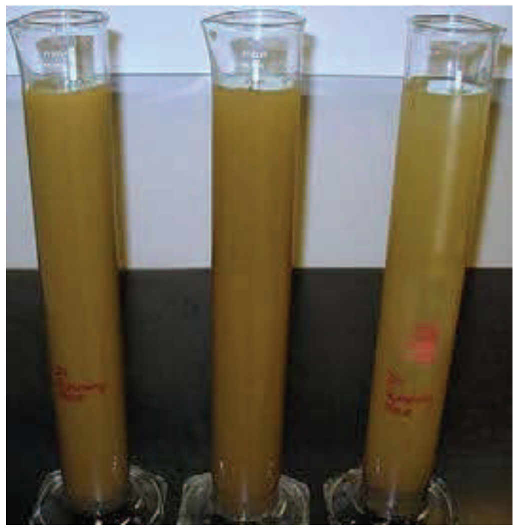
Alaska Department of Transportation & Public Facilities
Alaska University Transportation Center

UAF INE AUTC

Use of the Micro-Deval Test for Assessing Alaska Aggregates



Juanyu Liu, Ph.D., P.E.
Anthony Mullin
Jason Rein

December 2012

Prepared By:

Alaska University Transportation Center
Duckering Building Room 245
P.O. Box 755900
Fairbanks, AK 99775-5900

Alaska Department of Transportation
Research, Development, and Technology Transfer
2301 Peger Road
Fairbanks, AK 99709-5399

INE/ AUTC 12.14

FHWA-AK-RD-12-22

REPORT DOCUMENTATION PAGE			Form approved OMB No.
Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-1833), Washington, DC 20503			
1. AGENCY USE ONLY (LEAVE BLANK) FHWA-AK-RD-12-22	2. REPORT DATE August 2013	3. REPORT TYPE AND DATES COVERED Final Report (7/2010-6/2012)	
4. TITLE AND SUBTITLE Use of the Micro-Deval Test for Assessing Alaska Aggregates			5. FUNDING NUMBERS DTRT06-G-0011 AUTC 410009 T2-10-08
6. AUTHOR(S) Juanyu Liu, Ph.D., P.E. Anthony Mullin Jason Rein			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Alaska University Transportation Center P.O. Box 755900 Fairbanks, AK 99775-5900			8. PERFORMING ORGANIZATION REPORT NUMBER INE/AUTC 12.14
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Innovative Technology Administration (RITA) (USDOT) 1200 New Jersey Ave, SE, Washington DC 20590 Fairbanks North Star Borough PO Box 71267, Fairbanks, AK 99707-1267			10. SPONSORING/MONITORING AGENCY REPORT NUMBER FHWA-AK-RD-12-22
11. SUPPLENMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT No restrictions			12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Choosing the right material is half the battle in building roads for Alaska. The extreme conditions typical to cold regions require a durable, abrasion resistant and freeze-thaw resistant aggregate. Recently the state has been wondering exactly how effective and accurate its selection methods are. Currently there is limited information regarding the Alaska Testing Method 313 (sometimes known as the Washington degradation test) used by ADOT&PF to test abrasion and degradation value. This project will examine a new testing method, the Micro-Deval test — a wet test of how aggregates degrade when tumbling in a rotating steel drum with water and steel balls — to determine whether it can provide safe and cost-effective aggregate testing with reproducible results that correlate with field performance. The Micro-Deval test is easy, safe, and less costly to perform than traditional testing methods. It is suitable for smaller equipment, requires smaller sample quantities and uses a simple procedure. This study will provide data and recommendations on the suitability of the
Micro-Deval test as a as a rapid, simple, repeatable and inexpensive technique for assessing the durability of Alaska aggregates.

14- KEYWORDS: Aggregates (Rbmddc), Aggregate gradation (Gbbmbc),			15. NUMBER OF PAGES
			16. PRICE CODE N/A
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A

NSN 7540-01-280-5500

STANDARD FORM 298 (Rev. 2-98)
Prescribed by ANSI Std. 239-18 298-1

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Author's Disclaimer

Opinions and conclusions expressed or implied in the report are those of the author. They are not necessarily those of the Alaska DOT&PF or funding agencies.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

ACKNOWLEDGMENT

The authors gratefully acknowledge AKDOT&PF personnel in regional materials labs for their great help to collect aggregates and laboratory testing data. They are Heidi Schaefer, Jeffrey Hart, Suzanne Janke, Andrew Culley, Todd Hughes, Steve Saboundjian, Leo Woster, Newton Bingham, and Bruce Brunette. Acknowledgement of financial support and matching dollars for this project is extended to the AKDOT&PF, as well as the Research and Innovative Technology Administration (RITA) at the United States Department of Transportation through the Alaska University Transportation Center (AUTC).

EXECUTIVE SUMMARY

Aggregate used in the construction of roads must be durable, abrasion resistant, and freeze-thaw resistant in order to perform well in a pavement or as base course. Tests for properly characterizing aggregate durability are critical. Currently, AKDOT&PF Standard Specifications for Highway Construction (2004) specifies percentage of Los Angeles (LA) wear by the LA abrasion test and degradation value by Alaska Testing Method (ATM) 313 (or Washington degradation test) along with other parameters for evaluating durability of aggregates for asphalt concrete pavements and base courses. The main objectives of this project are to evaluate the feasibility of using the Micro-Deval test to assess the durability of Alaskan base course aggregates in pavement construction, and to explore the potential of utilizing it as a better alternative to the current Washington degradation test.

In this study, a thorough literature review was first conducted to summarize research findings, performance data, current practices, and other information relative to the testing and evaluation of the durability of aggregates used in base course. A variety of aggregates representing all physiographic regions in Alaska was then collected. The Micro-Deval, LA abrasion, sodium sulfate, and Washington degradation tests were conducted and compared. The results were used to examine how well these methods correlate with each other in terms of assessing aggregate durability and degradation.

The Micro-Deval test was found from the literatures to be a good indicator of aggregate durability, toughness, and abrasion resistance. It considers both degradations due to mechanical abrasion and weathering, which better simulates field performance during construction and under traffic and

undesirable environment. A number of state DOTs have been implementing specification requirement of Micro-Deval loss values for quality aggregates.

Within the scope of this study (16 aggregates from three regions of Alaska), the Micro-Deval test data had lower values of the coefficient of variation (COV) and standard deviation (SD) than LA abrasion test. Similar conclusions that the Micro-Deval test is a reliably repeatable procedure reported in the literatures (Hunt 2001; Nyland 2005; Jayawickrama et al. 2007). A more precise method of comparing test result data was achieved by normalizing each test result to its standard limiting criteria to pass durability. The Micro-Deval test was generally in high agreement with the other test methods regarding an overall pass/fail determination, and a best correlation was found between the Micro-Deval and Washington degradation tests.

The Micro-Deval test is a rapid, simple test — takes a couple of hours to complete. Smaller equipment size, lower sample quantities and a simpler procedure make this method easier and less costly to perform than traditional methods.

Our study along with practices in other states confirmed the feasibility of using Micro-Deval test to assess the durability of Alaskan base course aggregates in pavement construction. However, other aggregate tests had a long running track record which allowed for contractors as well as AKDOT&PF personnel to feel comfortable with results related to actual performance. It is recommended that the Micro-Deval test be an additional test for a period of time. This will allow for a history of performance to be built as well as a comfort level with the results. Tests of more Alaskan aggregates are also needed to facilitate the implementation of specification requirement of Micro-Deval loss values for quality aggregates.

As for the Washington degradation test, it has been used in only a few states according to current states practices. DOT materials engineers' experience also indicated the Washington degradation test results had more variations thus poorer repeatability than other tests. It is a clay leaching test dependent on surface area of charge, and finer samples will indicate more degradation. It indeed measures the size of fines (how fine) but not quantity of fines (how much). It is suggested the Micro-Deval test along with current LA abrasion and sodium sulfate tests be used to provide a more reliable assessment of Alaskan aggregates’ durability.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

Aggregate used in the construction of roads must be durable, abrasion resistant, and freeze-thaw resistant in order to perform well in a pavement or as base course. In this study, a variety of aggregates representing all physiographic regions in Alaska was collected. The Micro-Deval, Los Angeles (LA) abrasion, sodium sulfate, and Washington degradation tests were conducted and compared. The results were used to examine how well these methods correlate with each other in terms of predicting aggregate durability and degradation. Findings were further summarized from which recommendations were provided regarding whether the Micro-Deval test will serve as a better alternative to the Washington degradation test used by AKDOT&PF to evaluate the quality of Alaska aggregates for use in pavement construction.

PROBLEM STATEMENT

Aggregates must be tough and abrasion resistant to prevent crushing, degradation, and disintegration when stockpiled, fed through an asphalt plant, placed with a paver, compacted with rollers, and subjected to traffic loadings (Wu et al. 1998; Rangaraju and Edlinski 2008). In addition to toughness and abrasion resistance, aggregates must be resistant to breakdown or disintegration when subjected to wetting and drying and/or freezing and thawing.

Tests for properly characterizing aggregate durability are critical. Currently, AKDOT&PF Standard Specifications for Highway Construction (2004) specifies percentage of LA wear by the LA abrasion test (AASHTO T96) and degradation value by Alaska Testing Method (ATM) 313 (or Washington degradation test) along with other parameters for evaluating durability of base course aggregates for asphalt concrete pavements. However, there is limited information regarding if these tests provide safe and cost-effective design; if the test results are reproducible; and if the results have good correlations with field performance.

The Micro-Deval test is a wet test of how aggregates degrade when tumbled in a rotating steel drum with water and steel balls. Compared with the Washington degradation test, Micro-Deval test considers both degradations due to mechanical abrasion and weathering, which better simulates field performance during construction and under traffic and undesirable environment. In several National Cooperative Highway Research Program (NCHRP) studies (Kandhal and Parker 1998; Saeed et al. 2001; Prowell et al. 2005), the Micro-Deval test was found to be a good indicator of aggregate 1.) durability, 2.) toughness, and 3.) abrasion resistance demonstrating the best correlation with field performance. The Micro-Deval test is also easy, safe and less costly to perform with small equipment size, low sample quantities and a simple procedure. Therefore, there is a need to evaluate the feasibility of using Micro-Deval test to assess the durability of Alaskan aggregates in pavement construction. Efforts are also needed to explore the potential of utilizing it as a better alternative to the current Washington degradation test used by AKDOT&PF to evaluate the quality of Alaska aggregates.

OBJECTIVES

The main objective of this project is to investigate whether the Micro-Deval test will serve as a better alternative to the current abrasion and degradation tests (i.e. Washington degradation test) used by AKDOT&PF to evaluate the quality of Alaskan base course aggregates for use in pavement construction.

