Performance of Steel Slag Aggregates in Hot-Mix Asphalt Pavement

A Report to the State Legislature
In Response to ESSB 6106, Section 307 (14)

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

During the 2015 session, the Washington State Legislature directed the Washington State Department of Transportation (WSDOT) to "… examine the use of electric arc furnace slag for new roads and paving projects …" In response, WSDOT prepared a review of available literature examining the properties of steel slag aggregate (SSA) and its use as an aggregate for pavement construction. The literature indicated that SSA is a viable substitute for some of the natural aggregate in hot mix asphalt (HMA) pavement. As a part of the literature review, WSDOT proposed a trial project in 2016 to evaluate the use of SSA on a WSDOT paving project.

WSDOT constructed the SSA trial section on SR 203 near Carnation in 2016. During the 2017 session, the Legislature provided further direction by instructing WSDOT to report on the trial section's "comparative wear resistance, skid resistance, and feasibility for use throughout the state in new pavement construction." This report fulfills that requirement.

The 2016 trial project included a one-mile trial section of hot-mix asphalt pavement constructed using steel slag aggregate as a replacement for 20 percent of the coarse aggregate in the HMA. The trial section was part of a project that improved five miles of SR 203 by grinding out the existing pavement and replacing it with new pavement. Construction of the remainder of the HMA used natural aggregates and served as the control section to compare against the performance of the steel slag aggregate trial section.

Trial Project Findings:

- Construction of the SSA trial section went smoothly without any major problems.
- Based on two years of post-construction testing, there was not a significant difference in performance. Wear/rutting and friction measurements were very similar between the SSA section and control sections. Friction measurements were within the normal range for new HMA pavement for both pavements.
- The cost of the SSA mix was about 24 percent higher than the cost of the conventional mix on the trial project. The higher cost would require a pavement life extension of four additional years over conventional HMA mix for the SSA trial section to be cost neutral.

Conclusions/Recommendations:

- The overall performance of HMA with 20 percent SSA is acceptable.
- WSDOT should continue to allow SSA as a replacement for up to 20 percent of the coarse aggregate in all HMA pavement statewide.
- Specific project economics, as opposed to mandated use, should dictate the use of SSA on future WSDOT projects. The cost of SSA can vary, depending on a number of factors including project location, distance from SSA sources, costs to transport, and natural aggregate availability. Mandated use would likely result in higher project costs that may not be matched by higher pavement performance or longer life.
- No further SSA trial sections or implementation efforts should be pursued at this time.

Background

In 2015, 2ESHB 1299 required the Washington State Department of Transportation (WSDOT) to study the use of electric arc furnace slag as aggregate in pavements as noted below:

> "The department shall examine the use of electric arc furnace slag for use as an aggregate for new roads and paving projects in high traffic areas and report back to the legislature on its current use in other areas of the country and any characteristics that can provide greater wear resistance and skid resistance in new pavement construction."

As a result, WSDOT prepared a literature review examining the properties of steel slag aggregate (SSA) and its use in both hot-mix asphalt (HMA) and cement concrete pavements. The report titled *WSDOT Strategies Regarding use of Steel Slag Aggregate in Pavements; A Report to the State Legislature in Response to 2ESSB 1299* provided the following recommendations on the use of SSA HMA in the state:

- The initial use of SSA at more than 20 percent of the total aggregate should be limited to surface courses of HMA and chip seals.
- All projects using more than 20 percent of SSA should be experimental features that compare their performance to control sections built with natural aggregates.

Action took place in 2016 on the second recommendation with the construction of a test section of HMA using 20 percent SSA to replace natural aggregates. Additional legislative action taken in 2017 under ESSB 6106 stated the following in Section 307 (14):

> "The department shall continue to monitor the test patch of pavement that used electric arc furnace slag as an aggregate and report back to the legislature by December 1, 2018, on its comparative wear resistance, skid resistance, and feasibility for use throughout the state in new pavement construction."

This report details the construction of the trial project, comparative wear and skid resistance data, and an assessment of the feasibility of using steel slag aggregates in new pavements throughout the state.

Project Location

The SSA trial section, constructed as part of Contract 8866, NE 24th St Vic to Tolt River Bridge Paving and ADA Compliance, is located on State Route (SR) 203, a rural minor arterial highway located in King County. The project resurfaced the existing pavement from Fall City to Carnation between state route mileposts (MP) 0.09 and 5.32.

The first step in the experimental evaluation was the collection of the data on the condition of the existing pavement on SR 203. Figure 1 shows the pavement layer types, thickness and construction year for this section of SR 203. The acronym BST in the figure stands for bituminous surface treatment also commonly referred to as a chip seal.

0.15' HMA (1996)
0.06' BST (1989)
0.15' HMA (1973)
0.06' BST (1963)
0.12" BST (1949)
0.06 BST (1939)
0.25' Crushed Stone (1939)
1.00' Untreated Base (1939)

Figure 1. The existing pavement structure.

The pavement surface was in fair condition with low to medium severity alligator cracking, low and medium severity longitudinal cracking, low severity transverse cracking and medium severity patching. Table 1 lists the Washington State Pavement Management System (WSPMS) pavement structural condition (PSC), wear/rutting measurements and roughness data for the trial and control sections. The data shows that there was very little difference between the pavement condition of the trial and control sections.

The wear/rutting was minimal at approximately 1/4 inch on both sections. The term wear/rutting is used for HMA pavements because the measurement may include both wear from studded tires and rutting from traffic consolidating or displacing the pavement in the wheel paths.

The control section pavement was slightly rougher than the trial section pavement when tested in 2015. The difference in roughness between the trial and control sections should have no detrimental effect on the skid resistance or wear/rutting of the new pavement surface, which is the major focus of the experiment.

The 2016 average annual daily traffic (AADT) for the entire section was 7,288 vehicles of which 10 percent were trucks.

Table 1. WSPMS data for the trial and control section. (2015)

Property	Trial Section	Control Section
Average Pavement Structural Condition (PSC)*	68	66
Range of PSC	51 - 85	28 - 92
Average Wear/Rutting (inches)	0.25	0.22
Roughness, IRI, (inches per mile)	77	116

* PSC is a measure of the amount of cracking in the pavement. PSC ranges from 100 for a pavement with no cracking to zero, a pavement that is in very poor condition.

The similarity of the pavement structure and performance data indicates that there was no substantial difference in the condition of the pavement underlying the SSA trial section versus that of the control section; therefore, any performance differences noted between the two can be attributed to the use of the steel slag aggregate.

