Minnesota
Department of
Transportation

RESEARCH
SERVICES

Office of
Policy Analysis,
Research &
Innovation

A Property-Based Specification for Coarse Aggregate in Pavement Applications

Magdy Abdelrahman, Principal Investigator
Department of Civil Engineering
North Dakota State University

October 2010

Research Project
Final Report 2010-35

LRRB
LOCAL
ROAD RESEARCH
BOARD

Your Destination...Our Priority

Technical Report Documentation Page

1. Report No. MN/RC 2010-35	2.	3. Recipients Accession No.
4. Title and Subtitle A Property-Based Specification for Coarse Aggregate in Pavement Applications		5. Report Date October 2010 6.
7. Author(s) Magdy Abdelrahman, Amy Hardy, Arash Saboori		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering North Dakota State University NDSU Dept 2470 PO Box 6050 Fargo, ND 58108-6050		10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 89243
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard, MS 330 St. Paul, MN 55155-1899		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/pdf/201035.pdf		

16. Abstract (Limit: 250 words)

The demand is increasing for high quality aggregate material. Quality aggregate sources are starting to diminish and transportation costs are significant. Coarse aggregate specifications for pavement mixtures for many states are outdated, and do not reflect the current level of knowledge. There is a need to evaluate aggregate quality based on the suitability of property-based testing requirements. A better understanding of testing requirements can lead to a better utilization of local aggregate materials and reduce the reliance on diminishing high quality sources. This study investigates what property-based testing requirements have been established in current specifications, and new areas of testing that need to be developed. A survey of professionals defined a set of testing requirements for different pavement applications, which were then compared to the current testing requirements. The results concluded that gaps exist between how professionals define quality aggregate and how current specifications define it. This creates the need for the inclusion of more property-based testing that could better characterize aggregates based on pavement performance.

To evaluate compliance and consistency, testing data from local sources in the state of Minnesota were compared to regional and national records on aggregate quality and specification requirements. Percent within limit calculations were conducted to evaluate the aggregate property compliance with current quality. The results demonstrated that aggregates complied current specifications. However, there was noticeable variability of test results between different sources though quality requirements were easily met by tolerance criteria. This study emphasizes the inconsistency of aggregate properties among sources subjected to the same (or similar) specification requirements.

17. Document Analysis/Descriptors Aggregates, Property-based, Concrete aggregate, Pavements, Asphalt pavements, Specifications		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 95	22. Price

A Property-Based Specification for Coarse Aggregate in Pavement Applications

Final Report

Prepared by:

Magdy Abdelrahman
Amy Hardy
Arash Saboori

Department of Civil Engineering
North Dakota State University

October 2010

Published by:

Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard
St. Paul, Minnesota 55155-1899

Acknowledgments

The research team would like to acknowledge the funding support of the Minnesota Department of Transportation (Mn/DOT). The research team would also like to acknowledge Mn/DOT and Local Road Research Board (LRRB) personnel for their help in conducting this research, especially Mr. Charles Howe of Mn/DOT and Mr. John Grindeland of LRRB. The research team also recognizes North Dakota State University (NDSU) students Mohammed Attia, Ahmed Al Yamany, Mike Bittner and Jacob Bongard for conducting the aggregate testing and for helping in the literature search.

Table of Contents

List of Tables

List of Figures

Executive Summary

Background

Aggregate is the principal material in pavement mixtures. Because aggregates carry the load in a pavement structure, they are very critical to the long-term performance of the pavement. The demand for pavements that can handle increasing loads has amplified the need for high quality aggregate material. Furthermore, encouragement is often given to exceed the minimum quality requirements defined in specifications. However, if the highest quality aggregate material is consumed for every application, even those less critical, eventually, high value resources will be more rapidly depleted than necessary. While once plentiful, quality aggregate sources are diminishing from resource depletion as well as through land development that prohibits mining. When sources of aggregate are eliminated locally and become more remote from places of need, the costs of construction can rise significantly mainly due to the price associated with transportation. These additional costs are often passed on to the public as higher taxes or reduced services.

Currently, not enough emphasis has been placed on the utilization of local aggregate materials. A better understanding of testing methodologies available for evaluating critical aggregate properties can lead to a better indication of pavement performance and help maximize the use of local sources. Some sources may contain aggregate material that is not commonly used in high quality mix applications. However, there is a possibility that some sources rejected for high class mixtures may be suitable for local and low-volume road applications.

Transportation departments specify and classify requirements for coarse aggregates used in bituminous and Portland cement concrete applications. Coarse aggregate specifications for many states date back to the 1930s and have been updated as more knowledge has become available. Aggregate specifications do not reflect the current level of knowledge concerning desirable properties for pavement applications. Furthermore, property-based testing methodologies are seen to be lacking in current specifications. The literature outlines the need for two main criteria in coarse aggregate specifications for asphalt and concrete mixes. First is the suitability of aggregate quality to mix applications, and second is the use of property-based testing as requirements in aggregate specifications. Specifications structured in such a manner could lead to a better prediction of pavement performance. It is important to distinguish between property-based and performance-based testing as used in this paper. A property-based testing is related to a built-in property of aggregate and is not a result of aggregate manufacturing or processing. For example, the resilient modulus of aggregates is a performance-based testing but is affected by aggregate size and shape. It is not a property-based testing.

In summary, not enough emphasis has been placed on the utilization of local aggregate materials. Some material rejected for high quality use may be suitable for low-volume applications. A better understanding of testing methodologies available to evaluate critical aggregate properties can lead to a better utilization of local aggregate material and reduce the reliance on diminishing high quality sources.

Research Objectives

This research is focused on two main points:

- Do current coarse aggregate requirements reflect Minnesota Department of Transportation (Mn/DOT) interests in aggregate quality?
- If new property-based requirements are to be introduced, would the new requirements

satisfy the performance-related properties of both asphalt and concrete mixes for pavement applications in Minnesota?

The research will evaluate compliance and consistency of coarse aggregate properties with respect to current specification requirements and will assess property-based requirements utilizing percent within limit and variability calculations. These calculations are used to evaluate compliance and variability among the most commonly specified properties of abrasion resistance, soundness, and percent spalling material. Such an evaluation will lead to a better understanding of material performance and property-based characterizations. This research will also evaluate the suitability of local coarse aggregate material with respect to current testing methodologies.

Research Approach

The study investigates local aggregate properties and testing requirements as related to the performance of asphalt and concrete pavement applications. Investigations are performed to determine what testing requirements have been established in current specifications and what areas of testing that may need further development. Literature is evaluated to determine current coarse aggregate specifications while a survey of professionals identifies strengths and weaknesses of these currently specified testing requirements. Local aggregate quality was evaluated by examining a sample of historical testing data from Mn/DOT. Standard specifications were examined in search of property-based testing on coarse aggregates in a sample of states/provinces.

An electronic survey was conducted by contacting researchers, engineers, and professionals from the pavement industry. The survey proposed a variety of different physical, chemical, and mechanical properties of coarse aggregates in concrete and bituminous applications. In general the survey was used to rank the significance of different aggregate properties and testing methodologies used to evaluate them.

The evaluation indicated that the surveyed states use the standardized procedures to test mainly for physical properties of coarse aggregates. The pavement industry typically relies on these physical characteristics of aggregates to predict pavement performance. Chemical and mechanical property testing was utilized, but not to the extent of physical property testing. The most common reason for testing a chemical property was to indicate reactivity with Portland cement, and the most common mechanical property test was to evaluate the degradation of materials.

Summary of Research Outcomes

The survey of professionals indicated that compressive strength is an important property that has the potential to improve current specification. For this reason, the compressive strength test was conducted as part of this project following ASTM C-170 “Standard Test Method for Compressive Strength of Dimension Stone.”

Test data on local aggregate sources was collected and analyzed from two main Mn/DOT data sources: The Laboratory Information Management System (LIMS) database and the Aggregate Source Information System (ASIS). According to the literature, 26 states use percent within limits (PWL) as a measure of quality for acceptance in pavement applications PWL calculations illustrate the overall performance of materials by constructing normal distribution curves. They are based on normal distribution assumptions and are not valid if the material behaves in any other way than normally. To perform the calculation, the area falling outside the specifications is subtracted from the total area under the curve (always equal to 1) to yield the PWL. In this study, variability was measured by means of the standard deviation and coefficient of variation. It is possible that two sources can have the same mean values for a testing property but one may have a much higher variability than the other. This variability is well known to affect pavement performance. For this reason these parameters were calculated for each quality characteristic. Average variability was also calculated among all quality characteristics at the statewide and district level.

The discussions with Mn/DOT engineers on including property-based testing in current specifications was focused on the following points:

1. Do current coarse aggregate requirements reflect Mn/DOT interests in aggregate quality?
2. Can an agency always specify the best aggregate based on current specifications and testing procedures?
3. If new property-based requirements are to be introduced, would the new requirements satisfy the performance-related properties of both asphalt and concrete mixes for pavement applications in Minnesota?
4. The need for additional testing must be justified by relating property-based testing to pavement performance. Mn/DOT expresses concerns that current relations between aggregate property-based and pavement performance are not sufficient and further correlations are needed before making changes to current specifications.
5. The ease and affordability of testing to conduct the testing frequently to ensure consistency of aggregate quality. Complicated and time consuming testing is likely to be conducted less frequently and will not be sufficient to characterize aggregate for their variability.
6. What is the applicability of the new testing on recycled materials? For example, is recycled asphalt pavement (RAP) aggregate?

Mn/DOT engineers are receptive to pursuing changes in the way they specify aggregates, but express concerns that current relations between aggregate property-based and pavement performance are not sufficient and further correlations are needed before making changes to current specifications.

1 Introduction

1.1 Background and Problem Statement

Aggregates used in highway construction are largely obtained from local supplies of natural rock. The natural rocks occur as either outcrops at or near the surface or as gravel deposits usually along old stream beds. Natural rocks are classified by geologists into three groups depending on their origin—igneous, sedimentary, and metamorphic. Aggregate is a broad term used to describe sand, gravel, and crushed rock mixtures. These materials can be further crushed, washed, and blended to meet specifications. Aggregate materials are the basic ingredients for a variety of construction products. Aggregate materials are known by other names including “aggregate,” “construction aggregates,” “sand and gravel,” “crushed rock,” and “construction sand & gravel.” Minnesota is the 12th largest state in the U.S. and covers 53.8 million acres including 2.6 million acres of water. The state contains a vast network of roads and infrastructure. One of the most highly visible uses for aggregate materials is in road construction and maintenance. Road construction accounts for about 25% of the aggregate used in Minnesota in any given year. Table 1-1 shows the amount of aggregate produced in Minnesota in the past 5 years.

Transportation departments specify requirements for coarse aggregates used in bituminous and Portland cement concrete applications. Coarse aggregate specifications, for many states, date back to the 1930s and have been updated as more knowledge has become available. Aggregate specifications do not always reflect the current level of knowledge concerning desirable “properties for pavement applications. Furthermore, current specifications lack property-based testing methodologies. Literature indicates the need to restructure coarse aggregate specifications to include more property-based testing [INDOT, 2006]. Overall, literature outlines the need for two main criteria in coarse aggregate specifications for asphalt and concrete mixes: (1) the suitability of aggregate quality to mix applications, and (2) the use of property-based testing as requirements in aggregate specifications. Specifications structured in such a manner could lead to better pavement performance. Table 1.2 presents a summary of current Minnesota specifications for coarse aggregate in pavement applications. In addition, Mn/DOT uses a few other specifications such as:

1) Insoluble residue
2) Absorption
3) %Carbonate in natural gravel
4) Chemical Reactivity
5) Oil Adhesion
6) Aggregate shape

Table 1.1 Minnesota Aggregate Productions (2000-2007)

(Productions in Million Metric Tons and Values in Million Dollars)

Year	Crushed Stone	Value	Sand & Gravel	Value	Total Production	Total Value
2000	12.4	68.1	395.0	158.0	407.4	226.1
2001	9.7	57.0	398.0	155.0	407.7	212.0
2002	9.7	57.9	424.0	168.0	433.7	225.9
2003	9.8	57.3	470.0	188.0	479.8	245.3
2004	10.4	64.9	549.0	235.0	559.4	299.9
2005	10.5	87.4	541.0	253.0	551.5	340.4
2006	12.4	121.0	503.0	240.0	515.4	361.0
2007	10.2	109.0	461.0	239.0	471.2	348.0

Source: USGS Mineral Industry Surveys, Minnesota [USGS, 2007]

Table 1.2 Summary of Minnesota's Coarse Aggregate Specifications for Pavements

QUALITY TEST	PCC	ASPHALT
Los Angeles Rattler Test (AASHTO T-96)	40% Maximum	40% Maximum
Magnesium Sulfate Soundness (AASHTO T-104)	15% Max Any Fraction	14% Max (3/4" to 1/2")
		18% Max (1/2" to 3/8")
		23% Max (3/8" to #4)
Spalling Materials (Shale, Iron Oxide, Unsound Chert, Pyrite, Weathered Phylitte, Argillite)	1.5% Maximum	Total 5% Maximum

There is a gap in the literature regarding the characterization of pavement mix quality based on the consistency of aggregate properties [INDOT, 2006]. For many years, research has concluded that aggregate properties are directly correlated with pavement performance. Aggregate specifications do not reflect the current level of knowledge concerning desirable properties for pavement applications but rather represent the adaptation of existing test procedures to select the best aggregate with those particular tests. Coarse aggregate specifications need to be restructured so that they are based on aggregate properties that are related to the performance of asphalt and concrete mixes. Some states have already taken a step in this direction by creating durability classes to distinguish aggregate quality. However, before a full specification restructuring can be accomplished, a clear understanding of aggregate quality based on current requirements needs to be obtained.

State-to-state specification requirements on aggregate quality are very similar. The most commonly specified properties are abrasion resistance, soundness, and limitations on percent spalling material. Specifications on these properties are based on compliance with tolerance levels with no requirements set on consistency. Tolerance levels vary from state to state based on local aggregate availability. It is important to note that this study focuses only on source properties. Properties based on manufacturing, such as gradation, are also very influential when it comes to mix stability, durability, and workability. However, properties of manufacturing are beyond the scope of this particular study.

To fully assess the quality of aggregate sources, both compliance and variability need to be considered. It is important to note that compliance and variability are not always congruent with one another. Two different aggregate samples can both have 100% compliance with specifications; however, variability can fluctuate drastically between the two. This undetected range in variability can significantly affect pavement performance. Compliance and variation of current quality requirements can be evaluated by mean, standard deviation and percent within limit (PWL) studies. The mean estimates the center value and the standard deviation gives an approximation of the spread about the mean. Percent within limit calculations illustrate the overall performance of a material that considers tolerances by constructing a normal distribution curve. These are based on normal distribution assumptions and are not valid if the material behaves in any way other than normally. Percent within limits is calculated by subtracting the area falling outside the specification limits from the total area under the normal distribution curve [Southwick, 2000].

Not enough emphasis has been placed on utilization of local aggregate materials. Some material rejected for high quality use may be suitable for low-volume applications. A better understanding of testing methodologies available for evaluating critical aggregate properties can lead to a better indication of pavement performance and help maximize the use of local sources. Some sources may contain aggregate material that is not commonly used in high quality mix applications. However, there is a possibility that some sources rejected for high class mixtures may be suitable for local and low-volume road applications.

1.2 Research Objectives

This research is focused on two main points:

- Do current coarse aggregate requirements reflect Mn/DOT interests in aggregate quality?
- If new property-based requirements are to be introduced, would the new requirements satisfy the performance-related properties of both asphalt and concrete mixes for pavement applications in Minnesota?

The research will evaluate compliance and consistency of coarse aggregate properties with respect to current specification requirements and will assess property-based requirements utilizing percent within limit and variability calculations. These calculations are used to evaluate compliance and variability among the most commonly specified properties of abrasion resistance, soundness, and percent spalling material. Such an evaluation will lead to a better understanding of material performance and property-based characterizations. This research will also evaluate the suitability of local coarse aggregate material with respect to current testing methodologies.

1.3 Research Approach

The study investigates local aggregate properties and testing requirements as related to the performance of asphalt and concrete pavement applications. Investigations are performed to determine what testing requirements have been established in current specifications and what areas of testing that may need further development. Literature is evaluated to determine current coarse aggregate specifications while a survey of professionals identifies strengths and weaknesses of these currently specified testing requirements. Local aggregate quality was evaluated by examining a sample of historical testing data from the Minnesota Department of Transportation (Mn/DOT). Standard specifications were examined in search of property-based testing on coarse aggregates in a sample of states/provinces. Table 1.3 presents an example of the literature evaluation of state specifications of coarse aggregates.

An electronic survey was conducted by contacting researchers, engineers, and professionals from the pavement industry (Survey questions are presented in Appendix E). The survey proposed a variety of different physical, chemical, and mechanical properties of coarse aggregates in concrete and bituminous applications. In general the survey was used to rank the significance of different aggregate properties and testing methodologies was used to evaluate them.

The evaluation indicated that the surveyed states use the standardized procedures to test mainly for physical properties of coarse aggregates. The pavement industry typically relies on these physical characteristics of aggregates to predict pavement performance. Chemical and mechanical property testing was utilized, but not to the extent of physical property testing. The most common reason for testing a chemical property was to indicate reactivity with Portland cement, and the most common mechanical property test was to evaluate the degradation of materials. More details on relating aggregate properties to pavement performance are presented in Appendices A and B.

The findings of this study were discussed with Mn/DOT engineers. Details of the discussions with Mn/DOT engineers are presented in Chapter 6.

Table 1.3 State Evaluation of Standardized Procedures for Coarse Aggregate

TEST NAME	STANDARD TEST	GENERAL PROPERTY	SPECIFIC PROPERTY	USE	MN	ND	SD	IL	WI	IA	NE	MT	TX	CA	CN	PERCENT USE BY STATES
Reactivity	AASHTO M-80	Chemical	Reactivity	CONCRETE		X										9%
Soundness of Aggregate by Freezing and Thawing	AASHTO T-103	Physical	Soundness	BOTH							X*					9%
Soundness by Sodium/Magnesium Sulfate	AASHTO T-104	Physical	Soundness	BOTH	X*	X		X*	X		X	X	X*	X*		73%
Material Passing No. 200 Sieve	AASHTO T-11	Physical	Particle Size	BOTH		X	X*	X*	X	X			X*	X*		64%
Clay Lumps and Friable Particles in Aggregate	AASHTO T-112	Physical	Physical Components	BOTH						X*	X*	X*				27%
Lightweight Pieces of Aggregate	AASHTO T-113	Physical	Deleterious Content	BOTH	X*	X		X*	X			X	X*			55%
Density/Voids of Aggregate	AASHTO T-19	Physical	Density/Voids	BOTH	X		X*	X*	X*	X		X*	X*	X*		73%
Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	AASHTO T-176	Physical	Dust/Fine Proportions	ASPHALT	X*											9%
Sampling	AASHTO T-2	Physical	Gradation	BOTH		X	X*	X*	X	X*	X*	X*	X*	X*		82%
Reducing Sample to Test Size	AASHTO T-248	Physical	Gradation	BOTH	X*	X	X*	X*		X	X			X*		64%
Total Moisture Content of Aggregate by Drying	AASHTO T-255	Physical	Adsorption, Permeability, Porosity	BOTH		X		X*								18%
Sieve Analysis	AASHTO T-27	Physical	Gradation	BOTH	X*	X	X*	X*	X	X	X*		X*	X*		82%
Mechanical Analysis of Extracted Aggregate	AASHTO T-30	Physical	Gradation	ASPHALT	X											9%
Uncompacted Void Content of Fine Aggregate	AASHTO T-304	Physical	Angularity	BOTH	X											9%
Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus	AASHTO T-327	Physical	Soundness, Absorption	BOTH							X*	X*	X*			27%
Sieve Analysis of Mineral Filler	AASHTO T-37	Physical	Gradation	ASPHALT				X					X*			18%
Specific Gravity and Absorption for Fine Aggregate	AASHTO T-84	Physical	Specific Gravity, Absorption	BOTH	X*	X	X*	X*	X	X	X	X*	X*	X*		91%
Specific Gravity and Absorption for Coarse Aggregate	AASHTO T-85	Physical	Specific Gravity, Absorption	BOTH	X*	X	X*	X*	X	X	X	X*	X*	X*		91%
Los Angeles Rattler Loss	AASHTO T-96	Mechanical	Degradation	BOTH	X	X	X	X*	X	X	X	X*	X*	X*		91%
Lightweight Particles in Aggregate	ASTM C123	Physical	Dust/Fine Proportions	BOTH	X											9%
LA Abrasion Test for Small Sized Coarse Aggregate	ASTM C131	Mechanical	Degradation	BOTH	X										X	18%
Potential Alkali-Silica Reactivity of Cement-Aggregate Combinations (Mortar Bar Method)	ASTM C227	Chemical	Reactivity	CONCRETE					X							18%
Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)	ASTM C289	Chemical	Reactivity	CONCRETE					X							9%
Petrographic Examination	ASTM C295	Physical	Particle Shape, Surface Texture	BOTH					X						X	18%
L.A Abrasion Test for Large Sized Coarse Agg.	ASTM C535	Mechanical	Degradation	BOTH	X										X	18%
Soundness	ASTM C88	Physical	Soundness	BOTH			X*					X			X	27%
Scratch Hardness	ASTM C851	Physical	Hardness	BOTH	X*		X*									18%
Alkali Reactivity of Aggregate (Mortar Bar Method)	ASTM C1260	Chemical	Reactivity	CONCRETE	X*											9%
Alkali Reactivity of Aggregate (Accelerated Mortar Bar Method)	ASTM C1567	Chemical	Reactivity	CONCRETE	X*											9%
Acid Insoluble Residue in Limestone and Dolestone	ASTM D3042	Chemical	Purity	ASPHALT	X*											9%
Flat and Elongated Particles in Course Aggregate	ASTM D4791	Physical	Particle Shape	ASPHALT	X*	X			X*				X*			36%
Coarse Aggregate Angularity	ASTM D5821	Physical	Particle Shape	ASPHALT	X*	X*	X*		X*			X*				45%
Resistance of Abrasion by Micro-Deval Apparatus	LS-618	Physical	Soundness	BOTH	X*											9%

1.4 Summary of Research Outcomes

The survey of professionals indicated that compressive strength is an important property that has the potential to improve current specification. For this reason, the compressive strength test was conducted as part of this project following ASTM C-170 “Standard Test Method for Compressive Strength of Dimension Stone.”

Test data on local aggregate sources was collected and analyzed from two main Mn/DOT data sources: The Laboratory Information Management System (LIMS) database and the Aggregate Source Information System (ASIS).

According to the literature, 26 states use percent within limits (PWL) as a measure of quality for acceptance in pavement applications [Hughes, 2005]. PWL calculations illustrate the overall performance of materials by constructing normal distribution curves. They are based on normal distribution assumptions and are not valid if the material behaves in any other way than normally. To perform the calculation, the area falling outside the specifications is subtracted from the total area under the curve (always equal to 1) to yield the PWL. In this study, variability was measured by means of the standard deviation and coefficient of variation. It is possible that two sources can have the same mean values for a testing property but one may have a much higher variability than the other. This variability is well known to affect pavement performance. For this reason these parameters were calculated for each quality characteristic. Average variability was also calculated among all quality characteristics at the statewide and district level [Williams, 2003]. More details on the PWL and variability of local Minnesota aggregate as compared to current specifications are presented in Appendix D.

The discussions with Mn/DOT engineers on including property-based testing in current specifications was focused on the following points:

1) Do current coarse aggregate requirements reflect Mn/DOT interests in aggregate quality?
2) Can an agency always specify the best aggregate based on current specifications and testing procedures?
3) If new property-based requirements are to be introduced, would the new requirements satisfy the performance-related properties of both asphalt and concrete mixes for pavement applications in Minnesota?
4) The need for additional testing must be justified by relating property-based testing to pavement performance. Mn/DOT expresses concerns that current relations between aggregate property-based and pavement performance are not sufficient and further correlations are needed before making changes to current specifications.
5) The ease and affordability of testing to conduct the testing frequently to ensure consistency of aggregate quality. Complicated and time consuming testing is likely to be conducted less frequently and will not be sufficient to characterize aggregate for their variability.
6) What is the applicability of the new testing on recycled materials? For example, is recycled asphalt pavement (RAP) aggregate?

The research team found Mn/DOT receptive to pursuing changes in the way they specify aggregates, although the team is not currently suggesting any changes. Rather discussing the question of the need for changes to current specifications and if current specifications are outdated or do not reflect the current level of knowledge concerning desirable properties for pavement applications. It is also reasonable to state that current testing does not provide all necessary property characterization to ensure field performance. Current testing may or may not be the best testing to characterize coarse aggregate properties.

2 Local Aggregates in Minnesota

2.1 Locations of Local Aggregate Sources in Minnesota

This chapter provides information on local aggregate sources and available testing data in Minnesota. The information presented in this chapter provides a background for the remaining sections of this report. The state of Minnesota is divided into eight districts. Minnesota's Local Road Research Board (LRRB) survey included data from 78 local aggregate sources in Minnesota that span over all eight of the districts. Table 2.1 summarizes the number of pits evaluated in each district.

Table 2.1 Number of Evaluated Pits

District #	District Name	# Sources Evaluated
1	Duluth	12
2	Bemidji	11
3	Brainerd	10
4	Detriot Lakes	6
6	Rochester	14
7	Mankato	11
8	Wilmar	4
Metro	Metro	10

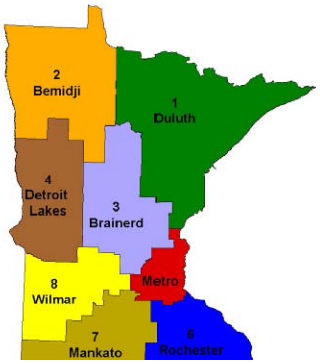


Figure 2.1 Map of Districts

2.2 Available Testing on Local Materials

The LRRB data included a series of tests on each local aggregate source that was evaluated to better understand the material. Tables 2.2 and 2.3 summarize all the tests included in the LRRB data and the number of times that each test was performed in the evaluation. The sample data contains data testing from 2002-2007. Currently in Minnesota, aggregate sources are tested at a minimum rate of once per year for quality. If the material in a particular source is considered to be marginal, the testing rate is increased to 1 sample per 10,000 tons of material produced. The rate of testing can be increased or decreased at any time as long as it does not fall below the minimum of once per year.

The Laboratory Information Management System (LIMS) and the Aggregate Source Information System (ASIS) are the two main digital databases used by the department. The LIMS database was created to store all testing done by Mn/DOT labs. The Office of Materials in Maplewood, Minnesota, created the Aggregate Source Information System (ASIS) to store and retrieve information on gravel pits, rock quarries, and commercial aggregate sources [Tilseth, 2008]. This database includes prospective sampling on aggregate used by engineers to recommend sources for future projects. Samples of data were collected from both the LIMS and ASIS databases to perform the analysis. State defined specifications identify requirements for aggregate testing to ensure quality. Aggregate testing data has been stored digitally at Mn/DOT since approximately 2000. The Laboratory Information Management System (LIMS) database was created to store all testing done by Mn/DOT labs (The LIMS database was queried to supply a sample of testing data. The study evaluated 76 local aggregate sources in Minnesota that span all Mn/DOT districts. The sample data contains testing information associated with 789 different project numbers from 2002 to 2007.

In the given data sample not all of the above tests were performed in each district. The following table summarizes the testing that is performed in each district. The most common tests that were performed on sources in every district include BA% total sample spall, magnesium sulfate percent loss (1/2”-3/8”, 3/4”-1/2”, 3/8-#4), percent iron oxide, percent shale, percent soft rock, percent shale in sand, percent spall and soft rock, weighted average BA spall +4, weighted average percent shale +1/2”, weighted average total spall +4 and weighted average total spall +1/2”.

