District Highway Maintenance Research On-Call (ROC) Task 4: Best Practices for using Slag in Chip Seal Treatments

Prepared by:
Ala R. Abbas
Munir Nazzal
Abedalrauf Alkalabani
Momen Alassi

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Prepared by:

Ala R. Abbas
Abedalrauf Alkalabani
Momen Alassi
Department of Civil Engineering
The University of Akron
Akron, Ohio 44325

Munir Nazzal
Department of Civil and Architectural Engineering
and Construction Management
The University of Cincinnati
Cincinnati, OH 45221

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16. Abstract

This research-on-call (ROC) task was conducted to assist the Ohio Department of Transportation (ODOT) in gaining a better understanding of slag materials that can be used as chip seal aggregates and the potential benefits and drawbacks from using these materials with chip seal treatments. An online survey was conducted in this study to gather information from state and local transportation agencies regarding the use of slag as a cover aggregate for chip seal treatments. The responses to the online survey indicated that slag is more commonly used by local transportation agencies as a cover aggregate for chip seal treatments than by state departments of transportations, with air-cooled blast furnace slag (ACBFS) being more widely used than basic oxygen furnace (BOF) or electric arc furnace (EAF) slags. Several local public agencies in northeast Ohio reported using #8 ACBFS with their chip seal treatments, even though it is more expensive than washed #8 limestone, due to its many advantages including less dust than limestone aggregates, darker surface resulting in better striping visibility and better public perception, better chip retention, improved durability and skid resistance, better resistance to polishing, and longer chip seal service life. One local public agency in northwest Ohio reported using #8 EAF slag as a cover aggregate for chip seal treatments. This agency reported being very satisfied with the performance of these chip seal treatments, but one concern that was raised regarding the use of EAF slag was the potential for vehicle/windshield damage due to the high density of this slag. A closer examination of the available slag sources in Ohio also revealed the availability of #8 BOF slag in eastern Ohio. However, this slag has not been commonly used for chip seal treatments due to its high percentages of fines. Based on the findings of this study, it was recommended to modify ODOT C&MS Item 422 (Chip Seal) to allow the use of ACBFS and EAF slag with chip seal treatments as an alternative to washed limestone or washed dolostone. Additional recommendations were provided in this study to help promote the successful implementation of chip seals with ACBFS or EAF slag by ODOT.

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1. Problem Statement

Chip sealing is a low-cost pavement treatment method that involves the application of liquid asphalt binder over a pavement surface followed by a coating of washed fine uniformly graded aggregate. This treatment provides a new wearing surface that retards oxidation, reduces water infiltration, and improves friction of the pavement surface. The typical service life of a chip seal treatment is approximately 5 to 7 years. When used properly, chip seal treatments offer a cost-effective alternative to traditional asphalt overlays; thus, allowing transportation agencies to extend their budgets to treat more pavement surface miles per year and provide the public with better overall pavement conditions.

In 2018, ODOT District 1 conducted a trial chip seal project in Defiance County on State Route 66, from mile marker 0.0 to mile marker 2.2, that utilized electric arc furnace (EAF) slag in lieu of the traditional limestone aggregate. This slag, which is a byproduct of steel production, is extremely dense in comparison to limestone aggregates, and it has a darker color than the limestone aggregates available in that region of the state. The results of this chip seal project have been mixed thus far. There was an increase in the number of windshield breakage claims following construction, which might be due to the relatively high density of the slag aggregates. In addition, some areas were found to have delaminated after the first winter plowing season. As can be noticed from Figure 1, the delamination mainly occurred at the middle of the lane in both directions and along the centerline. However, on a positive note, the rest of the pavement surface has remained sealed, and no delamination occurred along the wheel paths. In addition, the use of slag aggregates resulted in a darker color for the pavement surface, which provided better contrast for pavement markings and resulted in better public perception. Furthermore, higher skid resistance numbers were obtained using ODOT's Locked Wheel Friction Tester for this section than chip seals constructed using limestone or dolostone as a cover aggregate. Because of the mixed results from this project, further study on the utilization of slag in chip seal applications is warranted prior to the placement of any future trial sections.

Figure 1. Chip Seal with Slag Section on State Route 66 in Defiance County
(Photograph Taken in July 2023, Approximately Five Years after Construction).

2. Objectives of the Study

The primary goal of research-on-call (ROC) task is to assist the Ohio Department of Transportation (ODOT) in gaining a better understanding of slag materials that can be used as chip seal aggregates and the potential benefits and drawbacks from using slag materials for this purpose.

The specific objectives of this task include:

- Document and summarize the results of various research projects related to the use of slag as a cover aggregate in chip sealing applications.
- Review and document available chip seal specifications where slag is permitted to be used as a cover aggregate.
- Provide recommendations for best practices for using slag as a cover aggregate for chip seal treatments.
- Provide recommendations for modifications to current ODOT specifications with regard to the use of slag as a cover aggregate in chip seal treatments.

3. Research Approach

3.1 Literature review

The literature review involved gathering information on slag types and properties as well as conducting a comprehensive literature review of past research studies that evaluated the performance of chip seals with slag. The initial information on slags collected by the research team from various sources indicated that not all slags are appropriate for use as a cover aggregate for chip seal treatments. A discussion of the production, processing, and treatment of the various types of slags and a description of their physical properties is included in Appendix A. A brief description of the main types of slags typically used as aggregates in chip seal treatments is included in the following paragraphs.

The three main slag types that have typically been used in chip seal applications are air-cooled blast furnace slag (ACBFS), basic oxygen furnace (BOF) slag, and electric arc furnace (EAF) slag. ACBFS is a byproduct of the processing of iron ore into molten iron in a blast furnace. BOF slag is a steel slag that is the byproduct of the smelting of molten iron, alloys, steel scrap, and fluxes in a basic oxygen furnace. EAF slag is a steel slag that is the byproduct of the smelting of alloys, steel scrap, and fluxes in an electric arc furnace.

The physical properties of ACBFS slag will vary depending on the chemical composition of the iron ore, coke, limestone, and fluxes used as inputs to the blast furnace during ironmaking (Wang 2016). The structure of ACBFS is mainly of a crystalline form, with cells or small holes created by gas bubbles that were dissolved in the molten slag, and it has a low coefficient of thermal expansion. Once it has cooled, the ACBFS can be crushed into particles that are approximately cubical in shape, have pockmarked surfaces, and have good angularity. The larger particle sizes of ACBFS have a lower bulk density than natural aggregates of the same gradation, while the finer particles (i.e., those passing a 4.75-mm or a No. 4 sieve) have a density that is nearly equal to that of natural sand. ACBFS also has a relatively high capacity for water absorption. The rough texture and relatively high porosity of the crushed ACBFS, along with its alkaline reactivity, enables it to bond well with both hydraulic cements and asphalt binders. In addition, the ACBFS does not readily polish upon wearing to generate slick surfaces, giving it high durability.

The properties of steel slags (i.e., BOF and EAF slags) mainly rely on the type of furnace(s) used in the steel production as well as the grade of steel being produced (Wang 2016). In terms of their physical properties, steel slags have higher hardness and higher density, and they are less vesicular than ACBFS. The specific gravity of steel slag is dependent on the viscosity and surface tension of the liquid steel slag as well as the amount of ferrous dioxide content and porosity of the slag. Moisture content of steel slag is 0.2–2.0%, specific gravity is 3.2–3.6, and compressive strength is between 169 and 300 MPa (24.5 and 43.5 ksi). Hardness and specific gravity of steel slags are greater than those of BF slag. Steel slags have remarkably high resistance to polishing and wear and, like ACBFS, they impart excellent skid resistance to pavement surfaces.

The research team found limited studies in the literature that evaluated the performance of chip seals with slag. A detailed summary of these studies is presented in Appendix B. In one of these studies, Boz et al. (2019) conducted a laboratory evaluation of two aggregates (natural and slag) and two emulsion types (CRS-2M and CSEA) commonly used in Michigan in an effort to establish threshold values for aggregate percent embedment to optimize the performance of chip seals with regard to aggregate loss and bleeding. The researchers obtained higher percent embedment depths for samples prepared using natural aggregates than those using slag aggregates, and they recommended to use a maximum percent embedment value of 70% to minimize bleeding for single-layer chip seals. In a follow-up study, general guidelines were proposed by Haider et al. (2019) for developing performance-based relationships for chip seal treatments, where the percent embedment of aggregates in the chip seal was selected as the acceptance quality characteristic and where aggregate loss and bleeding were selected as the chip seal performance indicators.

Additional work was conducted by researchers at three universities in Turkey. Uz and Gokalp (2017) conducted a laboratory evaluation of polishing and skid resistance of chip seals prepared using different types and sizes of aggregates, including limestone (LS), basalt (BS), crushed river gravel (BLD), electric arc furnace (EAF) steel slag, and ferrochromium (FER) slag. The researchers found that chip seals prepared using slag aggregates showed better skid resistance – as demonstrated by the higher British pendulum numbers (BPNs) – at all levels of polishing than those prepared using natural aggregates. In a follow-up study, Ergin et al. (2020) conducted a laboratory evaluation of the skid resistance of chip seals prepared using the same types of aggregates as the 2017 study but using only two chip sizes (8−10 mm and 10−12 mm) and two levels of polishing (10,500 and 31,500 cycles) in the Micro-Deval test. Similar to the previous study, the test results in this study indicated that slag aggregates have better resistance to polishing and better skid resistance before and after polishing than natural aggregates.

In a study conducted at Wuhan University of Technology in China, Cui et al. (2021) evaluated the use of recycled steel slag as an aggregate in chip seals, assessing its effectiveness and environmental impact compared to different types of aggregates. Additionally, the study compared the financial costs of using steel slag with those of traditional surface layers. The results showed that using recycled steel slag as an aggregate in chip seals is more environmentally beneficial than landfilling or dumping the slag. Compared to basalt, steel slag can significantly improve the heating and de-icing efficiencies of chip seal. Furthermore, steel slag can enhance the self-bonding function, which is indicated by the retention of aggregates and their durability.

3.2 Online Survey and Follow-up Interviews

An online survey was conducted in this study to identify transportation agencies that have previously used or are currently using slag as a cover aggregate for chip seal treatments. Information was also sought about recommendations for best practices to improve the performance of chip seals with slag. A draft survey questionnaire was prepared by the research team and sent to the Technical Advisory Committee (TAC) for this project in April 2023. Modifications were made and some questions were deleted or added based on comments received from the advisory committee, and the revised survey was implemented by the research team in Qualtrics. Survey invitations were sent out in early May 2023 to state and local transportation agencies in Ohio and other states via the American Association of State Highway and Transportation Officials (AASHTO) Research Advisory Committee (RAC), the No Boundaries pooled fund project, and the Ohio Department of Transportation (ODOT) Local Technical Assistance Program (LTAP) contact lists. The due date for completing the survey was June 1, 2023.

A copy of the survey questionnaire along with a detailed summary of the responses to the online survey are presented in Appendix C. In summary, a total of 59 responses to the online survey were received. Of these, 32 responses were received from state department of transportation representatives, 6 responses were received from ODOT District representatives, 17 responses were received from Ohio local public agency (LPA) representatives, and four responses were received from LPA representatives outside Ohio.

The majority of the respondents indicated that their agencies have never used slag as a cover aggregate for chip seal treatments. This includes departments of transportation (DOTs) in Arkansas, Alaska, California, Connecticut, Delaware, Florida, Georgia, Idaho, Indiana, Kansas, Kentucky, Louisiana, Massachusetts, Maryland, Minnesota, Mississippi, Nebraska, New Jersey, Nevada, Ohio, Oregon, Rhode Island, South Carolina, Texas, Virginia, Vermont, and Wyoming. In addition, representatives from Tuscarawas County, Scioto County, Defiance County, Coshocton County, Putnam County as well as ODOT Districts 2, 9, and 10 indicated that their agencies have never used slag as a cover aggregate for chip seal treatments.

Five respondents indicated that their agencies have used slag as a cover aggregate for chip seal treatments in the past but no longer use it. Table 1 provides a summary of the reasons provided by the respondents on why their agencies stopped using slag with chip seal treatments.

Table 1. Reason for Stopping the Use of Slag with Chip Seal Treatments.

Agency	**Reason**
Carroll County, OH	Availability of the material, also the cost in times that it is/was available.
Williams County, OH	We were using both slag and limestone at the time. Our box was an older model and when we switched to slag the belts would drag. I assume because of the weight difference. For production it was easier to stay consistent with the limestone. We have a newer box but have not tried slag again. We have tried naturals because of access which is a good material.
Carlisle Township, OH	Mostly availability, but cost plays a part in our decision to go to limestone.
Winneshiek County, IA	The aggregate was too expensive to haul compared to local aggregates.
North Carolina DOT	It's been decades since our DOT has used it, so I do not have an answer as to why.

