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Case study

Long term performance of gravel base course layers in asphalt pavements

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ABSTRACT

This research investigated the performance of base layer aggregates in HMA pavements using laboratory tests (standard compaction, particle size analysis, Atterberg Limits, sodium sulfate soundness, Micro-Deval abrasion, absorption, specific gravity, and soaked CBR) on existing base layer materials as well as pavement surface visual and automated distress surveys. The purpose of this research was to investigate potential degradation of aggregate bases, strength variations over time, and the likely causes for both.

Analysis of laboratory and field test results indicated significant variability in the properties and characteristics of base layer aggregate materials in various pavement test sections. Based on the results of the laboratory and field tests, the research team believes that the long-term performance of the base layer aggregates impacted the overall pavement performance of the corresponding test sections. While base aggregate materials in general did not exhibit severe degradation or disintegration – as demonstrated by laboratory tests – nor significant contamination from subgrade, the performance of such materials was lower compared with typical crushed stone materials.

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1. Introduction

Unbound aggregate base layers support traffic loads from the asphalt concrete surface layer and dissipate and transfer such loads to the underlying pavement layer or subgrade. Therefore, the unbound aggregate layers constitute a significant intermediate component that contributes to pavement stability and performance. Performance of unbound aggregate materials – crushed stone and gravel/crushed gravel bases – in base course layers depends on the characteristics/properties of the individual aggregate particles and the interaction behavior of groups of particles associated/aggregated in a matrix (e.g., in base course layers). The importance of the individual particle properties comes from its influence on the group behavior within the matrix. Relevant particle properties include: size, shape, texture, angularity, durability, specific gravity, absorption, toughness, and mineralogical composition. Relevant properties of the aggregate within a matrix (such as aggregate base layers) include shear strength, stiffness, density, resistance to permanent deformation, permeability, and frost susceptibility [1].

Saeed et al. [1] discussed the sources of distress that are attributed to the poor performance of unbound base course layers. These include:

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(a)` Fatigue cracking occurring in areas subjected to repeated traffic loading. High flexibility in the aggregate base allows excessive bending strains in the asphalt concrete surface. The same result can also be caused by inadequate thickness of the aggregate base. Changes in the base properties with time can render the base inadequate to support loads. Factors contributing to fatigue cracking as related to the base layer are: low elastic modulus of the base layer, improper gradation, high fines content, high moisture levels, lack of adequate particle angularity and surface texture (poor interlocking), and degradation under repeated loads and freeze-thaw cycling.

(b) Rutting resulting from permanent deformation in one or more layers or at the subgrade, usually caused by consolidation and/or lateral movement of the material due to load. Inadequate shear strength in the base allows lateral displacement of particles with applications of wheel loads, causing a decrease in the base layer thickness within the wheel path. Inadequate density causes settlement of the base. The contributing factors to rutting are: low shear strength of the aggregate base, inadequate compaction (as illustrated by low density), improper gradation, high fines content, high moisture levels, lack of adequate particle angularity and surface texture, and degradation under repeated loads and freeze-thaw cycling.

The purpose of this project is to investigate the long-term performance of gravel as base course layer material and assess the potential degradation over time. Aggregate degradation is defined as the breakdown of an aggregate into smaller particles [2].

2. Pavement test site selection and material sampling

Eight pavement test sections, with over 18-year-old gravel base course layers, were selected for field and laboratory investigation. Base layer gravel samples with a volume of approximately three 5-gallon buckets were collected from these sites using three different methods: coring the pavement surface; saw cutting of the pavement surface; and removing the pavement surface using the contractor's heavy equipment during reconstruction work. The aggregate samples were removed from the base layer with the aid of basic tools such as small shovels and hand-held pick-axes to dig down to the bottom of the base-course aggregate layer. It should be noted that the authors visually inspected the base course layers during sampling and looked for evidence of contamination, infiltration, or pumping of fine materials from subgrade soils.

All the investigated aggregates consisted of natural gravel and crushed gavel with various rock origins, but predominantly carbonates (limestone/dolostone). Shapes of these aggregates are mostly round and semi-round with approximately smooth texture. A detailed description of the aggregate types collected from the investigated pavement test sections is shown in Fig. 1. The thicknesses and ages of the pavement and base course aggregate layers are shown in Table 1. The age of the constructed bases ranged from 18 to more than 50 years, with thicknesses varying between 3 and 20 inches, as measured in the field.

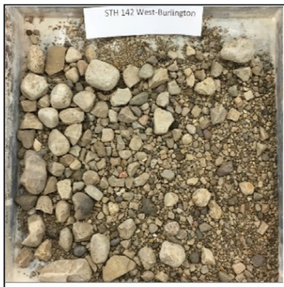
2.1. Laboratory testing of base layer gravel

The aggregate samples collected from the investigated pavement sites were subjected to the following standard test procedures: sampling aggregates (ASTM D75); reducing samples of the aggregates to testing size (ASTM C702); sieve analysis of fine and coarse aggregates (ASTM C136); specific gravity and absorption of fine and coarse aggregates (ASTM C128 and ASTM C127); standard compaction (ASTM D698); California Bearing Ratio (CBR) (ASTM D1883); Micro-Deval abrasion coarse and fine aggregates (MD) (ASTM D6928 and ASTM D7428; and sodium sulfate soundness (SSS) (ASTM C88) [3–5].

Fig. 2 depicts the particle size distribution of the investigated base aggregate as well as the historical Wisconsin Department of Transportation (WisDOT) base course layer gradation specifications corresponding to the construction year of the base layer [6]. Visual examination of the figure shows that the particle size distributions of the aggregate samples generally are outside WisDOT specification limits, particularly towards the fines fraction. The percentages of materials finer than 75 μm (#200 sieve), sand, and gravel, the observed maximum particle size (D_{max}), and the results of the Atterberg Limits (LL, PL, and PI) of base aggregate fraction finer than 0.425 mm (#40 sieve) are summarized in Table 2. Inspection of the particle size distribution data shows that three base gravel samples possessed fines (<75 μm) content greater than 10%, 12%, and 15%, which exceeds the corresponding WisDOT specifications limits at the time of base layer construction. Base gravel samples from Edgerton Avenue and STH 142 E near Burlington, WI possessed the highest percentages of fines with 34.1 and 28.0%, respectively. In total, seven base aggregate specimens possessed particle size distributions that exceeded the corresponding historical WisDOT specification limits.