Table 2.2 LRRB Aggregate Test Summary

Test Description	# Tests Ran	Percentage
BA % Total Samp Spall (Type 31,32,61,62)	443	1.7%
Bulk Specific Gravity Avg	142	0.5%
Los Angeles Rattler (Type A) Pct Loss	29	0.1%
Los Angeles Rattler (Type B) Pct Loss	645	2.5%
Los Angeles Rattler (Type C) Pct Loss	471	1.8%
Los Angeles Rattler (Type G) Pct Loss	11	0.0%
Mag Sulfate Percent Lost 1 1/2" - 1"	21	0.1%
Mag Sulfate Percent Lost 1" to 3/4"	37	0.1%
Mag Sulfate Percent Lost 1/2" to 3/8"	403	1.5%
Mag Sulfate Percent Lost 2" to 1 1/2"	1	0.0%
Mag Sulfate Percent Lost 3/4" to 1/2"	259	1.0%
Mag Sulfate Percent Lost 3/8" to #4	449	1.7%
Mag Sulfate Total Percent Lost	22	0.1%
Pct Carbonate - Weighted Average	969	3.7%
Pct Class-A - Weighted Average	6	0.0%
Pct Disintegrated Rock - Wtd. Average	50	0.2%
Pct Iron Oxide - Weighted Average	2446	9.4%
Pct Misc Spall - Weighted Average	691	2.6%
Pct NonSpallArgillite - Weighted Average	83	0.3%
Pct Ochre - Weighted Average	392	1.5%
Pct Other Rock - Weighted Average	1563	6.0%
Pct Pyrite - Weighted Average	192	0.7%
Pct Sandstone - Weighted Average	1744	6.7%
Pct Schist - Weighted Average	210	0.8%
Pct Shale - Weighted Average	1625	6.2%
Pct Slate - Weighted Average	199	0.8%
Pct Soft Rock - Weighted Average	1394	5.3%
Pct Unsound Chert - Weighted Average	1377	5.3%
Pct Weathered Phyllite - Wtd. Average	225	0.9%
Percent Absorption Avg	142	0.5%
Percent Shale in Sand	1815	6.9%
Percent Soft Iron Oxide	371	1.4%
Percent Spall And Soft Rock	2317	8.9%
Total % Absorption of +4 and -4 BA	61	0.2%
Total Bulk SpG of +4 and -4 BA	59	0.2%
WA % BA Spall +4	429	1.6%
WA % Shale +1/2"	836	3.2%
WA % Total Spall +4	2263	8.7%
WA%Total Spall +1/2"	1602	6.1%
Weighted Average Pct Non-Class A	133	0.5%

Table 2.3 Testing Present in Districts from Data Sample

	Testing Present In Districts							
Test Description	**1**	**2**	**3**	**4**	**6**	**7**	**8**	**Metro**
BA % Total Samp Spall (Type 31,32,61,62)	X	X	X	X	X	X	X	X
Bulk Specific Gravity Avg	X	X	X			X		X
Los Angeles Rattler (Type A) Pct Loss			X		X			X
Los Angeles Rattler (Type B) Pct Loss	X	X	X		X	X	X	X
Los Angeles Rattler (Type C) Pct Loss	X		X		X	X		X
Los Angeles Rattler (Type G) Pct Loss					X	X		
Mag Sulfate Percent Lost 1 1/2" - 1"			X		X	X		X
Mag Sulfate Percent Lost 1" to 3/4"			X		X	X		X
Mag Sulfate Percent Lost 1/2" to 3/8"	X	X	X	X	X	X	X	X
Mag Sulfate Percent Lost 2" to 1 1/2"					X			
Mag Sulfate Percent Lost 3/4" to 1/2"	X	X	X	X	X	X	X	X
Mag Sulfate Percent Lost 3/8" to #4	X	X	X	X	X	X	X	X
Mag Sulfate Total Percent Lost	X	X	X			X		X
Pct Carbonate - Weighted Average	X	X	X	X		X	X	X
Pct Class-A - Weighted Average			X					
Pct Disintegrated Rock - Wtd. Average	X	X	X	X		X	X	X
Pct Iron Oxide - Weighted Average	X	X	X	X	X	X	X	X
Pct Misc Spall - Weighted Average	X		X	X	X	X	X	X
Pct NonSpallArgillite - Weighted Average	X		X	X		X	X	X
Pct Ochre - Weighted Average	X	X	X	X		X	X	X
Pct Other Rock - Weighted Average	X	X	X	X	X	X	X	X
Pct Pyrite - Weighted Average	X		X	X		X	X	
Pct Sandstone - Weighted Average	X		X	X	X	X	X	X
Pct Schist - Weighted Average	X	X	X	X		X	X	X
Pct Shale - Weighted Average	X	X	X	X	X	X	X	X
Pct Slate - Weighted Average	X	X	X	X		X	X	X
Pct Soft Rock - Weighted Average	X	X	X	X	X	X	X	X
Pct Unsound Chert - Weighted Average	X	X	X	X		X	X	X
Pct Weathered Phyllite - Wtd. Average	X		X	X		X	X	X
Percent Absorption Avg	X	X	X				X	X
Percent Shale in Sand	X	X	X	X	X	X	X	X
Percent Soft Iron Oxide	X	X	X	X		X	X	X
Percent Spall And Soft Rock	X	X	X	X	X	X	X	X
Total % Absorption of +4 and -4 BA	X	X	X			X	X	
Total Bulk SpG of +4 and -4 BA	X	X	X			X		X
WA % BA Spall +4	X	X	X	X	X	X	X	X
WA % Shale +1/2"	X	X	X	X	X	X	X	X
WA % Total Spall +4	X	X	X	X	X	X	X	X
WA%Total Spall +1/2"	X	X	X	X	X	X	X	X
Weighted Average Pct Non-Class A			X		X	X		

3 Coarse Aggregate Property Survey

In December 2007 and January 2008 an Internet email survey was conducted. The objective of the survey was to rank the significance of different physical, chemical, and mechanical properties of aggregates in concrete and bituminous paving applications. Researchers and pavement engineers from each of the surveyed states as well as some professionals from the pavement industry were asked to take part in the survey. A copy of the email survey and contacted professionals can be located in Appendix E.

3.1 Survey Results for Coarse Aggregate in Asphalt Pavement

3.1.1 Physical Properties

Physical properties of aggregates comprise most of the testing currently conducted by state departments. Typically these physical properties are used to predict and to distinguish performance of pavements. The physical properties of an aggregate are the outcome of its mineral and chemical makeup. Table 3.1 below summarizes different physical properties of aggregates and what percentage of respondents ranked them from “not significant” or “1” to “very significant” or “5” on a 1-5 scale. The highest percentage of responses is bolded in red. There was also a column that participants could select if they were not familiar with the property that they were ranking.

Table 3.1 Survey Results for Physical Properties-Asphalt Pavement

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Particle Size (angularity)- ASTM D5821	0.0%	0.0%	0.0%	16.7%	**77.8%**	5.6%
Particle Shape (flakiness, elongation)- ASTM D4791	0.0%	0.0%	16.7%	33.3%	**44.4%**	5.6%
Particle Size (maximum)- ASTM D75	0.0%	5.6%	11.1%	33.3%	**44.4%**	5.6%
Particle Size (distribution)- AASHTO T-2	0.0%	0.0%	0.0%	27.8%	**61.1%**	11.1%
Particle Surface Texture- ASTM C1252	0.0%	0.0%	5.6%	**38.9%**	**38.9%**	16.7%
Pore Structure, Porosity	0.0%	0.0%	16.7%	22.2%	**38.9%**	22.2%
Specific Gravity & Absorption- AASHTO T-85	0.0%	5.6%	5.6%	**44.4%**	38.9%	5.6%
Soundness, Weatherability – AASHTO T-104	11.1%	5.6%	5.6%	27.8%	**44.4%**	5.6%
Unit Weight, voids – AASHTO T-19	5.6%	11.1%	16.7%	**33.3%**	11.1%	22.2%
Volumetric Stability – freeze/thaw	5.6%	5.6%	11.1%	**33.3%**	27.8%	16.7%
Integrity during heating	0.0%	0.0%	22.2%	**27.8%**	22.2%	**27.8%**
Deleterious Constituents – AASHTO T-112	5.6%	0.0%	5.6%	**44.4%**	27.8%	16.7%

As seen above all of the physical properties that are listed were ranked as either a 4 or a 5. Integrity due to heating tied for highest responses between 4 and “not familiar with property.” Surface texture, specific gravity and absorption, unit weight, volumetric stability, integrity during heating, and deleterious constituents had the highest number of responses ranking them a 4 on a 1-5 scale. The physical properties of particle angularity, particle shape (elongation), particle distribution, surface texture, pore structure, and soundness all had the highest percentage of responses with ranks of a 5, or “very significant,” on a 1-5 scale.

3.1.2 Chemical Properties

Typically, chemical properties of aggregates are not part of the specifications for asphalt pavement. The four chemical properties that were surveyed as having potential to be a part of a coarse aggregate specification were surface charge, asphalt affinity, volume stability, and coatings. Table 2.2 below summarizes different chemical properties of aggregates and what percentage of respondents ranked them from “1” or “not significant” to “5” or “very significant.” The highest percentage of respondents is bolded in red. There was also a column that participants could select if not familiar with the property that they were ranking.

Table 3.2 Survey Results for Chemical Properties-Asphalt Pavement

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Surface Charge	0.0%	5.6.%	27.8%	16.7%	16.7%	**33.3%**
Asphalt Affinity - ASTM D1075	0.0%	0.0%	11.8%	17.6%	23.5%	**47.1%**
Volume Stability	5.6%	0.0%	22.2%	16.7%	16.7%	**38.9%**
Coatings	0.0%	0.0%	5.6%	**33.3%**	**33.3%**	27.8%

The survey results regarding the chemical properties were more dispersed than the responses regarding the physical properties. For the most part, the responses most frequented selected was the “not familiar with property” column. This column was marked the highest for surface charge, asphalt affinity, and volume stability. The chemical property of coating was ranked equally between 4-5.

3.1.3 Mechanical Properties

Mechanical properties of aggregates are more common than chemical properties of aggregates in asphalt pavement specifications. However, they are still not utilized remotely as much as physical property tests. The main mechanical properties that apply to asphalt pavement applications are toughness, abrasion resistance, character of products of abrasion, mass stability, and polishability. Table 3.3 below summarizes different mechanical properties of aggregates and what percentage of respondents ranked them from “1” or “not significant” to “5” or “very significant.” The highest percentage of respondents is bolded in red. There was also a column to that participants could select if they were not familiar with the property that they were ranking.

Table 3.3 Survey Results for Mechanical Properties-Asphalt Pavement

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Toughness - ASTM C131	5.6%	0.0%	5.6%	**33.3%**	27.8%	27.8%
Abrasion Resistance – ASTM C131	0.0%	0.0%	22.2%	**38.9%**	33.3%	5.6%
Character of Products of Abrasion – AASHTO T-96	5.6%	0.0%	22.2%	11.1%	16.7%	**44.4%**
Mass Stability (Stiffness, Resilience) – AASHTO T-292	5.6%	5.6%	16.7%	11.1%	16.7%	**44.4%**
Polishability – AASHTO 279	5.6%	5.6%	11.1%	22.2%	16.7%	**38.9%**

The above results indicate that the mechanical properties of abrasion, mass stability, and polishability were the ones with which most survey respondents were not familiar. Toughness and abrasion resistance had the most respondents ranking it somewhere between moderately significant and very significant. The results demonstrate that survey participants did not demonstrate strong opinions regarding the relative of these properties.

3.2 Survey Results for Coarse Aggregate in Concrete Pavement

3.2.1 Physical Properties

Table 3.4 below summarizes the survey results for physical properties in Portland cement concrete applications. The properties that the most respondents marked “very significant” were particle size (angularity), particle shape (flakiness, elongation), maximum particle size, particle size distribution, porosity, soundness, and volumetric stability. The properties that were ranked somewhere between “moderately significant” and “very significant” were surface texture, specific gravity and absorption, unit weight and deleterious constituents. The properties of wet/dry volumetric stability and freeze/thaw volumetric stability were properties with which almost half of the respondents were unfamiliar.

Table 3.4 Survey Results for Physical Properties-Concrete Pavement

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Particle Size (angularity)- ASTM D5821	0.0%	5.9%	11.8%	23.5%	**52.9%**	5.9%
Particle Shape (flakiness, elongation)- ASTM D4791	0.0%	0.0%	29.4%	17.6%	**47.1%**	5.9%
Particle Size (maximum)- ASTM D75	0.0%	0.0%	17.6%	29.4%	**47.1%**	5.9%
Particle Size (distribution)- AASHTO T-2	0.0%	0.0%	5.9%	23.5%	**64.7%**	5.9%
Particle Surface Texture- ASTM C1252	0.0%	6.3%	**31.3%**	**31.3%**	18.8%	12.5%
Pore Structure, Porosity	0.0%	5.9%	17.6%	23.5%	**41.2%**	11.8%
Specific Gravity & Absorption- AASHTO T-85	0.0%	17.6%	17.6%	**35.3%**	23.5%	5.9%
Soundness, Weatherability – AASHTO T-104	11.8%	0.0%	0.0%	17.6%	**64.7%**	5.9%
Unit Weight, voids – AASHTO T-19	0.0%	17.6%	11.8%	**41.2%**	17.6%	11.8%
Volumetric Stability – thermal	0.0%	0.0%	35.3%	11.8%	11.8%	**41.2%**
Volumetric Stability – wet/dry	0.0%	0.0%	25.0%	18.8%	6.3%	**50.0%**
Volumetric Stability – freeze/thaw	0.0%	0.0%	5.9%	29.4%	**41.2%**	23.5%
Deleterious Constituents – AASHTO T-112	0.0%	0.0%	17.6%	**47.1%**	23.5%	11.8%

3.2.2 *Chemical Properties*

Table 3.5 below summarizes the survey results for significance levels of chemical properties in Portland cement concrete applications. Chemical properties are more significant in PCC applications due to reactivity of the Portland cement. The survey indicates that many of the survey respondents were not familiar with the properties of solubility and coatings. The survey indicates that the participants feel that reactivity to chemicals and volume stability are “moderately significant” to “very significant” chemical properties of aggregates in Portland cement concrete.

Table 3.5 Survey Results for Chemical Properties-Concrete Pavement

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Solubility	0.0%	0.0%	5.9%	23.5%	23.5%	**47.1%**
Reactivity to Chemicals - AASHTO M-80	0.0%	5.9%	5.9%	29.4%	**35.3%**	23.5%
Volume Stability	0.0%	0.0%	12.5%	**43.8%**	12.5%	31.3%
Coatings	0.0%	0.0%	17.6%	29.4%	11.8%	**41.2%**

3.2.3 *Mechanical Properties*

Many of the respondents to the survey were not familiar with many of the mechanical properties proposed in the survey. Compressive strength and resistance to abrasion were ranked to be the most significant mechanical properties out of the group. Table 3.6 summarizes the results on mechanical properties.

Table 3.6 Survey Results for Mechanical Properties-Concrete Pavement

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property
Compressive Strength	0.0%	5.9%	17.6%	17.6%	**47.1%**	11.8%
Toughness - ASTM C131	5.9%	0.0%	0.0%	29.4%	29.4%	**35.3%**
Abrasion Resistance – ASTM C131	0.0%	0.0%	0.0%	**41.2%**	29.4%	29.4%
Character of Products of Abrasion – AASHTO T-96	0.0%	5.9%	11.8%	11.8%	17.6%	**52.9%**
Mass Stability (Stiffness, Resilience) – AASHTO T-292	0.0%	11.8%	0.0%	23.5%	0.0%	**64.7%**
Polishability – AASHTO 279	0.0%	6.3%	12.5%	25.0%	12.5%	**43.8%**

3.3 Index Value Analysis

The results of the survey responses and discussion with professionals provided data to develop an average index value from 1-5 to indicate the significance level of each property. The average index values were used to rank the different properties in order of their significance in both concrete and bituminous applications. The survey results helped explore the gap between the current level of knowledge about aggregate properties and what is actually being considered in specifications. Figures 3.1 and 3.2 summarize all of the properties evaluated for both PCC and asphalt aggregate and how they ranked according to the results of the survey. Note that the overall ranking determined by the total highest point.

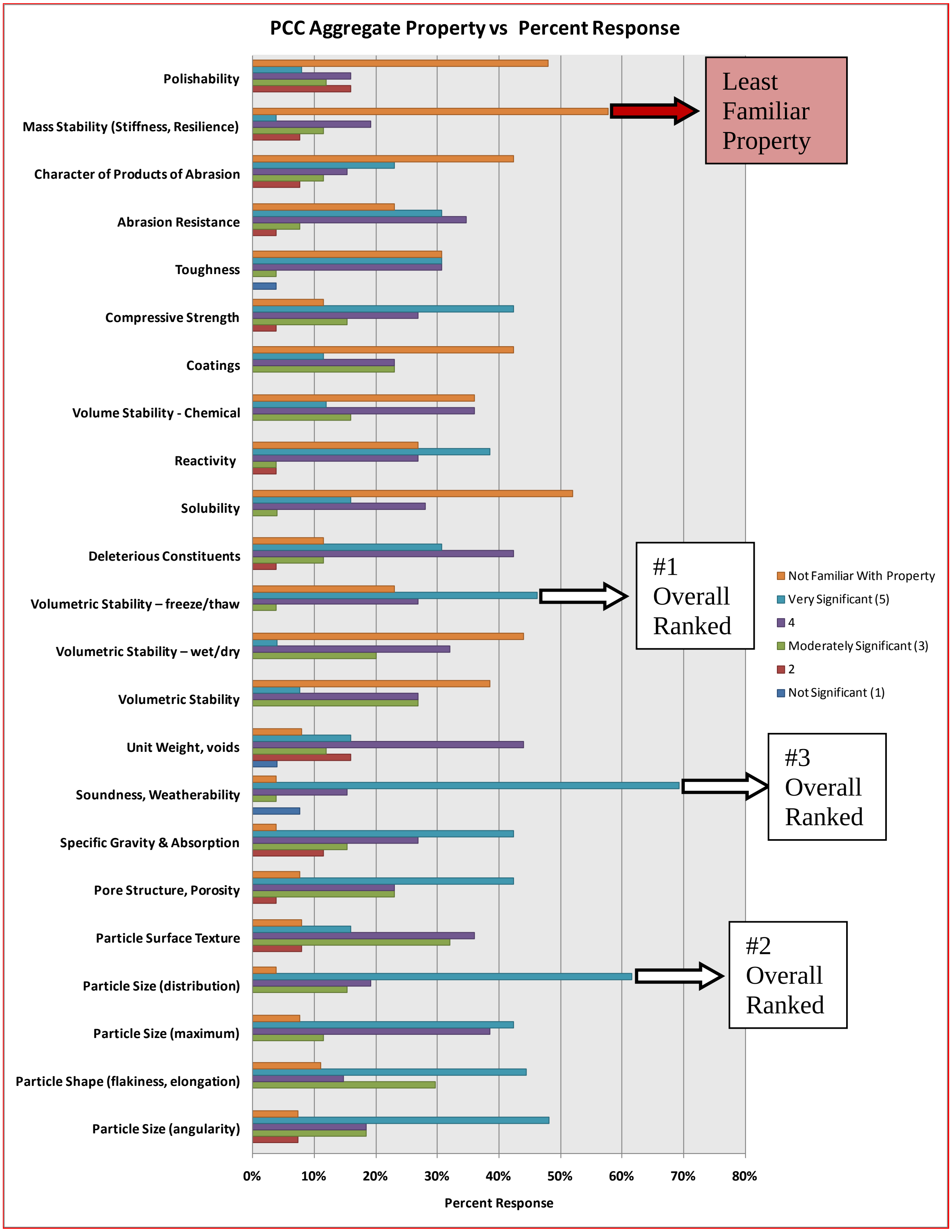


Figure 3.1 Survey Response Results – Portland Cement Concrete Aggregates

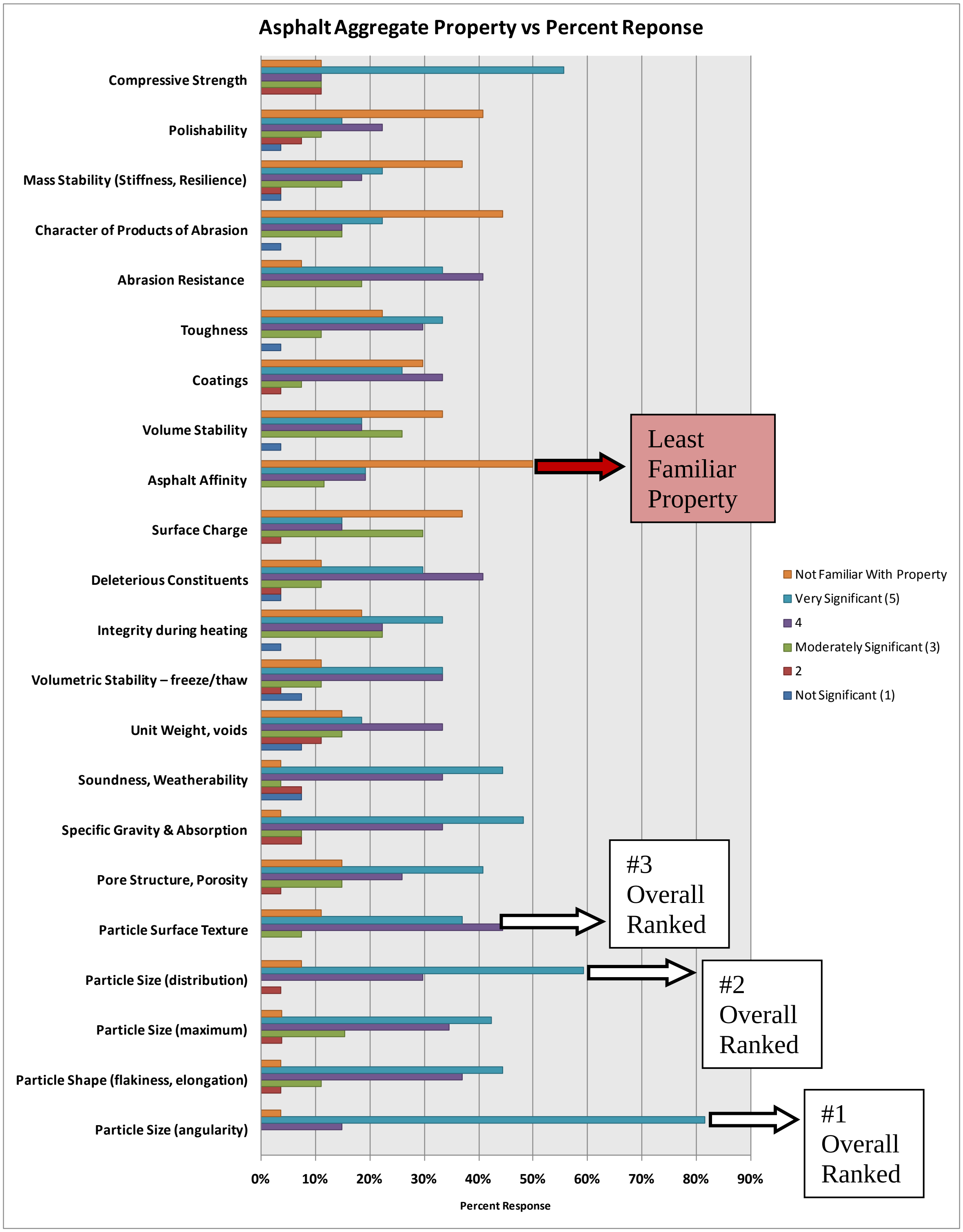


Figure 3.2 Survey Response Results – Asphalt Aggregates

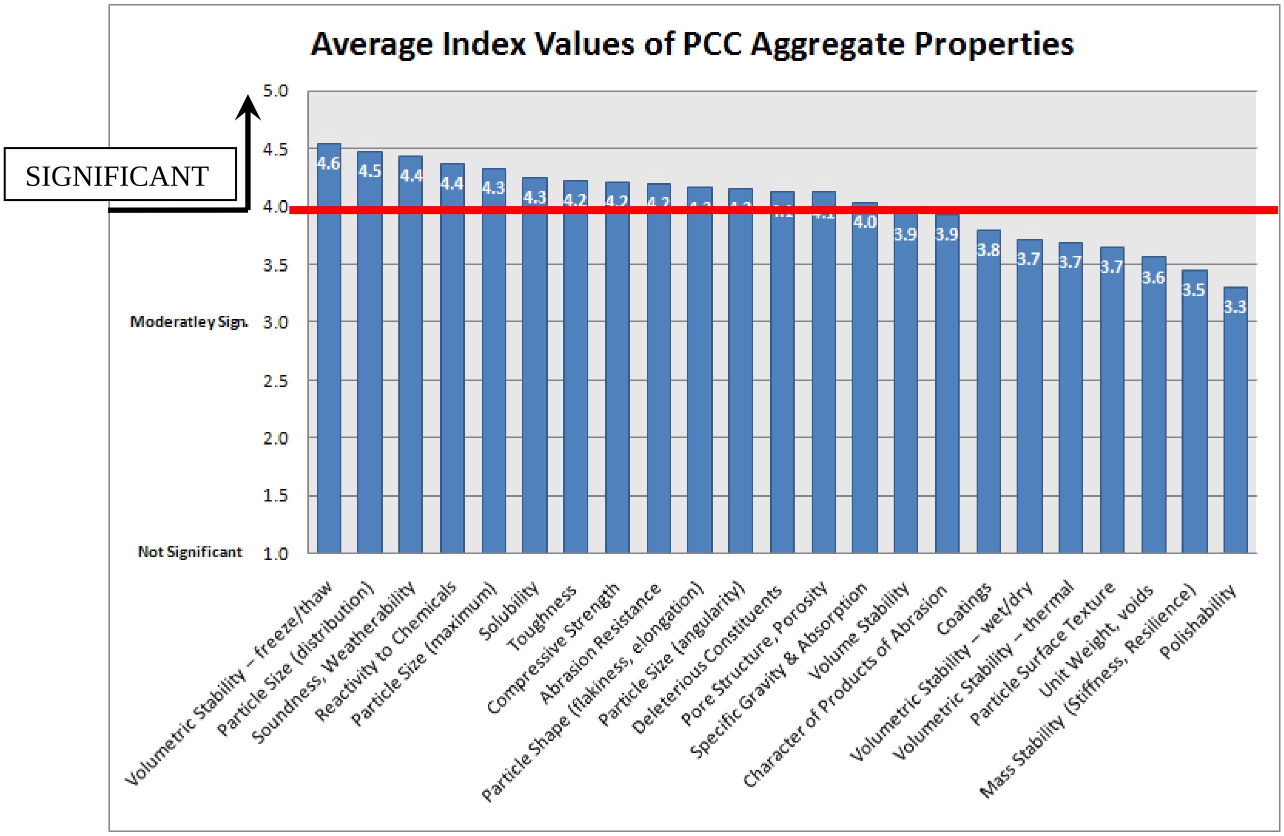


Figure 3.3 Significance Indices of Portland Cement Concrete Aggregate Properties

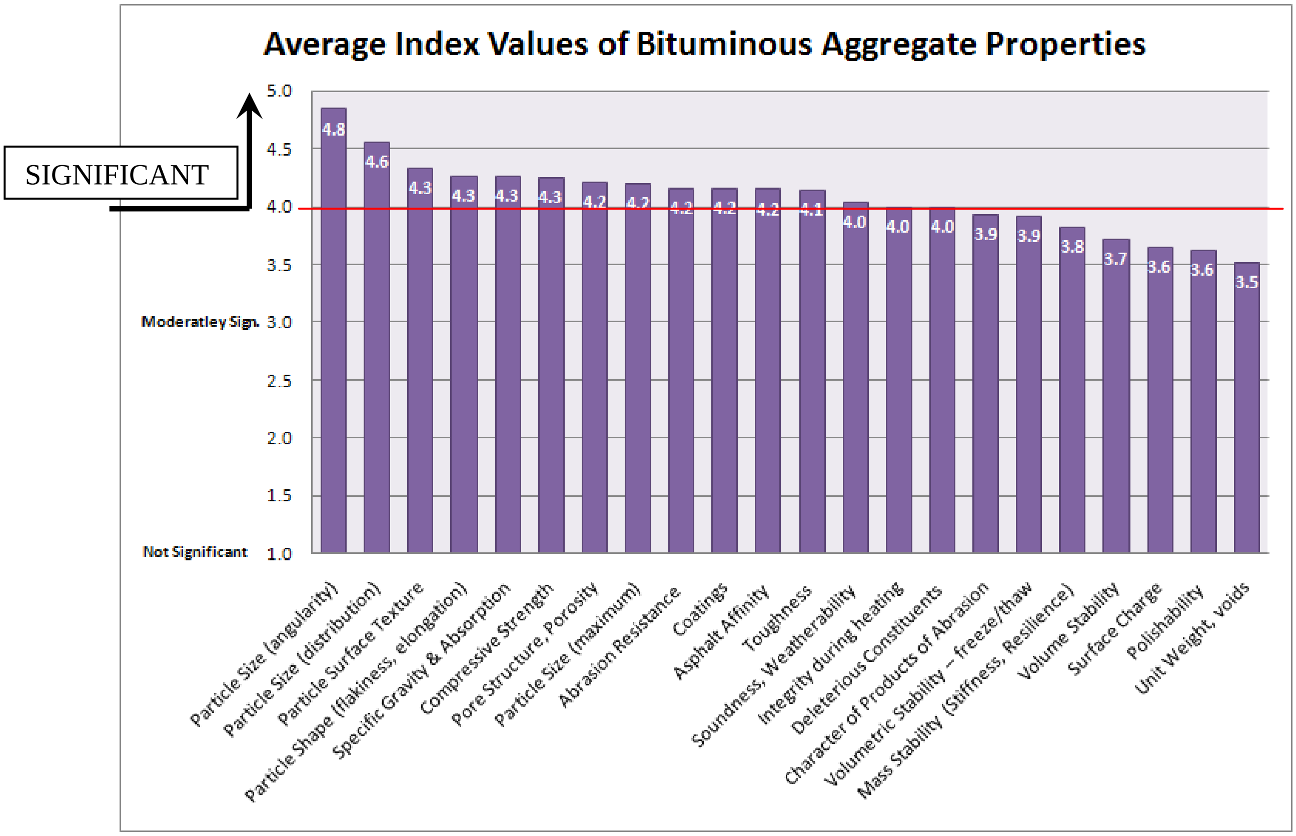


Figure 3.4 Significance Indices of Bituminous Aggregate Properties

Testing all the proposed properties of Figures 3.3 and 3.4 would be neither practical nor cost-effective. The calculated index values were used to prioritize properties to a refined list of the most significant properties. Properties that generated an index value of 4.0 or greater were selected as significant. The value of 4.0 was selected based on the survey evaluation of aggregate properties. Evident in the survey results is that some properties were widely judged to be significant and marginal. The highly ranked properties were the ones that were later brought up for discussion with personnel at the Minnesota Department of Transportation.

Tables 3.7 and 3.8 summarize the refined lists of aggregate properties ranking a 4.0 or higher for coarse aggregates used in concrete and in bituminous applications respectively. The tables include the rank of the property, index value, and category of the property (physical, chemical, or mechanical). The table also related these properties to current established testing of the states evaluated in the previous section. Overall, this is an assessment of how professionals would rank aggregate properties based on performance compared to what is actually specified.