Responses to the online survey indicated that slag is more commonly used as a cover aggregate for chip seal treatments by local transportation agencies than by state DOTs. Only two representatives from state DOTs (South Carolina and Utah) indicated that their agencies use or allow using slag as a cover aggregate for chip seal treatments. The two respondents reported that slag is not commonly used for this purpose in their states due to high cost and/or lack of availability.

Several local public agencies reported using slag as a cover aggregate for chip seal treatments, including Medina County, Portage County, Lake County, Stark County, City of Canton, City of Chagrin, City of Toledo, and Beaver Township in Ohio as well as Louisa County in Iowa and Boone County in Indiana. The Wisconsin Transportation Information Center at the University of Wisconsin-Madison also reported that slag is used as a cover aggregate for chip seal treatments by local public agencies in Wisconsin. The majority of these agencies reported using ACBFS with chip seal treatments, while some agencies reported using EAF slag for this purpose. The main advantages reported by these agencies for chip seals with slag include: less dust than those with limestone aggregates, darker surface resulting in better striping visibility and better public perception, better chip retention, improved durability and skid resistance, better resistance to polishing, and longer chip seal service life. Lower slag cost was reported by some agencies as an "advantage", while other agencies reported that slag aggregates are more expensive than natural aggregates. Slag availability and inconsistency in slag cleanliness were also reported by some agencies as disadvantages for using slag with chip seal treatments. Another disadvantage reported for EAF slag, which is significantly denser than natural aggregates and ACBFS, is the higher potential for windshield damage.

Follow-up interviews were conducted with selected LPAs in Ohio and other states that use chip seal with slag to obtain additional information about the testing and specifications used by the agency to ensure the quality of the slag; the distance between the slag source and the LPA's location; shipping, handling, and stockpiling of slag when chip seal is installed by in-house crews; recommended best practices when using slag as opposed to other natural aggregates with chip seal treatments; effect of snow plowing on chip seal performance; and potential damage to vehicles. The follow-up interviews revealed that all local public agencies that use slag as a cover aggregate for chip seal treatments are located within a one-hour drive from the slag source; thus, resulting in a reasonable transportation cost for the slag aggregate. Otherwise, it may not be cost effective to use slag with chip seal treatments. To ensure the quality of the slag, most agencies reported relying on a visual inspection of the slag for cleanliness rather than standardized testing. In general, no major differences in the installation practices were reported by the interviewed agencies when using slag aggregates instead of natural aggregates with chip seal treatments. However, a lower aggregate application rate was reported when using ACBFS and a higher aggregate application rate was reported when using steel slags as compared to alternative natural aggregates. This is expected since ACBFS has lower density and steel slags have higher density than natural aggregates. It was also reported to be more challenging to achieve the target aggregate application when using steel slags due to their higher densities. Some agencies also reported that steel slag was too heavy for their aggregate spreader to chip seal multiple lanes in one pass. With regard to the emulsion application rate, the City of Toledo reported using a lower emulsion application rate with EAF slag, while agencies in northeast Ohio reported using the same emulsion application rate when using ACBFS or limestone aggregates. It was also reported that steel slags are easier to compact than natural aggregates and may not need to be fog sealed to contain the dust like some limestone aggregates. However, they might cause more damage to vehicles due to their higher densities especially when used on roads with higher speed limits.

3.3 Available Specifications for Chip Sealing with Slag

As discussed in the previous section, state transportation agencies in South Carolina and Utah reported using or allowing the use of slag as a cover aggregate for chip seal (also called seal coat by some agencies) treatments. A thorough review of chip seal construction and material specifications used by other state transportation agencies also revealed that slag is allowed to be used as a cover aggregate by Michigan, Indiana, and Louisiana DOTs. A summary of these specifications is included in Appendix D. By examining these specifications, it was observed that some of these agencies (such as Michigan DOT) only allow ACBFS to be used, while others (like Indiana DOT) allow ACBFS as well as steel slag to be used. It was also observed that some state transportation agencies (such as Louisiana DOT) use the same aggregate property requirements for slag aggregates as for natural aggregates when used in chip seals, while others (such as Michigan and South Carolina DOTs) have different requirements for some aggregate properties such as the specification for Los Angeles (LA) abrasion. Some state transportation agencies also require modifying the asphalt emulsion application rate and/or aggregate application rate when using slag as a cover aggregate for chip seal treatments. South Carolina DOT requires increasing the asphalt emulsion application rate by 15% when using ACBFS with chip seals to account for the higher aggregate absorption. Indiana and Utah DOTs require modifying the aggregate application rate based on the bulk unit weight or the specific gravity of the cover aggregate. As such, lighter aggregates such as ACBFS will have a lower application rate than natural aggregates or heavier aggregates such as steel slag.

3.4 Slag Availability in Ohio and Nearby States

ODOT Construction and Material Specifications (C&MS) Item 422 (Chip Seal) calls for using washed limestone or washed dolostone conforming to 703.05 as cover aggregates for chip seal treatments. Figure 2 shows the locations of limestone/dolostone aggregate sources in the state represented by pink triangles, with the size of the triangle indicating the relative amount of aggregate produced at that particular aggregate source in 2019. These aggregates are obtained from surface or underground mines in Ohio, with the overwhelming majority of the aggregates being sourced from surface mines. As can be noticed from Figure 2, the largest limestone/dolostone operations are located in the western part of the state, with a relatively small amount of limestone/dolostone produced in the eastern part of the state. To compensate for the lack of local limestone/dolostone aggregate sources in the eastern half of the state, limestone/dolostone aggregates are commonly shipped to different redistribution yards in that part of the state by rail (especially for yards that are inland), by barge (on the Ohio River), and by lake freighter (on the Lake Erie), resulting in a higher cost for these aggregates due to transportation.

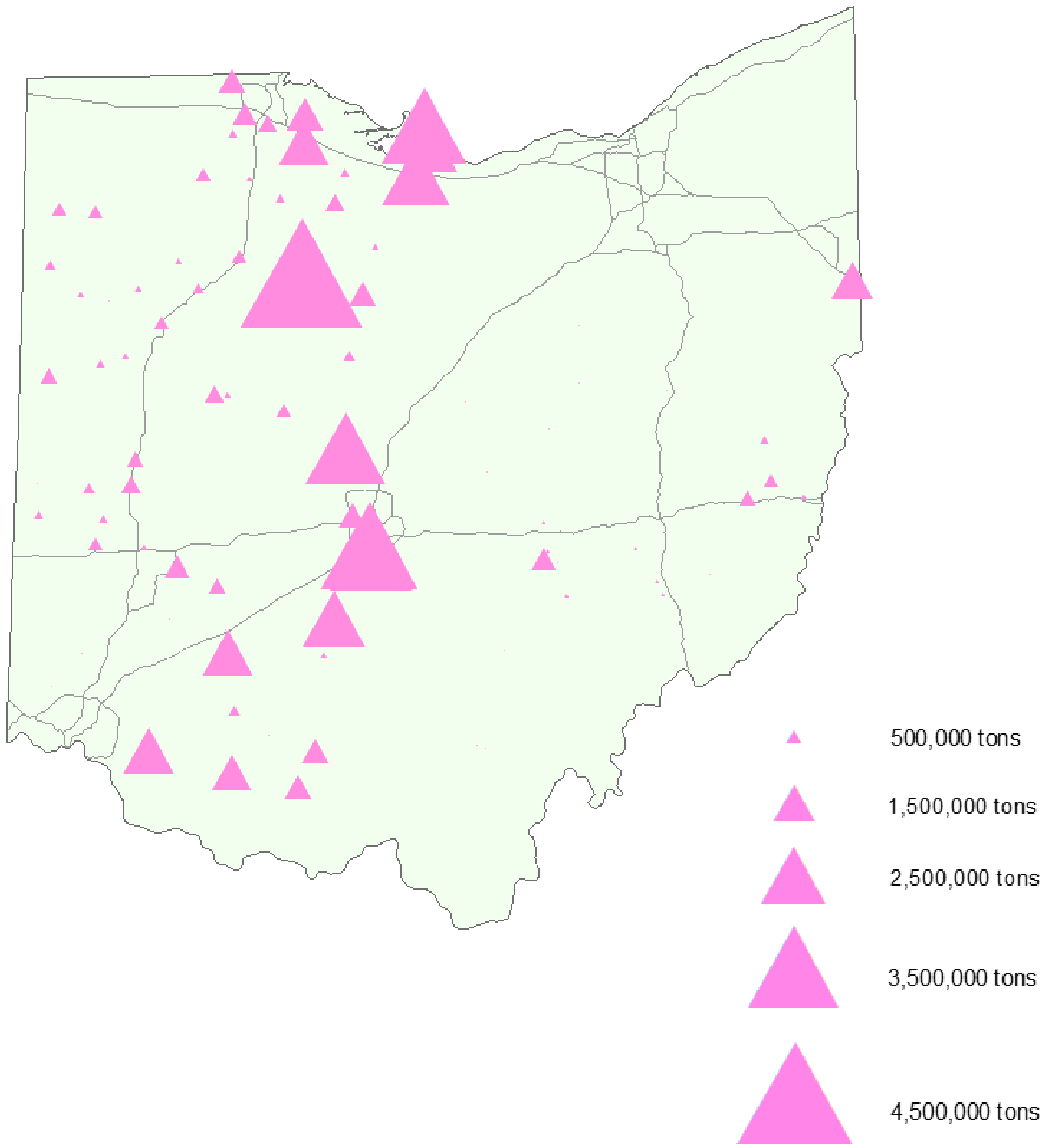

Figure 2. Locations of Aggregate Sources and 2019 Aggregate Production for Limestone and Dolostone Mining Operations (in *Pink*).

Table 2 presents the aggregate gradation requirements for ODOT C&MS Item 422 (Chip Seal) Type A (single course) and the gradation limits for ODOT aggregate size #8. As can be noticed from this table, aggregate size #8 has relatively similar graduation requirements to ODOT Item 422 Type A. Therefore, this aggregate size is the most commonly used aggregate size for chip seal treatments by ODOT. Figure 3 presents a map showing the locations of ODOT-approved sources of #8 slag in Ohio and neighboring states. As can be noticed from this figure, #8 slag is only available at a few select locations that have or used to have iron and/or steel production facilities such as Cleveland, Toledo, Cincinnati, Steubenville, and Pittsburgh. Table 3 presents the particle size distributions, specific gravities, and absorptions of these #8 slags.

Table 2. Gradation Requirements for ODOT C&MS Item 422 (Chip Seal) Type A (Single Course) and ODOT Aggregate Size #8.

		Total Percent Passing	
Sieve Size		Item 422 Type A	ODOT Size #8
1/2 inch	12.5 mm	100	100
3/8 inch	9.5 mm	85 to 100	85 to 100
No. 4	4.75 mm	5 to 25	10 to 30
No. 8	2.36 mm	0 to 10	0 to 10
No. 16	1.18 mm	0 to 5	0 to 5
No. 200	75 mm	0 to 1.5 [1]	No Requirement

[1] Washed gradation value

Due to the lack of locally available limestone/dolostone aggregates in the eastern half of the state, slag has been used more commonly as an alternative cover aggregate for chip seal treatments by many local public agencies (including Medina County, Portage County, Lake County, Stark County, City of Canton, City of Chagrin, City of Toledo, and Beaver Township) in this part of the state. All these agencies reported using ACBFS, which originated from the Cleveland or Pittsburgh areas. The BO steel slag available in this region of the state was reported to lack the desired cleanliness for chip seal applications and require a higher aggregate application rate due to the higher density of the BO slag. The City of Toledo reported using EAF slag in the past as a cover aggregate for chip seal treatments but no longer using it due to the discontinuation of the chip seal program. It was mentioned during the follow-up interview with the City of Toledo that the slag offered at a relatively low price, which made it more cost effective than using limestone/dolostone. Aside from the City of Toledo, no other local public agency in the western part of the state reported using slag as a cover aggregate for chip seal treatments. This could be due to the wider availability of local limestone/dolostone aggregate sources in western Ohio.

