble organic carbon may represent unburned fuel or incomplete combustion products (partially decomposed tars and oils). The No. 2 fuel produced the lowest amount of soluble organic carbon at optimum conditions and higher amounts at insufficient and excess air. The other fuels at insufficient oxygen produced similar levels of soluble organic carbon. The No. 6 fuel again produced the greatest amount of soluble organic carbon, as expected.

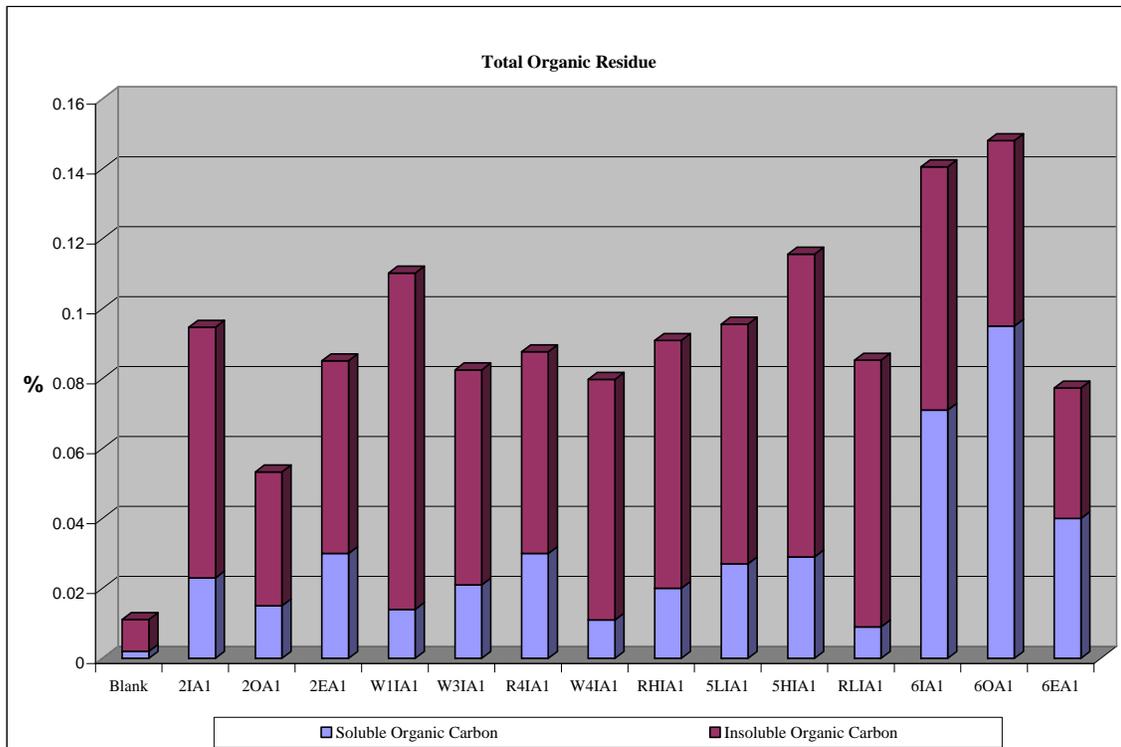


Figure 4: Total Organic Residue

Figure 3 compares the methylene soluble organic residues, insoluble organic carbon residues and inorganic carbon residues for each aggregate tested. All of the residues are below 0.1% of the initial weight of the aggregate. Figure 4 shows a comparison of the soluble and insoluble organic carbon contents for the different fuels at insufficient oxygen plus the No. 2 and No. 6 fuels at the other two conditions. Organic carbon could come from the fuel used to heat the aggregates.

Those fuel and burner conditions that could possibly be suspected of producing contamination based on the exhaust gas composition analysis in the preceding section were examined to see if there was any relationship between exhaust gases and residue content. (These comparisons are summarized in Appendix M, Tables 109-110.) The 5H and 5L fuels at insufficient oxygen had yielded two of the three highest total hydrocarbon contents when no asphalt was added. The 5H also had a higher CO content than the other fuels at insufficient oxygen. At excess oxygen, the total hydrocarbons and the CO in the exhaust gases were lower than at insufficient oxygen. The residue on the aggregate heated with the No. 5H, however, was lower at insufficient than at excess oxygen conditions.

The No. 6 fuel at “optimum” and insufficient oxygen had the highest soluble organic residue and highest total hydrocarbon contents. The No. 6 at insufficient was taken as the worst case in this research. As described later and in Appendix M, the highest correlation between exhaust gas contents and gravimetric residue was found with the No. 6 fuel, but the correlation was very poor and could not be used to reliably predict whether contamination is occurring.

Continuing to look at those fuel and burner conditions that could be suspected of producing contamination based on the exhaust gas composition, the RFO5H and RFO5L produced two of the three highest hydrocarbon contents at insufficient oxygen when asphalt was added (third highest and highest,

respectively). These cannot be directly compared to the heated aggregate residues since, obviously, no asphalt was added when the bare aggregates were heated. For comparison purposes, however, these two recycled fuels produced soluble organic carbon residue contents similar to the No. 2 at optimum and insoluble organic carbon contents slightly higher than the No. 2 at optimum, comparable to most of the other fuels. Waste fuel #1 has the second highest hydrocarbon content in the exhaust gases at insufficient oxygen with asphalt, but the soluble organic carbon residue was the same as the No. 2 at optimum and less than the No. 2 at insufficient. This fuel did produce this highest insoluble organic residue, but it was still less than 0.1%.

A detailed comparison of the exhaust gas and gravimetric data for waste fuels 3 and 4 was attempted since these are the same fuel with different water contents (3% vs. 12% water). It was suspected that the higher water content of W4 could have interfered with the burn and produced higher amounts of residue or increased CO and C_xH_x exhaust gas contents. In fact, the residue content is higher for Waste 3 with the lower water content than it is for Waste 4 with added water (0.21% vs. 0.11% at insufficient oxygen). The amount of organic carbon is similar for the two fuels (0.0615% for W3 vs. 0.0688% for W4). Statistical analysis of this data alone would not be meaningful since there are not enough data points. No definitive conclusions can be reached, but the hypothesis that the additional water would interfere with the burn is clearly not supported. During production it was not possible to determine how well the water mixed with the fuel. If it stratified in the tank, it would not interfere with combustion. With either fuel, the residue content is very minute. The difference between the residue contents is insignificant.

Attempts were made to statistically correlate the results of the gravimetric analysis with the exhaust gas data reported earlier. No correlation would be expected between inorganic carbon and exhaust gases since the inorganic carbon would be from the aggregate; no correlation was found. Conceivably, there could be correlations between soluble organic (which could be unburned or partially burned fuel) or insoluble organic (char) residues, but no reliable correlations were found between any of the parameters. An example of the relation between CO, NO and CO₂ versus soluble organic residue is shown in Figure 5. (The data for this figure is in Appendix M, Table 109.) As this figure shows, there is no trend apparent in the data. Statistical analysis was done to determine the R² value for this and other combinations contrasting the residue contents versus the exhaust data. No reliable trends could be identified. The statistical analysis is summarized in Table 7. These low to extremely low R-squared values demonstrate the lack of relationships between the exhaust gas data and the residue contents. (An R² value of 1.0 reflects a perfect relationship. Values less than 0.5 indicate essentially no relationship exists.) The best correlation is with total hydrocarbons vs. soluble organic residue, but is still not a reliable correlation (R² = 0.526). The research team conferred with Dr. Anthony Kriech at Heritage Research regarding this analysis. The team concluded that the residue contents are so low that all we are seeing is normal variability in producing, sampling and testing. There are no meaningful differences in the residue contents due to the different fuels, consequently there would not be any relationship between residue content and exhaust gas data.

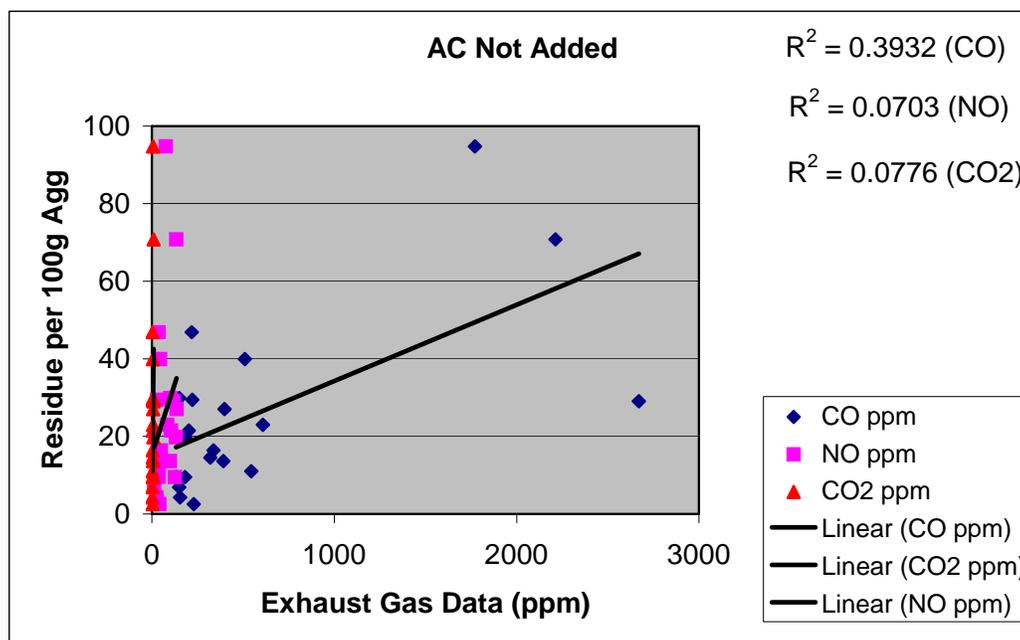


Figure 5: CO, NO and CO₂ Content in Exhaust Gas vs. Residue on Aggregate for All Fuels and Burner Conditions