Table 3.7 Significant Portland Cement Concrete Aggregate Property Rankings

				Use in State Specifications											
PROPERTY	INDEX	TEST	CATEGORY	MN	ND	SD	IL	WI	IA	NE	MT	TX	CA	CANADA	Pct. Use
Volumetric Stability – freeze/thaw	4.6	N/A	PHYSICAL												0%
Particle Size (distribution)	4.5	AASHTO T-2	PHYSICAL		X	X	X	X	X	X	X	X	X		82%
Soundness, Weatherability	4.4	AASHTO T-104	PHYSICAL	X	X		X	X		X	X	X	X		73%
Reactivity to Chemicals	4.4	ASTM C1260	CHEMICAL	X											9%
Particle Size (maximum)	4.3	AASHTO T-2	PHYSICAL		X	X	X	X	X	X	X	X	X		82%
Solubility	4.3	N/A	CHEMICAL												0%
Toughness	4.2	ASTM C131	MECHANICAL	X	X	X	X	X	X	X	X	X	X	X	100%
Compressive Strength	4.2	ASTM D2938	MECHANICAL												0%
Abrasion Resistance	4.2	AASHTO T-96	MECHANICAL	X	X	X	X	X	X	X	X	X	X	X	100%
Particle Shape (flakiness, elongation)	4.2	ASTM D4791	PHYSICAL	X	X			X				X			36%
Particle Size (angularity)	4.2	ASTM D5821	PHYSICAL	X	X	X		X			X				45%
Deleterious Constituents	4.1	AASHTO T-112	PHYSICAL						X	X	X				27%
Pore Structure, Porosity	4.1	AASHTO T-19	PHYSICAL	X		X	X	X	X		X	X	X		73%
Specific Gravity & Absorption	4.0	AASHTO T-85	PHYSICAL	X	X	X	X	X	X	X	X	X	X		91%

Table 3.8 Significant Bituminous Aggregate Property Rankings

				Use in State Specifications											
PROPERTY	INDEX		CATEGORY	MN	ND	SD	IL	WI	IA	NE	MT	TX	CA	CANADA	Pct. Use
Particle Size (angularity)	4.8	ASTM D5821	PHYSICAL	X	X	X		X			X				45%
Particle Size (distribution)	4.6	AASHTO T-3	PHYSICAL	X	X	X	X	X	X	X	X		X		82%
Particle Surface Texture	4.3	ASTM D5821	PHYSICAL	X	X	X		X			X				45%
Particle Shape (flakiness, elongation)	4.3	ASTM D4791	PHYSICAL	X	X			X				X			36%
Specific Gravity & Absorption	4.3	AASHTO T-85	PHYSICAL	X	X	X	X	X	X	X	X	X	X		91%
Compressive Strength	4.3	ASTM D2938	MECHANICAL												0%
Pore Structure, Porosity	4.2	AASHTO T-19	PHYSICAL	X											9%
Particle Size (maximum)	4.2	AASHTO T-2	PHYSICAL		X	X	X	X	X	X	X	X	X		82%
Abrasion Resistance	4.2	AASHTO T-96	MECHANICAL	X	X	X	X	X	X	X	X	X	X	X	100%
Coatings	4.2	N/A	CHEMICAL												0%
Asphalt Affinity	4.2	N/A	CHEMICAL												0%
Toughness	4.1	ASTM C131	MECHANICAL	X	X	X	X	X	X	X	X	X	X	X	100%
Soundness, Weatherability	4.0	AASHTO T-104	PHYSICAL	X	X		X	X		X	X	X	X		73%
Integrity during heating	4.0	N/A	PHYSICAL												0%
Deleterious Constituents	4.0	AASHTO T-112	PHYSICAL						X	X	X				27%

Professionals ranked the properties of solubility and compressive strength as significant properties for coarse aggregates in PCC applications. However, none of the evaluated states are testing for either of these properties. Professionals ranked compressive strength, coatings, asphalt affinity, and integrity during heating as significant properties for coarse aggregates in bituminous applications. Currently none of the 11 evaluated states/provinces are testing for these properties. This may possibly indicate that specifications do not reflect the current level of knowledge concerning desirable coarse aggregate properties. More detailed results of the survey are presented in Appendix C. Actual survey forms are included in Appendix E.

4 Evaluation of Property Based Testing

Testing performed on sources in the above section classify the percentages of different spalling rocks that may be present in a particular source. Property-based testing that has been conducted, along with the mineralogical testing, include the bulk specific gravity and absorption, LA rattler test, and the magnesium sulfate test. The LRRB data sample was used to calculate the average values resulting from the tests in each district, Figures 4.1 through 4.7. The averages were then compared with the standard deviations to discover how closely the values corresponded to other test results in same area. The following sections summarize the testing results from each of these property-based test by districts.

4.1 Bulk Specific Gravity and Absorption

The bulk specific gravity is a measure of the unit weight aggregate compared to the unit weight of water. The absorption is a measure of the percentage of moisture that an aggregate can absorb. Bulk specific gravity and absorption are both physical properties of an aggregate. In the LRRB sample data the bulk specific gravity test was run in districts 1, 2, 3, 7 and Meto. The averages range between 2.61 in district 7 and 2.71 in the Metro district. The standard deviations are all very small due to the fact that all values between sources should be relativly similar. The following chart summarizes the testing for bulk specific gravity among the districts.

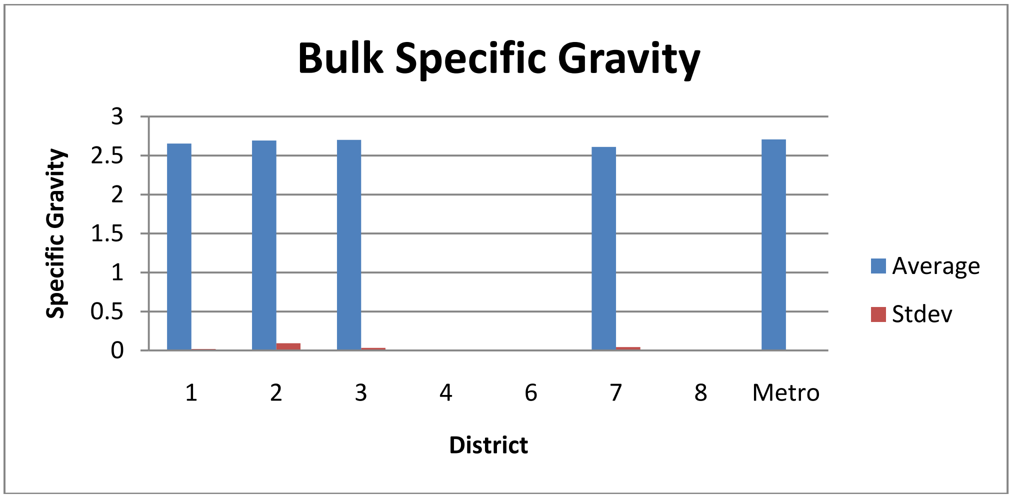


Figure 4.1 Bulk Specific Gravity

The total percent absorption test also included testing in Districts 1, 2, 3, 7, and Metro. The total percent absorption ranged from 1.06% in the Metro district to 1.195% in District 1. District 7 had the highest standard deviation with 1.074%. The percent absorption test was included 61 times in the data sample, all of which were performed on bituminous aggregate samples. The following chart summarizes the testing for total percent absorption among the districts.

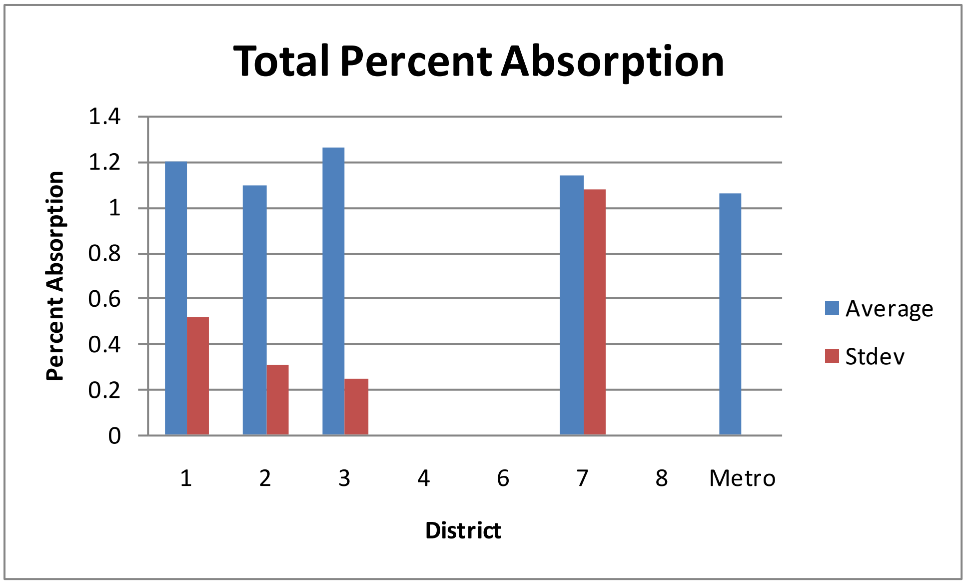
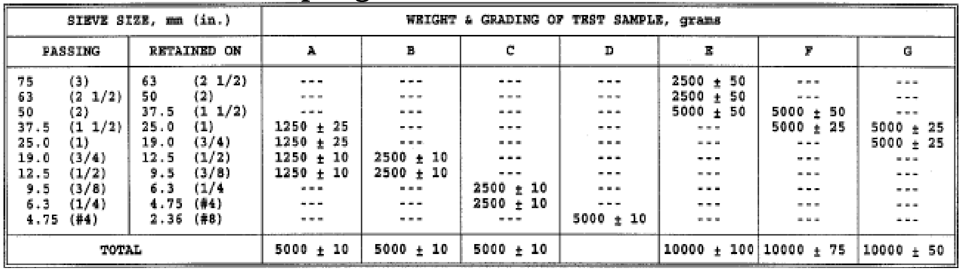


Figure 4.2 Total Percent Absorption

4.2 LA Rattler Test

The LA rattler test was performed very frequently among all the districts. The LA rattler test is a measure of the degradation of mineral aggregates by a combination of actions including abrasion, impact, and grinding. The test is divided into types A, B, C, and G. The type refers to the gradation of the sample. Table 4.1 summarizes the weight and grading of test samples as specified in the Minnesota Department of Transportation Lab Manual. Regardless of type the percent loss on a sample is limited to 40% by the current specifications.

Table 4.1 LA Rattler Sampling [Mn/DOT, 2005]



SIEVE SIZE, mm (in.)		WEIGHT & GRADING OF TEST SAMPLE, grams						
PASSING	RETAINED ON	A	B	C	D	E	F	G
75 (3)	63 (2 1/2)	---	---	---	---	2500 ± 50	---	---
63 (2 1/2)	50 (2)	---	---	---	---	2500 ± 50	---	---
50 (2)	37.5 (1 1/2)	---	---	---	---	5000 ± 50	5000 ± 50	---
37.5 (1 1/2)	25.0 (1)	1250 ± 25	---	---	---	---	5000 ± 25	5000 ± 25
25.0 (1)	19.0 (3/4)	1250 ± 25	---	---	---	---	---	5000 ± 25
19.0 (3/4)	12.5 (1/2)	1250 ± 10	2500 ± 10	---	---	---	---	---
12.5 (1/2)	9.5 (3/8)	1250 ± 10	2500 ± 10	---	---	---	---	---
9.5 (3/8)	6.3 (1/4	---	---	2500 ± 10	---	---	---	---
6.3 (1/4)	4.75 (#4)	---	---	2500 ± 10	---	---	---	---
4.75 (#4)	2.36 (#8)	---	---	---	5000 ± 10	---	---	---
TOTAL		5000 ± 10	5000 ± 10	5000 ± 10		10000 ± 100	10000 ± 75	10000 ± 50

In the given data sample, the type A LA rattler test was performed in Districts 3, 6, and Metro. The values ranged from an average of 18% loss in District 3 to 31.37% loss in District 6. District 6 had the highest standard deviation for this test with 1.64%. Also, the data sample indicated that the type B LA rattler test was performed in Districts 1, 2, 3, 6, 7, 8, and metro. Type B was the most commonly performed test among the four LA rattler test types. The values ranged from an average of 16.7% loss in District 1 to 32.28% loss in District 6. District 2 had the highest standard deviation for this test with 5.127%. The following chart summarizes the averages and standard deviations for types A & B.

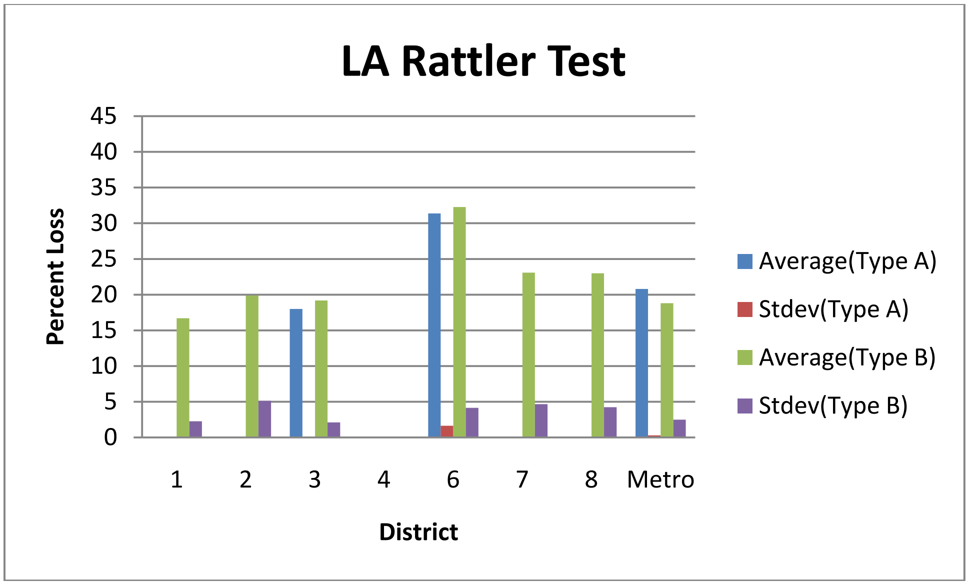


Figure 4.3 LA Rattler Test (Types A&B)

In the given data sample the Type C LA rattler test was performed in Districts 1, 3, 6, 7, and Metro. Type C is the second most commonly performed of the four testing types. The values ranged from an average of 15.0% loss in District 1 to 32.77% loss in District 6. District 7 had the highest standard deviation for this test with 5.22%. Also, the data sample indicated that the type G LA rattler test was performed in districts 6 and 7. This test was perfomed the least out of all the types with only eleven tests in the data sample. The values ranged from an average of 29.00% loss in District 7 to 30.6% loss in District 6. District 7 had the highest standard deviation for this test with 1.43%. The following chart summarized the averages and standard deviations for types C and G.

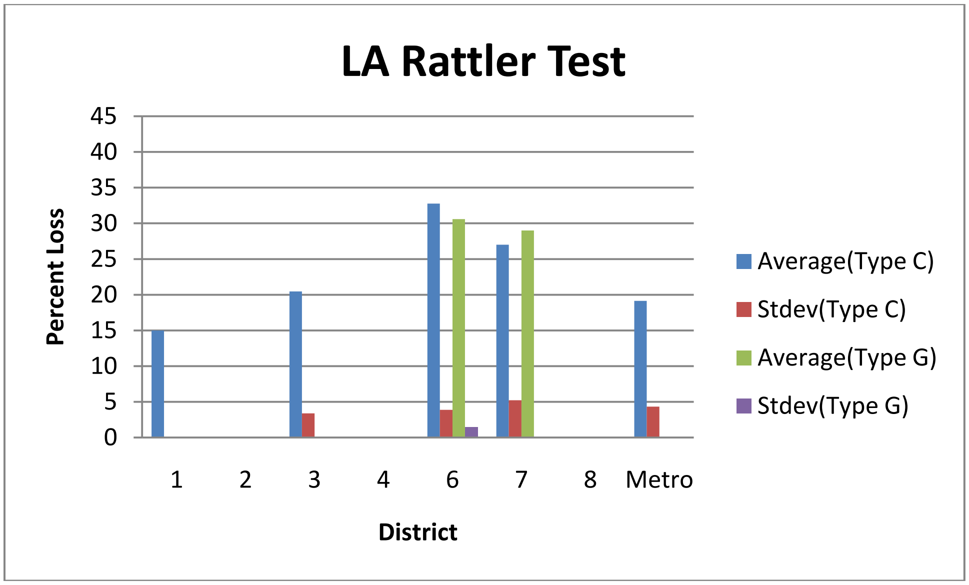


Figure 4.4 LA Rattler Test (Types C&G)

4.3 Magnesium Sulfate Percent Loss

The magnesium sulfate percent loss test is a property-based test that was performed frequently throughout all the districts. Like the LA ratter test, the magnesium sulfate percent loss test measures the physical property of soundness. The material is separated into its given sieve sizes and tested for percent loss.

The first size tested was from 1/2” to 3/8”. In the given data sample, this test was performed on local sources in every district. The current Minnesota specifications limit the percent loss on this size of material to 18% for bituminous aggregate. The values ranged from an average of 2.4% loss in District 3 to 12.37% loss in District 6. District 6 had the highest standard deviation for this test with 8.48%. The following chart summarizes the averages and standard deviations among the districts.

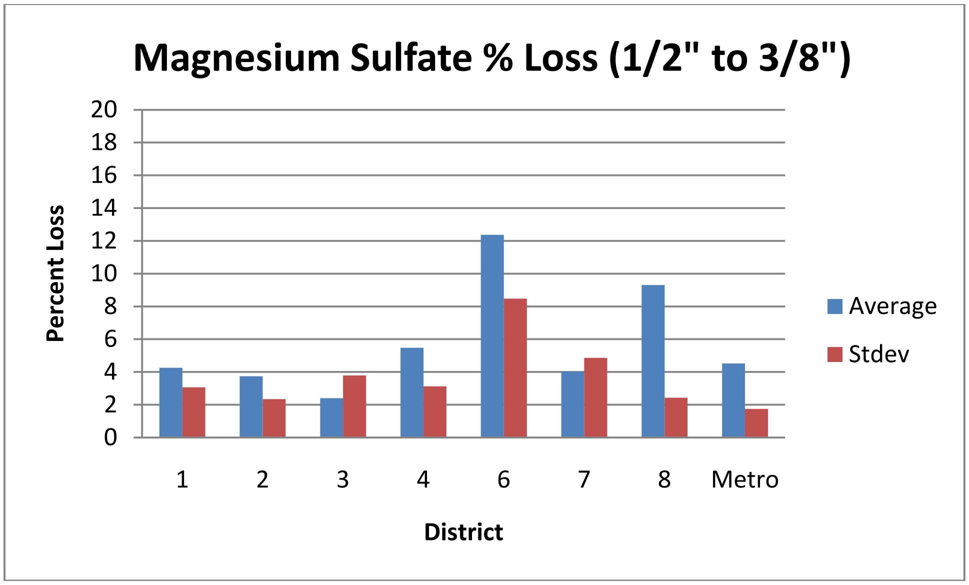


Figure 4.5 Magnesium Sulfate Percent Loss (1/2” to 3/8”)

The second size tested was from 3/4” to 1/2”. In the given data sample this test was performed on local sources in every district. The current Minnesota specifications limit the percent loss on this size of material to 14% for bituminous aggregate. The values ranged from an average of 1.17% loss in District 3 to 6.67% loss in District 6. District 6 had the highest standard deviation for this test with 3.50%. The following chart summarizes the averages and standard deviations among the districts.

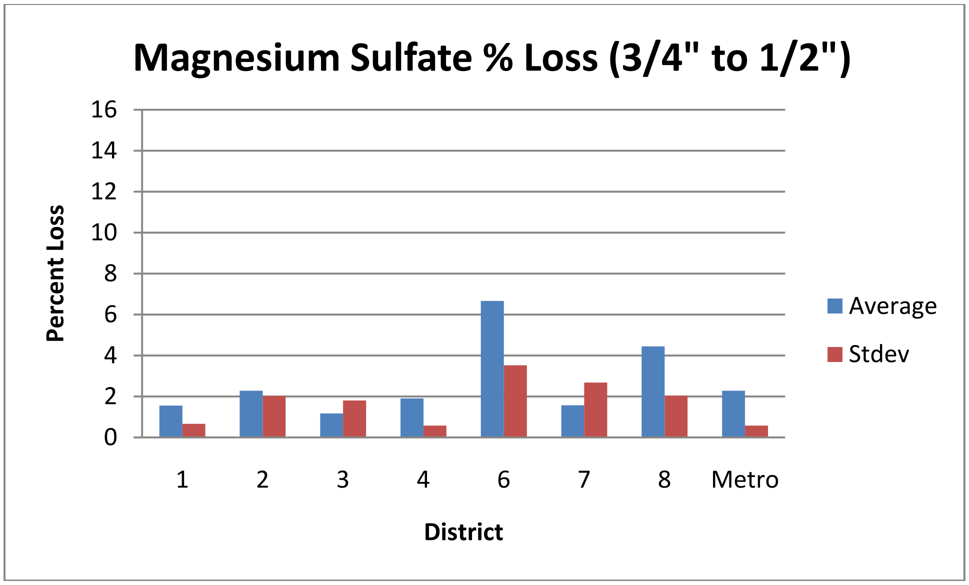


Figure 4.6 Magnesium Sulfate Percent Loss (3/4” to 1/2”)

The third size tested was from 3/8” to #4. In the given data sample, this test was performed on local sources in every district. The current Minnesota specifications limit the percent loss on this size of material to 23% for bituminous aggregate. The values ranged from an average of 3.24% loss in District 3 to 15.29% loss in District 8. District 6 had the highest standard deviation for this test with 7.99%. The following chart summarizes the averages and standard deviations among the districts.

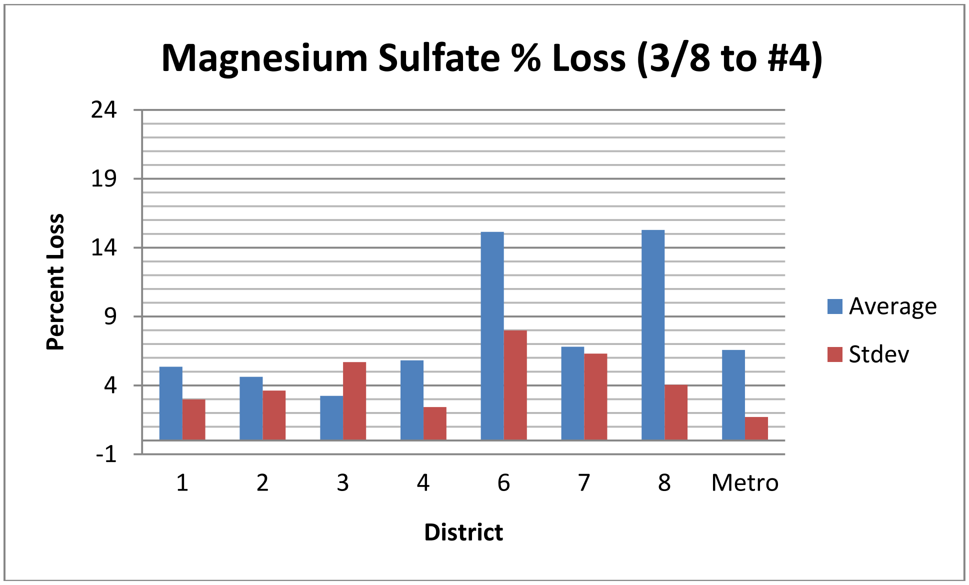


Figure 4.7 Magnesium Sulfate Percent Loss (3/8” to #4)

4.4 Failure Rate

The Los Angeles rattler test and magnesium sulfate test were evaluated on the basis of indicated failure. Each of these tests has different maximum thresholds to determine whether a material passes. The thresholds for the evaluated tests are as follows:

1) Los Angeles Rattler (Type B) Percent Loss – Maximum 40%
2) Los Angeles Rattler (Type C) Percent Loss – Maximum 40%
3) Magnesium Sulfate Percent Lost 1/2” to 3/8” – Maximum 18%
4) Magnesium Sulfate Percent Lost 3/4” to 1/2” – Maximum 14%
5) Magnesium Sulfate Percent Lost 3/8” to #4 – Maximum 23%

The test failures are summarized in Table 4.2 below. Note that all of the failed tests are from quarries located in District 6.

Table 4.2 Test Failure Percentage

Test Description	Source	District	# Tests Ran	# Failed	% Failure
Los Angeles Rattler (Type B) Pct Loss	43 Quarry	6	20	2	10.00%
	Aaland	6	17	6	35.29%
	Goldberg	6	171	2	1.17%
	Penz	6	57	4	7.02%
	Stussy	6	9	2	22.22%
Los Angeles Rattler (Type C) Pct Loss	43 Quarry	6	17	1	5.88%
	Aaland	6	7	2	28.57%
	Goldberg	6	90	1	1.11%
	Penz	6	81	1	1.23%
	RS&G Quarry	6	60	1	1.67%
Mag Sulfate Percent Lost 1/2" to 3/8"	Abnet	6	20	1	5.00%
	Glenville (Ulland)	6	22	1	4.55%
	Hammond Quarry	6	95	1	1.05%
	Penz	6	81	19	23.46%
	RS&G Quarry	6	66	2	3.03%
Mag Sulfate Percent Lost 3/4" to 1/2"	Penz	6	23	1	4.35%
Mag Sulfate Percent Lost 3/8" to #4	Abnet	6	19	1	5.26%
	Glenville (Ulland)	6	30	1	3.33%
	Penz	6	86	12	13.95%
	RS&G Quarry	6	76	1	1.32%

Collectively the test that had the highest percentage of failure was the magnesium sulfate percent loss test from 1/2” to 3/8”. The percentage of tests in a particular source varied from 35% for the LA rattler test (Type B) in the Aaland source to as little as 1% failure in the Hammond Quarry for the magnesium sulfate percent loss test from 1/2” to 3/8”. All failure was indicated in the evaluation.

4.5 Analyzing Mn/DOT Data Records

To assess aggregate quality, both compliance with specification limits and variability in aggregate properties are considered. Please note that compliance and variability are not always congruent with one another. Two different aggregate samples can both have 100% compliance with specifications; however, variability can fluctuate drastically between the two. This undetected range in variability can drastically affect predicted pavement performance.

Current mix specifications on asphalt or concrete pavement do not include direct measures of variability in aggregate quality, even though it is well known to affect the mix consistency. For most agencies, acceptance is based on tolerance levels of quality requirements with no requirements on consistency. Data evaluation will attempt to assess the levels of variability in aggregate sources in Minnesota. Overall, the data analysis will support the following three objectives:

- Analyze compliance and variability among statewide concrete and bituminous aggregate sources.
- Analyze compliance and variability among district concrete and bituminous aggregate sources.
- Analyze compliance and variability among specific properties among aggregates used in concrete and bituminous applications.

First, the quality requirements defined by the Mn/DOT specification book were identified for coarse aggregates in PCC and bituminous mixtures. The mean and standard deviations for each type of aggregate source (concrete or bituminous) was calculated based on the testing data supplied by the LIMS/ASIS data sample. The mean gives an idea of the center value and the standard deviation gives an approximation of the spread about the mean.

4.5.1 Compliance

Compliance was determined by calculating the percent within limits (PWL). According to literature, 26 states use percent within limits as a measure of quality for acceptance in pavement applications [Hughes, 2005]. Percent within limit calculations illustrate the overall performance of materials by constructing normal distribution curves based on normal distribution assumptions and are not valid if the material behaves in any other way than normally. To perform the calculation, the area falling outside the specifications is subtracted from the total area under the curve (always equal to 1) to yield the percent within limit. Also, when performing such calculations, it is possible to get distributions that show over 100% probability or negative values. This is because these calculations are based on the normal distribution theory and may not always reflect reality in all cases.

4.5.2 Variability

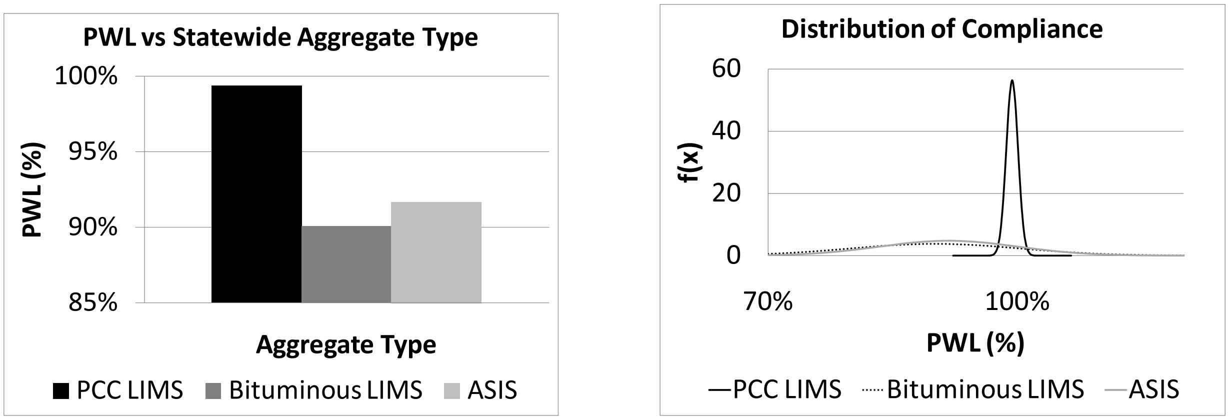
Variability was measured by means of standard deviation and coefficient of variation. These were calculated for each quality characteristic. Average variability was also calculated among all quality characteristics at the statewide and district level [Williams, 2003]. Variability displays the fluctuation about the mean. It is possible that two sources can have the same mean values for a testing property but one may have a much higher variability than the other. This variability is well known to affect pavement performance.

4.6 Data Analysis Approach

Statistical analyses of compliance and variability were used in the study to evaluate the significance of properties on aggregate quality with respect to existing specifications. A case study was conducted using testing data from Minnesota's local aggregate sources in comparison to regional and national records on aggregate quality and specification requirements. The study evaluated how coarse aggregates for use in concrete and bituminous applications rate according to current property requirements.