RESEARCH METHODOLOGY

To achieve the objectives of this study, the following major tasks were conducted:

- Task 1: Literature Review
- Task 2: Aggregates Collection and Tests
- Task 3: Data Processing and Analyses
- Task 4: Conclusions and Recommendations

Task 1: Literature Review

The purpose of this task was to collect and review relevant domestic and foreign literature, research findings, performance data, current practices, and other information relative to the testing, and evaluation of the durability of aggregates used in base course. These test procedures are further evaluated on the basis of performance predictability, accuracy, practicality, complexity, precision, and cost. This task is documented in Chapter II.

Task 2: Aggregates Collection and Tests

16 aggregate sources from three regions in Alaska: Central, Northern, and Southeast Regions for base course were identified for the study. The Micro-Deval and other aggregate degradation tests (such as Washington degradation, LA abrasion, and sodium sulfate resistance tests) were conducted on all source samples. Other tests performed included sieve analysis, hydrometer test, and sand equivalent test. Chapter III describes the work in this task.

Task 3: Data Processing and Analyses

Test results were compared and statistically analyzed. The similarities and difference between the different aggregate durability and degradation tests were examined. The results were compared with the specifications for aggregates in base course construction stated in AKDOT&PF Standard Specifications for Highway Construction (2004) as well. Chapter III presents the work in this task.

Task 4: Conclusion and Recommendations

As presented in chapter IV, this task leads to a summary of research findings as well as recommendations on whether the Micro-Deval test will provide better, timelier, and more repeatable information about the quality of an aggregate than the Washington degradation test.

CHAPTER II

LITERATURE REVIEW

Aggregate is one of the most widely used construction materials. The key aspect of aggregate quality is its durability, or its ability to withstand the stresses to which it is subjected during production, transport, and placement and throughout its intended service life. Primary stressors during production, transport, and placement include impact and abrasion such as freezing and thawing cycles, wetting and drying cycles, traffic abrasion, and tire wears, etc. (Hossain et al. 2007).

Various test methods related to aggregate durability have been used by state transportation agencies. The LA abrasion test (a dry test) is used by the great majority; however, a number also indicated use of some type of wet abrasion or attrition procedure including aggregate impact value, aggregate crushing value, gyratory degradation, durability index, Washington degradation, Idaho degradation, Micro-Deval, etc. (Saeed et al. 2001). In Alaska, LA abrasion test, Washington degradation test along with sodium and magnesium sulfate soundness test have been used to characterize aggregate durability (toughness/abrasion resistance and soundness) (AKDOT&PF 2004 Table 703_1 for Base Course). Also in Alaska for special cases the Nordic Abrasion test (ATM 312) is sometimes used for aggregates in a HMA wearing course. This chapter intends to summarize research findings, performance data, current practices, and other information relative to the testing and evaluation of the durability of aggregates used in base course.

LA ABRASION TEST

The ASTM summary of the LA abrasion for small coarse aggregate (ASTM C 131-06, AASHTO T96) describes it as a test that measures degradation of mineral aggregates from abrasion, impact, and grinding. Most states in the

U.S., including Alaska, use the LA abrasion test as a measure of aggregate durability. The LA abrasion test was developed in the mid 1920's by the Municipality of Los Angeles, CA (Kandhal and Parker 1998). In their study, the LA abrasion test was chosen as a test to measure toughness and abrasion, which are related to raveling, pop-outs and potholing.

The LA abrasion value is one of the source properties (others are sulfate soundness, and deleterious materials) (Brown et al. 2005). Values for the source properties are allowed to be set by the local agencies to account for local material variability. The range for an acceptance value for the LA abrasion from agencies submitting to this report was between 30% and 50% with and the most common value being 40%. Brown et al.'s report (2005) also stated the LA abrasion cannot be run wet. It is difficult to remove the fines to get accurate values. Some aggregate degrades quicker when moisture is present.

WASHINGTON DEGRADATION TEST

Marshall (1967) explained how the Washington degradation test came. All aggregates submitted to the Washington State Department of Highways Materials Commission for approval as a surfacing material underwent a degradation test in addition to other quality tests. The degradation test had been revised several times since the test was first used. Past conventional quality tests on certain Washington aggregate did not provide caution for failure when these aggregates were used in roadways. According to Marshall's study (1967), failures occurred when the aggregates degraded into plastic fines that created a loss of stability in the roadway. The plastic fines were created from the abrasion of aggregates against each other in the presence of water. The Washington degradation test was meant to simulate this action.

L. H. Morgan started research for the Washington Degradation test in 1958 (Marshall 1967). Originally the test used 1000 grams of aggregate sample in a one gallon jar with water. The filled jar was then rolled on a ball mill for one hour. Minus #200 material was washed into a sand equivalent tube with sand equivalent stock solution. At the end of 20 minutes the sediment height was read. A final determination was obtained through a calculation using the material loss through #10 and #200 sieves as shown in Equation 2.1.

$$D = \left[0.3x\left(1.0 - \frac{L_{200}}{L_{10}}\right) + 0.7x\left(\frac{6-.4H}{6+.6H}\right)\right]x100 \qquad (2.1)$$

Where:

D = Degradation Factor,
L_{200} = Grams lost thru #200 sieve,
L_{10} = Grams lost thru #10 sieve, and
H = Height of sediment in tube.

In 1962 the manner of abrading the aggregate was changed from the one-hour rolling to 20 minutes in a Tyler Portable Sieve Shaker. For this version the aggregate was contained in a 7 ½” x 6” plastic canister. The remainder of the test was the same.

The test changed again in 1965 by calculating a degradation value based only on the fines produced (Marshall 1967). There was no requirement to determine the loss through the #10 and #200 sieves. This version is what is used today and shown in Equation 2.2. Both methods, Equations 2.1 and 2.2, were computed simultaneously for two years, and correlation coefficient was 0.98 for 584 samples. The average for this group of samples was 53.9 by Equation 2.1, and 52.9 by Equation 2.2, respectively. The new method realized a greater spread in values and therefore thought to be more discriminatory. Since the average was only slightly above the minimal acceptable level of 50, different values were allowed for various situations. Table 2.1 suggests the minimum degradation factors for the various situations.

$$D = \left[\frac{15 - H}{15 + 1.75H} \right] x100 \quad (2.2)$$

Table 2.1 Minimum degradation factors for various materials (Marshall 1967).

Material	**Min. DegradationFactor**
Crushed surfacing, top course	25
Crushed surfacing, base course & ballast	15
Mineral aggregate for bituminous surface treatment	30
Mineral aggregate for bituminous road mix	30
Mineral aggregate for asphalt concrete:	
Wearing course	30
All other courses	20

Platts and Llyod (1966) performed an evaluation comparing six different aggregate degradation tests, and the goal of their study was to recommend one test that would be most suitable for Alaskan aggregates. The six tests were 1) Oregon air degradation test, 2) California durability test, 3) Washington degradation test, 4) Idaho kneading test, 5) Idaho rattler degradation test, and 6) Alaska degradation test. The evaluation criteria were 1) the validity and reproducibility of results, 2) the time required for completion of the test and simplicity of procedure, and 3) the total cost and adaptability to field laboratory use. A total of 19 projects were selected for investigation. Of the 19, four sites were selected for field performance. The four sites were chosen to represent a different type of material at each site. At each of these locations material was tested at the pit location, after placement, and 1 -12 months after placement. A visual evaluation system was used to provide a correlation between field and laboratory values, as defined in Table 2.2.

Table 2.2 Rating system for aggregate degradation (Platts and Llyod 1966).

Rating	Description

Very Good	No measurable breakage or wearing.
Good	Measurable breakage, but no production of detrimental fines or breakage to the extent that the gradation has altered enough to change any properties intended for the road system.
Fair	The material exhibits a tendency to break easily upon initial placement and compaction but stabilizes and does not wear appreciably upon reaching maximum density. The abrasive effect of traffic causes some fines at the surface.
Poor	The material degrades measurably during placement and compaction and continues to degrade gradually while in service, eventually altering the gradation to the extent of rendering it unsuitable for use as a base course. On road systems where paving is not anticipated, this material is unsuitable as the wearing course.
Very Poor	The material breaks easily upon handling, gradation changes considerably during construction and continues to change in service. The fines produced are sometimes plastic and in quantities that render the material undesirable for embankment.

All degradation tests evaluated subject aggregate to abrasive action either by air or water. The value measured was either a change in gradation or a production of fines or both. They predict the potential susceptibility of material to degrade but are not intended to predict actual degradation due to the fact there are too many variables that contribute to degradation. In the end, Platts and Llyod (1966) recommended Alaska use the Washington degradation test due to the reasons listed in Table 2.3. A requirement of 50 as a minimum to be acceptable was recommended as well.

Table 2.3 Beneficial reasons for using the Washington degradation test (Platts and Llyod 1966).

Reason No	Description
1	Test results and field evaluations agree well.
2	One value is given as a result as opposed to two values, one for fines and one for coarse materials.
3	A small sample is needed which was thought to give more consistent results.
4	Equipment needed is typical of a materials lab and can be used in the field.
5	Performed well on tested Alaskan aggregates.

The procedure to determine degradation value for aggregates according to Alaska Test Methods (ATM) 313 (ATM Manual 2009) , is similar to that based on Washington degradation test T113 as described in the Washington State Department of Transportation, WSDOT, Standard Specifications for Road, Bridge, and Municipal Construction (2012). One difference is that Washington degradation test T113 uses two replicates, and the average of the two replicates is used but each result cannot be more than 6 points different as described in the T113 test calculation.

The Washington degradation test makes use of the sand equivalent solution which is calcium chloride, 7 ml, a sand equivalent graduated cylinder and similar calculation. The purpose for the version used for the ATM 313 is to determine a relative amount of clay like particles produced when subjected to a prescribed abrasion process.

Aggregates can degrade into excess plastic fines that can cause reduction in aggregate interlock and increase lubrication between coarse particles that will lead to pavement failures. The Washington degradation test tends to indicate the susceptibility of an aggregate to degrade into plastic fines when abraded in the presence of water. Goonewardane (1977) looked into the variations of the Washington degradation test values with particle sizes and times of agitation. He described the Washington degradation test as a clay leachate test in which a sand equivalent technique was employed. As the fines are produced by attrition and extraction in the Washington degradation test, it is dependent on the surface area of the aggregate, and the fines production increases linearly with time. Finer samples will indicate more degradation.

A correlation was found between the Washington degradation test and the sand equivalent test using the data from Alaska and Melbourne, Australia (Moors 1972). He further stated that the sand equivalent test is a cleanliness test and not a degradation test. The Washington degradation test is therefore redundant to the sand equivalent test. In addition, a Washington degradation test performed on limestone gave a value of 34 but the fines are not hydrophilic or plastic fines therefore producing doubtful results. In Moors' report it is stated that Washington state reduced a minimal value to 30 from 50 while Melbourne increased the value to 70 from 50 (Moors 1972). The degradation factor is still used by Washington DOT (Polodna 2012).