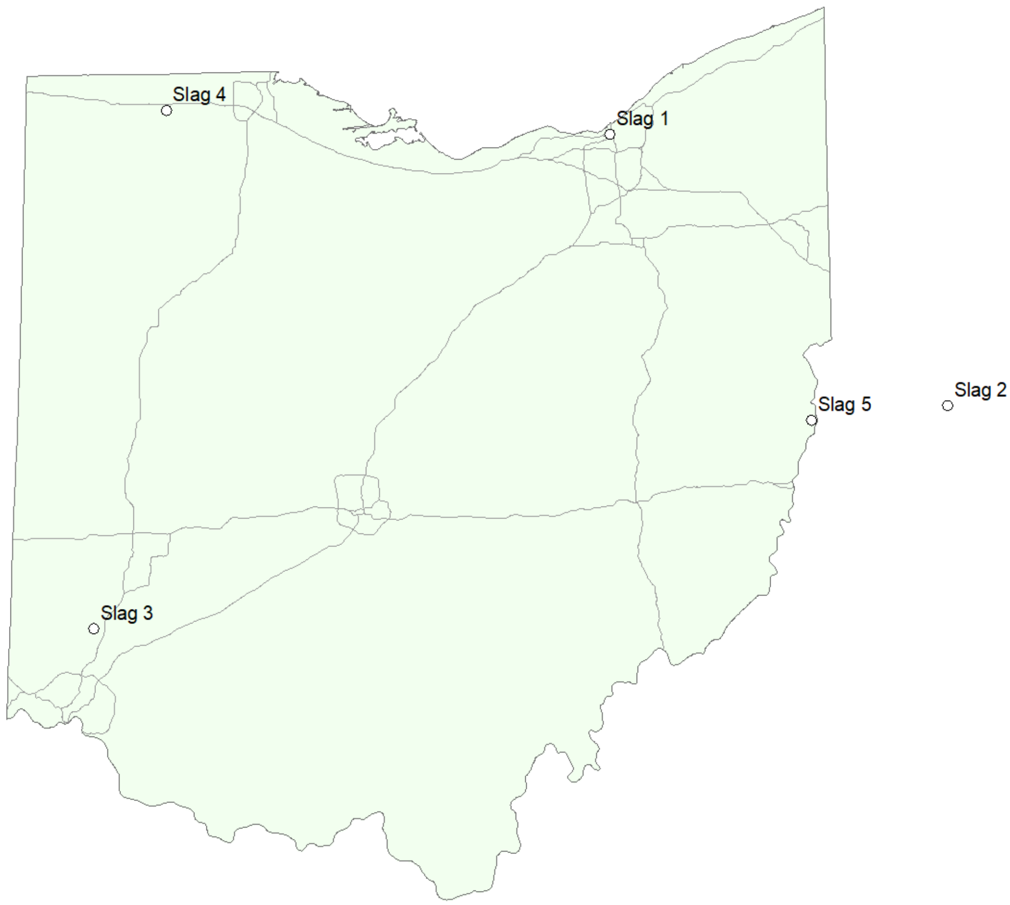

Figure 3. Locations of Sources of ODOT-Approved #8 Slags.

Table 3. Particle Size Distributions, Specific Gravities, and Absorptions of ODOT-Approved #8 Slags.

		Total Percent Passing				
		Slag 1	Slag 2	Slag 3	Slag 4	Slag 5
		ACBFS	ACBFS	ACBFS	EAF Slag	BOF Slag
Sieve Size		Cleveland	Pittsburgh	Cincinnati	Toledo	Steubenville
1/2 inch	12.5 mm	100	100	100	100	100
3/8 inch	9.5 mm	88	91	98	89	98
No. 4	4.75 mm	15	18	22	19	18
No. 8	2.36 mm	6	3	5	2	4
No. 16	1.18 mm	5	2	4	1	4
Specific Gravity		2.430	2.404	2.372	3.632	2.677
Absorption		2.38%	2.73%	2.77%	0.84%	4.74%

3.5 Interview of Chip Seal Contractor with Experience with Slag

The research team interviewed a chip seal contractor with extensive experience in using slag as well as limestone as cover aggregates for chip seat treatments in northeast Ohio to document their experience with these aggregates. The chip seal contractor reported using ACBFS from the Cleveland and Pittsburgh areas with chip seal treatments and avoiding the use of BOF slag from the Steubenville area for this purpose due to lack of cleanliness and the higher density. The ACBFS price was reported to be \$8 to \$10 higher per ton than limestone, but a lower aggregate application rate is needed for ACBFS due to its lower density (19 to 20 lb/yd^2 for ACBFS versus 22 lb/yd^2 for limestone). The same emulsion application rate was reported to be used for chip seals constructed with limestone or ACBFS as cover aggregates. The chip seal contractor noted the ACBFS does not meet the ODOT gradation requirements for Item 422 Type A as it may contain higher amounts of fines than specified and may not meet the hardness requirement. Issues encountered during construction with ACBFS may also include inconsistent aggregate gradation. However, the chip seal contractor noted that ACBFS works well with chip seal treatments, and this is why local public agencies continue to use it in northeast Ohio.

3.6 Best Practices for Chip Sealing with Slag

As mentioned earlier, no major differences in chip sealing practices were reported by agencies that use slag instead of natural aggregates with chip seal treatments with the exception of adjusting the aggregate and emulsion application rates. Several requirements are included in ODOT C&MS Item 422 to ensure the quality of chip seal treatments, including the checking of the aggregate gradation and the percentage of fines; the use of proper binder distributors, rollers, aggregate spreaders, and power sweepers or rotary brooms; placing the chip seal under favorable environmental conditions; the use of a test strip to determine the required emulsion and aggregate application rates to achieve 2/3 aggregate embedment; among others. While these requirements were developed for chip sealing with limestone/dolostone aggregates, they are also applicable to chip sealing with slag.

3.7 Cost Comparison of Chip Seals with Slag versus Limestone

Most transportation agencies that use chip sealing with slag reported a unit cost of \$2 to \$4 per square yard. The wide range in cost provided by these agencies is likely due to using in-house crews versus external contractors for the chip seal installation as well as variations in material, labor, equipment, and mobilization costs. In general, the cost of aggregates used for chip sealing is dependent on many factors including the local availability of quality aggregates that meet ODOT's specifications, the cost of aggregate processing to obtain the desired aggregate gradation and cleanliness, the demand for that aggregate, and the cost of transportation from the aggregate source to the job site (or from the aggregate source to a redistribution yard to the job site if the aggregate is brought in from another region in the state).

As discussed in the previous sections, #8 ACBFS obtained from the Cleveland and the Pittsburgh areas have been the most commonly used slag for chip sealing by local transportation agencies in Ohio. Due to the relatively high demand for this slag in northeast Ohio, the cost of #8 slag is $8 to $10 per ton higher than #8 limestone aggregates ($20 per ton for #8 limestone versus $28 to $30 per ton for #8 ACBFS). Having a limited number of ACBFS slag suppliers also results in a higher transportation cost for some of agencies that are not close to the slag source. Therefore, chip seals with slag have generally been more expensive than those with limestone aggregates for local transportation agencies in northeast Ohio. It is noted though that asphalt emulsion accounts for the majority of the material cost in chip seal applications. Therefore, since the same emulsion application rate has been used for chip seals constructed with limestone or ACBFS as cover aggregates (as discussed in Section 3.2), the higher cost of the ACBFS is not expected to significantly increase the overall cost of the chip seal treatment. Regardless of the higher cost, local public agencies in northeast Ohio have continued to use slag for chip sealing because of its many advantages including less dust than limestone aggregates, darker surface resulting in better striping visibility and better public perception, better chip retention, improved durability and skid resistance, better resistance to polishing, and longer chip seal service life.

On the other hand, the City of Toledo, Ohio, and Boone County, Indiana, reported that the main objective from using EAF slag in their chip sealing programs was to reduce cost. Boone County, Indiana reported a $10 per ton cost for EAF slag versus $15 per ton for limestone. Even though a higher aggregate application rate is needed for EAF slag due to its higher density, both agencies reported a cost reduction from using EAF slag as compared to limestone aggregates in their chip sealing programs.

4. Research Findings and Conclusions

Below are the main research findings and conclusions of this study:

- The literature review revealed that not all slags are appropriate for use as a cover aggregate for chip seal treatments. The three main slag types that have typically been used in chip seal applications are ACBFS, BOF slag, and EAF slag. ACBFS is a byproduct of iron production, while BOF and EAF are byproducts of steel production. These slags have very different properties.
- The responses to the online survey indicated that slag is more commonly used as a cover aggregate for chip seal treatments by LPAs rather than by state departments of transportations, with ACBFS being more widely used than BOF or EAF slags.
- Several LPAs in northeast Ohio reported using #8 ACBFS with their chip seal treatments, even though it is more expensive than washed #8 limestone, due to its many advantages including less dust than limestone aggregates, darker surface resulting in better striping visibility and better public perception, better chip retention, improved durability and skid resistance, better resistance to polishing, and longer chip seal service life.
- One LPA in northwest Ohio also reported using #8 EAF slag as a cover aggregate for chip seal treatments. This agency reported being very satisfied with the performance of these chip seal treatments. One concern that was raised regarding the use of EAF slag was the potential for vehicle/windshield damage due to the high density of this slag.
- A closer examination of the available slag sources in Ohio also revealed the availability of #8 BOF slag in eastern Ohio. However, this slag has not been commonly used for chip seal treatments due to its high fines content.

5. Recommendations for Implementation

Several local public agencies in Ohio have successfully used ACBFS and EAF slag with their chip seal treatments and are very satisfied with their performance. However, unsatisfactory results were reported when using BOF slag obtained from eastern Ohio as a cover aggregate for chip seal treatments. Therefore, it is recommended to modify ODOT C&MS Item 422 (Chip Seal) to allow the use of ACBFS and EAF slag with chip seal treatments as an alternative to washed limestone or washed dolostone.

It is recognized that some of the ACBFS and EAF slag sources in Ohio may not meet ODOT's Item 422 Type A (single layer) gradation and cleanliness requirements due to inconsistent aggregate gradation and higher percentage of fines than specified. Therefore, some changes might need to be made to the processing of these slag materials before allowing them to be used in ODOT projects. Additional research is also recommended to investigate the possibility of using different specification limits for ACBFS or EAF slag than for limestone/dolostone in ODOT C&MS Item 422. Furthermore, additional research is needed to determine the optimum emulsion and aggregate application rates to use for chip seals installed using these slag aggregates. As part of this effort, it is recommended to construct a chip seal test section using different combinations of emulsion and aggregate application rates and evaluate the performance of the resulting chip seals to aid in the selection of the optimum application rates.

It is also recognized that EAF slag has a relatively high density (in comparison to limestone and ACBFS) and, when used for chip seals on roadways with higher speed limits (such as those overseen by ODOT), may result in more potential for damage to vehicles/windshields. Therefore, care should be taken when deciding which roads to chip seal with EAF slag. Alternatively, additional traffic control might be needed after chip seal installation and compaction until the excess amount of loose EAF slag aggregate has been removed from the surface.

The use of slag as a cover aggregate can also impact a surveyor's ability to locate buried survey pins and monuments due to the slag's metallic characteristics resulting from the insufficient separation of metal from the slag during iron or steel production. A potential solution would be to identify all property pins and survey monuments within the work area and protect them with a disposable temporary cover prior to the chip seal operation.

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Appendix A
Slag Types and Properties

A.1 Introduction

The term "slag" generally refers to molten by-products of metal smelting or other processes (such as high-temperature incineration of nonmetallic substances) that are drawn off and cooled to a solid form. In a comprehensive overview of the utilization of slag in civil infrastructure construction, Wang (2016) classified slags into three main groups, as shown in Figure A.1, based on their elemental composition: 1. *ferrous slags*, which are byproducts of iron and steel production; 2. *nonferrous slags*, which are byproducts of the production of other metallic materials (i.e., metals that are not iron or steel), and 3. *Non-metallurgical slags*, which are byproducts of non-metallurgical processes and can include materials such as boiler slag (from the combustion of coal) and incinerator slag (from waste incineration). Of the various types of slags, ferrous slags are the most commonly used in construction. Therefore, this appendix will focus on the production and processing of ferrous slags.

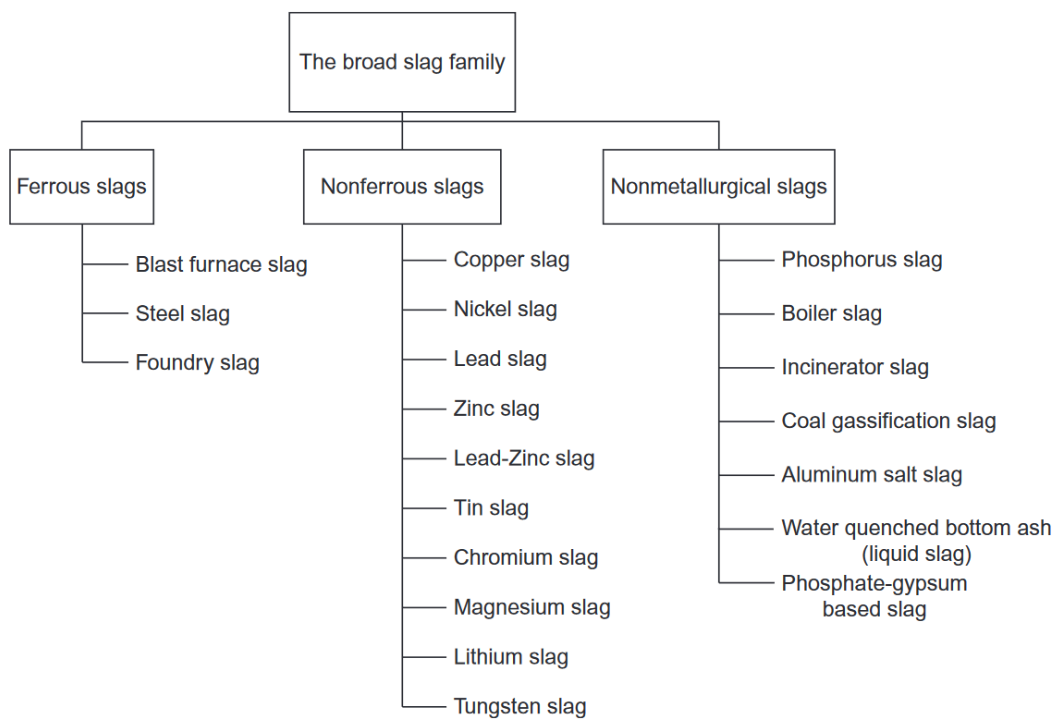


Figure A.1. Broad Classification of Slags (Wang 2016).