Project Description

Watson Asphalt Paving Company (WAPC), located in Redmond, WA built the project. The top layer of the existing pavement was removed by milling 0.15 feet (1.8 inches) and replaced with 0.15 feet of new HMA. The milled and filled area extended 1-foot outside the fog lines of both lanes. Steel slag aggregate replaced 20 percent of the natural aggregates in the trial section that included both lanes between MP 3.78 and 4.87. The remainder of the project was constructed using natural aggregates and serves as the control section against which the performance of the trial section will be judged.

Mix Designs

Contractors must use a WSDOT approved mix design for each class of HMA specified on a project. WSDOT tests the submitted mix designs to assure that the contractor's design has; (1) the correct proportioning and gradation of aggregates, (2) the optimum asphalt binder content, (3) is not susceptible to moisture damage, (4) can be compacted to an acceptable density in a gyratory compactor, (5) will withstand repeated wheel loadings without excessive rutting, and (6) has sufficient strength to resist cracking under load.

Conventional Class 1/2 Inch HMA

WAPC submitted their design using natural aggregates from commercial pit site A309, PG64-22 performance graded asphalt binder supplied by U.S. Oil and Refining, and ZycoTherm anti-stripping additive supplied by Zydex Industries, Inc. The anti-stripping additive improves the adhesion between the asphalt binder and the aggregate in the presence of moisture to prevent water damage (stripping) of the HMA. The dosage rate for the anti-stripping additive was 0.10 percent by weight of asphalt binder. The mix ID for this design is MD150048. Table 2 shows the stockpile designations, gradations, proportion of each stockpile, the resulting combined job mix formula (JMF), the specification, and the tolerance limits for the aggregate portion of the mix design.

Table 2. Conventional Class 1/2 Inch HMA mix design gradation (MD150048).

Material	5/8" – 3/8"	3/8" – No. 0	No. 4 – 0	Combined (JMF)	Specification	Tolerance
Ratio	28.0%	62.0%	10.0%			
3/4 in.	100.0	100.0	100.0	100	99 – 100	99 – 100
1/2 in.	79.8	100.0	100.0	94	90 – 100	90 – 100
3/8 in.	30.4	98.6	100.0	80	90 Max	74 – 86
No. 4	2.9	61.5	100.0	49		44 – 54
No. 8	2.4	43.4	84.7	36	25 – 58	32 – 40
No. 16	2.3	24.2	44.1	20		
No. 30	2.2	17.2	25.3	14		
No. 50	2.2	12.1	7.3	9		
No. 100	2.0	8.9	2.8	6		
No. 200	1.6	7.0	1.9	5.0	2.0 – 7.0	3.0 – 7.0

WSDOT verified the mix design by testing the asphalt binder and aggregate supplied by the Contractor. The mix design was targeted to meet 4.0 percent air voids (Va) at 100 (Ndesign) gyrations at a binder content (Pb) of 5.4 percent. Table 3 contains the verification data for samples at three binder contents with the sample at 5.4 percent binder content meeting all specifications.

Table 3. WSDOT verification test data for the conventional Class 1/2 Inch HMA (MD150048).

Mix Design Property	Gyrations	Trial Designs			Specification
Pb (% asphalt)		4.9	5.4	5.9	
% Gmm @ Ninitial	8	84.4	86.1	87.3	≤ 89.0
% Va @ Ndesign	100	6.7	4.4	2.7	2.5 - 5.5
% VMA @ Ndesign	100	15.0	14.1	13.7	≥ 14.0
% VFA @ Ndesign	100	55	69	81	65 - 75
% Gmm @ Nmax	160		97.6		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.4	1.2	1.1	0.6 – 1.6
Pbe		3.7	4.2	4.7	
Gmm		2.507	2.486	2.467	
Gmb		2.339	2.377	2.401	
Gb		1.028	1.028	1.028	
Gse		2.707	2.705	2.705	
Hamburg Wheel-Test (mm)			5.3		≤ 10.0
Stripping Inflection Point			Pass		None @ 15,000
Indirect Tensile Strength			104		≤ 175

Va = air voids   VMA = voids in the mineral aggregate   VFA = voids filled with asphalt
D/A = percent passing #200 to asphalt binder content ratio   Pbe = effective asphalt content
Gmb = bulk specific gravity   Gmm = rice specific gravity   Gsb = bulk specific gravity of aggregate
Gb = specific gravity of asphalt binder

SSA Class 1/2 Inch HMA

The SSA mix design used natural aggregate from pit site A309, steel slag aggregate supplied by the Levy Company, PG64-22 binder supplied by U.S. Oil & Refining, and ZycoTherm anti-stripping additive from Zydex Industries. The dosage rate for the anti-stripping additive was 0.05 percent. Table 4 shows the stockpile designations, gradations, proportion of each stockpile, the resulting combined JMF, the specification, and the tolerance limits for the aggregate portion of the SSA mix design.

WSDOT verified the mix design by testing the asphalt binder and aggregate supplied by the Contractor. The design was targeted to meet 4.0 percent air voids (Va) at 100 (Ndesign) gyrations at binder content (Pb) of 5.6 percent. Table 5 contains the verification data for the mix design showing that the sample with 5.6 percent binder met specifications.

Table 4. SSA Class 1/2 Inch HMA mix design gradations (MD160070).

Material	5/8"-3/8"	3/8"-No. 4	Fine Aggregate	Steel Slag	Bag House Dust	Combined (JMF)	Specification	Tolerance
Ratio	21.0%	31.0%	27.0%	20.0%	1.0%			
3/4 in.	100.0	100.0	100.0	100.0	100.0	100	99 – 100	99 – 100
1/2 in.	79.1	100.0	100.0	81.7	100.0	92	90 – 100	90 – 98
3/8 in.	34.6	98.4	100.0	63.5	100.0	78	90 Max	72 – 84
No. 4	2.7	61.6	100.0	33.3	100.0	54		48 – 60
No. 8	1.7	38.8	75.0	18.2	100.0	37	25 – 58	31 – 43
No. 16	1.5	25.5	48.2	11.1	100.0	24		
No. 30	1.4	19.1	24.8	7.1	100.0	15		
No. 50	1.3	10.5	10.5	4.8	100.0	8		
No. 100	1.1	9.5	2.8	3.1	95.0	6		
No. 200	0.8	6.7	1.0	2.0	90.0	3.8	2.0 – 7.0	2.0 – 5.8

Table 5. WSDOT verification test data for SSA Class 1/2 Inch HMA mix design (MD160070).

