WSDOT Strategies Regarding

Use of Steel Slag Aggregate in Pavements

A Report to the State Legislature
In Response to 2ESHB 1299

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Construction Division Pavements Office

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Executive Summary

2ESHB 1299, Section 307 (5) in the 2015 Legislative Session required the Washington State Department of Transportation to study the use of electric arc furnace slag for use as aggregates 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 by December 1, 2015, 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, a literature review was conducted to examine the properties of steel slag aggregate (SSA) and its use as an aggregate for pavements. The discussion below condenses the literature review and provides WSDOT's action plan to further evaluate electric arc furnace slag.

Steel slag aggregate (SSA) is a byproduct of the production of steel in an electric arc furnace. The high iron oxide content of the aggregate results in an aggregate that is very hard and very dense (SSA is 20-30% heavier than naturally occurring aggregates such as basalt and granite). It also contains a high content of calcium and magnesium oxides, which make it expand when it comes into contact with moisture. It is very angular and porous.

The primary use of SSA is as a substitute for natural aggregates in the production of hot-mix asphalt (HMA). It is used less often in supporting courses (bases and subbases) beneath HMA or bituminous surface treatment (BST) wearing courses. It is not used in cement concrete pavements or other concrete applications due to the expansive nature of the aggregates since expansion causes the concrete to crack. All users specify that the aggregate be cured in a water saturated condition for a period of 3-6 months prior to use in non-HMA applications. Many states require an expansion test in addition to the water curing.

The higher weight and high porosity of the aggregate can result in additional cost when used in HMA. The higher weight increases the cost of hauling the aggregate from the source to the job site and the high porosity of the aggregate results in a demand for more asphalt binder than mixes using natural aggregates. The higher weight of the SSA mix means that a given weight of mix will not cover the same volume of pavement as a conventional mix with natural aggregate, therefore more tons of mix are required to cover the same length, width and depth of pavement than conventional HMA. This, along with the need for more asphalt binder, raises costs.

Most of the states that use SSA are located in the steel producing states between Minnesota and Iowa on the west and Pennsylvania, Virginia and West Virginia on the east. The requirements for acceptance of the aggregates varies between the states, with some requiring moist curing or an expansion test and others allowing its use in hot-mix asphalt without curing or expansion testing. Most states use the SSA in the top layer of the pavement to increase the frictional properties of the pavement; however, two states do not allow SSA in the top layer, so use is mixed.

The use of SSA in bases and subbases was not specifically called out in the language of the transportation bill; however, the literature indicated that the high pH of some steel slag aggregates may be a problem with respect to corrosion of culverts and aquatic life in streams and rivers adjacent to roadways. Without adequate testing the use of SSA is not recommended for use as aggregate base for WSDOT roadways.

Information on the cost of using SSA is difficult to quantify. The states that use SSA as a friction enhancer indicate that the added cost is equivalent to the cost of importing better aggregates from adjacent states. The Washington state contractor that uses SSA in the Seattle area on private projects indicates a cost savings over using natural aggregates from company owned sources. Due to limitations on the availability of SSA, limited to Nucor facility in Seattle, it is not economical to use SSA to replace natural aggregate where long haul distances to an asphalt producer are involved.

The use of SSA in Washington seems to be a viable option with the primary advantage being the conservation of natural aggregates. Use should be limited to hot-mix asphalt with laboratory testing required to assess the quality of the aggregate and its strength under repeated loads and moisture. All projects using steel slag aggregate should be classified as experimental.

WSDOT is proposing a pilot project in 2016 to evaluate the use of SSA on an asphalt paving project. The proposed project will be constructed in the Northwest Region within a reasonable distance to Nucor facility to make the project economical. The project will include a one mile long test section of steel slag aggregate with the remainder of the project built using conventional HMA with natural aggregates. This section will be monitored for a minimum of five years to ensure that performance is equivalent to pavements built with natural aggregates.

Introduction

2ESHB 1299, Section 307 (5) in the 2015 Legislative Session required the Washington State Department of Transportation to study the use of electric arc furnace slag for use as aggregates 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 by December 1, 2015, 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 a literature review was conducted to examine the properties of steel slag aggregate (SSA) and its use as an aggregate for pavements.