Bingham (2012) discussed how the degradation mechanism with the ATM 313 is different than with the LA abrasion and sulfate soundness tests. He pointed out that the LA abrasion is more of a mechanical abrasion break down whereas the degradation values represents the production of fines, minus 200 sieve particles which is a different type of degradation. According to Johnson's experience (2012), previous Washington degradation test results were in a broad range with poor repeatability. The original intent of using it in Alaska was to determine the general quality of aggregate pits. This test correlated fairly well with fines produced, but not well for specification. McHattie (2012) emphasized the difference of testing procedure and mechanism between Washington degradation test and LA abrasion test. Higher sediment height (clay height) in the sand equivalent cylinder indicates lower degradation value. The Washington degradation test indeed measures the size of fines (how fine) but not quantity of fines (how much).

MICRO-DEVAL TEST

Many aggregates have a reduction in resistance to abrasion when wet. “Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus” (ASTM 6928-08, AASHTO T327) is a test for the abrasion resistance and durability of mineral aggregate from abrasion and grinding of steel spheres and sample immersed in water.

Several states recommend using the Micro-Deval test in addition to current test for aggregate quality (Hossain et al. 2007). These states included Texas, South Carolina, Colorado, and Oklahoma. Ontario, Canada was mentioned as well. British Columbia's Ministry of Transportation planned to use the Micro-Deval test to replace the degradation test because the Micro-Deval test is more reproducible (Nyland 2005). Kandhal and Parker (1998) found that the Micro-Deval correlates well to raveling, pop-outs, and potholing and suggests using the Micro-Deval test instead of the LA abrasion for this purpose. In a study investigating the long term durability of aggregates used for Wisconsin transportation projects to include industrial by-products and recycled materials, Williamson (2005) suggested that the Micro-Deval test be included for measuring abrasion resistance. A 15% loss for coarse aggregate and 20% loss for high quality fine aggregates are considered suitable (Hossain et al. 2007). Others suggested 17% or 18% of acceptance level for Micro-Deval abrasion loss (Kandhal et al. 1998; Hunt 2001; Edlinski and Rangaraju 2008).

OTHER AGGREGATE DURABILITY TESTS

Other tests in literature that the Micro-Deval has been compared to are the sodium and magnesium sulfate soundness (AASHTO T104 and ASTM C88). The range of acceptable loss is 10% - 20%. The level of acceptance might be related to aggregate type (Brown et al. 2005). 73% of the responding agencies have a requirement level for ASSHTO T104. Of that 64% require the sodium sulfate, 30% require the magnesium sulfate, and 6% (two states) state either sodium or magnesium is allowable.

Williamson (2005) performed an evaluation on aggregate tests for Wisconsin aggregates to determine if current quality protocol was sufficient to assess aggregate quality for long term performance and the use of industrial and construction by-products and recyclables. His study indicated that the sulfate test cannot be used on recycled concrete aggregates because the chemical reaction could cause erroneous results. The sodium sulfate soundness test demonstrated variability for both single operator testing as well as multi-laboratory testing. However, Brandes and Robinson (2007) did find a good correlation with the magnesium sulfate soundness test and pavement performance for aggregate in Hawaii, as the aggregate breakdown in Hawaii is the result of a chemical process.

The sand equivalent test was originally developed by Hveem in 1953 to control the quality of aggregate (Kandhal and Parker 1998). The purpose of the Sand Equivalent is to quickly determine the relative proportion of plastic fines or clay like particles in a sample of fine aggregate. The difference between the sand equivalent test and ATM 313 is that material passing the 4.75 mm sieve (No 4) is used in a solution of calcium chloride instead of crushing aggregate to pass the No 12 sieve and producing a sample that combines 500 g passing the 12.5 mm (1/2”) but retained on the 6.3 mm and 500 g passing the 6.3 mm but retained on the 2 mm. The calculation for the sand equivalent test is shown in Equation 2.3.

$$SE = \frac{Sand\,\mathrm{Re}ading}{Clay\,\mathrm{Re}ading} x100 \qquad (2.3)$$

The higher the sediment reading the more clay like material exists in the sample and therefore not as suitable for road aggregate whether used as a bound or unbound layer.

Clough and Martinez (1961) reported good correlation between the sand equivalent value and resistance to stripping. However, even though the sand equivalent test can show an aggregate’s susceptibility to moisture related damage it determines a relative proportion of clay like particles and not the quality of the clay like particles. The sand equivalent test was not chosen as a quality test for aggregate being used in HMA pavements (Kandhal and Parker 1998). Another NCHRP study indicated that no relationship can be corroborated between the presence of clay like particles, as measured by the sand equivalent test, and HMA performance (Prowell et al. 2005). In this study, 92% of the responding agencies reported using the sand equivalent test but the results of the sand equivalent test were controversial. Crusher fines were sometimes identified as harmful clay like particles.

The Nordic Abrasion Ball Mill test was also used previously to measure aggregate resistance to studded tire wear as stated by Frith et al. (2004). This study related studded tire wear to a Nordic Abrasion Ball Mill value and created a regression model. Acceptance loss values were recommended based on traffic levels. The Nordic Ball Mill test is currently being used in Alaska on some occasions for HMA wearing courses where studded tire wear is anticipated.

CORRELATIONS AND COMPARISONS

Tests for properly characterizing aggregate durability are critical and these tests need to be cost effective, efficient, repeatable, and should correlate to actual performance. Extensive studies have been conducted to investigate the correlations among different tests, compare the effectiveness of these tests of assessing aggregate quality, and evaluate if one can be an alternative or supplement to the others. Table 2.4 summarizes findings from some of references.

Table 2.4 Correlations and comparisons among aggregate tests.

Reference	Aggregates	Findings
Kandhal and Parker (1998)	16 common aggregates from four different climatic zones: 10 from wet-freeze regions; known historical performance from good to poor	LA abrasion: fair predictive capability and reproducibility for coarse aggregate; reasonable cost to run the test; simple to perform Micro-Deval: able to discern the good and fair from the poor
Hossain et al. (2007)	20 coarse aggregates and 10 fine aggregates from nine districts of Virginia DOT	Micro-Deval: correctly identified 70% of the poor performers from fair/good performers for the coarse aggregates and 80% for the fine aggregates; less variable than the LA abrasion and magnesium sulfate tests
Edlinski and Rangaraju (2008)	23 different aggregates of known performance in South Carolina	Micro-Deval test with an acceptance level of 18% separated the fair/poor performers from the good better than did the LA abrasion, sodium sulfate, and magnesium sulfate.
Hunt (2001)	30 aggregate samples from Oregon and Alaska	Micro-Deval test with an acceptance level of 17% was not any more discriminating for abrasion degradation than the LA abrasion test with an acceptance level of 30%
Baker et al. (2001)	12 different aggregates from seven different states including freeze and thaw areas as well as non-freeze and thaw areas with known	Micro-Deval test demonstrated the best correlation to pavement performance by measuring the abrasion loss of the aggregate.

	pavement performance history	
Prowell et al. (2005)		Good correlation between the Micro-Deval test and pavement particle abrasion; good correlation between LA abrasion and Micro-Deval and the Magnesium Sulfate Soundness; the Micro-Deval has demonstrated greater precision over the sulfate soundness tests; LA abrasion: holds wide acceptance correlated to the aggregate impact value and the aggregate crushing value but a fair correlation with pavement performance; deterioration mode differs from Micro-Deval, good to assess breakdown due to construction stresses
Kandhal et al. (1998)	Three replicates of nine different tests were run for 16 different aggregate sources from FL, GA, IA, IN, MN, NY, OR, PA, NV, SC, VA, and TX	The Micro-Deval with a loss acceptance level of 18% was the only test used for toughness and abrasion resistant that was able to discern poor from the fair to good rated aggregates; Micro-Deval and magnesium sulfate tests were strongly related to asphalt concrete pavement performance.
Cuelho et al. (2007)	32 aggregate samples in Montana	Micro-Deval test: better correlation with actual pavement performance, more repeatable than the sodium sulfate test; most appropriate test over the LA abrasion and sodium sulfate tests
Schaefer (2012)	Aggregates in Northern Region of Alaska	LA abrasion: takes less than a day to run; Sodium and magnesium tests: takes about seven days to complete the required five cycles; Micro-Deval test: takes a

		couple of hours to complete; Washington degradation test: quick to run but has more variation to the results than other tests.
Hoare (2003)	Aggregates in Texas	Micro-Deval: more sensitive to aggregates with lower absorption; completed in a couple of hours; Magnesium sulfate soundness test: more sensitive to aggregates with a higher absorption; a minimum of seven days to run; issues with the repeatability of the results on multiple samples from the same quarry as well as reproducibility between different labs; correlation between is fair.

CURRENT STATES PRACTICES

Table 2.5 summarizes acceptance levels for the Micro-Deval, LA abrasion, sodium sulfate, and magnesium sulfate tests for base course aggregates and HMA in various states and provinces. It can be seen that the Micro-Deval, LA abrasion, and sodium/magnesium sulfate tests have been implemented in a number of states and provinces, though the acceptance levels vary.

Table 2.5 Acceptance levels for aggregate tests.

States/Provinces /Reports/Articles	**Micro-Deval Acceptance Level**	**LA Abrasion**	**Sodium Sulfate Soundness**	**Magnesium Sulfate Soundness**
Hossain et al. (2007) VA	15 - 18% CA 20% FA	40 Gr A 45 Gr B	not reported	30%
Richard and Scarlett (1997) Ontario	25%		not reported	not reported
Richard and Scarlett (1997) Quebec	25%	50%	not reported	not reported
Richard and Scarlett (1997) New Brunsiwick	25%	not reported	not reported	not reported
Richard and Scarlett (1997) Newfoundland	20%	not reported	not reported	15%
Kandhal and Parker (1998) NCHRP 405 (HMA)	18%	40-45%	11-15%	18%
Rangaraju and Edlinski (2005)	18%	55%	15%	not reported

SC (not specified whether for HMA or base)				
Cuelho et al. (2007) (not specified whether for HMA or base) MT	18%	40%	12%	not reported
Brandes and Robinson (2006) HI (not specified whether for HMA or base)	not reported	30%	9%	not reported
Gatchalian et al. (2006) TX A&M (Stone Matrix)	15%	30%	not reported	not reported
Hoare (2003) TX Tech (HMA)	not reported	not reported	not reported	20%
Hunt (2001) ORDOT (HMA)	17%	30%	not reported	not reported
Saeed et al. (2001) NCHRP 453 HT-high traffic MT-medium traffic LT-low traffic F-frost NF-non frost	5% HT-F 15% MT-F, HT-NF 30% MT-NF, LT-F	not reported	13% HT-F 30% MT-F, HT-NF 30% MT-NF, LT-F	not reported
Prowell et al. (2005) NCHRP 539 (Superpave Mix)	18%	40% most states	12%	18%
Wu et al. (1998) NCAT 98-4	18%	40 - 45% Most	5 – 25% most states	10 – 30% most states

(Asphalt Concrete)		states		18% for study
Williamson (2005) WI	18%	50%	12%	18%
AKDOT&PF (2004)	na	50%	9%	na

In addition, Washington degradation test has been used only in a few states based on our literature search. Currently the AKDOT&PF has an acceptance level of 45% for base course aggregates (ATM 313, 2009), while Washington state specifies a minimum value of 30% (WashDOT, 2012).