Ferrous slags can be classified into three broad types: blast furnace slags, steel slags, and foundry slags. The first two types are byproducts of iron and steel refining. Blast furnace slags are byproducts from the refining of iron, and steel slags are byproducts from the refining of steel. Foundry slag is a byproduct that is produced during the casting process in iron foundries when molten iron drawn from the blast furnace is poured into molds. Any impurities from the use of other materials (such as sand or clay) in the molding process may be left behind in the form of foundry slag. This slag is therefore considered as a waste material, and it is removed from the casting and discarded (Cardoso et al. 2018).

A.2 Production of Ferrous Slags

The processes for producing iron and steel as well as the different types of ferrous slags generated from each process are presented in Figure A.2. The first step in the process is the refining of iron in a blast furnace (BF) by smelting iron ore, iron scrap, coke, and fluxes (which are materials added to the furnace to aid in removing impurities) as shown in the left side of Figure A.2. The flux reacts with impurities to form a material that can be drawn off and discharged — this molten material is known as blast furnace slag (or BF slag). Steel can be produced by two main processes. In the first, molten iron from the blast furnace is combined with scraps, fluxes, and alloys in a basic oxygen furnace (BOF) to produce molten steel and molten BOF slag. In the second steelmaking process, steel scraps, alloys and fluxes are combined in an electric arc furnace (EAF) to produce molten steel and EAF slag. Molten steel from the BOF or the EAF can be transferred to a secondary refining furnace (also known as a "ladle furnace") for removal of additional impurities, producing molten refined steel and ladle slag. The molten steel from the BOF or EAF or the refined molten steel from the secondary refining furnace are sent to a continuous caster (to be poured into billets, blooms, or slabs, which are subsequently rolled and formed into various products), while the iron slag (BF slag) or steel slag (either BOF slag, EAF slag, or ladle slag) is discharged in molten form and is cooled and further treated or processed for use in various applications.

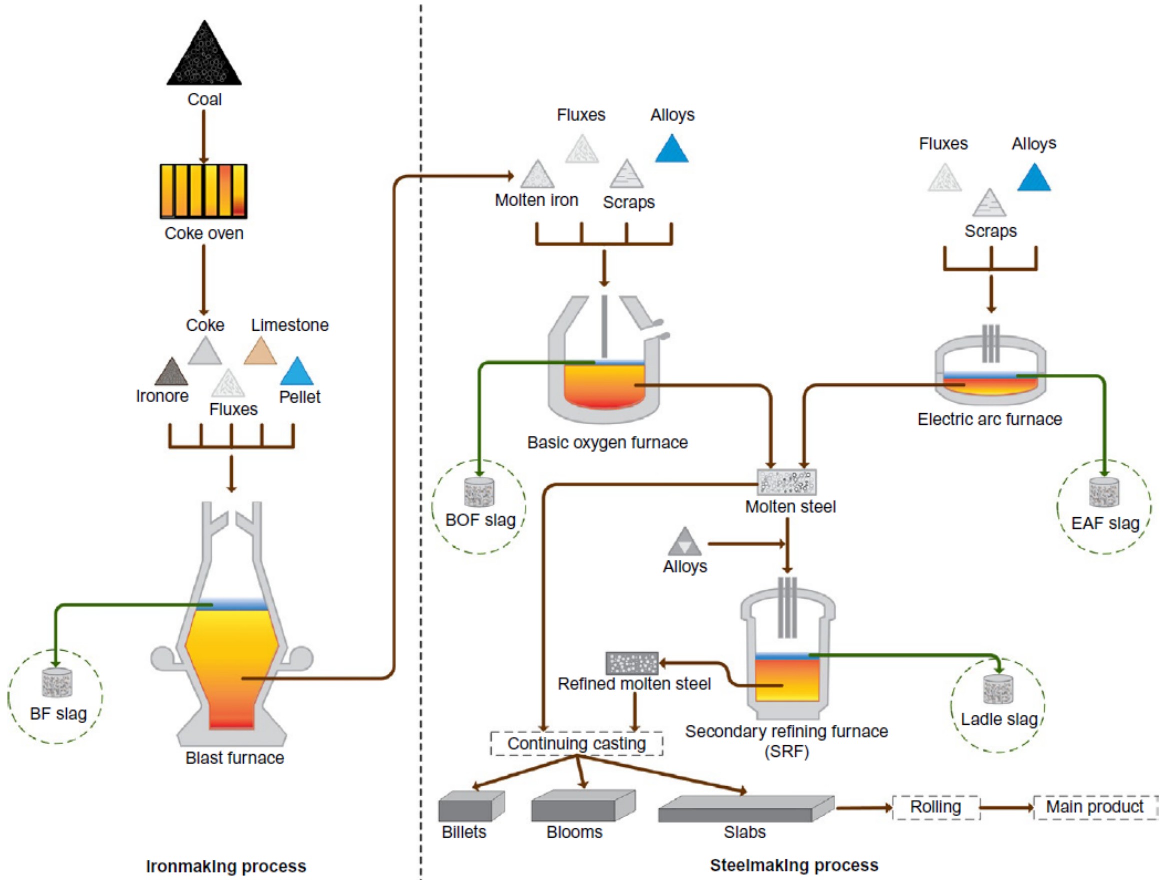


Figure A.2. Iron and Steel Production and the Resulting Generation of Different Types of Ferrous Slags (Wang 2016, as adapted from Yildirim and Prezzi 2011).

Worldwide, the BOF steelmaking process is the dominant steelmaking technology, accounting for approximately 60% of the world's total output of crude steel. While the use of BOF has increased throughout the rest of the word, the production of steel using the BOF process in the United States (US) has decreased from 55% in 2001 to 33% in 2018 (Wang 2016, Nimbalkar 2022). This drop has been mainly attributed to the wider availability of recycled steel scrap (which is less costly to use for steelmaking, since it eliminates the need for mining and extracting iron ore), the increased use of the EAF process (due to its lower energy consumption and CO_2 emissions), and the particular grades of steel produced in the US (Wang 2016, Hasanbeigi and Springer 2019).

A.3 Processing of Ferrous Slags

A.3.1 Processing of Blast Furnace Slags

The BF slag produced during iron smelting is controlled to maintain the amount of aluminum oxide (Al_2O_3) in the slag to approximately 10% to achieve a stable melting point temperature within a typical range of 1400−1500 °C (2552−2732 °F) and keep the slag in a fluid state over a wide range of lime and silica contents (Wang 2016). The cooling conditions will dictate the arrangement of the crystalline structure of the resulting BF slag as well as its density and porosity, as these conditions determine the growth of the mineral crystals and the number and size of the gas bubbles that can emanate as the slag solidifies (Wang 2016). After the molten BF slag is poured from the blast furnace, the slag is subjected to processing and handling to make it suitable for different applications, as shown in Figure A.3.

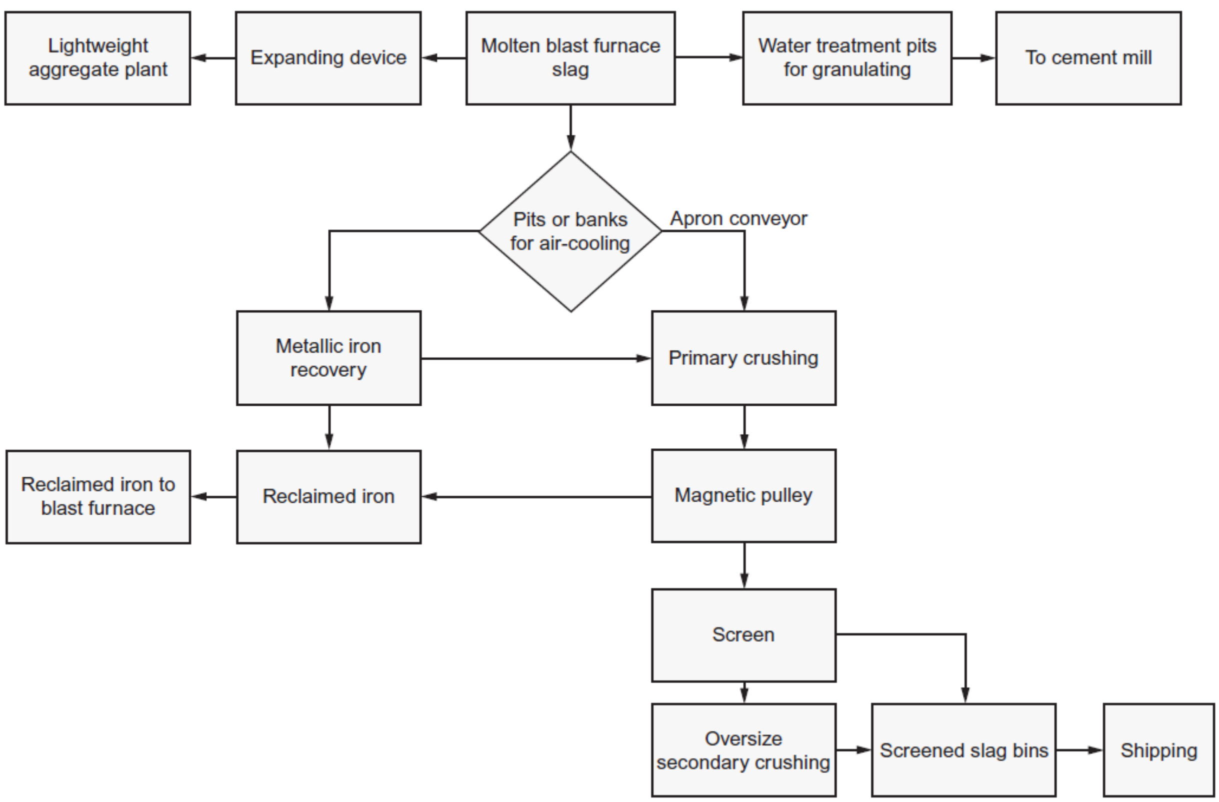


Figure A.3. Processing of Blast Furnace Slag (Wang 2016).

The following list provides a summary of the different types of BF slags and their production:

- Air-cooled blast furnace slag (ACBFS): After molten BF slag is discharged from the blast furnace, it is immediately poured into a cooling pit for air cooling at ambient temperatures. Because the molten slag is poured on top of the previous layer of slag that is partially cooled, it causes cracking. As a result, the material can easily be picked up and moved using power shovels. Water is also used in the process to promote further fragmentation of the slag and to help hydrate any incompletely fused flux materials that might result in spalling or popouts if the slag will be used as an aggregate in the production of concrete. Once the slag has reached 93 °C (200 °F) or lower, it can be taken to a plant for crushing and screening. A photograph of a sample of ACBFS is presented in Figure A.4.

Figure A.4. Air-Cooled Blast Furnace Slag (Cao et al. 2022).

- Granulated slag: In the granulation process, molten slag is solidified by quenching it in water, which fragments the material into the form of granules (Wang 2016). The resulting slag, which is in a glassy state, is a valuable material for cement manufacturing, as it can be used to replace Portland cement (Xie et al. 2010). A photograph showing granulated and ground granulated blast furnace slags is presented in Figure A.5.

Figure A.5. Granulated Blast Furnace Slag (*Right*)
and Ground Granulated Blast Furnace Slag (*Left*) (Dinh 2023).

- Dry granulated slag: In the process of dry granulation, the molten slag is converted into very fine droplets by applying centrifugal forces on a spinning disc, and the slag droplets are quenched and solidified rapidly using air (Xie et al. 2010). The resulting slag is used for the production of cement and concrete (Liu et al. 2020). A photograph of dry granulated slag is presented in Figure A.6.

