University of Massachusetts
Transportation Center

Street Sweeping Reuse at MassHighway – Barriers, Economics, and Opportunities

Massachusetts Transportation Research Program

EOT Massachusetts Executive Office of Transportation

U.S. Department of Transportation Federal Highway Administration

Deval Patrick	**Tim Murray**	**Bernard Cohen**	**Luisa Paiewonsky**
Governor	***Lieutenant Governor***	***Secretary***	***Commissioner***

December 2007 **Office of Transportation Planning** SPRII.01.12

Technical Report Document Page

1. Report No. SPRII.01.12	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle Processing and Reuse of Street Sweeping and Catch Basin Cleaning		5. Report Date December 2007 6. Performing Organization Code n/a
7. Author(s) Dr. Sukalyan Sengupta		8. Performing Organization Report No. UMTC-09-2
9. Performing Organization Name and Address University of Massachusetts Dartmouth Civil & Environmental Engineering 285 Old Westport Road, North Dartmouth, MA 02747		10. Work Unit No. (TRAIS) 11. Contract or Grant No. ISA# 0041070
12. Sponsoring Agency Name and Address Executive Office of Transportation and Public Works Office of Transportation Planning Ten Park Plaza, Suite 4150 Boston, MA 02116		13. Type of Report and Period Covered Final Report 2005-2007 14. Sponsoring Agency Code N/A
15. Supplementary Notes		

16. Abstract

The Massachusetts Highway Department (MassHighway) is responsible for the disposal of approximately 30,000 cubic yards of street sweepings and catch basin cleanings every year. Existing Department of Environmental Protection policy allows for disposal of this material in a landfill or use as daily landfill cover. However, with rapidly shrinking landfill space and high cost of disposal (tipping fees), it is critical to consider reuse and recycle alternatives for this material. This study conducted an extensive analysis of the physical, chemical, and geotechnical properties of fresh, virgin sand, street sweepings and catch basin cleanings. Physical properties were examined including grain size, density, organic content, moisture content, uncompacted void content, and specific surface area. Chemical contaminants analyzed include RCRA-8 metals, volatile organics, polynuclear aromatic hydrocarbons, benzene, toluene, ethyl benzene and xylene, gasoline-range petroleum hydrocarbons and diesel-range petroleum hydrocarbons. Geotechnical characterization included image analysis for angularity, form and texture, uncompacted void content, and British Pendulum Number (BPN) test. The primary reuse options evaluated for street sweepings and catch basin cleanings include (a) reuse on pavements to provide traction and anti-skidding, (b) reuse as fine aggregates in bituminous concrete pavement, and (c) as a compost additive.

17. Key Word Street Sweepings, Catch Basin Cleanings, Grain-Size Distribution, British Pendulum Numbers, Granular Angularity, Texture, Form, Rut Test, Organic Content		18. Distribution Statement Unclassified	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 149	22. Price N/A

Form DOT F 1700.7 (8-72)

Street Sweeping Reuse at MassHighway – Barriers, Economics, and Opportunities

Final Report

Prepared By:

Sukalyan Sengupta, Professor

University of Massachusetts Dartmouth
Department of Civil and Environmental Engineering
285 Old Westport Road
North Dartmouth, MA 02747

Prepared For:

Executive Office of Transportation and Public Works
Office of Transportation Planning
10 Park Plaza, Suite 4150
Boston, MA 02116

December 2007

Acknowledgements

Prepared in cooperation with the Massachusetts Executive Office of Transportation and Public Works, Office of Transportation Planning, and the United States Department of Transportation, Federal Highway Administration.

The Principal Investigator would like to acknowledge the contributions and assistance provided by many individuals over the course of this project. Several employees of the Massachusetts Highway Department deserve special mention: Kenneth Leach provided major support throughout the project; MassHighway District Representatives Douglas Spink (District Two), Michael Giando, Matt Faron and Arthur Resca, James Hoey (District Three), Kenneth Leach (District Four), Gregory Fulgione, Terry Roche and Daniel Holgan (District Five) provided complete support for the collection of samples; Professor Walaa Mogawer and Alex Austermann of the Pavement Research Institute of Southeastern Massachusetts at the University of Massachusetts at Dartmouth provided technical assistance in analyzing the reuse options in bituminous concrete pavement. Professor Eyad Masad of Texas A&M University contributed significantly with image analysis for texture, form and angularity. At the University of Massachusetts at Dartmouth, graduate and undergraduate students Kumaravel Palaniswamy, Marina Perriera and Bryan Engstrom contributed toward critical aspects of this project.

Disclaimer

The use of sand or abrasives for snow and ice control has been the focus of discussion in the snow and ice community for many years. In Massachusetts, the use of sand has diminished over the last ten years. A federal report issued by SHRP TE-28, titled “Manual of Practice for Ant-Icing and De-Icing” changed the way most agencies perceived the use of deicing chemicals in the 1980’s.

Massachusetts contains a number of high speed; high volume interstate highways and has predominantly used sodium chloride (NaCl) as the preferred deicer. Over the last few years the State has refined the process of when, where and quantity appropriate to be used in the spread of deicing chemicals and sand. The use of sand is defined in the Reduced Salt Zone Policy updated 2009, Massachusetts Report.

Massachusetts Executive Office of Transportation and Public Works does not advocate the use of sand for roadways other than reduced salt zones. The management practices and policies of MassDOT, provide the tools necessary for its personnel to fight a multiple array of snow and ice events. Sand is a tool that should be used for very low temperatures and when other deicers are ineffective. Other acceptable uses include, when other deicing chemicals are in short supply or if an emergency exits.

Executive Summary

This study, Street Sweeping Reuse at MassHighway - Barriers, Economics, and Opportunities, was undertaken as part of the Executive Office of Transportation and Public Works (EOT) Research Program. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

This research was conducted for the Massachusetts Highway Department (MassHighway) by researchers at the University of Massachusetts Dartmouth (UMass Dartmouth) through an Interdepartmental Service Agreement. The primary goal of the project was to conduct research on characterization of street sweepings and catch basin cleanings and determine possible reuse options for these materials.

MassHighway is responsible for disposal of approximately 30,000 cubic yards of street sweepings and catch basin cleanings every year. Existing MassHighway policy is to conduct short term stockpiling of the sweepings and catch basin cleanings and then transport the material for disposal in a landfill or as daily landfill cover. In rare cases, MassHighway has applied for and received Massachusetts Department of Environmental Protection (DEP) approval for a Beneficial Use Determination (BUD) to use street sweepings as construction fill. With rapidly shrinking landfill space and high cost of disposal (tipping fees), it is critical to consider reuse and recycle alternatives for this material.

Street sweepings and catch basin cleanings were sampled fresh at the time of collection (from trucks) and from stockpiles of previously collected material in MassHighway depots. This was supplemented with control samples of fresh, virgin sand collected from MassHighway depots. A detailed characterization - physical, chemical, and geotechnical - of all samples was undertaken. The physical properties examined include grain size, density, organic content, moisture content, uncompacted void content, and specific surface area. Analysis was performed for chemical contaminants including RCRA-8 metals, volatile organics, poly-nuclear aromatic hydrocarbons, benzene, toluene, ethyl benzene and xylene (BTEX), gasoline-range petroleum hydrocarbons and diesel-range petroleum hydrocarbons. Geotechnical characterization included image analysis for angularity, form and texture, uncompacted void content, British Pendulum Number (BPN) test, and Model Mobile Loading System (MMLS) rut test. Samples were evaluated for reuse on pavement to prevent skidding and to provide traction, and as fine aggregates in bituminous concrete pavements. Compostability of the material was also evaluated as it has the potential to reduce the mass or volume of the material to be disposed and, at the same time, can also produce a soil amendment that can be marketed commercially.

Research findings indicate that processed street sweepings and catch basin cleanings have similar geotechnical characteristics to the fresh virgin sand that is currently used on pavements to prevent skidding and to provide traction for vehicles. Based on its geotechnical characteristics the processed street sweepings and catch basin cleanings may be used for the

same purpose. This reuse option is not allowed under current DEP policy (BWP-94.092). The researchers found no difference between street sweepings and catch basin cleanings that would prevent the reuse of catch basin cleanings on pavements for anti-skidding and to provide traction. Therefore, it is recommended that MassHighway request a BUD to include catch basin cleanings in the current DEP Policy on Street Sweepings in order to allow this reuse option. Moreover, a review of current literature in this area suggests that about a third to half (33% - 50%) of the sand applied is collected as street sweepings. Therefore, if the current policy were preserved, MassHighway would have to purchase at least 50% of fresh sand every year. But if catch basin cleanings are included in a BUD application, or in a modified version of BWP-94.092, it is conceivable that the combined mass/volume of street sweepings and catch basin cleanings annually collected would minimize the need for fresh purchase of virgin sand beyond the first year.

In order to collect and process sufficient amounts of street sweepings and catch basin cleanings, it is recommended that MassHighway request a BUD to allow the storage period be increased, to at least two years. Current DEP policy requires storage to be no more than one year unless regional DEP permission is given. The extended storage period will allow sufficient material to be screened and inventoried. The processed material can then be placed on a statewide database, and made available to contractors and MassHighway sanding crews for reuse. Based upon the researchers' economic benefit analysis, if this reuse recommendation is implemented, MassHighway may derive savings as high as $700,000 per year.

Based on the study of the physical, chemical, and geotechnical properties of fresh, virgin sand, street sweepings and catch basin cleanings, it can be concluded that street sweepings and catch basin cleanings can be reused as fine aggregate in bituminous concrete pavements. This reuse option is not allowed under current DEP policy. The policy does not apply to catch basin cleanings or street sweepings mixed with catch basin cleanings. The researchers found no difference between street sweepings and catch basin cleanings that would prevent the reuse of catch basin cleanings as fine aggregate in bituminous concrete pavements. Therefore, it is recommended that MassHighway request a BUD to include catch basin cleanings under the current DEP Policy on Street Sweepings.

Although the research indicates that catch basin cleanings and street sweepings can be used as aggregate in bituminous concrete pavement, pilot studies should be undertaken before this is planned on a Statewide (or District-wide) scale to evaluate if (i) any toxic fumes are generated when the organic matter in the solid waste (especially in the case of catch basin cleanings) is heated with bitumen while preparing the mixture, and (ii) if any toxics (organic and inorganic) leach from the pavement after water percolates through it. Based upon the researchers' limited cost benefit analysis, if this reuse recommendation is implemented, MassHighway may derive savings as high as $1,300,000 per year.

The physical analyses in this report indicate that the average organic content in street sweeping samples is approximately 3%. This is too low for direct composting, and thus, street sweepings should be used as an additive to compost as mentioned in DEP Policy.

However, the average organic content of catch basin cleanings was found to be much higher, approximately 8.7%.

Current DEP policy does not allow for the composting of catch basin cleanings. The researchers' preliminary findings indicate that catch basin cleanings are more suitable for composting. Since the researchers found ample evidence to indicate that catch basin cleanings - either alone or as an additive - are amenable to composting, it is recommended that MassHighway request a BUD to include catch basin cleanings under the current DEP policy on street sweepings. It is also recommended that additional, long-term composting studies be conducted on catch basin cleanings. Successful composting substantially reduces the mass or volume of the material to be disposed and simultaneously produces a marketable soil amendment and therefore could reduce MassHighway costs.

Disposal of street sweepings and catch basin cleanings is a major strain on MassHighway's budget. The disposal costs of street sweepings and catch basin cleanings as a percentage of MassHighway's total budget will continue to grow as the number of landfills shrink over time and landfill tipping fees continue to rise. The results of this study provide technical and economic analyses to highlight the economic and environmental benefits in reusing these materials on pavements for traction and anti-skidding, as fine aggregates in bituminous pavements, and by composting.

Table of Contents

List of Tables

List of Figures

1.0 Introduction

The study of the Street Sweeping Reuse at MassHighway – Barriers, Economics, and Opportunities, was undertaken as part of the Executive Office of Transportation and Public Works Research Program for the Massachusetts Highway Department. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Background

The Massachusetts Highway Department (MassHighway) faces a challenge that is common to transportation departments of many states, cities, and communities: devising policies - in lieu of land filling or as daily cover at solid waste landfills - to handle material that is collected annually and is termed "street sweepings" or "catch basin cleanings." The primary reasons for this approach are rapidly shrinking landfill space and high cost of disposal (tipping fees).

MassHighway applies sand and salt to roads every winter for de-icing and traction. In the following spring, when the snow and ice finally melt, MassHighway cleans accumulated material by either sending out its own street sweeping equipment and crews or by contracting out with private firms to have the street swept clean. The collected material is designated "street sweepings." Estimates of the mass or volume of this material generated are difficult due to fluctuations in the weather (mildness/severity of the winter, amount of snowfall), variation in the recovery fraction due to the traffic volume, contamination of the material by other sources such as tire shreds, particulate vehicular exhaust, plastic, glass, etc.

MassHighway is not responsible for all roads within Massachusetts. Based on MassHighway disposal costs over the last ten years, some conservative estimates suggest that MassHighway generates approximately 15,000 tons or 11,100 cubic yards (based on a material density of 100 lb/ft^3) of street sweepings per year.

Another major waste stream in need of disposal is catch basin cleanings. To calculate the mass or volume of catch basin cleanings that MassHighway has to deal with, let us take an example. There are 8,000 catch basins in District Four, each with a capacity of 0.75 cubic yards. If we assume that each is filled to two thirds of its capacity (0.5 cubic yards), the annual volume of catch basin cleaning generated in District Four is 4,000 cubic yards. However, when samples were collected from trucks while they were cleaning catch basins, many catch basins were found to be almost full. As with street sweepings, some conservative calculations estimate that statewide, MassHighway personnel are responsible for15,2000 tons or 15,000 cubic yards (assuming a material density of 75 lb/ft^3) of catch basin cleanings annually.

1.2 DEFINITIONS

Street sweepings refer to materials consisting primarily of sand and soil with lesser amounts of leaves, twigs, litter, garbage, animal waste, and trace amounts of metals, petroleum hydrocarbon, plastics, rubber, glass, and other chemical contaminants such as volatile organics and polyaromatic hydrocarbons, generated during the routine cleaning of public roadways, parking lots and sidewalks. Street sweepings do not refer to the material generated during the clean-up of a hazardous waste spill or due to illegal dumping. Catch basin cleanings are the materials such as sand, silt, leaves and debris that accumulate in and are removed from catch basins. Materials that are removed from other drainage structures such as swirl concentrators, separators, detention and retention basins are often similar to catch basin cleanings. The material removed from catch basins, generally contain a higher percentage of fine-grained material such as silt and clay. Catch basin cleanings are usually wet and have higher organic content from decomposing wet leaves than do street sweepings. Catch basin cleanings are also more likely to have been affected by spills and polluted runoff than street sweepings.

While street sweepings and catch basin cleanings are considered solid wastes, they do have some useful value as widely-used civil engineering materials and therefore if they are collected, temporarily stored and then reused, they can be considered "temporary wastes." This study evaluated various options to affect this shift from solid waste to temporary waste with some reuse value.

1.3 REGULATORY LANDSCAPE

DEP policy l classifies street sweepings and catch basin cleanings as solid waste, potentially subject to the following regulations as applicable:

- 310 CMR 16 – Site Assignment Regulations for Solid Waste facilities
- 310 CMR 19 – Solid Waste Management Facility Regulations
- 310 CMR 30 – Hazardous Waste Regulations
- 310 CMR 40 – Massachusetts Contingency Plan

Further information on these regulations is available in the following documents:

Classification and Reuse Options for Street Sweepings and Catch Basin Cleanings, DEP Memorandum 1/6/95: This documents states that generally street sweepings must either be disposed of in landfills or used as landfill daily cover, or applications can be made for "beneficial use" subject to DEP approval. Catch basin cleanings must be disposed of in landfills, or application can be made for "beneficial use" subject to DEP approval.

Reuse and Disposal of Street Sweepings, DEP Bureau of Waste Protection Final Policy # BWP-94-092: This document states that street sweepings must either be disposed of in landfills; used as landfill daily cover, fill in roadways, or an additive to restricted use compost (subject to stipulations such as use outside residential areas, placement above water table, not used in designated "No Salt Areas", placement outside the 100-foot buffer zone of a wetland, placement outside 500 feet of a groundwater or surface drinking water supply); or an application can be made for "beneficial use" (not specified) subject to DEP approval. A major stipulation in this policy document is that street sweeping storage must be temporary (less than one year). Catch basin cleanings are not mentioned in this document.

1.4 Research Objectives

It is clear from the regulations that current DEP policy has been to landfill these two solid waste streams or use street sweepings as landfill daily cover. However, with rapidly shrinking landfill space (e.g., District 5 has no landfill that accepts street sweepings) and high tipping fees (in the general range of $15-20/ton, but can be as high as $75/ton), it is critical to consider alternatives for handling street sweepings and catch basin cleanings. The basis of this research project is to evaluate and validate potential for reuse of both waste streams.

1.5 Scope of Work

The research objectives were divided into the following tasks that defined the scope of work for this project:

1. Conduct physical characterization of street sweepings and catch basin cleanings.
2. Conduct chemical characterization of street sweepings and catch basin cleanings.
3. Conduct geotechnical characterization of street sweepings and catch basin cleanings.
4. Evaluate processes for managing street sweepings and catch basin cleanings to produce a product that meets the specifications for reuse alternatives.
5. Develop recommendation for changes in the current DEP policy on the management of street sweepings and catch basin cleanings.
6. Calculate cost ($/ton) of potential reuse alternatives.

Based on many discussions with the MassHighway Technical Representative, it was decided that the sample collection be done mostly in Northeastern Massachusetts (District 4), Southeastern Massachusetts (District 5) and Central Massachusetts (District 3) due to certain factors (traffic volume, potential for contamination, etc.) and sampling logistics.

The MassHighway Technical Representative and the Principal Investigator established certain criteria regarding laboratory requirements, sampling locations, sampling procedures, analyte constituents and methodology. With the criteria set, the project was then divided into distinct phases, which are described in the Methodology section.

2.0 Literature Review

The investigators searched available literature on handling street sweepings and catch basin cleanings. Some states use different terminology for street sweepings (e.g., road waste, street waste solids, and road sand sweepings) and catch basin cleanings (storm water system residuals, and storm water detention basin solids). The investigators also communicated (through telephone or email) with personnel from departments of transportation in other states (Virginia, Maine, Oregon, Connecticut, New Jersey, Florida, and Texas) who are dealing with this issue. The scope of work of these research studies can be classified into the following categories:

1. Characterization of the waste materials: physical, chemical, and geotechnical. Camp, Dresser and McKee, 1995; University of Massachusetts Dartmouth, 1997; University of South Florida, 1998; Brinkman et al., 1999; Collins & Moore, 2000; Ghezze et al., 2001; Leibens, 2001; and Townsend et al., 2002 provide details of these studies.
2. Best Management Practices (BMPs) to deal with these materials. Please see EPA, 1992; Washington State Department of Ecology, 1995; and Connecticut DEP, 1998, for details.
3. Feasibility of treatment technologies: screening, catalyzed peroxide wash, thermal destruction, air knife sorting, composting, etc. Perla, 1996; ReTAP, 1997, Edwards & Kuhl, 1998; and Ghezze et al., 2001, provide details of these aspects of study.
4. Potential Reuse Options; road sanding, aggregate in bituminous and concrete pavement, fill/backfill in construction projects, land reclamation backfill, park reclamation backfill, fill for potholes with asphalt binder. Mathisen et al., 1999, National Cooperative Highway Research Program Project 25-25, 2004, and Connecticut DEP, 2007 provide details of these aspects of study.

Based on a review of available literature, the observations and conclusions may be stated as follows:

1. Connecticut, New Jersey and Washington have prepared guidance documents similar to Massachusetts' Policy on Street Sweepings, although there are some important differences. The Connecticut document includes guidelines on highway construction demolition, debris management and a list of associated recycling facilities. The New Jersey policy includes catch basin cleanings and requires sampling and analysis of wastes to be reused. The Washington document is the most detailed state policy and it includes specific examples and characteristics of street wastes.

2. Screening of street sweepings and catch basin cleanings has been demonstrated to show positive results in terms of reuse of the screened material in Bloomington, Minnesota; Colorado Springs, Colorado; Snohomish County, Washington; and Oregon.

3. Catalyzed peroxide wash costs were approximately \$50/ton in 1996, which adjusted for inflation at a rate of four percent translates to \$77/ton in 2007. The high cost of this treatment relative to present land filling costs precluded it from being considered as a viable option and therefore it was not evaluated any further in this research project. Communications with researchers, department of transportation officials, and hazardous waste management officials in other states resulted in the conclusion that this treatment technology is only a viable option for soil contaminated with high amounts of solvents or petroleum hydrocarbon (as in a leaking underground storage tank), however, this scenario is outside the scope of this project.

4. Thermal treatment costs more than \$100/cubic yard in 2001, which adjusted for inflation at a rate of four percent translates to more than \$127/cubic yard in 2007. The high cost of this treatment compared to present land filling cost, combined with a lack of response from two technology providers identified through the literature review, precluded it from being considered as a viable option and therefore it was not evaluated any further in this research project. Communications with researchers and hazardous waste management officials in other states resulted in the conclusion that this treatment technology is only a viable option for soil contaminated with high amounts of solvents or petroleum hydrocarbon as in a leaking underground storage tank, however, this scenario is outside the scope of this project.

5. Air knife sorting proved impractical as a sorting method for street sweepings in a field-scale trial in Oregon (Ghezzi et al., 2001). Conversations with Oregon Department of Transportation officials involved in this project led us to conclude that it is not a feasible reuse of street sweepings and catch basin cleanings and therefore this technology was not evaluated any further.

3.0 Methodology: Material Characterization

The project investigators at Univeristy of Massachusetts at Dartmouth (UMass) scheduled sample pick-up with the MassHighway Technical Representative, MassHighway District Representatives, and cleaning crews. Upon arrival near the sample pick-up site, sampling personnel would comply with safety guidelines (hard hats, orange vest, nitrile gloves, etc.) and transfer from their personal vehicles to a MassHighway truck. After the state police cruiser would give the go ahead, the MassHighway truck would park near the street sweeper or catch basin cleaning sweeper truck, the sampling personnel would alight from the truck, collect samples according to the protocol detailed in Appendix A, take relevant notes, preserve the sample for analysis, and return to the MassHighway truck. Upon returning to UMass Dartmouth, the samples were screened and subsequently stored under appropriate conditions for further analysis. Details of material characterization studies are provided in subsequent subsections.

3.1 Sample Collection/Analysis

A major activity of this project was the collection of ten samples of street sweepings and twenty samples of catch basin cleanings and the analysis of each sample for the following chemical contaminants: specific conductance, total solids, chloride, trace metals, volatile organics, poly aromatic hydrocarbon, gasoline-range petroleum hydrocarbon, and diesel-range petroleum hydrocarbon. Appendix A details the procedure for collection of street sweepings and catch basin cleanings collected at different locations.

Sampling of street sweepings and control (fresh, virgin sand) from MassHighway depots began in September 2005. Since a fresh sample taken directly from the truck is preferred for chemical analysis, as many direct-from-truck samples were taken as possible. It was anticipated that MassHighway and private contractors would begin collection of street sweepings and catch basin cleanings from March to August 2006. However, the frequency of sample collection remained slow due to a very rainy spring in 2006. Due to the lower frequency of sample collection, additional samples were collected from March through early September of 2007.

Samples were collected for analysis from MassHighway Districts 3, 4 and 5. A total of thirty-nine samples were collected. The District sampling location and sampling dates are summarized in Table 3.1. The duplicates mentioned in the table include stockpiles of four street sweeping samples and five catch basin cleaning samples.

Table 3.1: Summary of Sampling Location and Time

Mass Highway District	Street Sweeping Samples	Catch Basin Cleaning	Duplicates (Street Sweeping & Catch Basin Stockpiles)	Control Samples	Sampling Dates
3		1 3			03/2006 – 08/2006 03/2007 – 08/2007
4	6	4 3	4	1	03/2006 – 08/2006 08/2007 – 10/2007
5	2	3 5	5	2	03/2006 – 08/2006 03/2007 – 08/2007
Total	8	19	9	3	

Of the collected samples, eight street sweeping, nineteen catch basin and two control samples were analyzed for their complete physical and chemical characterization. One sample was found considered to be contaminated during sample pick-up and was not processed for physical or chemical characterization. Twelve samples (three control, four street sweeping and five catch basin cleaning) were analyzed for their geotechnical characterization.

Table 3.2 (next page) shows the analyzed sample types, their locations and sample IDs at different MassHighway Districts. Figure 3.1 shows a map of the locations where the samples are collected.

Table 3.2: Sample Identification

Mass Highway District	Sample Type	Sample ID	Location	Highway
District 3	**Catch Basin Cleaning**	WORCB8 AUBCB9 DUDCB10	Worcester Auburn Dudley	Route 290 Route 12 North Route 197
District 4	**Fresh Virgin Sand (FVS)**	PEAFVS6	Peabody	Peabody Depot
	Street Sweeping	SBYSS2 RDGSS3 MLTSS4 PEASS6 WMNSS7 REVSS8	Salisbury Reading Milton Peabody Wilmington Revere	Route 95 North Route 128 Route 93 Route 1 Route 93 Route 1
	Catch Basin Cleaning	CFDCB4 RDGCB5 TBYCB6 NBYCB17 RDGCB18 BTRCB19	Chelmsford Reading Tewksbury Newbury Reading Braintree	Route 3 Route 128 Route 495 Newbury Depot Reading Depot Braintree Depot
District 5	**Fresh Virgin Sand**	DMFVS1	Dartmouth	Dartmouth Depot
	Street Sweeping	DMSS1 MARSS5	Dartmouth Marion	Route 6 West Route 195 East
	Catch Basin Cleaning	STOCB1 ATBCB2 PLYCB3 BTRCB7 PLICB11 SAGCB12 BOUCB13 MIDCB14 BRWCB15 WFDCB16	Stoughton Attleboro Plymouth Braintree Plympton Bourne Bourne Middleboro Bridgewater Westford	Route 24 South Route 95 South Route 3 North Route 93 Route 3 A Route 6 West Route 25 West Route 495 South Route 28 North Route 495 South

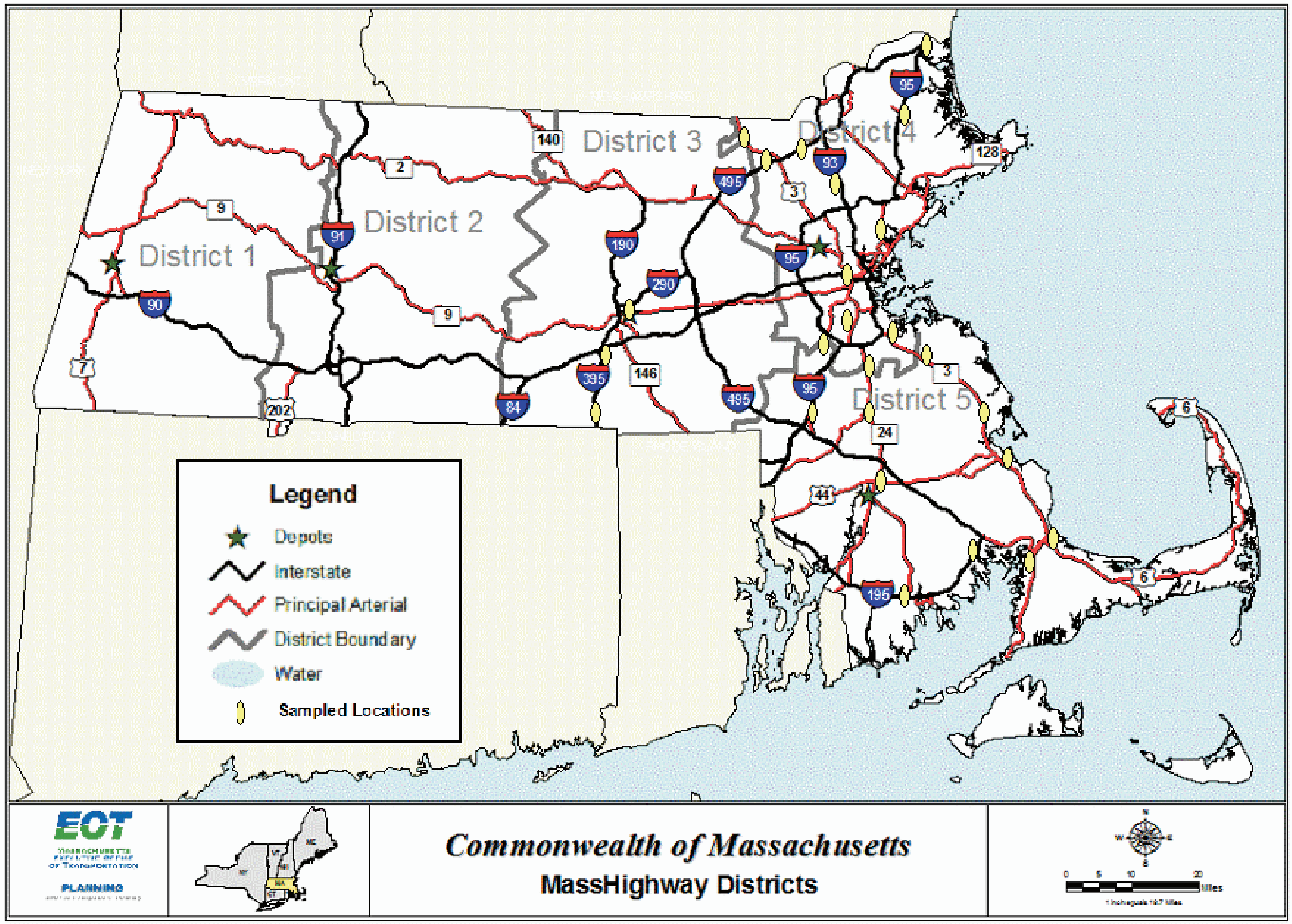


Figure 3.1: Sample Collection Locations at Different Districts

3.2 Physical Characterization

In general, the street sweeping and catch basin cleaning can be characterized as a mixture of silty sand, litter and organic matter. However, the percentage of each component can vary considerably even within each sample, since it is dependent on location, weather, traffic use, time of year when the materials are collected, etc.

The physical characterization parameters tested are as follows:

- Grain-size Distribution
- Moisture Content (%)
- Organic Content (%)
- Specific Surface Area
- Density

The project scope called for the determination of permeability of street sweepings and catch basin cleanings. However, since permeability is critical in applications where rapid drainage of water is important (such as backfill in construction projects, land reclamation fill, park reclamation, etc.) and the reuse options considered in this project (reuse as anti-skid material, use in bituminous concrete, and composting) do not require any drainage component, sample permeability was not determined.

3.2.1 Grain-Size Distribution

The grain-size distribution was determined using the sieve analysis method (American Association of State Highway and Transportation Officials (AASHTO) T27)). The sieve analysis, commonly known as the "gradation test" is a basic but essential test for all aggregate technical analysis. The sieve analysis determines the gradation (the distribution of aggregate particles, by size, within a given sample) in order to determine compliance with design, production control requirements, and verification specifications. The gradation data can be used to calculate relationships between various aggregate or aggregate blends, to check compliance with such blends, and to predict trends during production by plotting gradation curves.

1,000 grams of sample is placed upon the top of a group of nested sieves (the top sieve has the largest screen opening - US#2 (9.5 mm) and the screen opening sizes decrease with each sieve down to the bottom sieve which has the smallest opening size screen - US#200 (75 µm) - for either street sweepings or catch basin cleanings) and shaken by mechanical sieve shaker for a standard period of 15 minutes as specified by the American Society for Testing and Materials (ASTM). After shaking the material through the nested sieves, the material retained on each of the sieves is weighed using one of two methods. The cumulative method requires that each sieve beginning at the top be placed in a previously weighed pan (known as the tare weight), weighed, the next sieve's contents added to the pan, and the total weighed. This is repeated until all sieves and the bottom pan have been added and weighed. The second method requires the contents of each sieve and the bottom pan to be weighed individually. The amount passing the sieve is then calculated. The experiment was conducted in the UMass Dartmouth construction lab using a sieving machine with four sieves. The sieve designation used for the sample analysis and their acceptable passing rates are shown in Table 3.3.

MassHighway specifications for supply of fresh sand are that it shall conform to the following: sand for snow and ice control shall consist of "washed, clean, hard, coarse bank run (not crushed stone)" meeting the following specifications (Table 3.3).

Table 3.3: Sieve Designation and Acceptable Passing Rate

Sieve ID (US Size)	Sieve Designation	Acceptable Passing Rate (Established by MassHighway)
2	9.5 mm	100% Minimum
16	1.18 mm	80% Maximum
50	300 μm	30% Maximum
200	75 μm	3% Maximum

The specifications also dictate that sand shall be "screened and then washed, with the water content not exceeding 5% by weight. Sand shall be stockpiled for drainage, if necessary, to remove the free excess water."

3.2.2. Organic Content Determination

The loss of ignition method for the determination of organic content is most applicable to those materials such as peats, organic mucks, and soils containing relatively undecayed or undecomposed vegetative matter or fresh plant materials such as wood, roots, grass or carbonaceous materials such as lignite, coal, etc. This method determines the quantitative oxidation of organic matter in these materials and gives a valid estimate of organic content. A known amount of sample with a mass of approximately 10 to 40 grams is placed in a crucible (a cup-shaped piece of laboratory equipment used to contain chemical compounds when heating them to very high temperatures) or a porcelain-evaporating dish whose tare weight is known. The crucible with the sample is then introduced into a muffle furnace (a front-loading box-type oven used for high-temperature applications to bake the moisture out of a sample to ensure complete oxidation of organics) for six hours at a temperature of 455±10 °C. Then the sample is removed from the furnace and allowed to cool by placing it in a desiccator (A glass jar, fitted with an airtight cover, containing some desiccating (drying) agent such as calcium chloride at the bottom). Complete details of this procedure are available in AASHTO T 267-86(2000).

3.2.3 Moisture Content Determination

This test method covers the determination of the percentage of evaporable moisture in a sample by drying both surface moisture and moisture in the pores of the aggregate. Some samples may contain water that is chemically combined with the minerals in the aggregate. Such water is not evaporable and is not included in the percentage determined by this test method. This method is sufficiently accurate for usual purposes such as adjusting batch quantities of ingredients for soil. Initially the mass of the sample is measured to the nearest 0.1%. A known amount of sample with a mass of approximately 10 to 40 grams is placed in a pre-weighed crucible or a porcelain-evaporating dish. The crucible with the sample is kept in a ventilated, controlled-temperature oven capable of maintaining the temperature around the sample at 110±5 °C for 21 hours. Then the sample is removed from the oven and is allowed to cool by being placed in a desiccator. Finally, the sample is weighed and calculations are performed. Complete details of this procedure are available in AASHTO T255-00.

3.2.4 Specific Surface Area Determination

Surface area and porosity are important characteristics, capable of affecting the quality and utility of many materials. The most commonly used technique for estimating surface area is the so called Brunauer, Emmett and Teller (BET) method, which uses a Quantachrome Nova 2200e Analyzer (Figure 3.2). Samples in a glass bulb (9-mm-diameter long-stem cell shown in the figure) were degassed at 150 ºC for three hours in a Multistation High Speed Gas Sorption Analyzer. Samples were then pressurized at 69 kPa (10 psi) using 99% high-purity Nitrogen and vacuumed using a Pfeiffer vacuum pump (2880 rpm and a nitrogen flow rate of 2.5 m^3/h). Surface area analysis was evaluated using NOVA Win2 software. Sample stem cells with filler rods were immersed in liquid Nitrogen during the analysis. Analysis conditions were set at relative pressure P/P_0 (a range from 0.05 to 0.3) with a 5-point BET.

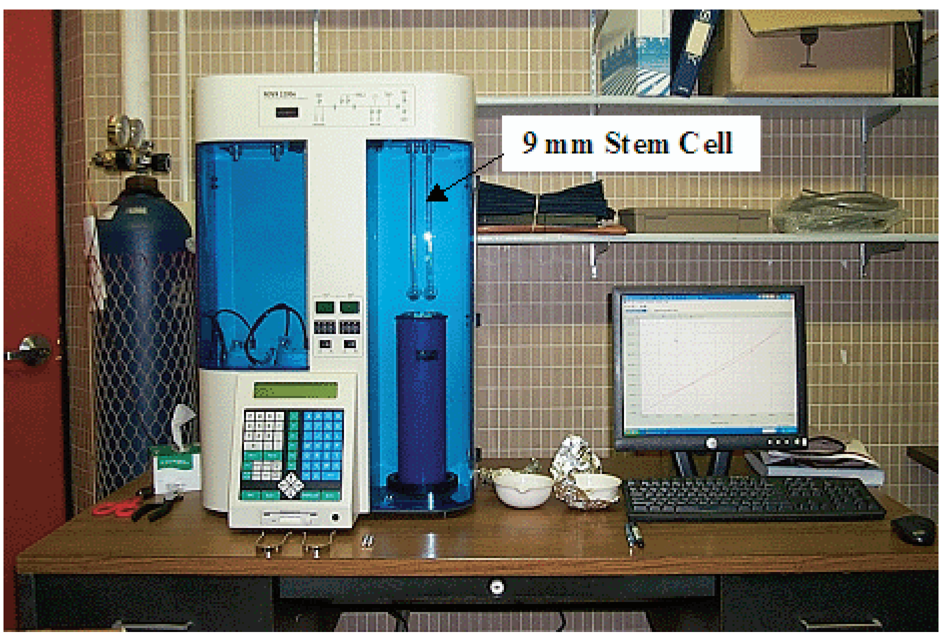


Figure 3.2: Quantachrome BET Surface Area Analyzer

3.2.5 DENSITY

The density, or the specific gravity to be more precise, was measured according to the procedure outlined in AASHTO T84. One kilogram of the material passing a US#4 (4.75 mm) sieve was dried in an oven at 110 ± 5 °C for 6 hours, cooled at room temperature and weighed (This weight is represented by "A" in the formulas below). The sample was then immersed in water at room temperature for 24 hours. Water was decanted from the sample carefully so as not to lose any fines. The "saturated, surface dry" (SSD) condition of the sample was confirmed using the cone test. Next, a specific gravity pycnometer flask was calibrated by filling it with water at 23 ± 1.7 °C to the calibration line. The weight of the pycnometer and the water was noted to the nearest 0.1g (represented as "C" in the formulas). The SSD sand was then placed into the pycnometer, which was brought to its calibrated capacity with additional water. The total weight of the pycnometer, specimen, and water was measured to the nearest 0.1 g ("B"). The following specific gravity measurements were calculated:

$$\text{Bulk Dry Specific Gravity} = A/(B-C)$$

By definition, Bulk Dry Specific Gravity is the ratio of the weight of a given volume of sample (street sweeping or catch basin cleaning) to the weight of an equal volume of water. Water at a temperature of 4 °C has a specific gravity of 1 and a density of 1,000 kg/m^3.

$$\text{Bulk SSD Specific Gravity} = B/(B-C)$$

By definition, Bulk SSD Specific Gravity is the ratio of the weight in air of a unit volume of sample (street sweeping or catch basin cleaning), including the weight of water within the voids filled to the extent be achieved by submerging in water for at least 15 hours, to the weight in air of an equal volume of gas-free distilled water at the stated temperature.

$$\text{Apparent Specific Gravity} = A/(A-C)$$

By definition, Apparent Specific Gravity is the ratio of the weight in air of a unit volume of the impermeable portion (does not include the permeable pores) of sample (street sweeping or catch basin cleaning) to the weight in air of an equal volume of gas-free distilled water at the stated temperature.