Mix Design Property	Gyrations	Trial Designs			Specification
Pb		5.1	5.6	6.1	
% Gmm @ Ninitial	8	85.6	87.0	88.1	≤ 89.0
% Va @ Ndesign	100	6.4	4.1	2.8	2.5 – 5.5
% VMA @ Ndesign	100	16.2	15.2	15.0	≥ 14.0
% VFA @ Ndesign	100	61	73	82	65 - 75
% Gmm @ Nmax	160		97		≤ 98.0
Dust to Asphalt Ratio (D/A)		0.9	0.8	0.8	0.6 – 1.6
Pbe		4.2	4.7	5.1	
Gmm		2.596	2.576	2.561	
Gmb		2.431	2.473	2.491	
Gb		1.028	1.028	1.028	
Gse		2.828	2.829	2.835	
Hamburg Wheel-Test (mm)			3.9		≤ 10.0
Stripping Inflection Point			Pass		None @ 15,000
Indirect Tensile Strength			93		≤ 175

Va = air voids   VMA = voids in the mineral aggregate   VFA = voids filled with asphalt
D/A = percent passing #200 to asphalt binder content ratio   Pbe = effective asphalt content
Gmb = bulk specific gravity   Gmm = rice specific gravity   Gsb = bulk specific gravity of aggregate
Gb = specific gravity of asphalt binder

Construction

Conventional Class 1/2 Inch HMA

Paving of the conventional mix took place between June 29 and October 11, 2016. A site visit by the Pavement Office on June 29, 2016 observed the paving operation. The weather was clear with ambient air temperature of 75°F and surface temperatures near 73°F although closer to 80°F nearest the paver during paving. The temperature of the mix at the screed was consistently around 290°F. The asphalt tack, which provides adhesion between the existing pavement and the new pavement, was delivered in a Bearcat distributor truck that applied CSS-1 at a rate of 0.05 gal/yd^2 at a temperature of 150°F. Dump trucks with pup trailers or flow boys were used to transport the HMA from the plant to the jobsite located approximately 20 minutes away (about 15 miles). The trucks dumped into a Roadtec Shuttle Buggy SB2500B Material Transfer Vehicle (MTV) for remixing prior to the transfer into the paver. A BG1055E Barber Greene paver equipped with a paver hopper (to hold additional material) and a CAT AS3301C screed laid down the mat. The compaction equipment consisted of a HAMM HD 120 oscillation steel-wheel breakdown roller used in vibratory mode, a Sakai GW 750-2 pneumatic vibratory intermediate roller used in vibratory mode, and a Sakai SW850 steel-wheel vibratory finish roller operated in non-vibratory mode. Figure 2 through Figure 9 show the construction process for the conventional mix in the control section.

Figure 2. Bearcat distributor on milled surface.

Figure 3. Milled surface with CSS-1 tack coat.

Figure 4. Flow Boy truck delivery to Shuttle Buggy MTV.

Figure 5. Shuttle Buggy MTV delivering HMA into hopper on the paving machine.

Figure 6. Barber Greene paver with storage hopper.

Figure 7. HAMM HD 120 steel wheel oscillatory breakdown roller.

Figure 8. Sakai GW 750-2 pneumatic vibratory intermediate roller.

Figure 9. Sakai SW850 steel wheel vibratory finish roller.

Paving proceeded in the northbound direction beginning at MP 0.09. The breakdown roller was rolling from the hot side of the joint approximately four minutes behind the screed. The total time for the breakdown rolling was about seven minutes. The intermediate roller was approximately seven minutes behind the screed and took approximately eight minutes to compact the mat. The finish roller was 11 minutes behind the screed and took approximately 10 minutes to complete compaction.

Infrared photos of the freshly placed HMA behind the paver show consistent temperatures across the width of the pavement indicating that the remixing produced a uniform mix (Figure 10). The temperature scale is the bar on the right side of the photo with white being the hottest and blues the coldest temperatures. The uniform red color across the width of the screed indicates minimal temperature differences in the mix. Individual temperature measurements are noted on the photo at Sp1 and Sp2. Also noted are two transverse temperature profiles, Li1 and Li2, showing the average temperature across the line as well as the minimums and maximums.

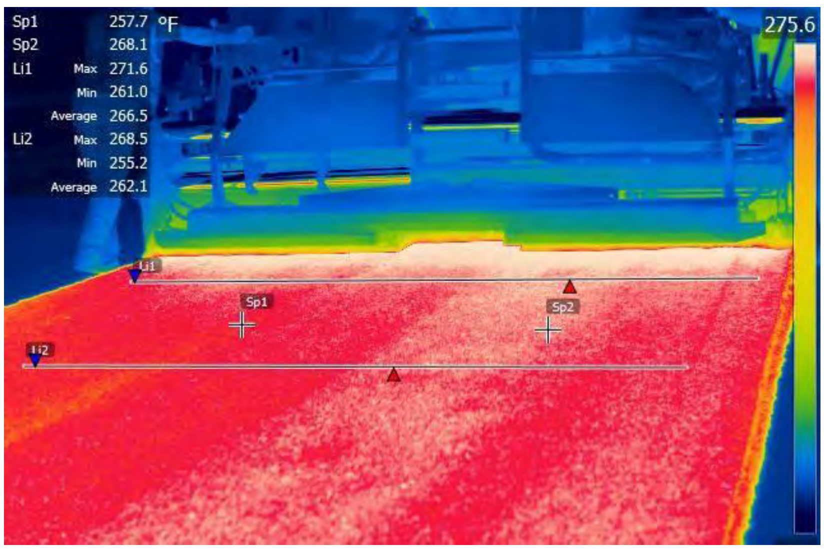

Figure 10. Infrared photo of the conventional HMA mix showing the temperature of the pavement behind the paver.

SSA Class 1/2 Inch HMA

The trial section of SSA Class 1/2 inch HMA was placed on the nights of October 10 and 11, 2016. A member of the Pavement Office visited the site on the first night of construction. The weather was clear and substantially cooler than the June site visit. Initial ambient air temperatures of 42°F dropped to a low of 38°F during construction. The temperature of the HMA in the trucks was approximately 300°F. The pavement surface temperature, directly in front of the screed, was around 48°F and temperature of the mix at the screed was 295°F.