Report Organization

The report will first look at the properties of SSA, followed by an examination of the research on the use of SSA in bituminous and cement concrete applications. The advantages and disadvantages of the use of SSA in bituminous and cement concrete applications as noted in various reviewed documents are reported next. Finally, an examination of the manner in which states use SSA in pavements and the acceptance processes applied that ensure the aggregates meet quality specifications.

Steel Slag Aggregate Properties

Electric arc furnace slag is a byproduct of the production of steel in an electric arc furnace. In electric arc furnaces the charge materials (scrap iron and steel) are loaded into the furnace and directly exposed to electric terminals. The current passing through the terminals creates an electric arc that melts the charge materials. Slag formers are added to the furnace to: (1) act as a destination for oxidized impurities; (2) act as a thermal blanket (stopping excessive heat loss); and (3) reduce erosion of the refractory lining. The usual slag formers are calcium oxide (CaO, in the form of burnt lime) and magnesium oxide (MgO, in the form of dolomite and magnesite) (Wikipedia). The slag is removed from the furnace at 1,600 to 1,800 ºC (2,900 to 3,300 ºF) and cooled to ambient temperatures before being crushed and screened into various sizes (NSA, 2003).

The slag produced is very angular and porous with a rough surface texture (Figure 1). The chemical properties of the aggregates vary depending on the furnace, feed stock and slag formers used to produce the steel. The aggregate formed from the slag is comprised of calcium oxide (CaO), silicon oxide (SiO_2), iron oxide (Fe_2O_3), magnesium oxide (MgO), manganese oxide (MnO), aluminum oxide (Al_2O_3) and sulfur oxide (SO_3) as detailed in Table 1. The table also provides information on the chemical composition of slags formed in other types of furnaces.

The electric arc furnace steel slag has the highest iron oxide content of any of the slags, which accounts for its increased hardness and higher density as compared to the other slags.

Figure 1. EAF steel slag aggregate. (from en.wikipedia.org/wiki/Construction)

Table 1. Typical oxides in iron and steel slags. (Stroup-Gardiner & Wattenberg-Komas, 2013)

Compounds	Blast Furnace			Steel Slag	
	Blast Furnace Slag %	Ground Granulated Blast Furnace Slag (Ger.) %	Ground Granulated Blast Furnace Slag (UK) %	Basic Oxygen Furnace Slag %	Electric Arc Furnace Slag %
Calcium Oxide (CaO)	32 to 45	39.2	40	43	35
Silicon Oxide (SiO_3)	32 to 42	40.0	35	15	14
Iron Oxide (Fe_2O_3)	0.1 to 0.75	1.8	0.2	25	29
Magnesium Oxide (MgO)	5 to 15	3.8	10	8	8
Manganese Oxide (MnO)	0.2 to 0.8	-	-	5	6
Aluminum Oxide (Al_2O_3)	7 to 16	13.5	12	2	5
Sulfur Oxide (SO_3)	0.4 to 2.0	0.2	-	0.07	0.1

The physical properties of iron and steel slags are detailed in Table 2. The much higher specific gravities of the steel slags stand out from the blast furnace slags which are closer to the specific gravities of natural aggregates. The dry and wet strengths of the steel slags are also much higher than the blast furnace slags.

Table 2. Typical engineering properties for iron and steel slags. (Stroup-Gardiner & Wattenberg-Komas, 2013)