Table 7: R-squared Values for Residue vs. Exhaust Gas (without Asphalt)

Exhaust Gas	Soluble Organic Residue per 100g of Aggregate	Insoluble Organic Residue, %	Inorganic Carbon Residue, %
CO	0.393	0.056	0.001
NO	0.070	0.341	0.001
CO ₂	0.078	0.247	0.005
C _x H _x	0.526	0.011	0.086

Chromatography and Other Chemical Analysis Findings

The original proposal for this project called for high pressure gel permeation chromatography (HP-GPC) to be conducted on the aggregate residues, fuels and recovered binders. This recommendation was based on the fact that Nelson and Wood had successfully used the technique in the 1980s to detect laboratory-induced fuel contamination at the 1% level. During discussions with members of the technical panel, particularly Thomas Harman, FHWA, as well as Dr. Kriech of Heritage Research Group and Dr. Ray Robertson of Western Research Institute, the possibility of other, more sensitive procedures was raised. Gas chromatography (GC) was cited as a possible test method that could be more sensitive than HP-GPC. GPC gives the molecular size distribution of the molecules, but does not give compositional information. That is why Nelson and Wood were able to detect contamination but not identify the particular contaminant. In addition, GC is much more sensitive to organic compounds than GPC. The gravimetric analysis, which showed very small quantities of residue, pointed to GC as the best choice to detect contamination.

In the end, HRG tried several different chemical analysis methods to detect and identify any contaminants on the heated aggregates or in recovered binders. WRI also used a different GC method to evaluate residue from two of the heated aggregates. (Details of the techniques used are provided in Appendix C.)

HRG first used gas chromatography with flame ionization device (GC-FID) and gas chromatography with mass spectrometer (GC-MS) to characterize the residue from aggregates heated with the extremes, the No. 2 at optimum (control) and the No. 6 at insufficient oxygen. The GC-FID and GC-MS showed that the residue consisted of a high molecular weight, non-volatile compound similar to compounds found in asphalt. The residue consisted of decomposed lighter oils from partially burned fuel, heavy tars from decomposition and carbon char. Repeated attempts to identify marker compounds in the residues from the heated aggregates that could be used to detect the presence of this residue in hot mix asphalt samples were unsuccessful; the residue was too much like asphalt, with no distinguishing characteristics.

HRG then attempted to use Fourier Transform Infrared analysis (FTIR) to characterize the residue. Initial comparisons of the residues from the aggregates heated with the No. 2 and No. 6 fuels showed distinguishable differences in two ranges of wave numbers, raising the possibility that these differences could also be distinguished in the recovered asphalt binder. FTIR scans were then conducted on the fuels, unheated asphalt binder and recovered binder from the mixes produced with the No. 2 (optimum) and No. 6 (insufficient) fuels. Comparison of these scans could not detect these differences, most likely because the minute amount of residue on the aggregate was too small to be apparent in the recovered binder. In effect, it was diluted to the point it could no longer be detected with FTIR, if it was there.

Due to the inconclusive nature of these attempts to detect and identify a contaminant, WRI was asked to try HP-GPC on two residues and the corresponding fuels. (Thomas Harman arranged for this testing to be completed through an ongoing FHWA contract with WRI.) Samples of the residue from the aggregate heated with No. 2 fuel at optimum and No. 6 fuel at insufficient oxygen conditions, residue from the unheated aggregate, and the two fuels were provided to WRI by HRG. WRI's standard procedure is to use a high-resolution, high carbon GC-FID as a screening analysis before running GPC. This helps them identify specific components of the material and determine if there is sufficient material to perform GPC. The GC-FID analysis performed by WRI differs from that run by HRG. WRI's specialized equipment allows them to look at higher molecular weight material, up to 80+ carbons. HRG's equipment can only analyze up to about 35 carbons.

WRI was able to determine that the residue from the unheated aggregate contained a series of hydrocarbons with up to 70 carbons. About half of these hydrocarbons were removed when the aggregates were heated with either the No. 2 or No. 6 fuel, indicating they were either volatilized or burned. The residue from the heated aggregates was then compared to the traces from the fuels used to heat them. Traces of both the No. 2 and No. 6 fuels were found to remain in the residue on the heated aggregates at extremely small concentrations. The No. 2 fuel residuum was 5 parts per billion (ppb) and the No. 6 residuum was 33 ppb. (By comparison, silicone, which is added as a surfactant to asphalt to reduce foaming, would be measured in ppm.)

At such small concentrations, WRI indicated that there was not enough material to be detected by HP-GPC. Nelson and Wood (5) had used HP-GPC to identify contamination at the 1% level in the lab, but were unable to detect any contamination in plant-produced mixtures. The amounts of contamination

detected by WRI are far below the 1% detection level Nelson and Wood had identified. HP-GPC testing, then, was not conducted because it had no chance of success.

Summary. An examination of all of the data from the combustion residue analyses shows that there is a minute amount of residue present on the heated aggregates. The residue content is generally higher for the insufficient oxygen condition, as expected. Also, the amount of residue observed with the No. 6 fuel, which was assumed to be the worst case based on field observations, was indeed higher than for the other fuels. The inorganic carbon content from the aggregate was very low and quite consistent, as would be expected since the same aggregates were used. The insoluble organic carbon content, representing carbon char on the heated aggregate, was very low, less than 0.1%, indicating that char was not generated in large quantities with any of the fuels. The soluble organic carbon could be produced by unburned or partially burned fuel residues. The soluble organic carbon content was also very low. The No. 6 fuel at insufficient and “optimum” conditions yielded the highest amount, but this was still less than 0.1%. There were no correlations between the exhaust gas compositions and the amount of residue, indicating that the CO content, for example, cannot necessarily be used to predict the amount of residue that will be produced.

Gas chromatography revealed that the residue consisted of a high molecular weight hydrocarbon similar to asphalt or partially decomposed tar. The residue was so much like asphalt that it could not be detected in samples of binder recovered from the plant-produced hot mix. Using extremely sensitive gas chromatography, WRI identified traces of the No. 2 and No. 6 fuels in the residue on the heated aggregates at extremely small concentrations of 33 parts per billion or less. The nature of the residue and its extremely low concentration indicate that it will have no detrimental effect on the hot mix produced. This was confirmed by binder and mixture testing under other tasks. Thus, although there is a residue on the heated aggregates, especially with the No. 6 fuel, it is virtually indistinguishable from asphalt and would have no detrimental effect on mix properties or performance.

Fuel Tests (Task 4)

As noted previously, 11 different fuel types were used in this study. The particular fuels used and the results of fuel quality tests performed as part of Task 4 are shown in Table 8.

Table 8: Standard Fuel Quality Tests

Description	PM Flash ASTM D 93	Required Flash Point	% Water ASTM D 95	% Solids ASTM D 2042
No. 2 Fuel Oil	160°F	100°F	<0.1%	0.04%
Non-spec Waste Oil # 1 (W1)	>210°F	--	2%	0.32%
Non-spec Waste Oil # 2 (W2)	>220°F	--	2%	0.21%
Non-spec Waste Oil # 3 (W3)	>200°F	--	3%	1.03%
Non-spec Waste Oil # 4 (W4)	>190°F	--	12%	0.49%
No. RFO4 Fuel Oil (R4)	180°F	100°F	1.25%	0.22%
No. 5L Fuel Oil (5L)	230°F	130°F	<0.1%	0.08%
No. 5H Fuel Oil (5H)	240°F	130°F	<0.1%	0.08%
No. RFO5H Fuel Oil (RH)	>210°F	130°F	2%	0.40%
No. RFO5L Fuel Oil (RL)	>210°F	130°F	2%	0.36%
No. 6 Fuel Oil	265°F	140°F	<0.1%	0.14%

The flash point was determined according to ASTM D93, Test Methods for Flash Point by Pensky-Martens Closed Tester. The water content was determined by ASTM D95, Test Method for Water in

Petroleum Products and Bituminous Materials by Distillation, and the solids content was determined by ASTM D2042, Test Method for Solubility of Asphalt Materials in Trichloroethylene. These tests are described in Appendix D.

The fuel types included conventional fuel oil grades No. 2, 5H, 5L and 6; recycled fuel oils 4, 5H and 5L; and four non-specification waste fuel oils. The waste fuels actually consisted of waste fuels from two sources with and without added water. That is, Waste Fuel #2 was Waste Fuel #1 plus water and Waste Fuel #4 was Waste Fuel #3 plus water. The specific amount of water added is not known, but the fuel was agitated after the addition of water. The results of the standard fuel quality tests, conducted by HRG, showed a much higher water content for Waste Fuel #4 than for #3. The water content of Waste Fuel #2 was not measurably higher than that of Waste Fuel #1. This may indicate poor sampling, poor agitation, separation of the fuel and water or simply that not enough water was added. Based on the water content test results, then, these two fuels would not be expected to perform differently.

The water contents of all of the waste fuels and the reclaimed fuels were relatively high and interfered with determination of the flash point. If this water separated out of the fuel in storage, it might increase corrosion of the tanks and equipment, but it would not be expected to interfere with burning of the fuel. If the water did not separate out of the fuel, it could interfere with proper firing of the burner. It is not possible in this case to determine if the water mixed thoroughly into the fuel or stratified despite recirculation.