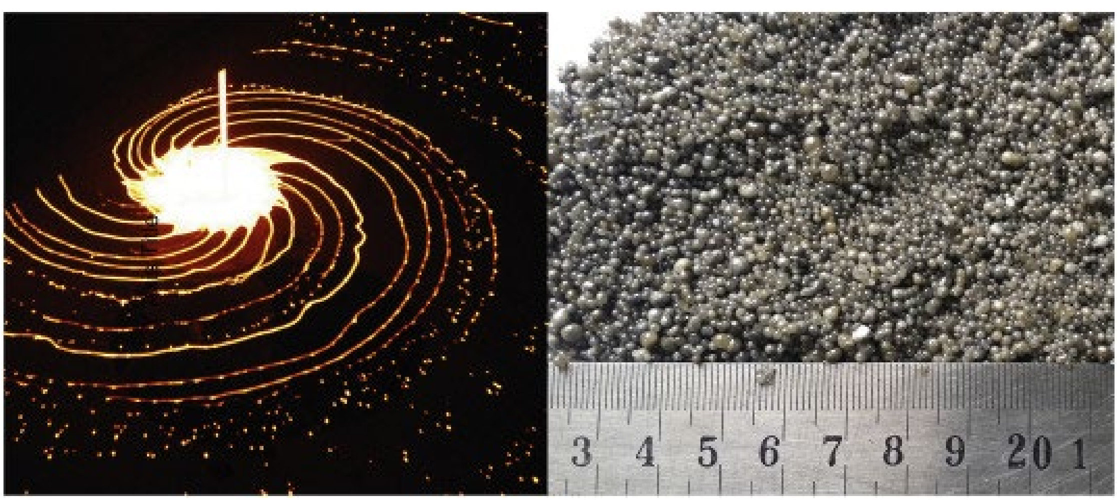


Figure A.6. Dry Granulation of Molten BF Slag (*Left*)
and the Resulting Slag Particles (*Right*) (Liu et al. 2020).

– Minor blast furnace slags: Two minor types of BF slags are expanded slag (also known as foamed slag or slag pumice) and pelletized slag. *Expanded slag* – which is produced when molten slag from the blast furnace is cooled and solidified through the use of controlled quantities of water, air, or steam – is a lightweight expanded or foamed product that has higher porosity and lower bulk density than ACBFS (FHWA 1997). The second minor BF slag, known as *pelletized slag*, is formed when molten BF slag is cooled and solidified through a combination of quenching (with water and air) and tumbling in a spinning drum (Wang 2016). The speed of the pelletization process can be controlled so that the pellets will either become more crystalline, which is advantageous for aggregates, or more glassy, which is advantageous for cementitious applications (FHWA 1997). Photographs of expanded slag and pelletized slag are shown in Figure A.7.

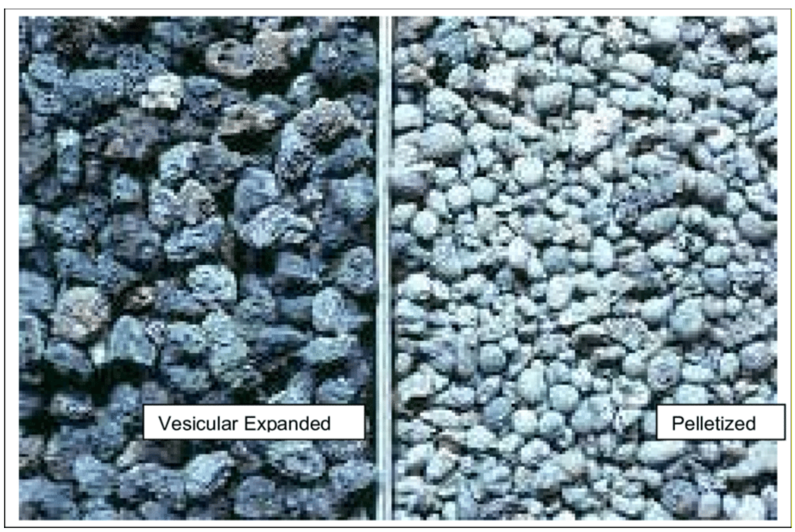


Figure A.7. Minor BF Slags: Vesicular Expanded Slag (*Left*) and Pelletized Slag (*Right*) (Emery 1980).

A.3.2 Processing of Steel Slags

Steel slag, which is comprised of silicates and oxides, forms when molten steel is separated from impurities. This is generally accomplished in integrated mills that use the basic oxygen process or in specialty plants (sometimes referred to as *steel mini mills*) that use the electric arc furnace process. Photographs of the resulting BOF and EAF slags are shown in Figure A.8 and Figure A.9, respectively. A photograph of a ladle slag, which is produced from a secondary refining furnace, is shown in Figure A.10. In the past, steel was produced in batches in an open-hearth furnace; however, this process is no longer in use (FHWA 1997). Numerous grades of steel are produced in the United States – high, medium, or low, based on the proportion of carbon in the steel. The properties of the slags resulting from each grade of steel can be very different. Lower grades of steel require the use of higher oxygen levels in the furnace as well as larger amounts of flux (in the form of lime and dolomitic quicklime) to remove the impurities (FHWA 1997).

Figure A.8. A Sample of Gravel-Sized Particles of BOF Slag (Yildirim and Prezzi 2011).

Figure A.9. A Sample of Gravel-Sized Particles of EAF Slag (Yildirim and Prezzi 2011).

Figure A.10. A Sample of Ladle Slag (Maghool et al. 2017).

A.4 Physical and Chemical Properties of Ferrous Slags

The appropriate and successful use of a particular ferrous slag generally requires an understanding of the chemical, mineral, and physical properties of the slag as well as the technical requirements of the end products and their applications (Wang 2016). The composition of the input materials used in the production of iron and steel – including the particular iron ore used in iron smelting (the source of which may change over time), the recycled scrap steel and alloys added to the electric arc furnace, or even the properties of the materials used as fluxing agents – can all have an influence on the properties of the resulting slag (Wang 2016). The following subsections present additional information on the properties of the different types of ferrous slags.

A.4.1 Properties of Blast Furnace Slag

Variations in the chemical composition of the inputs to the blast furnace will affect the relative contents of the four major constituents of the BF slag (lime, silica, alumina, and magnesia) as well as the amounts of the minor constituents (such as sulfide, ferrous oxides, and manganese oxides). The range in chemical compositions of BF slags is presented in Table A.1.

Table A.1. Range in Chemical Compositions of Blast Furnace Slag (Wang 2016).

Component	Percent Content (%)
Calcium oxide (quicklime; CaO)	31–50
Silicon dioxide (silica; SiO_2)	27–45
Aluminum oxide (alumina; Al_2O_3)	7–24
Magnesium oxide (magnesia; MgO)	1–18
Iron (in the form of FeO or Fe_2O_3)	0.3–2
Manganese oxide (MnO)	0.1–2.3
Sulfur (S)	0.6–3
Phosphorus pentoxide (P_2O_5)	< 0.1

The structure of ACBFS is mainly of a crystalline form, with cells or small holes created by gas bubbles that were dissolved in the molten BF slag, and it has a low coefficient of thermal expansion. Once it has cooled, the ACBFS can be crushed into particles that are approximately cubical in shape, have pockmarked surfaces, and have good angularity. The larger particle sizes of ACBFS have a lower bulk density than natural aggregates of the same gradation, while the finer particles (i.e., those passing a 4.75-mm or a No. 4 sieve) have a density that is nearly equal to that of natural sand. ACBFS also has a relatively high capacity for water absorption. The rough texture and relatively high porosity of the crushed ACBFS, along with its alkaline reactivity, enables it to bond well with both hydraulic cements and asphalt binders. In addition, the ACBFS does not readily polish upon wearing to generate slick surfaces, giving it high durability (Wang 2016).

A.4.2 Properties of Steel Slags

The properties of steel slags mainly rely on the type of furnace(s) used in the production of the steel (i.e., BOF, EAF, or secondary refining furnace) as well as the grade of steel being produced (Wang 2016). Table A.2 provides the range in chemical compositions of the resulting steel slags.

Table A.2. Range in Chemical Composition of Steel Slags (Wang 2016).

Component	**BOF Slag Percent Content (%)**	**EAF Slag Percent Content (%)**	**Ladle Slag Percent Content (%)**
Calcium oxide (quicklime; CaO)	35–45	40–60	30–60
Silicon dioxide (silica; SiO_2)	12–17	10–30	2– 35
Aluminum oxide (Al_2O_3)	0.98–3.4	2–9	5–35
Iron (in the form of FeO)	10–25	10–30	0–15
Magnesium oxide (MgO)	3–15	3–8	1–12.6
Manganese oxide (MnO)	5–15	2–5	0– 5
Sulfur trioxide (SO_3)	0–0.3	0.1–0.6	0.1–1
Phosphorus pentoxide (P_2O_5)	0.2–4	0–0.12	0–0.4

Note: Some steel slags also contain trace amounts of vanadium pentoxide (V_2O_5) and the titanium oxide TiO_5; however, the trace components are not included in the above table.

In terms of their physical properties, steel slags have higher hardness and higher density, and they are less vesicular than ACBFS. The specific gravity of steel slag is dependent on the viscosity and surface tension of the liquid steel slag as well as the amount of ferrous dioxide content and porosity of the slag. Moisture content of steel slag is 0.2–2.0%, specific gravity is 3.2–3.6, and compressive strength is between 169 and 300 MPa (24.5 and 43.5 ksi). Hardness and specific gravity of steel slags are greater than those of BF slag. Steel slags have remarkably high resistance to polishing and wear and, like ACBFS, they impart excellent skid resistance to pavement surfaces.

Appendix B
Literature Review

B.1 Introduction

A thorough literature search was conducted in this research task that revealed limited research studies on chip seals with slag. The following subsections provide a detailed summary of these research studies, which were conducted by researchers in Michigan, Turkey, and China.

B.2 Studies by Researchers in Michigan

Boz et al. (2019) conducted a laboratory study to establish threshold values for aggregate percent embedment to optimize the performance of chip seals with regard to aggregate loss and bleeding. Two types of aggregates (natural and slag) and two types of emulsions (CRS-2M and CSEA) commonly used in Michigan were included in the study. The properties of the natural and slag aggregates used in the study are presented in Table B.1.

Table B.1. Natural and Slag Aggregate Properties (Boz et al. 2019).

Aggregate property	Test method	Aggregate type	
		Slag	Natural
Bulk specific gravity	AASHTO T84&85	2.417	2.734
Voids in loose aggregate	ASTM C29	0.46	0.45
Loose unit weight (lbs/ft^3)	ASTM C29	82.9	96.1
Median particle size (in.)	McLeod (1969)	0.27	0.28
Flakiness ratio (%)	Mn/DOT FLH T 508	3	20
Average least dimension (in.)	McLeod (1969)	0.22	0.2
Percent passing #200	–	1.7	0.5

The chip seal samples were prepared using three emulsion application rates of 0.39, 0.42 and 0.46 gal/yd^2 and an aggregate application rate of 20 lb/yd^2 (minimum aggregate application rate allowed by Michigan DOT for chip seals). The chip seal sample preparation procedure is presented in Figure B.1. A three-dimensional photogrammetric software (3DF Zephyr) was used to generate the surface topography of the chip seal samples, which was analyzed using MATLAB to estimate the mean profile depth of each sample. Digital image analysis techniques were also used to quantify the percent embedment of the aggregates in the chip seal samples, as shown in Figures B.1 and B.2. Figure B.3 presents the percent embedment of the natural and slag aggregates for different emulsion application rates. As can be noticed from this figure, higher percent embedment depths were obtained for samples prepared using natural aggregates than slag aggregates. This can be attributed to the higher aggregate flakiness ratio and the lower absorption of the natural aggregates.

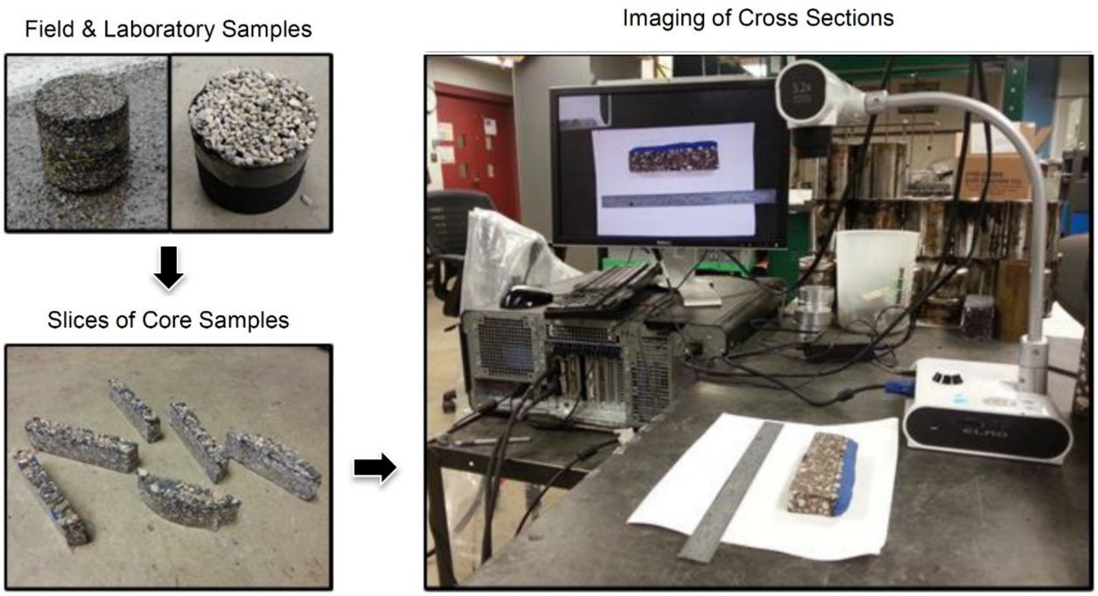


Figure B.1. Chip Seal Sample Preparation for Measurement
of Aggregate Percent Embedment (Kutay et al. 2017).