4.6.1 Statewide Data Evaluation

On the samples of testing data from both databases, the average PWL was calculated from each of the individual quality characteristics as mentioned in the introduction. Figure 4.8(a) shows the average PWL from each database for sources located throughout the state. The figure indicates that aggregate sources in Minnesota used for Portland cement concrete applications had a higher compliance than aggregates used in bituminous applications.



(a) PWL vs. Aggregate Type (b) Distributions of Aggregate Type

Figure 4.8 Percent within Limits for Statewide Local Aggregate Sources

The mean PWL from the Figure 4.8(a) was then coupled with the standard deviation to construct the normal distribution curves shown in Figure 4.8(b). As expected, the variability of compliance was higher for bituminous aggregates than for concrete aggregates. Aggregate sources used for Portland cement concrete applications appear to demonstrate much higher compliance and lower variability than aggregate sources used for bituminous.

When evaluating aggregate sources from the data samples, compliance appears to be very high ranging from 91 to 99%. The results indicate that the high majority of material tested is acceptable for use according to current specifications. However, the normal distributions indicate that even though compliance is high, variability can fluctuate drastically. This variability is known to cause inconsistency in the desired performance of pavements.

4.6.2 District Data Evaluation

The average PWL from each of the individual quality characteristics was calculated for aggregates used at the district level. Figure 4.9 shows the average PWL from each database for sources located within individual districts throughout the state. The purpose of a district evaluation was to demonstrate how quality can vary drastically within even a small region. The data used to develop the figures are presented in Appendix D. Tables D.1 to D.4 present the average, standard deviation, number of data points and PWL for each property within each district for bituminous aggregate and concrete aggregates.

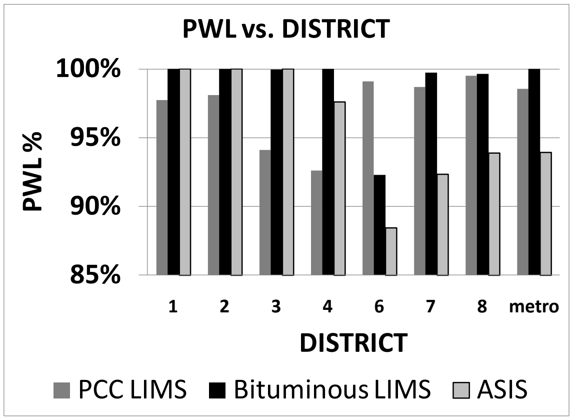


Figure 4.9 PWL vs. District Aggregate Type

When evaluating aggregate sources from the data samples, compliance ranged from 88 to 99% within limit among different districts in the state of Minnesota. Variability ranges from 0.01 to 14.75%. Once again this indicates that high compliance does not always indicate low variability. Table 4.3 outlines the average PWL values and standard deviations of quality components in aggregate sources among districts. The statewide values are also indicated at the bottom of the table.

Table 4.3 Averages PWL and Standard Deviation Values Among Districts

	PCC AGGREGATE (LIMS)		ASPHALT AGGREGATE (LIMS)		AGGREGATE (ASIS)	
District	Average PWL	Standard	Average PWL	Standard	Average PWL	Standard
1	97.73%	4.87%	100.00%	0.00%	99.99%	0.03%
2	98.10%	4.78%	100.00%	0.00%	100.00%	0.01%
3	94.11%	13.11%	99.97%	0.10%	99.99%	0.01%
4	92.62%	14.75%	100.00%	0.00%	97.58%	5.40%
6	99.09%	1.51%	92.28%	10.71%	88.45%	9.29%
7	98.70%	1.83%	99.72%	0.60%	92.34%	13.74%
8	99.52%	0.83%	99.64%	1.00%	93.87%	12.03%
Metro	98.55%	2.62%	100.00%	0.00%	93.93%	13.37%
Statewide	98.13%	2.34%	94.00%	8.68%	91.51%	8.25%

4.7 Evaluation of Individual Quality Characteristics

This section explores the effect that individual specified properties have on aggregate quality. Sample sizes were greater than 30 for each property making it reasonable to assume a normal distribution. The mean, standard deviation, and percent within limits were used to evaluate the normal distributions of the material.

4.7.1 Abrasion Resistance

The Los Angeles rattler percent loss test [AASHTO T-96, 2006] is one of the most commonly used tests among transportation departments to evaluate aggregate quality. The test is used to indicate aggregates' toughness and abrasion resistance characteristics. Abrasion characteristics are significant because aggregate material must resist crushing, degradation, and disintegration in order to produce high quality pavements [Hoffman, 2007]. Figures 4.10 and 4.11 outline the distributions of Los Angeles rattler testing results among the data sample. The dashed lines indicate the specification limits on the property.

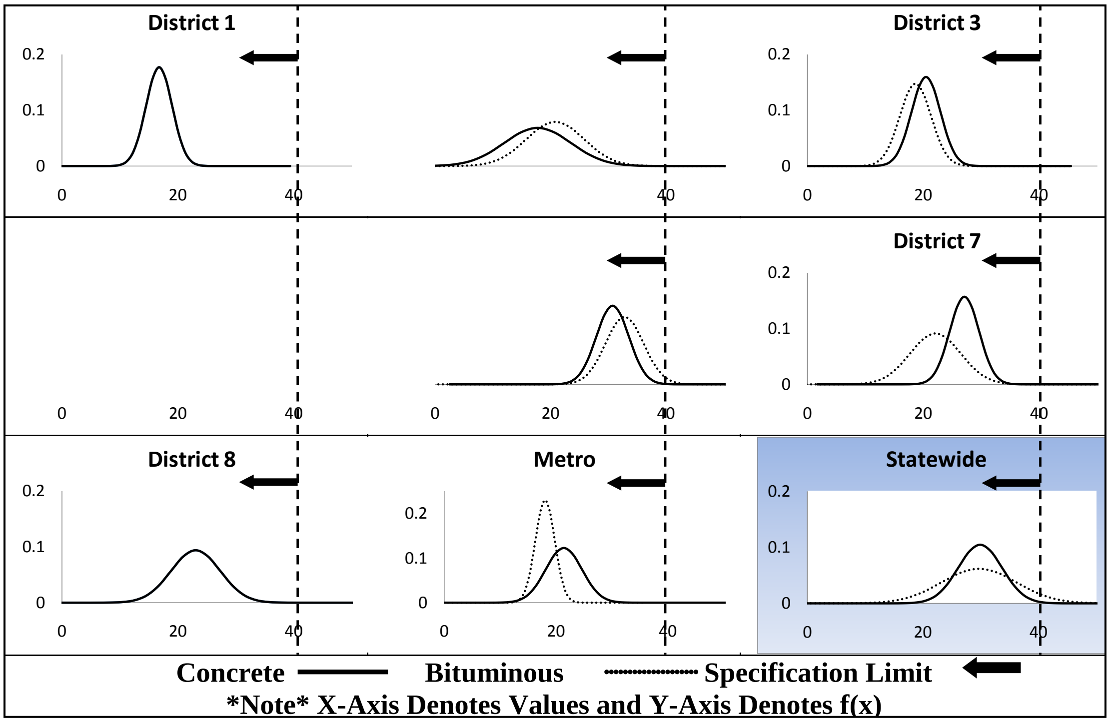


Figure 4.10 Distributions of Los Angeles Rattler Percent Loss – LIMS Database

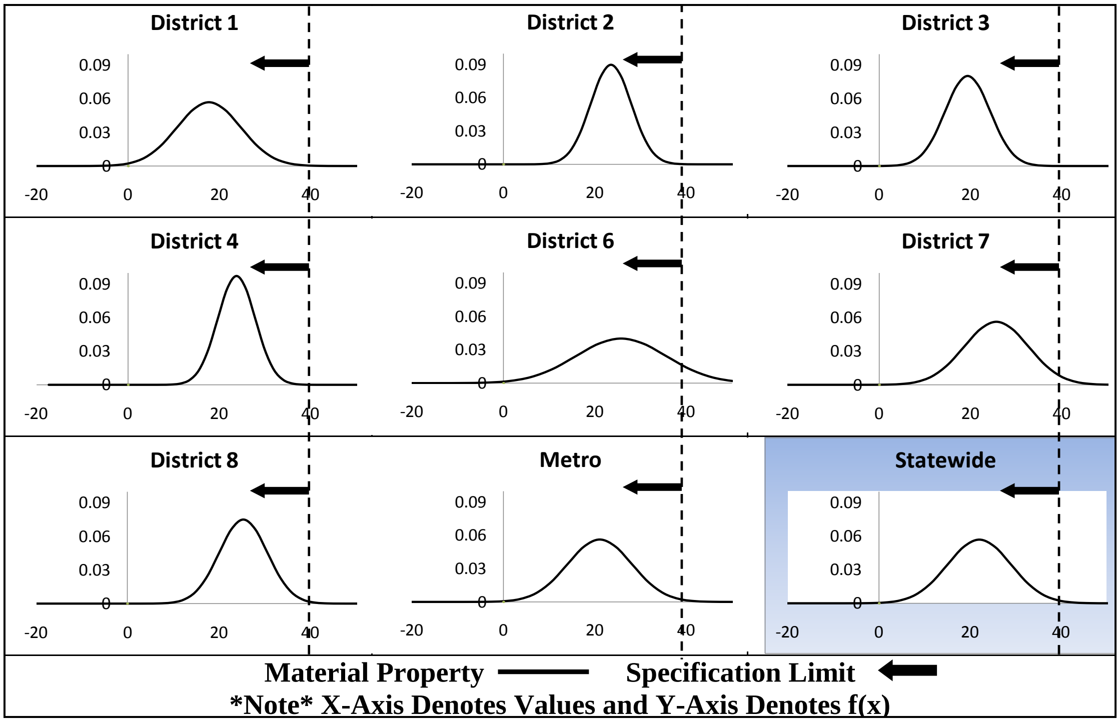


Figure 4.11 Distributions of Los Angeles Rattler Percent Loss – ASIS Database

Compliance and variability were first evaluated in each of the districts. It appears that compliance was easily met by both concrete and bituminous aggregates among the state. Table 4.4 summarizes the mean, standard deviation, and percent within limits for the Los Angeles rattler test. Compliance of aggregate sources from the data samples ranged from 92.7 to nearly 100 percent within limit indicating that materials generally complied well with this property. Variability of standard deviations ranged from 1.7 to 9.9%. Some regions with higher compliance also demonstrated higher variability. This demonstrates that high compliance may not always be an indicator of low variability.

Table 4.4 Averages, Standard Deviations, and PWLs for Los Angeles Rattler Test

DISTRICT	VALUES	PCC - LIMS	ASPHALT - LIMS	ASIS
1	AVERAGE	16.70	16.70	17.77
	STD. DEVIATION	2.26	2.26	6.98
	PWL	100.00%	100.00%	99.93%
2	AVERAGE	17.65	20.71	23.59
	STD. DEVIATION	5.76	5.02	4.45
	PWL	99.99%	99.99%	99.99%
3	AVERAGE	20.43	18.64	19.34
	STD. DEVIATION	2.51	2.70	4.95
	PWL	100.00%	100.00%	100.00%
4	AVERAGE	26.61	18.64	23.84
	STDEV	2.26	2.70	4.12
	PWL	100.00%	100.00%	100.00%
6	AVERAGE	30.65	32.74	25.67
	STD. DEVIATION	2.83	3.31	9.88
	PWL	99.95%	98.60%	92.66%
7	AVERAGE	27.06	22.00	25.65
	STD. DEVIATION	2.54	4.37	7.05
	PWL	100.00%	100.00%	97.92%
8	AVERAGE	23.00	23.00	25.32
	STD. DEVIATION	4.24	4.24	5.29
	PWL	100.00%	100.00%	99.73%
METRO	AVERAGE	21.32	18.00	21.02
	STD. DEVIATION	3.26	1.74	7.04
	PWL	100.00%	100.00%	99.65%
STATEWIDE	AVERAGE	29.99	29.95	21.99
	STD. DEVIATION	3.79	6.29	7.00
	PWL	99.58%	94.50%	99.50%

Compliance and variability were also evaluated at the statewide level. The bottom right-hand corner of Figures 4.10 and 4.11 is an average of the statewide Los Angeles ratter testing over all the districts. Bituminous aggregates showed lower compliance and higher variability than sources used in Portland cement concrete. The means for both sources were very similar with approximately 30% loss. However, concrete sources showed a much lower standard deviation with 3.8% versus 6.3 for bituminous aggregates. This may possibly indicate that priority of the highest quality material is given to Portland cement concrete applications due to higher traffic volumes.

4.7.2 Percent Spall

Spalling materials are rocks that are undesirable for use in pavement mixtures. Certain minerals are linked with adverse distresses and poor performing pavements. Percent spall usually is a large portion of quality requirements in aggregate specifications. Limitations vary depending on the types and amounts of spalling minerals present in a region or state [Mn/DOT, 2000].

Specifications limit the amount of spalling material that can be present in both concrete and bituminous mixtures. Because the study was limited to coarse aggregate, only the testing on percent spall retained on the #4 sieve was taken into account. Figures 4.12 and 4.13 outline the distributions of percent spall testing results among the districts in the state. The dashed lines indicate the specification limits on the property. Minnesota’s specifications limit spalling materials to 1.5% in concrete aggregate and 5% in bituminous aggregates [Mn/DOT, 2005].

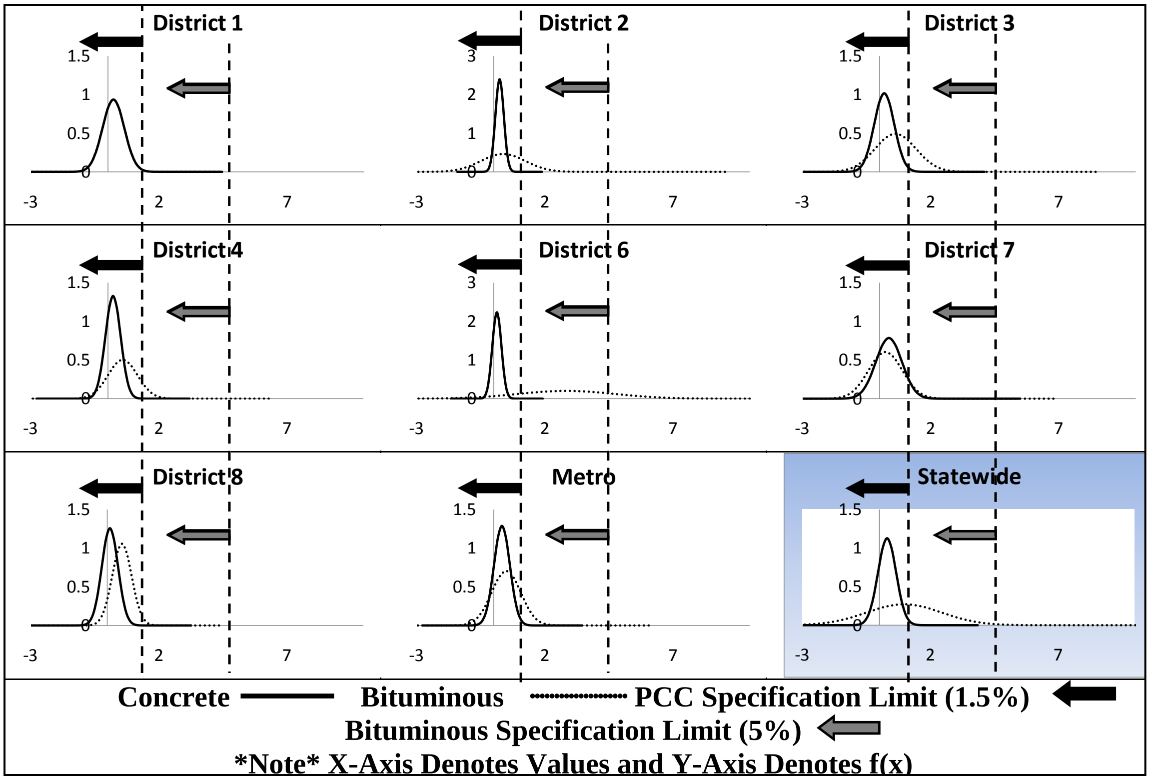


Figure 4.12 Distribution of Percent Spall Retained on #4 Sieve – (LIMS)

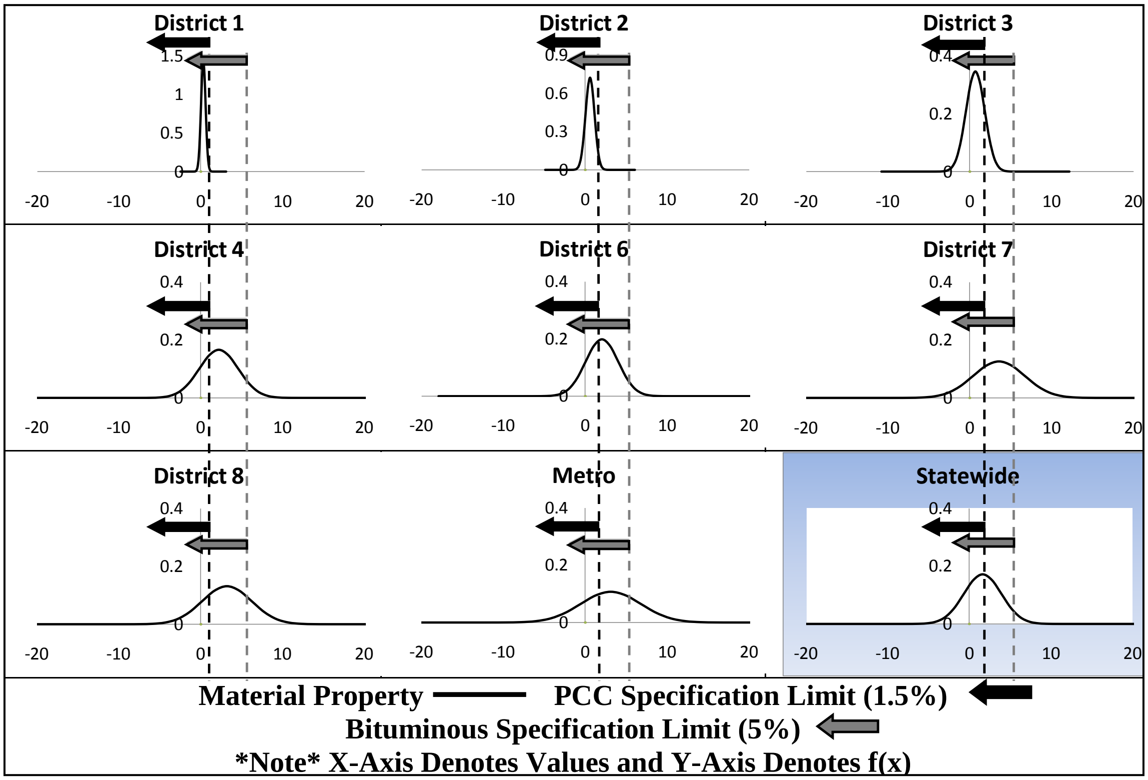


Figure 4.13 Distribution of Percent Spall Retained on #4 Sieve – (ASIS)

Spall compliance and variability were first evaluated in each of the districts. The evaluation demonstrated much more variability among the districts than when evaluating abrasion resistance. Table 4.5 summarizes the mean, standard deviation and percent within limits for percent spalling material. Compliance of aggregate sources from the data samples ranged from 67.8 to nearly 100% within limit. Variability of standard deviations ranged from 0.2 to 3.7%. This demonstrates that depending on the region percent spall can fluctuate drastically.

Table 4.5 Averages, Standard Deviations and PWLs for Percent Spall Test

DISTRICT	VALUES	PCC - LIMS	ASPHALT - LIMS	ASIS
1	AVERAGE	0.21	0.20	0.33
	STD. DEVIATION	0.42	0.43	0.28
	PWL	99.88%	100.00%	100.00%
2	AVERAGE	0.24	0.36	0.55
	STD. DEVIATION	0.17	0.87	0.55
	PWL	100.00%	100.00%	100.00%
3	AVERAGE	0.19	0.62	0.68
	STD. DEVIATION	0.39	0.80	1.15
	PWL	99.96%	100.00%	99.99%
4	AVERAGE	0.21	0.58	2.21
	STDEV	0.30	0.57	2.38
	PWL	100.00%	100.00%	87.92%
6	AVERAGE	0.12	2.83	2.04
	STD. DEVIATION	0.18	1.89	2.00
	PWL	100.00%	87.42%	93.04%
7	AVERAGE	0.36	0.22	3.55
	STD. DEVIATION	0.51	0.66	3.14
	PWL	98.76%	100.00%	67.78%
8	AVERAGE	0.09	0.56	3.19
	STD. DEVIATION	0.32	0.38	3.03
	PWL	100.00%	100.00%	72.46%
METRO	AVERAGE	0.33	0.49	3.08
	STD. DEVIATION	0.31	0.57	3.66
	PWL	99.99%	100.00%	70.02%
STATEWIDE	AVERAGE	0.32	0.96	1.63
	STD. DEVIATION	0.35	1.46	2.30
	PWL	99.96%	99.71%	92.84%

Compliance and variability were then evaluated at the statewide level. The bottom right-hand corner of Figures 4.12 and 4.13 is the average of the statewide percent spall testing over all the districts. Bituminous aggregates showed lower compliance and higher variability than sources used in Portland cement concrete. The mean was 0.32% for Portland cement concrete sources and 0.96 for bituminous sources. Also, concrete sources showed a much lower standard deviation with 0.35% versus 1.46% for bituminous aggregates. This is reasonable considering that aggregate for use in Portland cement concrete have stricter requirements on percent spall.

4.7.3 Soundness

The magnesium sulfate soundness test is a property-based test that evaluates the overall soundness of the aggregate and its resistance to freeze/thaw deterioration. The common standard procedure for this test is AASHTO T-104. This procedure is used to determine resistance of an aggregate to deterioration by saturated solutions of sodium sulfate or magnesium sulfate [Mamlouk, 2006]. The significance of this test is to determine the ability of an aggregate to resist physical weathering related to freeze/thaw cycles. Aggregates that resist weathering are less likely to degrade in the field and cause premature pavement distresses and potential failure [Davis, 2008]. This test is also useful when there is little historical information about how the materials hold up to actual weathering conditions [Mn/DOT, 2005].

Testing requirements are different for concrete and bituminous aggregates. For aggregates used in concrete applications, percent loss is not to exceed 15% for any gradation. Bituminous aggregates are separated onto sieve sizes for testing. The 15% applies to the weighted average of the three different gradations. Often, the smaller gradation has a loss >15%, but when weighed with the other two larger gradations, it generally lowers the total. There is often debate about why the smaller gradation yields higher losses; some say it is because the smaller material is generally the poorer quality and that is why it is small while others say the smaller sizes have more surface area and therefore breakdown more easily.

The current specifications for Minnesota state that the maximum percent losses due to the magnesium sulfate test for bituminous aggregate are as follows:

- Magnesium Sulfate Percent Lost 3/4” to 1/2” – Maximum 14%
- Magnesium Sulfate Percent Lost 1/2” to 3/8” – Maximum 18%
- Magnesium Sulfate Percent Lost 3/8” to #4 – Maximum 23% [Mn/DOT, 2005]

Figures 4.14 and 4.15 outline the distributions of magnesium sulfate soundness testing results among the districts in the state. The dashed lines indicate the specification limits on the property. Compliance of aggregate sources from the data samples ranged from 70 to nearly 100 percent within limit. Variability of standard deviations ranged from 0.6 to 8.8%. The sulfate soundness test demonstrated the most issues with compliance out off all the quality requirements.

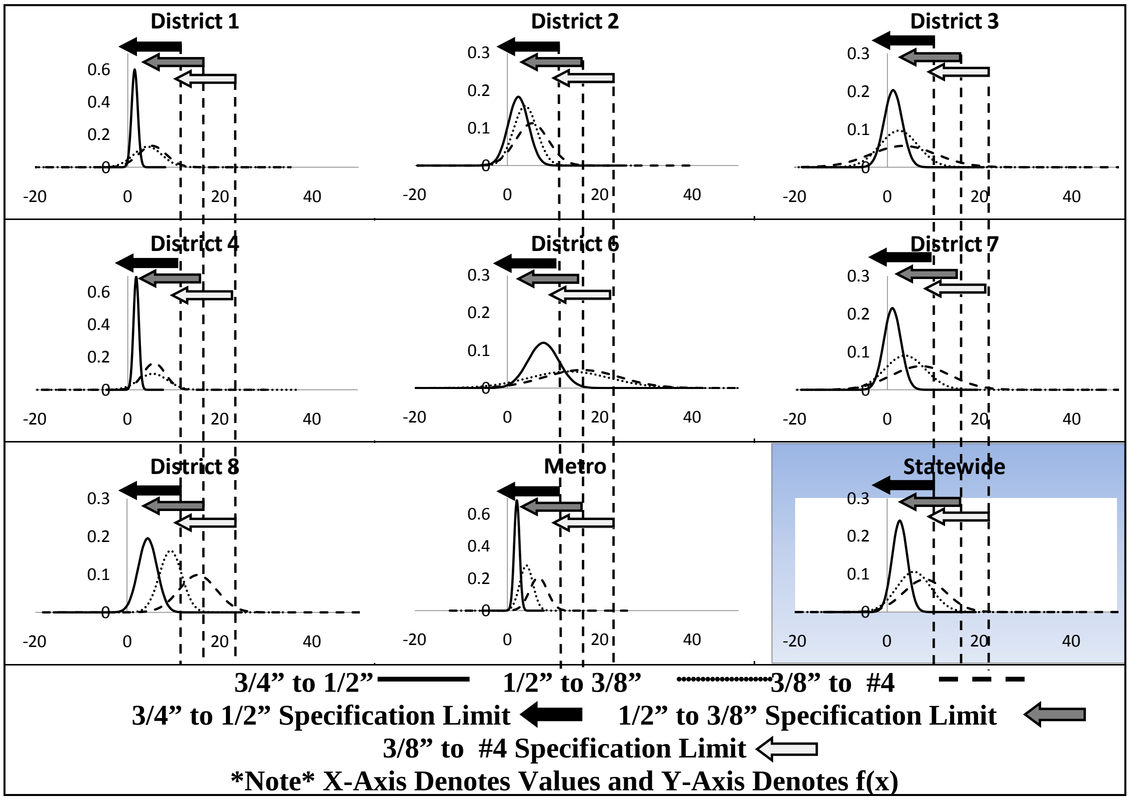


Figure 4.14 Distributions of Magnesium Sulfate for Bituminous Aggregates (LIMS)

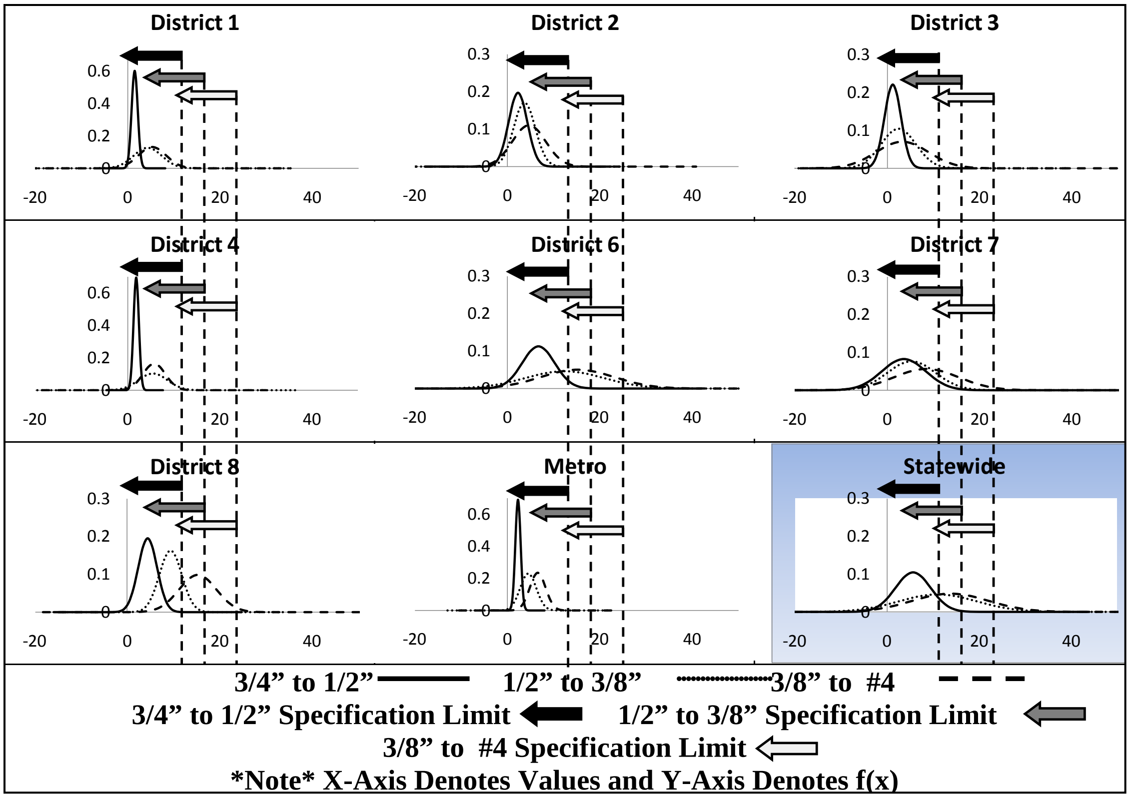
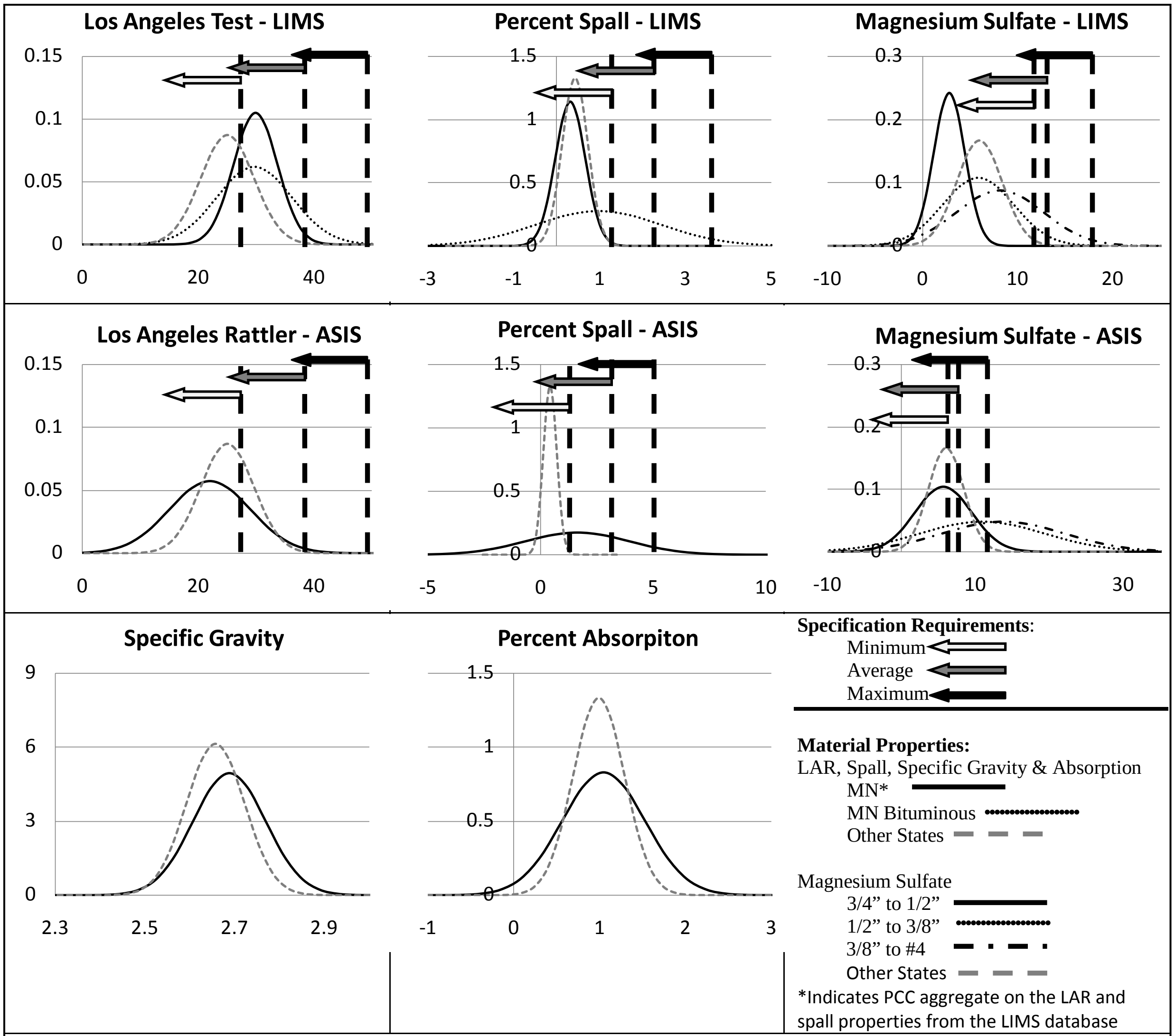


Figure 4.15 Distributions of Magnesium Sulfate for Bituminous Aggregates (ASIS)

4.8 Comparison of Minnesota’s Aggregate Material to Surrounding States

The above sections outline a case study of how Minnesota’s coarse aggregate perform according to current quality requirements. This portion of the study attempts to relate how aggregate materials in Minnesota compare to materials in other states. Many states call for very similar quality requirements with different limitations. The different limitations typically are created to reflect aggregate material that can be achieved by local contractors.