Aside from the high water content of some of the fuels, there are no apparent quality problems, so these fuels could all be expected to burn relatively well, if properly preheated and atomized. In all 11 cases, the flash points are well in excess of the minimum. Minimum flash point values, shown in Table 8, are those required by ASTM D396, *Specification for Fuel Oils*, and D6448, *Standard Specification for Industrial Burner Fuels from Used Lubricating Oils*. The water plus solids content should be below a maximum of 0.05% for the No. 2 fuel, 1.0% for the No. 5L and No. 5H fuels and 2% for the No. 6 fuel (with less than 0.5% sediment for the No. 6). The water plus solids contents for the recycled fuels should be less than 2.0% for the RFO4 and less than 3.0% of the RFO5L and RFO5H fuels, of which less than 1.0% should be solids (sediment). There are no specifications for the four waste fuels.

Attempts were made to correlate the fuel quality test results to the gravimetric analysis results, as summarized in Appendix M, Table 111. No relationships were found. Since all of the fuels met the quality requirements for their grade, except for a high water content with the non-specification waste fuels, this is not a surprising finding.

Summary. The waste fuels did have high water contents, but otherwise all of the fuels met the standard fuel quality specifications. Merely meeting the fuel quality standards does not mean that the fuel *will* be burned properly, but is a first step in assuring that it *can* be burned properly. It seems prudent to require fuels to meet a minimum quality level, then to ensure that they are being properly combusted in the field. This is the approach used later in the development of recommendations for specification and inspection procedures. No correlations between the fuel quality data and gravimetric analysis data were found. This is not unexpected since the fuels met minimum quality standards, for the most part.

Tests on Original and Extracted Asphalt Binder (Tasks 5 and 7)

If a contaminant were present in the binder phase of the hot mix produced with various fuels under differing combustion conditions, the hypothesis underlying this experiment is that contaminant could

either soften or stiffen the binder, depending on its nature. A char-like residue could stiffen the binder and unburned fuel could soften it. Several different performance graded binder tests were performed on samples of the original (unheated) binder as well as recovered binders. These binder tests have been shown in previous research to be sensitive to changes in the binder stiffness. This section describes those test results.

Dynamic Shear Rheometer Testing

The Dynamic Shear Rheometer (DSR) is used to measure the high temperature stiffness of a binder. The parameter of interest is called $G^*/\sin \delta$, or the storage modulus, and is related to rutting at high temperatures. This test is typically run on unaged binder and on binder that has been aged in the rolling thin film oven (RTFO) to simulate the binder aging that occurs during construction. Since the binders were recovered from the plant-produced hot mix, these recovered binders would be expected to compare to RTFO-aged binder. RTFO aging is only an approximation, however. Different materials, plants and operating conditions can affect the amount of aging that actually occurs. The test procedure was described briefly in Task Description section and is described in more detail in Appendix D.

Samples of the original, unheated binder were tested in the DSR before and after RTFO aging. The original binder before RTFO aging would be expected to be significantly softer than the aged materials. Samples of the recovered binders from hot mix produced with all 11 fuels at insufficient oxygen conditions as well as the No. 2 at optimum (control) were also tested at three temperatures. These results are summarized in Table 9 below. This table shows the average of three tests. (See Appendix F for the individual data points and Appendix M, Tables 110-112, for statistical analyses.)

Table 9: Dynamic Shear Rheometer Test Results

Binder	G*/sin (kPa)		
	@ 52°C	@ 58°C	@ 64°C
Tank	2.78	1.22	0.59
RTFO-aged	7.29	3.12	1.43
2O	10.62	4.48	2.06
2I	5.57	2.41	1.11
6I	8.22	3.48	1.55
5LI	6.90	2.90	1.33
5HI	7.73	3.39	1.57
RLI	8.56	3.69	1.67
RHI	7.43	3.19	1.46
R4I	6.73	2.93	1.34
W1	7.91	3.38	1.53
W2	9.26	3.80	1.83
W3	7.33	3.16	1.50
W4	7.26	3.07	1.40

It is important to remember that these tests were conducted on extracted and recovered material. The extraction and recovery processes used were the best available methods, but nonetheless can introduce more variability in the results than when testing virgin binders aged in the laboratory before testing. Although the p-value of this data is low, various means comparisons cannot differentiate between the results. (See Appendix M.) There is too much overlap between the groups to conclusively discriminate between the results. The unaged binder is clearly different from the other binders, as it should be.

Based on the stiffness results at three temperatures, it is possible to determine the "critical temperature," or the temperature at which the binder just meets the PG specification level, which is 2.20 kPa (0.319 psi) for RTFO or plant aged binder and 1.00 kPa (0.145 psi) for original (tank) binder. The binder is tested at various temperatures, increasing in 6°C increments according to the grades in MP1, until the binder fails. The critical temperature is determined by simply interpolating between the failing test result and the next lowest passing test result. The critical temperatures are shown in Table 10.

Table 10: Binder Critical Temperatures from DSR and BBR

Binder	Critical Temperature, °C	
	High from DSR	Low from BBR
Tank	60.1	-21.6
RTFO-aged	61.3	-23.7
20	63.6	-24.4
2I	59.0	-25.6
6I	62.0	-25.8
5LI	60.7	-23.0
5HI	61.9	-23.3
RLI	62.4	-23.9
RHI	61.4	-24.8
R4I	60.8	-22.3
W1	61.8	-22.4
W2	62.9	-25.7
W3	61.5	-25.6
W4	61.1	-24.5

When comparing the critical temperatures of the recovered binders to the RTFO-aged binder, it can be seen that the results agree within ± 2.5 degrees, which is not considered significant. This test is subject to fairly high variability, especially when testing recovered binders, since the extraction and recovery process can induce added variability. The observed differences in critical temperatures, agreeing within such a narrow range, are essentially the same. Because the residue from the heated aggregates appeared to be "asphalt-like," HRG performed DSR testing on samples of the original binder and the original binder that was intentionally contaminated with the residue extracted from the unheated and heated aggregates. The samples containing residue were prepared by extracting the residue from 100 g of the heated or unheated aggregate using methylene chloride. The solvent extract was transferred to a beaker and the solvent was allowed to evaporate. The remaining residue was then mixed with 6.5 g of unaged binder and mixed well before testing. In order to verify that residue from the methylene chloride did not affect the results, 100 g of methylene chloride was allowed to evaporate. This residue was then mixed with 6.5 g of binder and tested. The amount of binder added corresponds to the design binder content of the mix.

The test results at 58°C are shown in Table 11. Analysis of variance showed that these values are not significantly different from each other (p-value 0.1344). (See Appendix M, Table 115) The tests were also conducted at 64°C to determine the critical temperature, as described before. The critical temperatures are also shown in Table 11.

Table 11: Stiffness and Critical Temperatures of Lab Contaminated Samples

Sample ID	Average $G^*/\sin \delta$ at 58°C	Critical Temperature, °C
Neat PG58-28	1.21	59.98
MeCl ₂ Blank	1.22	59.80
Aggregate Blank	1.24	59.60
6IA1	1.24	59.75
2OA1	1.25	59.85
Note: Neat PG58-28 = original, unaged binder Methylene Chloride Blank = residue from evaporated methylene chloride solvent in binder Aggregate Blank = residue extracted from unheated aggregate with binder 6IA1 = residue from aggregate heated with No. 6 fuel at insufficient oxygen with binder 2OA1 = residue from aggregate heated with No. 2 fuel at optimum with binder		

These results show that the residuum had no effect on the binder stiffness or failure temperature. Even deliberately contaminating the binder with the residue did not change the high temperature binder properties.

Bending Beam Rheometer Testing

Bending beam rheometer (BBR) testing is used to assess the low temperature stiffness and relaxation of a binder and is related to cracking at low temperatures. The test procedure was briefly described in Task Description section and is detailed in Appendix D. BBR results were obtained for the same recovered binders and compared to BBR results for the unheated binder (after RTFO aging).

BBR tests were conducted at -18°C and -24°C on at least two replicates. Using this data, the critical low temperature, or the temperature at which a binder just meets the specification limit, can be determined by interpolating between a passing and failing test value. For the BBR, there are two parameters of interest, the stiffness S and the slope of the log stiffness vs. log time curve called the m -value. (The m -value relates to a binder's ability to relax under stress without cracking.) The highest (less negative) critical temperature, based on either S or m -value, controls. The low critical temperatures are shown in Table 10 above. All of the critical low temperatures agreed within $\pm 2.1^\circ\text{C}$. Statistical analysis showed that the stiffnesses of the recovered binders heated with each of the 11 fuels at insufficient oxygen, the No. 2 at optimum and the virgin binder after RTFO aging were not significantly different, indicating again that the fuel types and burner conditions had no effect on binder properties. (See Appendix M for more details.)

Direct Tension Testing

Direct tension testing was also conducted on samples of the binder recovered from mix produced with the No. 2 fuel at optimum conditions and the No. 6 fuel at insufficient oxygen conditions. The procedure was briefly described in Task Description section and is discussed in more detail in Appendix D. In essence, the test involves pulling a sample of binder at low temperature until it breaks. The deformation of the sample before it breaks, and the test temperature, are the parameters of interest, since they indicate the tensile strength of the binder.

The direct tension test results were then used in combination with the BBR results to predict a critical cracking temperature for the binder according to AASHTO MP1a, *Specification for Performance Graded Binder*. The BBR results at various temperatures are used to estimate how thermal stresses will build up in a pavement with that binder. The direct tension test results then indicate the tensile strength of the binder. When the pavement stresses exceed the strength of the binder (that is, where the curves cross), the

binder will crack. According to current protocols for this prediction, the highest four stress values are used to determine the critical cracking temperature and the lower results are discarded.

As the direct tension test is a relatively new test, the variability of the test method has not been established, but it is suspected to be relatively high, due to the amount of aging and processing of the binder before testing, as well as to other sampling and testing variability. The direct tension results are shown in Appendix F.