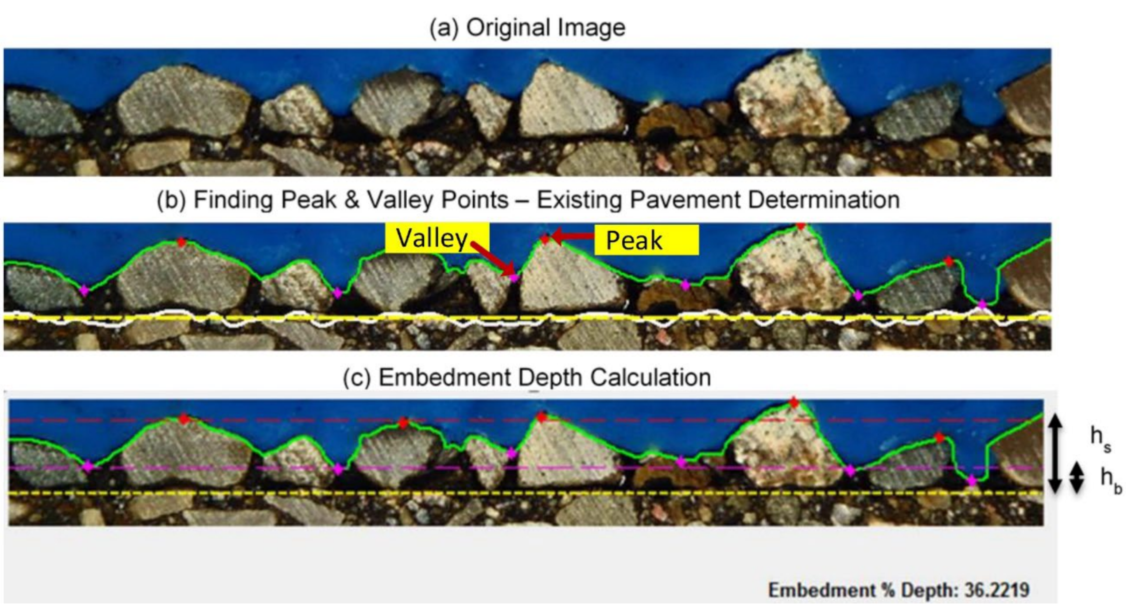


Figure B.2. Measurement of Aggregate Percent Embedment
in Chip Seal Samples using Image Analysis (Kutay et al. 2017).

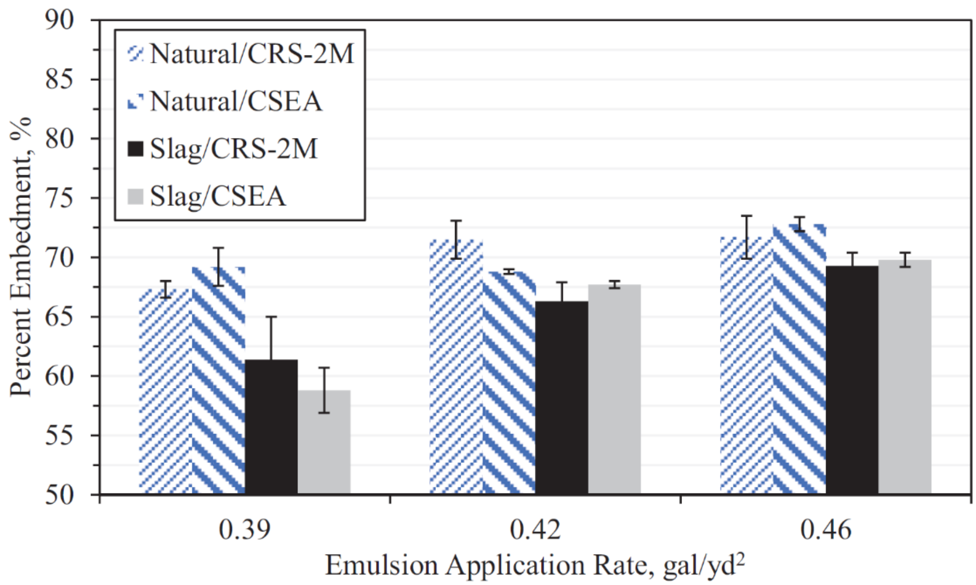


Figure B.3. Percent Embedment of Natural and Slag Aggregates at Different Emulsion Application Rates (Boz et al. 2019).

A Hamburg wheel tracking device retrofitted with a rubber wheel was used to evaluate chip seal susceptibility to aggregate loss and bleeding (Figure B.4). A rubber wheel was used instead of the standard steel wheel in this test to avoid aggregate abrasion. Loose aggregate particles were removed from the chip seal samples by slight hand brushing prior to placing the samples in the Hamburg wheel tracking device. To evaluate the performance of the chip seal samples for aggregate loss, the samples were subjected to 10 cycles in the Hamburg wheel tracking device at 19 ºC, and the aggregate loss by abrasion (ALA) – which was used to quantify aggregate loss – was computed by dividing weight of the aggregates lost due to abrasion by the initial weight of the aggregates prior to loading in the Hamburg device. Figure B.5 presents the percentage loss of aggregates for the different aggregate types and emulsion application rates. As can be noticed from this figure, higher percent ALA values were obtained for slag aggregates than for natural aggregates, with slightly higher ALA values at lower emulsion application rates. This figure shows no discernible trend due to the emulsion type. To evaluate the performance of the chip seal samples for binder bleeding, the samples were subjected to 2,500 cycles in the Hamburg wheel tracking device at 54 ºC. Digital image analysis was utilized to estimate the amount of bleeding by dividing the black area (representing the binder) by the total area of the sample.

Figure B.4. Hamburg Wheel Tracking Device Retrofitted with a Rubber Wheel.

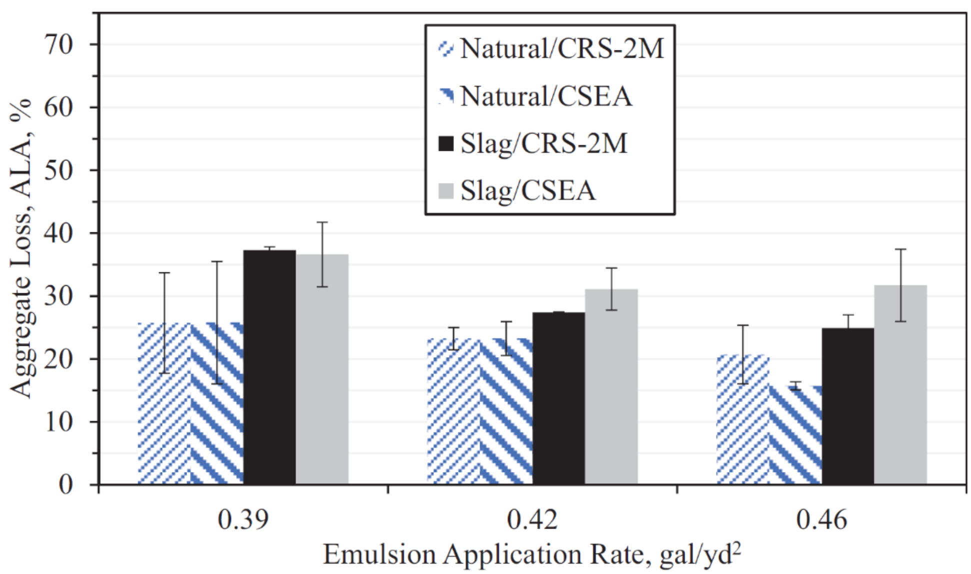


Figure B.5. Aggregate Loss by Abrasion at Different Emulsion Application Rates (Boz et al. 2019).

Figure B.6 shows the relationship between aggregate loss by abrasion and the aggregate percent embedment. As can be noticed from this figure, none of the chip seals examined in the study had an aggregate loss that exceeded the maximum limit of 40% allowed by Michigan DOT specifications. This figure also shows that a minimum allowable percent embedment of 58% is needed to ensure that chip seals will not exceed this maximum aggregate loss limit. By analyzing the bleeding test results, a maximum allowable threshold percent embedment limit of 71.5% was obtained for natural aggregates and 69.3% was obtained for slag aggregate, as shown in Figure B.7. Therefore, for practical reasons, it was recommended to use a maximum percent embedment value of 70% to minimize bleeding for single-layer chip seals.

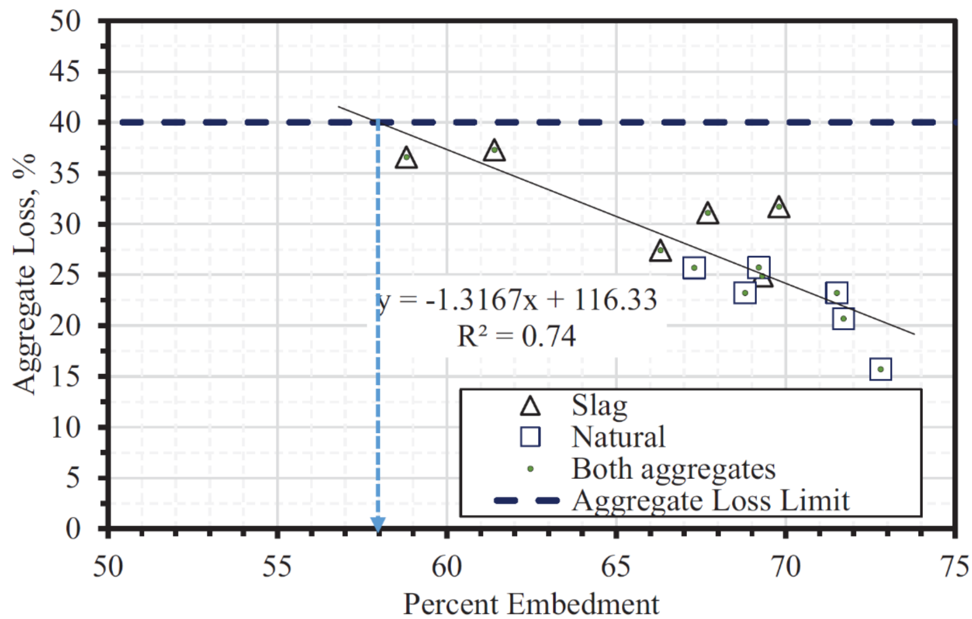


Figure B.6. Relationship between Aggregate Loss by Abrasion and Percent Embedment (Boz et al. 2019).

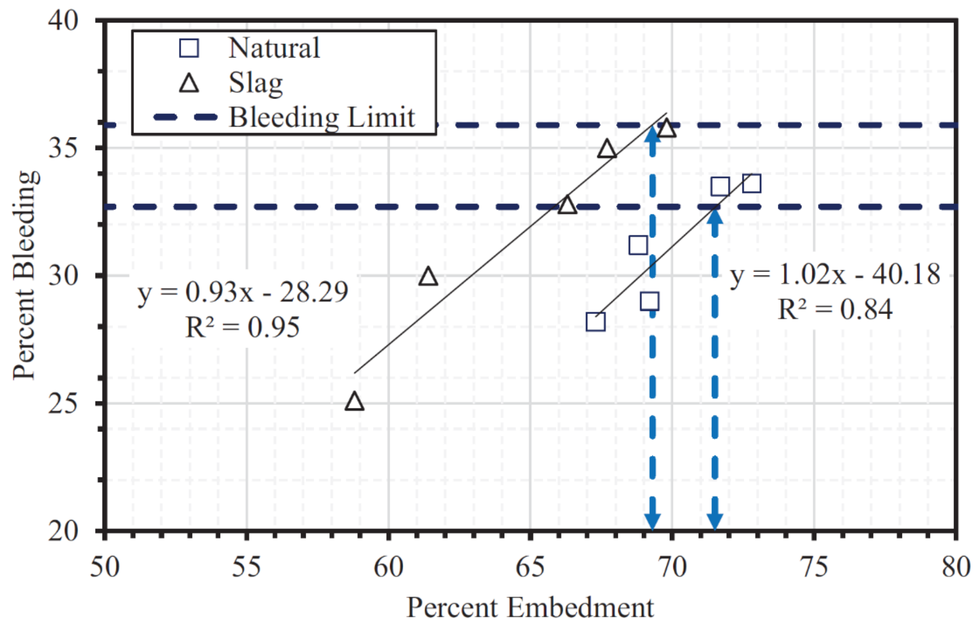


Figure B.7. Relationship between Percent Bleeding and Percent Embedment (Boz et al. 2019).