The compaction equipment for the SSA mix was the same as that used on the conventional HMA mix; however, their order was different. Breakdown rolling was accomplished with the Sakai SW850 steel-wheel roller used in vibratory mode, intermediate rolling by the Sakai GW 750-2 pneumatic roller in vibratory mode, and finish rolling by the HAMM HD 120 oscillation steel-wheel roller used in non-vibratory mode. The breakdown roller continued the process of rolling from the hot side and was about one minute behind the paving screed. The total time for breakdown rolling was approximately six minutes. The intermediate roller was approximately nine minutes behind the screed and the total time for intermediate rolling was generally five minutes. The finish roller was 45 minutes behind the screed and took about 14 minutes to complete. Figure 11 shows the uniform red color of the mix across the width of the pavement indicating uniform temperatures.

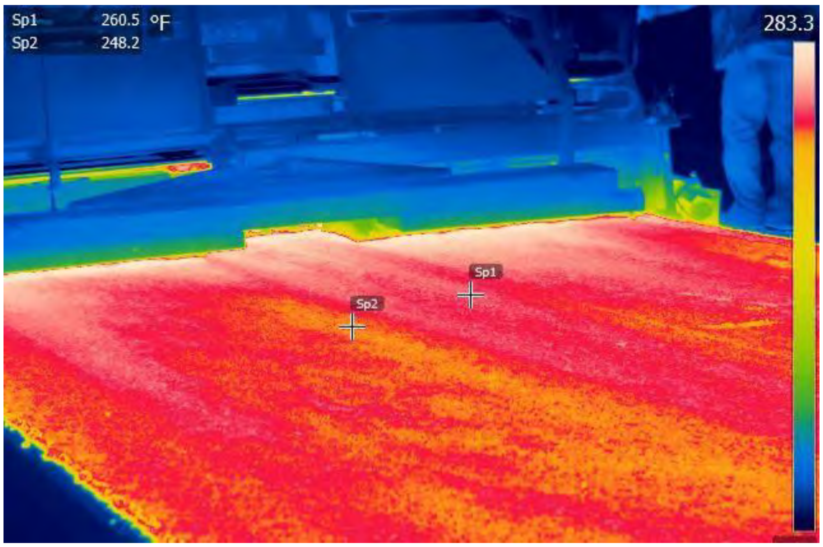

Figure 11. Infrared photo of the SSA mix showing the temperature of the pavement behind the paver.

Production Mix Testing

Conventional Class 1/2 Inch HMA

The asphalt mix was sampled during the paving operation to make sure that the gradation of the aggregates, asphalt content, and volumetric properties met specifications. The average test results for these properties remained constant throughout production for the conventional Class 1/2 inch HMA. Table 6 shows the JMF, upper and lower acceptance criteria, standard deviation and mean results for the control section. Although the gradation had a higher percent passing for all sieves, the average gradation results fell within specification limits.

Table 6. Conventional mix (MD150048) gradation job mix formula, average gradation, upper and lower limit acceptance criteria, standard deviation and mean data.										
Sieve Size	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Percent Passing	100	94	80	49	36	20	14	9	6	5
Sublot Average	100	95	84	52	35	24	17	12	8	6.3
Upper Acceptance	100	100	90		58					7
Lower Acceptance	99	90			28					2
Std. Deviation	0.0	1.2	1.6	2.2	1.7	1.2	1.0	1.0	0.8	0.5
Mean	100	95	83	52	34	23	17	12	8	6.3

The sublot gradation test results are listed in Table 7, with each sublot consisting of 1,000 tons of mix. Sublot 001 was above the upper specification limit on the #200 sieve. The remaining sublots were all within specification limits.

Table 7. Conventional mix (MD150048) sublot gradation data.											
Sublot	Date	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF	-	*100*	*94*	*80*	*49*	*36*	*20*	*14*	*9*	*6*	*5*
001	6/28	100	94	85	55	37	25	18	13	10	7.5
002	6/28	100	94	82	53	35	25	18	13	9	7.0
003	6/29	100	95	83	50	34	23	17	12	9	6.7
004	6/29	100	94	82	50	33	23	16	12	8	6.4
005	6/30	100	95	84	52	34	23	17	12	8	6.2
006	7/20	100	94	81	50	33	23	16	12	8	6.4
007	7/21	100	94	82	48	32	22	16	11	8	5.9
008	7/26	100	97	86	54	37	24	17	12	8	5.8
009	8/29	100	94	83	53	35	24	17	12	8	6.1
010	9/21	100	97	85	55	36	24	17	12	8	6.1
011	9/21	100	95	84	51	34	23	16	11	8	5.8
012	10/11	100	96	85	55	37	25	17	12	9	6.2
Sublot Average		100	95	84	52	35	24	17	12	8	6.3

The JMF, upper and lower acceptance criteria, standard deviation and mean results for the asphalt content and volumetric properties are listed in Table 8. All volumetric results fell within specification limits.

Table 8. Conventional mix (MD150048) volumetric JMF, upper and lower acceptance criteria, mean and standard deviation data.

	Binder (%)	Va (%)	VMA (%)	VFA (%)	D/A	Pbe (%)	Gmb	Gmm	Gsb	Gb
Volumetric JMF	5.4	4.4	14.1	69	1.2	4.2	2.377	2.486	2.705	1.028
Sublot Average	5.5	4.0	13.9	72	1.5	4.3	2.383	2.482	2.624	1.028
Upper Acceptance	5.9	5.5			1.6					
Lower Acceptance	4.9	2.5			0.6					
Mean	5.5	4.1	14.0	70.8	1.5	4.3	2.380	2.482	2.617	1.028
Std. Deviation	0.2	0.9	0.5	5.8	0.1	0.2	0.0	0.0	0.0	0.0

Va = air voids VMA = voids in the mineral aggregate VFA = voids filled with asphalt
D/A = percent passing #200 to asphalt binder content ratio Pbe = effective asphalt content
Gmb = bulk specific gravity Gmm = rice specific gravity Gsb = bulk specific gravity of aggregate
Gb = specific gravity of asphalt binder

The JMF sublot volumetric and binder percentage data show that the control on the aggregate production was consistent (see Table 9).

Table 9. Conventional mix (MD150048) sublot volumetric and percent binder data.