The direct tension results themselves show that both binders pass the minimum acceptable strain level of 1% at -18°C but both fail at -24°C, which is expected for a -28 grade binder. (These tests are conducted at a temperature 10° warmer than the low temperature grade of the binder.) Statistical analysis of the results for both failure stress and failure strain at -18C are shown in Appendix M. This analysis shows that there are no significant differences in the results (p-value for stress = 0.250 and for strain = 0.135).

These results were combined with the specific BBR test results for the No. 2 at optimum and No 6 at insufficient oxygen conditions to determine the critical cracking temperature according to MP1a. This procedure uses the BBR data to estimate how the tensile stresses will accumulate in a pavement and the DT results to estimate the tensile strength of the binder. When the tensile stresses exceed the tensile strength, a crack will develop. The procedure used to estimate the critical cracking temperature requires the use of complex mathematics and is, therefore, computerized. The results are graphically illustrated in Appendix F (Figures 36 and 37). The critical cracking temperature for the No. 2 fuel at optimum oxygen was estimated to be -20.4°F (-29.1°C) and for the No. 6 insufficient -24.5°F (-31.4°C). The difference in these values is not considered significant.

Summary: The binder test results consistently demonstrate that the fuels used to heat the asphalt mixture under different burner conditions did not change the properties of the recovered asphalt binders. No significant differences were noted in the recovered binders when tested in the dynamic shear rheometer at high temperatures or the bending beam rheometer and direct tension tester at low temperatures. The critical cracking temperatures determined according to AASHTO MP1a specifications did not change for the different fuels. All of these test methods have been demonstrated to be sensitive to changes in binder stiffness, either softening or stiffening, in past research.

Even when the binder was deliberately contaminated with the residue from the heated aggregates, there was no effect on the binder properties. This clearly demonstrates that the residue is not detrimental to the binder properties, as suggested by the “asphalt-like” nature of the residue determined by chromatography.

Tests on Asphalt Concrete (Task 6)

A variety of tests of the plant-produced asphalt mixture was also conducted. These tests included evaluation of compaction properties in the Superpave Gyratory Compactor; Frequency Sweep, Repeated Shear and Simple Shear tests in the Superpave Shear Tester (SST); dynamic modulus; AASHTO T283 stripping test; and loaded wheel testing in the Purwheel device. The findings are presented below.

Gyratory Compaction Parameters

The Superpave Gyratory Compactor is used to compact mixture specimens for Superpave mix design and performance testing. The device uses a slight angle between the loading platens and the mold walls to impart a kneading action to the mixture inside, which helps to orient aggregate particles and compact the mixture. The rate of compaction, or increase in density, can be estimated based on the change of the

height of the mixture versus the number of gyrations. The compaction parameters are sensitive to changes in mix stiffness and could conceivably be affected by mix contamination. Excessive compaction at a low number of gyrations ($N_{initial}$) may be indicative of tender mixtures. The slope of the compaction curve may also be related to mix stiffness, though current thinking is that this is not a rigorous relationship. Contamination could conceivably affect the mixture stiffness either by softening the mix or stiffening it, depending on the nature of the contaminant.

The compaction parameters for the mixtures produced with the No. 2 and No. 6 fuels at all three burner conditions were compared to determine if any differences existed. This data was collected during production by compacting mixes at the plant. Data from six specimens at each fuel-burner combination were compared and the results are summarized in Table 12 below. The data was normalized so that the height at 0 gyrations was equal to 1.00 so that the values could be compared easily. (The weight of mixture in each specimen, and therefore the volume of each specimen, differed somewhat.) The height reduction is virtually identical in all cases, indicating that there were no differences in the mixture stiffness.

Table 12: Normalized Gyrotory Compaction Parameters

Fuel	Burner	Normalized Height Reduction at Gyration #			
		2	4	7	10
No. 2	Insufficient	0.96	0.93	0.91	0.90
	Optimum	0.96	0.93	0.91	0.90
	Excess	0.96	0.93	0.91	0.90
No. 6	Insufficient	0.95	0.93	0.91	0.90
	Optimum	0.95	0.93	0.91	0.90
	Excess	0.96	0.93	0.91	0.90

Although this comparison of the extreme cases showed no differences in compaction parameters, the analysis was extended to all of the mixtures at all burner conditions. The analysis, summarized in Appendix G, confirmed that none of the fuel-burner condition combinations affected the mixture compaction properties. In other words, the mixture stiffness did not change depending on the fuel or burner condition during production.

No statistical analysis was conducted since the results are identical except for three cases at two gyrations. At two gyrations, the mix is not well compacted and conditions are changing rapidly, so more variation is to be expected. Even so, the differences that were observed were only 0.01% (0.95 vs. 0.96). At four, seven and ten gyrations, the results were identical.

Superpave Shear Tester (SST) Results

Specimens for SST testing were cut from gyrotory specimens compacted at the plant lab during production. SST samples are disks 6 in (150 mm) in diameter and 2 in (50 mm) tall. Typically, two SST tests, Frequency Sweep (FS) and Simple Shear (SS), are conducted on specimens compacted to 7% air voids. Repeated Shear (RS) tests are typically conducted on specimens compacted to 3% air voids, since that test is supposed to examine the possibility of plastic flow at low air voids late in the life of the pavement. (These test protocols are described in Appendix D.) These air void levels are obtained by changing the number of gyrations applied to the specimen during compaction. Due to the aggressive production schedule, there was little time to fine-tune the gyration levels in the field. This resulted in somewhat lower air voids and more variability in the air void content than is typical for laboratory

compacted mixtures. (Despite this variability in air voids, the variability in test results was within normal ranges for this extremely sensitive and highly variable test.) Samples of all of the mixtures produced at insufficient oxygen conditions, as well as the control mix (No. 2 at optimum) were tested. In most cases, there were three replicates of each test.

The Frequency Sweep (FS) test applies a horizontal shear load to the specimen in a repeated, sinusoidal loading pattern. The shear load is applied at ten frequencies from 10 to 0.01 Hertz (Hz). The data allows calculation of the complex shear modulus (G^*), or stiffness, of the mixture. To resist rutting, a stiffer (higher G^*), more elastic mixture will generally perform better.

The FS data, summarized in Table 13 and detailed in Appendix H, was collected at 68 and 104°F (20 and 40°C), the standard test temperatures. Table 13 also shows the average air void level for the specimens tested. This data shows that none of these specimens are particularly strong. For laboratory specimens compacted to $7.0 \pm 0.5\%$ air voids, a mix is expected to demonstrate good rutting resistance if its complex shear modulus at 10 Hz and 104°F (40°C) is about 35,000 to 50,000 psi or higher. Since these field samples were not compacted to 7% air voids, the same modulus values may not apply. For comparison purposes, note that the Indiana Department of Transportation (INDOT) uses this test as a referee test for failed materials that have low air voids (less than 2%) at production. INDOT will allow a contractor to leave a mixture in place if the complex modulus of field cores tested at 10 Hz and 104°F (40°C) is at least 36,200 psi. The complex modulus of these mixtures is well below that level.

Cut specimens were examined and found to consist of a comparatively fine mixture with few coarse aggregate particles and a large amount of binder and fine aggregate as a matrix. This internal structure explains the low stiffness values observed. Since these are shoulder mixes, the low stiffness may not be a problem. Durability would likely be more of a concern for shoulder mixtures in South Dakota’s climate than rutting and would likely be enhanced by the thick binder coating.

Table 13: Average Frequency Sweep Results

Fuel Type	% Air Voids	Complex Modulus, G^* , psi at 10 Hz	
		68°F (20°C)	104°F (40°C)
20	6.4	114352	9354
2I	3.3	379634	14341
6I	5.0	160215	13006
5LI	3.6	199480	15739
5HI	6.2	123543	12270
W1I	4.8	360473	15153
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	4.9	403389	16195

Data from all 11 fuel types at insufficient oxygen and the No. 2 fuel at optimum were compared using standard statistical analysis. A variety of comparison of means test was used to determine if the mixes

produced with different fuels had different stiffness values. (See Appendix L for a discussion of comparison of means.) No meaningful differences could be determined. No one fuel type or combustion condition could be singled out as distinct from the others due to excessive overlap between groups of data that are statistically the same. For example, see Table 14. Bonferroni’s test identified three groups of data that are statistically the same for FS modulus at 40°C. The great overlap between the groups indicates that none of these fuels can be singled out as causing a change in the mix stiffness. The different groupings are related to sample and testing variability, rather than to any systematic difference in the fuels. Different statistical comparison of means tests were also used with the same result; there was no difference between the mixes produced with different fuels and combustion conditions.

Table 14: Comparison of FS Means at 40°C by Bonferroni’s Test

Fuel	Group A	Group B	Group C
RLI	A		
W2I	A	B	
RHI	A	B	
5LI	A	B	
W4I	A	B	
W1I	A	B	
W3I	A	B	
2I	A	B	
6I	A	B	C
R4I		B	C
5HI		B	C
2O			C

The Simple Shear test was run on the same specimens after the FS test at both 68 and 104°F (20 and 40°C). (Both tests are considered non-destructive and can be run on the same specimens.) This test is not considered to be as meaningful as the FS test by the research team, but it can be conducted in just a few minutes on the same specimens, so it is typically included in the testing program. In this test, the sample is sheared one time at a specified shear stress. The amount of shear deformation is recorded. In concept, a more rut resistant mix will exhibit less shear deformation than a rutting-prone mix.