Base layer materials could experience durability issues such as particle size reduction (degradation) as a result of disintegration and degradation due to factors such as heavy loads and freeze/thaw cycles, which is more significant when the aggregate material quality is poor. It may not be possible to draw conclusions regarding base gravel degradation and disintegration based only on particle size analysis.

In order to further evaluate the gravel gradation, the fineness modulus (FM) was calculated according to ASTM C125. The results are also depicted in Table 2. Inspection of the data presented shows that aggregates from STH 36 S#2, STH 142 E, STH 142 W, and Edgerton Avenue exhibited fineness modulus values of approximately $\leq$3.96, which corresponds to the current WisDOT gradation lower limit. In addition, all of these aggregates possessed a sand fraction greater than the gravel fraction (% sand size particles >% gravel size particles). Base gravel from USH 53 and USH 45 PL can also be considered among the

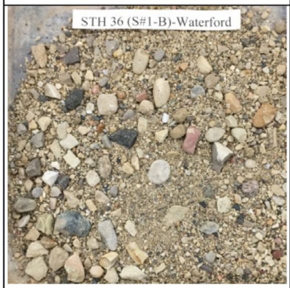


STH 142 W: Natural gravel of sedimentary rock origin (carbonates). Round and semi-round particles, large percentage with smooth surface texture, some crushed particles with semi-angular shape.

USH 45: Natural gravel of mixed rock origin – igneous, metamorphic and sedimentary (carbonates). Round and semi round particle shape and smooth surface texture; some crushed gravel particles with semi angular/angular shape and rough surface texture.

STH 142 E: Natural gravel of sedimentary rock origin (carbonates) with a smaller amount of igneous and metamorphic rock origin. Semi-round particle shape with smooth surface texture. Some crushed particles with semi-angular shape. Large size particles.

STH 32 FC: Natural gravel of igneous and metamorphic rock origin. Crushed particles of semi-round shape with smooth surface texture and some particles with semi angular particles.



STH 36 Site #1: Natural gravel of mixed rock origin with a majority of sedimentary rock (carbonates). Presence of crushed gravel of semi-round particles with smooth surface texture. Some semi-angular particles of rough surface texture present.

Edgerton Ave.: Natural gravel of sedimentary rock origin (carbonates) with lesser amounts of particles of igneous and metamorphic rocks. Semi-round particles, large percentage with smooth surface/ texture, some crushed particles with semi-angular shape.

USH 53: Natural gravel of igneous and metamorphic rock origin. Semi-round particles of smooth surface texture. Crushed gravel of semi-round particles of rough surface texture.

STH 36 Site #2: Natural gravel of mixed rock origin with a majority of sedimentary rock (carbonates). Presence of crushed gravel of semi-round particles with smooth surface texture. Some semi-angular particles of rough surface texture present.

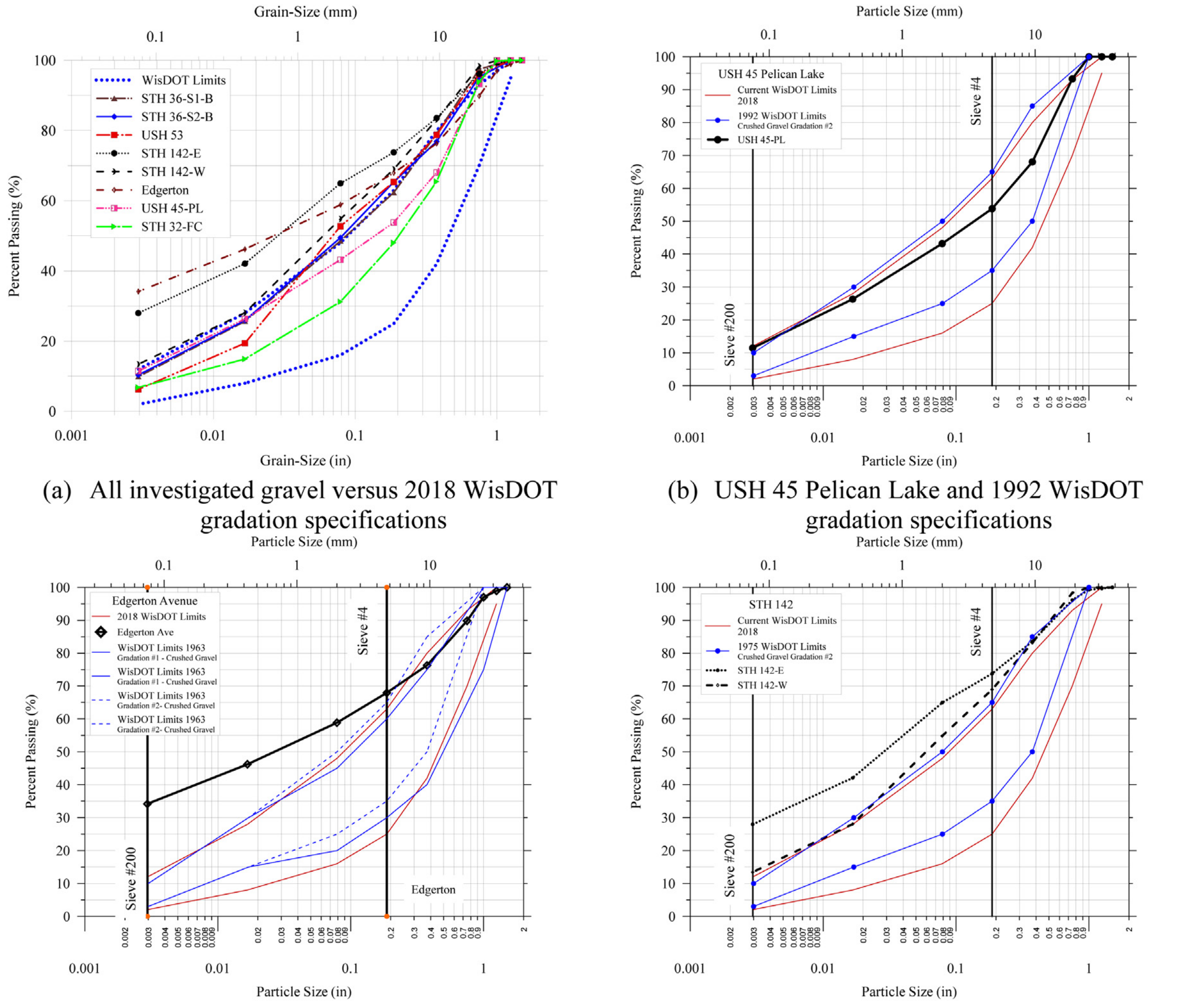
Fig. 1. Geological and particle characteristics description of the investigated base course layer gravel.