<table>
<tr><th colspan="2" rowspan="2">Physical Property</th><th>Blast Furnace Slag</th><th colspan="2">Steel Slag</th><th rowspan="2">Test Method</th></tr>
<tr><th>ACBFS*</th><th>BOF**</th><th>EAF***</th></tr>
<tr><td colspan="6">Open Graded</td></tr>
<tr><td rowspan="2">Specific Gravities</td><td>Dry</td><td>2.450 – 2.550</td><td>3.300 – 3.400</td><td>3.300</td><td rowspan="2">ASTM C127/128: Density, Specific Gravity, and Absorption</td></tr>
<tr><td>SSD</td><td>2.550 – 2.650</td><td>3.350 – 3.475</td><td>3.400</td></tr>
<tr><td colspan="2" rowspan="2">Water Absorption, %</td><td rowspan="2">3 to 7</td><td>1 to 2 Coarse</td><td>1 to 2 Coarse</td><td rowspan="2">ASTM C566: Moisture Content by Drying</td></tr>
<tr><td>2 to 4 Fine</td><td>2 to 4 Fine</td></tr>
<tr><td colspan="2">Dry Strength, ksi</td><td>19.0 to 22.5</td><td>61.8</td><td>56.0</td><td rowspan="3">AS 1142.22: Australian Test Method for Wet/Dry Strength Variation</td></tr>
<tr><td colspan="2">Wet Strength, ksi</td><td>14.6 to 20.3</td><td>51.7 to 67.4</td><td>54 to 67.4</td></tr>
<tr><td colspan="2">Wet/Dry Strength Variation, %</td><td>10 to 20</td><td>5 to 20</td><td>5 to 15</td></tr>
<tr><td colspan="2">Micro Deval, %</td><td>15 to 22</td><td>12 to 18</td><td>16</td><td>ASTM D6928: Degradation by Abrasion</td></tr>
<tr><td colspan="2">Polished Aggregate Friction Value (PAFV)</td><td>53</td><td>58 to 63</td><td>58 to 63</td><td>ASTM D3319: Accelerated Polishing of Aggregates</td></tr>
<tr><td colspan="2">Sodium Sulfate Soundness, %</td><td>5</td><td><4</td><td><4</td><td>ASTM C88: Soundness of Aggregates</td></tr>
<tr><td colspan="6">Dense Graded Aggregate Material</td></tr>
<tr><td colspan="2">Maximum Dry Density, lb/ft^2</td><td>128.0 to 134.2</td><td>143.6 to 149.8</td><td>143.6 to 149.8</td><td rowspan="2">ASTM D698: Compaction Characteristics of Soils</td></tr>
<tr><td colspan="2">Optimum Moisture Content, %</td><td>8 to 12</td><td>8 to 12</td><td>8 to 12</td></tr>
</table>

* Air-Cooled Blast Furnace Slag.
** Basic Oxygen Furnace
***Electric Arc Furnace

Typical engineering properties for iron and steel slags are listed in Table 3.

Table 3. Typical engineering properties for iron and steel slags. (Stroup-Gardiner & Wattenberg-Komas, 2013)

Property	Iron Slag ACBFS	Steel Slag (type not identified)
LA Abrasion, %	35 to 45	20 to 25
Sodium Sulfate Soundness, %	12	<12
Angle of Internal Friction	40º to 45º	40º to 50º
CBR, %	Up to 250	Up to 300
Hardness (Moh's)	5 to 6	6 to 7

CBR = California bearing ratio.

The Los Angeles (LA) abrasion test provides an indication of aggregate toughness and abrasion characteristics. Lower numbers indicate greater toughness and abrasion resistance. The sodium sulfate soundness test determines an aggregate's resistance to disintegration by weathering and, in particular, freeze-thaw cycles. Again, lower numbers indicate more resistance to weathering and freezing than thawing. The California Bearing Ratio (CBR) test is a strength test that compares the load carrying capacity of a material to that of a well-graded crushed stone. Higher values indicate greater load carrying capacity. Moh's hardness scale measures the hardness of materials based on a scale from 1 (talc) to 10 (diamond). SSA approaches quartz (7 on Moh's scale) in hardness. Source: Pavement Interactive.

In summary, SSA is angular and porous, has a high specific gravity, is more resistant to abrasion and weathering, is highly stable due to high angles of internal friction, has high load carrying capacity as measured by the CBR, and has hardness that approaches quartz.

Steel Slag Aggregate Research

The following sections review the literature on the use of SSA for: (1) bituminous pavements; (2) bases and subbases; and (3) concrete pavements. The reports are provided in chronological order, oldest to most recent, in each section

Steel Slag Aggregate For Hot-Mix Asphalt, Chip Seals and Stone Mastic Asphalt

Ali et al, (1991) investigated the use of SSA to solve an instability problem that was resulting in rutting of HMA pavements in Canada. Laboratory testing of mixes with SSAs, natural aggregates and mixtures of the two indicated that the mixes with higher contents of SSA had higher resilient modulus values, less deformation, higher tensile strengths, and were less susceptible to moisture damage than the mixes with the higher natural aggregate contents. Mixes with 100% SSA required 25 percent more asphalt binder than the other mixes. The conclusion was that the SSA could be used as an alternative source of aggregate for HMA pavements. Note that the expansive nature of SSA was not considered in this study and as noted below, it became a problem in some of their pavements.