CHAPTER III

TESTS AND RESULTS

This chapter describes the experimental details in this study to include the materials, testing methods, test results, and comparisons between tests. Aggregate properties presented are aggregate gradations, abrasion resistances, and fines content.

MATERIALS

D-1 base course materials from 16 sources in three regions (North, Central, and Southeast regions) of Alaska were sampled. Table 3.1 lists source information of these 16 aggregate samples.

Table 3.1 Aggregate sources.

Label	Region	Source	Provider
Granite Birchwood	Central-Anchorage	Granite's Birchwood Pit	State
Anchorage C street	Central-Anchorage	QAP's C Street Pit	QAP
QAP Cange	Central-Wasilla	QAP's Cange Pit	QAP
QAP Dyno-Nobel	Central-willow	QAP's Dyno-Nobel Pit on MP 78 of the Parks Highway	QAP
Dalton Hwy	Northern	MS 64-9-076-2	State
AK Hwy 1222-1235	Northern-Fairbanks	Paradise Pit	HC
AK Hwy TRB	Northern-Fairbanks	MS-62-2-005-2	AIC
AK Hwy MP 1412-1422	Northern-Fairbanks	MP 1416.5	Granite
Fairbanks Vanhorn	Northern-Fairbanks	Exclusive material Van Horn Pit	Exclusive materials
Elliot 28-72	Northern-Fairbanks	Barrow	Brazo
Nome	Northern-Nome	Cape Nome	State
Sitka	Southeast	S&S Quarry	State
Skagway River	Southeast	Hunz & Hunz	R&M
Juneau	Southeast	Stablers Quarry	State
Ketchikan	Southeast	Hamilton Quarry	State
Haines	Southeast	Haines Hwy MP 4.5 PIT	State

AGGREGATE PROPERTIES TESTS

Property tests were conducted on the selected materials including particle distribution analysis, sand equivalent, Micro-Deval, LA abrasion, Washington degradation, and sodium sulfate resistance. All tests were conducted at UAF or AKDOT&PF materials labs according to appropriate testing standards. Three samples per source for each of the 16 sources were tested for each of the tests.

Particle Distribution Analysis

Aggregate gradation analysis conformed to ASTM D6913 (2004) "Particle Size Distribution of Soils Using Sieve Analysis" was performed at the UAF materials lab. This was necessary to determine correct procedures for subsequent degradation tests. Two replicates were used for each aggregate source and average values were used to create the gradation curves.

The hydrometer analysis for aggregate fines particle distribution was also performed according to ASTM D422-63 (2007) "Particle Size Analysis of Soils". This test is for aggregate particles passing the No.10 sieve. The test was conducted at a constant room temperature of 22°C with a 151H type hydrometer. Samples were dispersed in a solution of $NaSO_4$ for a day and mixed using a high speed mechanical stirrer. Figure 3.1 shows the sedimentation cylinders with mixed samples ready for reading. Before results could be correctly analyzed, the specific gravity of particles passing the No. 10 sieve were determined according to ASTM D854 (2010) "Specific Gravity of Soil Solids by Water Pycnometer". Results from the hydrometer test give a finer distribution of a particular aggregate. A percentage of particles with sizes less than .02 mm can be used to determine if the material is frost susceptible according to Casagrande's criteria (1932). Two replicates were used for each aggregate source.

Figure 3.1 Hydrometer test in progress.

Sand Equivalent

The sand equivalent of aggregate particles with sizes less than the No. 4 sieve was conducted using ASTM D2419 (2009) “Sand Equivalent Value of Soils and Fine Aggregates”. The procedure involves filling a cylinder with the prepared sample, adding a solution of calcium chloride and allowing to soak for 10 minutes. A stopper is then placed over the end of the cylinder and the closed cylinder is placed in a mechanical shaker which agitates the sample/solution mixture. Immediately after agitation more of the calcium chloride solution is introduced by siphon through a metal wand which penetrates the sample to the bottom of the cylinder, enough solution is added until a specified volume is achieved ensuring all of the clays and fines are washed off the coarse particles. The cylinder is left undisturbed for 20 minutes. First the height of clay suspended in the cylinder (clay reading) is read. Next the height of sand is measured (sand reading) using a tamping rod. The sand equivalent is then calculated by Equation 2.3. The purpose of this test method is to indicate the relative proportions of fine dust or claylike materials in aggregate. The lower the result from this test, the higher the fines content. Cleaner aggregates will have higher sand equivalent values.

Micro-Deval

Micro-Deval test was conducted according to the ASTM D6928 (2010) "Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus" utilizing a Gilson MD-2000 Micro-Deval testing apparatus (Figure 3.2).

Figure 3.2 Micro-Deval testing apparatus.

The Micro-Deval abrasion jars are approximately 5 liters in capacity, 198 mm in diameter, internal height of 174 mm, smooth surfaces inside and out, with a water tight locking cover. The abrasive charge is magnetic stainless steel balls possessing a diameter of 9.5 mm. The amount of abrasive charge used for each test totals 5000 g. There are three sample configurations specified for ASTM 6928-08: nominal maximum aggregate size (NMAS) of 19.0 mm, NMAS of 12.5 mm, and NMAS of 9.5 mm. Prior to grading each sample needs to be dried to a consistent mass at 110 ^{o}C. Each of these samples has a total mass of 1500 g as seen in Table 3.2.

Table 3.2 Micro-Deval NMAS gradation schedule.

Passing	Retained	19.0 mm	12.5 mm	9.5 mm
19.0 mm	16.0 mm	375 g		
16.0 mm	12.5 mm	375 g		
12.5 mm	9.5 mm	750 g	750 g	
9.5 mm	6.3 mm		375 g	750 g
6.3 mm	4.75 mm		375 g	750 g
	Total	1500 g	1500 g	1500 g

The graded test sample needs to be 1500 g +/- 5 g. This weight is recorded as "A". The test sample is then immersed in 2.0 liters of water for a minimum of one hour in the Micro-Deval container. Then add the 5000 g charge of steel balls. For the 19.0 mm NMAS the machine is run at 100 rpm for 2 hours. For the 12.5 mm NMAS the machine is run at 100 rom for 105 min +/- 1 min. For the 9.5 mm NMAS the machine is run at 100 rpm for 95 min +/- 1 min. If a counter is available the 19.0 mm test can be run for 12 500 revolutions +/- 100 revolutions, 12.5 mm can be run for 10 500 revolutions +/- 100 revolutions, and the 9.5 mm can be run for 9 500 revolutions +/- 100 revolutions.

Once the proper amount of time or revolutions is achieved the sample and charge are poured over a #4 sieve over a #16 sieve. The stainless steel spheres are removed and the material passing the #16 sieve is discarded. The material on the 4.75 mm sieve and 1.18 mm sieve is combined and dried to a consistent mass at 110 C. The material is weighed and recorded as "B". The calculation for Micro-Deval loss is expressed by Equation 3.1.

$$\frac{(A - B)x100}{A} \tag{3.1}$$

LA Abrasion

The LA abrasion test was conducted in AKDOT&PF materials lab conforming to AASHTO T96 standards (2002). The LA abrasion involves rolling a standardized gradation of a dry aggregate sample with a charge of steel balls in a steel drum with a shelf on the inside. Figure 3.3 shows the LA abrasion testing apparatus.

Figure 3.3 LA abrasion testing apparatus.

The LA abrasion test takes place in a steel rotating drum with a diameter of 711 mm and a thickness of not less than 12.4 mm and an inside length of 508 mm. The steel drum needs to be level within 1 in 100. Interior is one shelf made of steel and protruding inward 89 mm. The steel shelf can be either a steel plate, 89 mm wide x 25.4 mm thick x 508 mm long, or steel angle, 52 mm x 102 mm x 12.7 mm x 508 mm, that runs the length of the drum. With the angle the 102 mm dimension needs to be mounted such that the outside of the angle will be flush with the outside of the drum. This will give 89 mm protruding inward. The rotation of the drum should be such that the sample and the charge are picked up on the outside of the angle if steel angle is used for a shelf.

The sample size is dependent on what gradation is being tested. There are four gradations, A, B, C, and D in ASSTHO T96 (2002), as shown in Table 3.3. Grade A is graded with larger sieves and more varied. Grade D is the one with the smallest sieve specified.

Table 3.3 Small coarse aggregate gradations for LA abrasion test.

Passing	Retained	A	B	C	D
37.5 mm (1 ½ in)	25.0 mm (1 in)	1250 g			
25.0 mm (1 in)	19.0 mm (3/4 in)	1250 g			
19.0 mm (3/4 in)	12.5 mm (1/2 in)	1250 g	2500 g		
12.5 mm (1/2 in)	9.5 mm (3/8 in)	1250 g	2500 g		
9.5 mm (3/8 in)	6.3 mm (¼ in)			2500 g	
6.3 mm (¼ in)	6.3 mm (¼ in)			2500 g	
4.75 mm (No 4)	2.36 mm (No 8)				5000 g

	Total	5000 g	5000 g	5000 g	5000 g

Steel spheres are used as charge each sphere having a diameter of 46.8 mm (1 27/32 in). The number of spheres used depends on the grading as stated in Table 3.3 as shown in Table 3.4.

Table 3.4 Number of steel spheres and total mass of charge for LA abrasion test.

Grading	Number of steel spheres	Mass of charge
A	12	5000 g
B	11	4584 g
C	8	3330 g
D	6	2500 g

After the sample is washed and reduced per specification it needs to be dried at 110 ^{o}C (230 ^{o}F) to a constant mass. After 500 revolutions at 30 to 33 rpm's a gradation is performed and the amount retained on a 1.70 mm (No 12) sieve and above is weighed. The test calculation is the difference between the weight rotated with charge and the original weight divided by the original weight times 100. This calculation is rounded to the nearest 1%.

The procedure of the LA Abrasion for large coarse aggregate (ASTM C 535-09) is the same as for small coarse aggregate, ASTM 131-06, except the gradations are for aggregate grading larger than 3/4 in. Table 3.5 shows the various gradations.