aggregates with high amounts of fine aggregates according to the FM values, which brings the total number of aggregates samples with excessive fines and sand to seven.

Another way to evaluate the base aggregate particle size distribution is by using the Grading Number (GN) defined by Dai and Kremer [7]. The maximum value of GN is 7 when 100% of the material passes sieve #200 (very fine material) and the

Table 1
Thickness and age of the base course layers at the investigated pavement sections.

Project Site	Surface Layer (HMA)		Base-Course Layer		
	Thickness (in)		Age (years)	Thickness (in)	
	WisDOT	Field		WisDOT	Field
STH 36 – Waterford	4–11	4	19	6	8
		9		4	6
USH 53 – Minong	9 (PCC)	9	18	6	6
STH 142 East – Burlington	14.5	14	43	10–12	20
STH 142 West – Burlington	8–14.5	7-10	43	10–12	5–12
Edgerton Ave –Greenfield	11	10	55	8.5	8
USH 45 Pelican Lake	6.25	5.75	26	14	10
STH 32 – Forest County	variable	10.5	55	variable	3



(a) All investigated gravel versus 2018 WisDOT gradation specifications

(b) USH 45 Pelican Lake and 1992 WisDOT gradation specifications

(c) Edgerton and 1963 WisDOT crushed gravel gradation specifications

(d) STH 142 and 1975 WisDOT crushed gravel gradation specifications

Fig. 2. Particle size distribution of the investigated base aggregates and the corresponding WisDOT gradation specification limits base course materials.

minimum value of GN is 0 when 0% passing the largest sieve (very coarse material). The calculated GN values for the investigated aggregates are presented in Table 2. The seven base aggregate samples described earlier with low FM values possess the highest GN values (~GN ≥ 4.2), indicating the presence of finer materials.

Atterberg Limits test results (Table 2) of the base aggregate fraction finer than 0.425 mm (#40 sieve) indicated that the majority of the investigated samples were non-plastic. These results are important with respect to the pumping or

Table 2
Particle size and plasticity characteristics of the investigated base aggregates.

Gravel Source	% Fines	% Sand	% Gravel	FM	GN	D_{max} (in)	Exceeding WisDOT Specs	Atterberg Limits		
								LL (%)	PL (%)	PI (%)
STH 36 S#1	9.9	52.5	36.4	3.97	4.2	1	✓	NP	NP	NP
STH 36 S#2	10.4	55.0	32.3	3.93	4.2	1	✓	NP	NP	NP
USH 53	6.3	59.1	32.7	4.07	4.2	1	✓	NP	NP	NP
STH 142 E	28.0	45.8	25.5	3.07	4.9	3	✓	20	15	5
STH 142W	13.4	55.5	31.0	3.68	4.5	3	✓	NP	NP	NP
Edgerton Ave.	34.1	33.8	29.1	3.18	4.7	1.5	✓	18	15	3
USH 45	11.5	42.3	46.2	4.3	4.0	1	✓	NP	NP	NP
STH 32	6.8	41.2	51.8	4.9	3.6	1	X	18	17	1

infiltration of fines from subgrade soils into the base course layers. The authors' visual inspection of the fines from the base aggregates indicated that these fines are of the same aggregate materials origin for the majority of the inspected samples.

Aggregate from USH 53 and STH 32 FC possessed fines contents that are comparable with subgrade soils. The percent fines in the base aggregates from Edgerton and STH 142 E are significant and with a plasticity index of 3% and 5%, respectively, indicating potential pumping and contamination of base aggregate from subgrade soils.

In order to further investigate potential pumping and contamination of the base aggregate from subgrade soils, the properties of subgrade soils were obtained from the USDA web soil survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm), soil reports and pavement coring reports available from WisDOT and private consultants, and soil testing by the research team. Fig. 3 presents a comparison of the percent fines of subgrade soils with percent fines from the investigated aggregates. Most of the subgrade soils possessed more significant amounts of fines compared with base layer gravel. When pumping occurred, fines/subgrade soil from pavement subgrade would infiltrate into the base layer material and could also be ejected to the surface through pores and cracks.

3. Durability-related tests of the investigated base gravel

3.1. Absorption

The absorption test results showed that the investigated gravel exhibited a range from 0.55% (STH 32) to 2.08% (STH 36 S-1), compared with an average of 1.35% reported by Tabatabai et al. [8,9] for Wisconsin coarse aggregates from pits. Based on the current study, five out of eight gravel samples possessed absorption values greater than the average Wisconsin coarse aggregates from pits.

3.2. Micro-deval abrasion

The mass loss (expressed as a percentage) by Micro-Deval abrasion of the number of the investigated base gravel (both coarse and fine fractions) are summarized in Table 3. Inspection of test results shows that the fine fraction exhibited more mass loss, in general, compared with coarse fraction for the same gravel source. The mass loss exhibited by fine fraction varies between 6.9% for USH 53 aggregate (fine natural sand from gravel of igneous and metamorphic rock in origin) and 16.5% for STH 36 S1 (natural gravel of mixed rock origin with a majority of sedimentary rock-carbonates). On the other hand, the mass loss for coarse aggregates fraction ranged from 7% for Edgerton Avenue aggregate (natural gravel of mixed origin, predominantly carbonates) to 14.2% for STH 36 S2 aggregate (natural gravel of mixed rock origin with a majority of sedimentary rock - carbonates).