All of the samples tested at 104°F (40°C) and most of the samples tested at 68°F (20°C) exceeded the measuring capability of the instrumentation, indicating that they experienced greater shear strain than typically observed. The data is summarized in Appendix I. An asterisk indicates that the LVDT capacity was exceeded for the replicate test results. The actual strains are higher for those flagged test results. The fact that some of the tests did not exceed the LVDT capacity does not necessarily mean that that specimen is better (stiffer) than the others. In setting up the test, it is necessary to zero the LVDT, which is like taring a balance. The LVDT is not set to zero at the middle of its stroke, but rather is set towards one side of the maximum stroke so that the LVDT can measure as much deformation as possible, especially with a mix as soft as this one. After manually adjusting the LVDT, this position is electronically set to be the zero point and deformations are measured relative to that point. So the LVDT actually starts at a slightly different place each time. As noted in the report, this mix is quite soft and shows high deformations and low moduli. That is why the LVDT capacity was exceeded most of the time. The LVDT may have been set to allow slightly more stroke when testing some samples than the others that exceeded the capacity.

Many of the measurements that exceeded the LVDT capacity were lower than the deformations recorded for those that did not; see for example the No. 2 and No. 6 fuels at 40°C. Some were higher too, of course. There is a high amount of variability in this test, even compared to the other SST tests, because this is a single shearing event. The other tests involve repeated loadings, which help to condition the specimens and smooth out the data. In all cases, the shear deformations are quite high. (Because the graphs almost all show flat lines, the replicate results are not included in this report.)

The finding of high shear strain agrees with the low stiffness values noted in the FS test. Again, this is not surprising based on the relatively fine nature and high binder content of the mixtures. Those specimens that did not exceed the LVDT capacity did not exhibit higher stiffnesses, confirming that they were not necessarily better (stiffer) than the samples that exceeded the capacity. Because the measuring capabilities were exceeded, statistical analysis of this data would not be meaningful.

The final test conducted in the SST was the Repeated Shear (RS) test at constant height. In this test, a repeated haversine shear load is applied to the specimen for 5,000 cycles. These tests are typically conducted on specimens compacted to 3% air voids, as noted earlier, since the results are related to the tendency of the mix to exhibit plastic flow late in its service life at low air void contents. As before, the variability in the air void content was quite high, due to the way the specimens were prepared. The usual procedure is to run this test at a temperature corresponding to the binder high temperature grade up to about 140°F (60°C) or so. (Testing becomes problematic at temperatures much higher than 140°F (60°C).) Repeated attempts were made to test this mix at 136°F (58°C) since a PG58-28 was used. The mixture was too soft at this temperature, and the equipment would automatically shut down. After trying increasingly lower temperatures, 115°F (46°C) was determined to be the highest temperature at which this material could be tested. This corresponds to the low shear stresses, high shear deformations and, ultimately, to the fine, binder-rich composition of this mix.

A material is considered to have failed this test if the accumulated shear strain exceeds 5% before the test is concluded at 5000 shear cycles. Almost all of these mixtures exceeded 5% strain before reaching 5000 cycles. (Data on the replicate test results is shown in Appendix J.) In general, the lower air void samples performed better than the higher air void samples. Apparently the soft mixture coupled with higher air voids allowed more strain to develop in the specimens. Since most of these specimens failed the test, statistical analysis of the results would not have been meaningful.

Because of the high variability and poor accuracy (relative to the 7% and 3% targets) of the air void contents of the mixtures compacted during production, a limited amount of testing was conducted on laboratory reheated and compacted specimens of the mix produced with the No. 6 fuel at insufficient oxygen conditions. This technique had been avoided due to concern that reheating and mixing the samples might allow any volatile contaminants, if any, to escape. While the air void control was greatly improved when compacting in the lab (for example, coefficient of variation (c.v.) reduced from 8% in field to 2% in lab for No. 6I specimens) and the testing variability was also reduced (c.v. dropped from 28% to 16% at 154°F (68°C) and from 10% to 5% at 104°F (40°C)), the overall averages did not improve. The complex shear modulus from the FS test was still low (average of four specimens at 104°F (40 °C) and 10 Hz was 13,880 psi). The LVDT capacity was still exceeded in the SS test, and four samples still failed the RS test. Had better control on the air voids in the field been possible, then, it does not appear that the results would have improved, although the repeatability would have likely been better.

Dynamic Modulus Testing

Dynamic modulus testing was conducted at two temperatures on samples of the mixtures produced with the No. 2 fuel at optimum and No. 6 fuel at insufficient oxygen conditions as described in Appendix D. Dynamic modulus is another measure of the stiffness of the mix, this time measured in axial compression rather than shear. It also relates to rutting, among other distresses. The lower test temperature (99.7°F or 37.6°C) corresponds to the effective temperature for South Dakota. The higher test temperature (129.9°F or 54.4°C) is a commonly used test temperature; testing was done at this temperature in order to be able to compare these results to other testing for illustrative purposes.

The testing results are shown in Table 15 and Table 16. This data shows that as the temperature increases, the modulus decreases, as expected. The average moduli are very similar at a given temperature. In fact, statistical analysis shows that there is no significant difference in the dynamic modulus at either temperature (p-value at 99.7°F equals 0.64 and at 129.9°F equals 0.93). That is, there is no difference in the compressive stiffness of the mixes produced with the No. 2 and No. 6 fuels.

The dynamic modulus needed to resist rutting varies depending on the environment and traffic. Since these shoulder mixes are not expected to carry much traffic, a low modulus value may be acceptable, as with the SST tests. For comparison purposes, recent testing at the NCSC of typical mixes from the North Central region showed modulus values at 129.9°F (54.4°C) ranging between about 50,700 psi (350 MPa) for a relatively fine mix used in the north to a little over 145,000 psi (1000 MPa) for a coarse interstate mix used in the southern part of the region. The South Dakota mix is lower in stiffness, but this is not unexpected based on its texture, binder content, the climate and its intended use on the shoulder. These results are also consistent with the shear test results.

Table 15: Dynamic Modulus Results for No. 2 Fuel at Optimum

Replicate No.	% Air Voids	Dynamic Modulus at 5 Hz, MPa	
		@ 37.6°C	@ 54.4°C
1	6.2	791	269
2	6.8	1081	303
3	8.0	1376	285
4	7.5	645	294
<i>Mean =</i>	<i>7.1</i>	<i>973.3</i>	<i>287.8</i>
<i>C. V., % =</i>		<i>33.3</i>	<i>5.0</i>

Table 16: Dynamic Modulus Results for No. 6 Fuels at Insufficient Oxygen

Replicate No.	% Air Voids	Dynamic Modulus at 5 Hz, MPa	
		@ 37.6°C	@ 54.4°C
1	7.1	1290	367
2	6.4	946	325
3	7.3	687	251
4	7.8	510	194
<i>Mean =</i>	<i>7.1</i>	<i>858.3</i>	<i>284.3</i>
<i>C. V., % =</i>		<i>39.5</i>	<i>27.1</i>

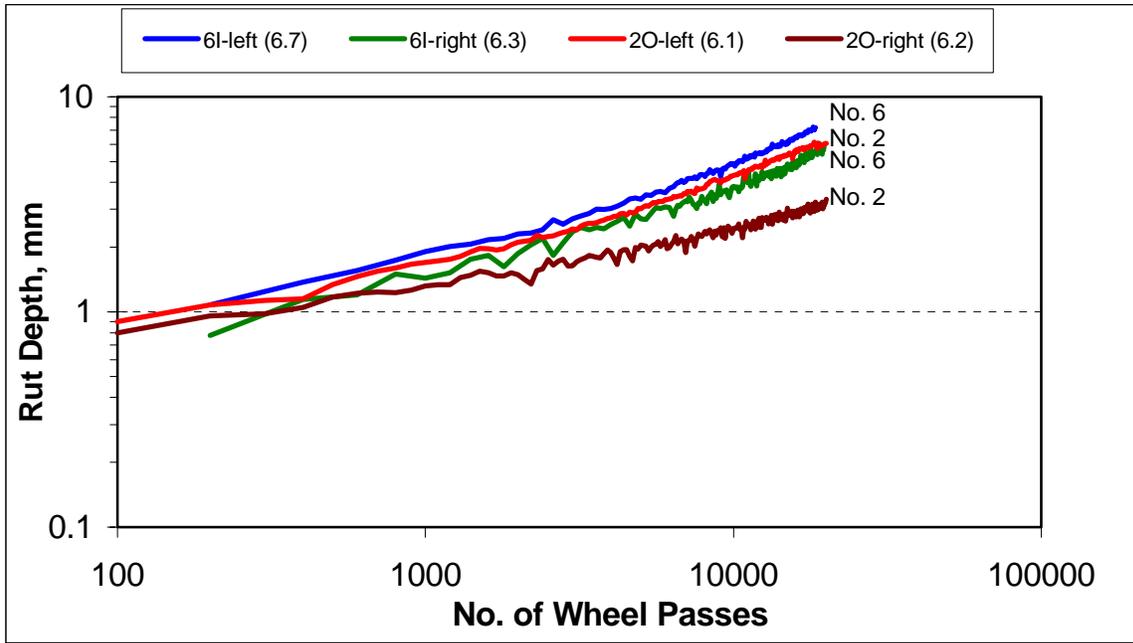


Figure 6: Purwheel Loaded Wheel Test Results

Statistical analysis of this data, summarized in Appendix M, Table 121, shows that there is no significant differences between the dynamic moduli of mix produced with No. 2 fuel at optimum and mix produced with No. 6 at insufficient oxygen.+

Loaded Wheel Testing

Loaded wheel testing was conducted in the Purwheel device, described in Appendix D, on slabs compacted in the linear compactor from plant-produced mix reheated in the lab. Tests were conducted on the two extreme cases, the No. 2 at optimum and the No. 6 at insufficient oxygen. The results are summarized graphically in Figure 6 and in tabular form in Appendix G. This testing was conducted at 99.7°F (37.6°C), the effective rutting temperature for South Dakota, as used for dynamic modulus testing. Normally this test is run at 122°F (50°C), but a lower temperature was used in this project to compare to the dynamic modulus test and based on difficulties running the SST tests at higher temperatures.