Sub Lot	Date	Binder (%)	Va (%)	VMA (%)	VFA (%)	D/A	Pbe (%)	Gmb	Gmm	Gsb	Gb
JMF	-	*5.4*	*4.4*	*14.1*	*69*	*1.2*	*4.2*	*2.377*	*2.486*	*2.705*	*1.028*
001	6/28	5.4	2.9	13.1	78	1.7	4.4	2.404	2.475	2.617	1.028
002	6/28	5.1	4.3	13.7	69	1.7	4.1	2.380	2.487	2.617	1.028
003	6/29	5.3	4.9	14.1	65	1.7	4.0	2.373	2.495	2.617	1.028
004	6/29	5.2	4.9	14.1	65	1.6	4.0	2.372	2.493	2.617	1.028
005	6/30	5.3	4.7	14.2	67	1.5	4.1	2.370	2.488	2.617	1.028
006	7/20	5.7	2.9	13.7	79	1.4	4.6	2.396	2.467	2.617	1.028
007	7/21	5.3	4.5	14.2	68	1.4	4.2	2.371	2.482	2.617	1.028
008	7/26	5.6	4.6	15.1	70	1.3	4.6	2.354	2.468	2.617	1.028
009	8/29	5.7	3.8	13.9	73	1.4	4.4	2.390	2.484	2.617	1.028
010	9/21	5.8	3.5	13.7	74	1.4	4.4	2.397	2.484	2.617	1.028
011	9/21	5.7	3.8	13.8	72	1.3	4.3	2.391	2.486	2.617	1.028
012	10/11	5.9	2.5	13.3	81	1.3	4.6	2.410	2.471	2.617	1.028
Sublot Average		5.5	4.0	13.9	72	1.5	4.3	2.383	2.482	2.624	1.028

SSA Class 1/2 Inch HMA

The SSA mix was also tested during production to assure that the mix was being produced according to all specifications. Average test results for gradation, asphalt content and volumetric properties remained constant throughout production. Table 10 contains the JMF, upper and lower acceptance criteria, standard deviation and mean results for the gradation of the SSA Class 1/2 inch HMA trial section during production.

Table 10. SSA Class 1/2 inch HMA trial section JMF percent passing, upper and lower limit acceptance criteria, standard deviation and mean data (MD160070).										
Sieve Size	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Percent Passing	*100*	*92*	*78*	*54*	*37*	*24*	*15*	*8*	*6*	*3.8*
Sub Lot Average	100	94	83	59	41	26	17	10	7	4.5
Upper Acceptance	100	98	84	60	43					5.8
Lower Acceptance	99	90	72	48	31					2
Std. Deviation	0	0	2.3	1.7	1.2	0.6	0.6	0.6	0.6	0.3
Mean	100	94	83.3	59.0	40.7	26.3	16.7	9.7	6.7	4.5

As shown in Table 11, with the exception of the first sublot, gradations were consistent although finer than the JMF. It appears from the results that the asphalt plant was not completely dialed in at the beginning of the production of the SSA mix.

Table 11. SSA Class 1/2 Inch HMA trial section sub-lot gradation data (MD160070).											
Sub Lot	Date	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF	-	*100*	*92*	*78*	*54*	*37*	*24*	*15*	*8*	*6*	*3.8*
001	10/10	100	94	86	61	42	27	17	10	7	4.6
002	10/11	100	94	82	58	40	26	16	9	6	4.2
003	10/11	100	94	82	58	40	26	17	10	7	4.8
Sub Lot Average		100	94	83	59	41	26	17	10	7	4.5

Table 12 shows the JMF, upper and lower acceptance criteria, standard deviation and mean results for the asphalt content and volumetric properties of the SSA mix. All volumetric results fell within specification limits.

Table 12. SSA Class 1/2 Inch HMA trial section volumetric JMF, upper and lower acceptance criteria, mean and standard deviation data (MD160070).										
	Binder (%)	Va (%)	VMA (%)	VFA (%)	D/A	Pbe (%)	Gmb	Gmm	Gsb	Gb
Volumetric JMF	*5.6*	*4.1*	*15.2*	*73*	*0.8*	*4.7*	*2.473*	*2.576*	*2.751*	*1.028*
Sub Lot Average	5.7	4.3	15.3	72	1.0	4.6	2.473	2.584	2.751	1.028
Upper Acceptance	6.1	5.5		75	0.16					
Lower Acceptance	5.1	2.5		65	0.6					
Mean	5.7	4.3	15.3	72	1	4.6	2.473	2.584	2.751	1.028
Std. Deviation	0.3	0.9	0.3	6.0	0.0	0.2	0.0	0.0	0.0	0.0

Va = air voids VMA = voids in the mineral aggregate VFA = voids filled with asphalt
D/A = percent passing #200 to asphalt binder content ratio Pbe = effective asphalt content
Gmb = bulk specific gravity Gmm = rice specific gravity Gsb = bulk specific gravity of aggregate
Gb = specific gravity of asphalt binder

Table 13 lists the sublot percent binder and volumetric data for the SSA mix. Sample 001 had a high binder content (6.1 percent) and lower Va and VFA as compared to the remaining samples. The remaining samples were all within specification limits.

The production mix properties of the SSA and conventional mix met all specifications and were very similar with the only difference being a slightly higher asphalt content required in the SSA mix. This is likely due to the porous nature of the steel slag aggregate causing it to absorb more asphalt than natural aggregate.

Table 13. SSA Class 1/2 Inch HMA trial section sub lot volumetric and binder percentage data (MD160070).

Sub Lot	Date	% Binder	Va	VMA	VFA	D/A	Pbe	Gmb	Gmm	Gsb	Gb
JMF	-	*5.6*	*4.1*	*15.2*	*73*	*0.8*	*4.7*	*2.473*	*2.576*	*2.751*	*1.028*
001	10/10	6.1	3.2	14.9	79	1	4.8	2.493	2.576	2.751	1.028
002	10/11	5.5	4.8	15.4	69	1	4.4	2.464	2.589	2.751	1.028
003	10/11	5.6	4.8	15.5	69	1.1	4.5	2.462	2.587	2.751	1.028
Sub Lot Ave.		5.7	4.3	15.3	72	1.0	4.6	2.473	2.584	2.751	1.028

Compaction Testing

The key to a long lasting pavement is adequate compaction. "Failures such as rutting, raveling and moisture damage are commonly attributed to poor compaction, and as a result, this is one of the main metrics measured when assessing quality" (Pavement Interactive, 2018). A Troxler 3450 nuclear gauge[1] operating in direct transmission mode at a depth of two inches was used to measure density. The relative density was determined by comparing the in-place density to the moving average of the theoretical maximum density[2] measured using AASHTO T 209 protocols[3]. The frequency of testing was one test for each 100-ton sublot.[4]