Table 3.5 Large coarse aggregate gradations for LA abrasion test.

Passing	Retained	1	2	3
75 mm (3 in)	63 mm (2 ½ in)	2500 g		
63 mm (2 ½ in)	50 mm (2 in)	2500 g		
50 mm (2 in)	37.5 mm (1 ½ in)	5000 g	5000 g	
37.5 mm (1 ½ in)	25 mm (1 in)		5000 g	5000 g
25 mm (1 in)	19 mm (3/4 in)			5000 g
	Total	10000 g	10000 g	10000 g

The charge is 12 spheres of approximately 47 mm in diameter with a total mass of 5000 g. Prior to grading the sample is washed dried to a constant mass at 110 ^{o}C (230 ^{o}F). The charge and sample are placed into the LA Abrasion machine and rotated at 30 to 33 rpm for 1000 revolutions. The sample is then sieved on a 1.7 mm (No 12) screen. The material retained on the 1.7 mm screen is then washed and dried to a constant mass at 110 ^{o}C (230 ^{o}F). The calculation for ASTM 535 is the difference between the rotated sample and the original mass divided by the original mass times 100. Round to the nearest 1%.

Washington Degradation

Test results from the Washington Degradation method were obtained by AKDOT&PF conforming to ATM 313 (2010). The procedure is described as follows.

Unprocessed aggregate is first sieved on a 12.5 mm(1/2") for five minutes. The minus 12.5 mm material is discarded. The material remaining on the 12.5 mm sieve is then crushed so that it all passes through the 12.5 mm sieve. This material is then sieved for five minutes into two groups; minus 12.5 mm to plus 6.3 mm and minus 6.3 mm to plus 2.0 mm. Each group is reduced so that there will be 500 grams after washing. Each grouping is then washed over a 2.0 mm sieve and dried to a constant mass. Then weigh out a 500 g sample for each grouping. The two groupings are combined in a plastic container with 200 ml of distilled water and placed on a sieve shaker for five minutes. Wash the material over nested 2.0 mm and 75 µm with distilled water until the wash water is clear and has reached the 500 ml mark on a graduated cylinder. If the wash water is not clear refer to ATM 313. 7 ml of Stock Sand Equivalent Solution is added to an empty Sand Equivalent cylinder. All of the solids in the 500 ml graduated cylinder are put into suspension. This is accomplished by placing a rubber stopper into the top of the cylinder and held firmly with the palm of the hand. The cylinder is turned end over end 10 times allowing the bubble to traverse the cylinder each time. This solution is then poured into the Sand Equivalent cylinder to the 15 mark and plugged with a rubber stopper. Next, mix the contents of the cylinder by turning end over end 20 times allowing the bubble to traverse each time. Stand the cylinder upright on a vibration free surface out of the sunlight and allow to stand for 20 minutes. Immediately read the height of the sediment to the nearest .1 graduation mark. The degradation value can be determined as shown in equation 2.2.

The sediment height is the height of the material suspended with the calcium chloride, sand equivalent solution. A degradation value can also be read from the chart provided with the ATM 313 document. The higher the degradation value the better the material.

Sodium Sulfate Resistance

Sodium sulfate soundness results were obtained in accordance with AASHTO T104 (1999) in the AKDOT&PF materials lab. This test simulates natural weathering by subjecting aggregates to a chemical reaction with sodium sulfate. This method simulates freeze thaw patterns and is commonly used to indicate the relevance of an aggregate to be used in concrete. It involves saturating a sample in a solution of sodium sulfate, drying, and then when rehydrating the sample an internal expansive force is exerted when the salt is rehydrated giving a similar effect of freezing water or salts from deicing. Results are given as a percentage of aggregate mass lost from the test, the lower the value the more resistant to degradation.

First the sample is oven dried to a consistent mass and then separated into specific sieve sizes. Then the sample is left to soak in a saturated solution of sodium or magnesium sulfate for 18 hours. The sample is removed from the solution and dried to a consistent mass at 110 ^{o}C. This cycle is repeated 5 times. The sample is then washed to remove the salt and dried. A loss for specific sieve sizes is determined as a percentage of the original mass.

Table 3.6 shows the recommended durability criteria for Micro-Deval, LA abrasion, Washington degradation, and sodium sulfate resistance of base course materials. AKDOT&PF Standard Specifications for Highway Construction (2004) provide criteria for LA abrasion, Washington degradation, and sodium sulfate resistance, and the MD criterion is based on the recommendation from Cuehlo, et al. (2007). They also recommended that for a Micro-Deval value between 18% and 24% a second degradation test be run to verify an aggregates condition.

Table 3.6 Durability criteria

Test Method	Micro-Deval	LA abrasion	Washington degradation	sodium sulfate resistance
Durability Criteria for Base Course	18% max	50% max	45% min	9% max

TEST RESULTS AND ANALYSIS

Aggregate Gradations

Gradation curves of aggregates are illustrated in Figure 3.4. The red dotted lines in Figure 3.4 indicate the upper and lower limits for D-1 type base coarse material specified in AKDOT&PF Standard Specifications for Highway Construction (2004). Lines in black indicate those of samples from Central Region, blue are from Northern and green are from Southeast Regions.

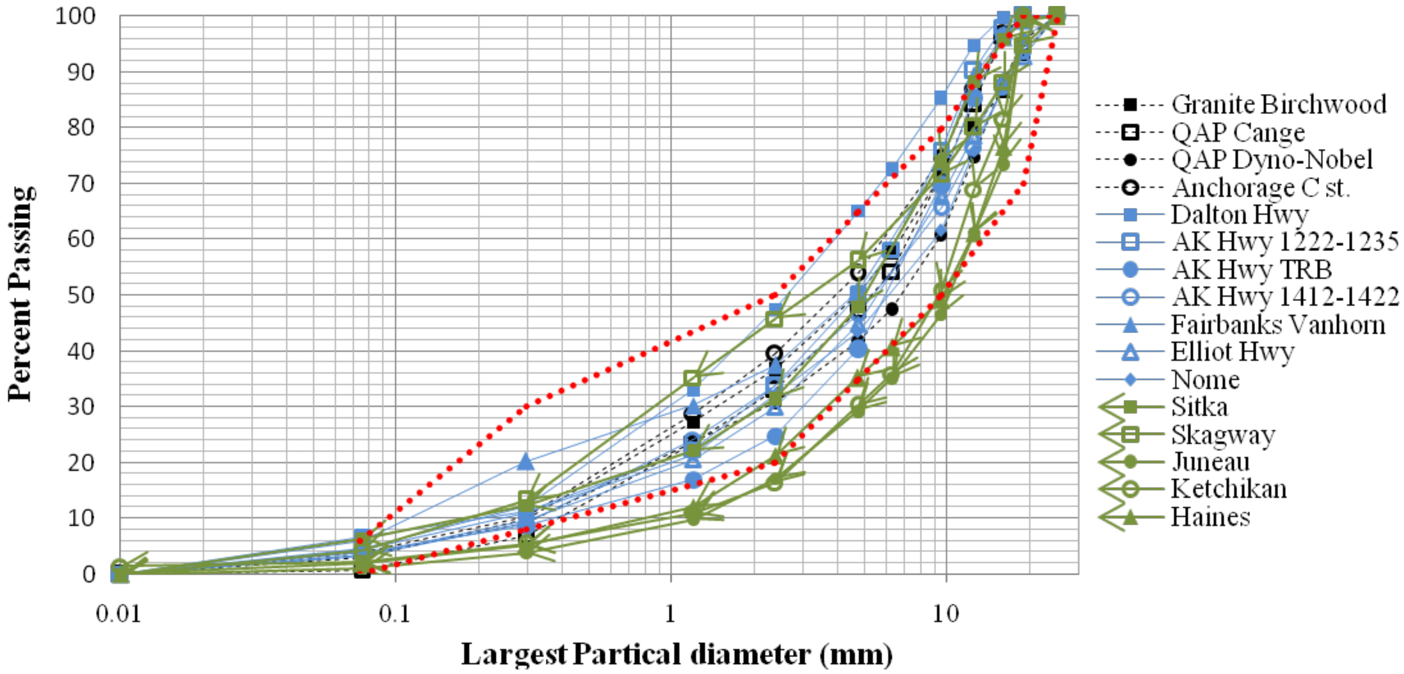


Figure 3.4 Gradation curves of aggregates.

It can be seen from Figure 3.4 that some of the aggregate sources did not entirely fit the D-1 classification range. Three of the five aggregates from Southeast Region were too coarse for D-1, while the aggregate from Dalton Hwy was the only aggregate too fine to fit the D-1 range. However, most of aggregates fit the D-1 requirements falling between the gradation limits.

The hydrometer particle distribution analysis was conducted on aggregate samples to determine fines distribution. The resulting gradations on semi-log charts are shown in Figure 3.5. Since the test can only be conducted on particles less than the No. 10 sieve, the percent passing is based on a representative total of the natural aggregate determined from the sieve analysis.

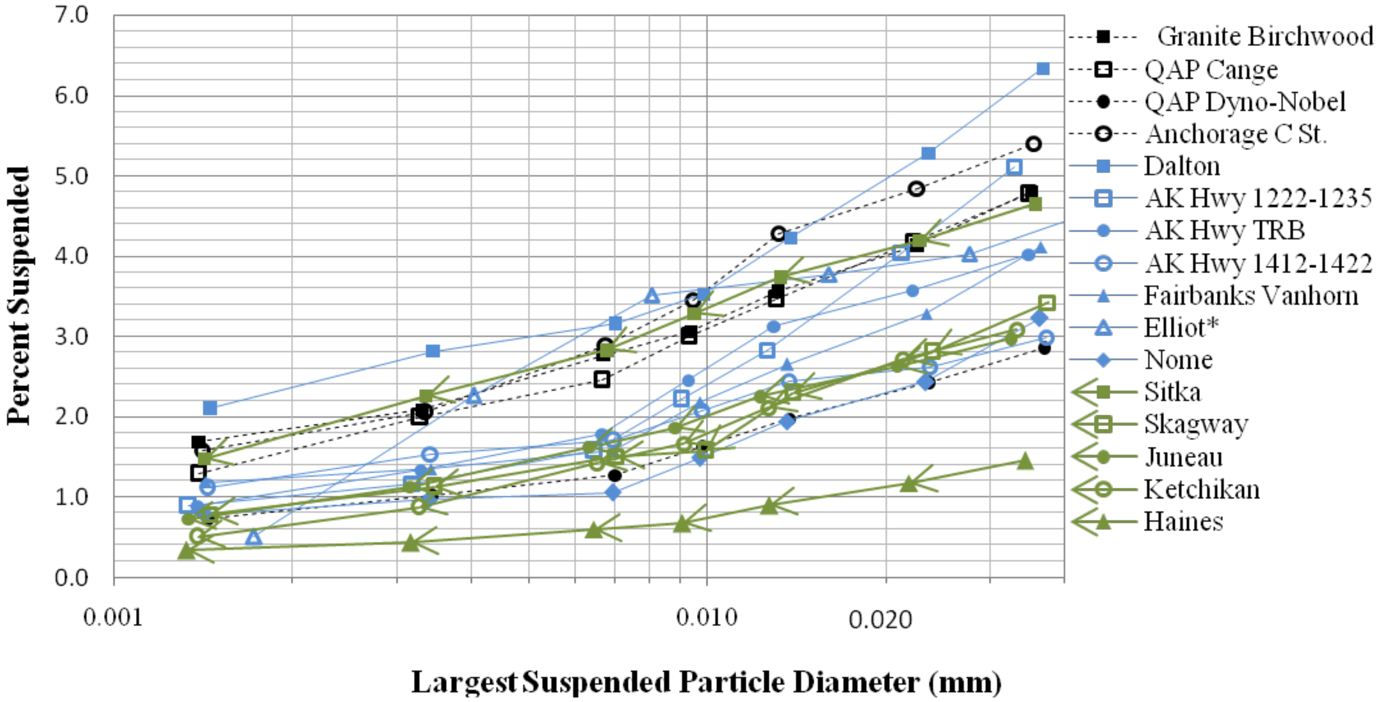


Figure 3.5 Hydrometer gradation curves of aggregates.