In 1995, the Ministry of Transportation of Ontario (MTO) investigated problems with HMA pavements built with SSA (Farrand & Emery, 1995). Random map cracking, grey veining around cracks, and flushing were the problems noted for pavements built in the 1970's. The problems were attributed to an excess of lime in the steel slag, which caused expansion when exposed to water. MTO worked with the steel industry to solve the excess lime issue and instituted a testing protocol to determine the expansion properties of SSA prior to use.

In 1995 Coomarasamy & Walzak found calcium deposits in SSA samples exposed to moisture in the laboratory and in field cores from projects using SSAs. The calcium deposits were found on the aggregates and in the cracks that developed as a result of the expansion. Failures in pavements containing SSA were attributed to volume expansion in the presence of moisture.

Pennsylvania Department of Transportation (PennDOT) examined volume expansion of steel slag fine aggregates for use in HMA pavements in 1997 (Kandhal & Hoffman, 1997). Pennsylvania has many steel mills, especially in the Pittsburgh/Philadelphia area. SSA had been used for many years in unbound subbase and backfill when the current study was initiated. The expansive nature of the raw aggregate had been identified earlier and a test was developed to determine their expansion potential. A criterion of 0.50 percent expansion was established as the limit for acceptability. It was also required that the raw aggregate be moist cured under sprayed water conditions in a controlled stockpile for six months to alleviate the expansion potential. SSA coarse aggregates were already being accepted by PennDOT in HMA, but not fine aggregate. Moisture cured and uncured samples of the SSA were exposed to hot-water bath and Lottman freeze-thaw conditioning. Samples with uncured SSA exceeded expansion limits and those with cured SSA passed. The cured and uncured SSAs were then mixed with asphalt binder and retested for expansion. None of the samples exhibited excessive expansion. The lack of expansion in the samples that used uncured aggregate was attributed to the coating of the particles with asphalt binder, which prevented their exposure to moisture. PennDOT accepts the use of SSA fine and coarse aggregates in combination with natural aggregates for HMA. The researchers however, did not recommend the use of 100% SSAs (both fine and coarse aggregates) in HMA pending further study.

A field trial by Oregon Department of Transportation in 2000 compared the performance of pavements built with 30% SSA with a control section of conventional HMA built using natural aggregates (Hunt & Boyle, 2000). Performance of the two pavements after five years of traffic was equal. The amount of pavement produced with the mix made with SSA was 30% less than the mix made with natural aggregates. Costs were much higher for the SSA mix due to the lower yield and higher transportation costs. No further use of SSA by ODOT has been reported in the literature.

Wu et al, (2007) documented a study done in China to assess the feasibility of using SSA in Stone Mastic Asphalt (SMA). China was searching for new aggregate sources to supplement diminishing natural stone sources. The SSA was wet cured for three years prior to use. The SSA mix was compared to one that used basalt aggregate. The SSA mixes used 80% SSA, limestone powder, and short-chopped polyester fibers. The SSA had a porous structure that required 24% more asphalt binder than the basalt aggregate. Expansion rates were below 1% confirming the use of the extended moist curing process. Rutting tests and indirect tensile tests showed that the

SSA mix was more resistant to rutting and low temperature cracking than the basalt mix. Test section results of the two mixes showed equal performance after two years of service.

Wilson & Black, (2008) performed a laboratory study in New Zealand comparing the skid resistance performance of steel slag, calcined bauxite and greywacke sandstone. The samples were tested using a special polishing machine. Friction values were determined before and after polishing. They concluded that all of the materials would make good friction resistant aggregate for chip seals. The bauxite performed the best of all the aggregates with the highest level of skid resistance and less than 15% loss after polishing. The SSA had the lowest initial friction numbers, but lost the least amount of skid resistance after polishing.

Kehagia, (2009) reported on a Greek study of the skid resistance of HMA wearing courses built with SSAs. The British Pendulum Tester was used to measure the performance of pavements built with SSA and SSA with limestone sand mixes. Tests performed over a one year period showed that the mixes with SSA had better anti-skidding performance as compared with natural hard aggregates. The high density, angular shape and the irregularities in the surfaces of the SSAs were reported to ensure that pavements built with these aggregates would be resistant to deterioration under construction and continuous traffic loading.