3.3 CHEMICAL CHARACTERIZATION

Since the street sweepings stay in an environment exposed to contamination from traffic and other sources (industrial discharges, municipal effluents, etc.) for months, there is a strong possibility that they will become contaminated with a variety of chemicals, and may be characterized as hazardous waste. However, existing literature regarding street sweepings (University of Massachusetts Dartmouth 1997) seems to suggest that for the most part, these waste streams are not hazardous, though the level of contamination has a correlation with the time elapsed (between application of the sand and street sweeping collected) and classification of the road. There is very limited data regarding catch basin cleaning contaminants. A detailed analysis of chemical characterization was conducted for each collected sample of street sweepings and catch basin cleanings, as shown in Table 3.4 below.

Table 3.4: Selected Analytes for Each Sample

General Constituent Category	Test #	Specific Constituents
Specific Conductance	9050A	
Total Solids	2540G	
Chloride	9251	
Trace Metals	3051	Arsenic, Barium, Cadmium, Chromium, Lead, Mercury, Selenium, Silver, Sodium
Volatile Organic Compounds by GC/MS	GC/MS 8260	Methylene chloride, 1,1-dichloroethane, chloroform, carbon tetrachloride, 1,2-dichloropropane, dibromochloromethane, 1,1,2-trichloroethane, 2-chloroethylvinylether, tetrachloroethane, chlorobenzene, trichlorofluoromethane, 1,2-dichloroethane, 1,1,1-trichloroethane, bromodichloromethane, trans-1,3-dichloropropene, bromoform, 1,1,2,2-tetrachloroethane, benzene, toluene, ethylbenzene, chloromethane, bromomethane, vinyl chloride, chloroethane, 1,1-dichloroethane, trans-1,2-dichloroethane, trichloroethene, 1,2-dichlorobenzene, 1,3-dichlorobenzene, methyl tert butyl ether, p/m-xylene, o-xylene, cis-1,2-dichloroethene, dibromomethane, 1,4-dibromomethane, iodomethane, 1,2,3-trichloropropane, styrene, dichlorodifluoromethane, acetone, carbon disulfide, 2-butanone, vinyl acetate, 4-methyl-2-pentanone, 2-hexanone, ethyl methacrylate acrolein, acrylonitrile, bromochloromethane, tetrahydrofuran, 2,2-dichloropropane, 1,2-dibromomethane, 1,3-dichloropropane, 1,1,1,2-tetrachloroethane, bromobenzene, n-butylbenzene, sec-butylbenzene, tert-butylbenzene, o-chlorotoluene, p-chlorotoluene, 1,2-dibromo-3-chloropropane, hexachlorobutadiene, isopropyl benzene, p-isopropyl toluene, naphthalene, n-propylbenzene, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, trans-1,4-dichloro-2-butene, ethyl ether
Polynuclear Aromatic Hydrocarbons	GC/MS 8270	Acenaphthene, 2-chloronaphthalene, Fluoranthene, Naphthalene, Benzo(a) pyrene, Benzo(b) fluoranthene, Benzo(k) fluoranthene, Chrysene, Anthraphthylene, Anthracene, benzo(g,h,I) perylene, Fluorene, Phenanthrene, Dibenzo(a,h) anthracene, Indeno(1,2,3-cd) pyrene, 1-methylnaphthalene, 2-methylnaphthalene
Petroleum Hydrocarbons by GC-GRO	GC-GRO 8015M	Benzene, Toluene, Ethylbenzene, Xylenes, Gasoline-range organics
Petroleum Hydrocarbons by GC-DRO	GC-DRO 8100M	Diesel-range organics

Chemical characterization was performed for eight street sweepings, two control and 19 catch basin cleaning samples, for a total of 29 samples. All samples were collected onsite (except for the control samples). The chemical analytes were tested in a private certified analytical laboratory, Alpha Analytical, Westborough, MA. The specifications for the collection procedure are described in the Appendix A.

3.4 Geotechnical Characterization

Researchers have distinguished between different aspects that constitute particle geometry. Particle geometry can be fully expressed in terms of three independent properties: form, angularity (or roundness), and surface texture. Figure 3.3 shows a schematic diagram that illustrates the differences between these properties. Form describes variations in the proportions of a particle. Angularity reflects variations at the corners. Surface texture is used to describe the surface irregularity at a scale that is too small to affect the overall shape. These three properties can be distinguished because of their different scales with respect to particle size (Wadell 1932, Barrett 1980).

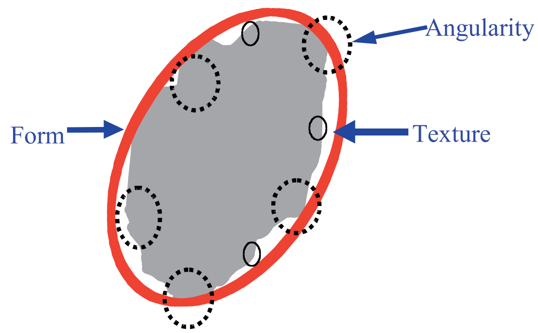


Figure 3.3: Components of Aggregate Shape: Form, Angularity, and Texture

3.4.1 Shape Analysis Method

The increasing capacity and performance of microcomputers and imaging technology has facilitated the evolution of several imaging techniques to directly measure aggregate physical properties of form, angularity, and texture. This section discusses an Automated Aggregate Imaging System (AIMS) used for this study that can characterize particles irrespective of their size. It is designed to be versatile enough to capture images at different resolutions and field of view, using different lighting schemes in order to be able to analyze the form, angularity, and texture of fine (< 4.74 mm) and coarse aggregates (Masad et al., 2001; Fletcher, 2002; and Fletcher et al., 2003). AIMS utilizes three closed-loop servo motor linear actuators with 250 mm of travel in the *x* and *y*-axes and 50 mm of travel in the *z* axis. This allows precise and independent movement of all three axes simultaneously. The *x*-axis runs on a slider bar where the camera is attached. The *y*-axis motion of the aggregate tray and backlit table runs on a bearing guide assembly, which creates smooth uniform motion. The *z*-axis controls auto focusing of the camera. The auto focus utilizes high spatial frequency for the signal of a video microscope connected to the camera.

The video microscope has a 16:1 zoom ratio, which allows one to capture a wide range of particle sizes without changing parts. A black and white video camera with external control is used. The camera is connected to a magnification lens. The camera and video microscope are attached to a dovetail slide with a range of motion of 300 mm in the z-axis in order to allow the capturing of images for a wide range of aggregate sizes. All motion is connected to a multiaxis external controller that offers both manual and automatic control of motion, as well as enhanced black level and contrast control. Figure 3.4 shows the AIMS setup.

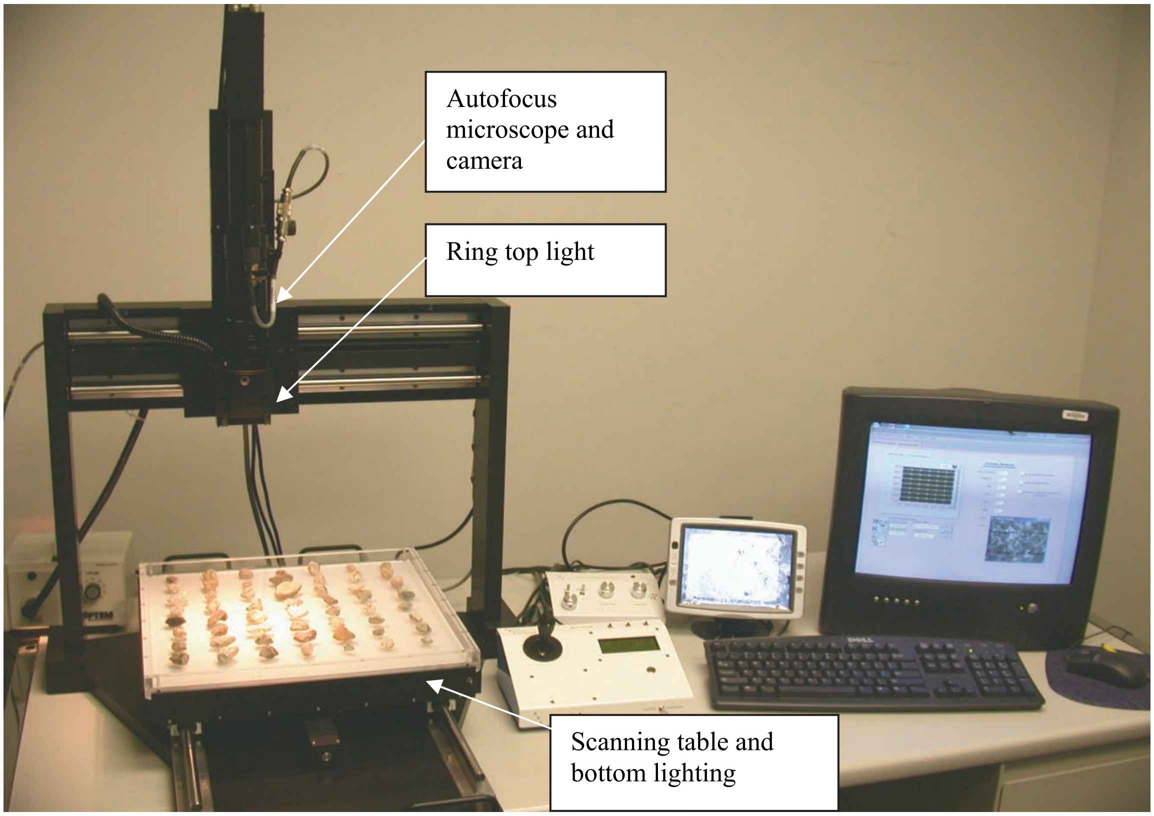


Figure 3.4: Aggregate Imaging System (AIMS) and Its Components

Shape analysis of fine aggregates starts by randomly placing an aggregate sample on the aggregate tray with the backlighting turned on. The camera and video microscope assembly moves incrementally in the *x* direction at a specified interval, capturing images at every increment. Once the x-axis range is complete, the aggregate tray moves in the y direction for a specified distance, and the x-axis motion is repeated. This process continues until the whole area is scanned. In each x-y scan, the z location of the camera and the microscope magnification are specified in order to meet the resolution criteria which is that the pixel size is less than 1% of the average aggregate diameter, and the field of view covers 6-10 aggregate particles. Aggregates that are not within the size for which the scan is conducted are removed from the images. Backlighting under the aggregate tray is used to capture images for angularity analysis. This type of lighting creates sharp contrast between the particle and the tray, thus giving a distinct outline of the particle.

3.4.2 FORM

The three dimensions of aggregates are needed to describe the form of coarse aggregates. The camera and microscope assembly are used to capture projections of particles placed on a lighting table. Particle projections are used to measure the longest and shortest dimensions using eigenvector analysis (Chandan et al. 2004). In this method, the binary image of an aggregate is treated as a two-dimensional population. Each pixel in the population is treated as a two-dimensional vector. These vectors are used to compute the eigenvectors, which are orthogonal to each other. The major and minor axes of an aggregate are aligned along these eigenvectors.

A particle depth is measured using the location of the auto focus microscope. First, the microscope is focused automatically on a point on the lighting table. The distance between the lighting table and the lens is recorded as the "reference position". Then, the microscope moves in the x and y directions and focuses on a particle surface. The focus on a particle surface requires the microscope to move upward to a "new position" on the z-axis. The distance between the two microscope positions is equal to the depth of a particle. The AIMS software sorts the three dimensions based on length and calculates the sphericity index as shown in Eq. (1):

$$\text{Sphericity} = \sqrt[3]{\frac{d_s . d_I}{d_L^2}} \tag{1}$$

where d_L is the longest dimension, d_I is the intermediate dimension, and d_s is the shortest dimension. A sphericity value of one indicates that a particle has equal dimensions.

The form of fine aggregates is determined by analyzing the black and white images of a particle projection. The index in Eq. (2) is used to quantify form:

$$\text{Form Index} = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{\left|R_{\theta+\Delta\theta} - R_{\theta}\right|}{R_{\theta}} \tag{2}$$

where θ is the directional angle, R is the radius in different directions, and Δθ is the incremental difference in the angle which is taken to be 4^{o}. By examining Eq. (2), we can see that the form index is zero for a perfect circle. Discussion on the development of the index in Eq. (2) and verification of its accuracy is provided by Masad (2003).

3.4.3 ANGULARITY

Although no single definition of angularity exists, it can be described as the shape feature, which measures how sharp the corners of a particle are. The idea behind the gradient method employed by AIMS is that at sharp corners of the edges of an image, the direction of the gradient vector for adjacent points on the edge changes rapidly. On the other hand, the direction of the gradient vector for rounded particles changes slowly for adjacent points on the edge, as shown in Figure 3.5.

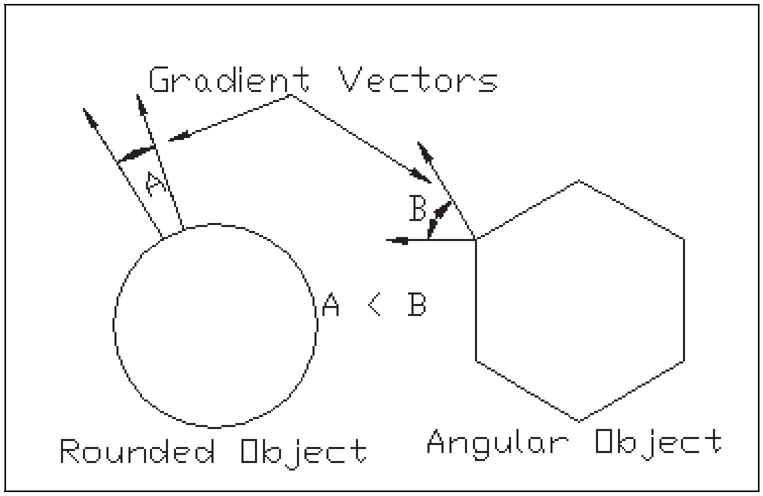


Figure 3.5: Comparison of Angularity of Particle with Rounded Edges and Sharp Edges

The gradient-based method for measuring angularity includes the following steps. The acquired image is first thresholded to get a binary image. Next, this binary image undergoes preprocessing steps to get rid of noise and unwanted artifacts brought about during image acquisition and/or thresholding. This is followed by the boundary-detection step. Next, the gradient vectors at each edge point are calculated using a Sobel mask, which operates at each point on the edge and its eight nearest neighbors. Based on the orientation of the gradient vectors at each edge point, the angularity index is calculated for the aggregate particle as described in the next paragraph.

The Sobel operator performs a 2-D spatial gradient measurement on an image, thereby emphasizing regions of high spatial gradient, which correspond to edges. The Sobel operator is most often used to find the gradient magnitude at each point in an input gray-scale image. It consists of a pair of 3x3 convolution masks as shown below:

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \qquad G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \tag{3}$$

These masks pick up the edges running horizontally (G_x) and vertically (G_y) in an image. They can be combined to find the absolute magnitude of the gradient at each point and the orientation of the gradient. The angle of orientation of the edge (relative to the pixel grid), which results in the spatial gradient, is given by:

$$\theta(x,y) = \tan^{-1}\left(\frac{G_x}{G_y}\right) \tag{4}$$

Angularity values for each of the boundary points are calculated and their summation around the edge is used to calculate the angularity index.

$$\text{Angularity Index (Gradient Method)} = \frac{1}{\frac{N}{\Delta}-1}\sum_{i=1}^{N-\Delta}\left|\theta_i - \theta_{i+\Delta}\right| \quad (5)$$

where the subscript i denotes the i^{th} point on the boundary of a particle, N is the total number of points on the boundary, and Δ is the difference in pixels between points where gradients are calculated. In this analysis, the boundary is divided to 30 segments (N/Δ = 30) to calculate the angularity index. The average rather than the summation is considered in Eq. (3) so that the angularity calculation is not biased by particle size.

3.4.4 TEXTURE

Texture refers to the smoothness or coarseness of the surface. There is no formal definition of texture in the literature. In image processing applications, texture can be described by three principal approaches: structural, spectral and statistical. The structural approach deals with the arrangement of certain image primitives, for example, looking for a frequently occurring pattern in the image. Spectral techniques use the properties of the Fourier transform of the image and are generally used to detect periodicity in the image, which occurs globally. Periodicity refers to a repetitive pattern of pixel values in an image and can be identified by observing high-energy, narrow peaks in the spectrum. Statistical approaches on the other hand characterize the texture of a surface as smooth, rough, coarse, or grainy based on statistical parameters such as local mean and standard deviation computed from the pixel values. AIMS uses a statistical approach using the wavelet transform. The advantages of using this method over other methods such as the Fourier analysis are discussed in several references (Mallat, 1989). The wavelet method has the advantage of decomposing an image into different levels. Consequently, each level is analyzed to quantify a certain texture scale. Wavelets have the advantage of capturing the sharp changes in texture in an image, as the basis functions have variable durations that can fit these sharp changes. However, the harmonic functions that constitute the basis for the Fourier analysis do not have limited duration, and they are not efficient in modeling these abrupt changes in texture on an image (Mallat, 1989).

The fundamental idea behind wavelets is to decompose a signal or an image at different resolutions. Wavelets are special functions that satisfy certain mathematical functions and are used to represent two kinds of data. These data can be a one-dimensional signal (speech) or a two-dimensional image. The wavelet transform maps an image onto a low-resolution image and a series of detail images. The low-resolution image is obtained by iteratively blurring the images and the detail images contain the information lost during this operation. The blurring operation eliminates fine details in the image while retaining coarse details. The fine details are captured in the detail images, producing a multi-resolution representation of the original image. The resulting low resolution and detail images help to analyze an image on different scales. The original image, after being wavelet transformed, is mapped onto a low-resolution image and three detail images. The low-resolution image is generally referred to as low-low (LL), whereas the detail images are referred to as high-low (HL), low-high (LH), or high-high (HH). The low resolution image can be further decomposed in a similar manner into the next level of low resolution image and detail images, thus creating a multi-resolution decomposition as shown schematically in Figure 3.6.

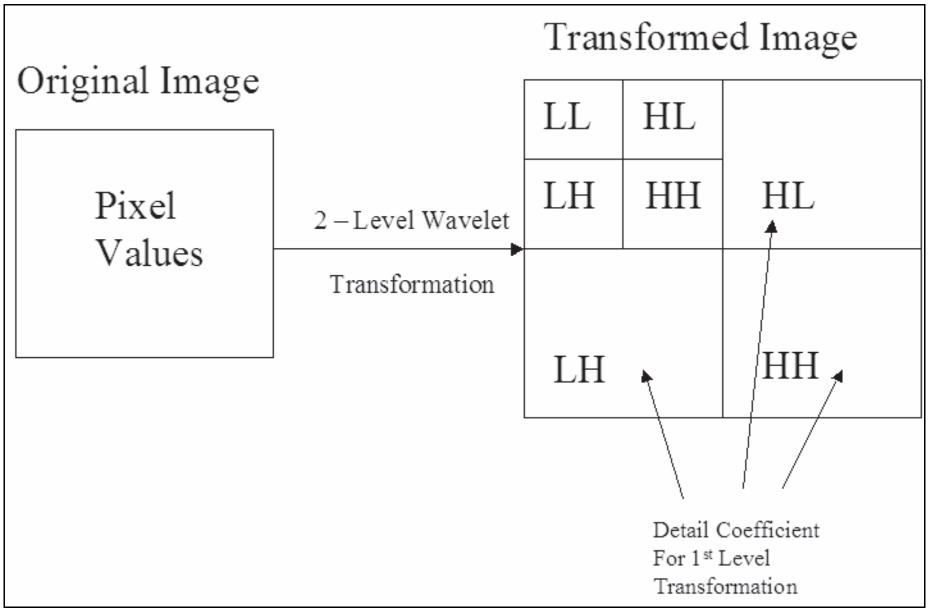


Figure 3.6: Two-level Wavelet Transformation

Since texture can be described by the nature of the local variation of pixel intensity levels in an image, once the image has been transformed from the space domain to the frequency domain, the presence (or absence) of the high frequency components indicates the nature of the texture content of the corresponding aggregate surface. A highly textured surface will have rapid variations in pixel intensity values in the image locally. This property will manifest itself as the presence of a dominant high-frequency component in the transformed domain. This suggests that once the image has been wavelet transformed, most texture information lies in the detail coefficients LH, HL, and HH. The LH coefficients pick up the high frequency content in the horizontal direction, and the HH coefficients pick up the high frequency content in the diagonal direction.

Thus, the wavelet analysis gives the texture details in the horizontal, vertical, and diagonal directions in three separate images. The texture index is taken at a given decomposition level as the arithmetic mean of the squared values of the wavelet coefficients for all three directions. The texture index is expressed mathematically as follows:

$$\text{Texture Index} = \frac{1}{3N}\sum_{i=1}^{3}\sum_{j=1}^{N}\left(D_{i,j}\left(x,y\right)\right)^{2} \qquad (6)$$

where D is the wavelet coefficient, N is the total number of coefficients, i takes a value 1, 2 or 3, for the three directions of texture, and j is the wavelet coefficient index.

The sphericity (Eq. 1), angularity (Eq. 5) and texture (Eq. 6) are used in the analysis of coarse aggregates (retained on sieve #4), while form index (Eq. 2) and angularity (Eq. 5) are used for the analysis of fine aggregates.

4.0 Methodology: Testing Procedures for Reuse Options

Material characterization was followed by exploration of reuse options for street sweepings and catch basin cleanings. The reuse options considered were reapplication of street sweepings on pavements as anti-skidding material, use of street sweepings and catch basin cleanings as fine aggregate in bituminous concrete pavements, and composting of catch basin cleanings. The following subsections provide details of each aspect related to reuse options.

4.1 BRITISH PENDULUM TEST

The ASTM E303-93 (2003) Standard Test Method is used to measure the surface frictional properties using the British Pendulum Tester. The British pendulum test is one of the most common laboratory test methods for the determination of low-speed micro texture-related skid resistance properties of pavement surface materials.

The British Pendulum Tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface (Figure 4.1). The tester is suited for laboratory as well as field tests on flat surfaces, and for polish value measurements on curved laboratory specimens from accelerated polishing-wheel tests. The values measured - British Pendulum Number (BPN) for flat surfaces and polish values for accelerated polishing wheel specimens - represent the frictional properties obtained with the apparatus and the procedures stated do not necessarily agree or correlate with other slipperiness measuring equipment.

Figure 4.1: British Pendulum Tester

4.2 Uncompacted Void Content

The AASHTO T304 test describes the determination of the loose uncompacted void content of a sample of sand. This test provides an indication of the sand particle's angularity, sphericity, and surface texture, when performed on an aggregate sample of a known, standard grading (Method A), and this measurement provides an indication of particle shape. The material angularity, roundness or surface texture relative to other materials of the same standard grading is indicated by the percent of voids determined by this test. The Superpave asphalt mix design method sets minimum requirements for void content that vary depending on traffic loads and depth from the surface of the asphaltic concrete pavement.

The test was performed on the samples of fresh, virgin sand, street sweepings and catch basin cleanings under the supervision of Professor Walaa Mogawer of UMD at the Pavement Materials Laboratory at the Advanced Technology Manufacturing Center (ATMC). In this method, the prepared sample is allowed to free-fall through a standard funnel of a specified diameter from a specified height into a small cylinder of known volume (nominal 100mL). The material is then leveled with the top of the calibrated cylinder and weighed. Because the volume and weight of the cylinder are known, the weight of the sample contained in the cylinder can be calculated. Using the Bulk Dry Specific Gravity (as determined by AASHTO T84), the volume of the material in the cylinder is calculated. By subtracting the calculated volume of material from the calibrated volume of the test cylinder, the volume of voids can be calculated. For details on the procedure to test for Uncompacted Void Content of Fine Aggregate, please refer to AASHTO T304. These testing results are to be used to determine whether sweepings/catch basin cleanings can be used in hot mix asphalt.

4.3 Composting

Composting is a process in which organic material undergoes biological degradation to a stable end product. As the organic matter in the solid decomposes, the compost heats to temperatures in the pasteurization range of 120 to 160 °F, and enteric pathogenic organisms are destroyed. Properly composted volatile solids may be used as soil amendment. The composting process involves the complex destruction of organic matter coupled with the production of humic acid to produce a stabilized end product. The involvement of the microorganisms falls into three major categories: bacteria, actinomycetes, and fungi. Although the interrelationship of these microbial populations is not fully understood, bacterial activity appears to be responsible for the decomposition of proteins, lipids and fats at thermophilic temperatures, as well as for much of the heat energy produced. Fungi and actinomycetes are also present at varying levels during the mesophilic and thermophilic stages of composting and appear to be responsible for the destruction of complex organics.

Composting is a cost-effective and environmentally sound alternative for stabilization of solids with high (> 8%) organic content. It is generally used as a waste management technique to promote the natural breakdown of organic waste into a useful soil amendment. The Minnesota Department of Transportation has reported a reduction in pollutant levels of its street sweepings through composting at a cost of $17/ton (MnDOT 1997). The city of Long Beach, CA, completed a pilot program which demonstrated that its street sweeping wastes were suitable for composting and the pilot-scale test costs averaged $34.50/ton

(Edwards & Kuhl; 1998). The Oregon Department of Transportation (ODOT) conducted field tests to investigate the reduction of street sweeping through composting (ODOT 2001). The results of these tests indicated wide variability in concentration of Total Petroleum Hydrocarbon (TPH) and Polyaromatic Hydrocarbons (PAHs). ODOT was unable to arrive at any conclusions regarding the feasibility of composting. The study did not include an economic analysis.

A common yard waste composter was used for this project. A picture of the unit is provided in Figure 4.2. The composter is open at the bottom for fast drainage of runoff water. Catch basin cleanings obtained from various locations were mixed and screened for trash, litter and debris. The screened material had a volume of approximately 30 gallons. The material was mixed thoroughly and a representative sample was collected and analyzed for the set of chemical contaminants listed in section 3.1. The composter was started on March 15, 2007. Water was added to the composter every two weeks and at the time of its addition the solids were stirred. On December 14, 2007, a representative sample was taken from the composter and analyzed for all chemical contaminants.

Figure 4.2: Catch Basin Cleaning Composter Setup

4.4 AGGREGATE IN BITUMINOUS CONCRETE PAVEMENT

The uncompacted void content data are needed for exploring reuse of the solid waste in bituminous concrete pavement. Two experiments are conducted to determine rutting resistance. Hot-Mix Asphalt (HMA) specimens are prepared using the Superpave Gyratory Compactor (AASHTO 312). Specimens are prepared from the fresh, virgin sand, street sweeping and catch basin cleaning samples collected from the site. These specimens are tested for their rutting resistance using the Asphalt Pavement Analyzer (APA) (AASHTO TP 63-03). Initially, the Superpave Gyratory Compactor is used to compact cylindrical specimens of HMA by means of gyrations under a specified compressive stress and angle of inclination. The procedure covers preparing specimens for determining the mechanical and volumetric properties of HMA. This procedure may also be used for field control of an HMA production process. Initially the mold is placed in a Pine/Brovold compactor prior to material being loaded into the mold. Preheated molds and plates are removed from the oven. The base plate and the paper disc are placed in the bottom of the mold. The sample is mixed with a heated spatula until it appears homogeneous. Then the mix is poured into the mold and leveled. The paper disc and the heated top plate are placed on the leveled sample. Finally, the mold is loaded into the compactor and set to the specified number of gyrations or required specimen height. Pressure is applied at 600 kPa ±18 kPa. Once the compaction is complete (after the specified number of gyrations), the compacted specimen is extruded from the mold and the paper discs are removed. The compressed sample (sample cake) is then cooled down to room temperature. These specimens are tested for their rutting resistance using the Asphalt Pavement Analyzer (APA) (AASHTO TP 63-03). Figure 4.3 shows the experimental apparatus with the sample cakes placed on the horizontal mold. A comparative evaluation of the rutting resistance of the street sweeping and the fresh virgin sand provides an indication of the reusability of street sweepings and catch basin cleanings in bituminous pavements.

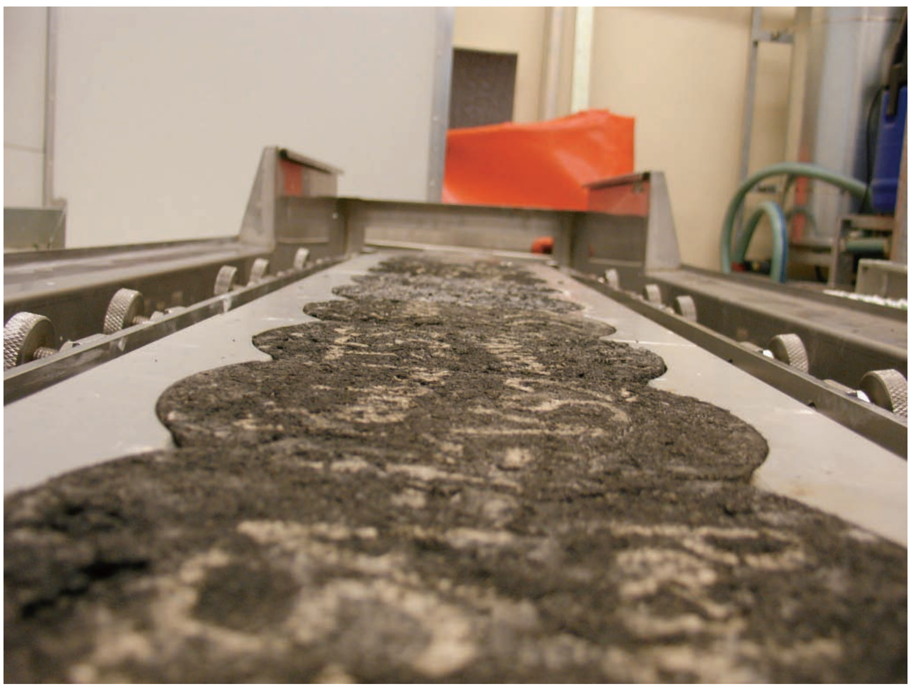


Figure 4.3: MMLS Rut Testing Equipment

5.0 Results

This chapter includes results of technical data collected during the course of this study, analysis and interpretation of the data to validate conclusions, and economic analysis of several reuse options, specifically, reuse on pavement as anti-skid material and reuse in bituminous concrete pavement. Technical data collected was used to characterize the street sweepings and catch basin cleanings and for exploration of reuse options. This aspect was followed by an economic analysis of the reuse options to gauge the magnitude of potential savings that can be realized by MassHighway if these options are put into practice.

5.1 Physical Characterization

Reuse of street sweepings and catch basin cleanings would hinge on validation of the hypothesis that the physical integrity of the fresh, virgin sand is not compromised by vehicular traffic and the time it spends in the environment before it is collected as a waste material. To accomplish this, a comparative evaluation of physical properties of the parent (fresh virgin sand) material and the waste (street sweepings and catch basin cleanings) is mandatory. Physical properties examined in this study include grain size analysis, organic content, moisture content, density, and specific surface area.

5.1.1 Grain Size Determination

Table 5.1 shows a comparative analysis of MassHighway specifications for fresh virgin sand, a fresh virgin sand sample, a street sweeping sample, and a catch basin cleaning sample passed through the four sieves. Figure 5.1 shows the percent passing and particle size for each of the samples. The remaining sample results are tabulated, graphed and presented in Appendix B.

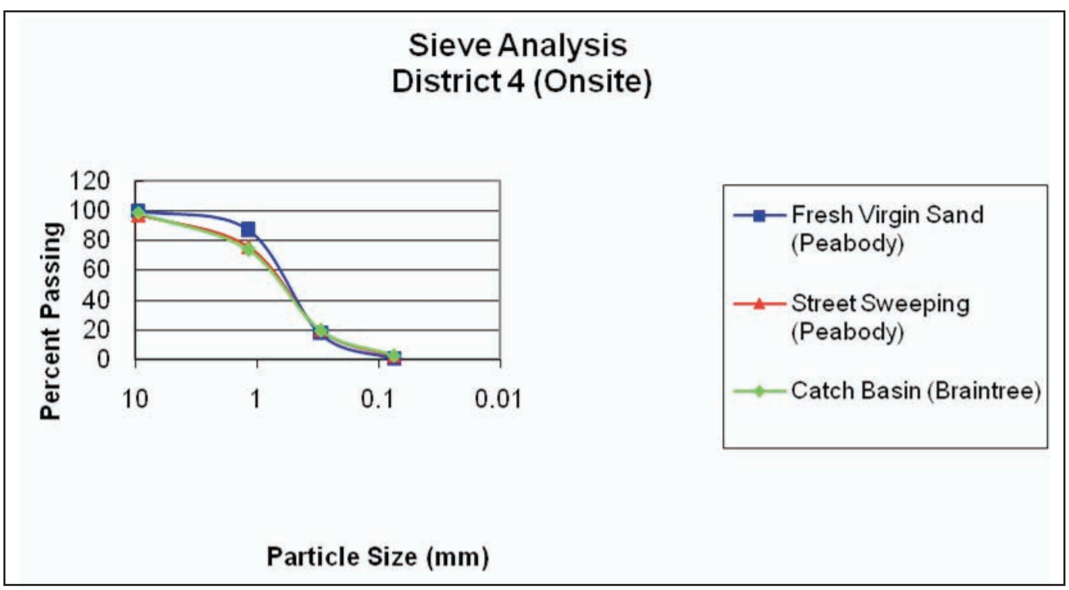


Figure 5.1: Comparative Sieve Analysis Results of Fresh Virgin Sand, Street Sweeping and Catch Basin Cleaning Sample

From the representative data set in Table 5.1 and Figure 5.1, and from other tables and graphs in Appendix B, it is clear that that all of the samples collected passed MassHighway standard specifications for sand to be applied on roads as anti-skid material. Currently, the only specification for the supply of sand to be applied on pavements is based on sieve analysis (Table 5.1). For this reason, we can safely conclude that, after processing to remove any solid wastes, street sweepings and catch basin cleanings can be reapplied on pavements without any compromise in the present specification.

Table 5.1: Comparative Sieve Analysis Results of Fresh Virgin Sand, Street Sweeping and Catch Basin Cleaning

DISTRICT 4								
			Fresh Virgin Sand (Peabody)		Street Sweeping (Peabody)		Catch Basin (Braintree)	
Sieve Size (US)	Acceptable Passing Rate (Established by MassHighway)	Sieve opening size (mm)	Mass Retained (gms)	Percent Passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	100% Minimum	9.5	1.47	99.704	24.73	97.48	12.67	98.642
16	80% Maximum	1.18	125.25	87.179	214.24	76.056	245.67	74.075
50	30% Maximum	0.3	698.5	17.329	564.5	19.606	544.76	19.599
200	3% Maximum	0.075	170.24	0.305	174	2.206	167.75	2.824
Final pan			3.05		22.06		28.24	
Initial Mass = 1000 g								

5.1.2 Organic Content Determination

The samples were collected and analyzed as per the AASHTO T 267-86(2003) procedure and are presented in Table 5.2. As expected, the organic content of catch basin cleanings (average of 8.66%) is much higher than that in street sweeping samples (2.93%). The major significance of this result is that most street sweeping samples are probably not suitable for composting due to the low fraction of organic matter. It should be noted that these results are contrary to the observations of Perla, 1996; ReTAP, 1997, Edwards & Kuhl, 1998; and Ghezze et al., 2001, all of whom claim that street sweepings and catch basin cleanings are amenable to composting. These referenced observations, however, are not supported by any data on organic content. Based on experimental results, this study checked for compostability of catch basin cleanings only.

Table 5.2: Organic Content Determination Results

Sample ID	Organic Content	Sample ID	Organic Content
	(%)		(%)
District 4		District 5	
Fresh Virgin Sand (Control Sample)		Fresh Virgin Sand (Control Sample)	
Lexington	6.97	Dartmouth	2.869
Burlington	0.4081	Wareham	0.2566
Reading	0.3679		
Peabody	0.408		
Tewksbury	0.4397		
Newbury	0.236		
Street Sweeping (Stockpiled)		Street Sweeping (Stockpiled)	
Westwood	2.013	Dartmouth	2.424
Burlington	2.2932	Wareham	1.532
Reading	2.884		
Peabody	2.8042		
Tewksbury	3.2275		
Street Sweeping (Onsite)		Street Sweeping (Onsite)	
Salisbury	5.015	Dartmouth	2.345
Reading	4.459	Marion	2.205
Milton	3.229		
Peabody	2.185		
Wilmington	1.989		
Revere	3.336		
Catch Basin Cleaning		Catch Basin Cleaning	
Chelmsford	6.753	Attleboro	10.872
Reading	8.462	Plymouth	9.627
Tewksbury	9.265	Bourne (Route 6)	9.298
Braintree	8.799	Bourne (Route 25)	8.459
		Bridgewater	7.263
		Middleboro	9.732
District 3			
Catch Basin Cleaning			
Auburn	6.982		
Dudley	9.51		
Westford	7.256		
Worcester	9.992		

5.1.3 Moisture Content Determination

The samples were collected and analyzed as per the AASHTO T-255-00 procedure and presented in Table 5.3.