The hydrometer distribution in Figure 3.5 corresponds with the original gradations in Figure 3.4 showing that the aggregate from Dalton Hwy (Northern Region) had the highest fines content and that from Haines (Southeast Region) had the lowest.

Table 3.7 summarizes the results of specific gravity, the percentage passing the No. 10 sieve, and the percentage passing 0.02 mm from the hydrometer tests of all aggregates. The values of percentage passing 0.02 mm were estimated by linear interpolation since the particle diameter is determined using a multivariable equation based on specific gravity, time and sample mass. Aggregates with less than 3% of particles passing 0.02mm are considered as non-frost susceptible soils by Casagrande's Criteria (1932). Among these 16 aggregates, nine were frost susceptible and most of them were from Central and Northern Regions. The other seven aggregates met the non-frost-susceptible criteria. These seven aggregates all exhibited coarser gradations than average gradation and had average degradation values.

Table 3.7 Data and results of hydrometer and sand equivalent tests.

	Hydrometer Information			Sand Equivalent
Labels	Specific Gravity	% Finer No. 10 Sieve	% Finer .02mm	% height sand/fines
Granite birchwood	2.71	33.7	3.98	32
QAP Cange	2.73	29.9	4.01	38
QAP Dyno	2.64	28.5	2.26	71
Anchorage C street	2.68	36	4.69	45
Dalton Hwy	2.58	42.9	4.89	22
AK Hwy 1222-1235	2.89	30	3.86	81
AK Hwy TRB	2.76	22.3	3.47	79
AK Hwy MP 1412-1422	2.63	30.6	2.56	53
Fairbanks Vanhorn	2.65	35.2	3.07	65
Elliot 28-72		26.9	3.86	33
Nome	2.61	28.7	2.27	66
Sitka	2.64	28.6	4.06	52
Skg River	2.63	42.3	2.6	80
Juneau	2.86	14.8	2.59	42
Ketchikan	2.77	14.7	2.62	61
Haines	2.95	18.4	1.12	49

Sand Equivalent Values

Sand equivalent values of all aggregates are also presented in Table 3.7. The sand equivalent results indicate the relative cleanliness of the aggregate. As expressed by Equation 2.3, the higher the value, the less clay or fines content in aggregate, the cleaner the aggregate.

The aggregate from Dalton Hwy had the lowest sand equivalent value (22%), which means it had the most fines. This is consistent with the hydrometer test result which indicated the aggregate from Dalton Hwy had the highest percentage of passing .02 mm sieve (4.89%). The aggregate from Skagway River had the highest sand equivalent value (80%) indicating the cleanest aggregate source. It also had a relatively low percentage of passing .02 mm sieve (2.6%).

Micro-Deval Loss

Table 3.8 summarizes the results and statistical analysis including the mean %loss, the standard deviation (SD), and the coefficient of variation (COV) from the Micro-Deval tests. The COV provides information about the variability of the test procedure. A higher value of COV indicates greater variability between repeated tests. According to the results listed in Table 3.8, the average COV for the Micro-Deval tests was 5.33%, and the average SD was 0.43%. These values were both lower than those for the LA abrasion tests (6.7% of COV and 1.7% of SD (Cuehlo et al. 2007)). Similar conclusions that the Micro-Deval test is a reliably repeatable procedure were reported in other literatures (Nyland 2005, Hunt 2001). In addition, the average percentage of Micro-Deval loss of all aggregates was 7.75%. Comparing with max limit of 18% recommended by Cuehlo et al. (2007), most of aggregates were acceptable in terms of degradation resistance. The aggregate from Elliot Highway had the highest degradation (18.33%), while that from Fairbanks VanHorn had the lowest one (3.81%).

Table 3.8 Micro-Deval results

Label	**Mean % Loss**	**SD**	**COV**
Granite birchwood	7.78	0.08	1.01
QAP Cange	7.22	0.93	12.88
QAP Dyno	6.91	0.69	10.02
Anchorage C street	6.35	0.09	1.42
Dalton Hwy	7.93	0.04	0.55
AK Hwy 1222-1235	8.73	0.16	1.80
AK Hwy TRB	5.22	0.12	2.27
AK Hwy MP 1412-1422	6.67	0.72	10.73
Fairbanks Vanhorn	3.81	0.03	0.73
Elliot 28-72	18.33	1.36	7.41
Nome	13.71	0.60	4.38
Sitka	5.36	0.15	2.82
Skagway River	6.04	0.15	2.54
Juneau	7.15	0.88	12.33
Ketchikan	5.95	0.42	7.04
Haines	6.84	0.50	7.28

Comparisons and Correlations

Table 3.9 presents the results from the Micro-Deval, LA abrasion, Washington degradation, and sodium sulfate resistance tests. According to Table 3.9, the average values were 7.75% for Micro-Deval test, 20% for LA abrasion test, 63% for Washington degradation test, and 1% for sodium sulfate resistance test. The following aggregates had the highest resistance to degradation: the aggregate from Fairbanks Vanhorn with respect to its lowest Micro-Deval loss; aggregates from Granite Birchwood, QAP Cange, and Haines with respect to their lowest LA abrasion losses; and the aggregate from Skagway River with respect to its highest Washington degradation value. The following aggregates had the lowest resistance to degradation: the aggregate from Elliott 28-72 with respect to its highest Micro-Deval loss; the aggregate from Nome with respect to its highest LA abrasion losses; and the aggregate from Elliott 28-72 with respect to its lowest Washington degradation value. Compared with the cutoff values listed in Table 3.6, i.e. 18% max for Micro-Deval, 50% max for LA abrasion, 45% min for Washington degradation, and 9% max for sodium sulfate resistance test, most of these results fall within acceptable degradation range. In addition, in most of cases these tests showed consistent results in terms of aggregate degradation resistance. For example, the aggregate from Fairbanks Vanhorn had the lowest Micro-Deval loss (3.81% (vs. 18% max criteria) indicating high resistance to degradation. Similar conclusions of this aggregate can be drawn from the results from LA abrasion and Washington degradation tests (25% vs. 50% max and 88% vs. 45% min, respectively). However, results from different tests were not always consistent. For example, the aggregate from Elliot 28-72 failed to be acceptable according to the results from Micro-Deval and Washington degradation tests (18.3% vs. 18% max and 4% vs. 45% min, respectively). However the LA abrasion result of this aggregate was significantly less than the fail criterion (21% vs. 50% max). Another example was the aggregate from Dalton Hwy. According to the results from Micro-

Deval and LA abrasion tests, it had good degradation resistance (8% vs. 18% max and 27% loss vs. 50% max, respectively). However it failed according to the Washington degradation test (32% vs. 45%min). This may be due to the different degradation mechanisms of these tests.

Table 3.9 Degradation/abrasion test results

Label	Micro-Deval	LA abrasion	Washington degradation	sodium sulfate resistance
Granite Birchwood	7.8	12	75	0
QAP Cange	7.2	12	73	0
QAP Dyno-Nobel	6.6	16	62	0
Anchorage C street	6.4	13	75	1
Dalton Hwy	8.0	27	32	1.2
AK Hwy 1222-1235	9.0	25	66	5
AK Hwy TRB	5.2	13	84	0
AK Hwy MP 1412-1422	6.7	32	78	1
Fairbanks Vanhorn	3.8	25	88	0
Elliott 28-72	18.3	21	4	-
Nome	13.7	41	67	1
Sitka	5.4	13	48	0
Skagway River	6.0	31	96	0.4
Juneau	7.2	14	54	1
Ketchikan	6.2	13	54	2
Haines	6.7	12	51	1

A correlation analysis was conducted between these tests and results are given in Table 3.10. A correlation (r) value of 1 means the tests correlate exactly, and a negative r value indicates an inverse correlation. Of all test methods compared, higher correlations were found between the Micro-Deval test and other tests. A value of -0.65 between Washington degradation and Micro-Deval tests indicated they correlate highest. The value was negative since the Washington degradation test results give higher values for more durable aggregates while the Micro-Deval test results give lower values. It is odd however that the LA abrasion data had a slight positive correlation to Washington degradation.

Table 3.10 Correlation of degradation tests

Correlation (r) between Test Methods				
Test Method	Micro-Deval	LA Abrasion	Washington Degradation	Sulfate Soundness
Micro-Deval	1.00	0.35	-0.65	0.35
LA Abrasion	-	1.00	0.13	0.22
Washington Degradation	-	-	1.00	-0.23
Sulfate Soundness	-	-	-	1.00

A more precise method of comparing test result data was achieved by normalizing each test result to its standard limiting criteria to pass durability. Recall from Table 3.6, the durability criterion for each degradation test is as follows:

- *Micro-Deval Pass ≤ 18%* (Cuehlo et al. 2007)
- *LA abrasion Pass ≤ 50%*
- *Washington Degradation Pass ≥ 45%*
- *Sodium Sulfate Resistance Pass ≤ 9%*

For instance, the Micro-Deval test result for aggregate from Granite Birchwood is around 8%, the normalized value Micro-Deval test result of this aggregate is $\frac{8\%}{18\%}$ or 0.43. For Micro-Deval, LA abrasion, and sodium sulfate resistance tests, a normalized value of 1 or greater indicates that the aggregate has a percent loss greater than the respective cutoff, and is considered non-durable. For the Washington Degradation test, normalized values are calculated as $\frac{(100\% - WDresult)}{(100\% - 45)}$ to make simple comparison since its results have an inverse relationship with the other tests. Table 3.11 gives the normalized values for each degradation test normalized to their respective pass-fail criteria. It can be seen from Table 3.11 that most of aggregates had an acceptable degradation resistance with normalized values less than one with the exception of aggregates from the Elliot 28-72 and Dalton Hwy.