A study done in Turkey by Ahmedzade and Sengoz, 2009 investigated the possible use of SSA as an electrical conductor in airfield HMA pavements. Electricity applied to the pavement would be used to heat the runway and melt snow and ice. The SSA mixes were found to have higher stiffness and were more resistant to permanent deformation. They also had better rutting resistance, better cohesive strength and were less susceptible to moisture damage. They also had better electrical conductivity than mixes with natural limestone aggregates, which satisfied the goal of the study.

Pasetto & Baldo, (2011) performed a laboratory study of SSA for use in HMA. Three SSA mixes were compared to one limestone aggregate mix. Both Marshall and Superpave design methods were used. SSAs were compatible with the asphalt binders normally used in HMA mixes. No excessive permanent deformation was predicted by the two mix design methods. Good overall performance was predicted in terms of stiffness and fatigue resistance and susceptibility to moisture damage. Mixes with the highest percentage of SSA (90%) performed the best as compared to the 60, 30, and zero percent SSA mixes.

NCHRP Synthesis 435 entitled "Recycled Materials and Byproducts in Highway Applications" gathered the experiences of transportation agencies and the beneficial use of SSA for highway applications (Stroup-Gardiner & Wattenberg-Komas, 2013). Issues identified included the expansive nature of the fresh slags, the higher specific gravities that result in lower yields of paving mixes and higher transportation costs, and the need to use locally available sources to reduce these haul costs.

SSA for Portland Cement Concrete Pavements

A laboratory study aimed at producing concrete with good properties using SSA was conducted by Manso et al, 2004. Cooled and crushed slag was weathered for 90 days using a wetting and turning process. The study showed that the crushed slag did not produce enough fines for concrete mixes and that the resultant mixes had high densities resulting in heavy concretes. Additionally, the high porosity of the SSA resulted in high water demand during concrete mixing. The final concrete samples had high abrasion resistance and low permeability. The authors concluded that good concrete mixes could be made from SSAs if they are conditioned properly to eliminate expansion potential.

Another laboratory study by Pellegrino & Gaddo in 2009 evaluated the mechanical properties and durability of concrete mixes made with SSA in Italy. Mechanical properties exceeded those of mixes made with natural aggregates. Durability was a concern raised by the study. Freeze-thaw and wet/dry cycling resulted in significant loss of strength. The addition of air-entrainment improved the results, but the SSA mixes were still vulnerable to repeated cycles of wetting and drying.

A report by Fronek et al, (2012) discussed the possible use of SSA in concrete pavement. None of the six states (Ohio, Indiana, West Virginia, Pennsylvania, Michigan, and Illinois) that use SSA allow its use in concrete or where expansion might be detrimental such as pipe backfill, granular backfill, etc. Most of the research on the use of SSA in concrete pavements has been done outside the United States. This research showed that when the SSA is properly aged it can be used in concrete applications without significant expansion problems. The authors concluded that most state DOT's would be reluctant to use SSA in concrete pavements unless test methods and specifications were developed to identify potentially harmful materials.

SSA for Bases and Subbases

The possible use of SSA as a base was researched in Brazil (Rohde et al, 2003). The source of the SSA was high in CaO indicating possible instability in the presence of water (volume increase). The slag was stockpiled for six months to allow for potential expansion. The SSA was poorly graded after crushing and had to be crushed again to produce the required fines. Resilient modulus testing indicated higher values than natural aggregates (up to 500 MPa). The conclusion was that SSA could lower costs and perform well when used as a base course, provided it was moist cured to reduce expansion potential.

A study on the use of SSA as a base was conducted in Saudi Arabia, a country devoid of good quality aggregate sources (Aiban, 2006). Various proportions of SSA to natural aggregates were tried from 100% to 30% SSA. The preferred mix was 100% SSA which was a free draining base that required no subsurface drainage system. A field trial of the mix showed excellent performance despite being submerged under water on many occasions due to rain and poor drainage.