WSDOT uses a percent within limits (PWL) specification to accept compaction. For a contractor to receive full pay, 87 percent of the HMA in a compaction lot must achieve a relative density of 91 percent or higher. The control section HMA was compacted to an average density of 92.2 percent with a range from 88.5 to 96.6 percent. Five of the eight compaction lots in the control section did not achieve the PWL requirements to receive full pay and the contractor was assessed a penalty of $29,415 for the five lots not meeting requirements. The SSA section was compacted to an average density of 93.5 percent with a range from 91.0 to 95.2 percent. The compaction control lot for the SSA exceeded the PWL requirements for full pay and received a bonus of

[1] WSDOT FOP for WAQTC TM 8, *In-place Density of Bituminous Mixes Using the Nuclear Moisture-Density Gauge.*
[2] WSDOT SOP 729, *Determination of the Moving Average of Theoretical Maximum Density (TMD) for HMA.*
[3] WSDOT FOP for AASHTO T 209, *Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures*.
[4] WSDOT Test Method T 716, *Method of Random Sampling for Location of Testing and Sampling Sites*

$2,486.45. Table 14 lists the data for the control and SSA sections. The standard deviation, a measure of the spread of the readings from the target density, was 1.50 for the control section and 1.30 for the SSA section, indicating less variation of the densities in the SSA section as compared to the control section.

Table 14. Total tonnage, amount, average, standard deviation, and range of percent compaction for SSA and control sections.

Section	Total Tonnage	Number of Tests	Average (%)	Std. Dev	High (%)	Low (%)
Control Section	11,980	118	92.2	1.50	96.6	88.5
SSA Trial Section	1,671	16	93.5	1.30	95.2	91.0

The average density of the SSA trial section was 1.3 percent higher than the average density of the control section. Figure 12 shows the percent frequency distribution of the control and SSA section density results. This illustrates the close grouping of the SSA section results in the 91-96 percent range and the more widespread distribution of the control section results in the 89-97 percent range. The densities were concentrated at 92 percent for the control section mix and at 95 percent for the SSA trial section mix.

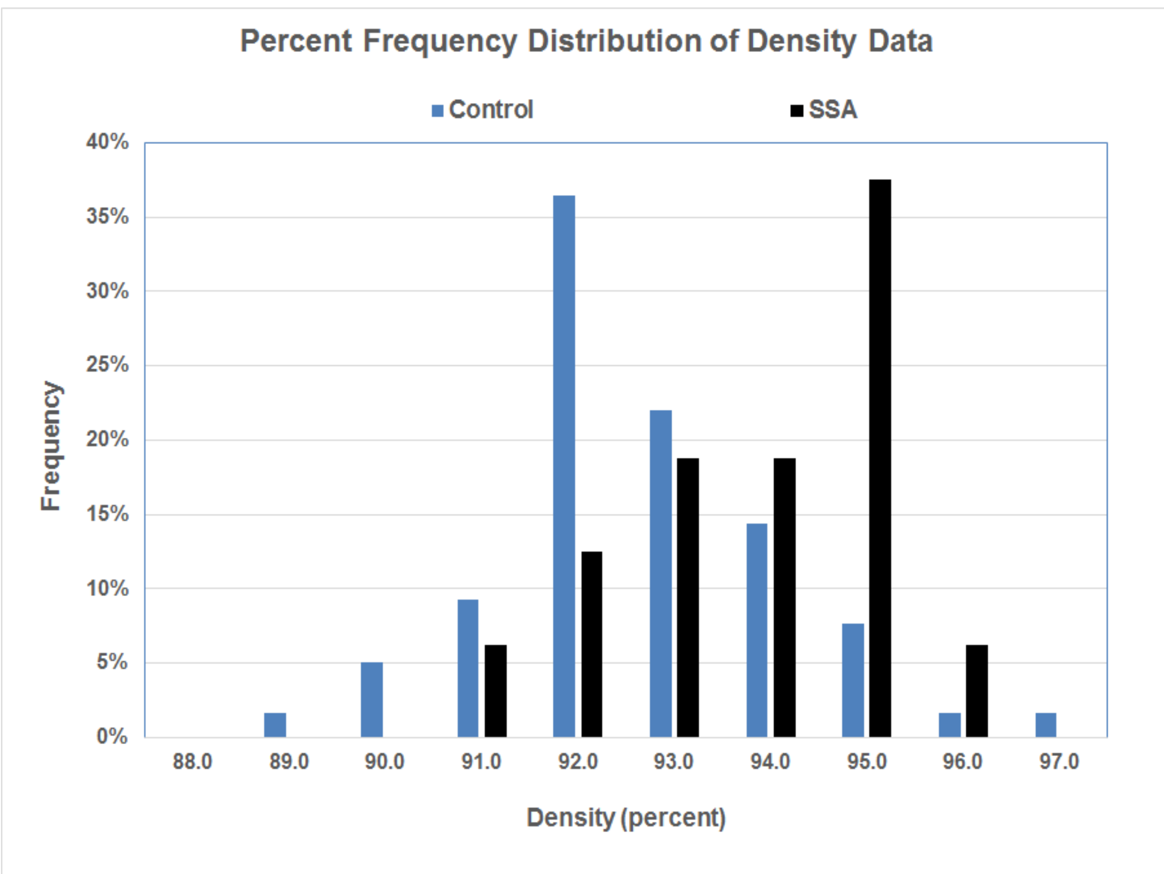

Figure 12. Percent frequency distribution of density test results for control and SSA sections.

The production mix properties of the SSA and conventional mix met all specifications and were very similar. The only significant difference was a slightly higher asphalt content required by the porous steel slag aggregate. Density testing showed that the SSA pavements was compacted to the specified density but the conventional HMA did not meet PWL requirements for full pay for most of the compaction lots.

Cost

The total cost for the SSA mix was $164,433.81 for the 1,671 tons resulting in a per ton cost of $98.40. The conventional mix total cost of $947,708.28 for the 11,980 tons resulting in a per ton cost of $79.11. The SSA mix cost was 24.4 percent higher than the conventional mix. Pavement alternatives are evaluated using life-cycle-cost analysis (LCCA). LCCA evaluates alternatives based on their cost, useful life and a discount rate to account for the time value of money. The current average pavement life for HMA on the west side of the Cascade Mountains is 17.3 years. Using LCCA and a discount rate of 4 percent the SSA pavement would need to last a little over 4 years longer than conventional HMA to have an equivalent life cycle cost.