Table 5.3: Moisture Content Determination Results

Sample ID	Moisture Content Determination (%)	Sample ID	Moisture Content Determination (%)
District 4		**District 5**	
Fresh Virgin Sand (Control Sample)		**Fresh Virgin Sand (Control Sample)**	
Lexington	1.4335	Dartmouth	2.407
Burlington	2.025	Wareham	2.738
Reading	2.906		
Peabody	2.597		
Tewksbury	3.409		
Newbury	3.992		
Street Sweeping (Stockpiled)		**Street Sweeping (Stockpiled)**	
Westwood	7.428	Dartmouth	5.217
Burlington	4.129	Wareham	2.6
Reading	6.057		
Peabody	3.744		
Tewksbury	9.62		
Street Sweeping (Onsite)		**Street Sweeping (Onsite)**	
Salisbury	22.714	Dartmouth	3.901
Reading	11.768	Marion	4.788
Milton	10.313		
Peabody	12.082		
Wilmington	2.37		
Revere	6.546		
Catch Basin Cleaning		**Catch Basin Cleaning**	
Chelmsford	12.86	Attleboro	12.762
Reading	14.756	Plymouth	22.572
Tewksbury	16.347	Bourne (Route 6)	20.754
Braintree	10.987	Bourne (Route 25)	18.976
		Bridgewater	14.72
		Middleboro	12.981
District 3			
Catch Basin Cleaning			
Auburn	20.546		
Dudley	14.587		
Westford	16.983		
Worcester	12.573		

Moisture content data has a strong correlation with recent precipitation in the area (from where the samples have been collected). There also appears to be a slight correlation with organic content. Presence of high percentage of moisture in the stockpiled material could make it more difficult to screen. However, once the materials are brought to a central depot for further processing, moisture content is not expected to play a significant role.

5.1.4 Specific Surface Area Determination

Table 5.4 below shows the specific surface area results for the fresh, virgin sand, street sweeping and catch basin cleanings. The only major conclusion one can draw from this limited data is that the specific surface area of all the samples is in the same order of magnitude. Specific surface area by itself is not a very important parameter but when coupled with surface angularity and form, they become major factors in determining whether the material is suitable for reuse for reuse on pavements for anti-skidding. Surface angularity and form are discussed in detail in section 5.3.

Table 5.4: Specific Surface Area Results for Fresh, Virgin Sand, Street Sweeping and Catch Basin Cleanings

Sample	Surface Area (m^2/g)
Fresh Virgin Sand (Passing through Sieve #50)	0.452
Street Sweeping (Passing through Sieve #50)	0.342
Catch basin Cleaning (Passing through Sieve #50)	0.17

5.1.5 Density

The bulk specific gravity (both dry and SSD) and apparent specific gravity values for each of the samples are provided in Table 5.5. From this table it should be noted that the specific gravity values of street sweepings and catch basin cleanings are not statistically significant, compared to the fresh, virgin sand that is supplied to MassHighway.

Table 5.5: Comparative Results of the Bulk Specific Gravity (Dry, SSD, Apparent)

Location	Type	Bulk Specific Gravity (Dry)	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (Apparent)
Lexington	FVS	2.425	2.453	2.496
Westwood	SS	2.661	2.679	2.709
Burlington	FVS	2.615	2.629	2.651
Burlington	SS	2.599	2.617	2.647
Reading	FVS	2.611	2.628	2.657
Reading	SS	2.600	2.615	2.640
Peabody	FVS	2.625	2.640	2.665
Peabody	SS	2.584	2.607	2.644
Tewksbury	FVS	2.612	2.627	2.653
Tewksbury	SS	2.547	2.573	2.614
Tewksbury	CBC	2.630	2.651	2.687

5.2 CHEMICAL CHARACTERIZATION

A major concern in formulating a reuse policy for street sweepings and catch basin cleanings is the degree of chemical contaminants that these materials have picked up as they stay in the environment before they are collected and stockpiled or landfilled. After their application on a pavement surface, these materials are exposed to a wide variety of chemical contaminants (primarily from vehicular exhaust), which may be transferred from the environment to the surface of these materials through various mechanisms (adsorption, ion exchange, diffusion, attachment through fine particulate matter, etc.).

Table 5.6 provides a summary of the volatile organic concentration range (low-high) found in each of the 29 samples analyzed. The order of magnitude of the concentration of all common volatile compounds except toluene is the same in street sweepings and catch basin cleanings. Please note that all samples were taken directly from sweeping trucks to ensure the maximum concentration possible. It is expected that if these materials are stockpiled in MassHighway depots for an extended duration (months), the concentration of volatile compounds will decrease substantially because these compounds will volatilize from the surface of the material to the atmosphere. Detailed results of analysis of each sample are provided in Appendix C.

Table 5.6: Summary of the Volatile Organic Concentration in Fresh, Virgin Sand, Street Sweeping and Catch Basin Cleanings

Volatile Organics			
	Fresh Virgin Sand (μg/kg)	**Street Sweeping (μg/kg)**	**Catch Basin Cleaning (μg/kg)**
Benzene	ND	ND - 1.6	ND
Toluene	ND	ND - 2.0	6.6 – 1500.0
Trichlorofluoromethane	ND	ND - 36.0	ND
Acetone	ND	91.0 – 360.0	9.4 – 390.0
2-Butanone	ND	24.0 – 44.0	31.0 – 75.0
4-Methyl-2-pentanone	ND	20.0 – 69.0	21.0 – 32.0
P-Isopropyl toluene	ND	ND - 220.0	8.1 - 3900
Naphthalene	ND	ND	ND - 24.0
Acrolein	ND	ND - 44.0	ND
ND – Non Detect			

In terms of toxicity, the group of contaminants that is perhaps of the most concern is polynuclear aromatic hydrocarbons (PAHs). Because these molecules are very hydrophobic, they are easily adsorbed by street sweepings and catch basin cleanings and have a strong correlation with organic content. This is borne out by the summary of the PAH concentration range (low-high) found in all the 29 samples analyzed. Please note that in general, catch basin cleanings display a higher degree of contamination compared to street sweepings. This is attributed to three factors: (i) catch basin cleanings have longer exposure to road runoff,

(ii) catch basin cleanings have higher organic content and thus are more prone to adsorption of hydrophobic PAH, and (iii) street sweepings periodically receive precipitation that desorbs PAHs from its surface through a rinsing action whereas catch basin cleanings do not undergo any rinsing once they settle in the catch basin.

Table 5.7: Summary of the Polynuclear Aromatic Hydrocarbons Concentration in Fresh, Virgin Sand, Street Sweeping and Catch Basin Cleanings

Polynuclear Aromatic Hydrocarbons			
	Fresh Virgin Sand (µg/kg)	**Street Sweeping (µg/kg)**	**Catch Basin Cleaning (µg/kg)**
Fluoranthene	ND	760 – 2500	700 – 15000
Benzo(a)anthracene	ND	290 – 780	89 - 4200
Benzo(a)pyrene	ND	330 – 1000	97 - 5200
Benzo(b)fluoranthene	ND	370 – 2100	140 - 7000
Benzo(k)fluoranthene	ND	410 – 1100	120 - 5100
Chyrsene	ND	400 – 1300	110 - 5400
Anthracene	ND	87 – 150	130 – 1000
Benzo(ghi)perylene	ND	350 – 730	94 - 3400
Fluorene	ND	ND	81 – 1300
Phenanthrene	ND	270 – 1200	120 - 5700
Dibenzo(a,h)anthracene	ND	110 – 210	55 – 820
Indeno(1,2,3-cd) Pyrene	ND	280 – 750	81 - 3600
Pyrene	ND	660 – 1900	220 - 11000
Perylene	ND	140 – 160	120 – 1100
Benzo(e)Pyrene	ND	370 – 970	93 - 3700
ND – Non Detect			

Table 5.8 provides a summary of diesel-range and petroleum-range hydrocarbon concentrations (low-high) determined from the 29 samples analyzed. In general, catch basin cleanings contain a higher magnitude of concentration of both of the aforementioned contaminants. This is attributed to three factors: (i) catch basin cleanings have longer exposure to road runoff, (ii) catch basin cleanings have higher organic content and thus are more conducive to adsorption of hydrophobic petroleum hydrocarbons, and (iii) street sweepings periodically receive precipitation that desorbs petroleum hydrocarbons from its surface through a rinsing action whereas catch basin cleanings do not undergo any rinsing once they settle in the catch basin.

Table 5.8: Summary of Petroleum Hydrocarbon and Total Solids Concentration in Fresh, Virgin Sand, Street Sweeping and Catch Basin Cleanings

Polynuclear Aromatic Hydrocarbons			
	Fresh Virgin Sand (µg/kg)	**Street Sweeping (µg/kg)**	**Catch Basin Cleaning (µg/kg)**
Petroleum Hydrocarbons			
Diesel Range Organics	ND	37000 – 980000	84000 – 980000
Gasoline Range Organics	ND	ND	5900 - 16000
ND – Non Detect			

Sorption of trace metals, especially toxic RCRA-8 metals, on the surface of the street sweeping and catch basin cleaning materials is a major concern if reuse options are explored. Table 5.9 shows the total concentration range (mg of contaminant per kilogram of sample) of each RCRA-8 metal in all the samples of street sweepings and catch basin cleanings analyzed.

Table 5.9: Summary of Trace Metal Concentration in Fresh, Virgin Sand, Street Sweeping and Catch Basin Cleanings

Metals	Fresh Virgin Sand (mg/kg)	Street Sweeping (mg/kg)	Catch Basin Cleaning (mg/kg)
Arsenic	1.9 – 2.3	2.1 – 6.1	1.9 – 6.5
Barium	2.7 – 3.2	14.0 – 76.0	13.0 – 53.0
Cadmium	ND	ND	ND - 0.73
Chromium	2.2 – 3.2	27.0 – 100.0	13.0 - 110.0
Lead	0.0 - 2.3	19.0 – 120.0	9.5 – 120.0
Selenium	ND	1.7	ND
Silver	ND	ND	ND
Sodium	0.0 – 110.0	350.0 – 2000.0	220.0 – 6100.0
ND – Non Detect			

Table 5.10: Highest Trace Metal Concentration Values for Fresh Virgin Sand, Street Sweepings and Catch Basin Cleanings

	Sample ID	Location	Arsenic	Barium	Chromium	Lead
			mg/kg	mg/kg	mg/kg	mg/kg
Fresh Virgin Sand						
District 4	PEAFVS6	Peabody	1.9	2.7	2.2	ND
District 5	DMFVS1	Dartmouth	2.3	3.2	3.2	2.3
Street Sweeping						
District 4	SBYSS2	Salisbury	6.1	26	53	90
	RDGSS3	Reading	6.1	49	100	40
	MLTSS4	Milton	4	54	94	65
	PEASS6	Peabody	4.3	16	27	53
	WMNSS7	Wilmington	5.4	30	40	19
	REVSS8	Revere	4.4	76	88	120
District 5	DMSS1	Dartmouth	2.1	18	44	110
	MARSS5	Marion	2.4	14	27	24
Catch Basin Cleaning						
District 3	WORCB8	Worcester	6.5	53	50	50
	AUBCB9	Auburn	5.2	33	46	52
	DUDCB10	Dudley	4.9	25	36	39
	WFDCB16	Westford	4.1	22	21	17
District 4	CFDCB4	Chelmsford	4.2	25	35	86
	RDGCB5	Reading	5.4	45	36	110
	TBYCB6	Tewksbury	3.6	23	23	45
	BTRCB7	Braintree	3.2	13	15	100
	NBYCB17	Newbury	5.1	62	49	130
	RDGCB18	Reading	4.7	49	110	96
	BTRCB19	Braintree	4.3	20	47	190
District 5	STOCB1	Stoughton	2.6	14	43	68
	ATBCB2	Attleboro	1.9	18	29	80
	PLYCB3	Plymouth	1.9	21	32	38
	PLICB11	Plympton	4	28	58	23
	SAGCB12	Bourne	4.9	19	13	9.5
	BOUCB13	Bourne	3.2	28	26	23
	MIDCB14	Middleboro	3.1	23	15	120
	BRWCB15	Bridgewater	3.6	25	27	53
ND – Non-Detect						

5.3 GEOTECHNICAL CHARACTERIZATION

The fine aggregates were sieved and aggregates passing sieve #8 and retained on #16 and passing sieve #16 and retained on sieve #30 (see page 128) were analyzed. This procedure ensures that contaminants that had adsorbed on the surface of street sweepings and catch basin cleanings did not alter the surface angularity or texture. The distributions of the shape characteristics for each aggregate size are given in the following table. An increase in the angularity index indicates a higher angularity, while an increase in form index indicates an increase in the elongation of particles. Please refer to section 3.4 for discussion of methods to calculate angularity and form indices. A summary of findings is presented in Tables 5.11 and 5.12.

Table 5.11: Summary of Average Characteristics of Each Size

	Sample ID	Size	Gradient Angularity	2D Form
		FRESH VIRGIN SAND		
DISTRICT 4	**PEAFVS**	Passing #8 retained on #16	4599.82	9.00
		Passing #16 retained on #30	3349.99	6.72
	RDGFVS	Passing #8 retained on #16	2816.57	6.13
		Passing #16 retained on #30	2922.25	6.34
DISTRICT 5	**DMFVS**	Passing #8 retained on #16	4414.87	8.29
		Passing #16 retained on #30	3156.68	6.55
		STREET SWEEPINGS		
DISTRICT 4	**PEASS6**	Passing #8 retained on #16	3343.82	7.64
		Passing #16 retained on #30	4188.90	7.94
	BURSS	Passing #8 retained on #16	2986.07	6.52
		Passing #16 retained on #30	3039.28	6.39
DISTRICT 5	**DMSS1**	Passing #8 retained on #16	4036.76	7.66
		Passing #16 retained on #30	3995.49	7.44
	WARSS	Passing #8 retained on #16	2921	6.346
		Passing #16 retained on #30	2853.79	6.189
		CATCH BASIN CLEANINGS		
DISTRICT 4	**BOUCB13**	Passing #8 retained on #16	2857.82	6.296
		Passing #16 retained on #30	2888.33	6.453
	STOCB1	Passing #8 retained on #16	4100.31	8.29
		Passing #16 retained on #30	3871.71	7.74
DISTRICT 5	**PLICB11**	Passing #8 retained on #16	5183.79	8.79
		Passing #16 retained on #30	3916.20	7.41
	SAGCB12	Passing #8 retained on #16	2844.56	6.37
		Passing #16 retained on #30	2909.97	6.22
	BTRCB7	Passing #8 retained on #16	4262.86	8.16
		Passing #16 retained on #30	4311.52	7.69

Table 5.12: Summary of Average Characteristics of Combined Sizes

	Sample ID	Gradient Angularity	2D Form
	FRESH VIRGIN SAND		
DISTRICT 4	**PEAFVS**	3974.90	7.86
	RDGFVS	2869.41	6.24
DISTRICT 5	**DMFVS**	3785.78	7.42
	STREET SWEEPING		
DISTRICT 4	**PEASS6**	3766.36	7.79
DISTRICT 5	**DMSS**	4016.12	7.55
	BURSS	3012.67	6.45
	WARSS	2887.95	6.27
	CATCH BASIN CLEANING		
DISTRICT 4	**STOCB1**	3986.01	8.01
	BOUCB13	2873.32	6.37
DISTRICT 5	**PLICB11**	4549.99	8.10
	SAGCB12	2877.26	6.30
	BTRCB7	4287.19	7.92

It may be noted from Table 5.11 and 5.12 that most of the samples tested can be classified to have a medium to high angularity except for DMDFVS Passing #16 retained on #30, PEAFVS Passing #16 retained on #30, and PEASS6 Passing #8 retained on #16. These aggregate sizes have low angularity. Based on discussions with Professor Walaa Mogawer (at UMass Dartmouth) and Professor Eyad Masad (at Texas A&M University), we concluded that a surface angularity value of > 2,500 is suitable for use on pavement as an anti-skid material, though a value > 3,000 is preferred. Please note that there is a wide range of angularity values (2869 to 3975) in the fresh, virgin sand samples as well. Against this background, it is not surprising to find the range of angularity values of street sweeping (2888 to 4016) and catch basin cleaning (2873 to 4550) samples. It can also be safely concluded that based on average form values, the different aggregate sizes can be classified to have a medium elongation, which is typical for fine aggregates.

The results in Table 5.11 indicate that all samples, excluding PLICB11, have similar angularity values. Based on these average values, PLICB11 is classified to have very high angularity, while all other samples are classified to have average angularity values. These average values are within typical values for crushed sand. As a point of reference (Fletcher et al. 2003), natural uncrushed sand would have an average value less than 2000.

A statistical paired t-test was conducted to verify if the surface angularity values of street sweepings and catch basin cleanings are statistically different from those of fresh, virgin sand. In this statistical approach, the difference in the angularity values between a street sweeping or catch basin cleaning sample with that of fresh, virgin sand is tabulated for each sample. A null hypothesis (with some level of significance) is posed that the two materials (that are being compared) perform the same (i.e., $\mu_d = 0$), and the hypothesis is evaluated using the equation (Eq. 7),

$$t = \frac{\bar{d} - \mu_d}{s_d / \sqrt{n}} \tag{7}$$

where $\bar{d}$ is the mean difference, s_d is the standard deviation, n is the number of sample pairs, and t is a quantile with (n-1) degrees of freedom.

$$
\begin{aligned}
&\textit{For our data set,}\\
&n = 18\\
&\bar{d} = \frac{\sum d_i}{n} = -283.36\\
&s_d^{\,2} = \frac{\sum (d_i - \bar{d})^2}{n-1} = 690511.93\\
&s_{\bar{d}} = \frac{s_d}{\sqrt{n}} = 195.86\\
&\textit{For a } 95\% \textit{ confidence interval,}\\
&\textit{and with } 17 (n-1) \textit{ degrees of freedom,}\\
&t = 2.11\\
&\bar{d} - (t * s_{\bar{d}}) = -696.62\\
&\bar{d} + (t * s_{\bar{d}}) = +129.91
\end{aligned}
$$

Because $\bar{d} - (t*s_d) < 0 < \bar{d} + (t*s_d)$, we can conclude with 95% confidence that the surface angularity values of fresh, virgin sand and street sweepings or catch basin cleanings are statistically no different.

5.4 Exploration of Reuse Options

The two primary reuse options considered are reapplication of street sweepings for skid resistance on streets and reuse of street sweepings and catch basin cleanings as fine aggregates in bituminous concrete pavement. Any decision on reuse has to be preceded by a thorough investigation of the properties of the reuse materials and performance evaluation. Comparison of material properties has been documented in sections 5.1, 5.2, and 5.3. Results of performance evaluation are detailed in the subsequent sections.

5.4.1 British Pendulum Test

The British Pendulum Number (BPN) for fresh, virgin sand and street sweepings and catch basin cleanings was compared. The British Pendulum test enables us to verify if the pass particle-size criterion can be used to determine whether street sweepings and/or catch basin cleanings can be reused for anti-skidding and traction. The BPN results for fresh, virgin sand, street sweepings and catch basin cleanings are tabulated below in Table 5.13.

Table 5.13: Summarized BPN Results of British Pendulum Test

		Dartmouth		Lexington/ Westwood		Wareham		Burlington		Reading		Peabody		Tewksbury		
		FVS	SS	FVS	SS	FVS	SS	FVS	SS	FVS	SS	FVS	SS	FVS	SS	CB
Runs	1	55	60	51	55	62	62	58	58	62	66	52	49	53	58	53
	2	55	65	52	58	61	62	59	61	60	64	48	49	53	55	52
	3	55	62	50	60	59	60	60	57	62	62	52	53	50	56	56
	4	56	60	48	60	59	58	59	60	59	64	51	52	50	55	53
Average		55.25	61.75	50.25	58.25	60.25	60.50	59.00	59.00	60.75	64.00	50.75	50.75	51.50	56.00	53.50

Units are BPN (British Pendulum Number)

The Interlocking Concrete Pavement Institute (ICPI) states that a BPN between 45 and 55 indicates a satisfactory surface in only favorable weather and vehicle conditions. A BPN rating of 55 or greater indicates a generally acceptable skid resistance in all but the most severe weather conditions (ICPI Tech. Spec. #13, originally published in 1998 and revised in March 2004). From the table above we note that BPN ratings of > 55 are maintained for all street sweeping samples but one.

A statistical paired t-test was conducted to verify if BPN of street sweepings and catch basin cleanings are statistically different from those of fresh, virgin sand. In this statistical approach, the difference in the BPN between a street sweeping or catch basin cleaning sample with that of fresh, virgin sand is tabulated for each sample. A null hypothesis (with some level of significance) is posed that the two materials (that are being compared) perform the same or have the same BPN (i.e., $\mu_d = 0$), and the hypothesis is evaluated using the equation (Eq. 7).

$$
\begin{aligned}
&\textit{For our data set},\\
&n = 28\\
&\bar{d} = \frac{\sum d_i}{n} = -3.214\\
&s_d^{\,2} = \frac{\sum (d_i - \bar{d})^2}{n-1} = 24.481\\
&s_{\bar{d}} = \frac{s_d}{\sqrt{n}} = 0.935\\
&\textit{For a } 95\% \textit{ confidence interval},\\
&\textit{and with } 27(n-1) \textit{ degrees of freedom},\\
&t = 2.052\\
&\bar{d} - (t * s_{\bar{d}}) = -5.133\\
&\bar{d} + (t * s_{\bar{d}}) = -1.295
\end{aligned}
$$

Because $\overline{d} - (t^*s_d) < 0$ and also $\overline{d} + (t^*s_d) < 0$ and d = BPN of FVS – BPN of SS/CBC, we can conclude with 95% confidence that the BPN of fresh, virgin sand is statistically lower than that of BPN of a street sweeping sample or catch basin cleaning sample. Based on the limited samples, statistically, a street sweeping sample may provide higher skid resistance than fresh, virgin sand.

5.4.2 UNCOMPACTED VOID CONTENT AND REUSE IN BITUMINOUS CONCRETE PAVEMENT

Section 4.2 has a detailed discussion of the significance of uncompacted void content and the AASHTO T304 method to conduct this test. A comparative evaluation of the uncompacted void content of fresh, virgin sand, street sweeping and catch basin cleaning samples was conducted. The combined overall results for Bulk Specific Gravity (see section 3.2.5 for details on the significance of this parameter and the AASHTO T84 test method) and the uncompacted void content are presented in Table 5.14 and 5.15. The detailed results are tabulated and presented in Appendix E.

Table 5.15: MMLS Rut Testing – Overall Results

	Rut Depth (mm) 50,000 cycles at 40C		
Location	**Fresh Virgin Sand**	**Street Sweeping**	**Catch Basin Cleaning**
Dartmouth	1.71	1.19	N/A
Wareham	2.17	1.26	N/A
Westwood	1.24	1.16	N/A
Burlington	2	1.04	N/A
Reading	0.92	1.27	N/A
Peabody	0.89	0.82	N/A
Tewksbury	1.83	1.68	1.23

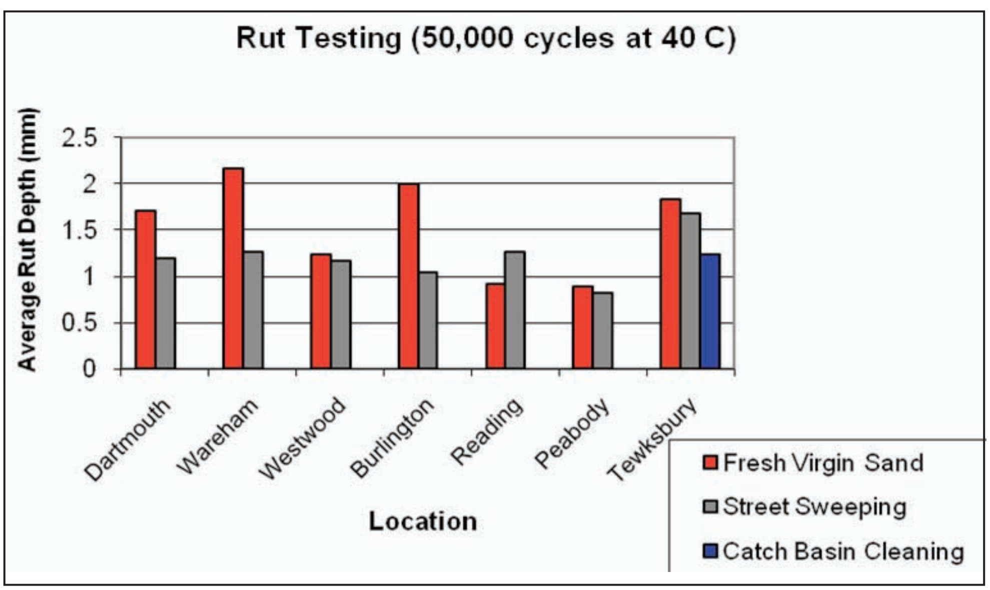


Figure 5.2: MMLS Rut Testing Overall Results

Table 5.14: Exploration of Reuse Options – Overall Results

		Lexington	Westwood	Burlington		Reading		Peabody		Tewksbury		
	Test	**Fresh Virgin Sand**	**Street Sweeping**	**Fresh Virgin Sand**	**Street Sweeping**	**Fresh Virgin Sand**	**Street Sweeping**	**Fresh Virgin Sand**	**Street Sweeping**	**Fresh Virgin Sand**	**Street Sweeping**	**Catch Basin Cleaning**
AASHTO T84	**Bulk Specific Gravity (dry)**	2.425	2.661	2.615	2.599	2.611	2.600	2.625	2.584	2.612	2.547	2.630
AASHTO T84	**Bulk Specific Gravity (SSD)**	2.453	2.679	2.629	2.617	2.628	2.615	2.640	2.607	2.627	2.573	2.651
AASHTO T84	**Bulk Specific Gravity (Apparent)**	2.496	2.709	2.651	2.647	2.657	2.640	2.665	2.644	2.653	2.614	2.687
AASHTO T84	**Absorption (%)**	1.18	0.66	0.52	0.7	0.66	0.58	0.58	0.88	0.58	1.00	0.80
AASHTO T304	**Uncompacted Void %**	50.7	48.8	40.4	45.6	41.2	46.6	42.0	41.7	40.3	45.9	43.4
ASTM E303	**Friction (BPN)**	50.25	58.25	59.0	59.0	60.75	64.00	50.75	50.75	51.50	56.00	53.50
Rut Testing 50,000 cycles @ 40C(12.5mm NMAS HMA Mix Design)												
	Rut Depth Specimen #1 (mm)	1.46	1.10	1.86	0.72	0.89	1.33	0.66	0.82	1.97	2.01	1.02
	Rut Depth Specimen #2 (mm)	1.03	1.22	2.13	1.36	0.95	1.21	1.12	0.82	1.68	1.35	1.44
	Average (mm)	**1.24**	**1.16**	**2.00**	**1.04**	**0.92**	**1.27**	**0.89**	**0.82**	**1.83**	**1.68**	**1.23**

From Table 5.14, it can be safely concluded that the uncompacted void content of street sweepings or catch basin cleanings are almost the same as that for fresh, virgin sand. An uncompacted void content of 40% or higher is suitable (in terms of particle interlocking) for reuse of the material in bituminous concrete. Thus, all the samples tested, fresh, virgin sand, street sweepings, and catch basin cleanings, are suitable for reuse in bituminous concrete pavement. This is also borne out by the data on rut depth. It should be noted that the rut depths using fresh, virgin sand are not very different from that using street sweepings or catch basin cleanings (Table 5.15). Additionally, the rut depths observed at 50,000 cycles (in the range of 1 mm) are much lower than what we find with normal bituminous concrete pavements (in the range of 10 mm, see Lee, 2003).

Thus, it can be safely concluded that street sweepings or catch basin cleanings can be reused in bituminous concrete instead of fresh, virgin sand without any compromise in pavement performance.

5.4.3 COMPOST ADDITIVE

The concentration of the primary contaminants in the catch basin cleanings, as reflected in a composite sample of the influent solids in the composter on day 1 (March 15, 2007), is provided in Table 5.16. Water was added to the composter every two weeks and at the time of its addition, the solids were stirred. On December 14, 2007, a well-mixed representative sample was taken from the composter and analyzed for all chemical contaminants. Detailed results of chemical analysis of this sample are provided in Appendix E. Major contaminant concentrations are shown in Table 5.16.

Table 5.16: Comparative Analysis of Composite Results with Influent Samples

Sample	Diesel Range Organic	Gasoline Range Organic	Fluoranthene	Pyrene
	µg/Kg	µg/Kg	µg/Kg	µg/Kg
Composite Sample on Day 1 (March 15, 2007)	479,267	3,800	3,509	2,771
Composite Sample Sampled on December 14, 2007	240,000	2,200	2,800	2,100

Based on the comparative analysis data in the above table, the composter was able to reduce the concentration of the primary groups of organics in nine months but the degree of reduction was not sufficient to consider the treatment complete. Based on the composting time there was a reduction in chemical contaminants and the longer composting period will result in a further decrease in chemical contaminants. However, all indications suggest that the catch basin cleanings should be mixed with other high-organic solid wastes (such as yard waste) for efficient composting. More studies are needed to explore this option and determine the optimal percentage of catch basin cleanings in the mixture.

5.4.4 SOURCE SEPARATION

In the original research scope, investigation of the benefits of source separation was listed. How would source separation affect the end reuse of street sweepings and catch basin cleanings. For example, would segregating urban and non-urban street sweepings, segregating catch basin cleanings from locations close to major highway from those that are far from major highways, etc. change the amount and/or type of processing required prior to reuse? Or, would source separation change the geotechnical characteristics of the materials? After analyzing the results of sample analysis and with input from MassHighway's technical representative, it was concluded that source separation is practically very difficult to implement due to the logistics of transport, storage space etc., and it does not provide any economic benefit. All experiments with unsegregated samples indicated that for the two primary reuse options investigated in detail – reuse in pavements for anti-skidding and traction and reuse as fine aggregates in bituminous concrete – unsegregated samples performed statistically (at 95% confidence level) the same as fresh, virgin sand. Therefore it was concluded that source separation was not needed. However, as part of processing for reuse, all street sweepings and catch basin cleanings have to be screened for trash, litter, and other debris.

5.5 *CALCULATION OF COST ($/TON) FOR EACH REUSE OPTION*

A comparative analysis was performed of the economics of reuse of street sweepings on pavement as anti-skidding material and of street sweepings and catch basin cleanings as fine aggregate in bituminous concrete pavement. The objective of this analysis is only to provide a general idea of the magnitude of savings possible with each reuse option, and it should not be considered as a strict accounting exercise.

5.5.1 COST ANALYSIS OF REUSE OF STREET SWEEPINGS ON PAVEMENTS

Table 5.17 provides a cost analysis of two options - using fresh sand every year and land filling the street sweepings or using fresh sand for the first time, collecting street sweepings, screening them in a portable screening equipment, and reapplying the screened street sweeping material on pavements next year for de-icing and anti-skid. The cost analysis is not meant to show actual costs, cost savings, etc, but is an exercise to show the economic potential of reusing street sweepings based on the following assumptions.

Assumptions:

1. 30,000 tons of sand is applied to roads each year and 50% of it (15,000 tons) is recovered.
2. Used screen equipment is purchased by MassHighway. For example, a used Read "Screen-All" Model RD 150-A Portable Screening Plant (Figure 5.3) can be purchased on today's market for $37,500.

3. The useful life of screening equipment, for example, the Read "Screen-All" Model RD 150-A is 10 years and it has no salvage value. The annual interest rate considered is 10%.
4. In one 8-hour shift, the screening plant can screen approximately 80 cubic yards or 108 tons.

Table 5.17: Comparative Cost Analysis of Land Filling Vs. Screening and Reapplication of Street Sweepings

Item	No Recycle (Fresh Virgin Sand Applied Each Year and Land Filled)			Street Sweeping Collected, Screened and Reapplied on Pavements		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Cost of Sand @ $10/ton	$300,000	$300,000	$300,000	$300,000	$165,000	$165,000
Cost of land filling (@$50/ton)	$750,000	$750,000	$750,000	$37,500	$37,500	$37,500
Annual Cost of Screen	None	None	None	$6,500	$6,500	$6,500
Annual Cost of Maintenance of Screen	None	None	None	$2,000	$2,000	$2,000
Labor Cost (to operate screen)	None	None	None	$60,000	$60,000	$60,000
Fuel Cost (to operate screen)	None	None	None	$4,200	$4,200	$4,200
Total Annual Cost	$1,050,000	$1,050,000	$1,050,000	$410,200	$275,200	$275,200

5. To run the screening plant, two persons will be employed at $30,000 each year, including fringe and benefits.
6. The annual maintenance costs for this screening plant will be $2,000.
7. The street sweepings will generate 5% trash and litter that will have to be land filled.
8. All other conditions remaining identical, every year 55% of the sand required to be applied to pavements has to be purchased fresh, if the material is screened and reapplied on pavements. In other words, 45% of the original mass of sand applied will be reusable.
9. The portable screening plant needs 10 gallons of fuel for 8 hours of operation. An assumption has been made of 140 days of operation at 8 hours per day and fuel cost of $3/gallon.
10. All calculations are based on the date of publication.

Figure 5.3: Used Read "Screen-All" Model RD 150-A Portable Screening Equipment

5.5.2 COST ANALYSIS OF REUSE OF STREET SWEEPINGS AND CATCH BASIN CLEANINGS AS FINE AGGREGATE IN BITUMINOUS CONCRETE PAVEMENTS

Table 5.18 provides a cost analysis of two options - using fresh sand every year and land filling the street sweepings and catch basin cleanings; and using fresh sand for the first time, collecting street sweepings and catch basin cleanings, screening them in a portable screening equipment, and using the screened material in bituminous concrete pavement.

Assumptions:

1. Used screen equipment is purchased by MassHighway. A used Read "Screen-All" Model RD 150-A Portable Screening Plant available for $37,500.00 has been considered.
2. The useful life of the Read "Screen-All" Model RD 150-A is 10 years and it has no salvage value. The annual interest rate considered is 10%.
3. In one 8-hour shift, the screening plant can screen approximately 80 cubic yards (108 tons of street sweeping or 81 tons of catch basin cleaning).
4. To run this screening plant, two persons will be employed at $45,000 per year, including fringe and benefits.
5. The annual maintenance costs for this screening plant will be $2,000.
6. The street sweepings and catch basin cleanings will generate 5% trash and litter that will have to be land filled.
7. The portable screening plant needs 10 gallons of fuel for 8 hours of operation. An assumption has been made of 250 days of operation at 12 hours per day and fuel cost of $3/gallon.

Table 5.18: Comparative Cost Analysis of Landfilling Vs. Screening and Reusing of Street Sweepings/Catch Basin Cleanings for Bituminous Pavements

Item	No Recycle (Fresh Virgin Sand Applied Each Year and Land Filled)			Street Sweeping and Catch Basin Cleaning Collected, Screened, and Reused in Bituminous Concrete Pavement		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Cost of Sand (30,000 tons @ $10/ton)	$300,000	$300,000	$300,000	$300,000	$300,000	$300,000
Cost of land filling @$50/ton	$1,500,000	$1,500,000	$1,500,000	$75,000	$75,000	$75,000
Annual Cost of Screen	None	None	None	$6,500	$6,500	$6,500
Annual Cost of Maintenance of Screen	None	None	None	$2,000	$2,000	$2,000
Labor Cost (to operate screen)	None	None	None	$90,000	$90,000	$90,000
Fuel Cost (to operate screen)	None	None	None	$11,250	$11,250	$11,250
Offset from selling street sweepings and catch basin cleanings to contractor for use in bituminous concrete pavement @ $5/ton	None	None	None	-$142,500	-$142,500	-$142,500
Total Annual Cost	$1,800,000	$1,800,000	$1,800,000	$342,250	$342,250	$342,250

8. The screened street sweepings and catch basin cleanings will be provided to the bituminous concrete pavement contractor at 50% discount, i.e., at $5/ton instead of the market price of $10/ton.
9. All calculations are based on the date of publication.

6.0 Conclusions and Recommendations

A detailed characterization of street sweepings, catch basin cleanings, and fresh, virgin sand (control) was conducted as part of this study. The physical properties examined include grain size, density, organic content, moisture content, uncompacted void content, and specific surface area. Classes of chemical contaminants analyzed for included RCRA-8 metals, volatile organics, polynuclear aromatic hydrocarbons, benzene, toluene, ethyl benzene and xylene (BTEX), gasoline-range petroleum hydrocarbons and diesel-range petroleum hydrocarbons. Geotechnical characterization included image analysis for angularity, form and texture, uncompacted void content, BPN test, and MMLS rut test.

6.1 REUSE OF STREET SWEEPINGS AND CATCH BASIN CLEANINGS ON PAVEMENT

Based on an intensive study of the physical, chemical, and geotechnical properties of the materials listed above, this report safely concludes that street sweepings and catch basin cleanings can be reused on pavements to prevent skidding and to provide traction for vehicles.

This reuse option cannot be made without MassHighway requesting a BUD or changes to current DEP policy BWP-94.092. Section 2 of BWP-94.092 states, “This policy applies to the reuse or disposal of street sweepings that are generated in the ordinary and customary maintenance of roadways. The policy does not apply to catch basin cleanings or street sweepings mixed with catch basin cleanings.” Data presented in this report support granting of a BUD by DEP to MassHighway or a modification to this policy to include catch basin cleanings. This study did not find any difference between street sweepings and catch basin cleanings as compared to fresh virgin sand that would prevent the reuse of catch basin cleanings on pavements for anti-skidding and to provide traction. Moreover, a review of current literature in this area suggests that between one third and one half (33% - 50%) of the sand applied is collected as street sweepings. Therefore, if the current policy were preserved, MassHighway would have to purchase at least 50% of fresh sand every year. But if the reuse of catch basin cleanings is included in a BUD application or a modified version of BWP-94.092, it is conceivable that the combined mass/volume of street sweepings and catch basin cleanings would minimize the need for fresh purchase of virgin sand beyond the first year.

The BUD would need to include a change in the storage time allowed for street sweepings and catchbasin cleanings. Article 7.2 of BWP-94.092 states, “Storage must be temporary. Street sweepings shall be used within one year of collection unless the DEP Regional Office in the region where the sweepings are stored grants a written extension.” The researchers recommend that in the BUD MassHighway requests, the allowable storage period be increased, to at least two years, so that sufficient material is screened, inventoried, placed on a statewide database, and then made available to contractors and MassHighway sanding crews for reuse. If MassHighway's BUD is allowed or a modification of current DEP policy occurs and this reuse option is implemented, MassHighway may derive savings as high as \$700,000 per year, as shown in the cost analysis in Section 5.