Illinois DOT studied the use of recycled asphalt pavement (RAP) containing SSA as a base material (Deniz et al, 2009). Comparisons were made between samples containing SSA RAP and virgin SSA. Virgin SSA had expansion rates as high as 6.2%. RAP samples with up to 92% SSA had expansion rates in the range of 1.46% to 1.69%. This indicated that the asphalt coating is preventing significant ingress of water. The authors concluded that SSA RAP could be used as a pavement base course. They also cautioned that porous and nonporous (virgin) SSAs should never be used in bases or subbases without curing that satisfies the limitation specified by ASTM

D2940, “Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports”.

User guidelines from the Federal Highway Administration cautions that the pH of leachate from SSA can exceed 11 and that at this level can be corrosive to aluminum or galvanized steel pipes placed in contact with the slag (FHWA, 2012). High pH leachate that enters streams and rivers may raise the pH level of the water, which can be detrimental to aquatic life.

Steel Slag Aggregate Advantages and Disadvantages

The advantages and disadvantages of using SSA in both bituminous and portland cement concrete applications, as noted in the literature reviewed, are as follows:

Advantages when used in bituminous pavements (HMA, SMA and chip seals)

- High skid resistance
- Resistant to wear
- High stability
- Resistant to stripping in the presence of moisture
- Resistant to rutting
- Higher stiffness
- Fatigue resistant
- Resistant to permanent deformation
- High cohesive strength
- Electrically conductive (electrical currents can be applied to the pavement to melt snow and ice)
- Compatible with typical asphalt binders

Disadvantages when used in bituminous pavements

- High volume expansion potential in the presence of moisture
- Increased binder demand (24% to 30%) due to its porous structure
- High specific gravity results in lower volumes of pavement mix and higher transportation costs
- Overall higher cost of applications

Advantages when used in portland cement concrete pavements

- Better abrasion resistance
- Low permeability

Disadvantages when used in portland cement concrete pavements

- Volume expansion
- High density results in heavy concretes
- High porosity results in higher water demand
- Durability is a question due to lack of long-term field evidence
- Freeze-thaw durability is a question

State Use of Steel Slag Aggregate

Sixteen states and the District of Columbia are reported to have used steel slag aggregate (SSA) (Stroup-Gardiner & Wattenberg-Komas, 2013). Acceptance criteria for the use of SSA are detailed following the list of states:

- Alabama
- Colorado
- Connecticut
- Indiana
- Illinois
- Iowa
- Kentucky
- Minnesota
- Missouri
- Ohio
- Oregon
- Pennsylvania
- South Carolina
- Virginia
- Washington D.C.
- West Virginia
- Wisconsin

Illinois

The Illinois Department of Transportation (IDOT) issued a Policy Memorandum in 2008 outlining a slag producer self-testing program. The memorandum spells out the procedures and testing required for a slag processor to supply SSA complying with applicable quality and gradation specifications. The key requirement is the control of specific gravity/absorption prior to shipment to IDOT. Non-compliance with the program results in the slag source's removal from the current "IDOT Approved Aggregate Source List". The IDOT procedure thus puts the responsibility of supplying a non-expansive aggregate directly on the slag producer/supplier.

Correspondence with IDOT personnel indicates that SSA is used as a high friction aggregate for surface courses in the Chicago area due to the absence of natural aggregates with good frictional properties. The cost of the SSA is higher than natural aggregates, but this cost is equivalent to the high transportation costs of shipping high friction aggregates from Minnesota and Wisconsin to Chicago (Beshears, 2015).

Indiana

The Indiana Department of Transportation (InDOT) includes steel slag aggregate in their standard specifications. SSA can be used for aggregate shoulders, HMA surface or SMA surface mixtures, dumped riprap, and snow and ice abrasives. SSA coarse aggregate may be used in

HMA base and HMA intermediate mixtures if the deleterious content is less than four percent. The test for deleterious content includes a test for expansion.

Weight adjustments for the SSA are required when payment is on a weight basis. Typical values for specific gravities are: natural aggregate both fine and coarse, 2.6 and SSA both fine and coarse, 3.4. The approximate quantity of tons to be supplied is determined by multiplying the pay item quantity of tons by the specific gravity of SSA divided by 2.6. The adjusted contract quantities will be determined by multiplying the accepted quantity of tons by 2.6 divided by the specific gravity of the SSA.