Material properties and specification limits on the properties as described above were evaluated in Minnesota, North Dakota, South Dakota, Illinois, Wisconsin, Iowa, Nebraska, Montana, Texas, California, and Manitoba. Neighboring states and states with similar aggregate properties were selected for the evaluation. Figure 4.16 outlines the properties evaluated from Minnesota at the statewide level in comparison to how aggregate materials perform and are specified in the other selected states. The minimum, maximum, and average specification limits from the evaluated states are indicated on the figures.



***Note* X-Axis Denotes Values and Y-Axis Denotes f(x)**

Figure 4.16 Comparison of Minnesota's Material Properties to Material in Other States

Minnesota shows slightly higher variability in material properties than the average of other states. The distribution of specification tolerance levels also indicates that states accept a wide range of material for pavement applications. For example, California had the lowest tolerance level of 25% maximum lost on the Los Angeles Abrasion test whereas Illinois had the highest tolerance level. The state of Illinois naturally contains more aggregate materials that break down easily. Therefore, specifications have to be relaxed somewhat to accommodate the material available.

In many states, it is very common to find testing for specific gravity and absorption among quality testing results. Aggregate for use in pavement applications would ideally have high specific gravities and low absorption values. However, for many states, specific gravity and absorption are not part of quality requirements in specifications for pavement applications. It is more common to find limitations on absorption in concrete used for structural applications such as bridges. The bottom two charts in Figure 4.16 outline the properties of specific gravity and absorption in comparison to the average of selected states. As shown in the figure, specific gravity does not vary much from state to state. However, aggregates in Minnesota tend to show more variation in absorption when compared to other states. Specific gravity and absorption are great examples of where property-based testing is currently available but not included as requirements in specifications.

Identifying gaps in property-based testing targets areas for improvement in future specifications. This study is the first task in restructuring future coarse aggregate specifications to be based on the performance of asphalt and concrete mixes. There is a possibility that local aggregate sources that are rejected for high-class pavement mixes can be used for local and low-volume road applications. By adopting specifications based on performance-related properties, a better understanding and utilization of local aggregate materials can be achieved. Literature indicates that currently established aggregate testing can be included in aggregate specifications to improve mix quality. An example of this approach is the Superpave mix specifications that include consensus aggregate properties in mix specifications. These consensus properties become stricter as traffic volumes increase and more relaxed as traffic volumes decrease [Roberts et al., 1996]. Because of its success, the Superpave mix specifications have been adopted by many departments.

5 Compressive Strength Testing

A key concept in fulfilling the objectives of this study is the selection of aggregate properties based on the quality of the aggregate sources, not the aggregate matrix as used in asphalt or concrete mixes. The survey of professionals indicated that compressive strength is an important property that has the potential to improve current specifications. Testing for compressive strength fills a gap on the characterization of local sources for possible new coarse aggregate specification requirements and also the evaluation of coarse aggregate using potential performance-related properties as outlined in the previous tasks. The collected literature and testing data along with the reviewed aggregate specifications identified a list of potential properties for evaluation in this task. Recommendations are made that local aggregate sources are evaluated for compressive strength as a potential aggregate property for consideration in future aggregate specifications. This task includes aggregate sampling from local Minnesota sources. Mn/DOT and NDSU managed the aggregate samples.

Compressive strength is one of the most basic parameters of rock strength. It is a fundamental property of aggregate strength. It is the capacity of a material to withstand axially directed pushing forces. When the limit of compressive strength is reached, the material is crushed. In other words, it is the amount of force that a material can handle before it fails completely. The value is typically obtained experimentally by means of a compression test where an increasing force is applied to a specimen (usually cylindrical). The compressive strength is calculated by taking the force needed to fail the material divided by the cross sectional area of the specimen.

Different aggregate types have different mechanical properties. Aggregate tensile strengths normally range from 2 to 15 MPa (300 to 2300psi) and compressive strengths range from 65 to 270 MPa (10,000 to 40,000 psi). Compressive strength of aggregates is a mechanical property that is rarely tested. However, the survey of professionals in the previous task indicated compressive strength as a very significant characteristic of coarse aggregates in PCC and bituminous applications.

To test the compressive strength, there are many standard protocols that can be utilized. The most common include the following:

1) ASTM C170: Compressive Strength of Dimension Stone
2) ASTM D2938: Unconfined Compressive Strength of Intact Rock Core Specimens
3) ASTM D5731: Determination of the Point Load Strength Index of Rocks

The uniaxial compressive strength of rock specimens is normally determined by the ASTM D 2938 test procedure. However, the sampling and material preparation associated with the test can be time consuming and expensive because that requires that rock core be taken at the quarry, which is not commonly done. If compressive strength testing were used for aggregate sources selection, extensive testing would be needed to supply the basis of information about statewide sources.

The point load test (ASTM D5731) is an alternative test to the unconfined compressive strength test. Although the test results should not be used for design purposes, they could possibly be used for selection of sources. This testing procedure can be used in the field to estimate the compressive strength of rock specimens. Overall, it can reduce the time and cost associated with coring samples used in compressive strength testing. It was agreed with Mn/DOT to conduct the testing of this task based onASTM C170: Compressive Strength of Dimension Stone (ASTM C170). This will allow comparisons with current testing methods adopted by Mn/DOT. Since aggregates carry the load in a pavement structure, the strength of the material can be used as one of the prime parameters to classify the quality of the rock. Compressive strengths of homogenous rock specimens such as granite and basalt have been well documented. Compressive strength testing can be used to evaluate the strength of aggregate material typical to sources and to better better determine its suitability in different paving applications.

5.1 Prior Research on Compressive Strength and Aggregate Suitability

Classification systems have been created in the past based on uniaxial compressive strength of rock materials. Figure 5.1 illustrates two classification systems. The top figure was created by the National Highway Institute (NHI) and the bottom was created by the International Society of Rock Mechanics (ISRM). This allows for classification of rock materials based on strength rather than on mineral type. Research was performed to evaluate simple methods for assessing the uniaxial compressive strength of rock.

Published data on 48 different rock types were used to evaluate the correlations between the uniaxial compressive strength values and the corresponding results of the point load test. The results indicated that the linear relations between the point load strength index and the uniaxial compressive strength values were within acceptable limits for most engineering purposes. The research concluded that the point load test provided a reliable estimate of the compressive strength of rocks. However, in order to obtain these reproducible results, test conditions must be controlled and maintained for all samples.

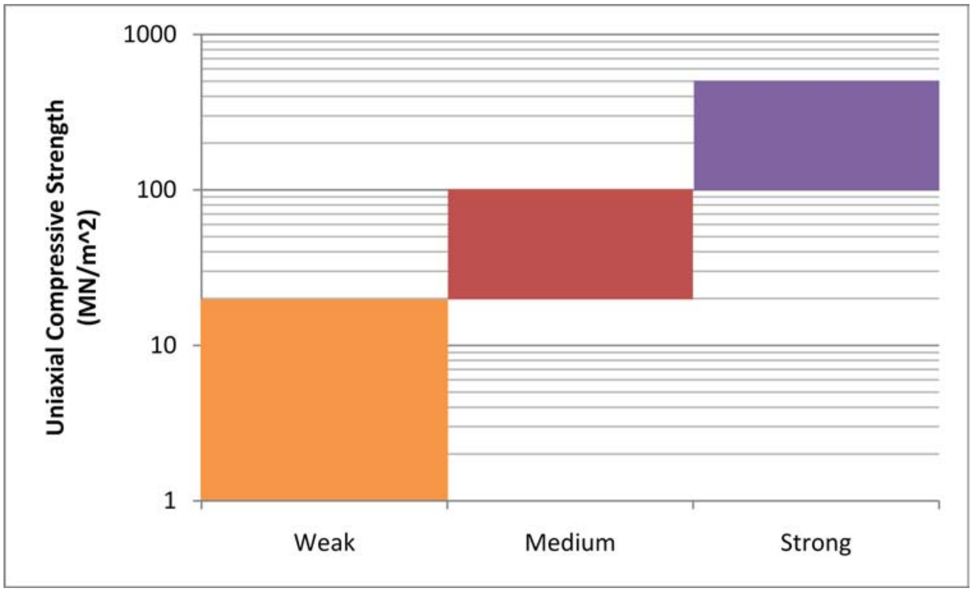
5.2 Compressive Strength of Minnesota Local Aggregate

Compressive strength test was conducted as part of this project following ASTM C-170 “Standard Test Method for Compressive Strength of Dimension Stone.” Table 5.1 presents a summary of the testing results and classification of the rock according to National Highway Institute (NHI), top, and the International Society of Rock Mechanics (ISRM), bottom. Figure 5.1 illustrates the two classification systems [NHI, 2007]. The results indicated that 3 of the 10 evaluated sources were medium according to NHI and ISRM classifications. Of the other 7 sources, 6 were classified as strong and one source was classified as very strong according to ISRM classification. Figure 5.2 presents the equipment used for compressive strength testing and one sample after the test. It should be noted that the strength classification terms presented by NHI and ISRM are for geotechnical assessments. A modified classification system may be appropriate for aggregates such as:

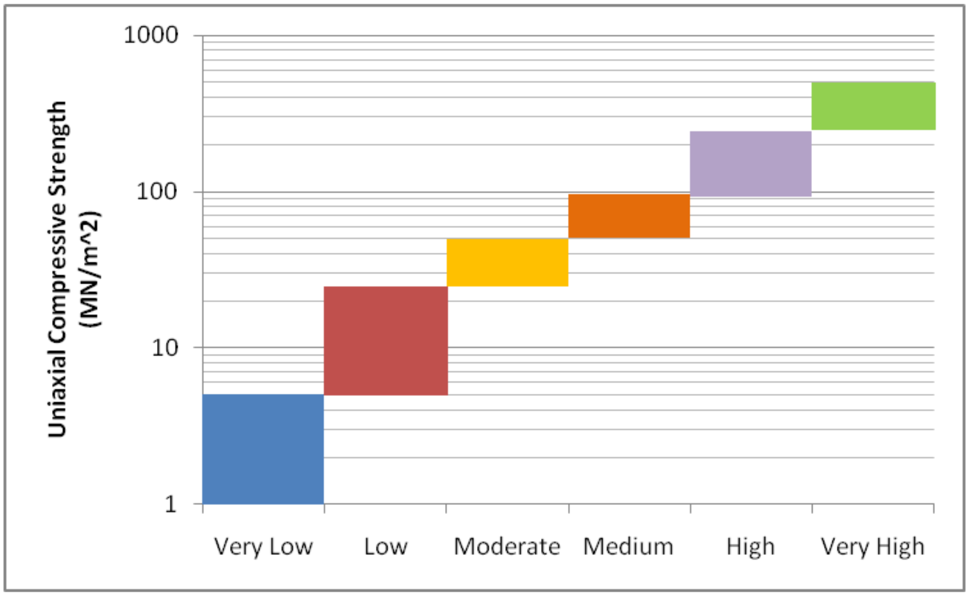
- Strong >2000 psi
- Medium 1200 - 1999 psi
- Weak < 1200 psi

Table 5.1 Summary of Testing Results

Source Name	Rock Type	Average compressive strength, psi	Classification according to NHI	Classification according to ISRM 1979
Beck, Zenith-CL A	Basalt	36200	Strong	Very high
Kelliher Quarry	Basalt	15280	Strong	High
Meridian - Saint Cloud	Granite	21640	Strong	High
OrtonVille	Granite	25510	Strong	High
New Ulm Quartzite	Quartzite	21170	Strong	High
Kraemer-Burnsville Limestone	Lime Stone "Carbonate"	1510	Strong	High
Aggregate Industry - Larson	Lime Stone "Carbonate"	10240	Medium	Medium
Kuehn Quarry	Lime Stone "Carbonate"	15670	Strong	High
Fountain Quarry	Lime Stone "Carbonate"	13830	Medium	Medium
S.M.C. Quarry	Lime Stone "Carbonate"	11150	Medium	Medium



NHI



ISRM

Figure 5.1 Classifications for Rock Material Strength

1 MN/m2 =144.9 psi, 20 MN/m2 =2900 psi, 100 MN/m2 =14490 psi

Based on classification of NHI and ISRM.

Figure 5.2 Compressive Strength Testing Machine

6 Discussions and Recommendations

This research is intended to provide new practical ideas and suggestions regarding improvements to current aggregate specifications. The research team found Mn/DOT receptive to pursuing changes in the way they specify aggregates, although the team is not currently suggesting any changes but rather discussing the question of the need for changes to current specifications. It is agreed that current specifications are still outdated and still do not reflect the current level of knowledge concerning desirable properties for pavement applications. It is also reasonable to state that current testing does not provide all necessary property characterization to ensure field performance.

The discussion with Mn/DOT engineers on including property-based testing in current specifications was focused on the following questions:

1) Do current coarse aggregate requirements reflecting Mn/DOT interests in aggregate quality?
2) Can an agency always specify the best aggregate based on current specifications and testing procedures?
3) If new property-based requirements are to be introduced, would the new requirements satisfy the performance-related properties of both asphalt and concrete mixes for pavement applications in Minnesota?

The following is summary of the concerns expressed by Mn/DOT practitioners during the meeting:

1) Mn/DOT expressed concerns that current relations between aggregate property-based and pavement performance are not sufficient and further correlations are needed before making changes to current specifications.
2) The ease and affordability of testing that would allow for frequent testing to ensure consistency of aggregate quality would need to be achieved. Complicated and time-consuming testing is likely to be conducted less frequently and will not be sufficient to characterize aggregate for variability.
3) What is the applicability of the new testing on recycled materials. Is RAP aggregate?
4) Interaction with the industry is important, but only after agreement is reached with Mn/DOT.

The concern regarding the relation between property-based testing and performance has two aspects: If those relations exist, then there is a need for a change in current specifications. If those relations do not exist, then marginal materials, including local sources that are poor in those properties, should be used successfully in most pavement applications. The research team agrees with Mn/DOT personnel that strong aggregate sources, as measured by the compressive strength, for example, would provide better performance, but the time and cost associated with the test may limit its use to characterize and to ensure aggregate quality on a daily basis. The research team strongly suggests alternative testing, for example the point load test (ASTM D5731), for assessing the quality of aggregate strength. If weak aggregate is an issue in pavement surface layers, then compressive strength is a possible solution that can help enhance current specs. This research project documented the current effort on the relation of property-based to pavement performance from literature and from experts. Additional research effort is needed to detail those relations. The research team explained that available data are a good start and that additional data from literature will be provided on this topic but additional research is a must to provide the needed details.

The research team explains that recommended property-based testing will run in addition to current testing. Frequency of testing may vary. Some property-based testing can be run less frequently than current specification tests, for example, compressive strength. The test may be difficult to run on each sample but can be used to approve sites or sources on a yearly basis. Compressive strength testing can be used to classify aggregate sources and then continue to be used to update approval of sources for quality considerations. A concern for Mn/DOT is the variability of the test and aggregate property that is normally addressed through more frequent testing. Test and sampling simplicity along with required resources must be addressed before adopting a new property-based testing method. Variability between layers of the same source has been a concern. The research team suggests indicator testing to cover the variability concerns due to additional testing times, as expressed by Mn/DOT, for the compressive strength testing. Indicator testing for property-based can help in testing and sampling simplicity. For aggregate compressive strength, for example, there are approximate methods of testing that are much easier to run and can provide reasonable accuracy. An example is the point load test (ASTM D5731) for conducting aggregate compressive strength. The use of indicator testing is recommended to confirm the need for the parent (or exact test) and also to confirm property consistence with proposed specifications. A combination of both testing procedures, the exact and the simplified procedures, can provide reliable reference data for aggregate sources and routine testing procedures for future aggregate specifications.

The discussion with Mn/DOT on aggregate quality was extended to define “best aggregates” for the job, which can guarantee best performance vs. “good enough” aggregates quality for pavement applications. Mn/DOT has aggregate requirements depending on the applications. An objective of this project is getting the best use of quality aggregates in pavement applications. Another objective concerns utilizing the lesser-quality aggregates for lower-traffic pavements. In concrete pavement, lower-quality aggregates are almost never used.

Current concrete pavement specifications encourage the use of best aggregates ignoring the existence of significant quantities of lower-quality aggregates that can be used in specific applications. Such lower-quality aggregates are only used for non-traffic lanes such as sidewalks. There is limited information about the property-based testing of those aggregate sources. On the other hand, bituminous applications are more open to the use of lower-quality aggregates. A related concern for Mn/DOT experts is recycled aggregates. For example, is RAP aggregate? It is not a naturally occurring material but can it be classified as aggregate? If so, what property-based testing might be conducted on RAP and on other recycled aggregates? RAP may not be meeting some specifications but is “good enough” for some pavement applications. All agree that RAP may not be the best available aggregate source for pavement surface applications. Recycled aggregates have been linked to specific cases of pavement failures. There is a need to further discuss the applicability of property-based testing on recycled materials as aggregates.

The need for further interaction with the industry on upgrading current aggregate specifications and on including property-based testing is postponed at the request of Mn/DOT. The input from industry on implementing new testing is necessary but agreement within the scientists and technologists on the properties to implement is also necessary before implementing any new specifications. Further discussions within the organization (Mn/DOT) must be completed before getting the industry involved in those issues. The contribution of the industry on including new testing should follow agreement within Mn/DOT on the new testing. The research team agreed on not offering a second questionnaire with the industry personnel until further discussions within Mn/DOT and agreement on specific recommendations, but that will be out of the scope of this project. The research team will provide a list of recommendations (as part of the final report) to Mn/DOT on aggregate property-based testing to be considered in future aggregate specs.

An important concept that was discussed with Mn/DOT is the emphasis on strength vs. durability when considering compressive strength testing. The research team agrees with Mn/DOT personnel on the need to adopt property-based testing methods that shows correlations to performance in future specifications. Mn/DOT personnel are concerned about sudden change to current specifications. Changes must be slowly implemented to allow proper understanding of the relation of property-based to pavement performance. The research team, steered by Chuck Howe, recommends a different system of aggregate classification that is not based on the A, B, or C current requirements and that has specific classifications for pavement applications using property-based testing, for example compressive strength. Mn/DOT personnel consider the current system reasonable until better relation(s) between proposed property-based testing and performance are confirmed to provide better performing pavements.

Sustainability is a major factor related to the use of local aggregate resources. The research team suggests that most local aggregate sources can be used successfully in asphalt low-volume road applications including cold mixes and surface treatment applications. Cost is a major factor in selecting aggregate sources for local road applications. Life cycle cost analysis is a useful tool in determining the use of local aggregate applications. Earlier tasks examined Mn/DOT records for available data on property-based testing on local aggregate quality that can be used in future research dealing with the sustainability of material resources in Minnesota. There is a potential that local aggregate sources that are rejected for high-class pavement mixes can be used for local and low-volume road applications. Aggregate quality is tied to the design process. Having better quality aggregate would facilitate the design of pavement with a longer life, an aspect of sustainability.

References

AASHTO M-80, 2003, “Standard Specification for Coarse Aggregate for Portland Cement Concrete,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-103, 1998, “Soundness of Aggregates by Freezing and Thawing,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-104, 2003, “Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-112, 1998, “Clay Lumps and Friable Parts in Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-19, 1998, “Standard Method of Test for Bulk Density (“Unit Weight”) and Voids in Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-2, 2006, “Sampling of Aggregates,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-248, 1998, “Reducing Samples of Aggregate to Testing Size,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-255, 1998, “Total Evaporable Moisture Content of Aggregate by Drying,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-27, 2006, “Sieve Analysis of Fine and Coarse Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-30, 1998, “Mechanical Analysis of Extracted Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-327, 1998, “Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-84, 1998, “Specific Gravity and Absorption of Fine Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-85, 1998, “Specific Gravity and Absorption of Coarse Aggregate,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO T-96, 2006, “Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine,” Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

AASHTO, 2008, “Aggregate Specifications,” http://www.transportation.org/. (Last accessed May 22, 2008).

Ad Hoc Aggregate Committee, 1998, “Minnesota’s Aggregate Resources - Road to the 21st Century,” Aggregate Resources Task Force, files.dnr.state.mn.us/lands_minerals/aggtf98.pdf. (Last accessed October 9, 2010).

Aggregate and Ready Mix Association of Minnesota, 2006, “Aggregate,” http://www.armofmn.com/resources/aggregates. (Last accessed May 21, 2008).

ASTM International, 2008, “Aggregate Industry,” http://www.astm.org. (Last accessed May 22, 2008).

ASTM Standard C1260 – 07, 2007, “Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method),” ASTM International, West Conshohocken, PA, DOI: 10.1520/C1260-07, www.astm.org.

ASTM Standard C131 – 06, 2006, “Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine,” ASTM International, West Conshohocken, PA, DOI: 10.1520/C0131-06, www.astm.org.

ASTM Standard C1567 – 08, 2008, “Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)”, ASTM International, West Conshohocken, PA, DOI: 10.1520/C1567-08, www.astm.org.

ASTM Standard C227-03, 2007, “Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method),” ASTM International, West Conshohocken, PA, DOI: 10.1520/C0227-03, www.astm.org.

ASTM Standard C289 – 07, 2007, “Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method),” ASTM International, West Conshohocken, PA, DOI: 10.1520/C0289-07, www.astm.org.

ASTM Standard C295 – 08, 2007, “Standard Guide for Petrographic Examination of Aggregates for Concrete,” ASTM International, West Conshohocken, PA, DOI: 10.1520/C0295-08, www.astm.org.

ASTM Standard C851-76, “Recommended Practice for Estimating Scratch Hardness of Coarse Aggregate Particles (Withdrawn 1984),” ASTM International, in press.

ASTM Standard C88 – 05, 2007, “Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate,” ASTM International, West Conshohocken, PA, DOI: 0.1520/C0088-05, www.astm.org.

ASTM Standard D2938-95, 1995, “Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens,” ASTM International, West Conshohocken, PA, DOI: 10.1520/D2938-95, www.astm.org.

ASTM Standard D3042 – 09, 2009, “Standard Test Method for Insoluble Residue in Carbonate Aggregates,” ASTM International, West Conshohocken, PA, DOI: 10.1520/D3042-09, www.astm.org.

ASTM Standard D4791-05, 2007, “Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate,” ASTM International, West Conshohocken, PA, DOI:10.1520/D4791-05, www.astm.org.

ASTM Standard D5821 - 01, 2007, “Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate,” ASTM International, West Conshohocken, PA, DOI: 10.1520/D5821-01R06, www.astm.org.

Atkins, H., *Highway Materials, Soils, and Concretes*. Upper Saddle River, NJ: Pearson Education, Inc., 2003.

Bowen, R., *Geology in Engineering*. Essex, England: Elsevier Applied Science Publishers, LTD, 1984.

Caltrans, 2006, “Standard Specifications,” California Department of Transportation, Sacramento, CA.

Davis, W., 2008, “Durability and Soundness,” http://www.pavementinteractive.org/index.php?title=Durability_and_Soundness. (Last accessed December 30, 2008).

Gregory, R., 2005, “Construction Aggregates,” http://www.wsgs.uwyo.edu/minerals/aggregate.aspx. (Last accessed May 19, 2008).

Hoffman, C., 2007, “Los Angeles Abrasion,” http://www.pavementinteractive.org/index.php?title=Los_Angeles_Abrasion. (Last accessed December 30, 2008).

Hughes, C., 2005, “State Construction Quality Assurance Programs,” NCHRP Synthesis 346.

Iowa DOT, 2007, “Standard Specifications,” Iowa Department of Transportation, Ames, IA.

IDOT, 2007, “Standard Specifications for Road and Bridge Construction,” Illinois Department of Transportation, Springfield, IL.

INDOT, 2006, “Aggregate Properties,” Indiana Department of Transportation, Indianapolis, IN.

Kosmatka, S., 2002, “Design and Control of Concrete Mixtures,” Portland Cement Association, Skokie, IL.

Krebs, R., *Highway Materials*. Blacksburg, VA: McGraw-Hill, Inc., 1971.

Mamlouk, M., *Materials for Civil and Construction Engineers*, Pearson, Upper Saddle River, NJ, 2006.

MDT, 2006, “Standard Specifications,” Montana Department of Transportation, Helena, MT.

Meininger, R., 2004, “Micro-level vs. LA Abrasion,” http://rockproducts.com/mag/rock_microdeval_vs_abrasion/. (Last accessed June 4, 2008).

Mn/DOT, *Lab Manual*, Minnesota Department of Transportation, Maplewood, MN, 2005.

Mn/DOT, *Lithological Summary*, Minnesota Department of Transportation, Maplewood, MN, 2000.

Mn/DOT. *Standard Specifications for Roads & Bridges*, Minnesota Department of Transportation, St. Paul, MN, 2005.

Mn/DOT, *Mn/DOT Standard Specifications for Construction*, Minnesota Department of Transportation, St. Paul, MN, 2005.

Montgomery, D., *Design and Analysis of Experiments*. Tempe, AZ: Hamilton Printing Company, 2006.

Musser, K., 2004, “Minnesota River Bed Glaciations.” Minnesota River Basin Data Center, www.mrbdc.mnsu.edu. (Last access April 1, 2008).

National Highway Institute, 2007, “Interpretation of Rock Properties,” s.l.: Federal Highway Administration, Washington, D.C.

National Stone, Sand and Gravel Association, 2008, “Aggregate,” http://www.nssga.org/. (Last accessed May 19, 2008).

NDDOT, 2002, “Standard Specifications,” North Dakota Department of Transportation, Bismarck, ND.

NDOR, 2007, “Standard Specifications,” Nebraska Department of Roads, Lincoln, NE.

Organization for Co-operation and Development, 1981, *Use of Marginal Aggregates in Road Construction*, Central Laboratory of France.

Roberts, F., 1996, “Hot Mix Asphalt Materials, Mixture Design and Construction,” National Asphalt Pavement Association, Lanham, MD.