In a follow-up study, general guidelines were proposed by Haider et al. (2019) for developing performance-based relationships for chip seal treatments. This study utilized the test data generated by Boz et al. (2019) for chip seal specimens prepared using aggregates and emulsions commonly used in Michigan. The percent embedment (PE) of aggregates in the chip seal was selected as the acceptance quality characteristic (AQC). Aggregate loss and bleeding were selected as the chip seal performance indicators. Relationships were developed between the chip seal quality measures, service life, and pay factors. The expected pay curves were used to establish acceptable and unacceptable quality levels, and the pay factors were evaluated to ensure fair payments for the quality of work produced.

B.3 Studies by Researchers in Turkey

Uz and Gokalp (2017) conducted a laboratory evaluation of polishing and skid resistance of chip seals prepared using different types of aggregates, including limestone (LS), basalt (BS), crushed river gravel (BLD), electric arc furnace (EAF) steel slag, and ferrochromium (FER) slag. Four chip sizes were included in the study (10–12.5 mm, 8–10 mm, 6.3–8 mm, and 4–6.3 mm). X-ray fluorescence was utilized to determine the chemical composition of the different aggregates. The Micro-Deval (MD) test was used to simulate aggregate polishing at five different levels (5,250, 10,500, 21,000, 31,500, and 52,500 cycles). Changes in aggregate surface texture due to polishing were observed using a scanning electron microscope (SEM). The sand patch test and the British pendulum test were also used to measure the mean texture depths (MTDs) and the skid resistance performance, respectively, of chip seals prepared with the unpolished and polished aggregates. The binder and aggregate application rates for the different chip seals were selected according to the United Kingdom's design method. In this study, chip seal samples were prepared by applying the binder and the aggregate on a steel plate with an inner diameter of 180 mm and a depth of 3 mm, followed by three rolling passes in both directions using a rubber cylinder.

Figure B.8 presents the surface textures obtained using the SEM for selected aggregates after different levels of polishing. As can be noticed from this figure, slag aggregates (particularly EAF slag) exhibited rougher surface texture even at the highest level of polishing than natural aggregates, which became relatively smooth upon polishing. Table B.2 also shows that chip seals prepared using slag aggregates exhibited higher MTDs both before and after polishing, which indicates that they are more resistant to polishing and abrasion as compared to natural aggregates. The effect of polishing on skid resistance of chip seals prepared using 10–12.5 mm aggregates is presented in Figure B.9. As can be noticed from this figure, chip seals prepared using slag aggregates showed better skid resistance – as demonstrated by the higher British pendulum numbers (BPNs) – at all levels of polishing than those prepared using natural aggregates.

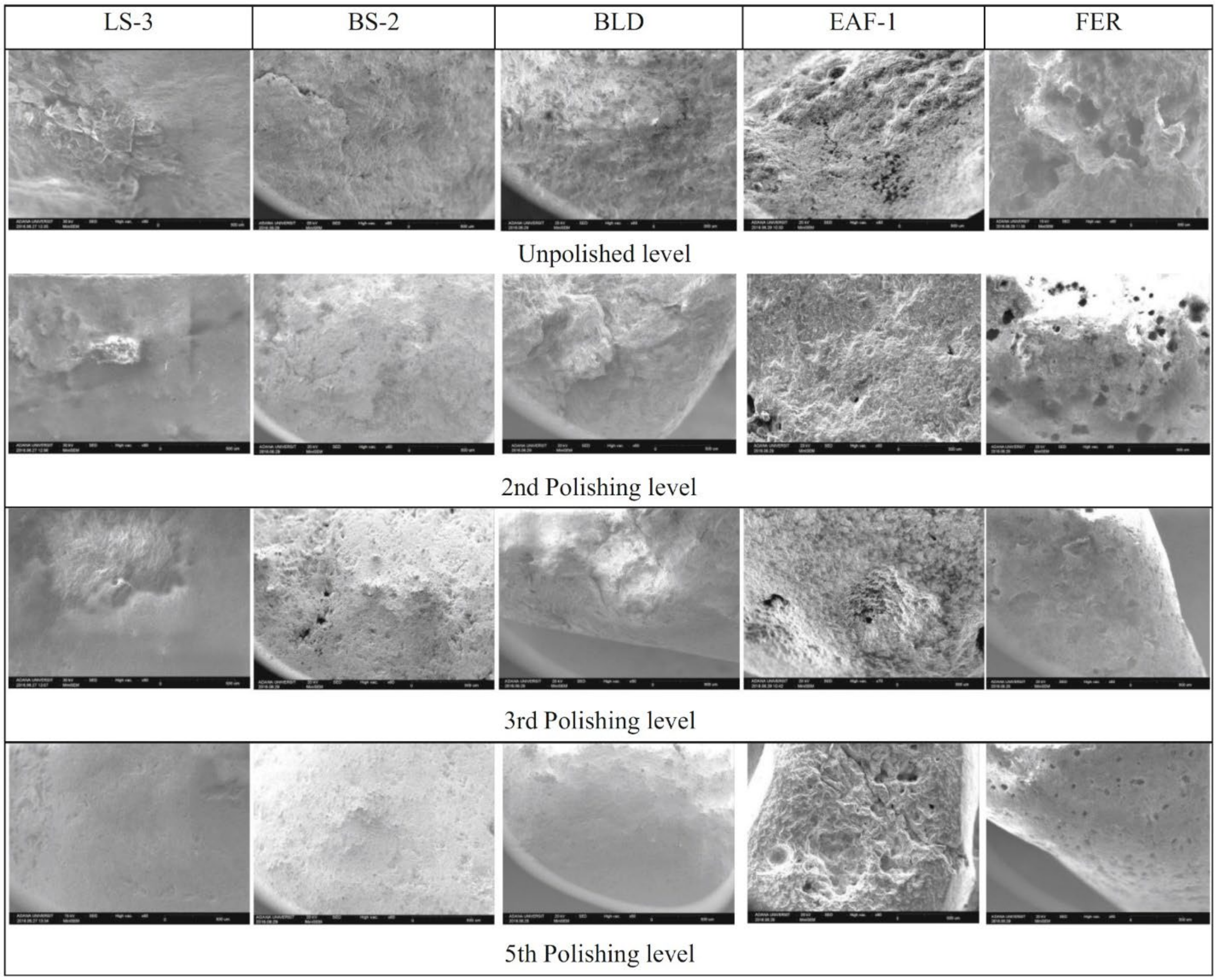


Figure B.8. Effect of Polishing on Aggregate Surface Texture (Uz and Gokalp 2017).

Table B.2. Effect of Polishing on Mean Texture Depth of Chip Seals
Prepared using 10–12.5 mm Aggregates (Uz and Gokalp 2017).

Grain sizes (mm)	Polishing level	Sample ID and MTDs (mm)									
		LS-1	LS-2	LS-3	BS-1	BS-2	BLD	EAF-1	EAF-2	EAF-3	FER
12.5–10	0	5.1	5.1	5.2	5.9	6.0	5.7	6.2	7.0	6.9	6.4
	1st	5.0	4.9	4.9	5.2	4.9	5.2	5.8	6.6	6.2	5.3
	2nd	4.8	4.4	5.0	4.6	4.9	5.1	6.1	5.8	5.8	5.4
	3rd	4.5	4.1	4.7	4.3	4.7	4.7	5.8	5.5	5.3	5.0
	4th	4.1	3.6	3.9	4.3	4.5	4.2	4.9	5.1	5.3	4.7
	5th	4.7	4.6	4.6	4.6	4.7	4.5	5.7	5.8	5.3	5.0
Average MTDs		4.7	4.7	4.4	4.7	4.8	5.0	4.9	5.8	6.0	5.8
Standard deviations		0.3	0.3	0.5	0.4	0.6	0.5	0.5	0.4	0.6	0.6

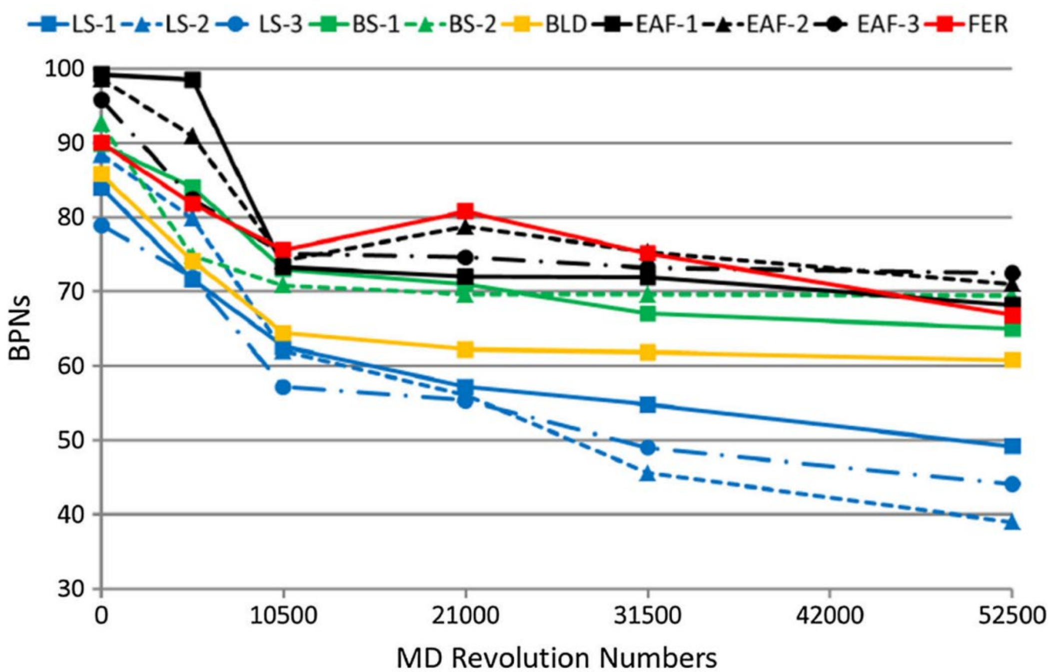


Figure B.9. Effect of Polishing on Skid Resistance of Chip Seals Prepared using 10–12.5 mm Aggregates (Uz and Gokalp 2017).

In a follow-up study, Ergin et al. (2020) conducted a laboratory evaluation of the skid resistance of chip seals prepared using the same types of aggregates as the 2017 study but using only two chip sizes (8−10 mm and 10−12 mm) and two levels of polishing (10,500 and 31,500 cycles) in the MD test. X-ray diffraction (XRD) was used to determine the mineral composition of the different aggregates. Scanning electron and optical microscopes were used to examine the changes in aggregate surface texture due to polishing. The outflow meter test was used to determine the MTDs of chip seals prepared with the unpolished and polished aggregates. The British pendulum test and the dynamic friction tester (DFT) were utilized to assess the skid resistance of the chip seals with the unpolished and polished aggregates. Table B.3 presents a summary of the physical and mechanical properties of the various aggregates used in the study. The chip seal sample preparation procedure is presented in Figure B.10. Similar to the previous study, the test results in this study indicated that slag aggregates have better resistance to polishing (Figure B.11 and Table B.4) and better skid resistance before and after polishing (Figures B.12 and B.13) than natural aggregates.

Table B.3. Physical and Mechanical Properties of Aggregates (Ergin et al. 2020).

Order	Tests	Methods	Units	Results					
				LS	BS	BLD	EAF	FER	Limitations[a]
1	Abrasion resistance	EN 1097-1	%	11.7	9.4	11.3	9.5	7.6	≤25
2	Fragmentation resistance	EN 1097-2	%	24.4	25.9	17.5	22.9	16.5	≤30
3	Weathering resistance	EN 1367-2	%	8.1	9.4	6.2	2.3	6.1	≤18
4	Polishing resistance	EN 1097-8	PSV	41.6	52.4	57.9	76.1	61.7	≥40
5	Dry unit weight	EN 1097-6	g/cm^3	2.69	2.67	2.73	3.40	2.93	—
6	Water absorption	EN 1097-6	%	0.28	1.44	0.90	1.79	1.10	≤2.5
7	Flakiness index	EN 933	%	15.9	23.8	17.9	8.1	10.4	≤20
8	Friable particle values	ASTM C 142	%	0.81	0.63	0.41	0.23	0.23	0.3

Note: LS = limestone; BS = basalt; BLD = river basin crushed aggregate; EAF = electric arc furnace steel slag; and FER = ferrochromium slag.
[a]Limit values in Turkish Highway Technical Specification.