Iowa

Steel slag is used in surface courses as a high friction aggregate on Interstate highways in the south central and south eastern part of the state near the only source of SSA in Iowa. The aggregate is not water cured prior to use. Cost is equivalent to importing high friction aggregates from South Dakota. The higher specific gravity of the SSA is compensated for in mix designs and in the yields in the field due to the heavier weight of the mix. Twenty-five to thirty percent of the coarse aggregate is replaced with the SSA aggregate (Boulet, 2015).

Minnesota

Minnesota Department of Transportation (MnDOT) accepts SSAs in their standard specifications for bituminous materials. The SSA cannot exceed 25% of the total aggregate quantity in the mix and must be free from metallic and other mill waste. The aggregate must not exceed an expansion of 0.50 percent as determined by ASTM D4792, "Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions". SSA cannot be used in permeable asphalt stabilized stress relief course, permeable asphalt stabilized base course, or ultra-thin bonded wearing course applications. SSA is also prohibited in cement concrete applications.

MnDOT does not use SSA. A single contractor uses it on non-MnDOT work. SSA is generally incorporated into the mixture at about 10% of the coarse aggregate (Garrity, 2015).

Missouri

Missouri Department of Transportation (MoDOT) includes SSA as a coarse aggregate in HMA. The SSA must be water cured for at least three months after crushing and screening. Steel slag from one source cannot be blended with steel slag from another source. Additional uses allowed are mineral aggregate for micro-surfacing and coarse aggregate for ultra-thin bonded asphalt wearing surfaces. SSA is also prohibited in cement concrete applications. (Missouri Department of Transportation, Standard Specifications for Highway Construction, Section 1002, Aggregate for Asphalt Concrete).

Ohio

Ohio Department of Transportation (ODOT) quality control requirements hold the steel slag processor responsible for a Steel Slag Quality Control Plan which includes requirements for both the producer and the processor. Steel slag aggregate is acceptable in all but surface courses of HMA, but is not allowed in cement concrete applications.

The producer quality control plan includes the designation of those responsible for carrying out the plan, a separate plan for each furnace, the methods used to handle extreme variations in the slag makeup due to changes in furnace operation, notification to the processor of changes in the furnace operation that may alter the steel slag quality produced, and documentation of all of the QC practices.

The processor quality control plan includes documentation of the quality of all sources of steel slag being processed, designation of older byproduct stockpiles from which steel slag is being produced, rejection/selection process for suitable steel slag, designation of all rejected/selected stockpiles, disposal method for rejected stockpiles, processing and testing verifying actual steel slag quality, product verification for gradations, absorption, percent soft pieces including lime agglomerations and other suitable steel slag quality testing, reprocessing procedure for failing material, minimum one month aging at moisture content greater than aggregate absorption (if after aging fine aggregate has crusting or other tests show a problem for coarse or fine aggregate, reprocessing or screening is required), moisture test prior to shipping, and the location of all quality control documentation. Test methods used by the processor include tests for deleterious substances, gradation, absorption, loss by washing, autoclave disruption, and expansion (1.5 percent as guide limit). (State of Ohio, Department of Transportation, Columbus, Ohio, Construction and Materials Specifications, Section 703, Aggregates, page 706).

Up to 100% of the coarse aggregate is allowed to be SSA, but if used at that replacement rate, the use of SSA fine aggregate is limited to 50%. Non-pavement use requires curing, stockpiling and expansion testing of the SSA before it is allowed. The cost of HMA is more driven by the cost of the binder than the cost of the aggregate (Zigmund, 2015).

Pennsylvania

Pennsylvania Department of Transportation (PennDOT) includes SSA in their standard specifications as fine aggregate for use in bituminous surface courses, selected material surfacing, selected granular material, and subbases. Crushed and graded SSA is formed into a stockpile which is sampled and tested for expansion using a PennDOT test procedure. The stockpile is acceptable if the expansion is less than 0.50 percent. If it does not pass the expansion test the stockpile must be soaked with water and cured for six months before it can be retested. If it again does not meet the expansion requirements an additional 2 months of moist curing is prescribed. SSA is not allowed to be used for pipe or structural backfill or in cement concrete. (Commonwealth of Pennsylvania Department of Transportation, Publication 408/2011 Construction Specifications, Section 703-Aggregates).