SDDOT, 2004, “Standard Specifications,” South Dakota Department of Transportation, Pierre, SD.

Southwick, D., *Aggregate Resource Inventory of the Seven County Metropolitan Area*, University of Minnesota, Minneapolis, MN, 2000.

Superpave, 2001, Asphalt Institute, Lexington, KY.

Tilseth, R., 2008, “Aggregate Source Information System,” Minnesota Department of Transportation, http://www.dot.state.mn.us/materials/asissearch.html. (Last retrieved July 7, 2008).

TxDOT, 2004, “Standard Specifications,” Texas Department of Transportation, Austin, TX.

USGS Minerals Information, 2010, “Minnesota,” http://minerals.usgs.gov/minerals/pubs/state/mn.html. (Last retrieved September 23, 2010).

Washington Asphalt Pavement Association, 2002, “Aggregate,” http://www.asphaltwa.com/wapa_Web/modules/03_materials/03_aggregate.htm. (Last accessed July 10, 2008).

Wikipedia, 2008, “Minnesota,” http://en.wikipedia.org/wiki/Minnesota. (Last accessed May 21, 2008).

Williams, C., 2003, “Implementing Percent within Limits for Hot Mix Asphalt,” Ames, IA: Iowa State University.

Winnipeg Department of Transportation, 2008, “Standard Specification,” Winnipeg Department of Transportation, Winnipeg, Manitoba, Canada.

WisDOT, 2007, “Standard Specifications,” Wisconsin Department of Transportation, Madison, WI.

Appendix A: Relation between Coarse Aggregate Properties and Hot Mix Asphalt Performance

This appendix reports a literature review on the main aggregate properties that affect hot mix asphalt performance. The major focus will be the factors that were suggested by the survey conducted on Task 3 and are currently used by Mn/DOT. The calculated index values from the survey conducted on Task 3 were used to prioritize properties to a refined list of the most significant properties. Properties that generated an index value of 4.0 or greater were selected as significant.

A.1 Asphalt Affinity and Coating

Roberts et al. reported that chemical properties of aggregate effect HMA performance mainly through the effect of adhesion of the asphalt binder to the aggregate and compatibility with anti-stripping additives that may be used in HMA [Roberts et al., 1996]. Asphalt cement must wet the aggregate surface and stick to it to produce a good performing mix and resist the stripping of the asphalt film in the presence of water. The adhesion of asphalt cement to aggregate is a complex phenomenon; it includes the physco-chemical interaction between many parameters. It has been firmly established that mineralogy and chemical properties of aggregate are of main importance of stripping phenomenon [Roberts et al., 1996].

Adhesion between asphalt binder and aggregate in a dry state and in the presence of water is critical to the performance and durability of asphalt mixtures. Distress mechanisms in asphalt mixtures such as rutting, fatigue cracking, and moisture damage are correlated to the nature and quality of adhesion between asphalt binder and aggregate [Little and Bhasin, 2006].

Curtis 1992 investigated fundamental aspects of asphalt-aggregate interactions including chemical and physical processes. A number of different aspects of this problem were evaluated including the chemistry of the interaction between asphalt and aggregate, the effect of the interstitial asphalt on the bond, the effect of the aggregate on aging, and the water sensitivity of the asphalt-aggregate pair. Curtis found that aggregate properties are much more influential in determining adsorption and stripping behavior than are asphalt properties [Curtis, 1992]. Net adsorption tests, which are tests that provide a method for determining the affinity of an asphalt-aggregate pair and its sensitivity to water was developed. These tests demonstrated the large differences in asphalt affinity and stripping susceptibility occur among aggregates of different mineralogy. The adsorption and desorption behaviors between asphalt and aggregate were more strongly influenced by the aggregate chemistry and properties than those of the asphalt [Curtis, 1992]. The interactions between asphalt and aggregate are dominated by aggregate chemistry, which directly influence the adhesion of asphalt to aggregate and determine the strength of the bond between them. Asphalt chemistry also has an influence, though much smaller than that of the aggregate, on asphalt-aggregate interactions. Curtis developed a test that evaluated the affinity of different asphalt-aggregate pairs and their susceptibility to water [Curtis, 1992].

Curtis et al. reported that the net absorption of an asphalt aggregate pair is dependent on both the asphalt composition and the aggregate chemistry and morphology. In an experiment the amount of asphalt adsorbed for eleven aggregates, which were composed of limestone, granites, greywacke, gravels, and basalt, ranged over an order of magnitude from 0.001mg/g to 1.9mg/g for a given asphalt source at a preselected asphalt solution concentration.

A.2 Aggregate Chemical Compositions

Abo-Qudais and Al-Shweily evaluated the effect of aggregate chemical composition on HMA performance. The hypothesis of the research was that the chemistry of the aggregate surface affects the degree of the water sensitivity of the asphalt aggregate bond. Two types of aggregates were used in the study, limestone and basalt. Limestone composed mainly of CaCO3, while basalt is composed principally of Al_2O_3. Compared to basalt aggregate, limestone aggregate contains less SiO2. Silica usually causes a reduction in the bond between asphalt and aggregate [Abo-Qudais and Al-Shweily, 2007]. Limestone bears a positive charge, while basalt bears a mixed charge. Normally stronger bonds are associated with more electro-positive charge. This property makes the basalt aggregate fall in the hydrophilic (water loving) category, while the limestone aggregate falls in the hydrophobic (water hating) category [Abo-Qudais and Al-Shweily, 2007]. Abo-Qudais and Al-Shweily calculated the adhesion work for different combinations of asphalt and aggregate types. Results indicate that the adhesion between aggregate and asphalt in HMA prepared using limestone aggregate is higher than that of mixes prepared using basalt aggregate. This means that the HMA prepared using limestone aggregate have higher resistance to stripping since the bond strength between asphalt and limestone aggregate, as reflected by the adhesion work, is stronger than that between asphalt and basalt aggregate. The adhesions between aggregate and 60/70 asphalt were 4.88 and 0.24 dyne cm for mixes prepared using limestone and basalt aggregate, respectively [Abo-Qudais and Al-Shweily, 2007]. They found that the adhesion between water and aggregate was higher than that between asphalt and aggregate, regardless of the types of asphalt and aggregate used in preparing the mix. The adhesion work between limestone aggregate and 60/70 asphalt was 4.88 dyne cm, while it was 11.63 dyne cm between the same aggregate and water. This means that the bond strength between water and aggregate is higher than that between asphalt and aggregate. This meant that water has the tendency to replace asphalt coating the aggregate and cause stripping [Abo-Qudais and Al-Shweily, 2007].

Unconditioned specimens indicated that hot-mix asphalt prepared using limestone aggregate experienced higher creep value than those prepared using basalt aggregate. The same trend was noticed regardless of the types of asphalt and the aggregate gradations used in preparing mixes. The results were explained by the fact that the basalt aggregate was rougher than the limestone aggregate, so the mechanical interlock between asphalt and basalt aggregate will be higher leading to higher resistance to creep [Abo-Qudais and Al-Shweily, 2007]. Conditioned HMA specimens prepared using basalt aggregate showed higher creep values than those prepared using limestone aggregate, which was different than the unconditioned samples. A similar trend was noticed regardless of the type of asphalt and aggregate gradations used in preparing the HMA. The results were explained by the fact that the limestone aggregate had better resistance to stripping than basalt aggregate. Limestone rock is hydrophobic (water hating) aggregate.

The stripping of HMA was found to be related to the amount of asphalt absorbed in aggregate permeable voids. The resultsindicate a strong direct relationship between resistance to stripping (creep strain resistance) and the amount of absorbed asphalt. This result can be explained by the fact that as absorbed asphalt increases, the mechanical bonding between asphalt and aggregate will increase as the amount of absorbed asphalt increases. The amount of absorbed asphalt is capable of explaining the effect of aggregate type and the effect of aggregate gradation and type of asphalt used in preparing the HMA. It should be noted that there are other factors that explain why HMA prepared with limestone aggregate has better resistance to stripping between asphalt and aggregate. These factors include chemical reactions, surface energy relationships, and polarity of the aggregate. [Abo-Qudais and Al-Shweily, 2007].

Abo-Qudais and Al-Shweily study concluded that HMA stripping resistance was significantly affected by the type of aggregate used in preparing the mix. Unconditioned HMA asphalt prepared using limestone had better stripping resistance than that prepared using basalt aggregate. This trend was reversed as the HMA was exposed to conditioning. The asorbed asphalt had the capability of reflecting the effect of aggregate type and gradation and type of asphalt on the HMA stripping resistance. The percent of absorbed asphalt had a strong reverse relationship with HMA stripping resistance. Adhesion work had the capability of reflecting the effect of aggregate type and gradation, and type of asphalt on stripping resistance. However it was not able to detect the effect of the type of asphalt used in preparing the HMA on stripping resistance [Abo-Qudais and Al-Shweily, 2007].

Wasiuddin et al. studied the wettability and adhesion using the surface free energy (SFE) method. Dynamic advancing–wetting contact angles were measured for wettability (coating) and dewetting. Receding contact angles were measured to evaluate adhesion. The SFE of an asphalt binder mainly comprises a polar component and an acid–base component that can be decomposed to Lewis acidic surface parameter and a Lewis basic surface parameter. These properties (wettability and adhesion) of selected binders were related the moisture-induced damage mechanisms of hot mix asphalt (HMA). In their study, moisture susceptibility was defined as “the amount of spontaneously released free energy due to the breaking of the binder–aggregate bond with water” [Wasiuddin et al., 2008].

A.3 Deleterious Constituents

Excessive clay lumps in a processed aggregate may interfere with the bonding between the aggregate and cementations material. This will result in spalling, raveling, or stripping and create weak points and pop-outs if the material is incorporated into the pavement (AASHTO T 112).

Aggregates must be relatively clean when used in HMA. Vegetation, soft particles, clay lumps, excess dust and vegetable matter may affect performance by quickly degrading, which causes a loss of structural support and/or prevents binder-aggregate bonding [Washington Asphalt Pavement Association's Asphalt Pavement Guide, 2003]. Deleterious materials refer to individual particles which are made up of unsatisfactory or unsound materials. In a survey that covered 45 states, it was found that 73% of the surveyed states measure the amount of deleterious material in a routine basis [Kandhal et al., 1997]. Mn/DOT currently tests for deleterious materials using Mn/DOT procedure # 1209.

A.4 Absorption

Brandes and Robinson evaluated the correlation of aggregate test parameters to HMA pavement performance in Hawaii. The focus of the research was the effect on HMA revelation. Based on the correlations between individual laboratory tests and historic distress records, they reported that degradation due to aggregate raveling is a stronger function of chemical processes than mechanical ones. Among the index tests, percent absorption and sand equivalent show the strongest correlation with performance. Percent absorption relates to the asphalt binder and water absorption potential of aggregate and is an important variable for basalts since these materials can occur in various stages ranging from extremely porous to impermeable, depending on such factors as geologic origin and degree of weathering. Sand equivalent can similarly be associated with the type of parent rock. Under unfavorable circumstances, undesirable basaltic aggregate could produce significant fines during aggregate transportation, storage, mixing with asphalt binder and pavement lay down, leading to a lower long-term performance [Brandes and Robinson, 2006].

A.5 Los Angles Abrasion Test

The Los Angles LA abrasion test subjects the aggregate sample to impact and crushing. The LA abrasion test is related to the expected breakdown during handling, mixing, and placement. Recent studies have only indicated a fair correlation with in-place performance although early developmental studies indicated better correlations [Prowell et al., 2005]. Prowell et al. surveyed 48 states and Canadian provinces and found that the LA abrasion test is used by 96% of the responding agencies. Agency specification values range from less than 30% to less than 55% loss, with 40% loss being the most frequently cited specification. Some research has been conducted to evaluate the micro-deval test as an alternative to LA abrasion. However, the two tests measure different deterioration methods. There is no evidence that the LA abrasion test should be replaced for assessing breakdown during construction. Individual agencies may wish to examine their criteria based on other agencies' experience [Prowell et al., 2005]. No relationship could be established between the Los Angeles abrasion test results and long-term wear of HMA pavement surfaces. This conclusion was based on reviewing materials and performance data from field experiments, including the LTPP SPS-1, 5, and 9 experiments and the WesTrack, FHWA ALF, MnROAD, and NCAT Test Track studies [Prowell et al., 2005].
Brandes and Robinson reported that LA abrasion test exhibited little negative correlation with raveling performance. They recommended possible replacements for LA test with the aggregate durability index test and the scratch hardness test [Brandes and Robinson, 2006].

A.6 Magnesium Sulfate

The magnesium sulfate soundness test appeared to present pavement performance and it was marginally better than the sodium sulfate soundness test [Brandes and Robinson 2006]. The magnesium sulfate soundness and Micro-Deval abrasion loss were found to be highly correlated, and there is a demonstrated relationship between Micro- Deval results and pavement particle abrasion [Brandes and Robinson, 2006].

References

AASHTO T-112, 1998, "Clay Lumps and Friable Parts in Aggregate," Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C.

Bhasin, Amit and Little, Dallas N., Application of Microcalorimeter to Characterize Adhesion between Asphalt Binders and Aggregates. Journal of Materials in Civil Engineering. Volume 21, Issue 6, June 2009, pp 235-243.

Brandes, Horst G., and Chet E. Robinson, Correlation of Aggregate Test Parameters to Hot Mix Asphalt Pavement Performance in Hawaii. Journal of Transportation Engineering, Vol. 132, 2006, pp. 86-95.

Curtis, C., Investigation of Asphalt-Aggregate Interactions in Asphalt Pavements. Auburn: American Chemical Society, 1992, http://www.anl.gov/PCS/acsfuel/preprint%20archive/Files/37_3_WASHINGTON%20DC_08-92_1292.pdf, (Last accessed March, 2010).

Kandhal, P., Parker, F., and Mallick, R., Aggregate Tests for Hot Mix Asphalt: State of the Practice: NCAT Report 97-06. National Center for Asphalt Technology, Auburn University, 1997, http://www.ncat.us/reports/rep97-06.pdf, (Last accessed March 2010)

Prowell, Brian D., Jingna Zhang, and E. Ray Brown, Aggregate Properties and the Performance of Superpave-Designed Hot Mix Asphalt. NCHRP report No. 539. Transportation Research Board, Washington, D.C. 2005.

Roberts, F.L., Kandhal P.S., Brown E.R., Lee, Dah-Yinn, Kenedy, T.W., Hot mix asphalt materials, mixture design, and construction. National Center for Asphalt Technology, 1996.

Saad Abo-Qudais, Haider Al-Shweily, Effect of aggregate properties on asphalt mixtures stripping and creep behavior. Journal of Construction and Building Materials, vol. 21, 2007, pp 1886–1898.

Washington Asphalt Pavement Association's Asphalt Pavement Guide http://www.asphaltwa.com/wapa_Web/modules/03_materials/03_aggregate.htm

Wasiuddin, N., Zaman, M., and O'Rear, E., Effect of Sasobit and Aspha-Min on Wettability and Adhesion between Asphalt Binders and Aggregates. Transportation Research Record, Volume 2051, 2008, pp 80-89.

Appendix B: Relation between Coarse Aggregate Properties and Portland Cement Concrete Performance

This appendix report a literature review for the main aggregate properties that affect Portland cement concrete pavement performance. The results of the survey responses and discussion with professionals provided data that was used to develop an average index value from 1-5 to indicate the significance level of each property.

B.1 Effect of Aggregate Freeze-Thaw Stability on Pavement Performance

Freeze-thaw deterioration is the most common and severe durability problem for PCC pavements in many states, and coarse aggregate D-cracking is often the source of these durability problems. D-cracking is a progressive distress associated primarily with the use of coarse aggregates that deteriorate when they are critically saturated and subjected to repeated cycles of freezing and thawing [Koubaa and Snyder, 1996]. D-cracking, or durability cracking, appears as a series of closely spaced, crescent-shaped cracks along joints or cracks [Folliard and Smith, 2003]. D-cracking occurs when water in certain aggregates freezes, leading to expansion and cracking of the aggregate and/or surrounding mortar. D-cracking to development depends on the aggregate type and pore structure, climatic factors, availability of moisture, and concrete properties [Folliard and Smith, 2003]. Coarse aggregate particles exhibiting relatively high absorption and having medium-sized pores (0.1 to 5 μm) experience the most freezing and thawing problems because of higher potential for saturation. Larger pores normally do not get completely filled with water and do not result in frost damage [ACI, 1996a]. Aggregates of sedimentary origin such as limestone, dolomites, and cherts are most commonly associated with D-cracking [Stark, 1976 and Folliard and Smith, 2003].

B.2 Particle Size Distribution

It was reported that the particle size distribution or gradation of fine and coarse aggregates has a significant effect on the fresh concrete properties (water demand, air content, segregation, and bleeding) and the hardened concrete properties (strength, permeability, drying shrinkage, and coarse aggregate-mortar bond). Most states specify an AASHTO No. 57 coarse aggregate and an AASHTO M 6 fine aggregate for concrete pavements. Some states use well-graded blends of aggregates to provide dense packing and to minimize cement content. Gradation can affect all of the following performance parameters, longitudinal cracking, roughness, spalling, transverse cracking, corner breaks, transverse joint faulting [Folliard and Smith, 2003]. Chupanit and Roesler evaluated the effect of aggregate gradation on fracture toughness of concrete. The results showed that the concrete mix with gap gradation showed a 20% higher cracking resistance at 28 days [Chupanit and Roesler, 2005].

Chupanit and Roesler evaluated the effect of aggregate top size for river gravel and trap rock concrete mixes. For the trap rock concrete mixes, the aggregate top sizes (38 mm vs. 25 mm) were different along with their gradations (gap vs. dense). For the river gravel concrete mixes, only the aggregate top size was different (38GRG vs. 25GRG). For both river gravel and trap rock concrete mixes, the larger-sized aggregate increased the cracking resistances. Concrete mixes with larger size aggregates created a rougher crack surface [Chupanit and Roesler, 2005]. The coarse aggregate size was found to have significant effect on the deterioration of concrete. In a field study, discussed by Yu et al. it was found that decreasing the maximum aggregate size from 38 to 25.4 mm increased the deterioration of cracks by 15%. Further decrease in aggregate size to 12.7 mm increased the deterioration by 100%. This indicates that the coarse aggregate sizes above 12.7 mm are the main contributors to aggregate interlock and load transfer [Yu et. el., 1996].

B.3 Compressive Strength

It was reported that the strength, stiffness, and fracture energy of concrete for a given water/cement ratio (W/C) depend on the type of aggregate [Wu et al., 2001]. The results of the report indicated that aggregate compressive strength is one of the factors that affect concrete compressive strength. Hansen et al. showed that compressive strength affects rigid pavement performance [Hansen et. al., 2001].

The effect of aggregate type on concrete cracking resistance and shear load transfer ability was investigated by Chupanit and Roesler by comparing concrete mixes that had the same gradation and maximum size aggregate. The only difference between these concrete mixes was the type of aggregate. Aggregate types with higher crushing values show lower fracture energies. Concrete pavements constructed using strong aggregate typically have greater cracking resistance [Chupanit and Roesler, 2005]. Jensen and Hansen found that the strongest aggregate (glacial gravel) had the highest fracture energy relative to limestone and slag [Jensen and Hansen, 2000, Jensen and Hansen, 2002 and Chupanit and Roesler, 2005].

B.4 Abrasion Resistance

The Micro-Deval test appears to be the best indicator for assessing the potential for aggregate breakdown. This method was developed in the 1960s in France, and it has been used extensively in Canada, and is now included in the Canadian Standards Association (CSA) specifications. It is a wet attrition test that that can be used with both fine aggregates [CSA A23.2-23A—Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus] and coarse aggregates [Ontario MOT Test LS-618, Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus]. The coarse aggregate version of this test is now available as AASHTO TP 58 (Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus). The test subjects an aggregate sample to wet attrition by placing it in a steel jar with steel balls (9.5 mm in diameter) and water, then rotating the jar at 100 rpm for 2 h for coarse aggregates or 15 min for fine aggregates. Aggregate damage is assessed by mass loss at the completion of the test using a 1.25-mm sieve and # 200 sieve for coarse and fine aggregates, respectively. The Micro-Deval test for fine aggregates has been found to correlate well with magnesium sulfate soundness testing but has better within- and multi-laboratory precision and is less sensitive to aggregate grading [Rogers et al., 1991].

A dry abrasion method that has been used extensively to study aggregate abrasion is AASHTO T 96 (*Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*). A survey was conducted over 43 states indicated that this method was used by most state DOTs (32 out of 43) [Fowler et al., 1996]. The test appears to have some merit in predicting aggregate breakdown or degradation during handling, but it has a limited ability to predict pavement performance.

Aggregate abrasion properties may also affect the surface wear or abrasion at or near the top surface of pavements. This is generally a concern only when studded tires are used. This abrasive action will affect pavement smoothness and may also lead to exposing and polishing the coarse aggregates. The Los Angeles Abrasion and Impact test is the most commonly used test for assessing potential damage [Fowler et al., 1996], although its ability to predict pavement performance is not well documented. Folliard and Smith documented that aggregate abrasion resistance is well correlated to specific distress in concrete pavements including: surface friction, longitudinal cracking, punchouts, transverse cracking and corner breaks [Folliard and Smith, 2003].

B.5 Bulk Specific Gravity and Absorption

Absorption is closely related to aggregate porosity and thus to aggregate frost susceptibility. Absorption alone is not a measure of frost resistance, although highly absorptive aggregates are often nondurable [Folsom, 1991, Koubaa and Snyder, 1996]. Koubaa and Snyder evaluated several aggregate sources with different absorption from 0.8 to 3.03%. A strong correlation is indicated between absorption and ASTM C666 Procedure B, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, with salt-treated aggregates, which is probably caused by the increased concentration of fluids after freezing, the effect of salt on the sorption and porosity of the aggregate, and the increased potential for water to infiltrate the pores. They reported that absorption capacities below 1.5% were associated with durability factors of 80 or more, whereas absorption capacities above 2.0% were linked to durability factors of 60 or less. DF, durability factor, was determined using relative dynamic modulus criteria.

The bulk specific gravity for the aggregate sources tested by Koubaa and Snyder varied from 2.52 to 2.74. It has been reported that as the bulk specific gravity of limestone decreases, the susceptibility to freeze-thaw damage increases [Girard, 1982 and Koubaa and Snyder, 1996]. The results indicate the strong correlation between specific gravity and ASTM C666 Procedure B with salt-treated aggregates. The results also suggest generally good durability for specific gravities greater than 2.6. Others researchers reported that no correlation was found between bulk specific gravity and D-cracking deterioration [Meininger et al., 1965 and Bukovatz and Crumpton, 1981].

Absorption is considered an indicator of coarse aggregate pore volume, and adsorption is considered a rough measure of aggregate surface area. Portland Cement CA developed acceptance criteria based on absorption and adsorption measurements and service records to estimate the frost susceptibility of coarse aggregates [Klieger et al., 1974 and Koubaa and Snyder, 1996]. The sample preparation and test procedure and equipment are described elsewhere. Klieger et al. reported that durable aggregates should have either an absorption capacity below 0.3%, an adsorption capacity below 0.1%, or both. Koubaa and Snyder 1996 evaluated aggregate samples that had absorption capacities between 0.9 and 4.9% and adsorption capacities between 0.23 and 1.01%. These aggregates are all outside the PCA criteria. This study and other researchers concluded that the absorption adsorption criteria for aggregate acceptance are very restrictive and may classify sources with good field records as nondurable [Kaneuji, 1978, Traylor, 1982 Marks and Koubaa and Snyder, 1996]. Koubaa and Snyder did not find any correlation between absorption and adsorption values and field performance or rapid freeze-thaw test results.

References

American Concrete Institute (ACI), Guide for Use of Normal Weight Aggregate in Concrete, ACI Report 221R, 1996.

Bukovatz, J. E., and C. F. Crumpton, Study of D-Cracking in Portland Cement Concrete Pavements, Vol. 2. Laboratory Phase. Report FHWA-KS-81-2. Kansas Department of Transportation, Topeka, 1981.

Chupanit, P., & Roesler, J. R., Improvement of Concrete Cracking Resistance and Joint Load Transfer Through Coarse Aggregate Selection. Transportation Research Record: Journal of the Transportation Research Board, vol 1913, 2005, pp 3-10.

Folliard, Kevin J. and Smith, Kurt D., Aggregate Tests for Portland Cement Concrete Pavements: Review and Recommendations Research Results Digest, Number 281, September 2003, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_281.pdf, (Last accessed March 2010).

Folsom, D., Synthesis Report of Aggregate Testing Methods Used to Prevent D-Cracking of Concrete Pavements, Minnesota Department of Transportation, 1991.

Fowler, D. W., Zollinger, D. G., Carrasquillo, R. L., and Constantino, C. A., Aggregate Tests Related to Performance of Portland Cement Concrete, Phase I, Unpublished Interim Report, NCHRP Project 4-20, 1996.

Girard, R. J., E. W. Myers, G. D. Manchester, and W. L. Trimm, DCracking: Pavement Design and Construction Variables. In Transportation Research Record 853, TRB, National Research Council, Washington, D.C., 1982, pp 25–30.

Hansen, W., E.A. Jensen, and P. Mohr, The Effects of Higher Strength and Associated Concrete Properties on Pavement Performance. Report No. FHWA-RD-00-161, Federal Highway Administration, Research, McLean, Virginia, June 2001, http://www.tfhrc.gov/pavement/pubs/00161a.pdf, (Last accessed April 2010).

Jensen, E. A., and W. Hansen, Crack Resistance of Jointed Plain Concrete Pavements. In Transportation Research Record: Journal of the Transportation Research Board, No. 1809, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 60–65.

Jensen, E. A., and W. Hansen, Fracture Energy Test for Highway Concrete: Determining the Effect of Coarse Aggregate on Crack Propagation Resistance. In Transportation Research Record: Journal of the Transportation Research Board, No. 1730, TRB, National Research Council, Washington, D.C., 2000, pp. 10–17.

Kaneuji, M., Correlation Between the Pore-Size Distributions and Freeze-Thaw Durability of Coarse Aggregates in Concrete. Ph.D. dissertation. Purdue University, West Lafayette, Ind., 1978.

Koubaa, A., and Snyder, M., Evaluation of Frost Resistance Tests for Carbonate Aggregates. Transportation Researh Record 1547, 1996, pp. 35-45.

Marks, V. J., and W. Dubberke, Durability of Concrete and the Iowa Pore Index Test. In Transportation Research Record 853, TRB, National Research Council, Washington, D.C., 1982, pp. 25–30.

Meininger, R. C., J. F. Fox, and H. A. Lepper, A Single Particle Freezing Test for Concrete Aggregate. Proc., ASTM, Vol. 65, 1965, pp. 801–808.

Rogers, C. A., and Fournier, B., Petrography and Alkali- Aggregate Reactions, Petrography and Alkali-Aggregate Reactivity—Course Manual, CANMET, Ottawa, pp. 71-124, 1991.

Stark, D., Characteristics and Utilization of Coarse Aggregates Associated with D-Cracking, Bulletin RD047.01P, Portland Cement Association, Skokie, IL, 1976. Traylor, 1982.

Wu, Ke-Ru, Bing Chen, Wu Yao, Dong Zhang, Effect of coarse aggregate type on mechanical properties of high-performance concrete. Cement and Concrete Research vol. 31, 2001, pp. 1421–1425.

Yu, H.T., Darter, M.I., Smith, K.D., Jiang, J., and Khazanovich, L., Performance of Concrete Pavements. Volume III – Improving Concrete Pavement Performance, Final Report. Contract No. DTFH61-91-C-00053. 1996, Federal Highway Administration, McLean, VA.