Table 3.11 Normalized test results

Label	Micro-Deval	LA-Abrasion	Washington Degradation	Sulfate Soundness
Granite birchwood	0.43	0.24	0.45	0.00
QAP Cange	0.40	0.24	0.49	0.00
QAP Dyno-Nobel	0.37	0.32	0.69	0.00
Anchorage C street	0.35	0.26	0.45	0.11
Dalton Hwy	0.44	0.54	1.24	0.13
AK Hwy 1222-1235	0.50	0.50	0.62	0.56
AK Hwy TRB	0.29	0.26	0.29	0.00
AK Hwy MP 1412-1422	0.37	0.64	0.40	0.11
Fairbanks Vanhorn	0.21	0.50	0.22	0.00
Elliott 28-72	1.02	0.42	1.75	-
Nome	0.76	0.82	0.60	0.11
Sitka	0.30	0.26	0.95	0.00
Skg River	0.34	0.62	0.07	0.04
Juneau	0.40	0.28	0.84	0.11
Ketchikan	0.34	0.26	0.84	0.22
Haines	0.37	0.24	0.89	0.11

The normalized values presented in Table 3.11 were plotted together to obtain a graphical representation of the relationship between the Micro-Deval and other tests (Figures 3.6-3.8). Figure 3.6 illustrates the normalized comparison between the Micro-Deval and LA abrasion tests. The two test methods were in agreement regarding an overall pass/fail determination for 15 out of 16 aggregates, or 93.8%. However, one aggregate (6.2% of the aggregates tested) would be considered problematic because the LA abrasion test indicated the aggregate durable (passing) but the Micro-Deval test result indicated the aggregate was non-durable (failure). The normalized comparison between these two tests exhibited a significant amount of scatter on both sides of the 45 degree line (black dotted line). The linear fit of the data had a slope less than one indicating that the Micro-Deval test was more likely to fail than the LA-A. In another words, the Micro-Deval test tended to provide more "conservative" result than the LA abrasion test. A poor R^2 value of 0.12 and the wide 95% confidence band range (black dashed curves) both indicated the overall poor correlation between these two tests.

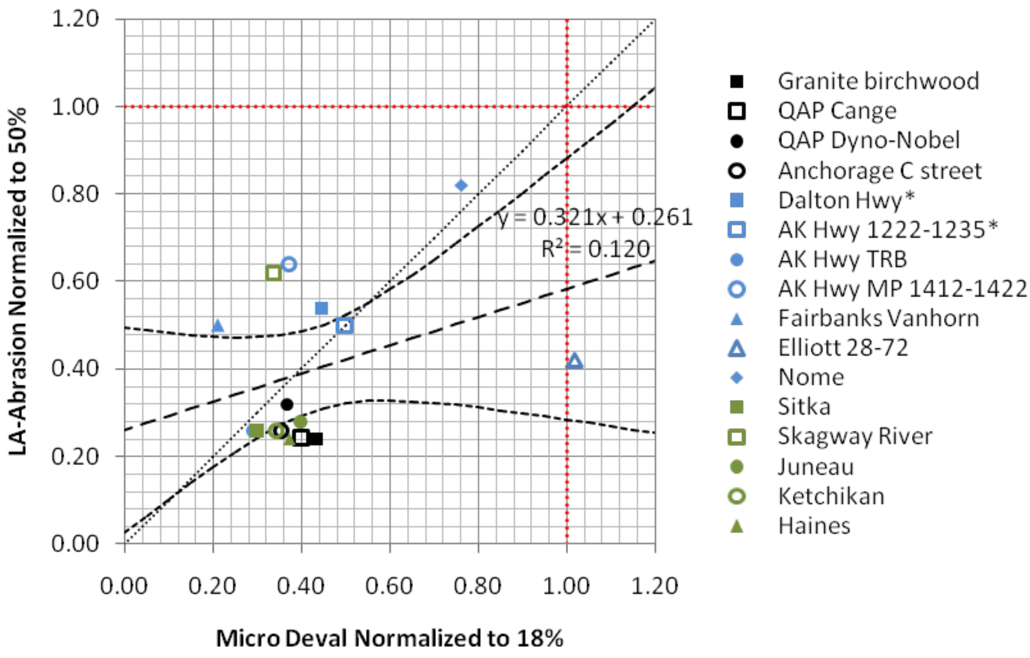


Figure 3.6 Normalized LA abrasion vs. Micro-Deval results.

Figure 3.7 illustrates the normalized comparison between the Micro-Deval and Washington degradation tests. The two test methods were in agreement regarding an overall pass/fail determination for 15 out of 16 aggregates, or 93.8%. Both tests had failing results (indicating non-durable aggregate) for only one of the aggregates. In this comparison, the aggregate from Dalton Hwy would be considered problematic because the Micro-Deval test indicated the aggregate was durable (passing) while the Washington degradation test not. The linear fit of the data had a slope greater than one indicating the Washington degradation test was more likely to fail (higher degree of non-durability) than the Micro-Deval test. However, the slope is also relatively close to one indicating a better correlation between these two tests than that shown in Figure 3.6. It can be also reflected by a less scattered data with a still poor but higher R^2 value of 0.416.

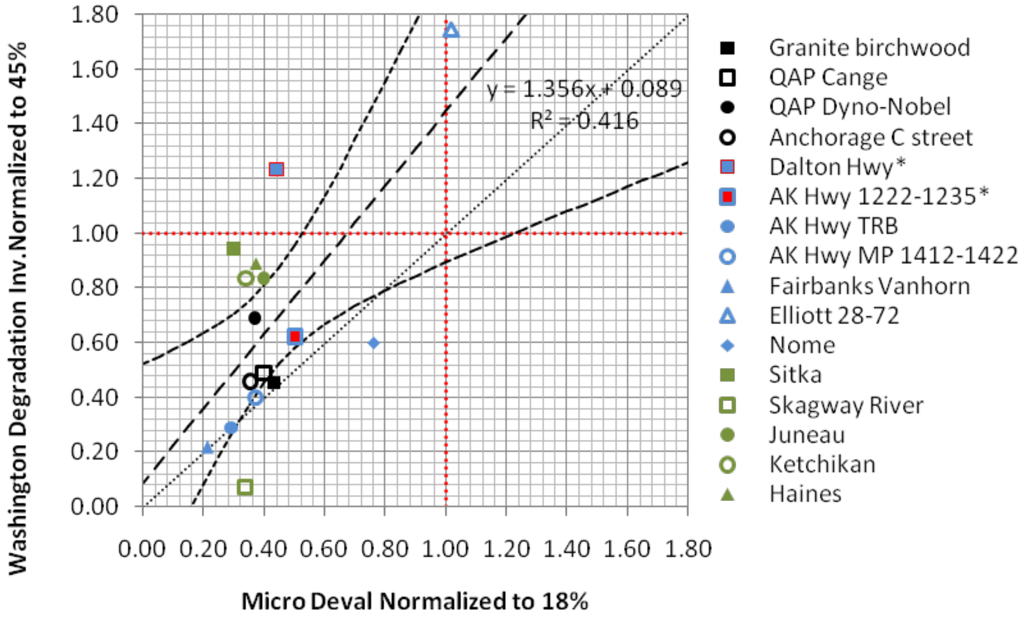


Figure 3.7 Normalized Washington degradation vs. Micro-Deval results.

As shown in Figure 3.8, the Micro-Deval and sodium sulfate resistance tests had similar passing results with a 93.8% agreement rate. One aggregate (from Elliot Hwy) was considered problematic because sodium sulfate resistance test indicated an acceptably durable aggregate while the Micro-Deval test did not. The linear fit of the data had a slope less than one indicating the Micro-Deval test was more likely to fail than the sodium sulfate resistance test. A low R^2 value of 0.121 indicated poor correlation between these two tests.

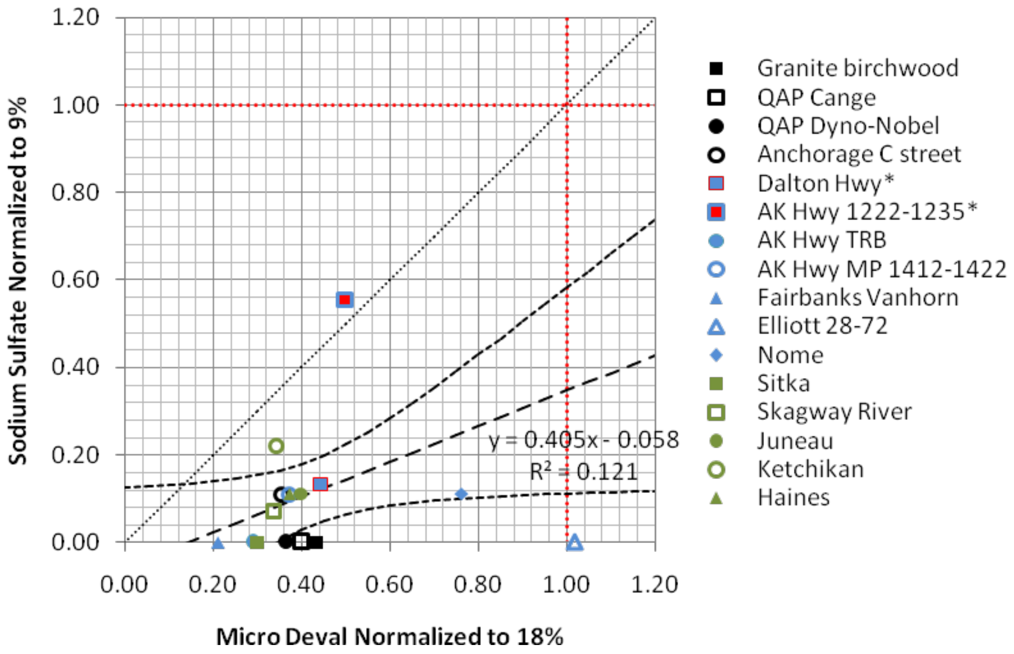


Figure 3.8 Normalized sodium sulfate resistance vs. Micro-Deval results.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

This study examined a variety of test methods including Micro-Deval, LA abrasion, sodium sulfate, and Washington degradation tests in terms of evaluating durability and degradation of typical Alaskan aggregates for base courses. This chapter presents a summary of research findings as well as recommendations on identifying the suitability of Micro-Deval test to assess the durability of Alaskan aggregates as a rapid, simple, repeatable and inexpensive technique.