6.2 *Reuse of Street Sweepings and Catch Basin Cleanings as Fine Aggregates in Bituminous Concrete Pavement*

Based on the study of the physical, chemical, and geotechnical properties of materials stated above, it can be concluded that street sweepings and catch basin cleanings can be reused as fine aggregate in bituminous concrete pavement. No difference in geotechnical properties was found between street sweepings and catch basin cleanings that would prevent the reuse of catch basin cleanings as fine aggregate in bituminous concrete pavements. As recommended in the previous section, this reuse application also cannot be made unless a BUD is granted to MassHighway or current DEP Policy BWP-94.092 is modified. The recommended change to Article 7.2 of BWP-94.092 identified in the previous section would also apply to reuse as fine aggregate in bituminous concrete pavement.

This reuse option should not be employed on a commercial scale until studies are undertaken to evaluate whether toxic fumes are generated when the organic matter in the solid waste (especially in the case of catch basin cleanings) is heated with bitumen while preparing the mixture, and if any toxics (organic and inorganic) leach from the pavement after water percolates through it. A leaching test such as Toxicity Characteristic Leaching Procedure would be appropriate for such a scenario. If this reuse recommendation is implemented, MassHighway may derive savings as high as $1,300,000 per year, as shown in the cost analysis in Section 5.

6.3 *Compostability of Street Sweepings and Catch Basin Cleanings*

The analysis of composting viability indicated that the average organic content in street sweeping samples was approximately 3%. This is too low for direct composting. Therefore, street sweepings should only be used as an additive to compost as mentioned in Article 4.3 of BWP-94.092. However, the average organic content of catch basin cleanings was found to be much higher (approximately 8.7%).

Catch basin cleanings are, based upon organic content, more suitable for composting. Indeed, the preliminary findings of the research team confirm this. Current DEP policy does not allow for the composting of catch basin cleanings. The researchers found ample evidence to indicate that catch basin cleanings - either alone or as an additive - are amenable to composting. Therefore, it is recommended that MassHighway request a BUD to include catch basin cleanings under the current DEP policy on the composting of street sweepings. The researchers also recommend that long-term composting studies of catch-basin cleanings be conducted.

Disposal of street sweepings and catch basin cleanings is a major strain on the budget of MassHighway. Compounding the problem is the decline in the number of landfills that accept this material as well as the increasing landfill tipping fees. The results of this study provide technical and economic analyses to highlight the economic and environmental benefits in reusing these materials on pavements for traction and anti-skidding, as fine aggregates in bituminous pavements, and by composting.

Appendices

APPENDIX A: SAMPLER'S INSTRUCTION MANUAL

This document details the procedure to be used while collecting samples of street sweepings and catch-basin cleanings.

Each Sample collection should keep the following items ready for sampling:

1. Field Notebook and pencil
2. Box of nitrile disposable gloves
3. Disposable plastic towels
4. Two Permanent marker (sharpie) pens
5. Dust Mask
6. Roll of clear tape
7. Ziploc bags
8. Chain of custody forms
9. Chain of custody tape
10. Digital camera
11. Cooler with Ice

Ice packs should be always refrigerated so that sampling can be conducted with short notice.

Procedure

The graduate student will be contacted by the Principal Investigator and will be requested to visit a MassHighway district office. The above set of items will be carried to the sample location at all times. Upon meeting the MassHighway Representative, the student will proceed to collect a sample. The sample could be an existing stockpile or from a truck that is carrying out street sweeping or catch basin cleaning at that time.

For collecting a sample from a stockpile, use the disposable plastic towel to scoop the sample directly from the stockpile into the sampling container. Nitrile gloves must be worn during all sample collection events. The student will carry pre-labeled bottles and they will be marked as to which sample they have collected and the location and the date/time of sampling. This will then be confirmed with the MassHighway Representative present at that time of sampling. The label will be initialed, sealed with a clear plastic tape and placed in a Ziploc bag and sealed. Finally the sealed bag will be stored in a cooler packed with ice packs.

For collecting a sample directly from a cleaning truck, the MassHighway representative will provide us with a protective vest, which must be worn at all times during sampling along State roadways. The procedure for collection of a sample from a stockpile remains similar; a MassHighway representative will accompany the student to the stockpile.

Control Samples

Fresh virgin sand will be collected as a control sample from several MassHighway District depots. The physical and geo-technical characterization of the control sample will be conducted at UMass Dartmouth. Similar analyses will be conducted for street sweeping and catch basin cleanings; the material will be collected in a 5-gallon plastic bucket.

Type of Container	Analysis
500-mL Amber Glass	Total Solids, Chloride, Trace Metals, AH (8270) & TPH Diesel (8100M)
4-Oz VOA Vial	TPH gasoline (8150M) and VOCS (8260)

Instructions for field Notebooks

Each sampling event must be documented in a field notebook. A field notebook will be available to each student in the project team. For each entry in the field notebook, record the time you arrive in the District office, the weather conditions, the name of the MassHighway representative working with you that day, and most importantly, all sampling activities. Never tear a page from the field notebook, nor erase anything. If you think you made an entry by error, just strike it out lightly and write the revised information by its side. Use military time (00 to 24 hours) to log entries in the field notebook. All pages in the field notebook should be numbered consecutively. Please include your signature at the end of each entry. Include the following information with each entry:

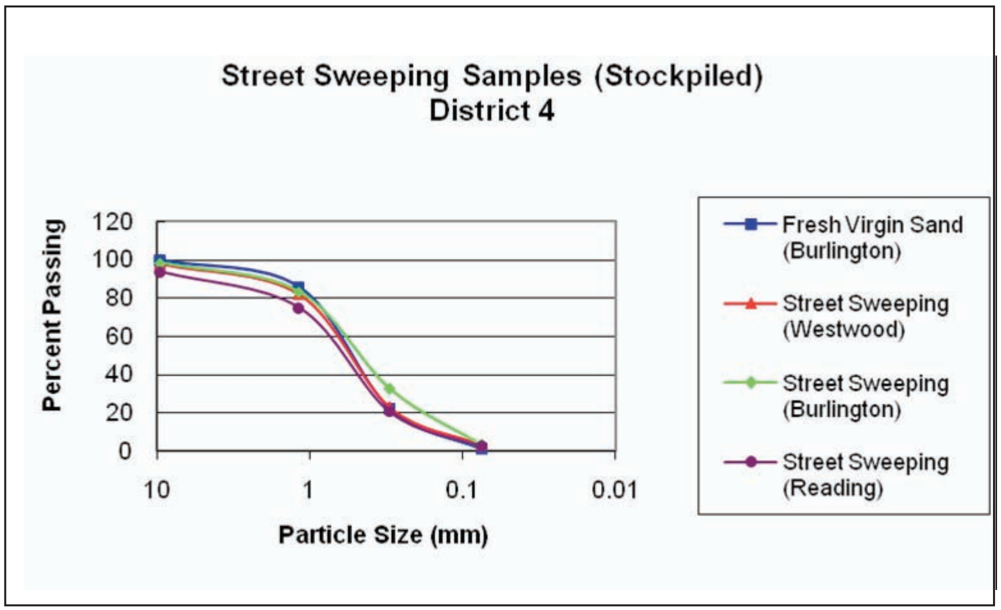
1. Traffic volume	Low Medium High	
2. Road Classification	Rural	Primary Secondary
	Urban	Interstate State Highway
3.Location	Rural Urban Commercial Industrial	
4. Coastal or Non-Coastal		

Information regarding sampling activity should include the time of sample collection, the sample collection procedure (directly from a truck or with a scoop or from a stockpile).

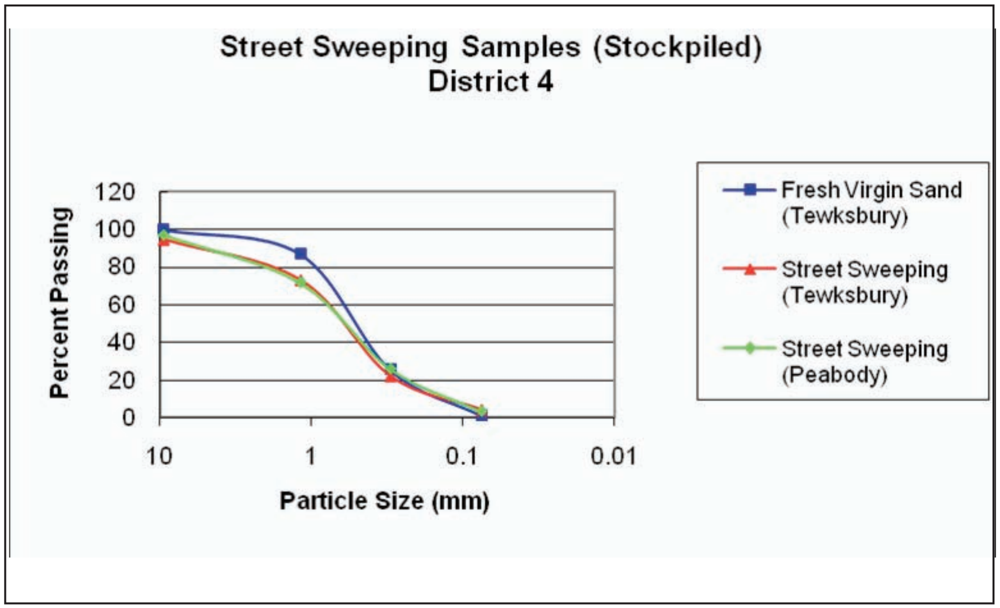
Each sampling event must include a brief description of the sampling that should include the color and composition of the sample. Also, note any other material or debris that may be present in the stockpile, including plastic, wood, metal, glass, etc. The sample should also be noted for any unusual odors that might emanate from the stockpile.

APPENDIX B: GRAIN SIZE DISTRIBUTION (SIEVE ANALYSIS)

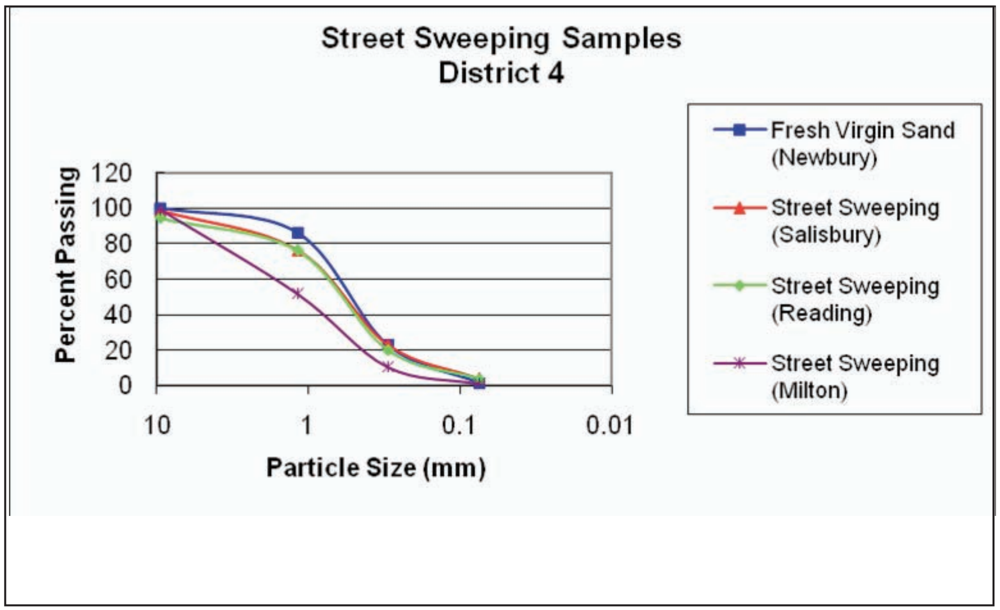
DISTRICT 4								
Sieve opening	Fresh Virgin Sand from Burlington		Street Sweepings from Westwood		Street Sweeping from Burlington		Street Sweeping from Reading	
size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent Passing	Mass Retained (gms)	Percent Passing
9.5	0	99.846	17.95	98.084	13.45	98.527	62.57	93.67
1.18	140.36	85.81	159.88	82.096	150.63	83.464	187.26	74.944
0.3	636.72	22.138	593.52	22.744	509.44	32.52	544.52	20.492
0.075	210.38	1.1	197.43	3.001	294.77	3.043	179.76	2.516
	11		30.01		30.43		25.16	



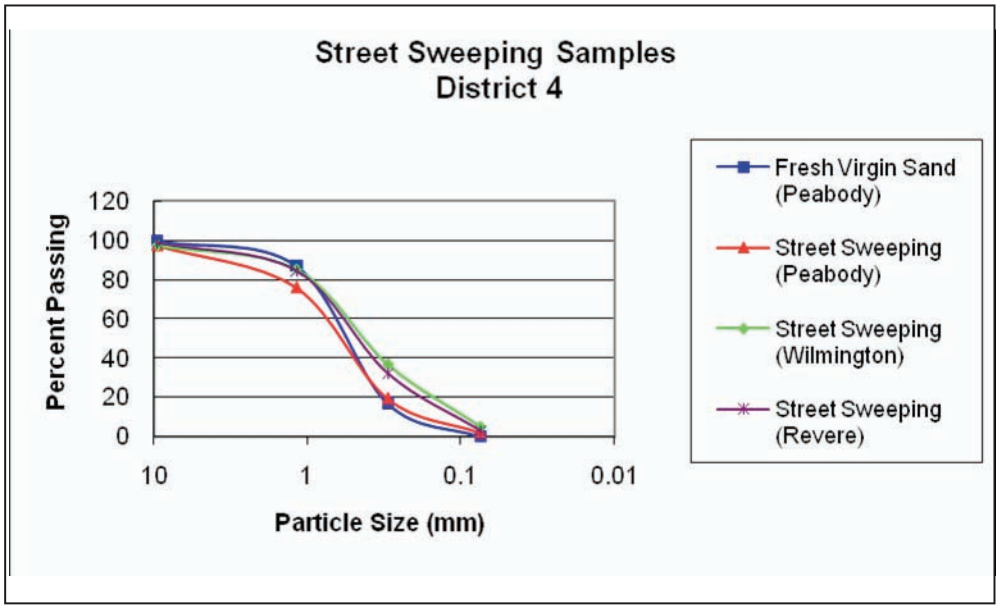
DISTRICT 4							
		Fresh Virgin Sand from Tewksbury		Street Sweeping from Tewksbury		Street Sweeping from Peabody	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent Passing	Mass Retained (gms)	Percent Passing
2	9.5	1.28	99.779	50.47	94.764	24.31	97.414
16	1.18	128.48	86.931	214.58	73.306	253.58	72.056
50	0.3	613.57	25.574	510.25	22.281	460.03	26.053
200	0.075	243.06	1.268	179.87	4.294	227.69	3.284
Final pan		12.68		42.94		32.84	
Initial Mass = 1000 g							



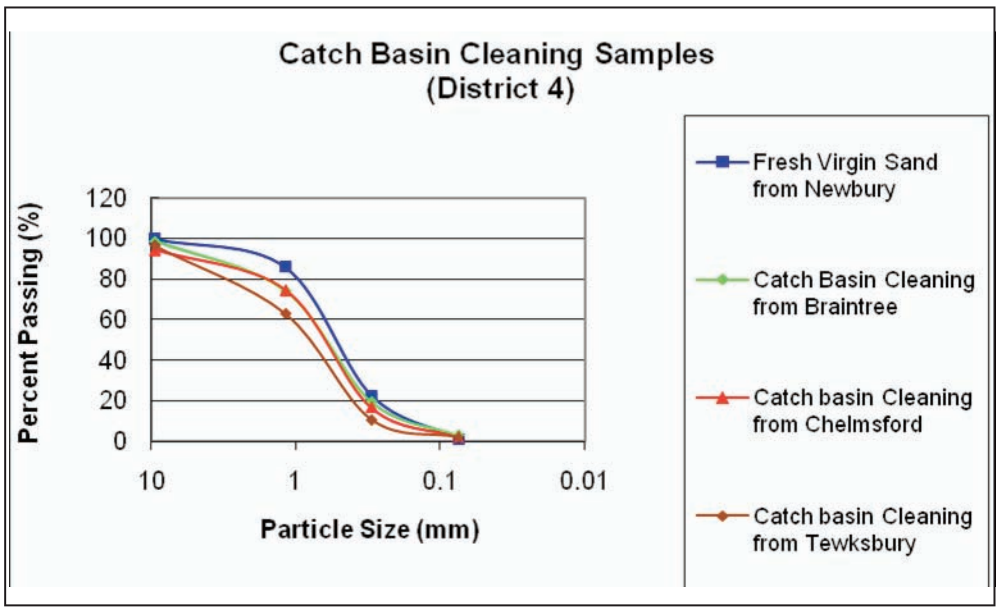
DISTRICT 4									
		Fresh Virgin Sand from Newbury		Street Sweeping from Salisbury		Street Sweeping from Reading		Street Sweeping from Milton	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	9.5	0	99.882	11.94	98.615	52.34	94.698	7.75	99.145
16	1.18	138.52	86.03	221.11	76.504	183.42	76.356	474.36	51.709
50	0.3	633.24	22.706	533.08	23.196	563.12	20.044	410.98	10.611
200	0.075	215.01	1.205	192.74	3.922	165.7	3.474	95.2	1.091
Final pan		12.05		39.22		34.74		10.91	
Initial Mass = 1000 g									



DISTRICT 4									
		Fresh Virgin Sand from Peabody		Street Sweeping from Peabody		Street Sweeping from Wilmington		Street Sweeping from Revere	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	9.5	1.47	99.704	24.73	97.48	20.8	97.848	13.14	98.578
16	1.18	125.25	87.179	214.24	76.056	122.43	85.605	140.61	84.517
50	0.3	698.5	17.329	564.5	19.606	484.86	37.119	522.05	32.312
200	0.075	170.24	0.305	174	2.206	318.39	5.28	292.41	3.071
Final pan		3.05		22.06		52.8		30.71	
Initial Mass = 1000 g									

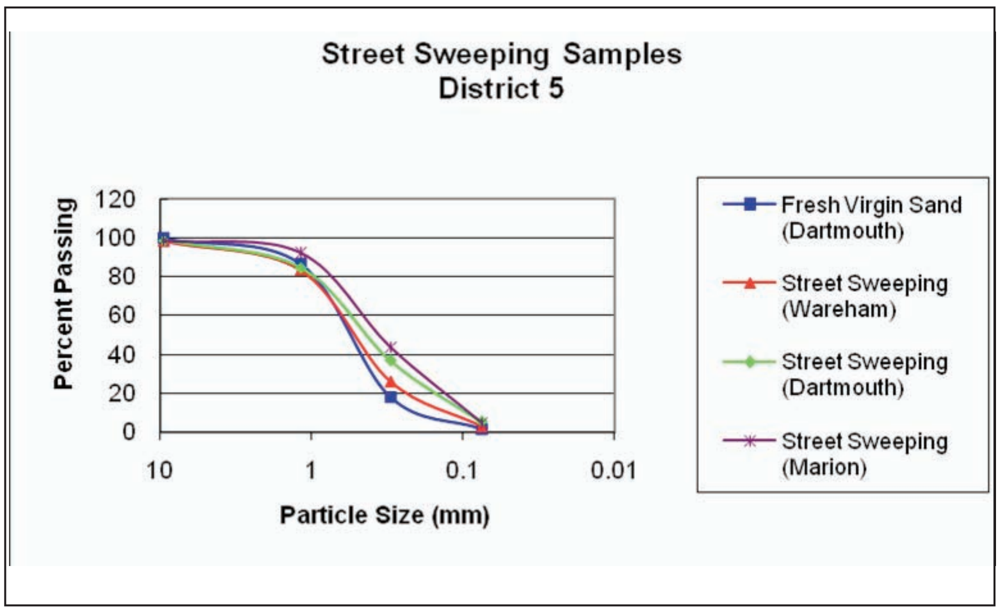


DISTRICT 4									
		Fresh Virgin Sand from Newbury		Catch Basin from Braintree		Catch Basin from Chelmsford		Catch Basin from Tewksbury	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	9.5	0	99.882	12.67	98.642	56.34	94.274	33.57	96.532
16	1.18	138.52	86.03	245.67	74.075	197.56	74.518	335.76	62.956
50	0.3	633.24	22.706	544.76	19.599	578.04	16.714	523.03	10.653
200	0.075	215.01	1.205	167.75	2.824	145.47	2.167	87.48	1.905
Final pan		12.05		28.24		21.67		19.05	
Initial Mass = 1000 g									

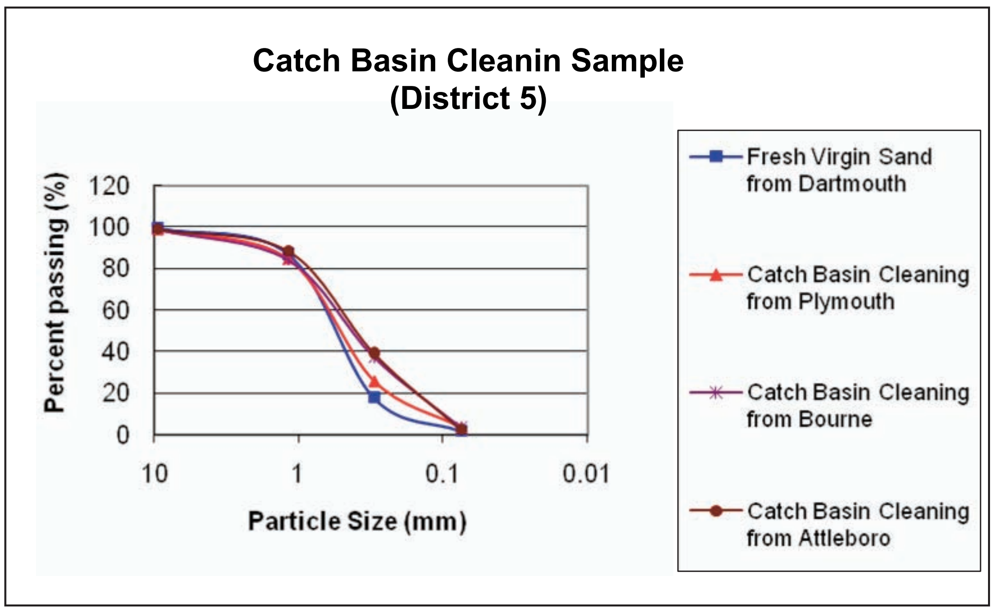


DISTRICT 5

		Fresh Virgin Sand from Dartmouth		Street Sweeping from Wareham		Street Sweeping from Dartmouth		Street Sweeping from Marion	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	9.5	2.29	99.681	13.51	98.562	10.67	98.808	12.76	98.628
16	1.18	129.12	86.769	148.73	83.689	139.94	84.814	61.08	92.52
50	0.3	686.95	18.074	576.57	26.032	478.79	36.935	485.75	43.945
200	0.075	164.41	1.633	232.18	2.814	316.39	5.296	388.3	5.115
Final pan		16.33		28.14		52.96		51.15	
Initial Mass	=1000g								



DISTRICT 5									
		Fresh Virgin Sand from Dartmouth		Catch Basin from Plymouth		Catch Basin from Bourne		Catch Basin from Attleboro	
Sieve Size (US)	Sieve opening size (mm)	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing	Mass Retained (gms)	Percent passing
2	9.5	3.25	99.531	12.95	98.613	11.25	98.745	10.69	98.861
16	1.18	125.43	86.988	140.78	84.535	145.67	84.178	103.66	88.495
50	0.3	692.32	17.756	589.02	25.633	467.89	37.389	492.98	39.197
200	0.075	158.98	1.858	224.76	3.157	336.87	3.702	367.33	2.464
Final pan		18.58		31.57		37.02		24.64	
Initial Mass = 1000 g									



APPENDIX C: CHEMICAL CHARACTERIZATION FOR STREET SWEEPINGS AND CATCH BASIN CLEANINGS

ANALYTE VALUES FOR CONTROL SAMPLES

	District 4	District 5
LOCATION		RTE 6
FVS- Fresh Virgin Sand	Newbury	Dartmouth
	FVS	**FVS**
SAMPLE ID	NBYFVS02	DMFVS1
SAMPLING DATE	5-Apr-06	30-Mar-06
	ug/kg	ug/kg
Solids, Total	96%	97%
Volatile Organics 8260 via low		
Benzene	ND	ND
Toluene	ND	ND
Trichlorofluoromethane	ND	ND
Acetone	ND	ND
2-Butanone	ND	ND
4-Methyl-2-pentanone	ND	ND
p-Isopropyltoluene	ND	ND
Acrolein	ND	ND
Polynuclear Aromatic Hydrocarbons		
Fluoranthene	ND	ND
Benzo(a)anthracene	ND	ND
Benzo(a)pyrene	ND	ND
Benzo(b)fluoranthene	ND	ND
Benzo(k)fluoranthene	ND	ND
Chrysene	ND	ND
Anthracene	ND	ND
Benzo(ghi)perylene	ND	ND
Phenanthrene	ND	ND
Dibenzo(a,h)anthracene	ND	ND
Indeno(1,2,3-cd)Pyrene	ND	ND
Pyrene	ND	ND
Perylene	ND	ND
Benzo(e)Pyrene	ND	ND
Petroleum Hydrocarbons		
Diesel Range Organics	ND	ND

TRACE METAL ANALYSIS FOR CONTROL SAMPLES

FRESH VIRGIN SAND

	DISTRICT 4	DISTRICT 5
Metals	Peabody	Dartmouth
	PEAFVS6	**DMFVS1**
	Mg/kg	mg/kg
Arsenic	1.9	2.3
Barium	2.7	3.2
Cadmium	ND	ND
Chromium	2.2	3.2
Lead	ND	2.3
Selenium	ND	ND
Silver	ND	ND
Sodium	ND	110

ANALYTE VALUES FOR STREET SWEEPINGS

	DISTRICT 4						DISTRICT 5	
LOCATION	RTE 95 N	RTE 128	RTE 93	RTE 1	RTE-93	RTE-1	RTE 6 W	I-195 E
	Salisbury	Reading	Milton	Peabody	Wilmington	Revere	Dartmouth	Marion
SS- Street Sweeping	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**
SAMPLE ID	SBYSS02	RDGSS03	MLTSS04	PEASS6	WMNSS7	REVSS8	DMSS1	MARSS5
SAMPLING DATE	5-Apr-06	5-Apr-06	5-Apr-06	1-Jun-06	1-Jun-06	1-Jun-06	30-Mar-06	20-Apr-06
	ug/kg	ug/kg	ug/kg	Ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
Solids, Total	82%	92%	92%	84%	98%	93%	97%	94%
Volatile Organics 8260 via low								
Benzene	ND	ND	ND	ND	ND	1.6	ND	ND
Toluene	ND	ND	ND	ND	ND	2	ND	ND
Trichlorofluoromethane	36	ND	ND	ND	ND	ND	ND	ND
Acetone	330	100	ND	91	200	360	210	240
2-Butanone	35	ND	ND	ND	24	44	32	27
4-Methyl-2-pentanone	69	ND	ND	ND	51	65	23	20
p-Isopropyltoluene	ND	ND	220	ND	ND	ND	ND	ND
Acrolein	ND	ND	ND	ND	ND	ND	44	ND

	DISTRICT 4						DISTRICT 5	
LOCATION	RTE 95 N	RTE 128	RTE 93	RTE 1	RTE-93	RTE-1	RTE 6 W	I-195 E
	Salisbury	Reading	Milton	Peabody	Wilmington	Revere	Dartmouth	Marion
SS- Street Sweeping	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**	**SS**
SAMPLE ID	SBYSS02	RDGSS03	MLTSS04	PEASS6	WMNSS7	REVSS8	DMSS1	MARSS5
SAMPLING DATE	5-Apr-06	5-Apr-06	5-Apr-06	1-Jun-06	1-Jun-06	1-Jun-06	30-Mar-06	20-Apr-06
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
Polynuclear Aromatic Hydrocarbons								
Fluoranthene	1800	760	2500	1400	1800	2100	1400	890
Benzo(a)anthracene	540	360	780	450	470	710	380	290
Benzo(a)pyrene	580	410	740	500	740	1000	580	330
Benzo(b)fluoranthene	1100	690	1400	840	1400	2100	830	370
Benzo(k)fluoranthene	610	410	880	510	630	1100	670	650
Chrysene	780	400	1100	640	1000	1300	710	530
Anthracene	ND	ND	ND	ND	ND	150	87	ND
Benzo(ghi)perylene	440	390	ND	380	530	730	410	350
Phenanthrene	640	270	1200	510	700	800	630	370
Dibenzo(a,h)anthracene	ND	ND	ND	ND	150	210	110	ND
Indeno(1,2,3-cd)Pyrene	460	380	ND	380	520	750	440	280
Pyrene	1300	670	1900	1100	1400	1800	1100	660
Perylene	160	140	ND	ND	ND	ND	140	ND
Benzo(e)Pyrene	530	380	790	460	710	970	530	370
Petroleum Hydrocarbons								
Diesel Range Organics	ND	ND	980000	360000	330000	890000	37000	170000

TRACE METAL ANALYSIS FOR STREET SWEEPINGS

	STREET SWEEPINGS							
	DISTRICT 4						DISTRICT 5	
Metals	Peabody	Salisbury	Reading	Milton	Wilmington	Revere	Dartmouth	Marion
	PEASS6	**SBYSS2**	**RDGSS3**	**MLTSS4**	**WMNSS7**	**REVSS8**	**DMSS1**	**MARSS5**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Arsenic	4.3	6.1	6.1	4	5.4	4.4	2.1	2.4
Barium	16	26	49	54	30	76	18	14
Cadmium	ND	ND	ND	ND	ND	0.79	ND	ND
Chromium	27	53	100	94	40	88	44	27
Lead	53	90	40	65	19	120	110	24
Selenium	ND	ND	ND	ND	ND	1.7	ND	ND
Silver	ND	ND	ND	ND	ND	ND	ND	ND
Sodium	360	990	1000	940	350	900	2000	520

ANALYTE VALUES FOR CATCH BASIN CLEANINGS

District 3				
LOCATION	RTE 290	RTE 12	RTE 197	RTE 495S
CB- Catch Basin Cleaning	Worcester	Auburn	Dudley	Westford
SAMPLE ID	WORCB8	AUBCB9	DUDCB10	WFDCB16
SAMPLING DATE	17-Aug-06	28-Mar-07	6-Apr-07	16-Aug-07
	Ug/kg	ug/kg	ug/kg	ug/kg
PARAMETER				
Solids, Total	60%	77%	91%	93%
Volatile Organics 8260 via low				
Toluene	1500	900	ND	ND
Ethylbenzene	ND	ND	ND	ND
Acetone	ND	ND	ND	9.4
2-Butanone	ND	ND	ND	ND
4-Methyl-2-pentanone	ND	ND	ND	ND
p-Isopropyltoluene	490	150	90	ND
Naphthalene	ND	ND	ND	ND
Polynuclear Aromatic Hydrocarbons				
Fluoranthene	4800	5800	5400	ND
Benzo(a)anthracene	1400	1700	1700	ND
Benzo(a)pyrene	1400	1600	1400	ND
Benzo(b)fluoranthene	2200	1700	1400	ND
Benzo(k)fluoranthene	1600	1800	1500	ND
Chrysene	2100	2000	1600	ND
Acenapthylene	ND	ND	ND	ND
Anthracene	ND	ND	1000	ND
Benzo(ghi)perylene	1300	1100	850	ND
Fluorene	ND	ND	530	ND
Phenanthrene	2800	2900	3900	ND
Dibenzo(a,h)anthracene	ND	ND	ND	ND
Indeno(1,2,3-cd)Pyrene	1100	1100	850	ND
Pyrene	3600	4700	4200	ND
1-Methylnapthalene	ND	ND	ND	ND
2-Methylnapthalene	ND	ND	ND	ND
Perylene	ND	ND	400	ND
Benzo(e)Pyrene	1300	1200	1000	ND
Petroleum Hydrocarbons				
Gasoline Range Organics	ND	ND	ND	ND
Diesel Range Organics	790000	600000	320000	600000

DISTRICT 4							
LOCATION	RTE 3	RTE 128	RTE 495	RTE 93	RTE 1	RTE 128	RTE 3
CB- Catch Basin Cleaning	Chelmsford	Reading	Tewksbury	Braintree	Newbury	Reading	Braintree
SAMPLE ID	**CFDCB4**	**RDGCB5**	**TBYCB6**	**BTRCB7**	**NBYCB17**	**RDGCB18**	**BTRCB19**
SAMPLING DATE	1-Dec-05	1-Dec-05	1-Dec-05	1-Jun-06	2-Oct-07	2-Oct-07	2-Oct-07
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
PARAMETER							
Solids, Total	76%	83%	66%	74%	91%	92%	92%
Volatile Organics 8260 via low							
Toluene	290	ND	6.6	300	ND	ND	ND
Ethylbenzene	ND	ND	ND	6.6	ND	ND	ND
Acetone	200	58	110	270	ND	28	ND
2-Butanone	34	ND	ND	55	ND	ND	ND
4-Methyl-2-pentanone	32	ND	ND	21	ND	ND	ND
p-Isopropyltoluene	18	ND	22	65	ND	ND	ND
Naphthalene	ND	ND	24	ND	ND	ND	ND

DISTRICT 4							
LOCATION	RTE 3	RTE 128	RTE 495	RTE 93	RTE 1	RTE 128	RTE 3
CB- Catch Basin Cleaning	Chelmsford	Reading	Tewksbury	Braintree	Newbury	Reading	Braintree
SAMPLE ID	**CFDCB4**	**RDGCB5**	**TBYCB6**	**BTRCB7**	**NBYCB17**	**RDGCB18**	**BTRCB19**
SAMPLING DATE	1-Dec-05	1-Dec-05	1-Dec-05	1-Jun-06	2-Oct-07	2-Oct-07	2-Oct-07
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
PARAMETER							
Polynuclear Aromatic Hydrocarbons							
Fluoranthene	6500	3300	1900	700	2600	2600	2600
Benzo(a)anthracene	1800	950	440	250	1500	1400	1600
Benzo(a)pyrene	1800	970	450	300	1600	1700	1700
Benzo(b)fluoranthene	3400	1600	830	460	1700	2000	2400
Benzo (k)fluoranthene	1800	920	490	220	1400	1400	1500
Chrysene	2900	1400	800	380	1600	1700	1900
Acenapthylene	ND	ND	ND	130	ND	ND	ND
Anthracene	ND	ND	140	130	ND	ND	ND
Benzo(ghi)perylene	1400	770	360	160	1200	1400	1500
Fluorene	ND	ND	ND	81	ND	ND	ND
Phenanthrene	2800	1400	970	500	2100	1300	1200
Dibenzo(a,h)anthracene	ND	ND	100	55	ND	ND	ND
Indeno(1,2,3-cd)Pyrene	1400	760	380	160	1000	1200	1200
Pyrene	5200	2700	1400	780	2000	1900	1700
1-Methylnapthalene	ND	ND	ND	48	ND	ND	ND
2-Methylnapthalene	ND	ND	ND	44	ND	ND	ND
Perylene	520	ND	120	ND	ND	ND	ND
Benzo(e)Pyrene	1800	930	450	240	1100	1400	1500
Petroleum Hydrocarbons							
Gasoline Range Organics	ND	ND	5900	ND	ND	ND	ND
Diesel Range Organics	560000	580000	440000	190000	84000	260000	240000

DISTRICT 5								
LOCATION	RTE 24 S	RTE 95 S	RTE 3 N	RTE 3A	RTE 6W	RTE 25W	RTE 495 S	RTE 28N
CB- Catch Basin Cleaning	Stoughton	Attleboro	Plymouth	Plimpton	Sagamore	Bourne	Middleboro	Bridgewater
SAMPLE ID	**STOCB1**	**ATBCB2**	**PLYCB3**	**PLICB11**	**SAGCB12**	**BOUCB13**	**MIDCB14**	**BRWCB15**
SAMPLING DATE	1-Nov-05	7-Nov-05	15-Nov-05	11-Jun-07	13-Jun-07	25-Jun-07	28-Jun-07	11-Jul-07
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
PARAMETER								
Solids, Total	89%	78%	83%	79%	96%	88%	76%	62%
Volatile Organics 8260 via low								
Toluene	ND	ND	320	ND	ND	ND	25	990
Ethylbenzene	ND	ND	ND	ND	ND	ND	ND	ND
Acetone	160	320	320	390	110	180	180	ND
2-Butanone	ND	31	33	75	ND	ND	23	ND
4-Methyl-2-pentanone	ND	ND	ND	ND	ND	ND	ND	ND
p-Isopropyltoluene	ND	ND	67	ND	ND	ND	8.1	3800
Naphthalene	ND	ND	ND	ND	ND	ND	ND	ND

DISTRICT 5								
LOCATION	RTE 24 S	RTE 95 S	RTE 3 N	RTE 3A	RTE 6W	RTE 25W	RTE 495 S	RTE 28N
CB- Catch Basin Cleaning	Stoughton	Attleboro	Plymouth	Plympton	Sagamore	Bourne	Middleboro	Bridgewater
SAMPLE ID	STOCB1	ATBCB2	PLYCB3	PLICB11	SAGCB12	BOUCB13	MIDCB14	BRWCB15
SAMPLING DATE	1-Nov-05	7-Nov-05	15-Nov-05	11-Jun-07	13-Jun-07	25-Jun-07	28-Jun-07	11-Jul-07
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg
PARAMETER								
Polynuclear Aromatic Hydrocarbons								
Fluoranthene	1600	2300	1600	2600	280	ND	780	15000
Benzo(a)anthracene	480	820	500	690	89	ND	ND	4200
Benzo(a)pyrene	460	740	440	850	97	ND	ND	5200
Benzo(b)fluoranthene	840	1200	650	1100	140	ND	ND	7000
Benzo(k)fluoranthene	490	710	420	990	120	ND	ND	5100
Chrysene	690	1000	700	900	110	ND	ND	5400
Acenapthylene	ND	ND	ND	ND	ND	ND	ND	
Anthracene	ND	ND	ND	ND	ND	ND	ND	660
Benzo(ghi)perylene	ND	520	ND	670	94	ND	ND	3400
Fluorene	ND	ND	ND	ND	ND	ND	ND	
Phenanthrene	680	1000	1000	750	120	ND	ND	5700
Dibenzo(a,h)anthracene	ND	ND	ND	ND	ND	ND	ND	820
Indeno(1,2,3-cd)Pyrene	ND	520	ND	660	81	ND	ND	3600
Pyrene	1200	2000	1200	2000	220	ND	610	11000
1-Methylnapthalene	ND	ND	ND	ND	ND	ND	ND	ND
2-Methylnapthalene	ND	ND	ND	ND	ND	ND	ND	ND
Perylene	ND	ND	ND	ND	ND	ND	ND	1100
Benzo(e)Pyrene	450	680	ND	700	93	ND	ND	3700
Petroleum Hydrocarbons								
Gasoline Range Organics	ND	ND	ND	ND	ND	ND	ND	16000
Diesel Range Organics	450000	410000	380000	290000	59000	530000	610000	980000