Appendix C: Survey Data

Table C.1 Ranked Properties for PCC as Indicated by Survey

RANK	TEST	PROPERTY	INDEX
1	Volumetric Stability – freeze/thaw	PHYSICAL	4.6
2	Particle Size (distribution)- AASHTO T-2	PHYSICAL	4.5
3	Soundness, Weatherability – AASHTO T-104	PHYSICAL	4.4
4	Reactivity to Chemicals - AASHTO M-80	CHEMICAL	4.4
5	Particle Size (maximum)- ASTM D75	PHYSICAL	4.3
6	Solubility	CHEMICAL	4.3
7	Toughness - ASTM C131	MECHANICAL	4.2
8	Compressive Strength	MECHANICAL	4.2
9	Abrasion Resistance – ASTM C131	MECHANICAL	4.2
10	Particle Shape (flakiness, elongation)- ASTM D4791	PHYSICAL	4.2
11	Particle Size (angularity)- ASTM D5821	PHYSICAL	4.2
12	Deleterious Constituents – AASHTO T-112	PHYSICAL	4.1
13	Pore Structure, Porosity	PHYSICAL	4.1
14	Specific Gravity & Absorption- AASHTO T-85	PHYSICAL	4.0
15	Volume Stability	CHEMICAL	3.9
16	Character of Products of Abrasion – AASHTO T-96	MECHANICAL	3.9
17	Coatings	CHEMICAL	3.8
18	Volumetric Stability – wet/dry	PHYSICAL	3.7
19	Volumetric Stability – thermal	PHYSICAL	3.7
20	Particle Surface Texture- ASTM C1252	PHYSICAL	3.7
21	Unit Weight, voids – AASHTO T-19	PHYSICAL	3.6
22	Mass Stability (Stiffness, Resilience) – AASHTO T-292	MECHANICAL	3.5
23	Polishability – AASHTO 279	MECHANICAL	3.3

*****Number of test samples/total samples

Table C.2 Significant Properties for PCC – Survey Results

			Use In Neighboring State's Specifications											
	Tesing Procedure	**% Total Sample Testing in Local Data***	**MN**	**ND**	**SD**	**IL**	**WI**	**IA**	**NE**	**MT**	**TX**	**CA**	**City of Winnepeg**	**Percent Use**
Physical														
• Size (angularity, maximum, distribution)	ASTM D5821, ASTM D75,	0%	X	X	X	X	X	X	X	X		X		82%
• Shape (elongation flakiness)	ASTM D4791	0%	X	X	X			X						36%
• Porosity	AASHTO T-19	0%	X											9%
• Specific Gravity & Absorption	AASHTO T-85	12.89%	X			X	X		X	X	X	X		64%
• Soundness	AASHTO T-104	6.78%	X	X	X	X	X	X	X	X	X	X	X	100%
• Volumetric Stability – freeze/thaw		0%												0%
• Deleterious Constituents	AASHTO T-112	0%	X					X	X	X				36%
Chemical														
• Reactivity to Chemicals	ASTM C1260, ASTM C1567	0%	X											9%
• Solubility		0%												0%
Mechanical														
• Compressive Strength		0%												0%
• Abrasion Resistance	ASTM C131	5.62%	X	X	X	X	X	X	X	X	X	X		91%
• Toughness	ASTM C131	0%	X	X	X	X	X	X	X	X	X	X		91%

Table C.3 Ranked Properties for Asphalt as Indicated by Survey

RANK	TEST	PROPERTY	INDEX
1	Particle Size (angularity)- ASTM D5821	PHYSICAL	4.8
2	Particle Size (distribution)- AASHTO T-2	PHYSICAL	4.6
3	Particle Surface Texture- ASTM C1252	PHYSICAL	4.3
4	Particle Shape (flakiness, elongation)- ASTM D4791	PHYSICAL	4.3
5	Specific Gravity & Absorption- AASHTO T-85	PHYSICAL	4.3
6	Compressive Strength	MECHANICAL	4.3
7	Pore Structure, Porosity	PHYSICAL	4.2
8	Particle Size (maximum)- ASTM D75	PHYSICAL	4.2
9	Abrasion Resistance – ASTM C131	MECHANICAL	4.2
10	Coatings	CHEMICAL	4.2
11	Asphalt Affinity - ASTM D1075	CHEMICAL	4.2
12	Toughness - ASTM C131	MECHANICAL	4.1
13	Soundness, Weatherability – AASHTO T-104	PHYSICAL	4.0
14	Integrity during heating	PHYSICAL	4.0
15	Deleterious Constituents – AASHTO T-112	PHYSICAL	4.0
16	Character of Products of Abrasion – AASHTO T-96	MECHANICAL	3.9
17	Volumetric Stability – freeze/thaw	PHYSICAL	3.9
18	Mass Stability (Stiffness, Resilience) – AASHTO T-292	MECHANICAL	3.8
19	Volume Stability	CHEMICAL	3.7
20	Surface Charge	CHEMICAL	3.6
21	Polishability – AASHTO 279	MECHANICAL	3.6
22	Unit Weight, voids – AASHTO T-19	PHYSICAL	3.5

*****Number of test samples/total samples

Table C.4 Significant Properties for Asphalt – Survey Results

			Use In Neighboring State's Specifications											
	Tesing Procedure	**% Total Sample Testing in Local Data***	**MN**	**ND**	**SD**	**IL**	**WI**	**IA**	**NE**	**MT**	**TX**	**CA**	**Canada**	**% Use**
Physical														
• Size (angularity, maximum, distribution)	ASTM D5821, ASTM D75, AASHTO T-2	0%	X	X	X	X	X	X	X	X		X		82%
• Shape (elongation flakiness)	ASTM D4791	0%	X	X	X			X						36%
• Surface Texture	ASTM C1252	0%												0%
• Porosity	AASHTO T-19	0%	X			X	X	X		X	X	X		64%
• Soundness	AASHTO T-104	12.89%	X			X	X		X	X	X	X		64%
• Specific Gravity & Absorption	AASHTO T-85	6.78%	X	X	X	X	X	X	X	X	X	X	X	100%
• Integrity during heating		0%												0%
• Deleterious Constituents	AASHTO T-112	0%	X					X	X	X				36%
Chemical														
• Coatings		0%												0%
• Asphalt Affinity	ASTM D1075	0%												0%
Mechanical														
• Toughness	ASTM C131	0%	X	X	X	X	X	X	X	X	X	X		91%
• Abrasion Resistance	ASTM C132	5.62%	X	X	X	X	X	X	X	X	X	X		91%
• Compressive Strength		0%												0%

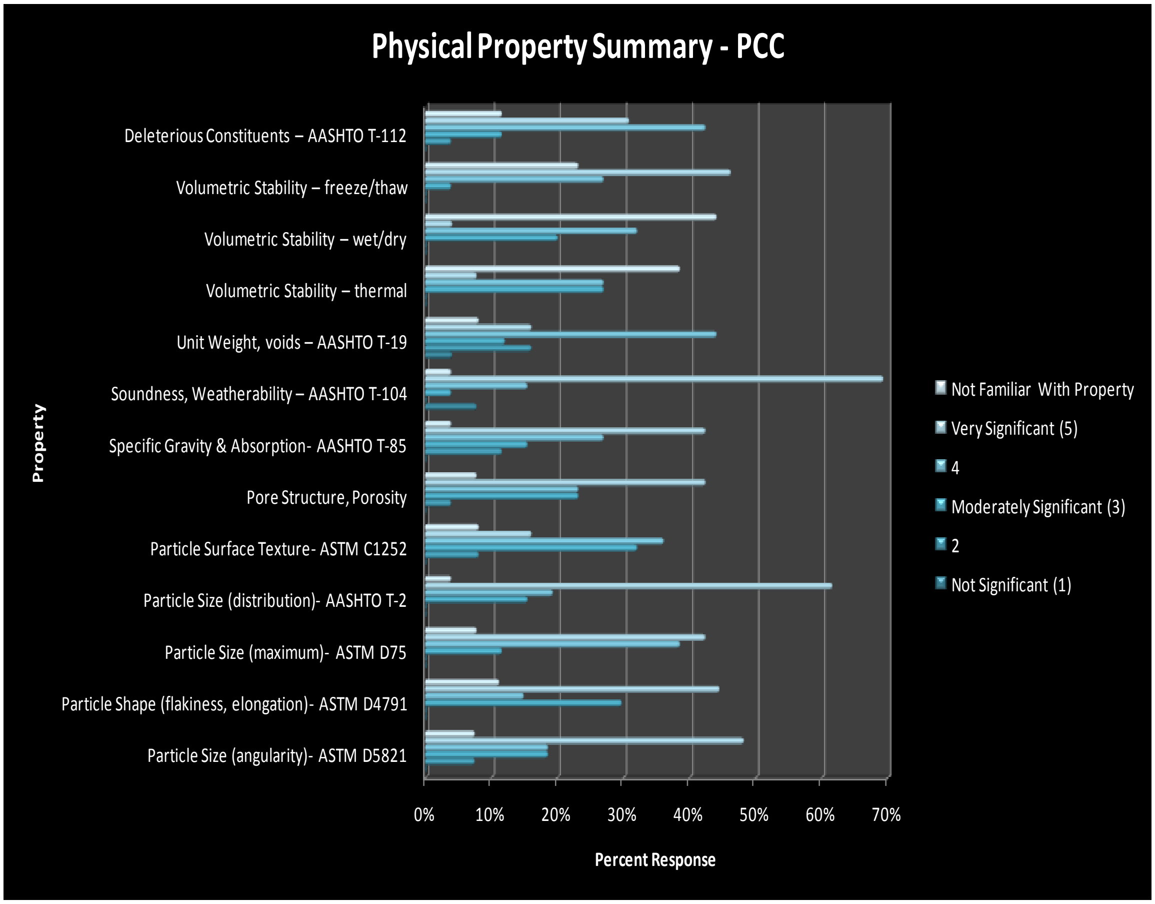


Figure C.1 Physical Property Summary – PCC

Table C.5 Summary of Physical Property Results for PCC Applications

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Particle Size (angularity)- ASTM D5821	0.0%	7.4%	18.5%	18.5%	48.1%	7.4%	4.2
Particle Shape (flakiness, elongation)- ASTM D4791	0.0%	0.0%	29.6%	14.8%	44.4%	11.1%	4.2
Particle Size (maximum)- ASTM D75	0.0%	0.0%	11.5%	38.5%	42.3%	7.7%	4.3
Particle Size (distribution)- AASHTO T-2	0.0%	0.0%	15.4%	19.2%	61.5%	3.8%	4.5
Particle Surface Texture- ASTM C1252	0.0%	8.0%	32.0%	36.0%	16.0%	8.0%	3.7
Pore Structure, Porosity	0.0%	3.8%	23.1%	23.1%	42.3%	7.7%	4.1
Specific Gravity & Absorption- AASHTO T-85	0.0%	11.5%	15.4%	26.9%	42.3%	3.8%	4.0
Soundness, Weatherability – AASHTO T-104	7.7%	0.0%	3.8%	15.4%	69.2%	3.8%	4.4
Unit Weight, voids – AASHTO T-19	4.0%	16.0%	12.0%	44.0%	16.0%	8.0%	3.6
Volumetric Stability – thermal	0.0%	0.0%	26.9%	26.9%	7.7%	38.5%	3.7
Volumetric Stability – wet/dry	0.0%	0.0%	20.0%	32.0%	4.0%	44.0%	3.7
Volumetric Stability – freeze/thaw	0.0%	0.0%	3.8%	26.9%	46.2%	23.1%	4.6
Deleterious Constituents – AASHTO T-112	0.0%	3.8%	11.5%	42.3%	30.8%	11.5%	4.1

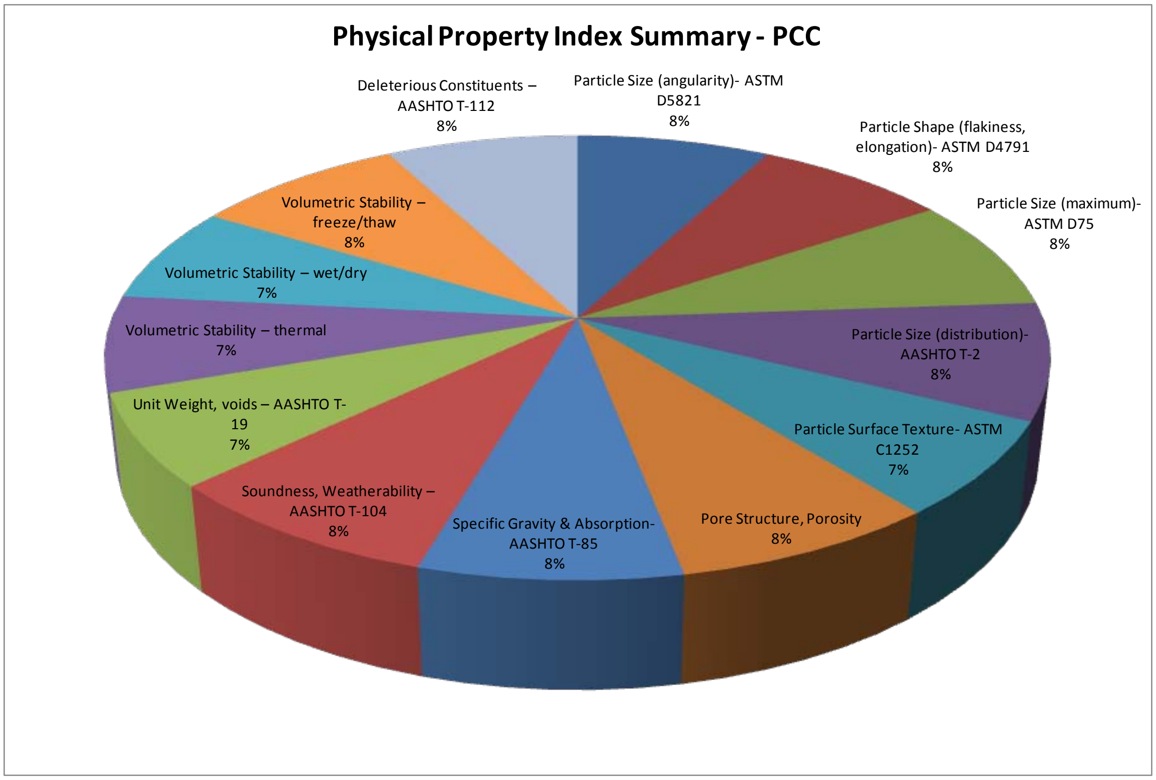


Figure C.2 Physical Property Index Summary-PCC

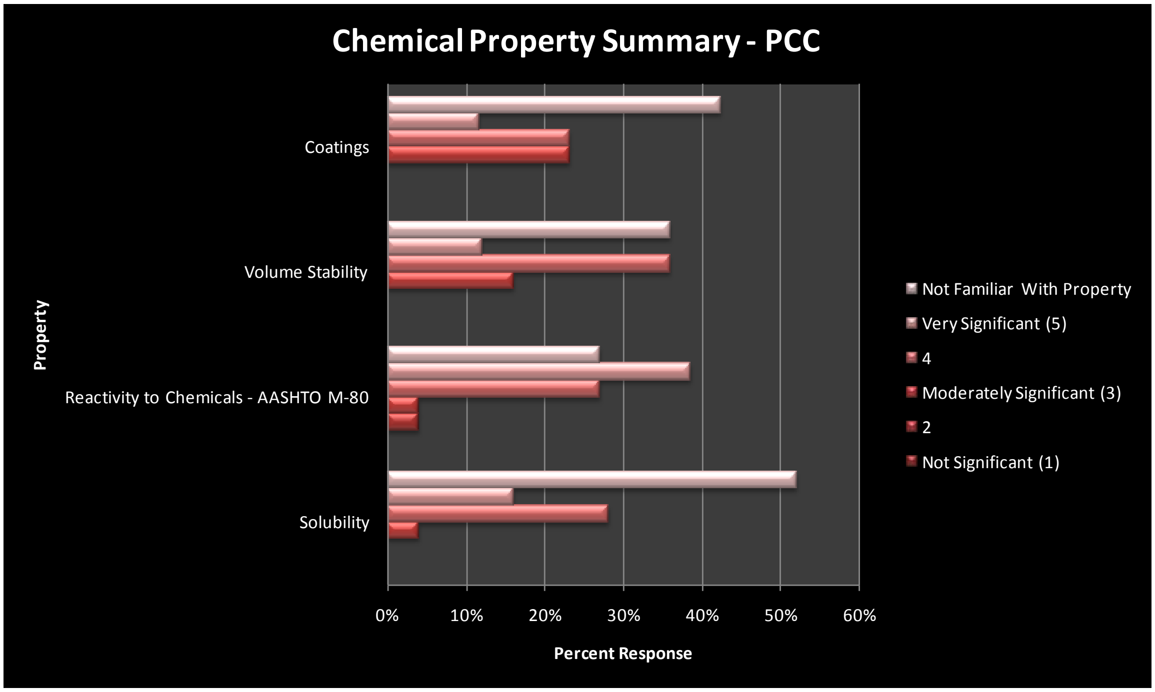


Figure C.3 Chemical Property Summary–PCC

Table C.6 Summary of Chemical Property Results for PCC Applications

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Solubility	0.0%	0.0%	4.0%	28.0%	16.0%	52.0%	4.3
Reactivity to Chemicals - AASHTO M-80	0.0%	3.8%	3.8%	26.9%	38.5%	26.9%	4.4
Volume Stability	0.0%	0.0%	16.0%	36.0%	12.0%	36.0%	3.9
Coatings	0.0%	0.0%	23.1%	23.1%	11.5%	42.3%	3.8

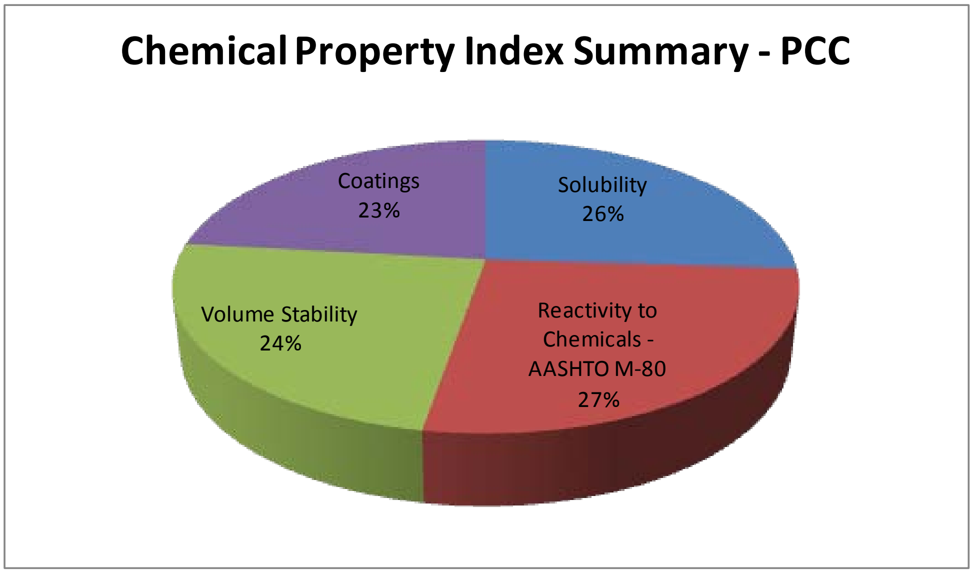


Figure C.4 Chemical Property Index Summary-PCC

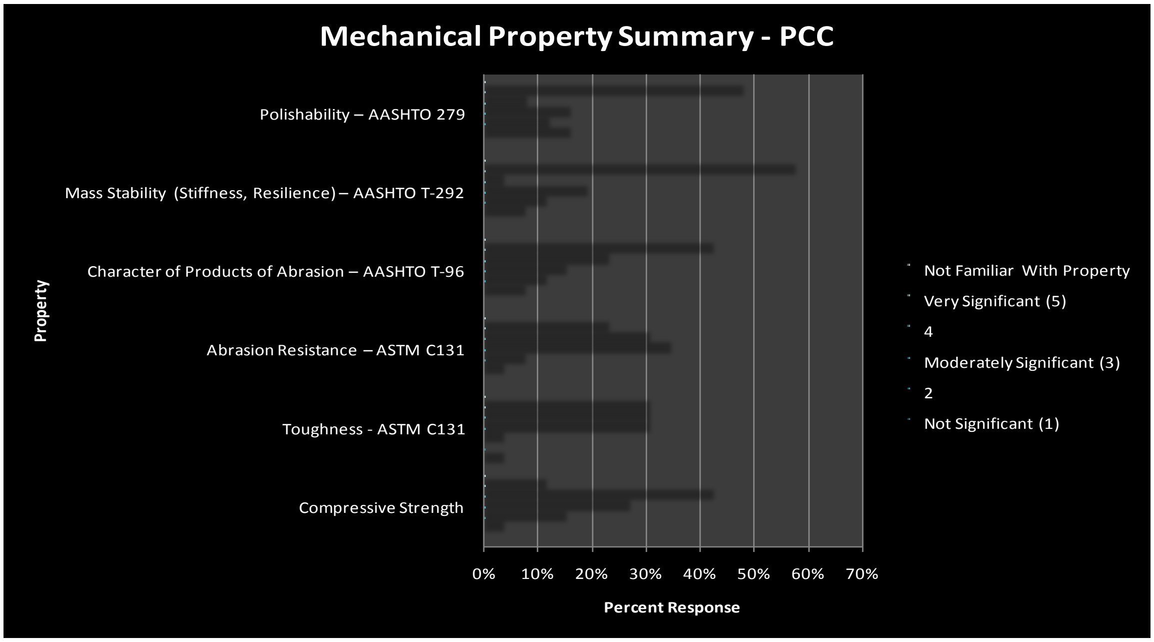


Figure C.5 Mechanical Property Summary–PCC

Table C.7 Summary of Mechanical Property Results for PCC

Portland Cement	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Compressive Strength	0.0%	3.8%	15.4%	26.9%	42.3%	11.5%	4.2
Toughness - ASTM C131	3.8%	0.0%	3.8%	30.8%	30.8%	30.8%	4.2
Abrasion Resistance – ASTM C131	0.0%	3.8%	7.7%	34.6%	30.8%	23.1%	4.2
Character of Products of Abrasion – AASHTO T-96	0.0%	7.7%	11.5%	15.4%	23.1%	42.3%	3.9
Mass Stability (Stiffness, Resilience) – AASHTO T-292	0.0%	7.7%	11.5%	19.2%	3.8%	57.7%	3.5
Polishability – AASHTO 279	0.0%	16.0%	12.0%	16.0%	8.0%	48.0%	3.3

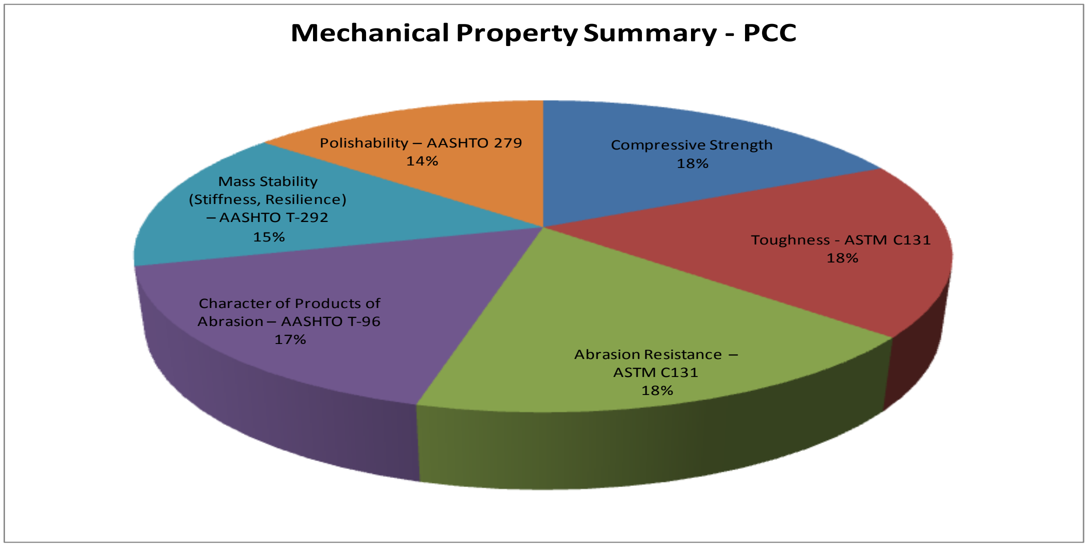


Figure C.6 Mechanical Property Index Summary-PCC

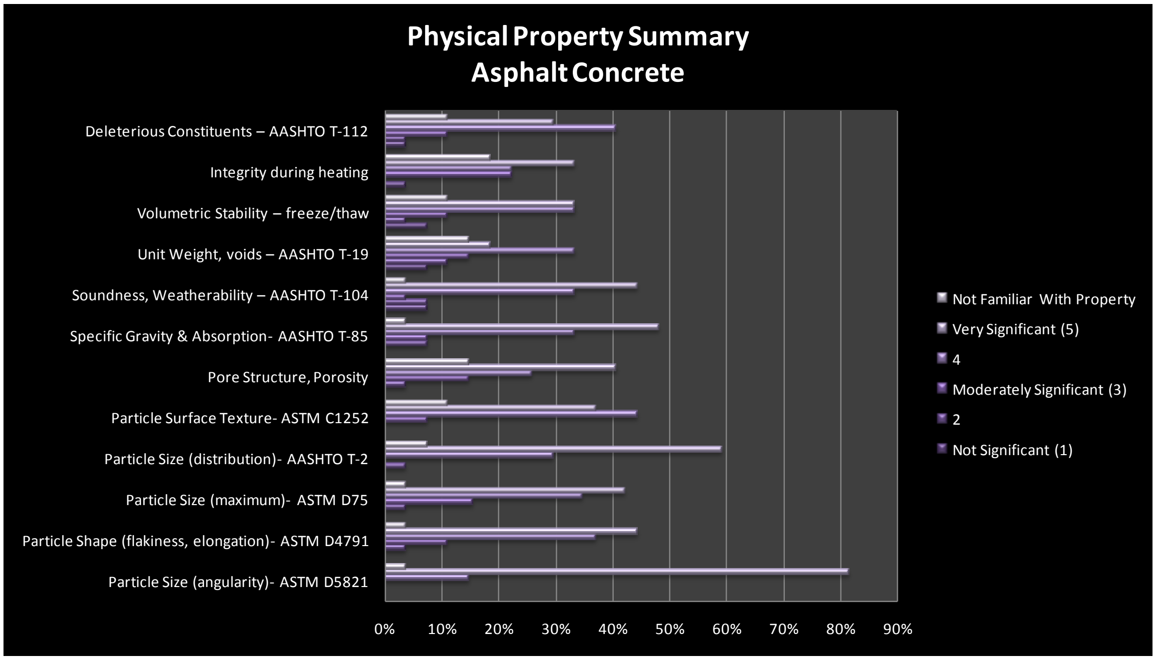


Figure C.7 Physical Property Summary–Asphalt

Table C.8 Summary of Physical Property Results for Asphalt Pavement

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Particle Size (angularity)- ASTM D5821	0.0%	0.0%	0.0%	14.8%	81.5%	3.7%	4.8
Particle Shape (flakiness, elongation)- ASTM D4791	0.0%	3.7%	11.1%	37.0%	44.4%	3.7%	4.3
Particle Size (maximum)- ASTM D75	0.0%	3.8%	15.4%	34.6%	42.3%	3.8%	4.2
Particle Size (distribution)- AASHTO T-2	0.0%	3.7%	0.0%	29.6%	59.3%	7.4%	4.6
Particle Surface Texture- ASTM C1252	0.0%	0.0%	7.4%	44.4%	37.0%	11.1%	4.3
Pore Structure, Porosity	0.0%	3.7%	14.8%	25.9%	40.7%	14.8%	4.2
Specific Gravity & Absorption- AASHTO T-85	0.0%	7.4%	7.4%	33.3%	48.1%	3.7%	4.3
Soundness, Weatherability – AASHTO T-104	7.4%	7.4%	3.7%	33.3%	44.4%	3.7%	4.0
Unit Weight, voids – AASHTO T-19	7.4%	11.1%	14.8%	33.3%	18.5%	14.8%	3.5
Volumetric Stability – freeze/thaw	7.4%	3.7%	11.1%	33.3%	33.3%	11.1%	3.9
Integrity during heating	3.7%	0.0%	22.2%	22.2%	33.3%	18.5%	4.0
Deleterious Constituents – AASHTO T-112	3.7%	3.7%	11.1%	40.7%	29.6%	11.1%	4.0

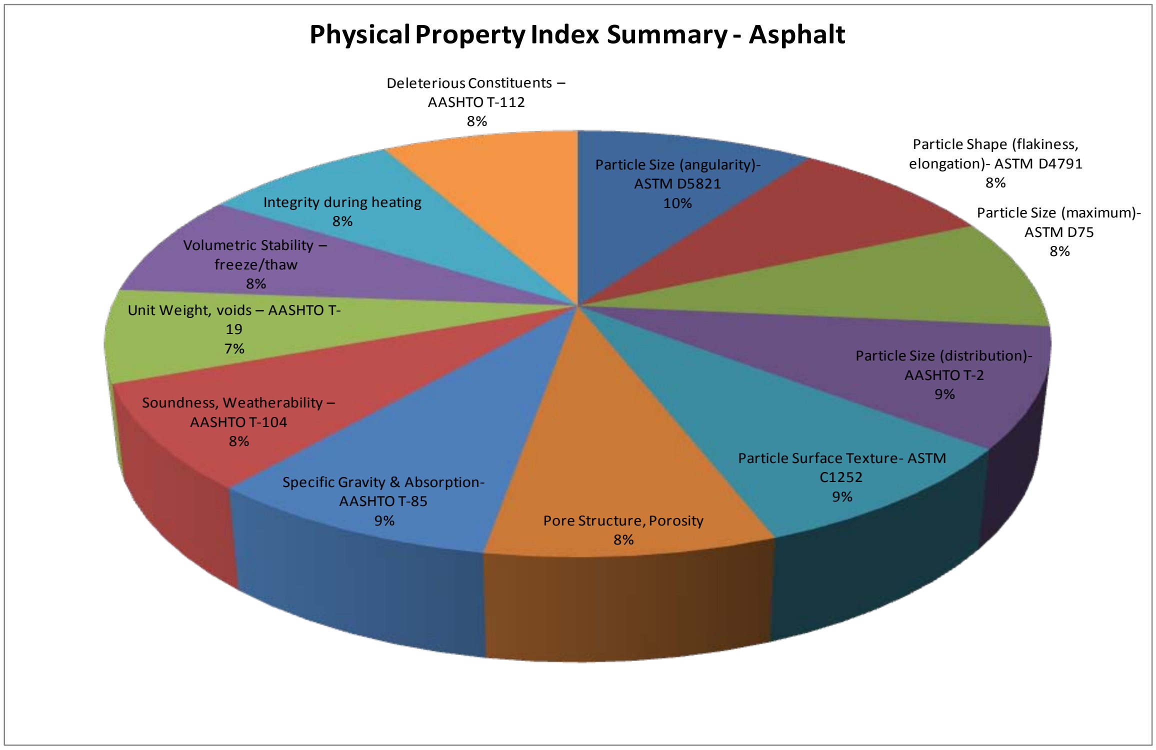


Figure C.8 Physical Property Index Summary-Asphalt

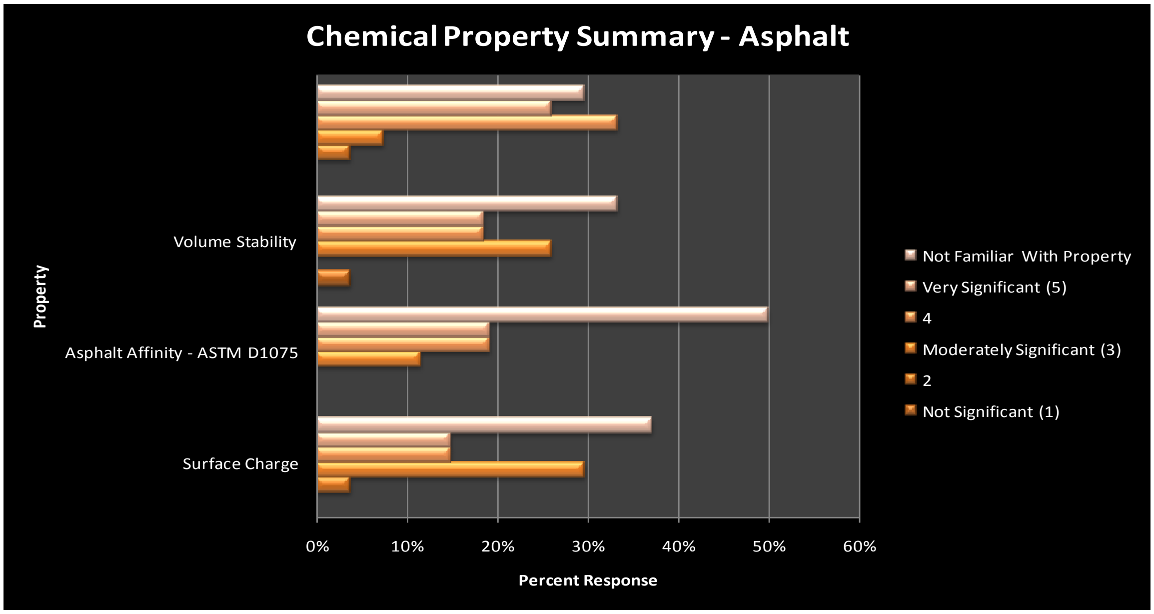


Figure C.9 Chemical Property Summary–Asphalt

Table C.9 Summary of Chemical Property Results for Asphalt Pavement

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Surface Charge	0.0%	3.7%	29.6%	14.8%	14.8%	37.0%	3.6
Asphalt Affinity - ASTM D1075	0.0%	0.0%	11.5%	19.2%	19.2%	50.0%	4.2
Volume Stability	3.7%	0.0%	25.9%	18.5%	18.5%	33.3%	3.7
Coatings	0.0%	3.7%	7.4%	33.3%	25.9%	29.6%	4.2