Figure 6 shows the results for two slabs from each fuel. (The numbers in parentheses in the legend are the air void contents of the replicate slabs.) This test was run to check for substantial differences in performance between the extreme cases (2O being the control and 6I being the worst case). The two slabs compacted from mix produced with the No. 6 fuel showed similar rut depth accumulations. The two slabs compacted from the mix heated with the No. 2 fuel did not agree with each other as well as the No. 6 slabs, for unknown reasons. The four slabs showed similar accumulated rut depths, though one of the No. 2 slabs appeared to show somewhat better performance. These differences are not significant based on previous experience with this test.

This data does not lend itself to statistical analysis but previous experience with this test method shows that this amount of variability in the test results is normal and does not indicate any significant difference in performance. These results do not point to any appreciable differences between the mixes, nor do they

indicate any gross instability or tenderness based on fuel type. The observed rut depths are somewhat lower than normal due to the lower test temperature.

AASHTO T283 Testing

The moisture sensitivity test described by AASHTO T283 was performed on field compacted samples of the mixes produced with the No. 2 fuel at optimum and the No. 6 fuel at insufficient oxygen conditions. The results are summarized in Table 17 below.

Table 17: AASHTO T283 Test Results

Fuel	Dry Set Averages		Wet Set Averages		TSR, %
	Strength (psi)	Air Voids, %	Strength (psi)	Air Voids, %	
No. 2 Opt.	698.5	6.9	664.6	7.0	95.2
No. 6 Insuff.	633.1	6.9	618.2	6.9	97.6

Air voids were controlled at 7.0% ±0.5%, the average air voids for each treatment subset were kept as uniform as possible, and attempts were made to keep the degree of saturation consistent as well at about 75%. The results show the mix produced with the No. 2 fuel at optimum were slightly stronger than the mix produced with No. 6 at insufficient oxygen, but there was no indication at all of any stripping damage. Both mixtures yielded very high tensile strength ratios. Stripping was one of the distresses that could be expected to result from mix contamination, particularly if the contaminant was petroleum based rather than char, since the petroleum based material could soften the asphalt. This contaminant could be especially critical at the interface between the aggregate and the asphalt binder, where stripping problems develop. These test results do not exhibit any increased stripping propensity in the mixture produced with the No. 6 fuel, despite the observed brownish tint on the heated aggregates and the fact that chromatography showed that residue to be petroleum based. In fact, the No. 6 fuel actually had a higher tensile strength ratio than the mix produced with No. 2 fuel.

Summary. The mixture tests included a variety of tests that have been shown in past research to be sensitive to changes in mixture properties and that are related to field performance. None of the tests conducted on the mixtures produced with different burner fuels under differing burner conditions revealed any differences in mixture behavior. There were no significant differences in the compaction properties, complex shear modulus (stiffness), permanent shear strain, dynamic modulus, loaded wheel test rutting or stripping tendencies. As noted before, the presence of a harmful contaminant could be expected to affect the stiffness of a mixture, which would affect moduli, strain, rutting and possibly compaction characteristics, or the stripping potential of a mix. Since no significant changes were observed in any of the mixture properties, that adds more compelling evidence that the minute traces of residue found on the heated aggregates are not detrimental to the properties of the hot mix produced.

Overall Conclusions from Aggregate, Binder and Mixture Testing

In summary, none of the test methods on the binder, aggregate or mixture offered any evidence of detrimental contamination. Although the gravimetric tests and high carbon chromatography identified minute amounts of residue, the quantities were extremely small. None of the subsequent binder rheology or mixture performance tests showed any significant differences in the plant-produced mixtures. This indicates that either the residue was not of a detrimental nature or it was not present in a great enough concentration to yield a significant performance difference. These results are consistent throughout the examination of binder and mixture testing and with the chromatographic analysis of the nature of the residue.

Performance Implications

As the previous sections show, none of the binder or mixture tests indicated any detrimental effects due to the presence of a residue from heating the materials with varying fuels under differing combustion conditions. The mixtures produced under all of the conditions tested were virtually the same. Therefore, no performance differences would be expected in the field.

Certainly this is not to say that there are never detrimental effects due to poor combustion. There is enough anecdotal evidence of burners that will not stay lit, atomizers that are in poor condition, heavy fuels that are not properly preheated, “puffing” plants and more to show that things can go very wrong. When plants are operating far out of their normal operating parameters, unburned fuel can reach the aggregates, exhaust gas compositions can change radically, smoke can be produced and char can form. This study, however, shows that the oxygen conditions in the drum can be fairly far from ideal without causing contamination of the mix. This supports the earlier industry representatives’ contentions that a plant would have to be malfunctioning severely before the mixtures would be harmed.

This is good news in the sense that it indicates by taking care to keep plants in reasonably good operating conditions and then operating them within normal ranges, it should be possible to produce good asphalt mixtures. It is in the best interests of contractors and mix producers to keep their plants maintained and operating properly in any case; downtime due to a plant breakdown or excessive fuel consumption caused by a malfunctioning burner and/or exhaust system are costly to the contractor.

Cost Implications

Since there are no differences in expected performance of the mixes produced with different fuels and under differing combustion conditions, there would be no changes in the life cycle of the pavement. The only cost implications, then, would be on initial costs. Allowing the use of economical heavier and/or recycled fuels would reduce initial costs without harming performance.

To attempt to estimate the initial cost savings possible through the use of recycled fuels, the research team consulted hot mix producers in several parts of the country. The following economic analysis is based on their data and certain reasonable assumptions regarding required BTUs for a given moisture content, etc. Due to the volatility and regional variability in fuel prices, the cost savings may vary from these estimates. The discussion below illustrates one method for comparing the cost effectiveness of various fuel types.

Typically, it requires about 275,000 BTUs to dry and heat one ton of aggregate at 5% moisture to a temperature of 300°F. This estimate also assumes no changes in the mixture, such as binder content, aggregate type or moisture content, etc. Also, not all fuel types are considered and some may offer even more BTUs than those shown here for illustrative purposes. The costs to heat one ton of aggregate with three different fuels are shown below.

Recycled fuel oils can provide about 138,000 to 142,000 BTUs/gallon at a cost of about \$0.63/gal. So, it would take between 1.9 and 2.0 gallons to heat one ton of aggregate. (275,000 BTU/ton ÷ 142,000 BTU/gal and 275,000 BTU/ton ÷ 138,000 BTU/gal)

At 2.0 gal/ton, the cost of fuel would be $2.0 \times \$0.63 = \1.26 per ton of aggregate. At 1.9 gal/ton the cost is only \$1.20 per ton.

No. 2 fuel typically provides between 136,000 and 138,000 BTU/gal at a cost of about \$1.15/gal. Again, it takes about 2.0 gal/ton ($275,000 \text{ BTU/ton} \div 138,000 \text{ BTU/gal}$) to heat and dry the aggregate. The associated cost in this case, however, is $2.0 \times \$1.15 = \2.30 per ton.

Natural gas can provide higher BTUs but its cost and availability vary widely. The cost can be between \$3.50 and \$11.00 per million BTUs. You could heat and dry about 3.6 tons of aggregate with 1 million BTUs ($1,000,000 \text{ BTU} \div 275,000 \text{ BTU/ton}$). The cost of fuel then could be between just under \$1 per ton ($\$3.50 \div 3.6 \text{ tons}$) to just over \$3 per ton ($\$11.00 \div 3.6 \text{ tons}$). If the natural gas price is around \$4.54 per million BTUs, the fuel cost will be comparable to recycled fuel oil ($\$1.26/\text{ton} \times 3.6 \text{ tons} = \4.54).

So, for the three fuel types illustrated here, the recycled fuel oil could save between \$1.04 and \$1.10 per ton of heated aggregate compared to No. 2 fuel (\$2.30 for No. 2 - \$1.26 or \$1.20 for recycled fuel). Depending on prevailing natural gas prices, the recycled fuel could be slightly higher (\$0.20-0.26 per ton) to quite a bit lower (\$1.80 per ton). Other fuel types could possibly offer even higher savings, depending on local market factors. Presumably, in a competitive market, these savings would be passed on to the DOT in lower bid prices. Based on these figures, a \$1 to \$2 per ton savings could be realized by allowing the use of alternative fuels.

Heavy fuels require preheating, however, which would reduce the cost savings. On the other hand, heavier fuels can also have higher BTUs per gallon. No. 6 fuel, for example, can provide around 150,000 BTU/gal and No. 4 can provide around 146,000 BTU/gal. (8) Even when allowing for the cost of preheating, these fuels can be very economical. To extend the previous example, if 275,000 BTUs are needed to heat and dry one ton of aggregate, and No. 6 fuel provides 150,000 BTU/gal, it would take about 1.8 gal of No. 6 fuel. It cost \$2.30 per ton to heat the aggregate using No. 2 fuel. Therefore, using No. 6 fuel would be economical if the price is less than \$1.28 per gallon ($\$2.30 \div 1.8 \text{ gal}$). (This estimate neglects preheating costs, so in fact the fuel would have to be somewhat less than \$1.28/gal.)

Cost savings are also affected by plant operations, particularly the amount of excess air, as discussed in Appendix K, so it behooves contractors to control their operations and make them as efficient as possible. Excess fuel consumption is literally money out of their pockets.

Specification Changes

The results of this study indicate that the South Dakota Department of Transportation can relax their burner fuel specifications to allow the use of more types of fuel. This section discusses the considerations that led to the final recommendations on specifications changes, which are detailed in the summary at the end of this section.

The current SDDOT specification reads:

Burner fuel used for production of asphalt concrete shall be propane, butane, natural gas and No. 1 or No. 2 fuel oils. Number five burner fuels may only be used providing the number five burner fuel is properly preheated and efficiently burned.