TRACE METAL ANALYSIS FOR CATCH BASIN CLEANINGS

Catch Basin Cleanings											
	District 3				District 4						
Metals	Worcester	Westford	Auburn	Dudley	Chelmsford	Reading	Tewksbury	Braintree	Newbury	Reading	Braintree
	WORCB8	**WFDCB16**	**AUBCB9**	**DUDCB10**	**CFDCB4**	**RDGCB5**	**TBYCB6**	**BTRCB7**	**NBYCB17**	**RDGCB18**	**BTRCB19**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Arsenic	6.5	4.1	5.2	4.9	4.2	5.4	3.6	3.2	5.1	4.7	4.3
Barium	53	22	33	25	25	45	23	13	62	49	20
Cadmium	ND	0.5	ND	ND	ND	0.73	ND	ND	ND	0.64	ND
Chromium	50	21	46	36	35	36	23	15	49	110	47
Lead	50	17	52	39	86	110	45	100	130	96	190
Selenium	ND	ND	ND	ND	ND	0.97	ND	ND	ND	ND	ND
Silver	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sodium	6100	220	370	450	1400	760	510	2200	520	370	3000

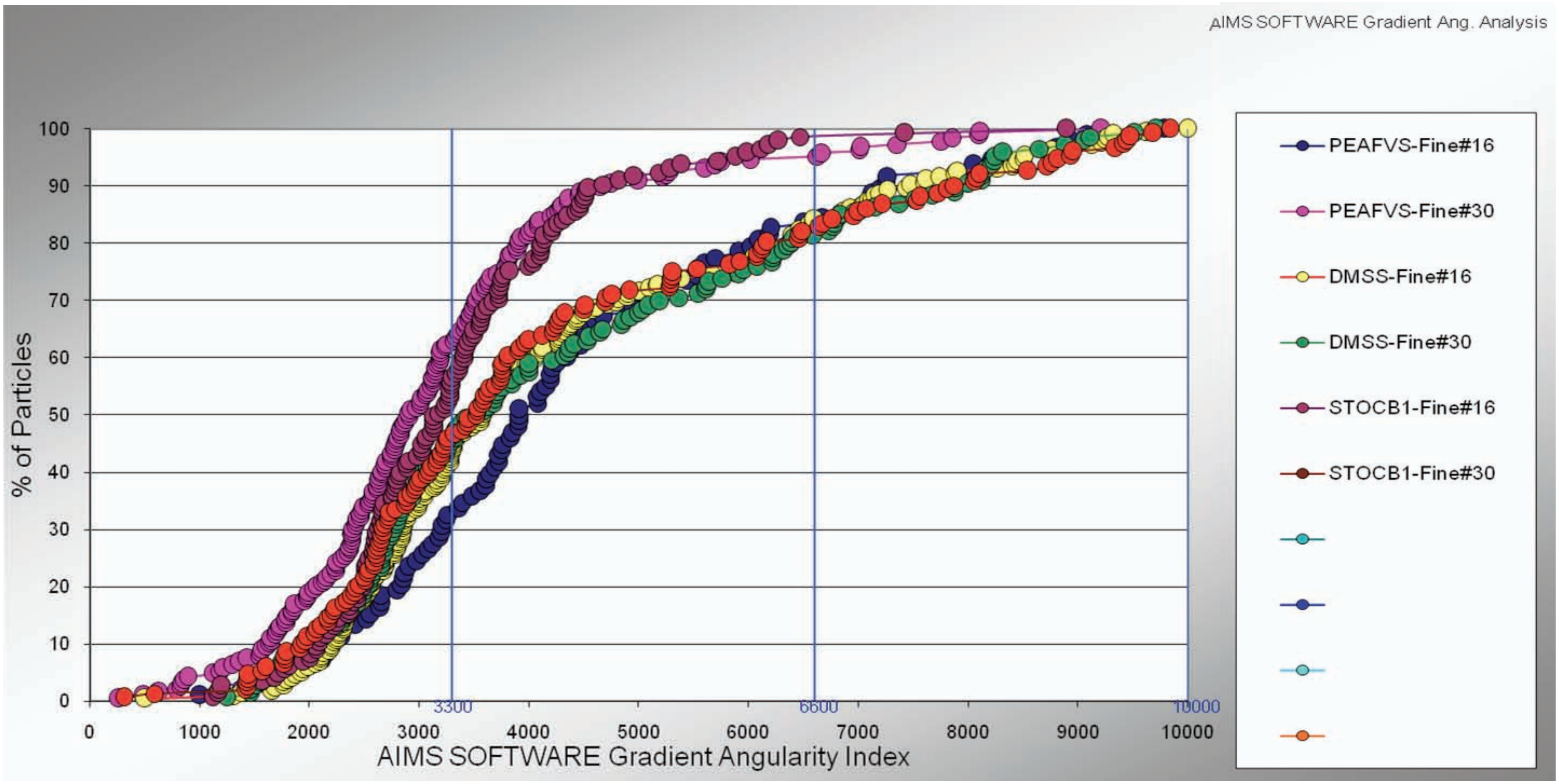
Catch Basin Cleanings

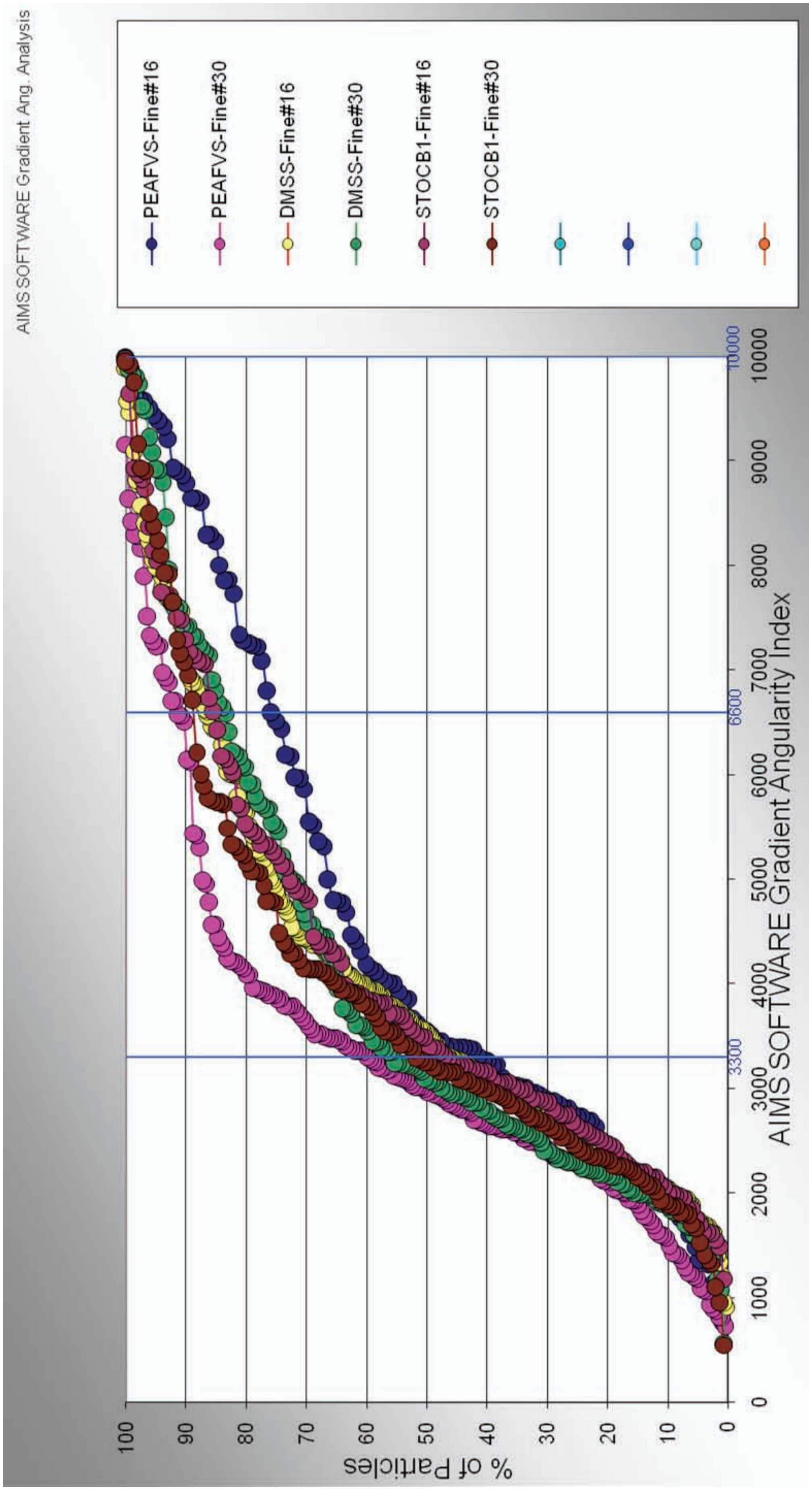
District 5

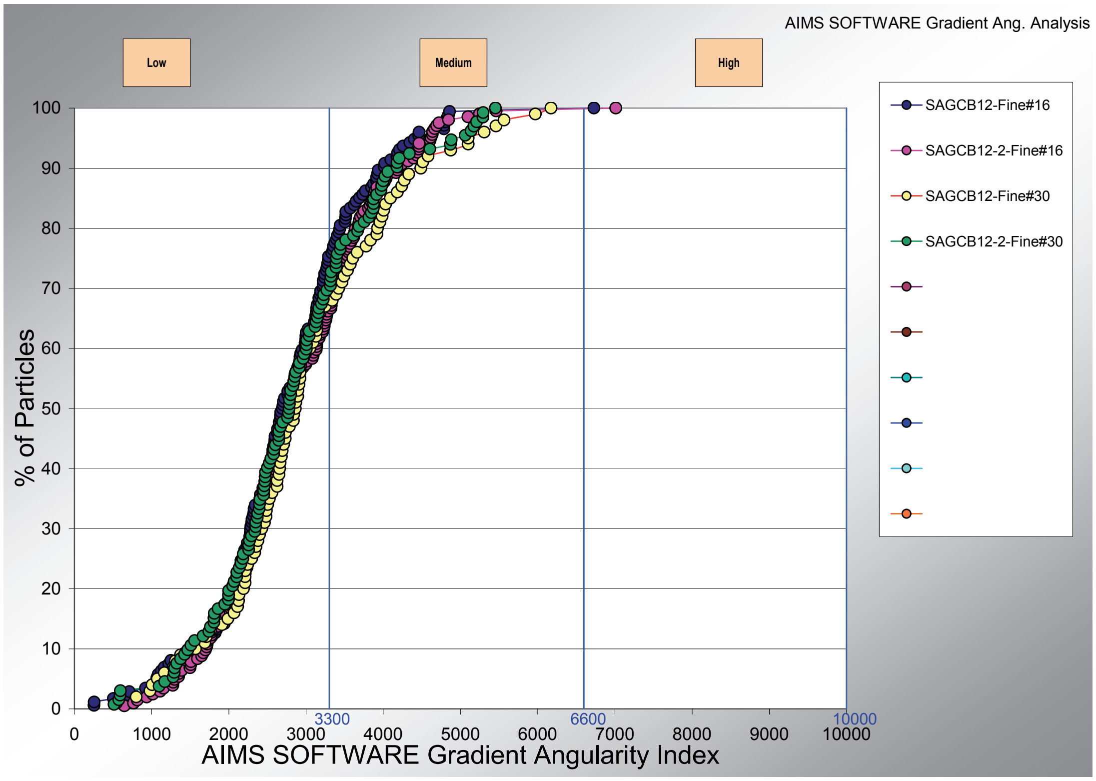
Metals	Stoughton	Attleboro	Plymouth	Plympton	Sagamore	Bourne	Middleboro	Bridgewater
	STOCB1	**ATBCB2**	**PLYCB3**	**PLICB11**	**SAGCB12**	**BOUCB13**	**MIDCB14**	**BRWCB15**
	mg/kg	mg/kg	mg/kg	Mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Arsenic	2.6	1.9	1.9	4	4.9	3.2	3.1	3.6
Barium	14	18	21	28	19	28	23	25
Cadmium	ND	ND	ND	ND	ND	ND	0.63	ND
Chromium	43	29	32	58	13	26	15	27
Lead	68	80	38	23	9.5	23	120	53
Selenium	ND	ND	ND	1.7	ND	ND	ND	ND
Silver	ND	ND	ND	ND	ND	ND	ND	ND
Sodium	480	680	2600	270	260	420	800	440

APPENDIX D: GEOTECHNICAL CHARACTERIZATION

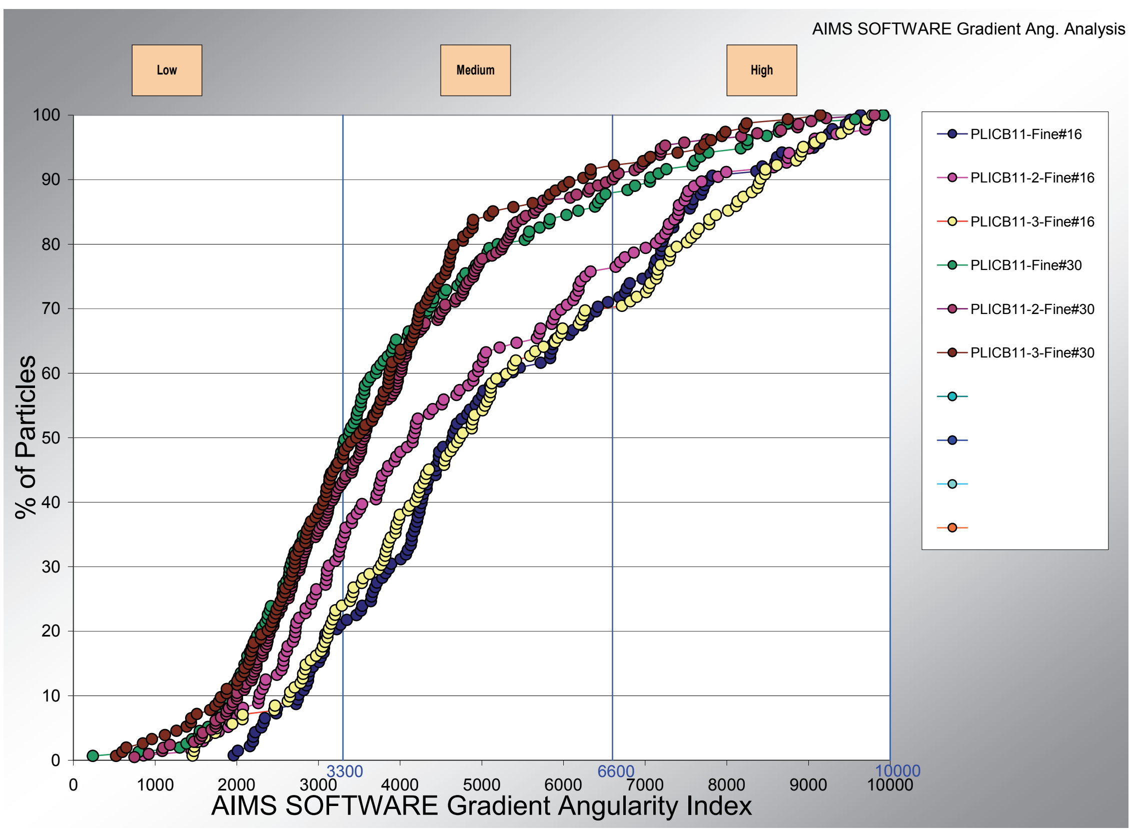
GRADIENT ANGULARITY INDEX CHARTS



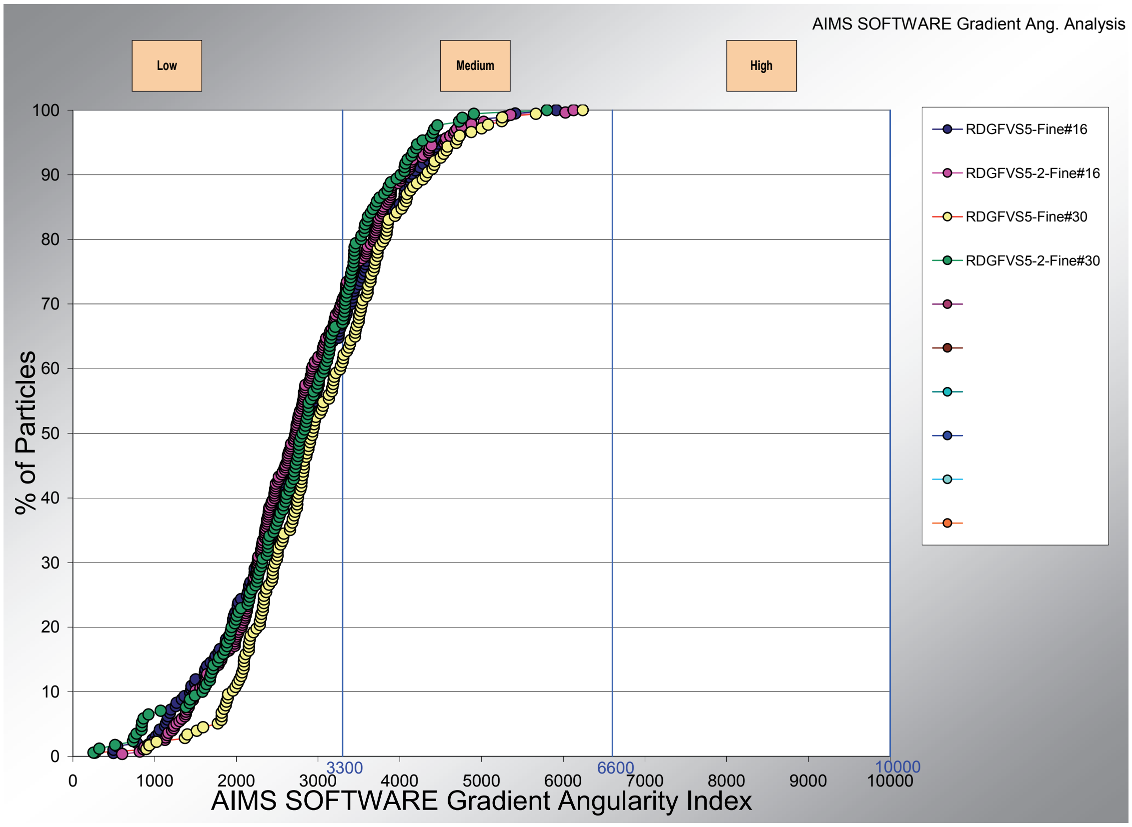

AIMS SOFTWARE Gradient Ang. Analysis
% of Particles
AIMS SOFTWARE Gradient Angularity Index
3300
6600
10000
PEAFVS-Fine#16
PEAFVS-Fine#30
DMSS-Fine#16
DMSS-Fine#30
STOCB1-Fine#16
STOCB1-Fine#30