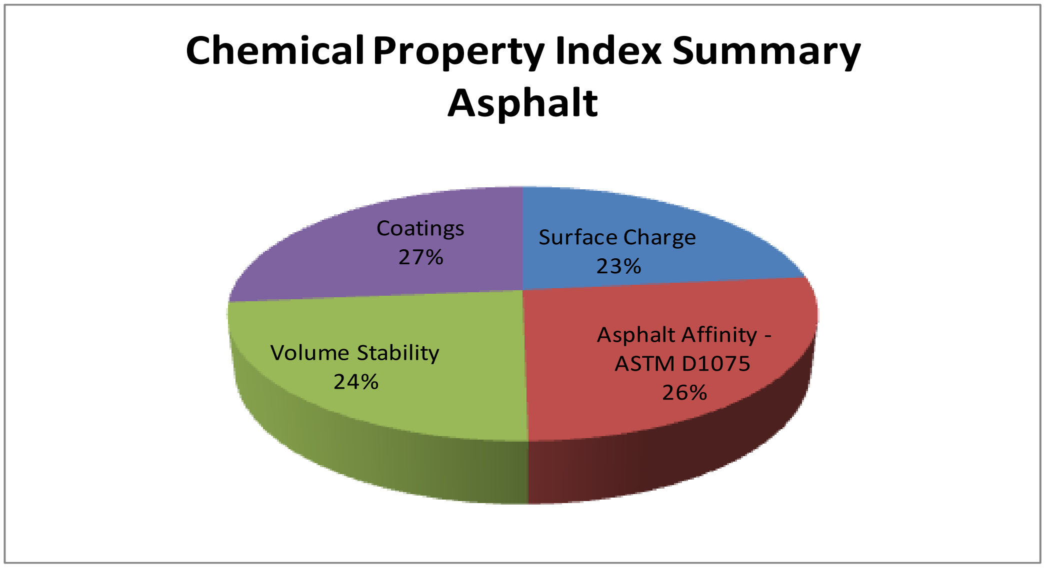


Figure C.10 Chemical Property Index Summary-Asphalt

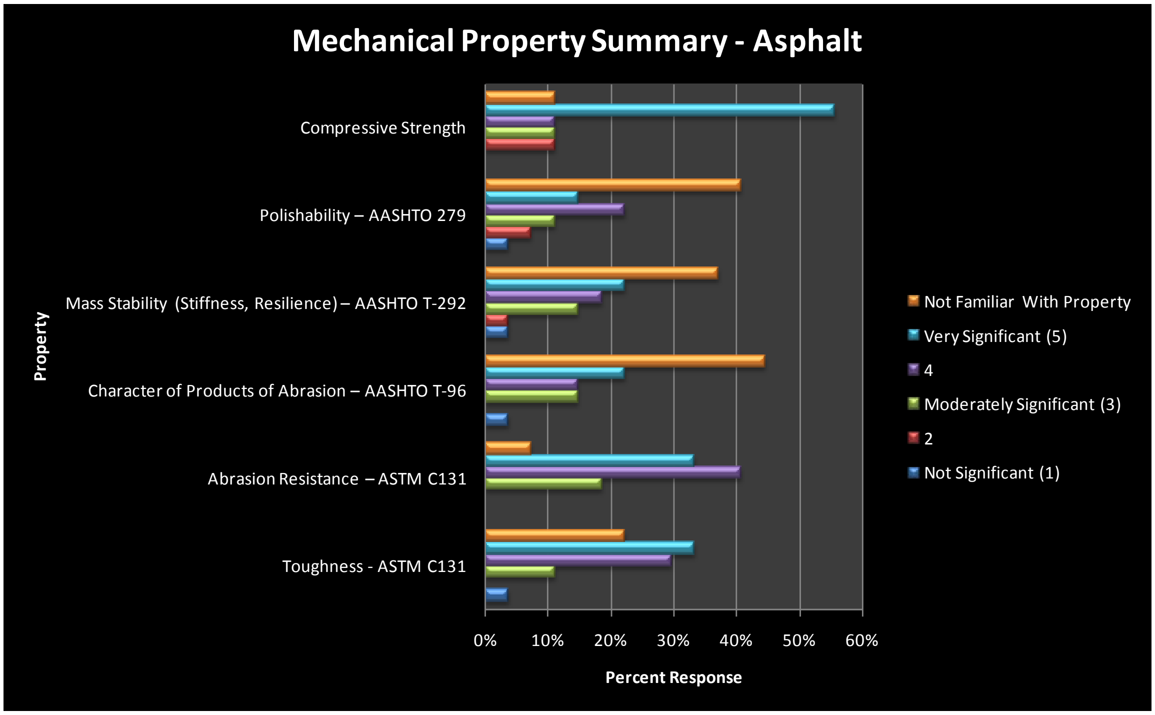


Figure C.11 Mechanical Properties Summary–Asphalt

Table C.10 Summary of Mechanical Property Results for Asphalt

Asphalt Concrete	Not Significant (1)	2	Moderately Significant (3)	4	Very Significant (5)	Not Familiar With Property	Rating Index
Toughness - ASTM C131	3.7%	0.0%	11.1%	29.6%	33.3%	22.2%	4.1
Abrasion Resistance – ASTM C131	0.0%	0.0%	18.5%	40.7%	33.3%	7.4%	4.2
Character of Products of Abrasion – AASHTO T-96	3.7%	0.0%	14.8%	14.8%	22.2%	44.4%	3.9
Mass Stability (Stiffness, Resilience) – AASHTO T-292	3.7%	3.7%	14.8%	18.5%	22.2%	37.0%	3.8
Polishability – AASHTO 279	3.7%	7.4%	11.1%	22.2%	14.8%	40.7%	3.6
Compressive Strength	0.0%	11.1%	11.1%	11.1%	55.6%	11.1%	4.3

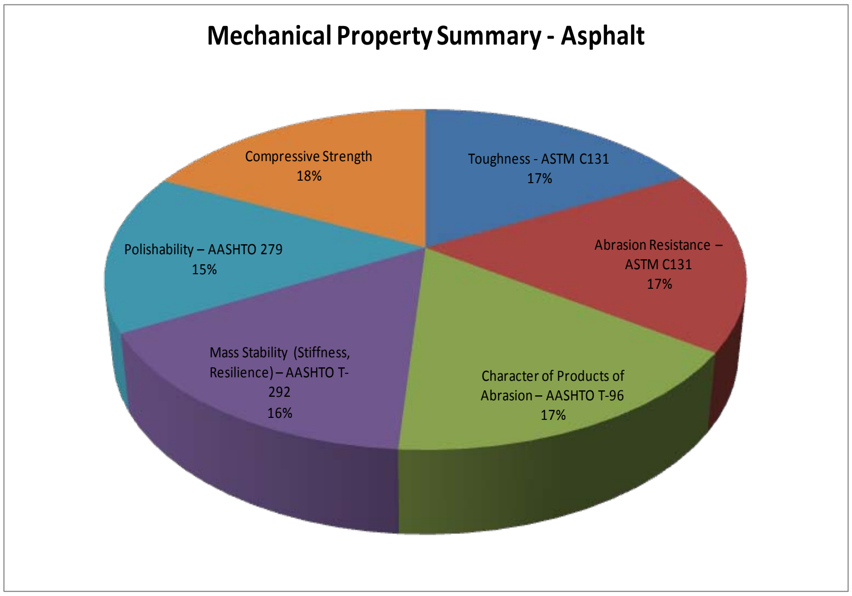


Figure C.12 Mechanical Property Index Summary-Asphalt

Table C.11 Listed Properties for PCC Aggregate

	Repetitions	% Question Response
Soundness (Freeze/Thaw)	8	80%
Strength	2	20%
Particle Size	2	20%
Spall Quality	1	10%
Absorption	4	40%
Reactivity	3	30%
Gradation	1	10%
Durability	2	20%
Angularity	1	10%
Quality	1	10%

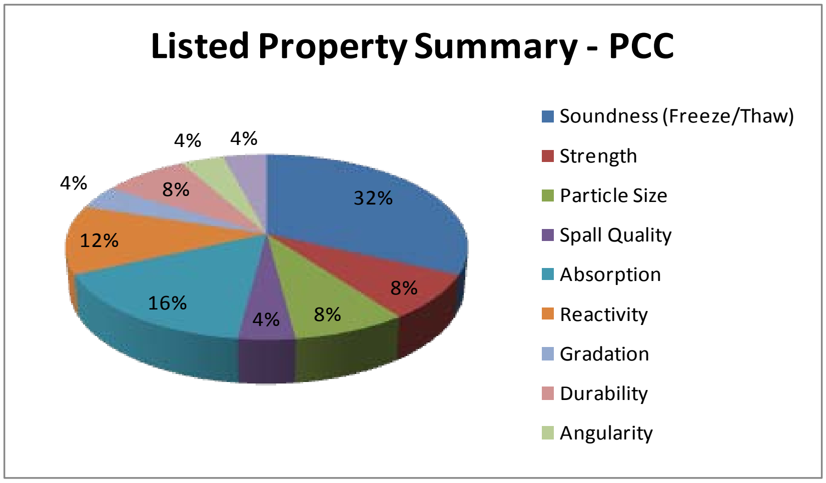


Figure C.13 Listed Properties for PCC Aggregates

Table C.12 Listed Properties for Asphalt Aggregate

	Repetitions	% Question Response
Soundness (Freeze/Thaw)	4	40%
Strength	2	20%
Absorption	4	40%
Particle Size	2	20%
Asphalt Absorption	1	10%
Specific Gravity	3	30%
Spall quality	1	10%
LAR Durability	3	30%
Angularity	4	40%
Deleterious Content	1	10%
Voids	1	10%
Shape	2	20%
Surface Texture	1	10%
Gradation	1	10%

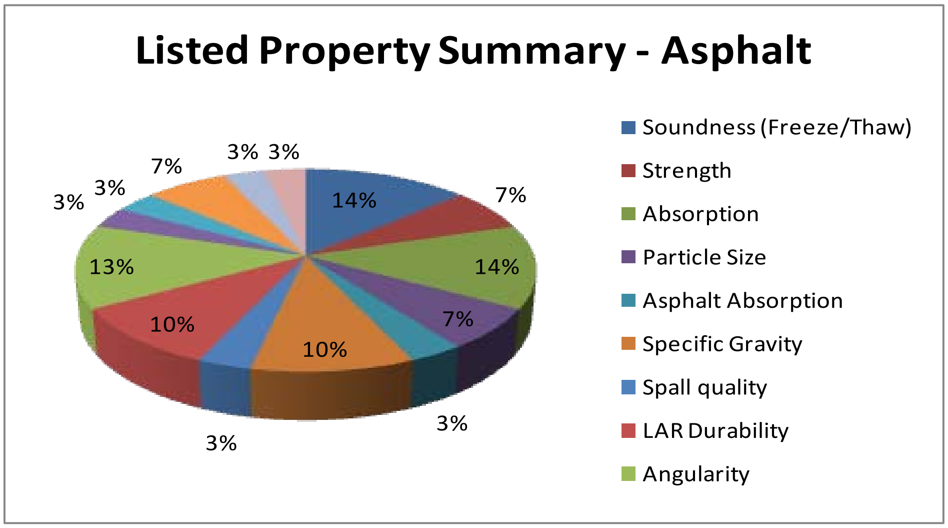


Figure C.14 Listed Properties for Asphalt Aggregates

Appendix D: Analysis of PWL for Aggregate Properties

Table D.1 Statistics for Bituminous Aggregate

BITUMINOUS		BA % Total Samp Spall (Type 31,32,61,62)	Los Angeles Rattler (Type B) Pct Loss	Los Angeles Rattler (Type C) Pct Loss	Mag Sulfate Percent Lost 1/2" to 3/8"	Mag Sulfate Percent Lost 3/4" to 1/2"	Mag Sulfate Percent Lost 3/8" to #4	Mag Sulfate Total Percent Lost	Pct Shale - Weighted Average
Max Percent		**5**	**40**	**40**	**18**	**14**	**23**	**18**	**5**
1	**AVERAGE**	0.17	16.70	15.00	4.26	1.56	5.36	5.00	0.00
	number of data	38.00	4.00	1.00	4.00	4.00	4.00	1.00	
	STDEV	0.40	2.26	0.00	3.07	0.66	2.99	#DIV/0!	0.00
	PWL	100.00%	100.00%		100.00%	100.00%	100.00%	#DIV/0!	#NUM!
2	**AVERAGE**	0.12	20.71		3.91	2.40	5.25	3.50	0.18
	number of data	50.00	8.00	0.00	6.00	6.00	6.00	6.00	
	STDEV	0.22	5.02		2.52	2.18	3.52	2.43	0.57
	PWL	100.00%	99.99%		100.00%	100.00%	100.00%	100.00%	100.00%
3	**AVERAGE**	0.40	18.64	18.23	2.55	1.31	3.48	10.00	0.10
	number of data	68.00	6.00	4.00	8.00	6.00	7.00	1.00	56.00
	STDEV	0.74	2.70	2.60	4.09	1.97	7.08	#DIV/0!	0.09
	PWL	100.00%	100.00%	100.00%	99.99%	100.00%	99.71%	#DIV/0!	100.00%
4	**AVERAGE**	0.47	#DIV/0!		5.48	1.90	5.82	#DIV/0!	0.36
	number of data	43.00	0.00	0.00	6.00	5.00	6.00	0.00	94.00
	STDEV	0.64	#DIV/0!	#DIV/0!	3.12	0.58	2.43	#DIV/0!	0.52
	PWL	100.00%	#DIV/0!		100.00%	100.00%	100.00%	#DIV/0!	100.00%
6	**AVERAGE**	1.56	32.74	32.55	13.29	7.83	16.15	#DIV/0!	0.77
	number of data	91.00	158.00	252.00	274.00	134.00	321.00	0.00	30.00
	STDEV	1.08	3.31	3.84	8.81	3.32	8.13	#DIV/0!	0.74
	PWL	99.93%	98.60%	97.40%	70.37%	96.82%	80.02%	#DIV/0!	100.00%
7	**AVERAGE**	0.28	22.00	27.65	3.77	1.09	7.25	3.83	0.17
	number of data	61.00	17.00	7.00	12.00	10.00	14.00	6.00	112.00
	STDEV	0.89	4.37	5.85	4.36	1.85	6.43	4.54	0.68
	PWL	100.00%	100.00%	98.26%	99.94%	100.00%	99.28%	99.91%	100.00%

Table D.1 Continue: Statistics for Bituminous Aggregate Properties

BITUMINOUS		BA % Total Samp Spall (Type 31,32,61,62)	Los Angeles Rattler (Type B) Pct Loss	Los Angeles Rattler (Type C) Pct Loss	Mag Sulfate Percent Lost 1/2" to 3/8"	Mag Sulfate Percent Lost 3/4" to 1/2"	Mag Sulfate Percent Lost 3/8" to #4	Mag Sulfate Total Percent Lost	Pct Shale - Weighted Average
8	**AVERAGE**	0.36	23.00		9.30	4.45	15.29	#DIV/0!	0.17
	number of data	7.00	2.00	0.00	3.00	3.00	4.00	0.00	14.00
	STDEV	0.21	4.24		2.43	2.04	4.05	#DIV/0!	0.17
	PWL	100.00%	100.00%		99.98%	100.00%	97.17%	#DIV/0!	100.00%
METRO	**AVERAGE**	0.44	18.00	17.85	4.14	2.10	6.75	5.00	0.28
	number of data	26.00	8.00	4.00	13.00	8.00	11.00	1.00	30.00
	STDEV	0.70	1.74	4.64	1.41	0.58	1.92	#DIV/0!	0.58
	PWL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	#DIV/0!	100.00%
COMBINED	**AVERAGE**	0.61	29.95	31.92	11.85	6.41	14.84	4.27	0.26
	STDEV	0.94	6.29	4.76	8.83	3.94	8.45	3.49	0.58
	PWL	100.00%	94.50%	95.54%	75.72%	97.29%	83.29%	100.00%	100.00%

Table D.2 PWL for Bituminous Aggregate Properties

	BITUMINOUS PWL										
District	BA % Total Samp Spall (Type 31,32,61,62)	Los Angeles Rattler (Type B) Pct Loss	Los Angeles Rattler (Type C) Pct Loss	Mag Sulfate Percent Lost 1/2" to 3/8"	Mag Sulfate Percent Lost 3/4" to 1/2"	Mag Sulfate Percent Lost 3/8" to #4	Pct Shale - Weighted Average	Percent Shale in Sand	WA % BA Spall +4	Average PWL by District	Stdev
1	100.00%	100.00%		100.00%	100.00%	100.00%		100.00%	100.00%	99.99995%	0.00014%
2	100.00%	99.99%		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	99.99925%	0.00212%
3	100.00%	100.00%	100.00%	99.99%	100.00%	99.71%	100.00%	100.00%	100.00%	99.96675%	0.09677%
4	100.00%			100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	99.99957%	0.00113%
6	99.93%	98.60%	97.40%	70.37%	96.82%	80.02%	100.00%	100.00%	87.42%	92.28302%	10.714%
7	100.00%	100.00%	98.26%	99.94%	100.00%	99.28%	100.00%	100.00%	100.00%	99.72079%	0.59529%
8	100.00%	100.00%		99.98%	100.00%	97.17%	100.00%	100.00%	100.00%	99.64362%	0.99961%
metro	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	99.99999%	0.00003%
combined	100.00%	94.50%	95.54%	75.72%	97.29%	83.29%	100.00%	100.00%	99.71%	94.00459%	8.68210%

Table D.3 Statistics for Concrete Aggregate Properties

CONCRETE		LAR	Mag Sulfate	Pct Carbonate - Weighted Average	Pct Slate - Weighted Average	Pct Soft Rock - Weighted Average	Percent Soft Iron Oxide	WA % Shale +1/2"	WA % Total Spall +4	WA%Total Spall +1/2"
Max Percent		**40.0**	**15.0**	**30.0**	**3.0**	**2.5**	**0.3**	**0.4**	**1.5**	**1.0**
1	**AVERAGE**	16.70	#DIV/0!	0.04	0.00	0.13	0.03	0.00	0.21	0.28
	Number of Data	4.00	0.00	168.00	154.00	158.00	154.00	144.00	168.00	155.00
	STDEV	2.26	#DIV/0!	0.28	0.02	0.29	0.16	0.04	0.42	0.66
	PWL	100.00%	#DIV/0!	100.00%	100.00%	100.00%	95.66%	100.00%	99.88%	86.27%
2	**AVERAGE**	17.65	1.55	19.47	#DIV/0!	0.30	0.00	0.06	0.24	0.23
	Number of Data	3.00	4.00	18.00	0.00	3.00	1.00	8.00	13.00	10.00
	STDEV	5.76	0.87	9.25	#DIV/0!	0.20	#DIV/0!	0.12	0.17	0.29
	PWL	99.99%	100.00%	87.27%	#DIV/0!	100.00%	#DIV/0!	99.78%	100.00%	99.64%
3	**AVERAGE**	20.43	2.25	0.35	0.00	0.09	0.14	0.00	0.19	0.21
	Number of Data	14.00	26.00	46.00	8.00	38.00	17.00	34.00	61.00	53.00
	STDEV	2.51	3.52	0.91	0.00	0.13	0.43	0.00	0.39	0.51
	PWL	100.00%	99.99%	100.00%	#NUM!	100.00%	64.82%	#NUM!	99.96%	94.00%
4	**AVERAGE**	#DIV/0!	#DIV/0!	25.67	#DIV/0!	#DIV/0!	0.10	0.05	0.21	0.15
	Number of Data	0.00	0.00	62.00	0.00	0.00	1.00	22.00	38.00	23.00
	STDEV	#DIV/0!	#DIV/0!	8.05	#DIV/0!	#DIV/0!	#DIV/0!	0.09	0.30	0.24
	PWL	#DIV/0!	#DIV/0!	70.49%	#DIV/0!	#DIV/0!	#DIV/0!	99.99%	100.00%	99.98%
6	**AVERAGE**	30.65	6.22	#DIV/0!	#DIV/0!	0.85	#DIV/0!	0.03	0.12	0.10
	Number of Data	459.00	212.00	0.00	0.00	2.00	0.00	3.00	5.00	4.00
	STDEV	2.83	4.16	#DIV/0!	#DIV/0!	0.92	#DIV/0!	0.06	0.18	0.14
	PWL	99.95%	98.25%	#DIV/0!	#DIV/0!	96.37%	#DIV/0!	100.00%	100.00%	100.00%
7	**AVERAGE**	27.06	5.78	1.78	0.00	0.26	0.00	0.04	0.36	0.22
	Number of Data	7.00	14.00	110.00	20.00	216.00	22.00	231.00	277.00	240.00
	STDEV	2.54	5.61	9.23	0.00	0.50	0.00	0.14	0.51	0.39
	PWL	100.00%	94.98%	99.89%	#NUM!	100.00%	#NUM!	99.48%	98.76%	97.75%

Table D.3 Continue: Statistics for Concrete Aggregate Properties

CONCRETE		LAR	Mag Sulfate	Pct Carbonate - Weighted Average	Pct Slate - Weighted Average	Pct Soft Rock - Weighted Average	Percent Soft Iron Oxide	WA % Shale +1/2"	WA % Total Spall +4	WA%Total Spall +1/2"
Max Percent		**40.0**	**15.0**	**30.0**	**3.0**	**2.5**	**0.3**	**0.4**	**1.5**	**1.0**
8	**AVERAGE**	23.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.09	0.12
	Number of Data	2.00	0.00	5.00	5.00	5.00	5.00	12.00	12.00	12.00
	STDEV	4.24	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.32	0.40
	PWL	100.00%	#DIV/0!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	100.00%	98.56%
METRO	**AVERAGE**	21.32	5.22	15.92	0.10	0.11	0.05	0.04	0.33	0.32
	Number of Data	5.00	18.00	467.00	5.00	943.00	166.00	354.00	1667.00	1077.00
	STDEV	3.26	2.12	9.58	0.10	0.16	0.09	0.15	0.31	0.41
	PWL	100.00%	100.00%	92.92%	100.00%	100.00%	99.76%	99.08%	99.99%	95.22%
COMBINED	**AVERAGE**	29.99	5.69	10.96	0.00	0.14	0.04	0.03	0.32	0.29
	STDEV	3.79	4.24	11.65	0.03	0.27	0.15	0.13	0.35	0.44
	PWL	99.58%	98.60%	94.90%	100.00%	100.00%	95.72%	99.78%	99.96%	94.64%

Table D.4 PWL for Concrete Aggregate Properties

CONCRETE PWL											
District	LAR	Mag Sulfate	Pct Carbonate - Weighted Average	Pct Slate - Weighted Average	Pct Soft Rock - Weighted Average	Percent Soft Iron Oxide	WA % Shale +1/2"	WA % Total Spall +4	WA%Total Spall +1/2"	Average PWL by District	Stdev
1	100.00%		100.00%	100.00%	100.00%	95.66%	100.00%	99.88%	86.27%	97.73%	4.87%
2	99.99%	100.00%	87.27%		100.00%		99.78%	100.00%	99.64%	98.10%	4.78%
3	100.00%	99.99%	100.00%		100.00%	64.82%		99.96%	94.00%	94.11%	13.11%
4			70.49%				99.99%	100.00%	99.98%	92.62%	14.75%
6	99.95%	98.25%			96.37%		100.00%	100.00%	100.00%	99.09%	1.51%
7	100.00%	94.98%	99.89%		100.00%		99.48%	98.76%	97.75%	98.70%	1.83%
8	100.00%							100.00%	98.56%	99.52%	0.83%
metro	100.00%	100.00%	92.92%	100.00%	100.00%	99.76%	99.08%	99.99%	95.22%	98.55%	2.62%
combined	1.00	0.99	0.95	1.00	1.00	0.96	1.00	1.00	0.95	98.13%	2.34%

Appendix E: Coarse Aggregate Survey

E.1. Survey Email

ATTENTION: Please forward this message to any engineers, researchers, geologists, TRB members etc that might knowledgeable in the area and willing to take the survey.

North Dakota State University Civil Engineering Department is conducting research on coarse aggregate properties in paving applications. The project's main goal is to designate property-based specifications on aggregate properties. Your participation is greatly appreciated. The survey asks you to rate the importance of physical, mechanical and chemical properties for aggregate usage in bituminous and concrete pavements. If you are not familiar with the property you are rating you may check that option in the final column. Please take a minute to fill out the survey. We will collect responses until January 25, 2008

Here is a link to the survey:

http://www.surveymonkey.com/s.aspx?sm=3c31pZAp90y1y7dogtNT1A_3d_3d

Thank you for your participation!

The Research Team
North Dakota State University

E.2. Survey

The following survey asks you to rate the importance of physical, mechanical and chemical properties for aggregate usage in bituminous and concrete pavements. If you are not familiar with the property you are rating you may check that option in the final column.

1. One a scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following physical properties of aggregates in Portland cement concrete?

		Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Particle Size (angularity) – ASTM D5821							
Particle Shape (flakiness, elongation) – ASTM D4791							
Particle Size (Maximum) – ASTM D75							
Particle Size (Distribution) – AASHTO T-2							
Particle Surface Texture - ASTM C1252							
Pore Structure, Porosity							
Specific Gravity & Absorption – AASHTO T-85							
Soundness, Weatherability – AASHTO T-104							
Unit Weight, voids – AASHTO T-19							
Volumetric Stability – thermal							
Volumetric Stability – wet/dry							
Volumetric Stability – freeze/thaw							
Deleterious Constituents – AASHTO T-112							

Other (please specify):

Figure E.1 - Survey

2. One a scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following chemical properties of aggregates in Portland cement concrete?

		Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Solubility							
Reactivity to Chemicals – AASHTO M-80							
Volume Stability							
Coatings							

Other (please specify):

3. One a scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following mechanical properties of aggregates in Portland cement concrete?

		Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Compressive Strength							
Toughness - ASTM C131							
Abrasion Resistance – ASTM C131							
Character of Products of Abrasion – AASHTO T-96							
Mass Stability (Stiffness, Resilience) – AASHTO T-292							
Polishability – AASHTO 279							

Other (please specify):

Figure E.1 Cont. - Survey

1. One a scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following physical properties of aggregates in Asphalt concrete?

	Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Particle Size (angularity) – ASTM D5821						
Particle Shape (flakiness, elongation) – ASTM D4791						
Particle Size (Maximum) – ASTM D75						
Particle Size (Distribution) – AASHTO T-2						
Particle Surface Texture - ASTM C1252						
Pore Structure, Porosity						
Specific Gravity & Absorption – AASHTO T-85						
Soundness, Weatherability – AASHTO T-104						
Unit Weight, voids – AASHTO T-19						
Volumetric Stability – freeze/thaw						
Integrity during heating						
Deleterious Constituents – AASHTO T-112						

Other (please specify):

Figure E.1 Cont. - Survey

2. One scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following chemical properties of aggregates in Asphalt concrete?

	Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Surface Charge						
Asphalt Affinity – ASTM D1075						
Volume Stability						
Coatings						

Other (please specify):

3. One a scale of 1-5 with 1 being not significant and 5 being very significant, how would you rank the following mechanical properties of aggregates in Asphalt concrete?

	Not Significant		Moderately Significant		Very Significant	Not Familiar With Property
Toughness - ASTM C131						
Abrasion Resistance – ASTM C131						
Character of Products of Abrasion – AASHTO T-96						
Mass Stability (Stiffness, Resilience) – AASHTO T-292						
Polishability – AASHTO 279						
Compressive Strength						

Other (please specify):

Figure E.1 Cont. - Survey