Tabatabai et al. [8,9] conducted analysis on Micro-Deval test results on various Wisconsin coarse aggregates. The mean Micro-Deval materials loss was found to be 15.05% for coarse aggregates. Based on the average materials loss of coarse fraction, all investigated base layer gravel exhibited a mass loss <15.05%.

3.3. Sodium sulfate soundness

The sodium sulfate soundness test was conducted on the coarse and fine aggregate fractions only on three of the investigated aggregates, due to the unavailability of enough sample materials from the rest of the investigated sites. The percentages of mass loss by sodium sulfate soundness for three base aggregate samples are summarized in Table 3.

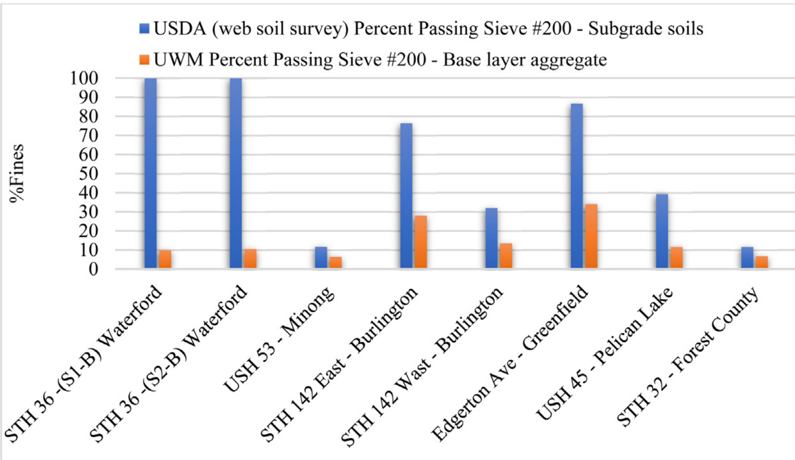


Fig. 3. Comparison of fines content in subgrade soils with fines found in the investigated base layer aggregates.

Table 3
Absorption and mass loss of coarse and fine aggregate by Micro-Deval and sodium sulfate soundness tests.

Base Layer Gravel Source	Absorption (%)	MD Mass Loss (%)		SSS Mass Loss (%)	
		Coarse	fine	Coarse	Fine
STH 36 S#1	2.08	8.4	16.5	6.6	10.8
STH 36 S#2	1.97	14.2	16.4	3.5	4.4
USH 53	1.70	13.9	6.9	3.9	5.3
STH 142 E	1.74	10.7	–	–	–
STH 142W	1.28	10.8	–	–	–
Edgerton Ave.	1.56	7.0	–	–	–
USH 45	0.95	7.3	–	–	–
STH 32	0.55	8.3	–	–	–

Examination of the test results shows that the mass losses for coarse fraction ranged from 3.5% to 6.6%, and for the fine fraction, varied between 4.4% and 10.8%. The sodium sulfate soundness test showed that the fine aggregates fraction exhibited a higher percentages of mass loss compared with the coarse aggregates fraction within the same aggregate source for the investigated aggregates (Table 3).

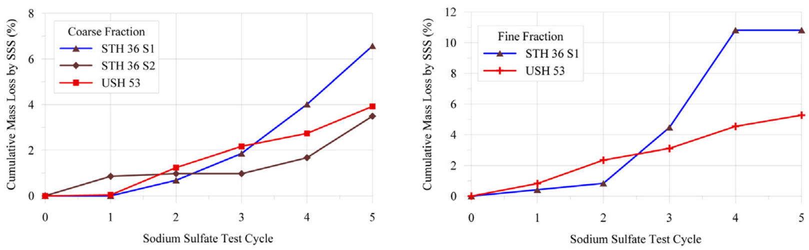
The cumulative mass loss was also determined after each sodium sulfate wetting/drying test cycle on the coarse fraction for the three samples and on the fine fraction for two samples, as depicted in Fig. 4. For the coarse fraction, the highest rate of mass loss occurred between cycles 4 and 5 for STH 36 S1 and S2 gravel samples. For the fine fraction, the highest rate of mass loss occurred between cycle 3 and 4 for STH 36 S1. Tabatabai et al. [8,9] reported that the mean for SSS test results on Wisconsin coarse aggregates from pits was 2.48% for the coarse fraction. Based on the average materials loss of coarse fraction, the three-investigated base layer gravel exhibited a mass loss >2.48%.

3.4. Analyses of durability test results

For the durability evaluation, the analysis of the Micro-Deval abrasion, sodium sulfate soundness, and absorption data was done for the investigated coarse fractions that were subjected to these tests. Regression analyses were performed on the Micro-Deval abrasion, sodium sulfate soundness, and aggregate absorption data collected for this study in combination with data obtained from other studies, namely: WHRP-1 [10], WHRP-2 [8,9], WHRP-3 and WHRP-4 [11] (data obtained from WisDOT materials testing files/database via personal communications with the research team).