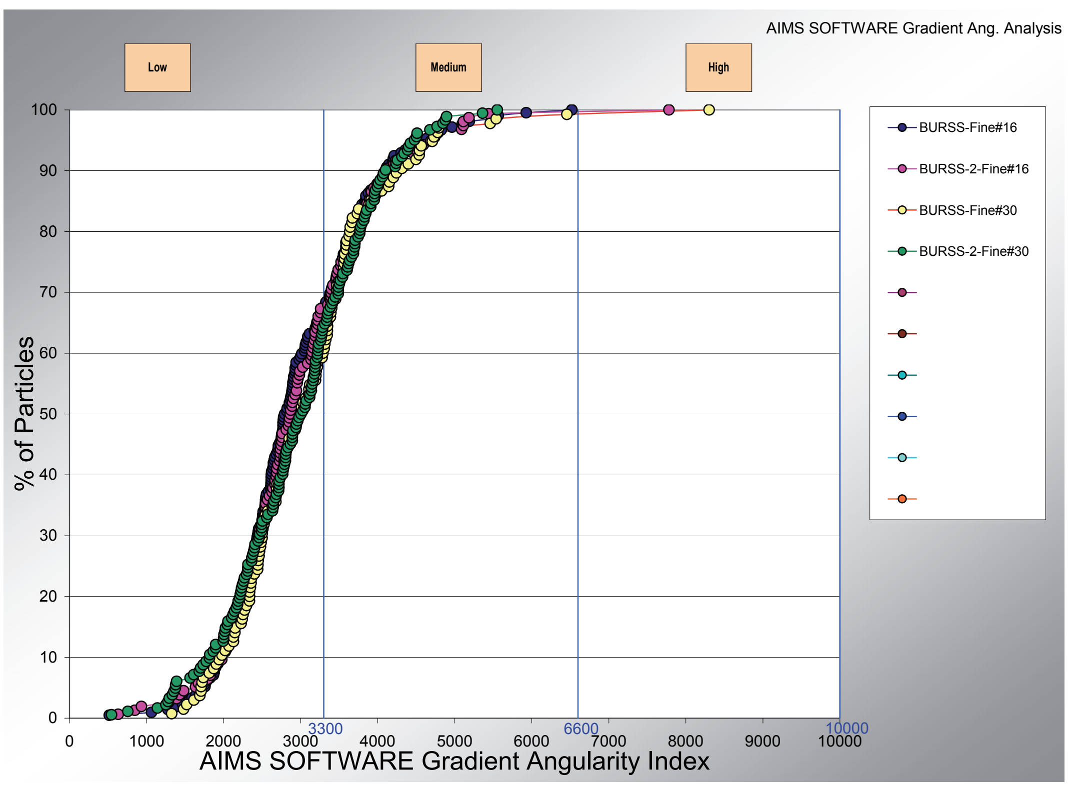
SAGCB12



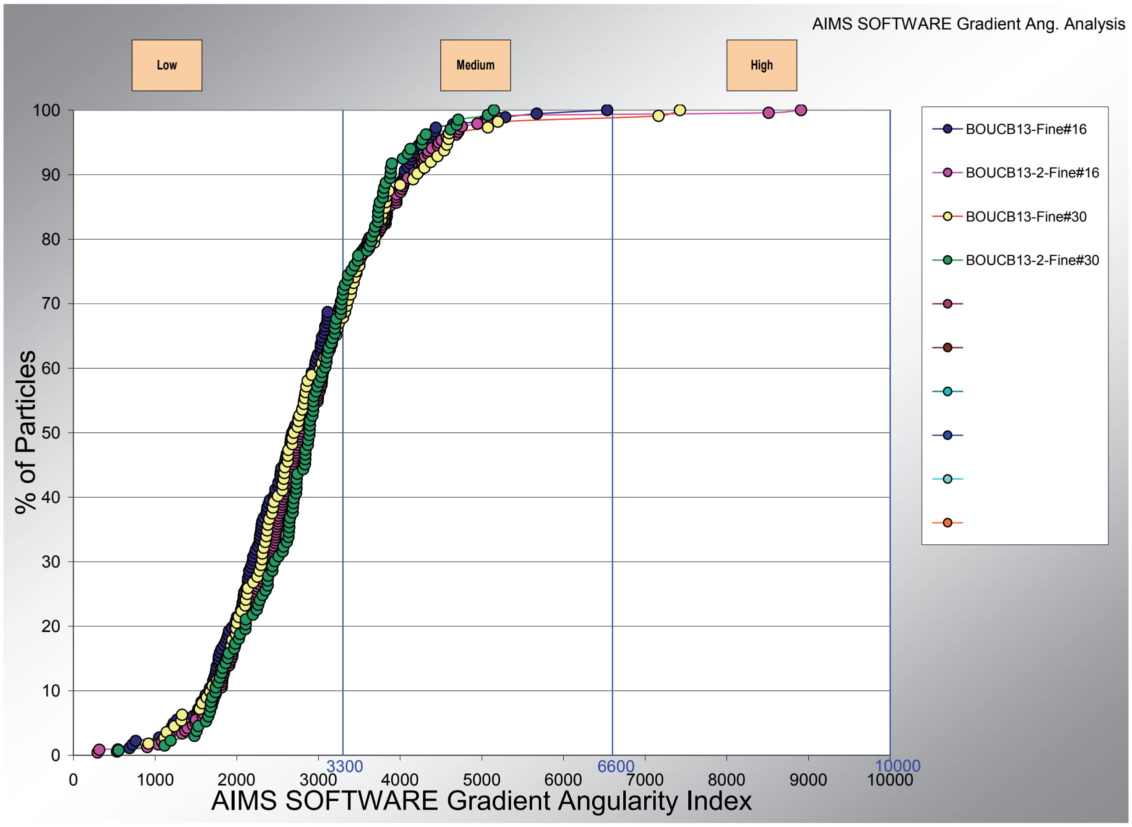
PLICB11



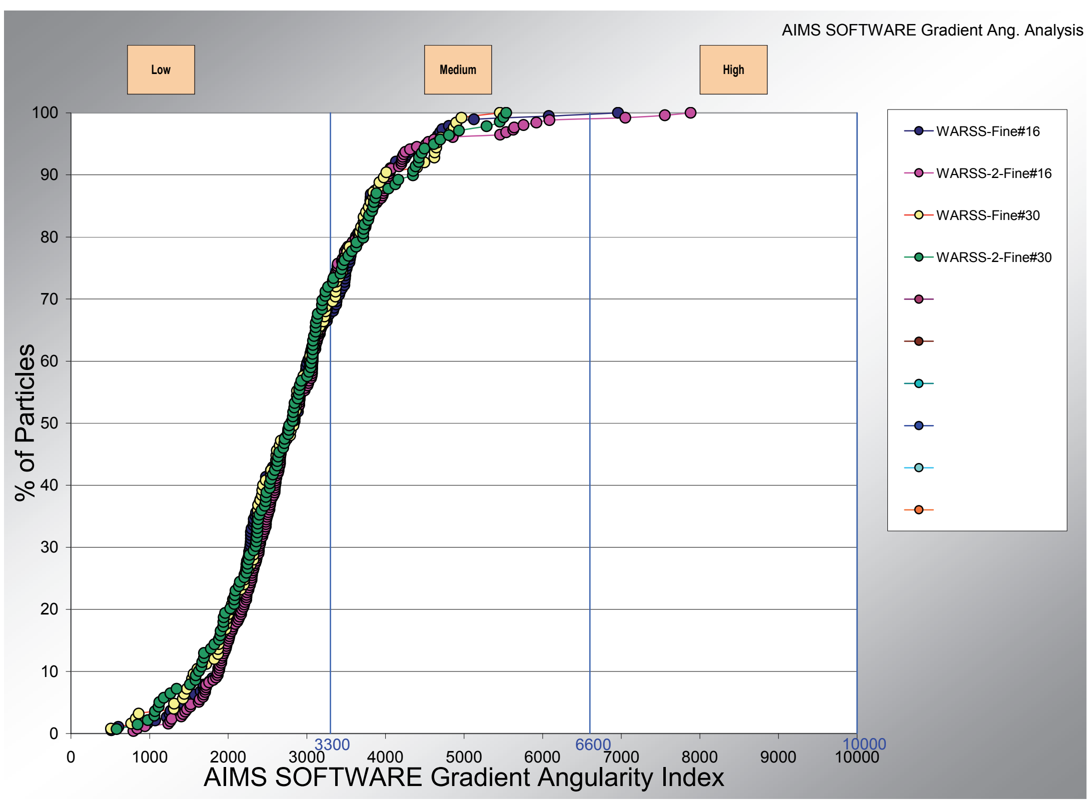
RDGFVS5



BURSS

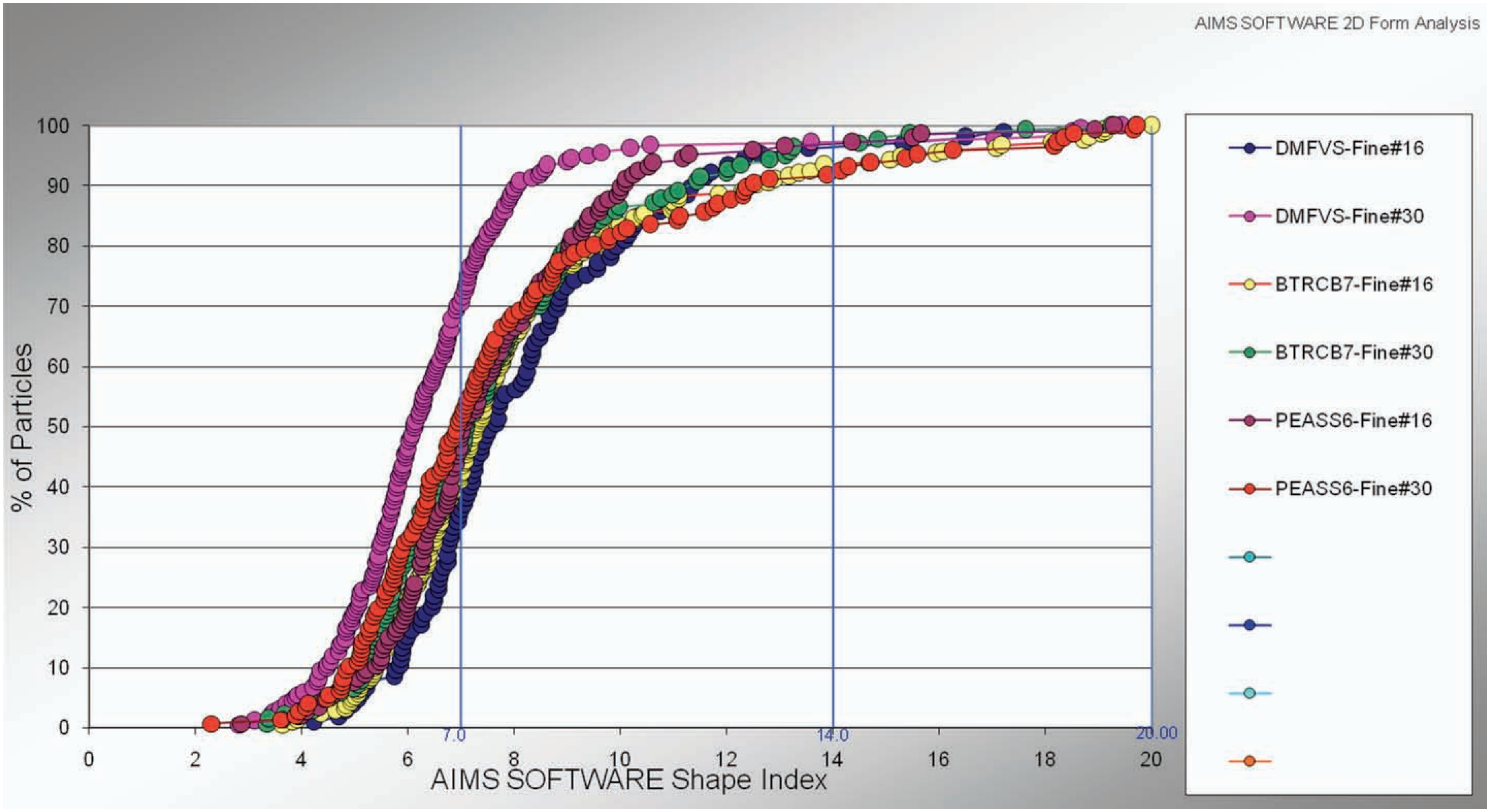


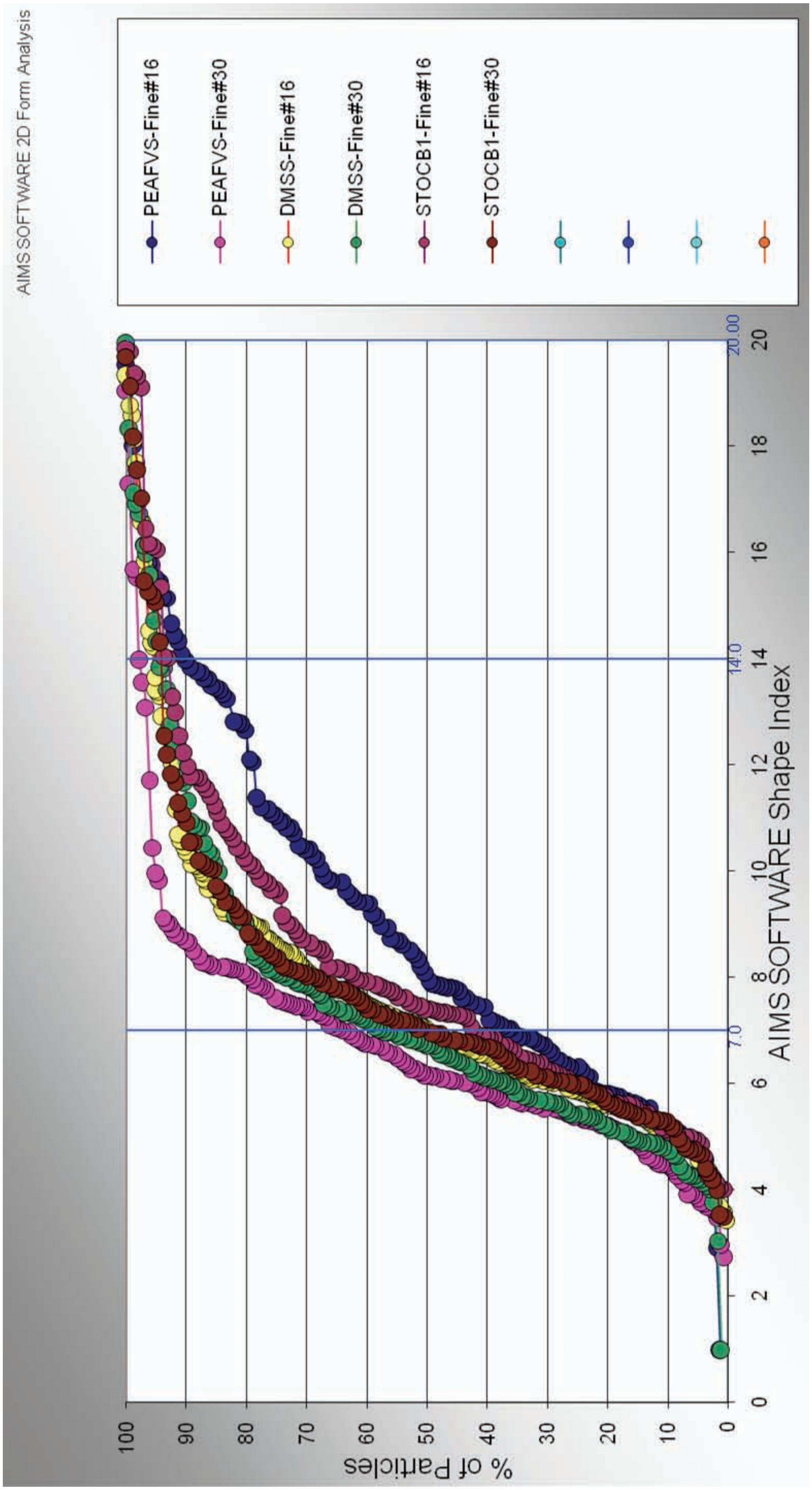
BOUCB13

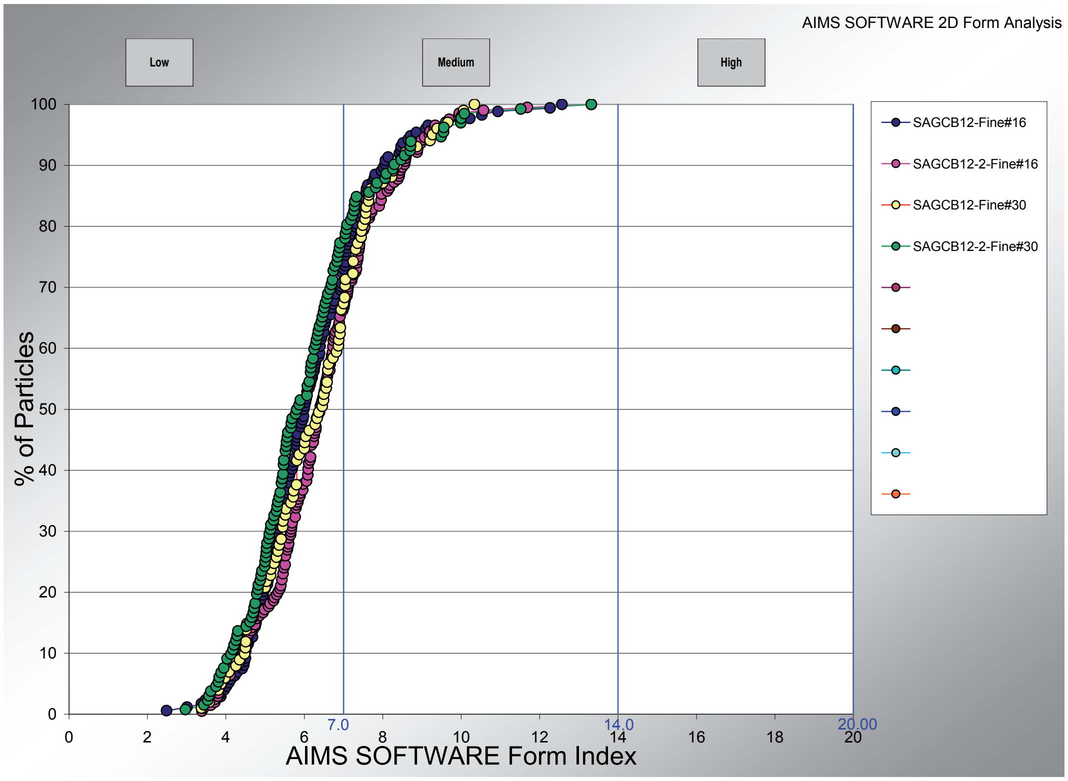


WARSS

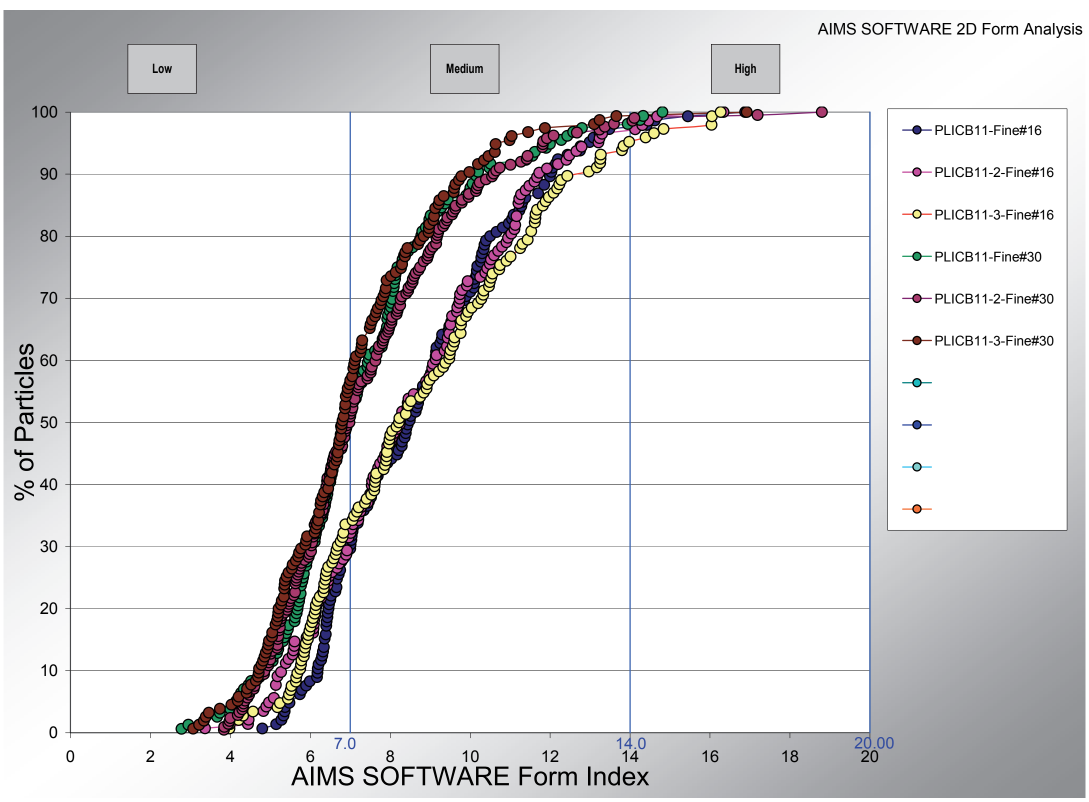
2D FORM INDEX CHARTS



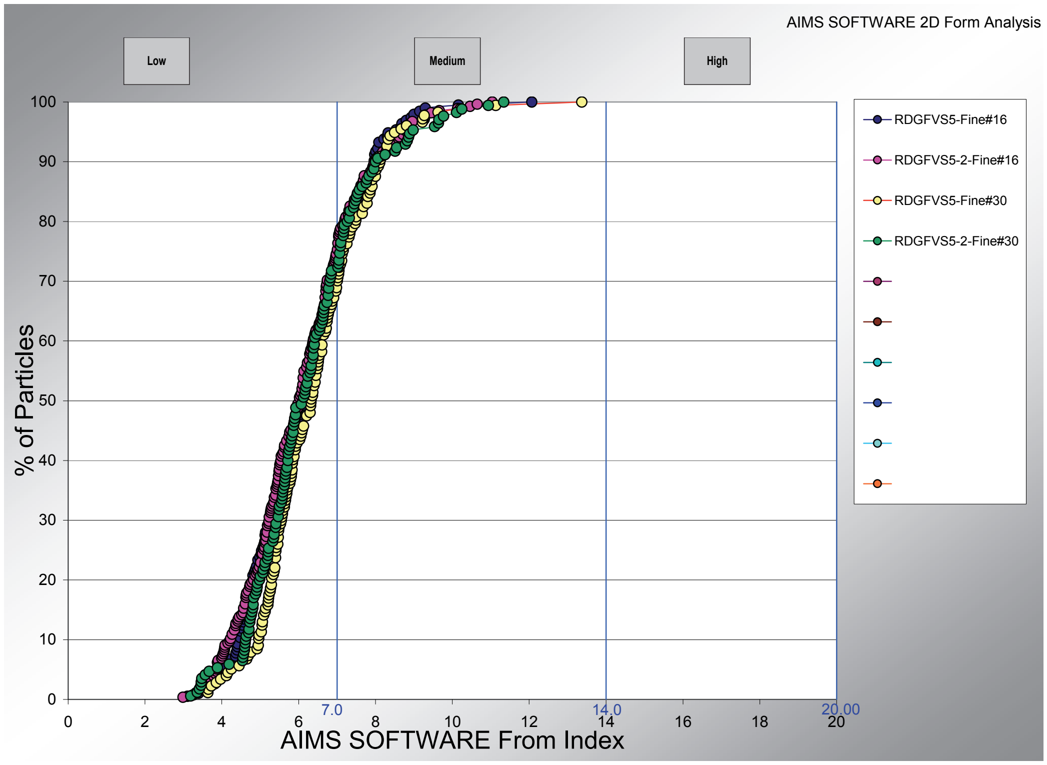

AIMS SOFTWARE 2D Form Analysis
PEAFVS-Fine#16
PEAFVS-Fine#30
DMSS-Fine#16
DMSS-Fine#30
STOCB1-Fine#16
STOCB1-Fine#30
% of Particles
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20
7.0
14.0
20.00
AIMS SOFTWARE Shape Index



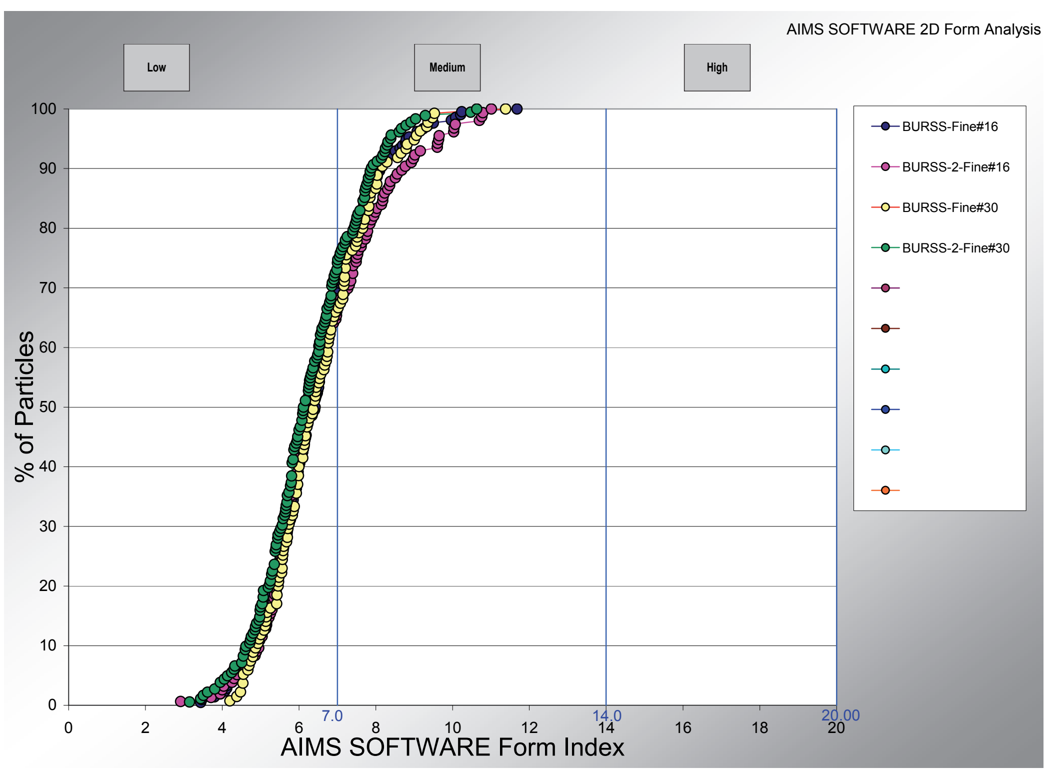
SAGCB12



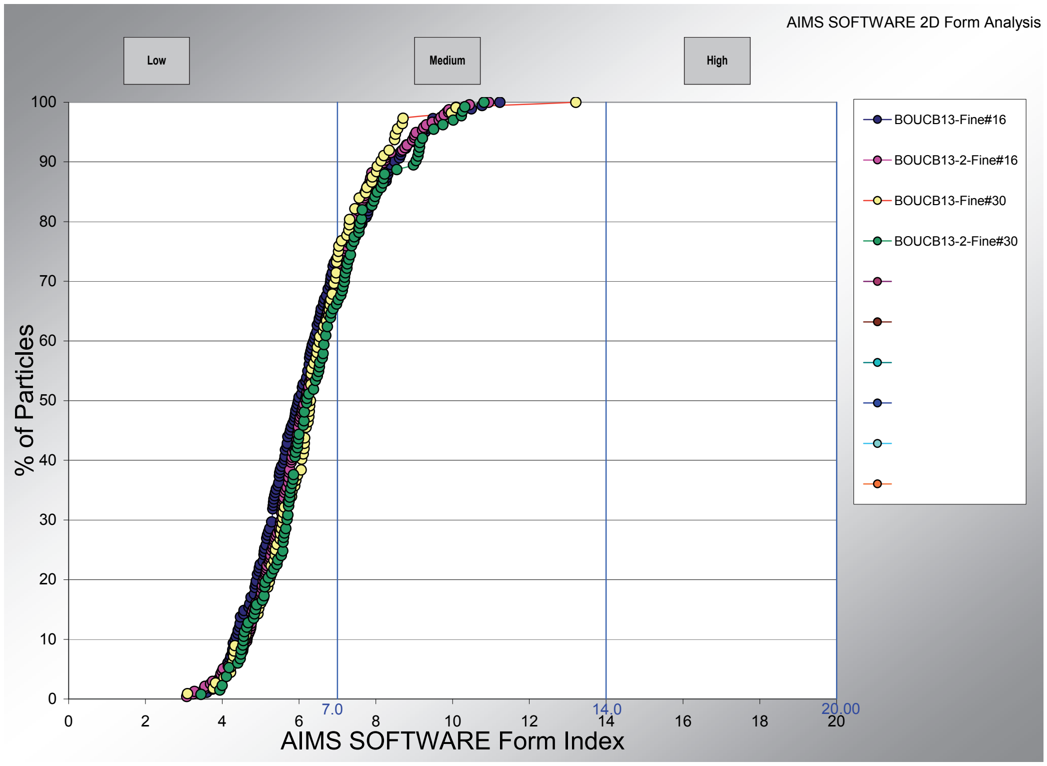
PLICB11



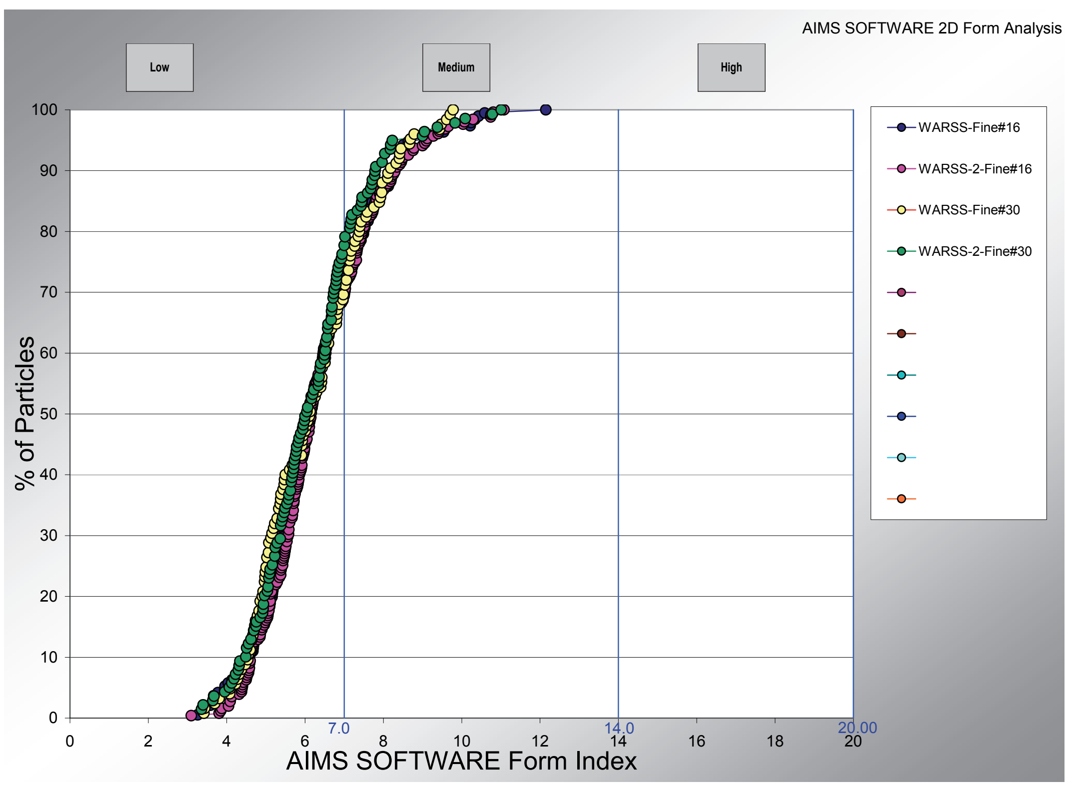
RDGFVS5



BURSS



BOUCB13



WARSS

APPENDIX E: EXPLORATION OF REUSE OPTIONS

SPECIFIC GRAVITY RESULTS

Bulk Specific Gravity Results Summary				
	BSG	BSG	BSG	Absorption
Sample Location	(Dry)	(SSD)	(Apparent)	(%)
District 4				
Lexington - FVS (A)	2.425	2.453	2.496	1.18
Lexington - FVS (B)	2.258	2.332	2.437	3.20
Westwood - SS	2.661	2.679	2.709	0.66
Burlington - FVS	2.615	2.629	2.651	0.52
Burlington - SS	2.599	2.617	2.647	0.70
Reading - FVS	2.611	2.628	2.657	0.66
Reading - SS	2.600	2.615	2.640	0.58
Peabody - FVS	2.625	2.640	2.665	0.58
Peabody - SS	2.584	2.607	2.644	0.88
Tewksbury - FVS	2.612	2.627	2.653	0.58
Tewksbury - SS	2.547	2.573	2.614	1.00
Tewksbury - CB	2.630	2.651	2.687	0.80
District 5				
Dartmouth - FVS	2.589	2.610	2.644	0.80
Dartmouth - SS	2.606	2.623	2.651	0.66
Wareham - FVS	2.626	2.639	2.660	0.48
Wareham - SS	2.541	2.577	2.636	1.42

Comparative Analysis of Composite Results with Influent Samples

Sample ID	Diesel Range Organic	Gasoline Range Organic	Fluoranthene	Pyrene
	µg/Kg	µg/Kg	µg/Kg	µg/Kg
WORCB8	790,000	2,700	4800	3600
AUBCB9	600,000	2,700	5800	4700
DUDCB10	320,000	2,700	5400	4200
CFDCB4	560,000	2,700	6500	5200
RDGCB5	580,000	2,700	3300	2700
TBYCB6	440,000	5,900	1900	1400
BTRCB7	190,000	2,700	700	780
STOCB1	450,000	2,700	1600	1200
ATBCB2	410,000	2,700	2300	2000
PLYCB3	380,000	2,700	1600	1200
PLICB11	290,000	2,700	2600	2000
SAGCB12	59,000	2,700	280	220
BOUCB13	530,000	2,700	69	760
MIDCB14	610,000	2,700	780	610
BRWCB15	980,000	16,000	15,000	11000
Average	479,267	3,800	3,509	2,771
Composite Compost				
Sampled Dec.14,2007	240,000	2,200	2,800	2,100

SSDetect & AVM (Reference T-84)	
Specimen:	Lexington FVS (A)
Date:	12/27/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.5
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	982.9
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-Vacuum] (g)	991.2
Film Coefficient	78
SSDetect	
Mass of Bowl + Cover (g)	284.5
Mass of Bowl + Cover + Specimen @ SSD	790.4
S = SSD Mass (g)	505.9
Bulk Specific Gravity Calculations	
BSG (dry)	2.425
BSG (SSD)	2.453
BSG (Apparent)	2.496
Absorption (%)	1.18

SSDetect & AVM (Reference T-84)	
Specimen:	Lexington FVS (B)
Date:	12/27/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.3
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-Vacuum] (g)	990.1
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.5
Mass of Bowl + Cover + Specimen @ SSD	800.7
S = SSD Mass (g)	516.2
Bulk Specific Gravity Calculations	
BSG (dry)	2.258
BSG (SSD)	2.332
BSG (Apparent)	2.437
Absorption (%)	3.2

SSDetect & AVM (Reference T-84)	
Specimen:	Westwood SS
Date:	12/27/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.5
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-Vacuum] (g)	1006.9
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	787.9
S = SSD Mass (g)	503.3
Bulk Specific Gravity Calculations	
BSG (dry)	2.661
BSG (SSD)	2.679
BSG (Apparent)	2.709
Absorption (%)	0.66

SSDetect & AVM (Reference T-84)	
Specimen:	Burlington FVS
Date:	12/19/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.6
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	1004.0
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1007.0
Film Coefficient	63
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	787.2
S = SSD Mass (g)	502.6
Bulk Specific Gravity Calculations	
BSG (dry)	2.615
BSG (SSD)	2.629
BSG (Apparent)	2.651
Absorption (%)	0.52

SSDetect & AVM (Reference T-84)	
Specimen:	Burlington SS
Date:	12/29/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.5
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1002.6
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	788.1
S = SSD Mass (g)	503.5
Bulk Specific Gravity Calculations	
BSG (dry)	2.599
BSG (SSD)	2.617
BSG (Apparent)	2.647
Absorption (%)	0.70

SSDetect & AVM (Reference T-84)	
Specimen:	Reading FVS
Date:	12/21/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.2
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	1002.9
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1007.0
Film Coefficient	67
SSDetect	
Mass of Bowl + Cover (g)	284.5
Mass of Bowl + Cover + Specimen @ SSD	787.8
S = SSD Mass (g)	503.3
Bulk Specific Gravity Calculations	
BSG (dry)	2.611
BSG (SSD)	2.628
BSG (Apparent)	2.657
Absorption (%)	0.66

SSDetect & AVM (Reference T-84)	
Specimen:	Reading SS
Date:	12/29/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.7
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1006.3
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	787.5
S = SSD Mass (g)	502.9
Bulk Specific Gravity Calculations	
BSG (dry)	2.600
BSG (SSD)	2.615
BSG (Apparent)	2.640
Absorption (%)	0.58

SSDetect & AVM (Reference T-84)	
Specimen:	Peabody FVS
Date:	12/21/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.1
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	1001.8
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1003.5
Film Coefficient	58
SSDetect	
Mass of Bowl + Cover (g)	284.5
Mass of Bowl + Cover + Specimen @ SSD	787.4
S = SSD Mass (g)	502.9
Bulk Specific Gravity Calculations	
BSG (dry)	2.625
BSG (SSD)	2.640
BSG (Apparent)	2.665
Absorption (%)	0.58

SSDetect & AVM (Reference T-84)	
Specimen:	Peabody SS
Date:	12/28/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.3
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1006.2
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	789.0
S = SSD Mass (g)	504.4
Bulk Specific Gravity Calculations	
BSG (dry)	2.584
BSG (SSD)	2.607
BSG (Apparent)	2.644
Absorption (%)	0.88

SSDetect & AVM (Reference T-84)	
Specimen:	Tewksbury FVS
Date:	12/21/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.2
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	1002.5
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1006.7
Film Coefficient	67
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	787.5
S = SSD Mass (g)	502.9
Bulk Specific Gravity Calculations	
BSG (dry)	2.612
BSG (SSD)	2.627
BSG (Apparent)	2.653
Absorption (%)	0.58

SSDetect & AVM (Reference T-84)	
Specimen:	Tewksbury SS
Date:	12/28/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.4
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1000.1
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	789.6
S = SSD Mass (g)	505.0
Bulk Specific Gravity Calculations	
BSG (dry)	2.547
BSG (SSD)	2.573
BSG (Apparent)	2.614
Absorption (%)	1.00

SSDetect & AVM (Reference T-84)	
Specimen:	Tewksbury CB
Date:	12/27/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.5
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1005.4
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	788.6
S = SSD Mass (g)	504.0
Bulk Specific Gravity Calculations	
BSG (dry)	2.630
BSG (SSD)	2.651
BSG (Apparent)	2.687
Absorption (%)	0.80

SSDetect & AVM (Reference T-84)	
Specimen:	Dartmouth FVS
Date:	12/14/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.5
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	997.8
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1002.4
Film Coefficient	68
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	788.6
S = SSD Mass (g)	504.0
Bulk Specific Gravity Calculations	
BSG (dry)	2.589
BSG (SSD)	2.610
BSG (Apparent)	2.644
Absorption (%)	0.80

SSDetect & AVM (Reference T-84)	
Specimen:	Dartmouth SS
Date:	12/29/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.6
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	N/A
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1003.0
Film Coefficient	#VALUE!
SSDetect	
Mass of Bowl + Cover (g)	284.7
Mass of Bowl + Cover + Specimen @ SSD	788.0
S = SSD Mass (g)	503.3
Bulk Specific Gravity Calculations	
BSG (dry)	2.606
BSG (SSD)	2.623
BSG (Apparent)	2.651
Absorption (%)	0.66

SSDetect & AVM (Reference T-84)	
Specimen:	Wareham FVS
Date:	12/16/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	695.4
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	1005.2
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1007.4
Film Coefficient	60
SSDetect	
Mass of Bowl + Cover (g)	284.6
Mass of Bowl + Cover + Specimen @ SSD	787.0
S = SSD Mass (g)	502.4
Bulk Specific Gravity Calculations	
BSG (dry)	2.626
BSG (SSD)	2.639
BSG (Apparent)	2.660
Absorption (%)	0.48

SSDetect & AVM (Reference T-84)	
Specimen:	Wareham SS
Date:	12/16/2005
Technician:	BE
AVM	
A = Mass of Dry Specimen (g)	500.0
B = Mass of Pyc. + Water @ Cal. (g)	691.7
Mass of Pyc. + Specimen + Water @ Cal. [Pre-vacuum] (g)	985.5
C = Mass of Pyc. + Specimen + Water @ Cal. [Post-vacuum] (g)	1002.0
Film Coefficient	88
SSDetect	
Mass of Bowl + Cover (g)	284.7
Mass of Bowl + Cover + Specimen @ SSD	791.8
S = SSD Mass (g)	507.1
Bulk Specific Gravity Calculations	
BSG (dry)	2.541
BSG (SSD)	2.577
BSG (Apparent)	2.636
Absorption (%)	1.42

UNCOMPACTED VOID CONTENT

Uncompacted void content of FinesT-304

Specimen =	Dartmouth FVS		
Date =	11/21/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	345.2	344.7	344.95
F	162.0	161.5	161.75
G	2.589	2.589	2.589
U	37.52	37.71	37.61

Uncompacted void content of FinesT-304

Specimen =	Dartmouth SS		
Date =	11/21/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	333.0	333.0	333
F	149.8	149.8	149.8
G	2.606	2.606	2.606
U	42.60	42.60	42.60

Uncompacted void content of FinesT-304

Specimen =	Wareham FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	322.8	321.7	322.25
F	139.6	138.5	139.05
G	2.626	2.626	2.626
U	46.92	47.33	47.13

Uncompacted void content of FinesT-304

Specimen =	Wareham SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	327.5	329.6	328.55
F	144.3	146.4	145.35
G	2.541	2.541	2.541
U	43.29	42.47	42.88

Uncompacted void content of FinesT-304

Specimen =	Lexington FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	302.7	303.2	302.95
F	119.5	120	119.75
G	2.425	2.425	2.425
U	50.79	50.59	50.69

Uncompacted void content of FinesT-304

Specimen =	Westwood SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	319.4	319.7	319.55
F	136.2	136.5	136.35
G	2.661	2.661	2.661
U	48.89	48.78	48.83

Uncompacted void content of FinesT-304

Specimen =	Burlington FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	339.5	339	339.25
F	156.3	155.8	156.05
G	2.615	2.615	2.615
U	40.32	40.51	40.41

Uncompacted void content of FinesT-304

Specimen =	Burlington SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	325.2	324.4	324.8
F	142.0	141.2	141.6
G	2.599	2.599	2.599
U	45.44	45.75	45.60

Uncompacted void content of FinesT-304

Specimen =	Reading FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	337.0	336.7	336.85
F	153.8	153.5	153.65
G	2.611	2.611	2.611
U	41.18	41.30	41.24

Uncompacted void content of FinesT-304

Specimen =	Reading SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	322.0	322.4	322.2
F	138.8	139.2	139
G	2.600	2.600	2.600
U	46.69	46.54	46.62

Uncompacted void content of FinesT-304

Specimen =	Peabody FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	335.6	335.8	335.7
F	152.4	152.6	152.5
G	2.625	2.625	2.625
U	42.03	41.95	41.99

Uncompacted void content of FinesT-304

Specimen =	Peabody SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	333.8	334.4	334.1
F	150.6	151.2	150.9
G	2.584	2.584	2.584
U	41.80	41.57	41.69

Uncompacted void content of FinesT-304

Specimen =	Tewksbury FVS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	339.9	339.0	339.45
F	156.7	155.8	156.25
G	2.612	2.612	2.612
U	40.09	40.44	40.27

Uncompacted void content of FinesT-304

Specimen =	Tewksbury SS		
Date =	11/28/2005		
Technician =	BE		
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	320.5	321.8	321.15
F	137.3	138.6	137.95
G	2.547	2.547	2.547
U	46.17	45.66	45.92

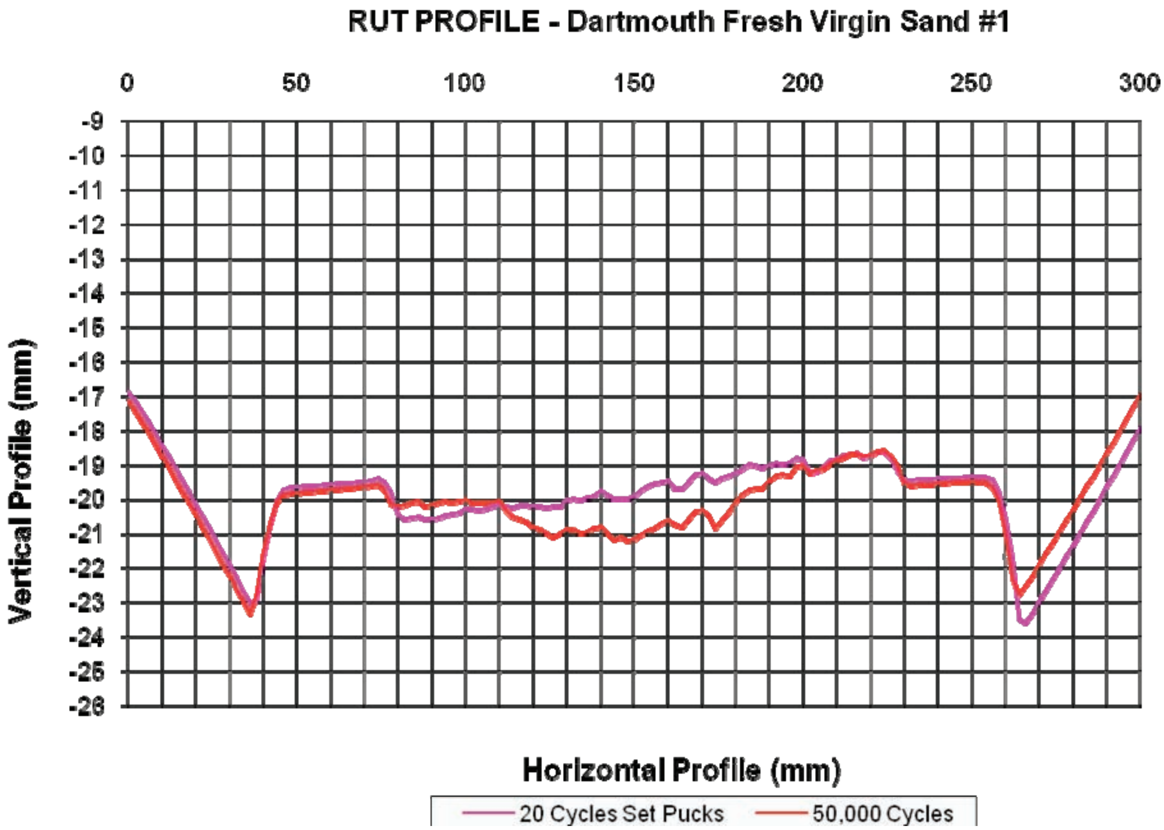
Uncompacted void content of FinesT-304

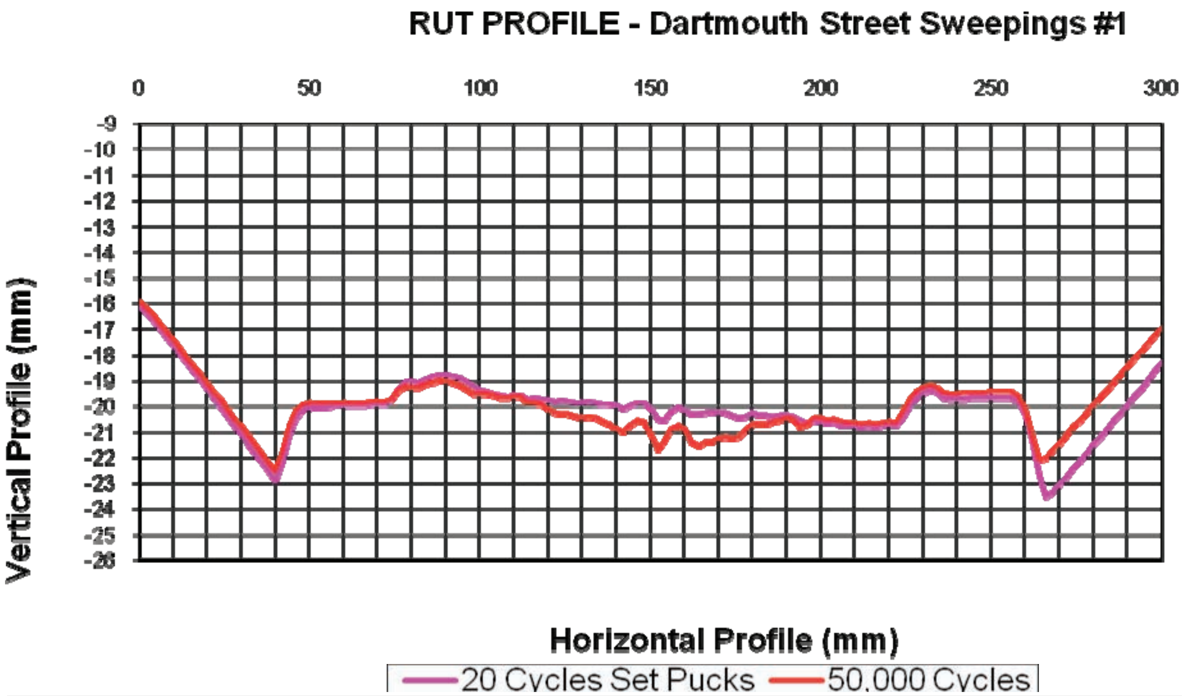
Specimen =	Tewksbury CB
Date =	11/28/2005
Technician =	BE

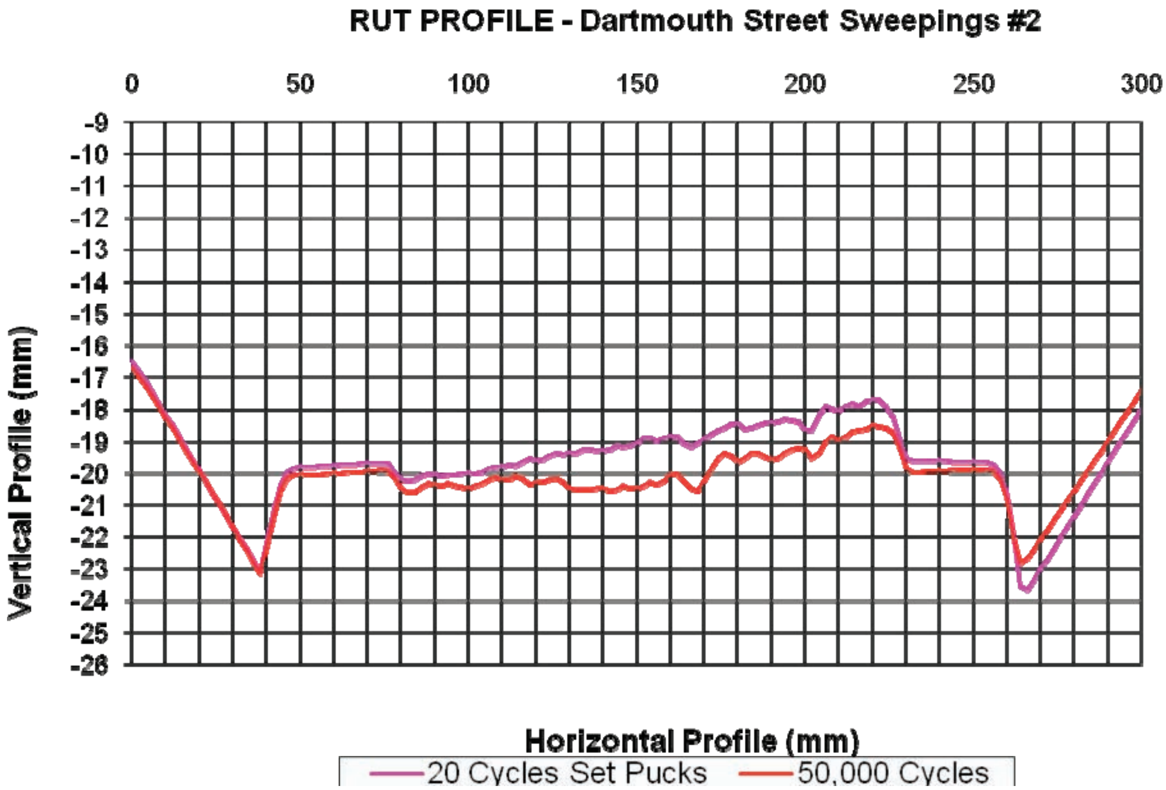
	Trial 1	Trial 2	Average U
Mass of water (g)	99.93	99.93	
Temp of water (°C)	21.4C	21.4C	
Density of Water (g/mL)	0.9979	0.9979	
V	100.1453	100.1453	
W	183.2	183.2	183.2
WF	331.5	332.8	332.15
F	148.3	149.6	148.95
G	2.630	2.630	2.630
U	43.69	43.20	43.45

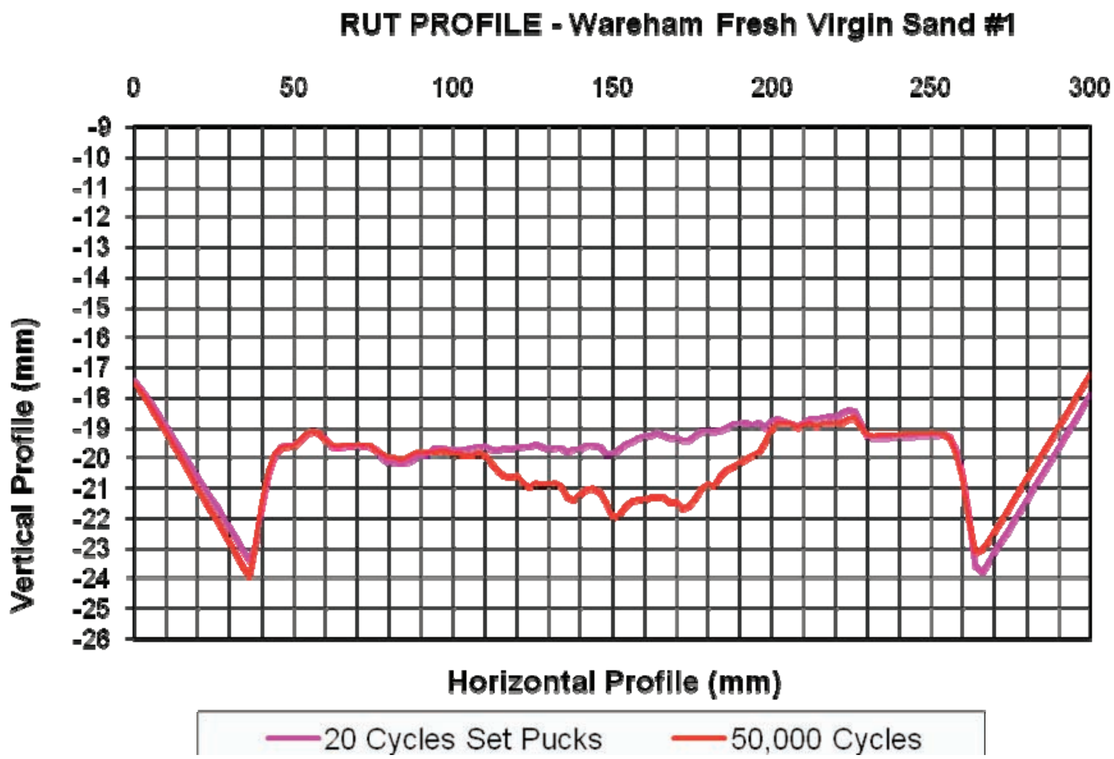
V= volume of cylindrical measure (mL)
F=net mass of fine aggregate in measure (g)
G=bulk dry specific gravity of fine aggregate
U=uncompacted voids in material
W=mass of empty container (g)
WF=container weight + sample weight (g)