Post Construction Performance Testing

Friction, wear/rutting and smoothness measurements were performed to evaluate the performance of the SSA and control section.

Wear/Rutting Testing

The amount of wear on the SSA and conventional asphalt sections was measured on October 5, 2017 and again on September 6, 2018 (Table 15). The measurements were made using a Pathway Pavement Distress Identification Van that measures wear/rutting and ride using a laser rut measurement system and an inertial profiler. The average wear measurements show very little difference between the two types of pavement with both showing minimal wear/rutting (as a reference to scale, a US dime is 1.3 millimeters in thickness).

Table 15. Rutting/Wear measurements.			
Section	Direction	Rutting/Wear (mm)	
		10/5/2017	9/6/2018
SSA Section	NB	2.1	2.8
SSA Section	SB	2.6	3.5
	Average	2.4	3.2
HMA (Control)	NB	2.5	3.0
HMA (Control)	SB	2.4	2.9
	Average	2.5	3.0

Ride Testing

The smoothness of the SSA and control sections was measured on October 5, 2017 and again on September 6, 2018 (Table 16). The average smoothness for the SSA section is about 30 inches/mile smoother than the control section. The smoothness of a roadway prior to resurfacing has a large impact on the smoothness after resurfacing. The smoothness of the SSA section before paving was 77 inches per mile and the smoothness for the control section was 116 inches per mile (see Table 1). The difference in smoothness before resurfacing is likely the major factor causing the smoothness of the completed control section to be higher than the SSA section.

Table 16. Ride measurements.				
SR	Direction	Pavement Type	Smoothness (inches/mile)	
			10/5/2017	9/6/2018
203	NB	SSA HMA	63	55
203	SB	SSA HMA	57	58
		Average	60	57
203	NB	HMA (Control)	91	85
203	SB	HMA (Control)	94	94
		Average	93	90

Friction Testing

Friction testing was conducted on the SSA and control sections in March of 2017 and September of 2018. The tests were performed using an ASTM E-274 locked-wheel tester with a ribbed tire at 40 MPH. The friction number average and range for the SSA and control sections are listed in Table 17. The friction numbers on the control sections ranging from 47.7 to 58.8 with an average of 55.5 in the initial testing in 2017. The SSA trial section had values ranging from 51.2 to 60.1 with an average of 55.7 on the initial test. The testing in September of 2018 revealed very little change in the values with a range of 42.6 to 56.2 with an average of 52.3 for the control section and a range of 49.1 to 58.4 with an average of 53.5 for the SSA trial section. A statistical analysis showed no significant difference between the means (averages) of the SSA and control section friction numbers; therefore, the more angular steel slag aggregate did not result in a statistically significant increase in skid resistance.

Table 17. Friction numbers for the SSA trial and control sections, March 16, 2017.

Date	Steel Slag		Control	
	Range (SN)	Average (SN)	Range (SN)	Average (SN)
March 2017	51.2 – 60.1	55.7	47.7 – 58.5	55.5
September 2018	49.1 – 58.4	53.5	42.6 – 56.2	52.3

Limitation of Test Results

The wear and friction results presented in this study show the pavement performance of HMA with 20 percent SSA and HMA with natural aggregates to perform similarly after two years of service. It is normal for pavements this age to be in good condition. As these pavement sections age, trends may appear in the data indicating that there is a difference in performance between the trial and control section. Additional years of testing will be required to determine if a difference in performance develops.

Feasibility for Use in Washington State

Correlation between the Source and the Use of Steel Slag Aggregates

Asphalt contractors in Washington as well as other states locate their asphalt plants at aggregate sources to minimize handling and to avoid a double haul of aggregate, once from the source to the asphalt plant and a second time when hauling HMA from the plant to the paving project. Figure 13 shows the location of steel plants in North America. The previously completed literature search on steel slag aggregate noted that Alabama, Colorado, Connecticut, Indiana, Illinois, Iowa, Kentucky, Minnesota, Missouri, Ohio, Oregon, Pennsylvania, South Carolina, Virginia, Wisconsin, and West Virginia have experimented with or used steel slag aggregate in asphalt pavements. It is evident from the map that states with SSA sources tend to be the ones that use or experiment with SSA in pavements due to their proximity to ample supplies of SSA.