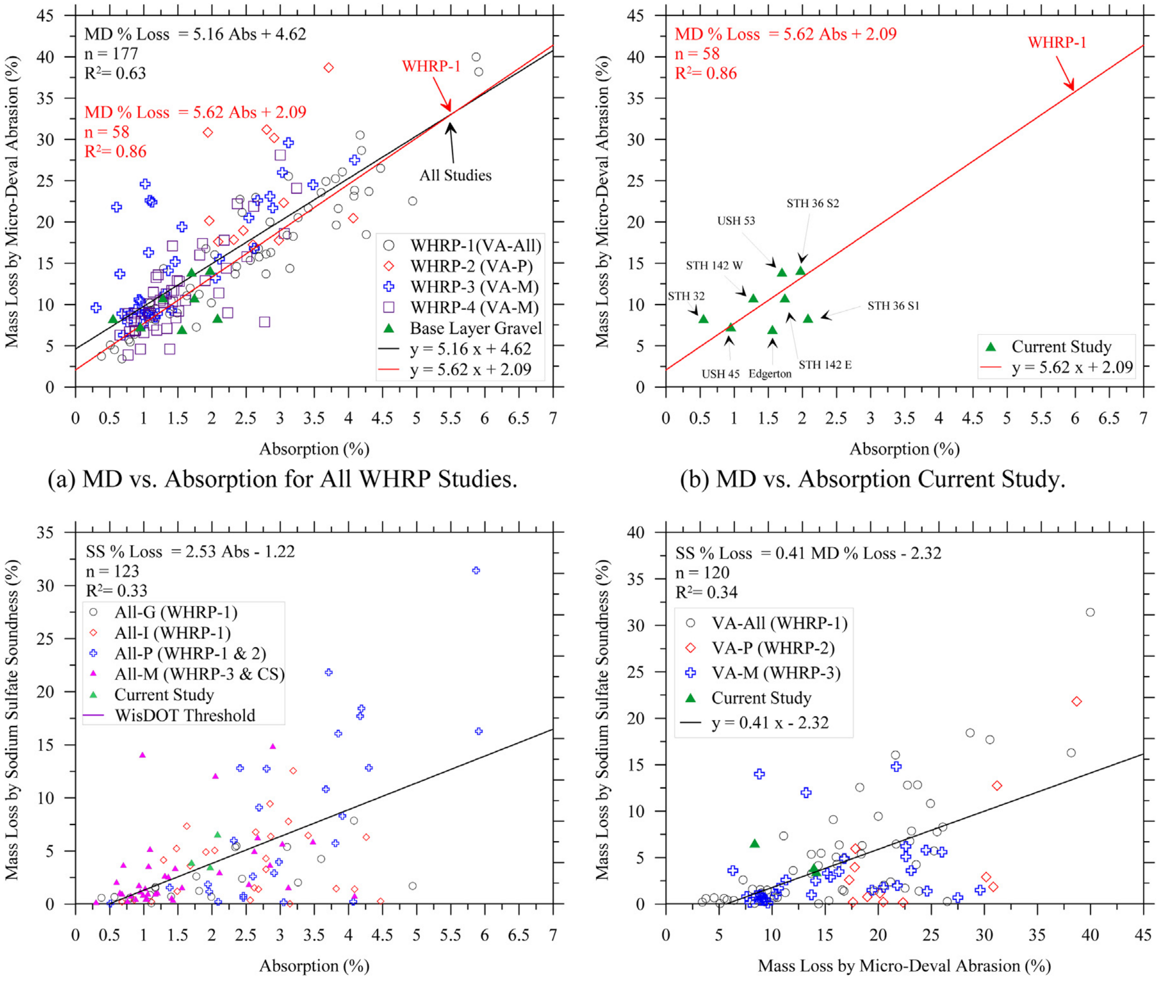
The mass losses of coarse aggregate quantified by the Micro-Deval abrasion and sodium sulfate soundness tests are plotted against absorption in Fig. 5 for various Wisconsin aggregates obtained from WHRP-1, WHRP-2, WHRP-3 and WHRP-4 studies as well as the aggregates of the current study. The best fit line for the test data points is also shown in each figure. For WHRP-1 results presented in Fig. 5a, the aggregates were obtained from Wisconsin pits and quarries (i.e., crushed stone and natural gravel) and consisted of virgin aggregates of good, intermediate, and poor performance quality as specified in Weyers et al. [10]. For this aggregate, mass loss by the Micro-Deval abrasion test ranges between 3.42% (for coarse aggregate with 0.68% absorption) and 39.98% (for coarse aggregate with 5.87% absorption). A correlation between coarse aggregate mass loss by Micro-Deval abrasion and absorption showed a coefficient of determination $R^2 = 0.86$. This trend is consistent with the results reported by Rismantojo [12] about the existence of a significant relationship between Micro-Deval abrasion and aggregate absorption.

Fig. 5b depicts comparisons of mass loss versus absorption for the investigated base layer gravel along with the best fit line for the various WHRP studies on Wisconsin virgin aggregates. Inspection of Fig. 5 (a and b) does not lead to solid conclusions with respect to a trend between the Micro-Deval abrasion test results and the gravel absorption or identifying the performance of the base aggregate layers based only on the results of the Micro-Deval test. However, both the Micro Deval abrasion and absorption test results provided important information about base layer gravel performance.



(a) Coarse aggregate fraction (b) Fine aggregate fraction

Fig. 4. Cumulative SSS mass loss per test cycle for the investigated aggregates.



(a) MD vs. Absorption for All WHRP Studies.

(b) MD vs. Absorption Current Study.

(c) SSS vs. Absorption for All WHRP Studies and the current study.

(d) SSS vs MD for All WHRP Studies the current study.

Fig. 5. Comparison of mass loss of coarse aggregates by Micro-Deval abrasion versus absorption for various Wisconsin virgin aggregates (VA: virgin aggregate, G: good performance, I: intermediate performance, and P: poor performance).

A sodium sulfate soundness test is specified as a standard acceptance test for base layer gravel with maximum loss by weight of 18% for dense graded bases and 12% for open graded bases (Section 301.2.4.5 of Wisconsin Standard Specifications for Highway and Structure Construction [6]). In order to evaluate the durability of the investigated base layer aggregate and to assess methods of identifying base layer aggregate performance, analysis was conducted on sodium sulfate soundness test results of the investigated base layer aggregate.

The mass losses of the base layer coarse aggregate quantified by the sodium sulfate soundness test are plotted against absorption in Fig. 5c and d. The best fit line for the test data points is also shown in the figure. Inspection of the figure shows that the percent mass loss ranges between 0.06% (for coarse aggregate with 0.59% absorption) and 31.42% (for coarse aggregate with 5.87% absorption). Test results from WHRP-1, WHRP-2, WHRP-3, and the current study on both virgin and base layer aggregates are presented in the figure. The best fit shown in the figure did not produce an acceptable correlation where $R^2 = 0.33$. Thus, it was reasonable to conclude that the sodium sulfate soundness test results may not be predicted solely using the aggregate absorption. It should be noted that three out of the 123 coarse aggregates with sodium sulfate test results exceeded the mass loss threshold of 18% set by WisDOT, none of which are from the investigated base layer aggregates.