The findings of this study strongly support allowing the use of other fuel types, including heavy and reprocessed fuel oils. The caveat to properly preheat and efficiently burn fuels heavier than No. 2 is an important point that should be retained.

Just because the results of this study indicate that mix contamination is not likely when different burner fuels and combustion levels are used, it does not mean that the South Dakota Department of Transportation should neglect to take reasonable precautions to preclude problems in the future. For example, although no detrimental effects were noted with the waste fuel oils, in reality only two were tested at two different water contents. Other waste fuels may have very different compositions and qualities that would be unknown. The experiences of other states point to occasional problems with waste fuels that are not covered by some specification. It is reasonable, therefore, to require that any burner fuel meet a minimum quality specification.

The recycled fuel oils evaluated in this study met ASTM D6448. This specification could be implemented as a means of assuring a minimum quality level in the fuels used. Montana's example could also be followed. They allow the use of reclaimed fuels provided they meet requirements listed in Table 18.

Table 18: Montana Recycled Fuel Specification

	Property	Range
Physical Properties	API Gravity	20-28
	Viscosity at 122°F (60°C) (Saybolt Flurol)	10-20
	Pour Point, °F (°C)	+10(-12)
	Flash Point, min, °F (°C)	100 (37.8)
	Water by Distillation %	Under 1
	Solids by Separation %	Under 1
	Ash %	Under 0.4
	Sulfur	Average 0.5%
	Kinematic Viscosity at 100°F (37.8°C) (centistokes)	54-100
	Kinematic Viscosity at 122°F (60°C) (centistokes)	15-75
Chemical Properties	Element or Compound	Permitted Level
	Vanadium	Under 100 ppm (100 mg/L)
	Cadmium	Under 2 ppm (2 mg/L)
	Chromium	Under 10 ppm (10 mg/L)
	Lead	Under 100 ppm (100 mg/L)
	Arsenic	Under 5 ppm (5 mg/L)
	Total Halogens	Under 1,000 ppm (1,000 mg/L)
	PCB's	Under 2 ppm (2 mg/L)
Notify the engineer in writing at least 48 hours before using EPA-UOF. Furnish a copy of the most current tests certified by the supplier and showing compliance with physical and chemical requirements with the notice. Also certify that the plant burner is designed and equipped to properly preheat and burn EPA-UOF. The right to sample and test to verify certified test results is reserved		
Immediately stop using EPA-UOF fuel if burner flame-outs or other evidence of incomplete combustion or mix contamination are evident. Begin using one of the other approved fuels to complete the work. No claim for additional compensation will be considered or allowed.		

This specification has several important points:

It does allow the use of a used burner fuel, but still requires that the fuel meet certain quality standards; ASTM D6448 provides another specification for recycled fuel oils and may be more widely used than the EPA specification.

Test results from the supplier are required to show that the fuel does meet the specifications.

The producer must certify that the plant burner can preheat and combust that type of fuel.

Lastly, the use of the alternate fuel must be discontinued if flame-outs or any evidence of incomplete combustion or mix contamination are noted. This last clause would seem to be a reasonable provision for any type of fuel.

These points were considered and incorporated in the final recommended specification. ASTM D6448 was ultimately selected as the primary basis for accepting reprocessed fuel oils due to its national acceptance and widespread availability. Other provisions were added to the proposed specification to incorporate the important points detailed above.

Another item considered in developing a revised fuel specification was how best to handle No. 6 fuel oil. This is the fuel that produced a visible discoloration on the heated aggregates and produced the highest gravimetric residue content by far. It also produced a spike in the CO exhaust gas, which is one possible warning sign of poor combustion. The binder and mixture tests did not show any evidence of detrimental effects of using this fuel, however, this data was collected for one truckload of No. 6 fuel at one plant on one contract. If a different plant using a different source of fuel had higher residue contents, the potential for contamination problems certainly exists. This potential needs to be considered when revising specifications to be used statewide.

The final recommendation on No. 6 fuel, after considering all of the data, is to allow the use of No. 6 fuel on pilot projects and evaluate their performance. Contractors who wish to use No. 6 fuel should be allowed to do so provided they agree to conduct exhaust gas data analysis at their cost and provide the data to the SDDOT. The DOT should monitor production on the pilot projects, as described below, to investigate whether there are any apparent mix contamination problems. Performance of the mixtures on the pilot projects should be monitored for a period of at least three years to determine if the pilot projects exhibit any unusual rutting due to decreased mix stiffness, cracking due to increased mix stiffness, or stripping due to contamination at the asphalt-aggregate interface. Following monitoring of the production and performance of these pilot projects, the SDDOT should consider revising the specifications again to allow routine use of No. 6 fuel at the contractors' option.

Based on the findings of this study, then, it is recommended that the South Dakota Department of Transportation relax their burner fuel requirements to a certain extent since there were no detrimental effects of fuel type or combustion condition (within the range of conditions evaluated here). The specification should be broadened to allow the use of recycled fuel oils meeting the requirements of ASTM D6448 as well as No. 5L and 5H fuel oils. It is not recommended that the SDDOT allow the use of non-specification waste fuels. Although there were no observed detrimental effects with the two waste fuels evaluated here, there are no assurances that other waste fuels would perform as well since there are no standards of quality for these fuels. No. 6 fuel oil should be allowed on pilot projects and the performance of these projects should be monitored to provide data for possible future inclusion of No. 6 fuel in the standard specifications.

The provision in the current specification that the fuels be properly preheated and efficiently burned should be retained. Lastly, the SDDOT should add a statement similar to that used by Montana stating that "the use of an alternate fuel shall be discontinued if flame-outs or any evidence of incomplete combustion or mix contamination are observed," or words to that effect. A provision such as that would allow the engineer to require that conditions such as those observed at start up with the No. 6 fuel creating a brownish residue on the heated aggregates not continue.

Summary. The SDDOT should revise its specifications to allow the use of a wider range of fuel types. Suggested wording of the revised specification is shown below.

Burner fuel used for production of asphalt concrete shall be propane; butane; natural gas; No. 1, No. 2 No. 5L, or No. 5H fuel oils; or recycled fuel oils RFO4, RFO5L or RFO5H meeting the requirements of ASTM D6448. Burner fuels heavier than No. 2 may only be used providing the fuel is properly preheated and efficiently burned. When using fuels heavier than No. 2, the producer shall furnish a copy of the most current tests certified by the supplier and showing compliance with physical and chemical requirements. The use of any fuel shall be discontinued if flame-outs or any evidence of incomplete combustion or mix contamination are observed. Begin using one of the other approved fuels to complete the work. No claim for additional compensation will be considered or allowed.

In addition, the SDDOT should implement a program to allow use of No. 6 fuel on pilot projects and study the production and performance of HMA using No. 6 fuel. Based on these pilot projects, the SDDOT should consider whether or not to allow the use of No. 6 fuel in the future.

Recommended Test Methods

In searching for simple, field applicable test methods to identify potential contamination problems or to monitor combustion in the plant, the research team looked to many sources for information. One survey response, from Tennessee, indicated they put heated aggregate in a pail of water to check for the presence of an oily film that could indicate contamination. To evaluate this method, samples of the retained heated aggregates and mixtures from this project were placed in water to check for the presence of a film. Water that had been heated to boiling was also used in an attempt to “loosen” any residue. The results of this effort were inconclusive and very subjective. The aggregate had so many fines that the water was clouded, and detecting the presence of any oily film was very difficult. When hot mix samples were placed in the water, a very slight film was detected, probably from the asphalt itself. This test, while simple, did not appear to be very useful. Also, obtaining samples of heated aggregates to inspect can be difficult or impossible in a drum plant.

There are, however, other means that can be used to assess whether a fuel is being preheated adequately so that it can be atomized and whether a plant is operating properly. These include checking the fuel viscosity, installing a flame eye on the burner to monitor the color of the flame, and checking the exhaust gas composition, in increasing order of complexity and expense. Simpler means are also available, including listening to the burner, watching for flame outs and problems keeping the burner lit, excessive fuel consumption and more. Plant inspections can help to ensure the plant is in good operating condition and the burner is well maintained; this would at least ensure that the plant is capable of burning fuel properly. Several alternatives for testing or monitoring were considered when developing recommendations for the SDDOT, including:

- Requiring plant inspections.
- Monitoring burner conditions.
- Testing fuel viscosity.
- Analyzing exhaust gases, in problem cases.
- Training to provide warning signs of possible plant burner problems.

- Monitoring to fine tune specifications and test methods.

After considering the options and in light of the findings of this research, a recommended staged implementation process was developed as described in detail below. Since this research shows the risk of detrimental contamination is low, elaborate and expensive monitoring systems are not justifiable. Requiring plant inspections over and above the periodic environmental monitoring of exhaust gases is also not warranted.

As a first step, DOT and industry personnel should be trained to be aware of the potential signs of burner and combustion problems. These include, but are not limited to, sputtering or puffing of the plant; flame outs or trouble keeping the burner lit; excessive fuel consumption; visible exhaust gases or smoke; and a visible residue on the aggregate. None of these signs definitively identifies poor combustion, but they can indicate that the plant is not operating properly. The burner primer in Appendix K could be used to provide or supplement this training. In addition, the DOT could consider sponsoring NHI course 131044A, *Hot Mix Asphalt Production Facilities*, which covers burners and other plant systems.

Second, the DOT should require that the fuel viscosity be appropriate so that proper atomization can occur. If the viscosity is too high, the fuel shall be preheated to make it more fluid. The DOT can verify that the fuel oil viscosity is appropriate by sampling and testing using an oil viscometer kit. This testing should be done with alternate fuels (heavier than No. 2) or in cases where the engineer has concerns about the burner's operations. A suitable viscometer kit is available from Hauck Manufacturing Company, Lebanon, Pennsylvania, and possibly other sources as well. The state could perform these checks or could require the contractor to do so, as it chooses.