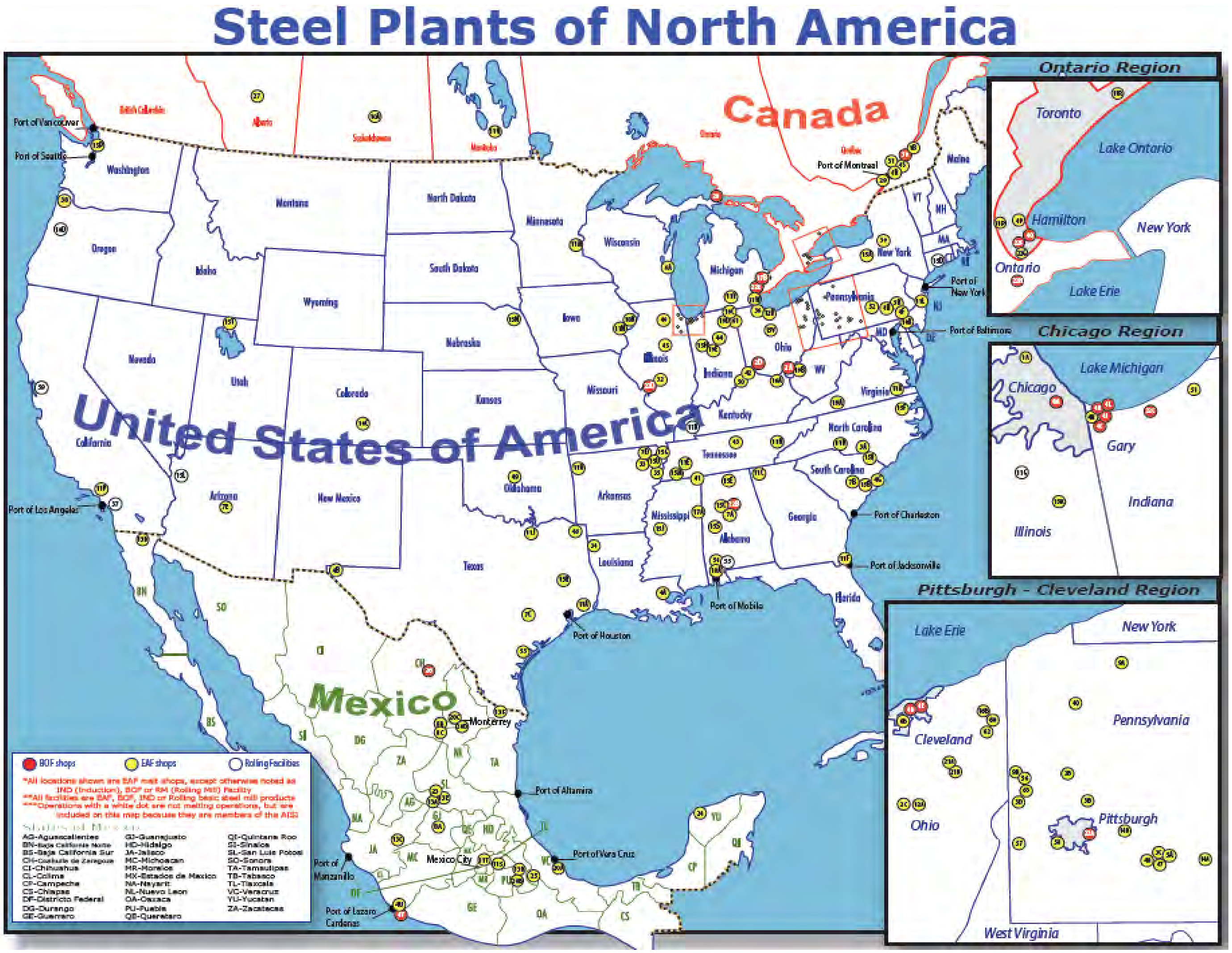

Figure 13. Location of steel plants in North America. (Courtesy of AIM Market Research, Pittsburg, PA)

WSDOT knows of only one contractor in Washington that uses SSA. That contractor operates out of Issaquah and uses the SSA on private projects as a 10-12 percent replacement for the coarse aggregate portion of the mix at a cost of $2 to $3 per ton less than natural aggregates. Issaquah is located about 19 miles from the Nucor Plant in Seattle.

Feasibility of using SSA throughout Washington

Constructing HMA pavement with SSA is possible as demonstrated by its successful use on the SR 203 project and use by at least one contractor in the greater Seattle area. WSDOT allows the use of SSA as HMA aggregate but use has been limited even near the SSA source in Seattle. The limited use suggests that the economics do not currently favor the use of SSA by HMA contractors.

Transportation costs would also limit its use. Table 18 lists the additional cost per ton for hauling the SSA to various cities in the state. The table assumes that traffic is free flowing and there is no commodity to backhaul. If the trucking entity were able to secure a load on the return trip the cost would be half of those shown on the table.

Table 18. Additional cost to transport SSA.

Distance Seattle SSA Source (miles)	Cities Reached	Added Transportation Cost (Dollars per Ton)
0 to 25	Greater Seattle Area	0 to 4.52
25 to 50	Everett, Tacoma	4.52 to 9.03
50 to 100	Olympia, Port Angeles	9.03 to 18.06
100 to 150	Aberdeen, Bellingham, Ellensburg, Yakima	18.06 to 27.10
150 to 200	Moses Lake, Vancouver, Wenatchee	27.10 to 36.13
200 to 250	Tri Cities	36.13 to 45.20
250 to 300	Spokane, Walla Walla	45.20 to 54.24

The Spokane area is the location in Washington that would benefit the most from reducing the wear from studded tires. The combination of high traffic volumes and a high rate of studded tire use results in deeper rutting from studded tires than anywhere else in the state. The cost of transporting steel slag aggregate to the Spokane area is calculated using a cost of $50.85 per ton. This cost is derived from a cost of $140 per hour provided by the asphalt paving industry to operate a truck and trailer combination (Gent, 2018). The cost of conventional HMA in the Spokane area runs about $72 per ton (based on costs from 2016 and 2017 projects on US-2 in Spokane). The cost of the SSA mix from this study was $19 per ton higher than the conventional asphalt mix. The cost of the SSA mix in Spokane would thus be $141.85 per ton ($19 higher cost of SSA mix plus $72 average cost of conventional mix in Spokane plus $50.85 for shipping). This is almost double the cost of conventional asphalt pavement using natural aggregates. To be cost effective, a pavement built at this higher cost would need to last over 24 years, which is almost 12 years longer than the 12.3-year average life of HMA pavements in the Spokane area.

For SSA to be feasible at a higher cost than conventional aggregate it must provide a benefit above conventional HMA aggregate to justify its higher cost. The wear and friction test results from this study show very little difference between the HMA with SSA and with conventional aggregate.

The lack of benefit and the increased cost to transport SSA makes it not feasible to use in locations located away from its source.

In summary, the costs associated with the use of SSA can vary depending on project location, distance from SSA sources, costs to transport, and natural aggregate availability.

Trial Project Findings

- Construction of the SSA trial section went smoothly without any major problems.
- Based on two years of post-construction testing, there was not a significant difference in performance. Wear/rutting and friction measurements were very similar between the SSA section and control sections. Friction measurements were within the normal range for new HMA pavement for both pavements.
- The cost of the SSA mix was about 24 percent higher than the cost of the conventional mix on the trial project. The higher cost would require a pavement life extension of four additional years over conventional HMA mix for the SSA trial section to be cost neutral.

Recommendations

- The overall performance of HMA with 20 percent SSA is acceptable.
- WSDOT should continue to allow SSA as a replacement for up to 20 percent of the coarse aggregate in all HMA pavement statewide.
- Specific project economics, as opposed to mandated use, should dictate the use of SSA on future WSDOT projects. The cost of SSA can vary, depending on project location, distance from SSA sources, costs to transport, and natural aggregate availability. Mandated use would likely result in higher project costs that may not be matched by higher pavement performance or longer life.
- No further SSA trial sections or implementation efforts should be pursued at this time.

References

Gent, D., "Trucking Cost for Steel Slag Aggregate", email to Mark Russell, January 24th, 2018.

Pavement Interactive, www.pavementinteractive.org, accessed October 1, 2018.