South Carolina

South Carolina Department of Transportation (SCDOT) includes SSA in their standard specifications for HMA aggregates. The crushed and graded SSA must be kept in a controlled and continuously saturated stockpile for a minimum of six months prior to use. Before use in HMA, the stockpiled material is tested for expansion following a SCDOT test method. Stockpiled materials that don't pass the expansion test are cured for an additional two months before retesting can occur. SSA is prohibited in cement concrete applications. (South Carolina

Department of Transportation 2007 Standard Specifications for Highway Construction, page 191)

Limited supply of SSA has decreased its use since 2010. An expansion test is required before acceptance. Used only in base courses with up to 20% replacement of the coarse aggregate (Lockman, 2015).

Washington

SSA is used by Lakeside Industries on private projects out of their Issaquah and Monroe facilities. They use 10-12% as a replacement for the coarse aggregate portion of the mix. The use of SSA conserves company owned aggregate sources. The aggregate cost is $2-3 per ton less than natural aggregates. The only problems encountered was minor yellow staining and surface roughness (due to the angularity of the SSA) when the aggregate was used on a painted tennis court (Bell, 2015).

West Virginia

West Virginia Department of Transportation (WVDOT) includes steel slag in their standard specifications. The slag must be crushed to its intended gradation and maintained in a constant wet condition for a period of at least six months. It must be made sufficiently inert to minimize potential expansion and the discharge of deleterious effluent. Expansion tests are required at the end of the six month period. Expansion values shall not be greater than 0.50 percent at seven days when tested in accordance with ASTM D4792. Expansion testing is not required when the slag is not confined, such as aggregate shoulders, road stabilization, snow and ice control, etc. Steel slag cannot be used as aggregate for portland cement concrete, backfill around drainage structures, piers, abutments, walls or where expansion might be detrimental. (West Virginia 2010 Standard Specification Roads and Bridges, page 890)

Summary of Acceptance Criteria

Indiana – expansion test prior to acceptance
Illinois – expansion test by supplier prior to acceptance
Minnesota – expansion test prior to acceptance
Missouri – three month moist curing
Ohio – one month moist curing and expansion test by supplier prior to acceptance
Pennsylvania – expansion test prior to acceptance
South Carolina - six month moist curing and expansion test prior to acceptance
West Virginia - six month moist curing and expansion test prior to acceptance

Summary of State Uses

None of the states allow the use of SSA in cement concrete applications due to the concerns for expansion. Moist curing of the SSA or an expansion test is required when the aggregate is used for non-HMA applications. Some states use uncured SSA in HMA surface course mixes; others only use it in base course mixes. Most states use the SSA as a high friction aggregate in surface courses due to an absence of hard aggregates in particular locations. The cost of SSAs is normally equivalent to the cost of natural aggregates that are imported from long distances.

Use in Washington State is limited to one local contractor on private jobs. Savings of $2-3 per ton are cited for the cost of SSAs over natural aggregates at asphalt plants near Nucor's Seattle facility. Longer haul distances will increase cost and make it uneconomical to use SSA to replace natural aggregate where long haul distances to an HMA production facility are involved. Some problems (staining and rough surface) have been encountered with the use of SSA in specialty applications, that is, tennis courts. The primary advantage of using SSA would be the conservation of natural aggregates since the friction properties of natural aggregates in Washington State is excellent.

Other States

Information could not be located in a search of the Alabama, Connecticut, Iowa, Kentucky, Oregon, Virginia, Washington D.C., and Wisconsin Department of Transportation's websites on their use of SSA. Colorado used SSA in combination with Trinidad Lake Asphalt binder to overlay the Glenwood Canyon section of I-70, however, no information was found in their standard specifications regarding the acceptance criteria for SSA.

Recommendations

Recommendations concerning WSDOT's possible use of SSA in pavements are:

- Prior to any use of steel slag aggregate, extensive testing should be conducted by the Headquarters Materials Laboratory to determine the expansive nature of the material and its long-term strength under repeated loads and moisture.
- All proposed WSDOT projects using SSA should be experimental features that compare their performance to control sections built with natural aggregates.
- The use of SSA in bases and subbases was not specifically called out in the language of the transportation bill; however, the literature indicated that the high pH of some steel slag aggregates may be a problem with respect to corrosion of culverts and aquatic life in streams and rivers adjacent to roadways. Without adequate testing the use of SSA is not recommended for use as aggregate base for WSDOT roadways.

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