4. Strength of the investigated base layer gravel

Determination of strength of the investigated base layer aggregates is important for the performance evaluation and design/analysis of pavements. California Bearing Ratio (CBR) provides a simple strength evaluation of the quality of the aggregate compared with the strength of well-graded crushed stone. In order to determine the CBR of base layer aggregate samples, they must be prepared at maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}); therefore, the standard compaction test is required to identify these two parameters.

4.1. Standard compaction test

The results of the laboratory compaction test on the base layer aggregates collected from eight sources are presented in Table 4. Inspection of the test results shows variations of the maximum dry unit weight and optimum moisture content among the investigated base layer aggregates. The range of γ_{dmax} is between 134.31 and 147.36 lb/ft^3. The optimum moisture content also varies between 5.0% and 6.60%.

4.2. California bearing ratio

The results of the soaked CBR test are depicted in Fig. 6, where the soaked base aggregate samples were prepared at maximum dry unit weight and optimum moisture content. Inspection of Fig. 6 shows that the soaked CBR values range from 20.2% for STH 142 E to 75.2% for STH 142W base aggregate. The soaked CBR test results are affected by many factors, including particle characteristics such as shape, size, size distribution, and percent fines in the aggregate specimen. In general, the base layer aggregate composed of gravel exhibited low soaked CBR values compared with typical crushed stone layer materials. The crushed stone particles with angular shape and rough surface texture result in better interlocking and resistance to penetration compared with natural gravel particles with round/semi round particles. Moreover, the presence of a large percentage of fines in the aggregate specimen attracts moisture due to soaking, which weakens the resistance to piston penetration during testing. The base layer materials composed of gravel/crushed gravel and high amounts of fines showed the lowest soaked CBR values of 20.2% and 24.3% for STH 142E (28% fines) and Edgerton Avenue (34.1) materials, respectively. The soaked CBR values are plotted against the percent fines in Fig. 7 in order to assess the possibility of correlation between the two values. The best fit line shows a weak correlation ($R^2 = 0.42$); however, the influence of the fines content on the CBR values and therefore the strength of base layer aggregate is significant.

5. Visual and automated pavement surface distress surveys

Visual surveys were conducted to identify and quantify the various types of pavement surface distress exhibited at the investigated pavements and to obtain data needed to evaluate pavement performance in terms of a Pavement Condition Index (PCI). The distress survey was conducted for one 528 ft. section at each pavement site. The section was selected to be representative of the overall pavement condition. It should be noted that the WisDOT Pavement Data Unit conducts automated pavement surface distress surveys as part of pavement management of the state/national highway network. The collected data are compiled in the Pavement Information File (PIF) database where the performance indicators such as the Pavement Condition Index and the International Roughness Index (IRI) are calculated for along the fourth $\frac{1}{10}$ of a mile for each highway segment. The research team was given time to work on the PIF workstations at WisDOT Truax Center to retrieve and analyze the corresponding pavement surveyed sections investigated in this study.

Fig. 8 depicts typical pavement surface distress, variation of ride quality, variation in the measured rutting, and Pavement Condition Index for USH 45 Pelican Lake pavement. Various pavement surface distresses were observed at USH 45 PL, including rutting and significant transverse and longitudinal cracking, as depicted in Fig. 8a. In addition, measured pavement surface profile roughness reflected on the ride quality, as indicated by the International Roughness Index shown in Fig. 8b. With such ride quality and pavement surface distresses, the Pavement Condition Index for this pavement indicated a rating that ranged between poor and very poor performance, as depicted in Fig. 8d.

Fig. 9 depicts a summary of the visual and automated distress surveys results in terms of calculated PCI and comparisons for investigated pavement test sections. The classification of the pavement condition as poor, fair, and good is also presented

Table 4
Maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}).

Project Site	Maximum Dry Unit Weight, $\gamma_{d,max}$		Optimum Moisture Content, w_{opt}
	(lb/ft^3)	(kN/m^3)	(%)
STH 36 S1	147.36	23.15	5.00
STH 36 S2	144.15	22.64	6.00
USH 53	134.31	21.10	6.40
STH 142 E	138.07	21.69	6.48
STH 142W	143.05	22.47	5.95
Edgerton Ave.	143.70	22.57	5.75
USH 45-PL	143.80	22.59	6.60
STH 32-FC	140.45	22.06	6.25

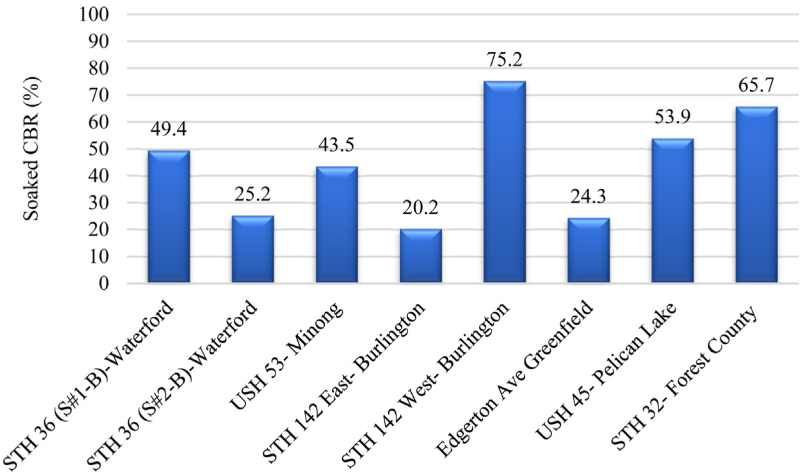


Fig. 6. Soaked CBR test results for the investigated base layer aggregates.