Third, the use of a heavy or recycled fuel should also require a monitoring period at start up to ensure the fuel is being properly combusted. The monitoring period could be based on time or tonnage and could require inspection of aggregates heated without binder to observe the presence of a residue. At start up with a heavy fuel, the contractor should be required to demonstrate that the fuel is being properly preheated to the appropriate viscosity and that the plant settings are appropriate for that fuel type. As a part of the monitoring period, the contractor should heat aggregates without the addition of binder to allow observation of any residue on the aggregates. Presence of a visible residue would require that the producer either change fuels or adjust the burner and plant to eliminate the residue. Other problems that should signal a need to change fuels or plant settings include trouble keeping the burner lit (flame-outs), sputtering of the burner, excessive fuel consumption and visible exhaust gases. Plant operations should be monitored closely for the first day of production by the DOT and occasionally throughout production. Any time the problems listed above are noted, the contractor should adjust the plant settings or change the fuel to eliminate the problems.

Fourth, if the DOT has concerns about a particular plant or particular fuel, more elaborate testing methods should be employed on a case-by-case basis. A flame eye could be added to the burner to monitor the color of the flame. If the flame color changes from that established when optimizing the burner, it is a sign that something has changed that may reduce combustion efficiency and possibly cause contamination. Based upon this research, mandating the use of a flame eye is not justified, but this could be implemented later if concerns about contamination persist or if problems are noted in the field. In addition, a combustion analyzer could be used to verify if the burner is completely combusting the fuel. The combustion analyzer could be used to measure the amount of oxygen, carbon monoxide, carbon

dioxide and other exhaust gases. As noted before, and as seen in the exhaust gas data, the oxygen content drops and carbon monoxide levels increase as the combustion conditions worsen. A suitable test kit is available for under \$5000 from Bacharach and Omni Controls. Use of the kit would require the probe *to be inserted in the drum* of the hot mix plant for best results and would require a trained and knowledgeable operator. If only occasional use is anticipated, it may be more economical to hire a consultant or require the contractors to do so under certain conditions. A request to use a heavy or unfamiliar waste fuel or observed difficulties in keeping a burner lit with a certain fuel could be grounds for requiring combustion analysis. Installing a flame eye or securing exhaust gas monitoring should be the contractor's option. The alternate to taking one of these steps, in cases where combustion problems are evident, would be for the contractor to switch to another fuel type or maintain/repair the burner to correct the problems. If this still does not resolve the problems, the project should be shut down until corrections are made.

Lastly, after implementing the specification changes and the steps outlined here, the SDDOT should monitor mix production for one construction season and reevaluate the changes. It may be possible to further relax some of the requirements or may be prudent to tighten some requirements depending on field experience. Based on a review of mix production, the new requirements should be reexamined. If no problems are observed, it may be possible to reduce the monitoring period or start-up requirements for some of the lighter fuels. For example, the start up inspection might be necessary only for No. 5 fuels. On the other hand, if problems are observed in the field, the need for formalized plant inspections or routine exhaust gas monitoring should be reexamined and strengthened.

Summary. It is recommended that the SDDOT take a staged approach to implementing changes in field procedures as follows:

- Provide training. The first step is to provide a memorandum or other brief instructional document to train field and plant personnel on potential signs of burner and combustion problems
- Check fuel viscosity. The fuel viscosity should be verified at the plant with a viscosity kit, especially with heavy fuels.
- Implement monitoring period. Another step that should be taken concurrently with relaxing the specifications as outlined in 5.9 is to implement a monitoring period at start up when a fuel heavier than No. 2 is used.
- Require more elaborate testing only for problem fuels or plants.
- A flame eye monitoring device could be installed to monitor the color of the flame and detect changes in the combustion efficiency.
- Require gas analysis for problem cases.
- Reevaluate after implementation. The SDDOT should follow mix production for at least one construction season following the implementation of the specification changes to determine if any problems are noted and if there are any patterns to these problems.

Based on the results of this research, which strongly suggest that mix contamination is not a prevalent problem, no routine testing by field personnel is justified other than checking fuel viscosity and monitoring plant operations at start up and occasionally during production. That is, there is no need to

require exhaust gas analysis at every plant or with certain fuels. There are simpler steps to ensure that adequate combustion is being achieved. If problems are observed, more elaborate testing can be required on a case-by-case basis.

Overall Conclusions and Recommendations

The results of this research effort indicate the following specific findings:

- A survey of state practices showed that few states control the types of fuel that are burned in hot mix plants within their jurisdictions. Some states limit the fuel types, particularly disallowing waste fuels; others have indirect limits through emissions testing.
- Most states have not observed apparent mix contamination problems. Those that have observed occasional problems identified particular problem fuels or plants. Due to the relatively rare occurrence of contamination problems, there has been little research on the topic.
- Industry representatives also reported few instances of contamination. They identified ways to determine if the plant is properly firing and what might signal plant problems.
- Gravimetric analysis of aggregates heated in the plant without the addition of asphalt binder did detect the presence of a minute amount of residue from aggregates heated with the No. 6 fuel at insufficient oxygen conditions and even smaller amounts of residue from the other fuels.
- Chromatographic and FTIR analysis of the residue identified it as a high molecular weight material representative of partially decomposed tars and fuel residues. The residue concentration was found to be less than 35 parts per billion by weight of the aggregate.
- Extracted binders from the plant produced hot mix were analyzed using a variety of binder tests. Neither dynamic shear rheometer testing at high temperatures, nor bending beam rheometer and direct tension testing at low temperatures detected any effect of the residue.
- Binder samples deliberately contaminated with the residue from the heated aggregates were tested in the DSR and no changes in the binder properties were detected.
- Samples of the hot mix asphalt produced in the hot mix plant with different fuels under differing burner conditions were tested in a variety of ways, including Superpave shear tests, dynamic modulus, gyratory compaction parameters, stripping susceptibility and loaded wheel testing. No significant differences were noted in any of the mixture tests, adding more compelling evidence that no detrimental contamination occurred.
- Based on the chemical and physical tests conducted in this research, no performance differences would be expected due to the use of different fuel types or varying combustion conditions.
- Initial cost savings are possible through allowing the use of alternate fuels. The actual savings is highly dependent on fuel prices and availability, but could be in the range of one to two dollars per ton of hot mix.
- Specification changes were recommended to allow use of alternate fuel types and grades while still maintaining the quality of the hot mix and asphalt concrete pavements.
- Simple methods to ensure proper atomization and combustion of burner fuels and proper plant operations were suggested. A monitoring period at start up when fuels heavier than No. 2 are used

was recommended. If problems are observed and are persistent, exhaust gas analysis should be required to continue using that particular fuel at that particular plant.

- The results of this research strongly suggest that mixture contamination is not a likely occurrence if burner fuels are properly preheated and the plant is operating reasonably well. This should give the DOT and industry confidence to use alternate fuels while implementing simple controls and checks to ascertain that the burner and plant are operating properly.

In light of these findings, the following specific recommendations are made.

- This research shows that SDDOT should relax its specifications regarding allowable fuel types to include fuels through No. 5 (L and H) and reprocessed fuel oils.
- Waste fuel oils should not be allowed.
- This research shows no detrimental effect of No. 6 fuel despite the observed discoloration of aggregates heated with that fuel. SDDOT should allow the use of No. 6 fuels on pilot projects and evaluate its performance to determine if it is reasonable to allow the widespread use of this fuel in the future.
- This research clearly shows no negative impact of using the alternate fuels, so elaborate and expensive test or monitoring procedures are not recommended for routine implementation. The research findings support a staged implementation process including the following steps:
 - Providing training to plant and field personnel to recognize signs of potential burner problems.
 - Checking fuel viscosity for fuels heavier than No. 2.
 - Implementing a monitoring period at start-up with a heavy fuel.
 - Requiring flame eyes or combustion gas monitoring only for problem cases (plants or fuel types).
 - Re-evaluating the changes after implementation.

As an overall summary, then, of the major findings of this study related to the primary objectives of the work:

- The fuel type, quality and burner combustion conditions evaluated in this study were found to have no detrimental effects on the physical or chemical properties of the hot mix produced.
- There was no evidence of any effects of fuel type, quality or combustion conditions on HMA performance or combustion.
- Based on the research testing results, supplemented with information from other states and industry, recommended specification changes were developed.
- Training and monitoring procedures were recommended for field and plant personnel to ensure adequate combustion is achieved.

IMPLEMENTATION

The results of this research clearly show that hot mix asphalt contamination is unlikely to occur in a plant operating within normal parameters and is even unlikely if the plant is somewhat outside normal parameters. This does not mean that any and all fuels should be used or that it is not necessary to exercise care in operating a plant properly. Contamination could still result if fuels are not properly preheated, if the atomizer and other parts of the burner or exhaust system malfunction, or if other problems exist. It does show, however, that under reasonably normal conditions, contamination is not likely to be a problem and pavement performance will not be compromised.

Based on these findings, wholesale changes in the specifications and test procedures are not recommended, but relaxing of the specifications to allow more fuel types is possible. The use of alternate fuels, including recycled fuel oils and No. 5L and 5H fuels, may allow contractors to use an economical fuel with high BTU's without sacrificing hot mix or asphalt pavement performance. The use of No. 6 fuel may also be feasible, but should be evaluated further through pilot projects before implementing. Simple changes in the specifications and monitoring procedures are recommended for consideration by the DOT. Following changes in the specifications, the SDDOT should review hot mix production for at least one construction season to observe the effects of the specification changes. Based on this review, the specifications and monitoring procedures can be relaxed, strengthened or allowed to stand accordingly.

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APPENDICES

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