MMLS RUT TESTING

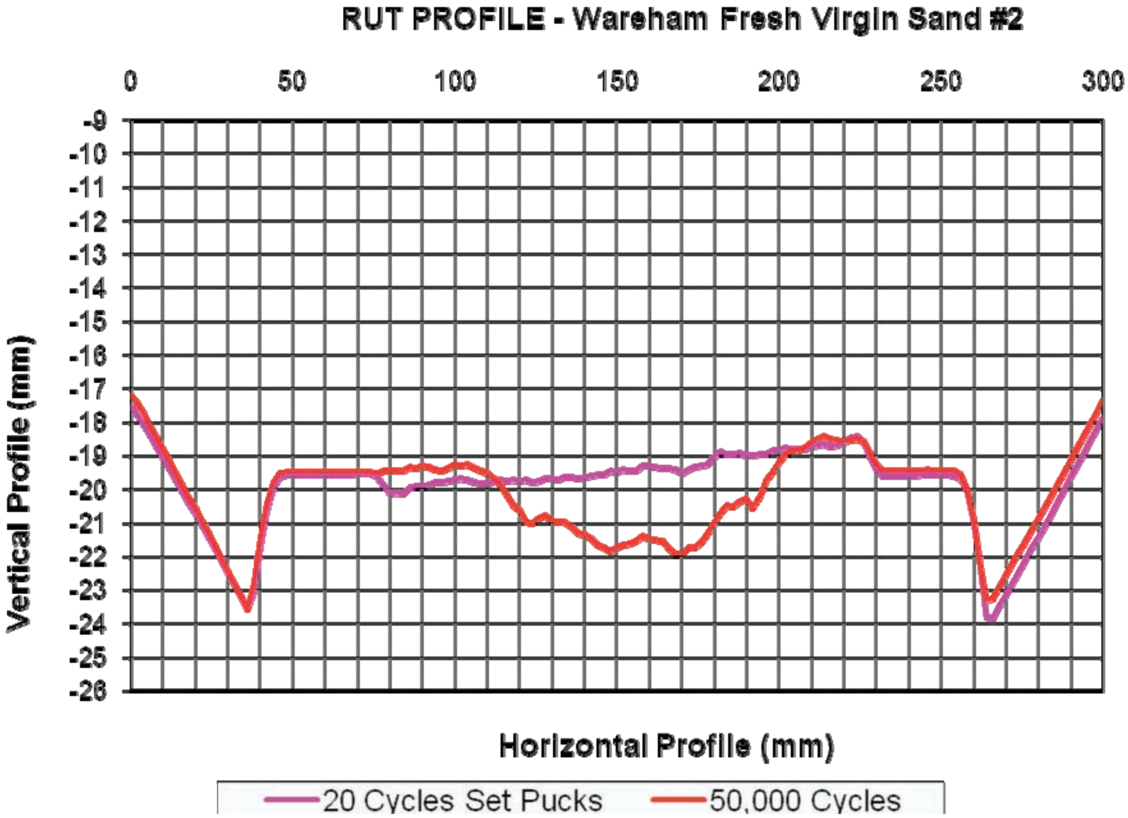


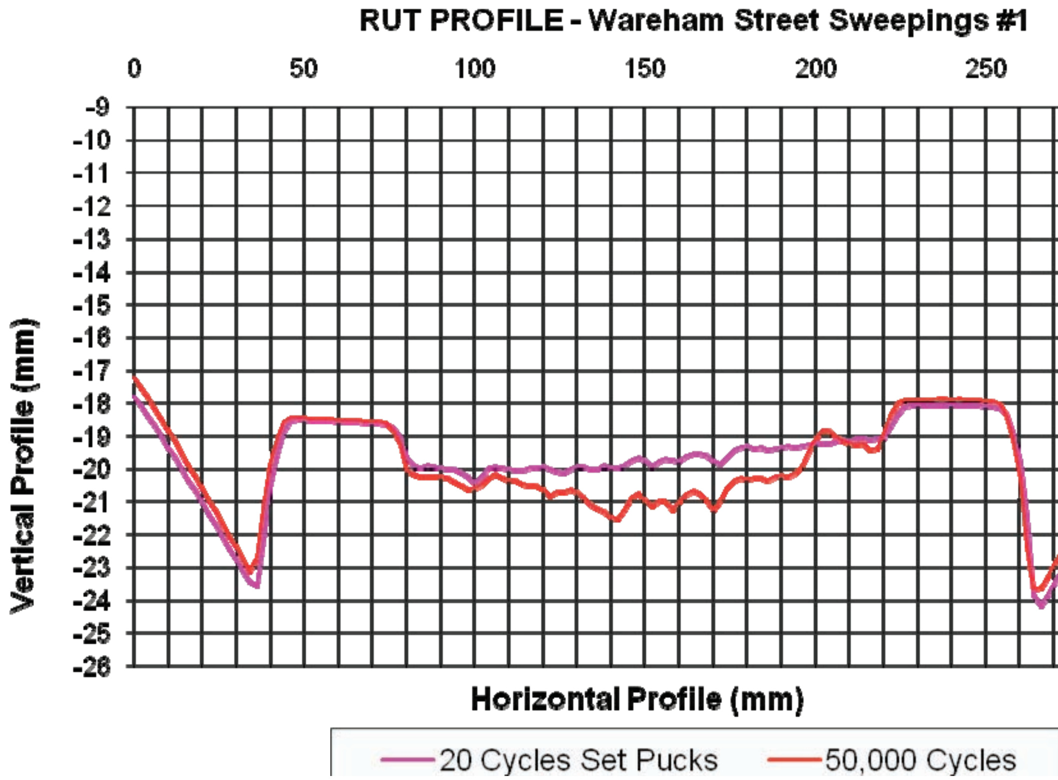

RUT PROFILE - Dartmouth Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

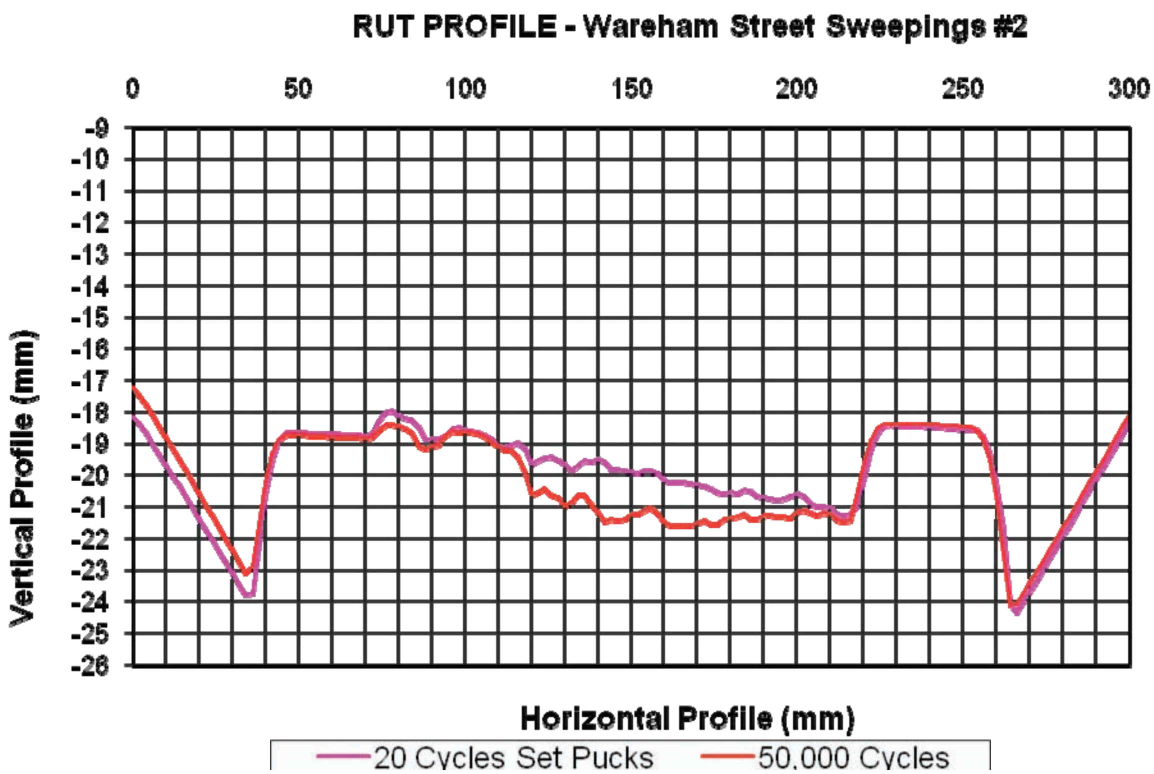

RUT PROFILE - Dartmouth Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

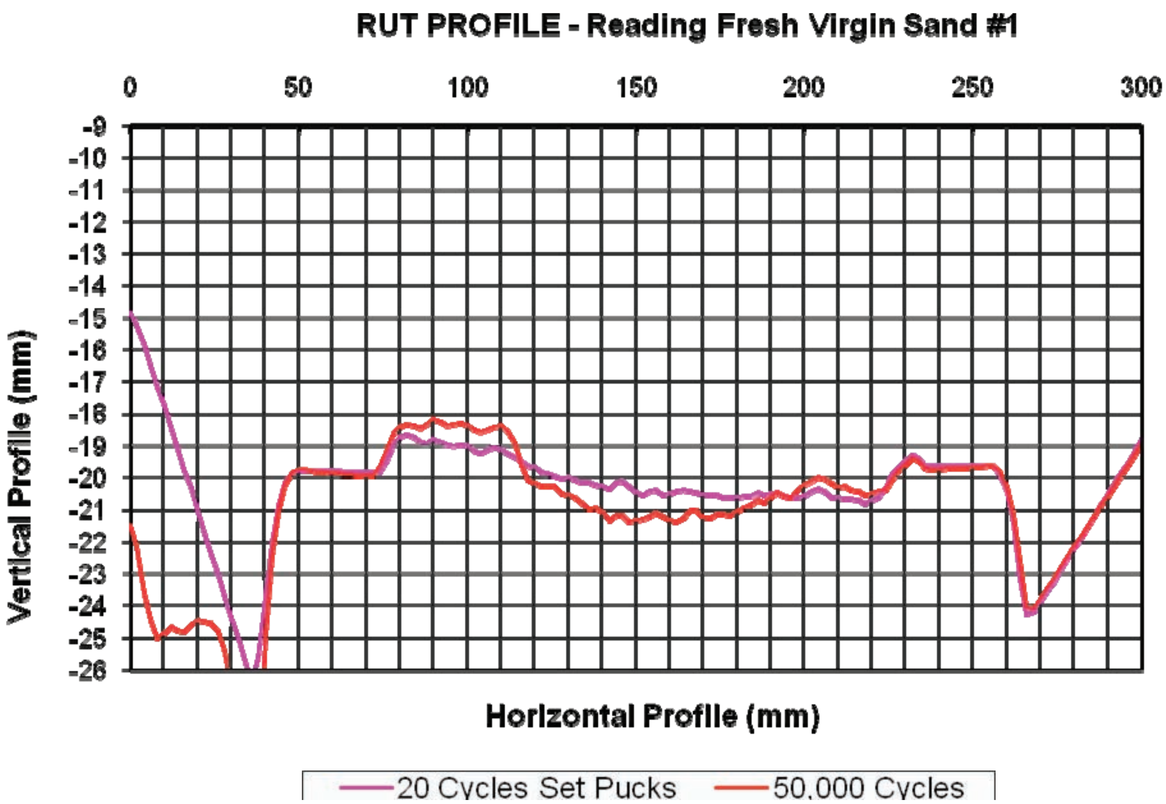


RUT PROFILE - Wareham Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

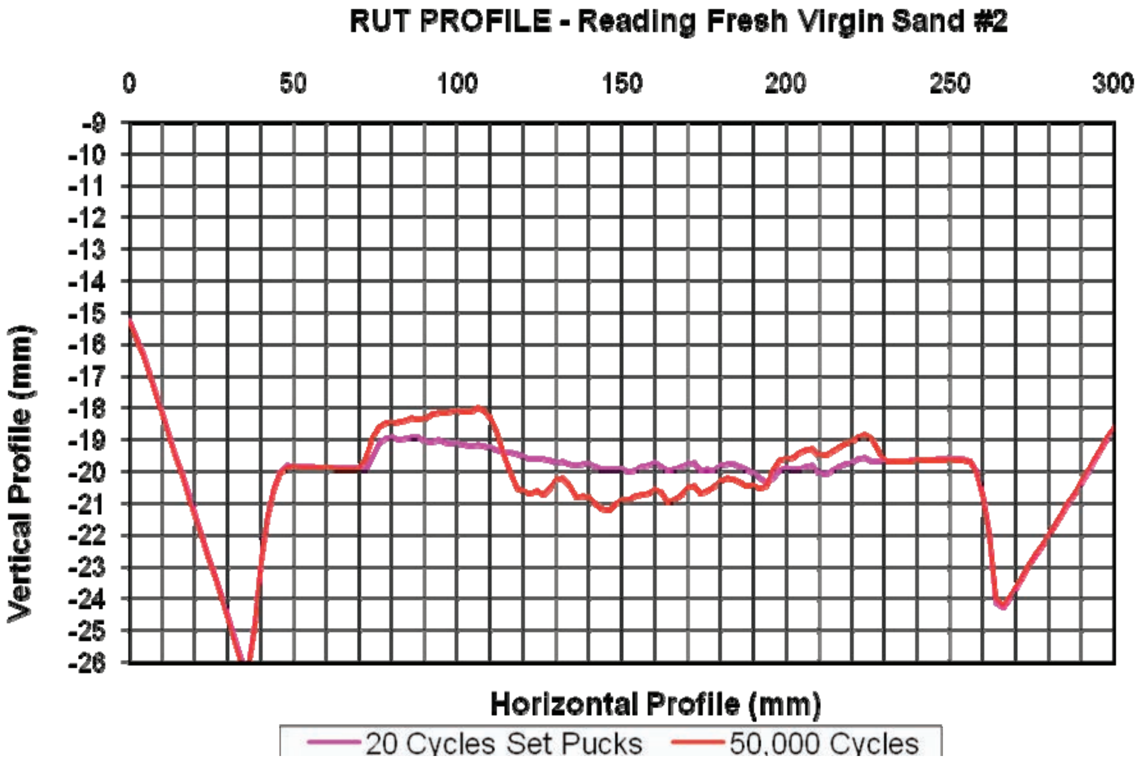

RUT PROFILE - Wareham Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

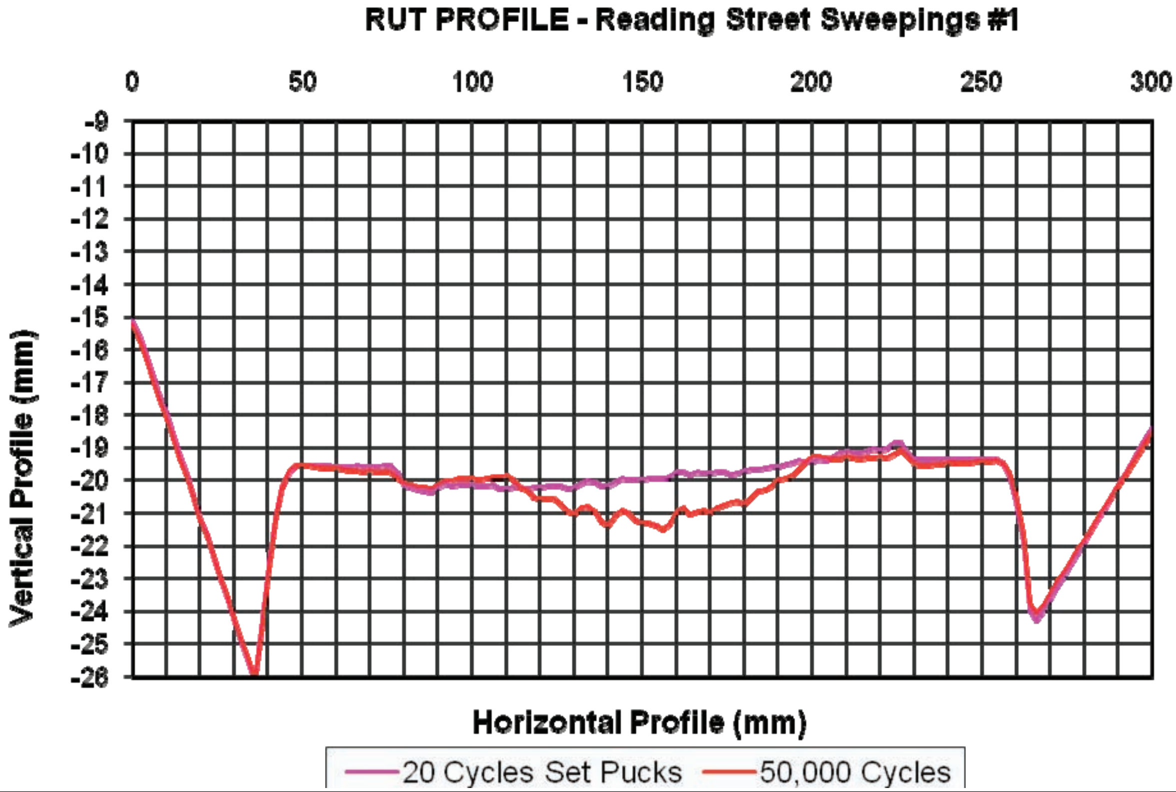

RUT PROFILE - Wareham Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

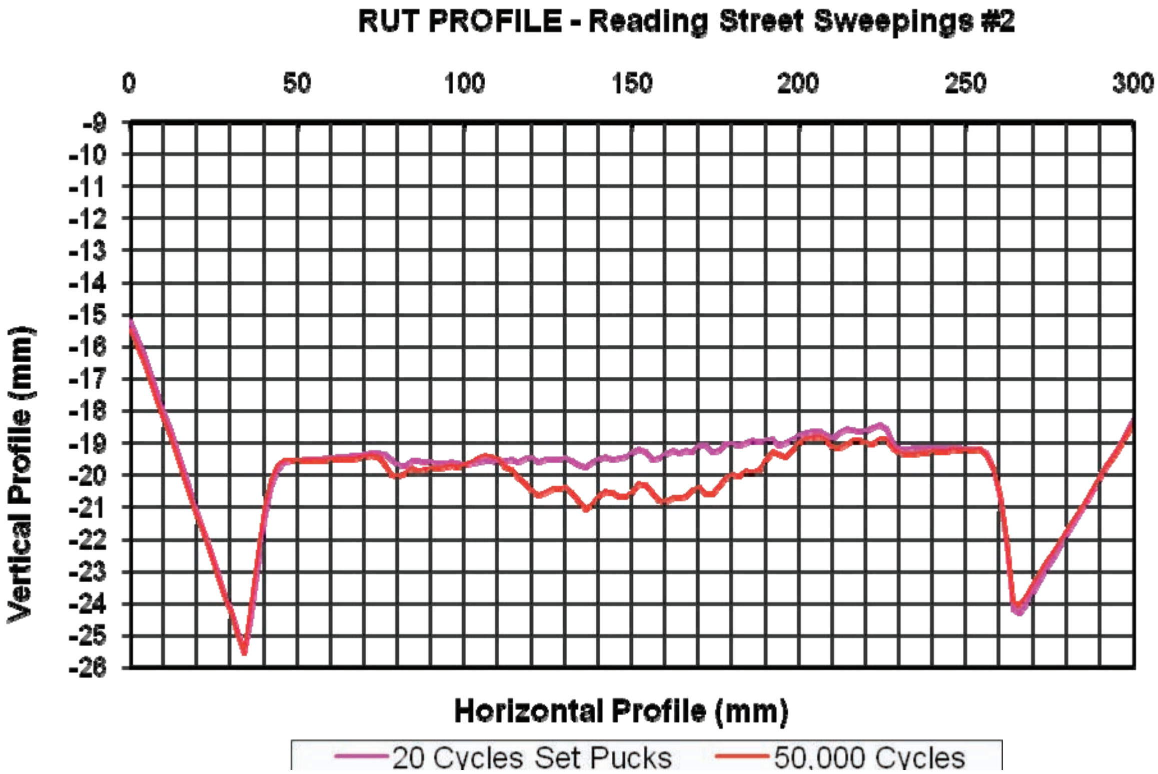

RUT PROFILE - Wareham Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

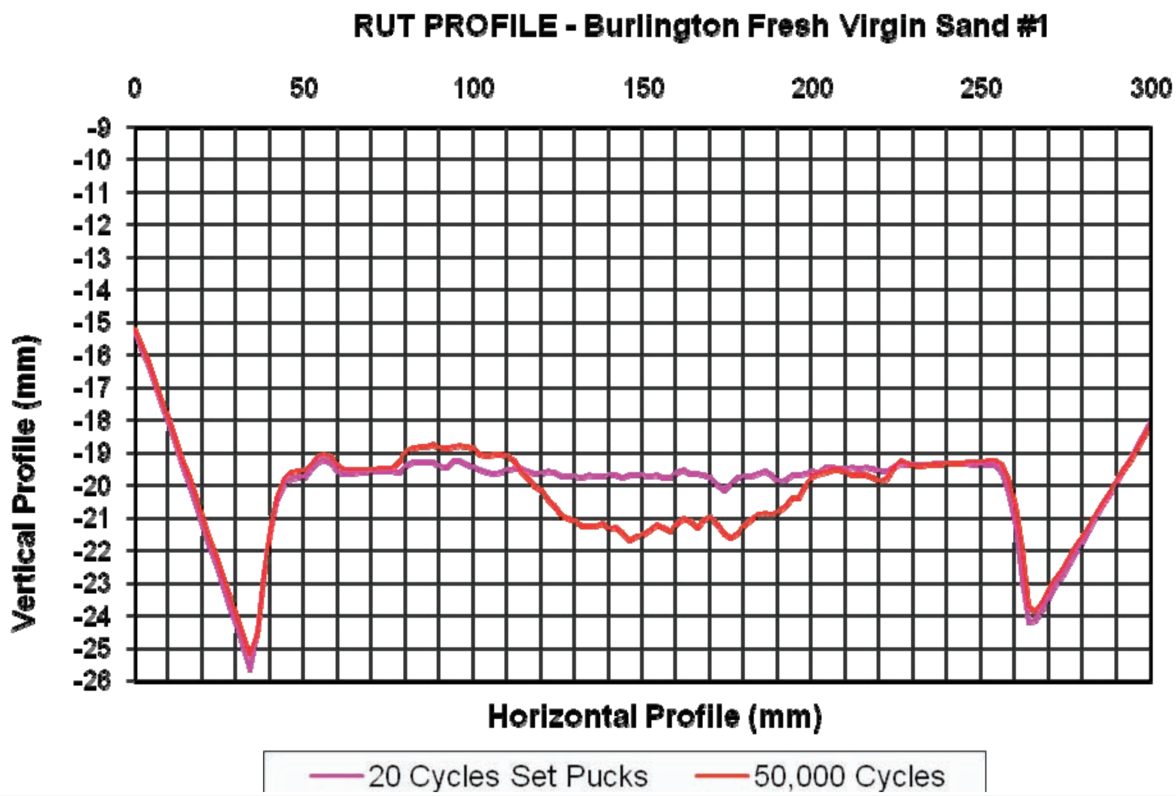


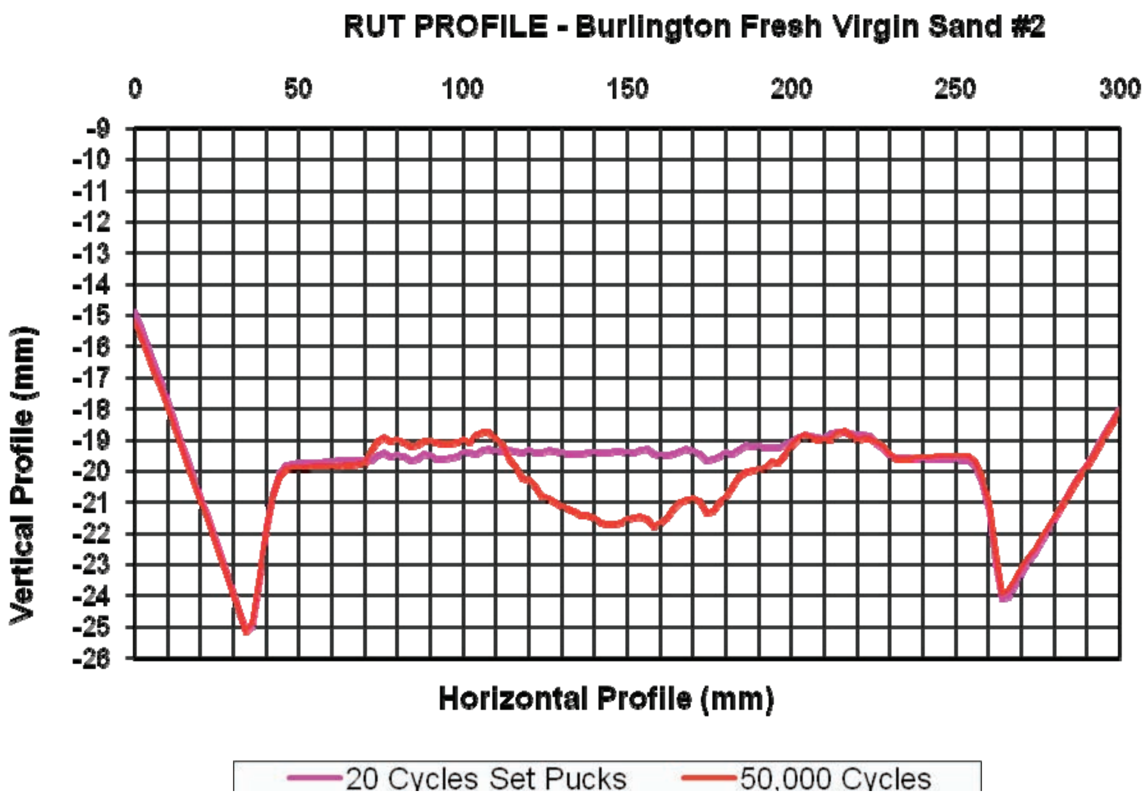
RUT PROFILE - Reading Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

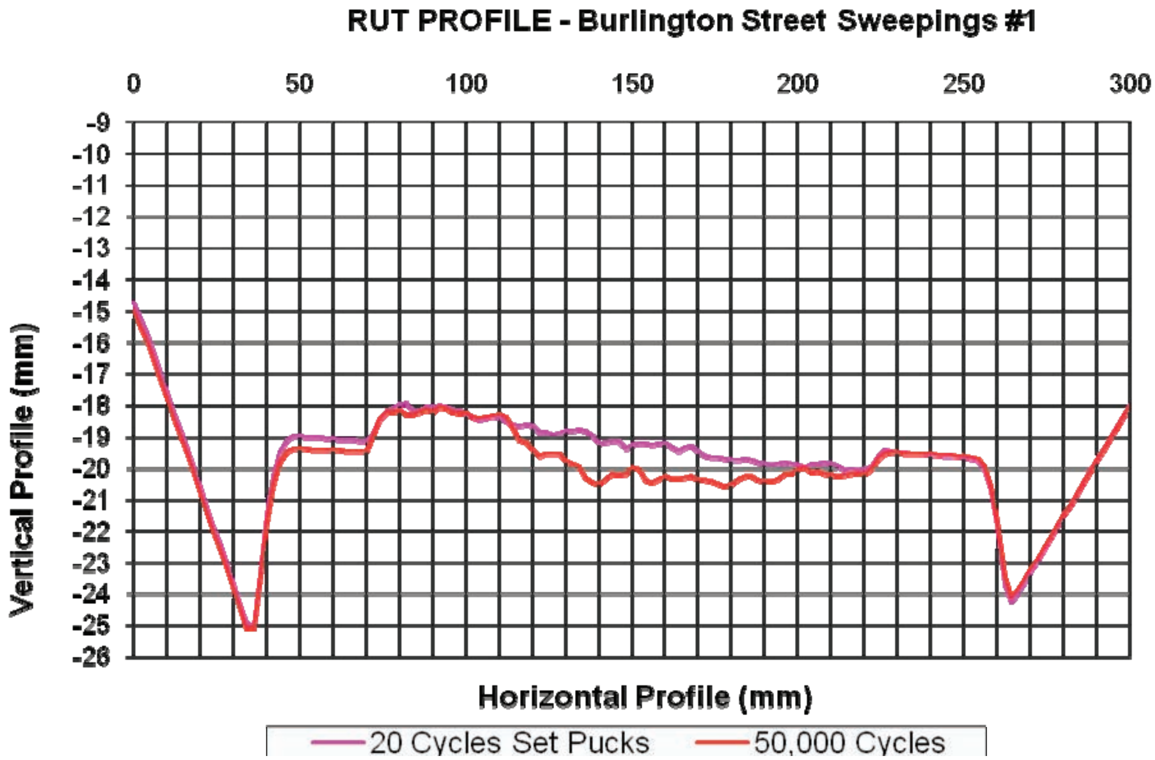

RUT PROFILE - Reading Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

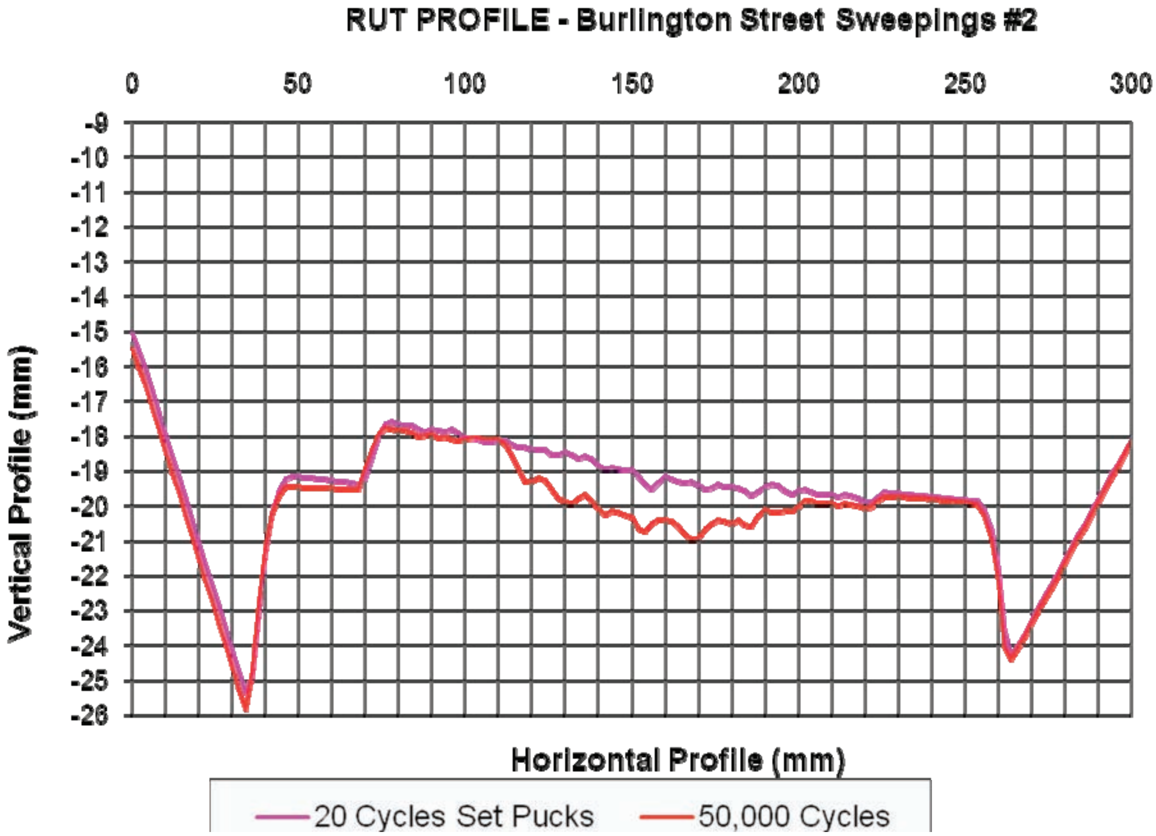

RUT PROFILE - Reading Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

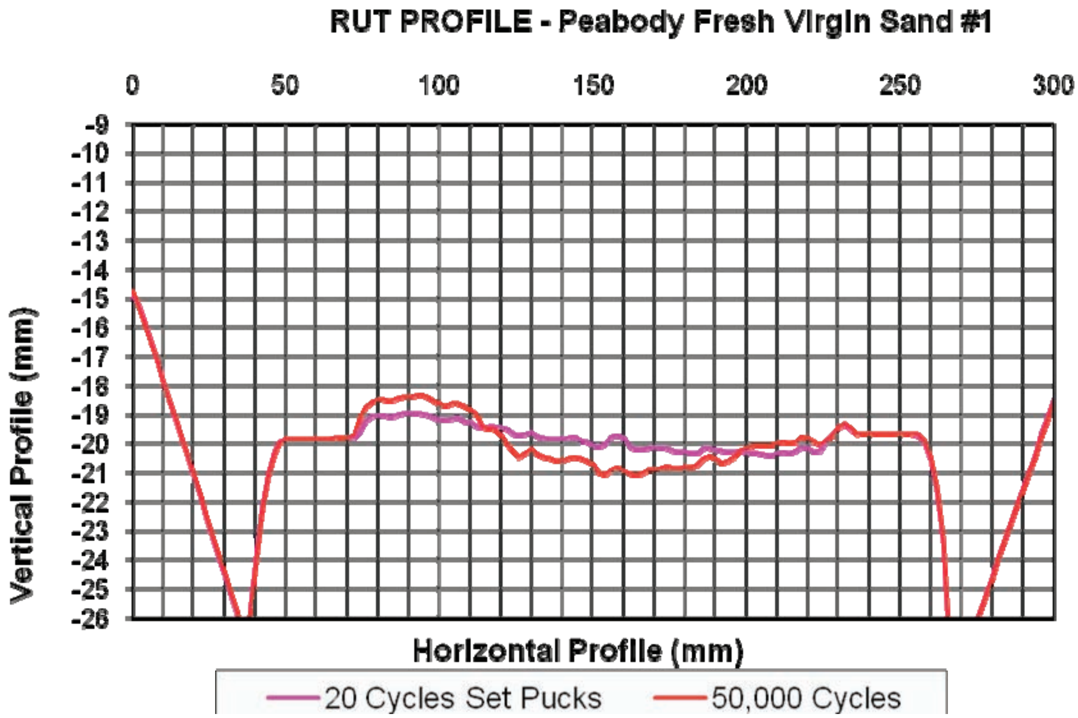

RUT PROFILE - Reading Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

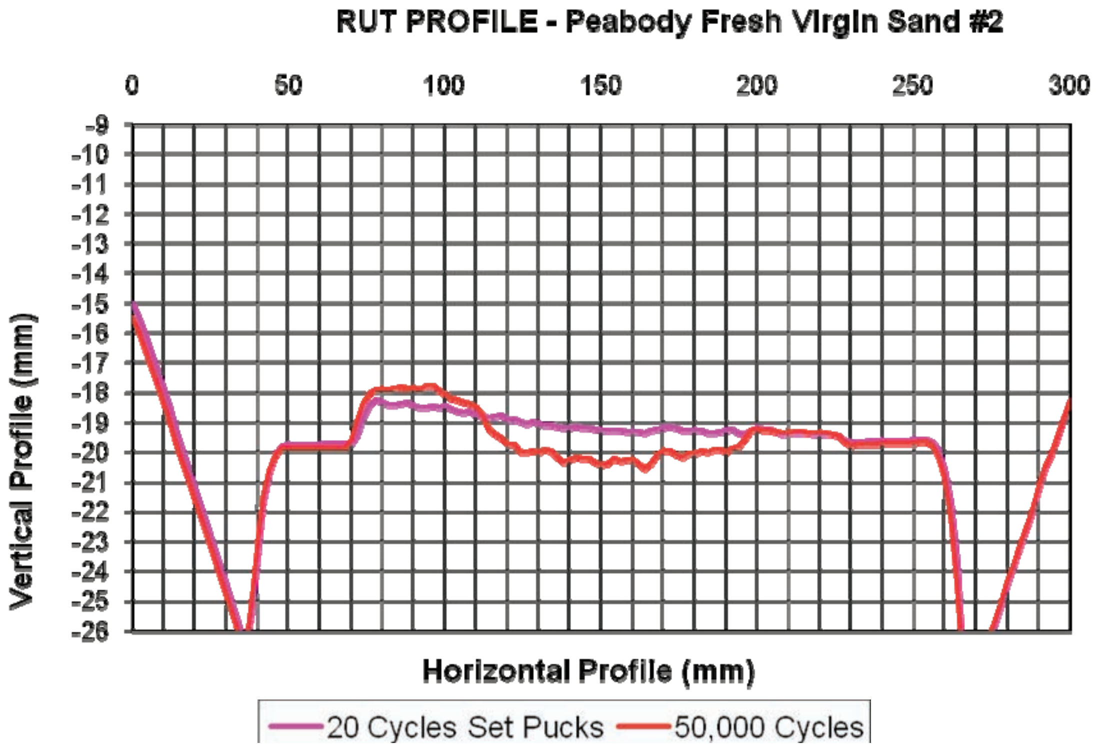

RUT PROFILE - Burlington Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

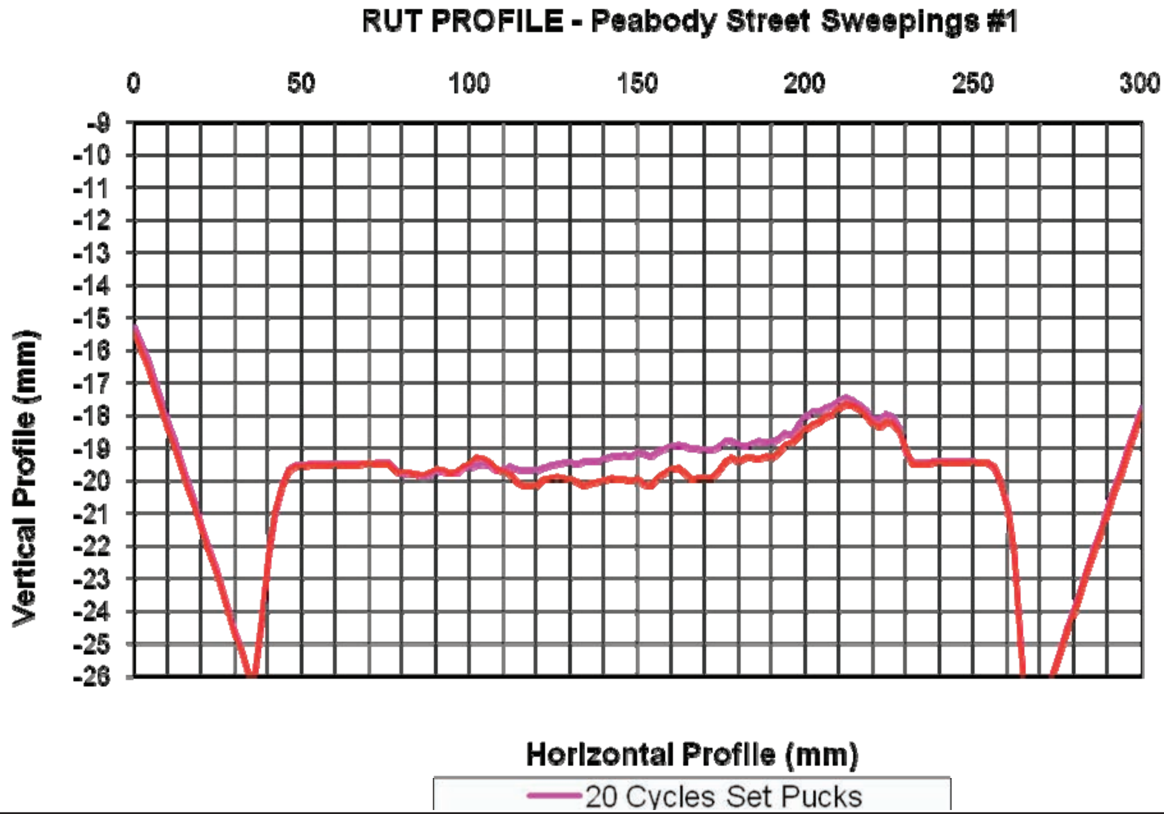

RUT PROFILE - Burlington Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Burlington Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