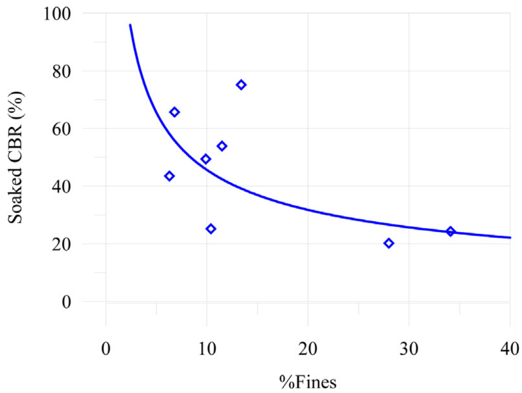


Fig. 7. Soaked CBR values versus percent fines present in the investigated base layer aggregates.

in the figure. The PCI values evaluated by the research team are in general lower than the PCI values obtained from WisDOT PIF files.

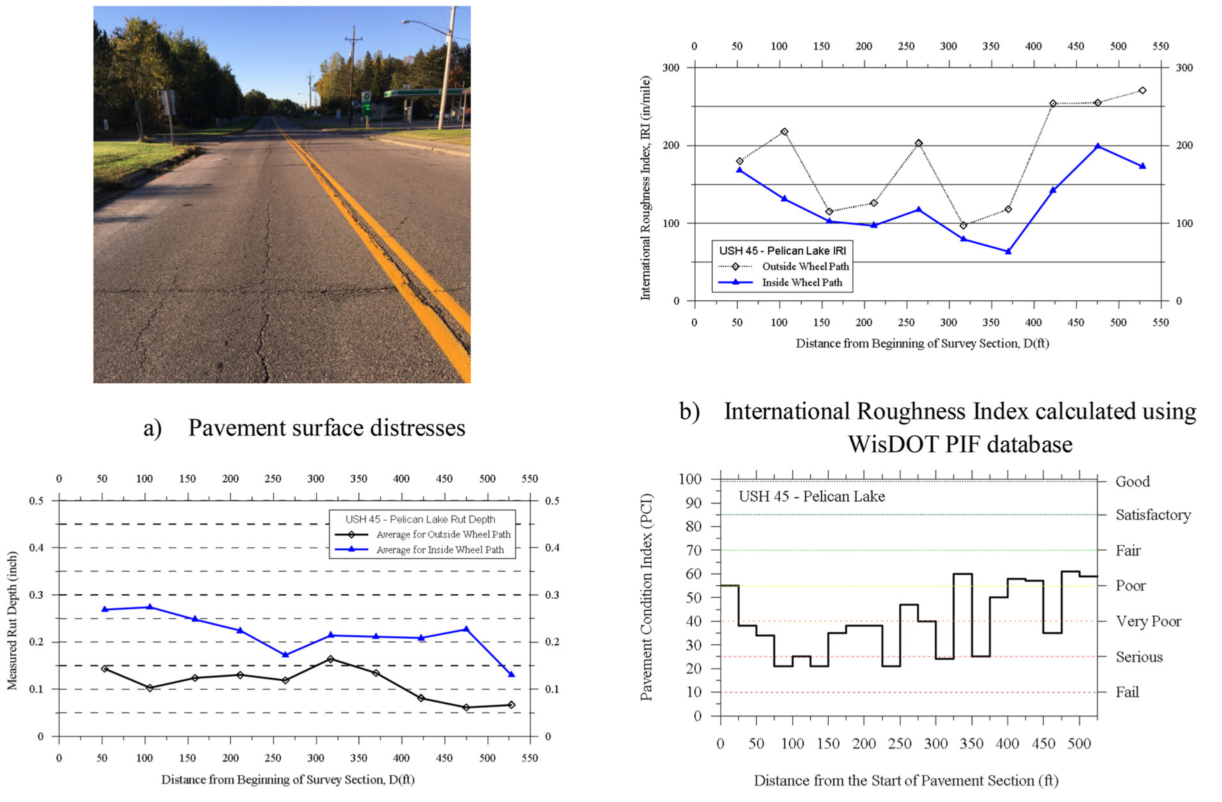
6. Evaluation of long term performance

Based on the results of the experimental program, a summary and discussions of the importance and relevance of the various conducted tests are provided in this section.

The tests that were performed could potentially be used to provide an indication of the long-term performance of gravel base layers. In terms of laboratory tests, the particle size reduction would be important because of the disintegration/breakage and degradation that could occur due to heavy loads, freeze/thaw cycles, etc. Changes in grain size distribution of base layer materials during service (from the time of original placement) could be used as a long-term indicator of durability performance of base layers. The CBR test results are related to the rock origin, grain size distribution and the amount of fines. Degraded base layer materials with a larger fraction of fines may exhibit lower CBR values. In addition, Atterberg limits of the base materials compared with those of subgrade soils are important with respect to identifying potential pumping or infiltration of fines from subgrade soils into the base layer.

Aggregate absorption results indicated reasonable correlation with the Micro-Deval abrasion test results. These tests, in addition to the soundness test, could be used to indicate the durability-related performance of base layers when compared with the original test data at the time of placement. In the absence of reference values, typical values based on the rock origin could provide a general basis for comparison.

Evaluation of pavement distress and ride quality in terms of condition and roughness indices are crucial in ranking and assessing the long-term performance of the pavement in general. Pavement surface distress related to the performance of base layers consists of fatigue cracking, rutting, and corrugation as summarized by Saeed et al. [1].



a) Pavement surface distresses

b) International Roughness Index calculated using WisDOT PIF database

c) Rut depth calculated using WisDOT PIF database

d) Pavement Condition Index calculated from the UWM visual distress survey

Fig. 8. Results of automated and visual distress surveys at USH 45 – Pelican Lake.

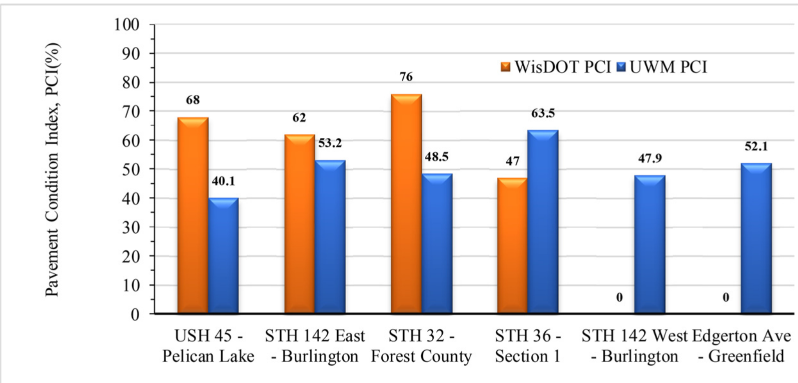


Fig. 9. Results of automated (WisDOT) and visual distress surveys (UWM).