CONCLUSIONS

Based on the literature review (presented in Chapter II) and laboratory testing and analysis (presented in Chapter III) from this study the following conclusions can be made:

The Micro-Deval test is a wet test of how aggregates degrade when tumbled in a rotating steel drum with water and steel balls. It considers both degradations due to mechanical abrasion and weathering, which better simulates field performance during construction and under traffic and undesirable environment. In several NCHRP studies (Kandhal and Parker 1998; Saeed et al. 2001; Prowell et al. 2005), the Micro-Deval test was found to be a good indicator of aggregate durability, toughness, and abrasion resistance with best correlation with field performance. Several state DOTs (such as Colorado, Texas, and Oklahoma) have been implementing specification requirement of Micro-Deval loss values for quality aggregates.

Within the scope of this study (16 aggregates from three regions of AKDOT&PF), the Micro-Deval test data had lower values of COV and SD than LA abrasion test. Similar conclusions that the Micro-Deval test is a reliably repeatable procedure were reported in other literatures (Hunt 2001; Nyland 2005; Jayawickrama et al. 2007). In most of cases the Micro-Deval, LA abrasion, sodium sulfate, and Washington degradation tests showed consistent results in terms of aggregate degradation resistance. However, results were not always consistent. A more precise method of comparing test result data was achieved by normalizing each test result to its standard limiting criteria to pass durability. The Micro-Deval test was generally in high agreement with any other testing method regarding an overall pass/fail determination, and a best correlation was found between the Micro-Deval and Washington degradation tests.

The Micro-Deval test is also a rapid, simple test — takes a couple of hours to complete. Smaller equipment size, lower sample quantities and a simpler procedure make this method easier and less costly to perform than traditional methods.

RECOMMENDATIONS

Tests for properly characterizing aggregate durability are critical. The guidelines that Saeed et al. (2001) adhered to was that the tests must relate to pavement performance, be consistent with the current state of knowledge, can be easily performed by most state DOT’s, in situ factors must be considered, and the procedures should be as simple as possible. Our study along with practices in other states confirmed the feasibility of using Micro-Deval test to assess the durability of Alaska aggregates in pavement construction. In addition, since the Micro-Deval could be completed in a couple of hours aggregate suppliers could run it more often to ensure compliance. The

AKDOT&PF could also perform quality checks on a more frequent basis or spot check more rapidly. However, other aggregate test had a long running track record which allowed for contractors as well as AKDOT&PF personnel to be more comfortable with results related to actual performance it is recommended that the Micro-Deval test be an additional test for a period of time. This will allow for a history of performance to be built as well as a comfort level with the results. Tests of more Alaska aggregates are also needed to facilitate the implementation of specification requirement of Micro-Deval loss values for quality aggregates.

According to current states practices of different tests for aggregate durability, the Washington degradation test has been used in only a few states. Based on DOT materials engineers' experience, Washington degradation test results had more variations thus poorer repeatability than other tests. The Washington degradation test is a clay leaching test dependent on surface area of charge, and finer samples will indicate more degradation. The Washington degradation test indeed measures the size of fines (how fine) but not quantity of fines (how much). It is suggested the Micro-Deval test along with current LA abrasion and sodium sulfate tests be used to provide a more reliable assessment of Alaska aggregates' durability.

REFERENCES

AKDOT&PF. (2004). “Standard Specifications for Highway Construction.” Alaska Department of Transportation and Public Facilities, Juneau, Alaska.

AKDOT&PF. (2009). “Alaska Test Methods Manual,” Alaska Department of Transportation and Public Facilities, Juneau, Alaska.

Alaska Test Method 306. (2010). “Determining the Percentage of Flat and Elongated Particles in Coarse Aggregate,” Alaska Department of Transportation and Public Facilities, Juneau, AK.

Alaska Test Method 313. (2010). “Degradation Value of Aggregates,” Alaska Department of Transportation and Public Facilities, Juneau, AK.

American Association of State Highway and Transportation Officials. (2010). *Determining the Liquid Limit of Soils*, T89, AASHTO, Washington D.C.

American Association of State Highway and Transportation Officials. (2002). *Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in The Los Angeles Machine*, T96, AASHTO, Washington D.C.

American Association of State Highway and Transportation Officials. (1999). *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*, T104, AASHTO, Washington D.C.

American Association of State Highway and Transportation Officials. (2009). *Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*, T327, AASHTO, Washington D.C.

American Association of State Highway and Transportation Officials. (2010). *Determining the Percentage of Fracture in Coarse Aggregate*, T335 (formerly T61), AASHTO, Washington D.C.

ASTM Standard C88, (2005). “Standard Test Method for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate” ASTM International, West Conshohocken, PA.

ASTM Standard C131, (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.

ASTM (2007) Designation: ASTM D422-63: “Standard Test Method for Particle-Size Analysis of Soils,” Annual Book of ASTM Standards.

ASTM Standard C535, (2009). “Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine” ASTM International, West Conshohocken, PA.

ASTM (2010) Designation: ASTM D854-10: “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer” Annual Book of ASTM Standards.

ASTM (2009) Designation: ASTM 2419-09: “Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate” Annual Book of ASTM Standards.

ASTM (2004) Designation: ASTM D6913: “Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis,” Annual Book of ASTM Standards.

ASTM Standard D6928, (2010). “Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus” ASTM International, West Conshohocken, PA.

Bingham, N., Central Region Materials Engineer, AKDOT&PF (2012). Personal communication.

Brandes, H, Robinson, C (2006). “Correlation of Aggregate Test Parameters to Hot Mix Asphalt Pavement Performance in Hawaii,” Journal of Transportation Engineering / ASCE, Vol. 132, January 1, Reston, VA.

Casagrande, A. (1932) Discussion on frost heaving. Highway Research Board, Bulleting No.12, 169
http://people.stfx.ca/bliengme/exceltips/regressionanalysisconfidence2.htm.

Chowdhury, A., Luce, A., Mahmoud, E., Masad, E. (2007).“Relationship of Aggregate Texture to Asphalt Pavement Skid Resistance Using Image Analysis of Aggregate Shape,” Transportation Research Board, Highway IDEA Project 114, Washington, D.C.

Cuehlo, E, Mokwa, R, and Obert, K (2007). “Comparative Analysis of Coarse Surfacing Aggregate Using Micro-Deval, LA Abrasion, and Sodium Sulfate Soundness Tests,” State of Montana Department of Transportation Research Programs, Report No FHWA/MT-06-016/8117-27, Helena, MT.

Edlinski, J, Rangaraju, P (2005). "Comparative Evaluation of Micro-Deval Abrasion Testwith Other Toughness/Abrasion Resistanceand Soundness Tests," TRB 84th Annual Meeting, Washington, D.C.

Frith, D., Morian, D., Saboundjian, S., Stoffels, S. (2004). "Hard Aggregate Resistance to Studded Tire Wear" Transportation Research Record: Journal of The Transportation Research Board, No 1874, pp. 19-28, Washington, D.C.

Gatchalian, D. (2005). "Characterization of Aggregate Resistance to Degradation in Stone Matrix Asphalt Mixtures," Master of Science Thesis, Texas A&M University, College Station, TX.

Gatchalian, D., Masad, E., Chowdhury, A., , Little, D., (2006). "Characterization of Aggregate Resistance to Degradation In Stone Matrix Asphalt Mixtures," Aggregates Foundation for Technology, Research, and Education, project no 400901, Alexandria, VA.

Goonewardane, K (1977). "Behavior of Aggregate in the Washington Degradation Test," Journal of Testing and Evaluation, Vol 5, No.1, 16-25.

Hoare, A (2003). "Feasibility of Using the Micro-Deval Test Method as an Aggregate Production Quality Control Tool," Master's Thesis, Texas Tech University, Lubbock, TX.

Hossain, S., Lane, S., Schmidt, B. (2007). "Use of the Micro-Deval Test for Assessing The Durability of Virginia Aggregates" Virginia Department of Transportation, Richmond, VA.

Hunt, E. (2001). "Micro-Deval Coarse Aggregate Test Evaluation," Oregon Department of Transportation Research Group, SR-547, Salem, OR.

Johnson, E. (2012). Personal communication.

Kandhal, P, Parker, F (1998). "Aggregate Tests Related to Asphalt Concrete Performance in Pavement," American Association of State Highway and Transportation Officials, NCHRP Report 405, Washington, D.C.

Marshall, T. R. (1967). "The Washington Degradation Test A Status Report," Washington State Highway Commission Department of Highways Materials Division, Report No 103, Olympia, WA.

McHattie, R., Retired Research Engineer, Northern Region AKDOT&PF (2012). Personal communication.

Moors, H.T. (1972). “The Washington Degradation Test Used and Abused – A Review,” Australian Road Research Board, 6th Conference, Part 5, 166-178.

Nyland, D. (2005). “Replacement of BCMoT Aggregate Degradation Test With The Micro-Deval Method Test ASTM D 6928-03” British Columbia Ministry of Transportation, Technical Circular T-06/05.

Platts, W. R. and Llyod, C. J. (1966). “Degradation of Embankment and Foundation Materials,” State of Alaska Department of Highways Materials Section, U.S. Department of Commerce Bureau of Public Roads, Washington, D.C.

Polodna, M., Structural Materials Testing Engineer, WSDOT (2012). Personal communication.

Prowell, B, Zhang, J., and Brown, E, (2005). “Aggregate Properties andthe Performance of Superpave-Designed Hot Mix Asphalt,” National Cooperative Highway Research Program, Report 539, Washington, D.C.

Richard, J, Scarlett, J (1997). “A Review and Evaluation of the Micro-Deval Test,” Public Works and Services Canada, Project 914222 Materials Testing Requirements and Procedures R&D Phase II, Ottawa, Ontario, Canada.

Saeed, A, Barker, W, Hall, J (2001). “Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers,” National Cooperative Highway Research Program, Report 453, Washington, D.C.

Schaefer, H. (2012). Personal communication.

Senior, S. A., and Rogers, C. A., 1991-2, “Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario,” Transportation Research Record 1301, Washington, D.C.

Washington State Department of Transportation (2012). “Standard Specifications for Road, Bridge, and Municipal Construction,” M 41 – 10, Olympia, WA.

Williamson, G. (2005). “Investigation of Testing Methods to Determine Long Term Durability of Wisconsin Aggregate Resource Including Natural Materials, Industrial By-Products, and Recycled/Reclaimed Materials,” Virginia Polytechnic Institute and State University, MS Thesis, Blacksburg, VA.

Wu, Y, Parker, F, Kandhal, K, (1998). “Aggregate Toughness/Abrasion Resistance and Durability Soundness Tests Related to Asphalt Concrete Performance in Pavements,” NCAT Report No. 98-4, Auburn University.