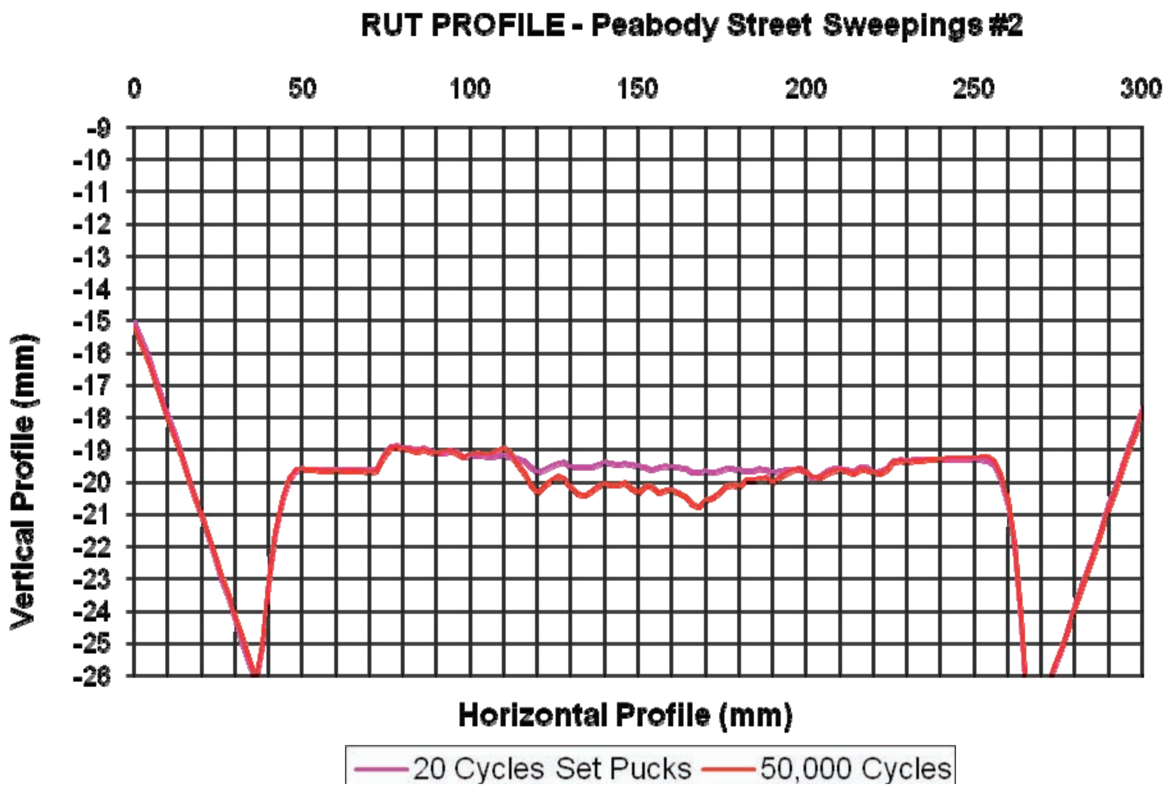

RUT PROFILE - Burlington Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Peabody Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

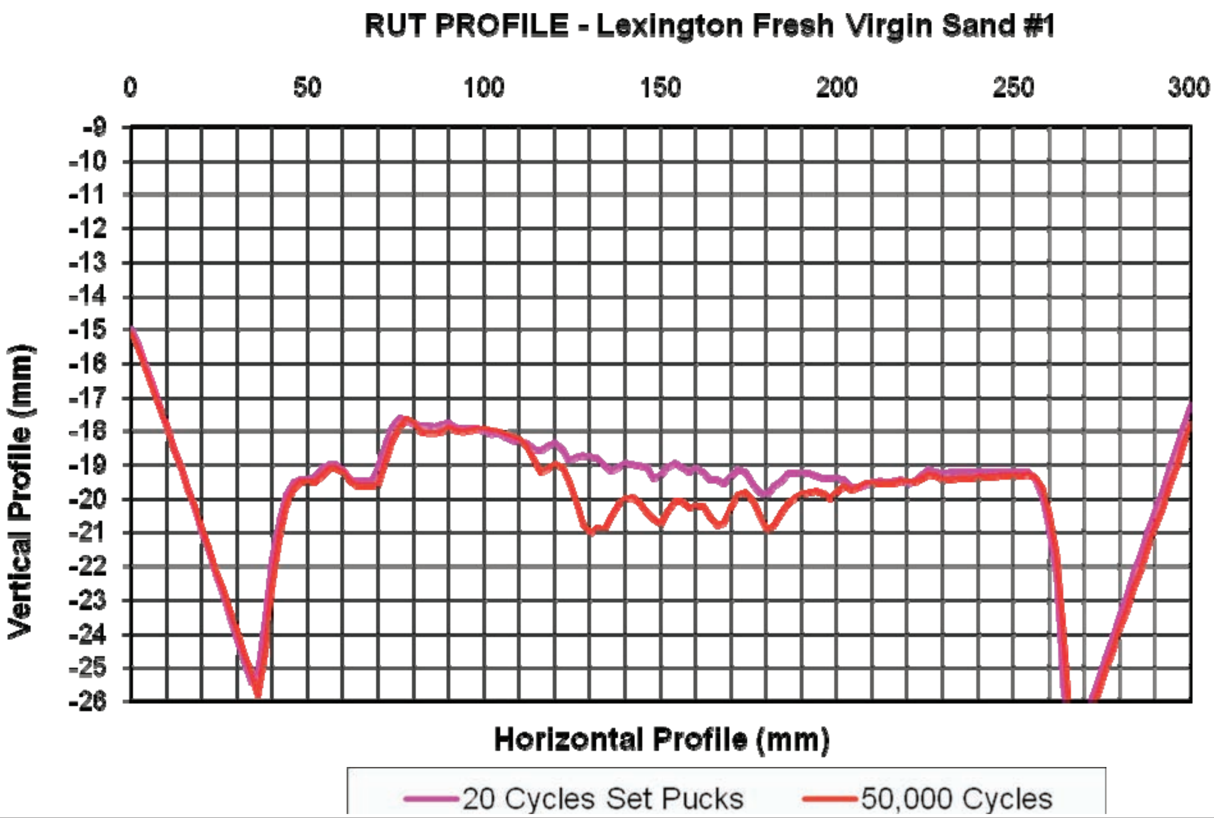

RUT PROFILE - Peabody Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

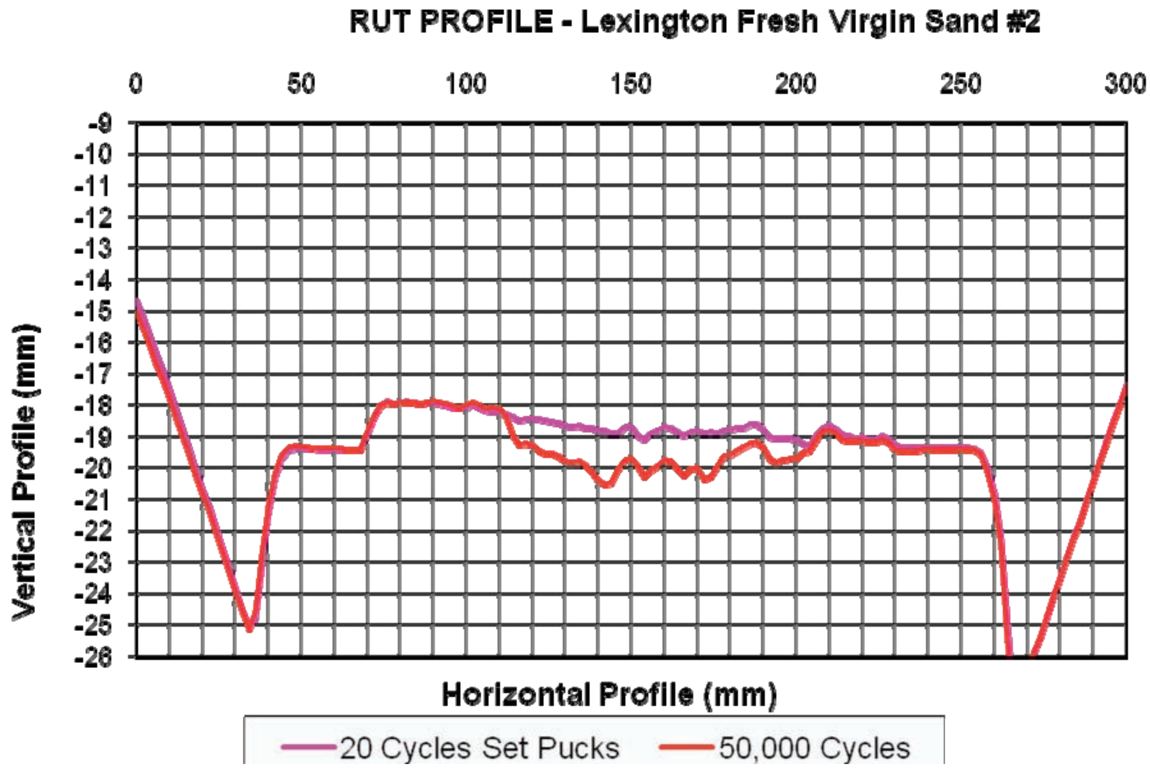


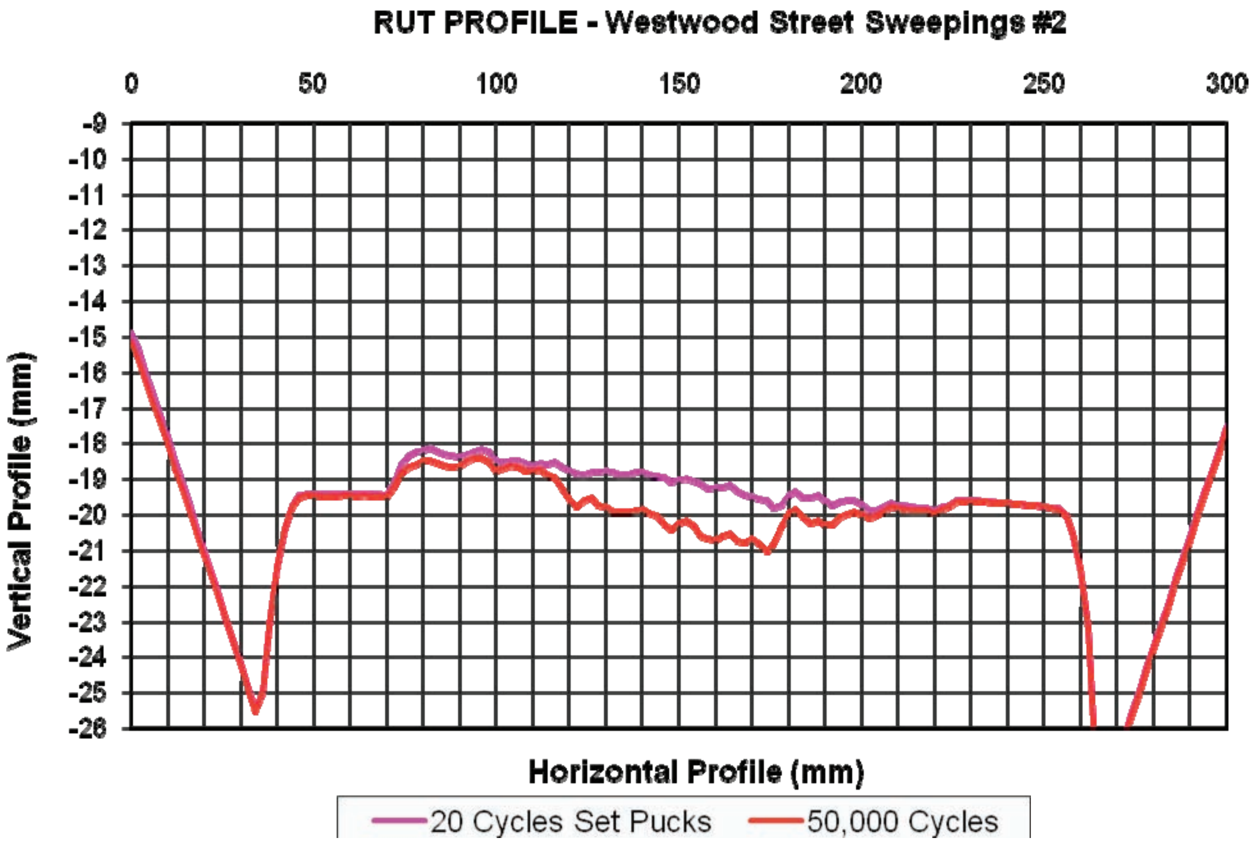
RUT PROFILE - Peabody Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks

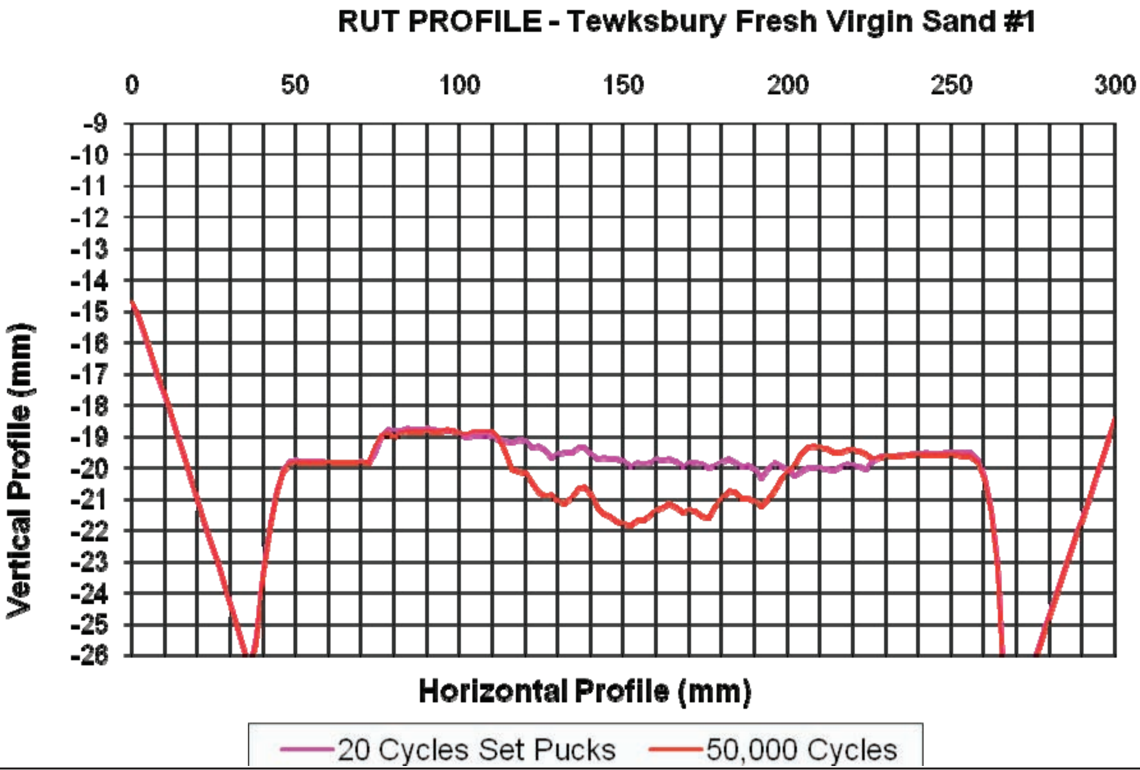


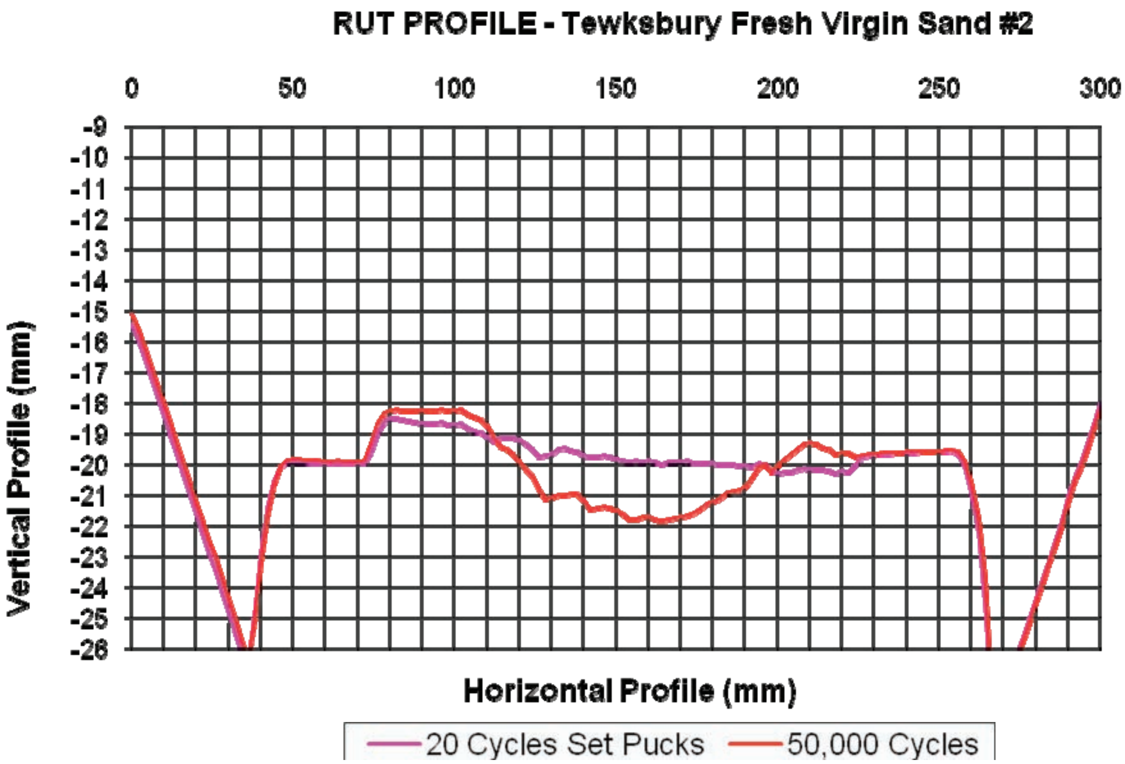
RUT PROFILE - Peabody Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Lexington Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

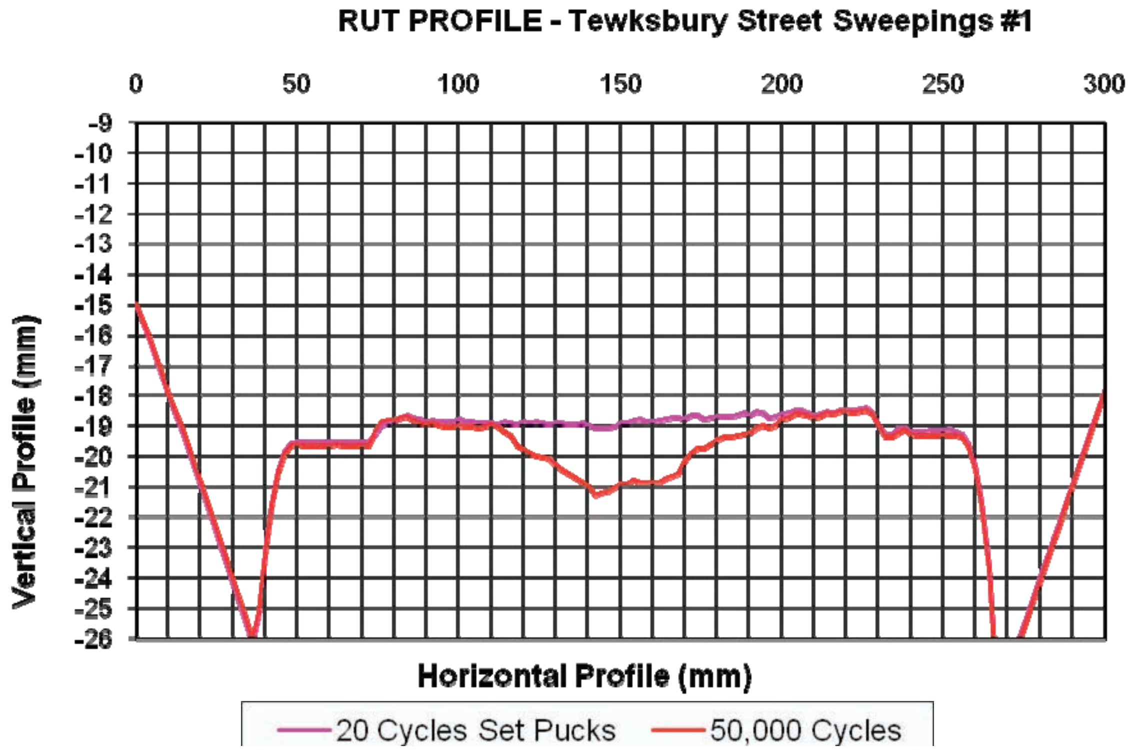

RUT PROFILE - Lexington Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

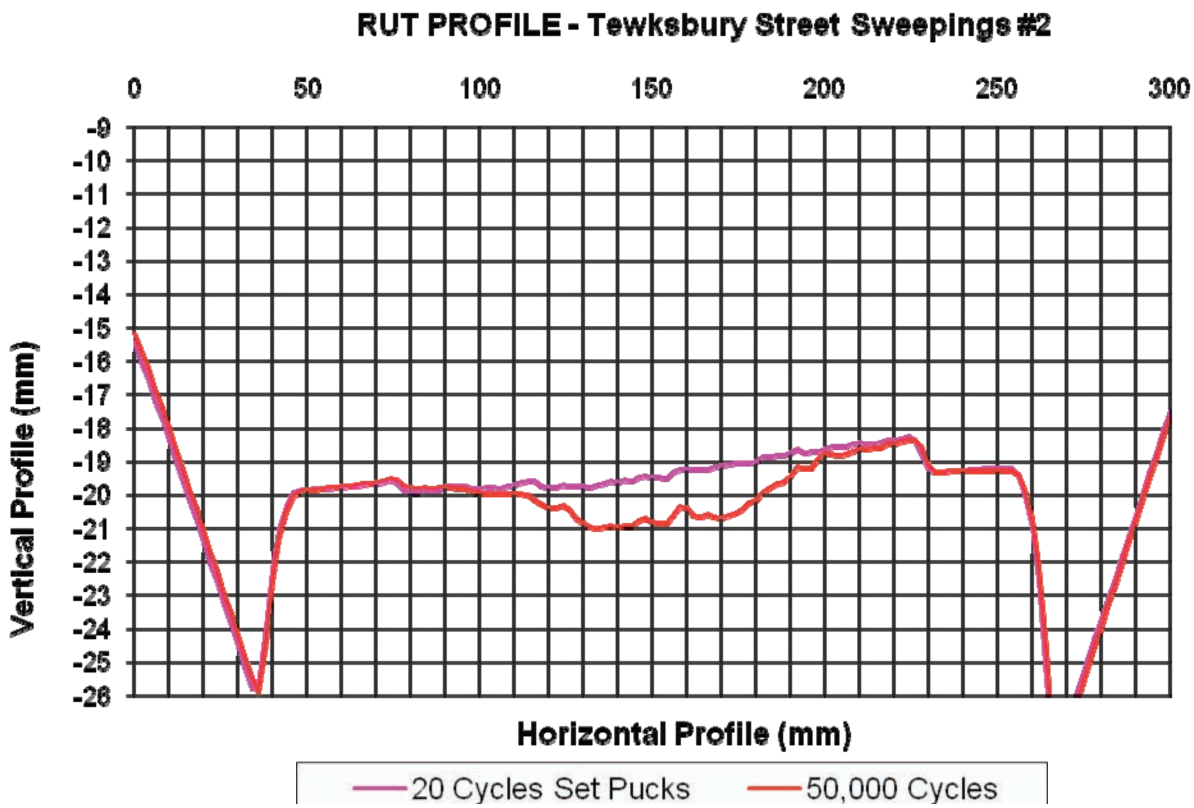

RUT PROFILE - Westwood Street Sweepings #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

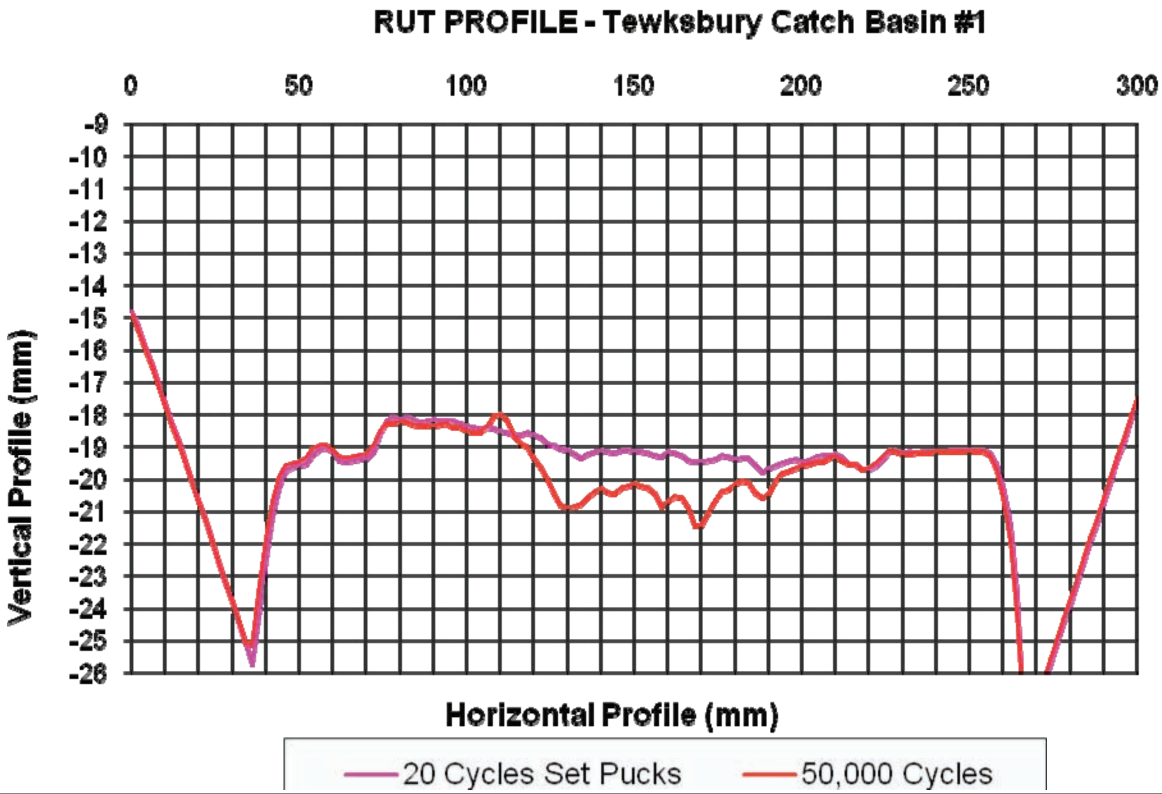

RUT PROFILE - Tewksbury Fresh Virgin Sand #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

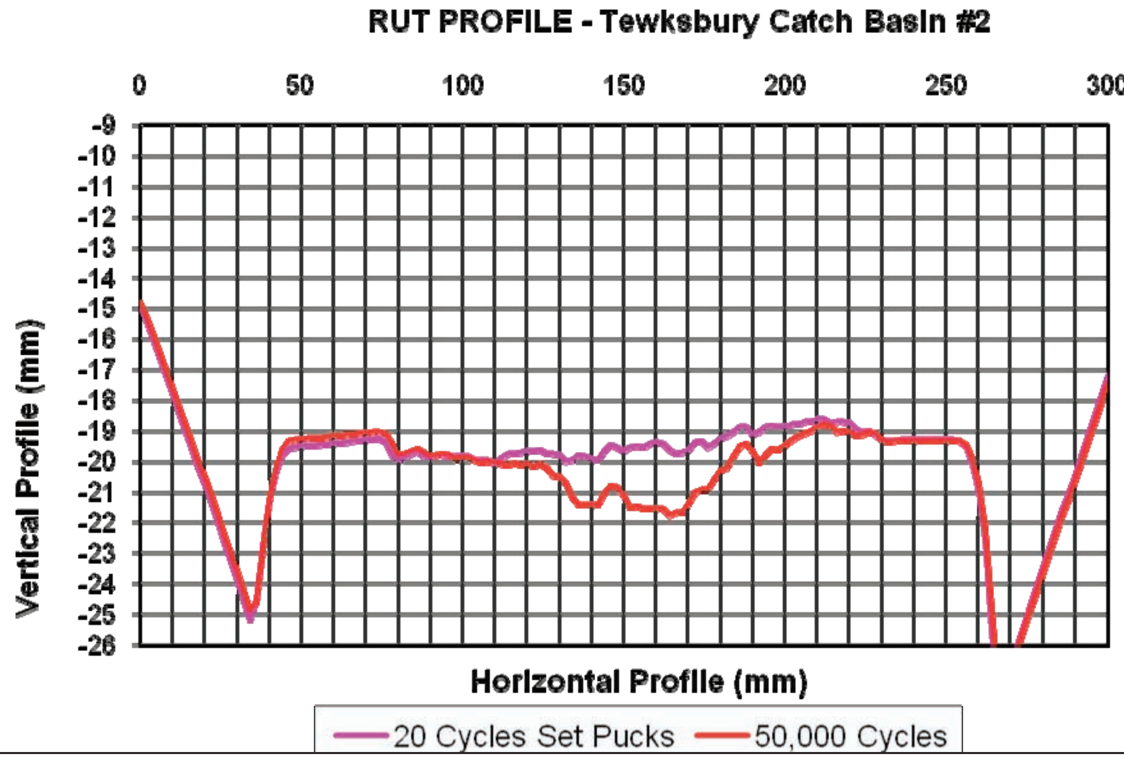


RUT PROFILE - Tewksbury Fresh Virgin Sand #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Tewksbury Street Sweepings #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Tewksbury Street Sweepings #2
Vertical Profile (mm)
Horizontal Profile (mm)
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Tewksbury Catch Basin #1
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles


RUT PROFILE - Tewksbury Catch Basin #2
0
50
100
150
200
250
300
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
Vertical Profile (mm)
Horizontal Profile (mm)
20 Cycles Set Pucks
50,000 Cycles

U. S. Sieve Size and Designation

Sieve ID (US Size)	Sieve Designation
2	9.5 mm
8	2.38 mm
16	1.18 mm
30	0.595 mm
50	300 µm
100	150 µm
200	75 µm

References

AASHTO 27, "*Standard Method of Test for Sieve Analysis for Fine and Coarse Aggregates.*"

AASHTO 312 "*Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor", 2004.*

AASHTO T84 "*Standard Method of Test for Specific Gravity and Absorption of Fine Aggregates.*"

AASHTO T255-0 "*Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying", 2003.*

AASHTO T267-86, "*Standard Method of Test for Determination of Organic Content in Soils by Loss of Ignition",* 2003.

AASHTO T304, "Standard Method to test for Uncompacted Void Content of Fine Aggregate", 2003.

AASHTO TP63-03, "Standard Method of Test for Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer (APA)."

Barrett, P. J. (1980). "The shape of rock particles, a critical review." *Sedimentology*, Vol. 27, pp. 291 - 303.

Brinkman, R., Emrich, C., Bilus, M., Dwyer, B., and Ryan, J. Chemical and Physical Characteristics of Street Sweeping Sediments in Tampa, Florida – Report #98-12. Florida Center for Solid and Hazardous Waste Management, University of Florida, May 1999.

Camp, Dresser and McKee, Inc. Street Sweepings Program Analytical Results, Worcester, Massachusetts Cambridge, Massachusetts, February 27, 1995 and August 2, 1995 (Two separate reports).

Chandan, C., Sivakumar, K., Fletcher, T., and Masad, E. "Geometry Analysis Of Aggregate Particles Using Imaging Techniques." *Journal of Computing in Civil Engineering, ASCE*, Vol. 18, No. 1, 2004, pp. 75-82.

Collins, J. T., and Moore, J. T. Roadwaste Management: A Tool for Developing District Plans. Final Report, Oregon Department of Transportation, October 2000.

Edwards, J., and Kuhl, J. Street Sweepings: The Latest Compostable Resource. Resource Recycling, August 1998

Environmental Protection Agency, Office of Water Enforcement and Compliance. Storm Water Management for Construction Activities: Developing Pollution Prevention Plans and Best Management Practices, EPA/832/R-92/005. Washington, D.C., September, 1992.

Fletcher, T. *Aggregate Imaging System for Characterizing Fine and Coarse Aggregate Shape. M.Sc.Thesis.* Department of Civil and Environmental Engineering, Washington State University, Pullman, 2002.

Fletcher, T., Chandan, C., Masad, E., Sivakumar, Krishna. "Aggregate Imaging System for Characterizing the Shape of Fine and Coarse Aggregates." *Transportation Research Record,* Paper No. 03-2174, Washington State University, Pullman, 2003.

Ghezzi, M. N., Moore, J. T., Collins, J. T., Bretsch, K., and Hunt, L. Roadwaste Management: Field Trials – Final Report SPR 385, Oregon Department of Transportation, March 2001.

ICPI Tech Spec Number.13. *Slip and Skid Resistance of Interlocking Concrete Pavements.* Interlocking Concrete Pavement Institute, March 2004.

Lee, S. Long Term Performance Assessment of Asphalt Concrete Pavements Using the Third Scale Model Mobile Loading Simulator and Fiber Reinforced Asphalt Concrete - Ph.D. Dissertation, North Carolina State University, 2003.

Leibens, J. Contamination of Sediments in Street Sweepings and Stormwater Systems: Pollutant Composition and Sediment Reuse Options – Report #00-10. Florida Center for Solid and Hazardous Waste Management, University of Florida, January 2001.

Mallat, S.G. "A Theory for Multiresolution Signal Decomposition: The Wavelet Representation." *IEEE Transactions on Pattern Analysis and Machine Intelligence,* Vol. 11, 1989, pp. 674-693.

Masad, E. *The Development of A Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties*. NCHRP-IDEA Project 77 Final Report, Transportation Research Board, Washington, D.C., 2003.

Mathisen, P. P., Graves, P. J. R., Roberge, J. A., and Ozdilek, H. G. Reuse of Street Sweepings and Catch Basin Cleanings in Worcester, Massachusetts – Regulations, Characteristics, Technologies, Implementation. Technical Report # 37, Chelsea Center for Recycling and Economic Development, University of Massachusetts, Spring 1999.

National Cooperative Highway Research Program (NCHRP) Project 25-25, Task 4. Environmental Stewardship Practices, Procedures and Policies for Highway Construction and Maintenance. Requested by American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on the Environment, September 2004.

Perla, M. Questioning Street Waste Regulations. *Public Works*, July 1996.

Recycling Technology Assistance Partnership (ReTAP). Reprocessing and Reuse of Street Waste Solids. The Clean Washington Center, Land Technologies, Inc., Price-Moon Enterprises, and Snohomish County Road Maintenance Division, June 1997.

State of Connecticut Department of Environmental Protection. Municipal Management Practices for the Reuse of Road Sand Sweepings. Bureau of Water Management Technical Guidance. Hartford, Connecticut, January 1998.

State of Connecticut Department of Environmental Protection. Guideline for Municipal Management Practices for Street Sweepings and Catch Basin Cleanings. Hartford, Connecticut, August 2007.

Townsend, T. G., Jang, Y-C., Thurdekoos, P., Booth, M., Jain, P., and Tolaymat, T. Characterization of Street Sweepings, Stormwater Sediments, and Catch Basin Sediments in Florida for Disposal and Reuse – Final Report. Florida Center for Solid and Hazardous Waste Management, University of Florida, December, 2002.

University of Massachusetts Dartmouth. Development of Guidelines for Presampling of Street Sweepings for Toxicity and Beneficial Reuse. February 1997.

University of South Florida, Tampa. Characteristics of Street Sweepings in Florida. April 1, 1998.

Wadell, H. (1932). "Volume, shape and roundness of rock particles," *Journal of Geology*, **40** (1932), 443 - 451.

Washington State Department of Ecology. Best Management Practices (BMPs) for Management and Disposal of Street Wastes. Olympia, Washington, July 1995.