7. Conclusions

Comprehensive field and laboratory testing programs were conducted to investigate base layer gravel at the selected pavement sites. Automated distress surveys were also conducted at the selected pavement sections. Base layer aggregate samples were collected from these pavement sites and were subjected to a comprehensive laboratory testing program including: standard compaction, particle size analysis, Atterberg Limits, sodium sulfate soundness test on both coarse and fine fractions, Micro-Deval abrasion test on both coarse and fine fractions, absorption, specific gravity, and the soaked CBR test. The collected base aggregates consisted of gravel/crushed gravel materials.

The results of sieve analysis indicated that the particle size distribution for seven of the investigated base aggregates fell outside – in part – of the corresponding WisDOT base aggregate gradation specifications, with three samples possessing % fines greater than the corresponding historical permitted % fines range of 10–15% (currently 12%). In addition, fineness modulus values for four samples were lower than the specification limit of 3.96%. It should be noted that six samples have a larger percentage of sand than gravel particles. Since these samples exceeded the corresponding gradation specification limits that were in effect at the time of construction, this result could be due to degradation and disintegration of aggregate particles from the impact of the freeze-thaw cycles coupled with repeated traffic loads. It should be mentioned that the historical gradation specifications were obtained for a number of these pavements and therefore the gradation of these materials was compared with the specifications at the time of construction.

The results of Atterberg Limits test showed that fines found in five of the aggregate samples were non-plastic, with only three samples possessing plastic fines with very low plasticity index. Visual inspection and comparisons with subgrade soils did not show – in general – a widespread pumping and contamination of the base layers from subgrade soils.

The absorption values of the investigated base aggregates varied between 0.55–2.08%, compared with 1.35%, the average coarse aggregate absorption obtained from earlier studies conducted on Wisconsin virgin aggregates [8,9]. Consequently, five gravel/crushed gravel samples possessed absorption values >1.35%.

Micro-Deval abrasion test results showed that fine aggregates exhibited more mass loss, in general, compared with coarse aggregates from the same aggregate source. The mass loss exhibited by the fine aggregate fraction varied between 6.9% and 16.5%. and ranged from 7% to 14.2% compared with a mean mass loss of 15.05% for Wisconsin virgin coarse aggregates obtained by Tabatabai et al. [8,9]. Earlier WHRP studies [8–10] indicated a correlation between aggregate absorption and Micro-Deval abrasion mass loss.

Sodium sulfate test results showed that fine aggregates exhibited more mass loss, in general, compared with coarse aggregates for the same aggregate source. For fine aggregates, the mass loss varied between 4.4% and 10.8%, and ranged from 3.5% to 6.6%, compared with a mean mass loss of 3.36% for Wisconsin virgin coarse aggregates by Tabatabai et al. [8,9]. Based on the WisDOT threshold mass loss limit of 18%, no base aggregate samples possessed mass loss values greater than 18%.

Strength evaluations of the investigated base aggregates and pavement test sections were achieved via soaked CBR, where test results ranged from 20.2% to 75.2%. The soaked CBR test results showed, in general, low CBR numbers, especially for aggregate samples with larger fines amounts and for gravel/crushed gravel aggregate samples.

The visual and automated distress surveys results in terms of calculated PCI and IRI comparisons for investigated pavement test sections showed high variability with pavement conditions classified ranging from poor to good. The PCI values calculated by the research team are in general lower than the PCI values obtained from WisDOT PIF files.

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References

[1] A. Saeed, J. Hall, W. Barker, “Performance-related test of aggregates for use in unbound pavement layers,” national cooperative highway research program (NCHRP) report 453, Transportation Research Board, National Research Council, Washington, D.C, 2001.
[2] R.D. Barksdale, The Aggregate Handbook, 4th ed, National Stone, Sand and Gravel Association, 2001.
[3] ASTM Standard Specification, Concrete and Aggregates, vol. 04.02, ASTM International, West Conshohocken, PA, 2018.
[4] ASTM Standard Specification, Road and Paving Materials; Vehicle-pavement Systems, vol. 04.03, ASTM International, West Conshohocken, PA, 2018.
[5] ASTM Standard Specification, Soil and Rock (I), vol. 04.08, ASTM International, West Conshohocken, PA, 2018.
[6] Wisconsin Department of Transportation (WisDOT), Standard Specifications for Highway and Structure Construction, 2018 ed., Madison, Wisconsin, 2018.
[7] S. Dai, C. Kremer, Improvement and validation of Mn/DOT DCP specifications for aggregate base materials and select granular (No. MN/RC-2005-32), Office of Materials Minnesota Department of Transportation, (2006) .
[8] H. Tabatabai, H.H. Titi, C.W. Lee, I. Qamhia, G. Puerta Fella, Investigation of testing methods to determine Long-term durability of Wisconsin aggregates, Research Report, Wisconsin Department of Transportation SPR # 0092-10-08, Wisconsin Highway Research Program, Madison, WI, 2013.
[9] H. Tabatabai, H.H. Titi, C.W. Lee, Assessment of tests to determine long-term durability of Wisconsin aggregates, J. Mater. Civil Eng. ASCE (2018), doi: http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0002463.
[10] Weyers, R.E., Williamson, G.S., Mokarem, D.W., Lane, D.S., and Cady, P.D. (2005). Testing methods to determine Long term durability of Wisconsin aggregate resources, Wisconsin Highway Research Program SPR# 0092-02-03, WHRP 06-07, 91.
[11] Wisconsin Department of Transportation (2018). Truax center materials testing unit, bureau of technical services, via personal communications with the research team.
[12] E. Rismantojo, Permanent Deformation and Moisture Susceptibility Related Aggregate Tests for Use in Hot-Mix Asphalt Pavements Ph.D. Thesis, Purdue University, West Lafayette, IN, 2002.