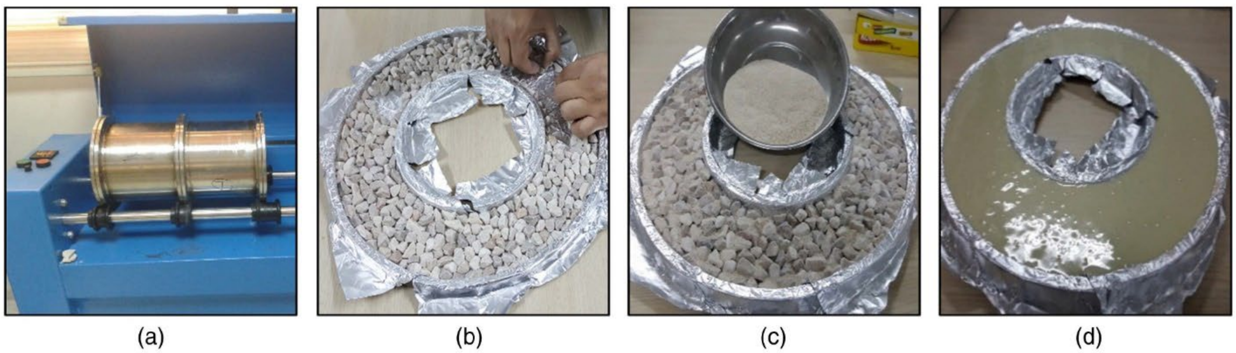


Figure B.10. Preparation of Chip Seal Samples: (a) Aggregate Polishing using the MD Test, (b) Measuring the Chips by Volume, (c) Filling the Gap between Chips, and (d) Curing Test Samples (Ergin et al. 2020).

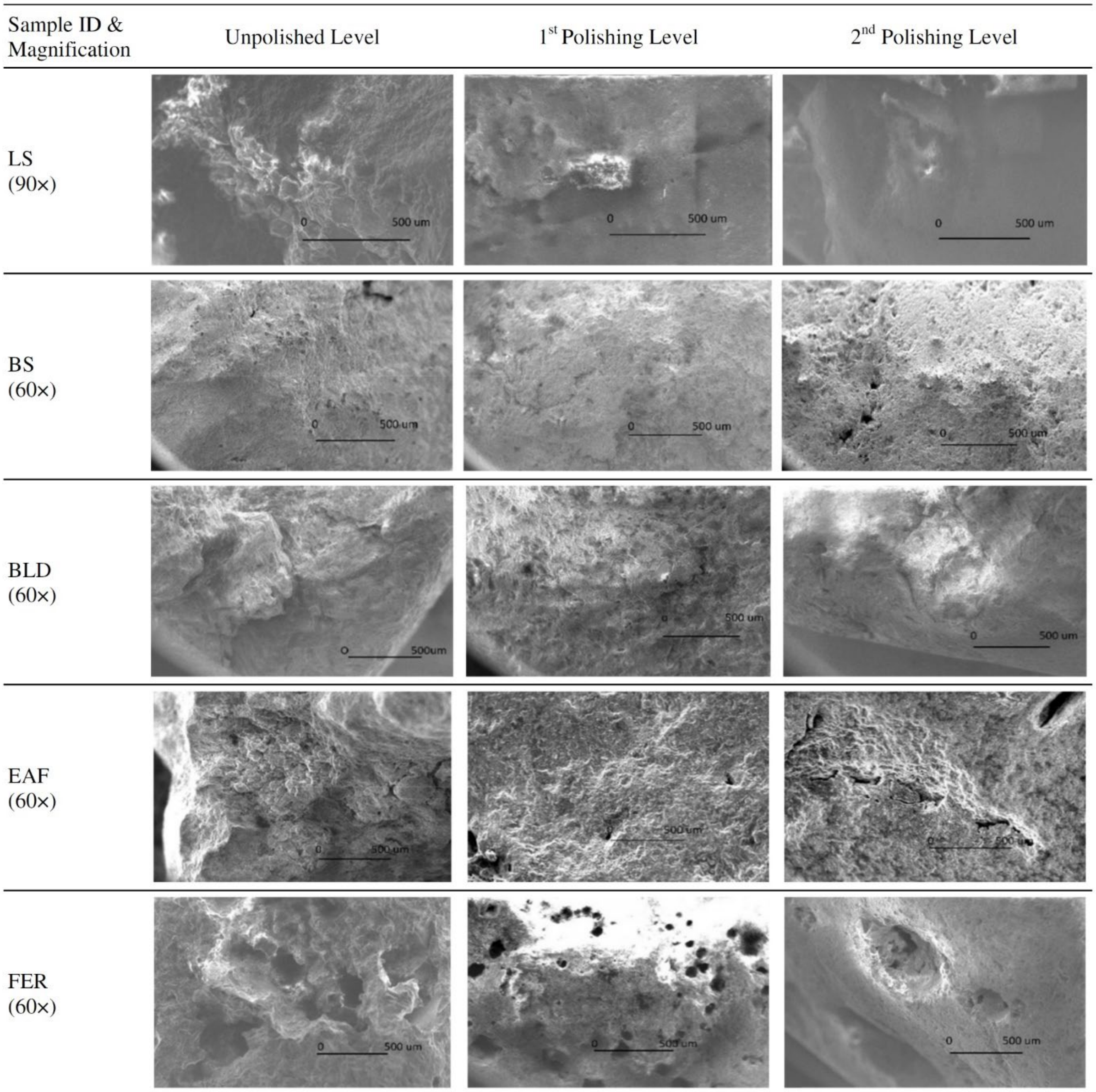
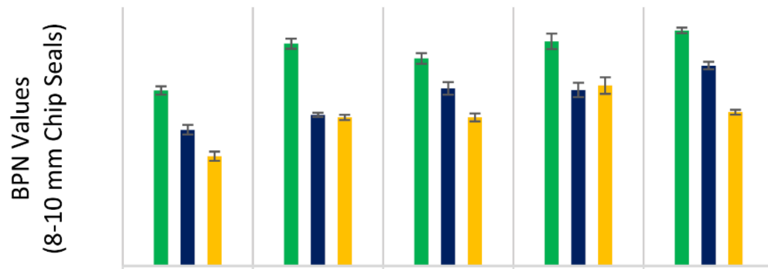


Figure B.11. Effect of Polishing on Aggregate Surface Texture (Ergin et al. 2020).

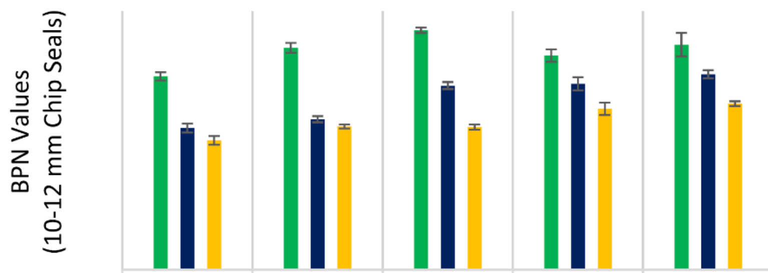
Table B.4. Mean Texture Depths (MTDs) for Chip Seal Samples at Different Levels of Polishing (Ergin et al. 2020).

Grain sizes (mm)	Polishing level	MTDs and StD (mm)									
		LS	StD	BS	StD	BLD	StD	EAF	StD	FER	StD
8–10	Unpolished	1.74	0.108	1.69	0.102	1.60	0.023	1.71	0.121	1.50	0.113
	1st polishing	1.59	0.243	1.42	0.069	1.39	0.065	1.62	0.261	1.39	0.067
	2nd polishing	1.34	0.094	1.43	0.230	1.29	0.097	1.47	0.093	1.40	0.043
10–12	Unpolished	2.09	0.273	1.78	0.065	1.76	0.109	2.14	0.192	1.63	0.115
	1st polishing	1.91	0.173	1.59	0.101	1.63	0.111	2.01	0.171	1.61	0.258
	2nd polishing	1.74	0.156	1.58	0.090	1.52	0.103	1.71	0.202	1.50	0.108

Note: LS = limestone; BS = basalt; BLD = river basin crushed aggregate; EAF = electric arc furnace steel slag; FER = ferrochromium slag; and StD = standard deviation.

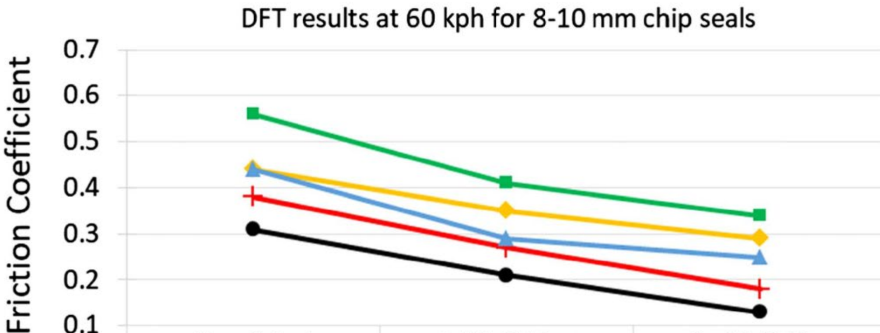


	LS	BLD	BS	EAF	FER
Unpolished	68	86	80	87	91
1st Polishing	53	58	69	68	77
2nd Polishing	42	57	57	70	59

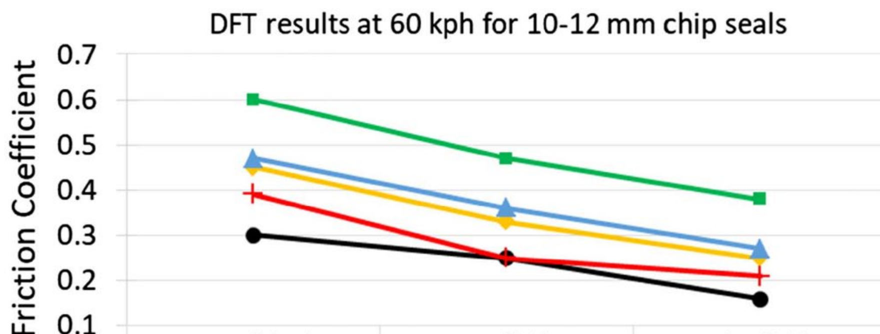


	LS	BLD	BS	EAF	FER
Unpolished	75	86	93	83	87
1st Polishing	55	58	71	72	76
2nd Polishing	50	55	55	62	64

Figure B.12. Effect of Polishing on Skid Number in the British Pendulum Test (Ergin et al. 2020).



	Unpolished	1st Polishing	2nd Polishing
LS	0.31	0.21	0.13
BLD	0.38	0.27	0.18
BS	0.44	0.35	0.29
EAF	0.44	0.29	0.25
FER	0.56	0.41	0.34



	Unpolished	1st Polishing	2nd Polishing
LS	0.30	0.25	0.16
BLD	0.39	0.25	0.21
BS	0.45	0.33	0.25
EAF	0.47	0.36	0.27
FER	0.60	0.47	0.38

Figure B.13. Effect of Polishing on Friction Coefficient in the Dynamic Friction Tester (Ergin et al. 2020).

B.4 Studies by Researchers in China

Cui et al. (2020) evaluated the durability as well as the heating and de-icing efficiencies of chip seals containing basic oxygen furnace slag to those containing basalt aggregates. Styrene-butadiene-styrene (SBS) modified asphalt binder was used in the preparation of the chip seal samples. Steel fibers were added to the binder at different dosage rates prior to the application of the aggregates in order to increase the thermal induction performance of the chip seals. As shown in Figure B.14b, a sweep test was performed on the chip seal samples to evaluate aggregate retention. The aggregate loss rate (ALR) was calculated by dividing the difference in weight of the chip seal samples before and after abrasion by the initial weight of the chip seal samples. In addition, the mean profile depths (MPDs) of the chip seal samples before and after abrasion were measured using a laser texture scanner (Figure B.14c). The chip seal samples were then subjected to 30 seconds of induction heating, microwave heating, or no heating (control) followed by 4 hours of cooling at 25 ^{o}C (Figure B.14d). This process was repeated five times to evaluate the effect of the repeated heating on the durability of the chip seal samples. The decrease in the MPDs due to abrasion for the different chip seal samples are presented in Table B.5. As can be noticed from this table, the chip seal samples containing slag aggregates exhibited lower reduction in MPD than those containing basalt aggregates, which suggests that the use of steel slag can improve the durability of chip seals.

The procedure for evaluating the heating and de-icing efficiencies of different chip seal samples using induction and microwave heating is presented in Figure B.15. As can be noticed from this figure, an infrared camera was used to record the temperature during the de-icing process. The time needed for the ice layer on the sample to completely melt is considered the de-icing efficiency. The melting times for the different chip seal samples when using the induction and microwave heating methods are presented in Figure B.16. As can be noticed from this figure, the melting times of the chip seal with slag were generally shorter than those of the chip seal with basalt. This suggests that the heating and de-icing efficiencies of chip seals can be improved by using steel slag.

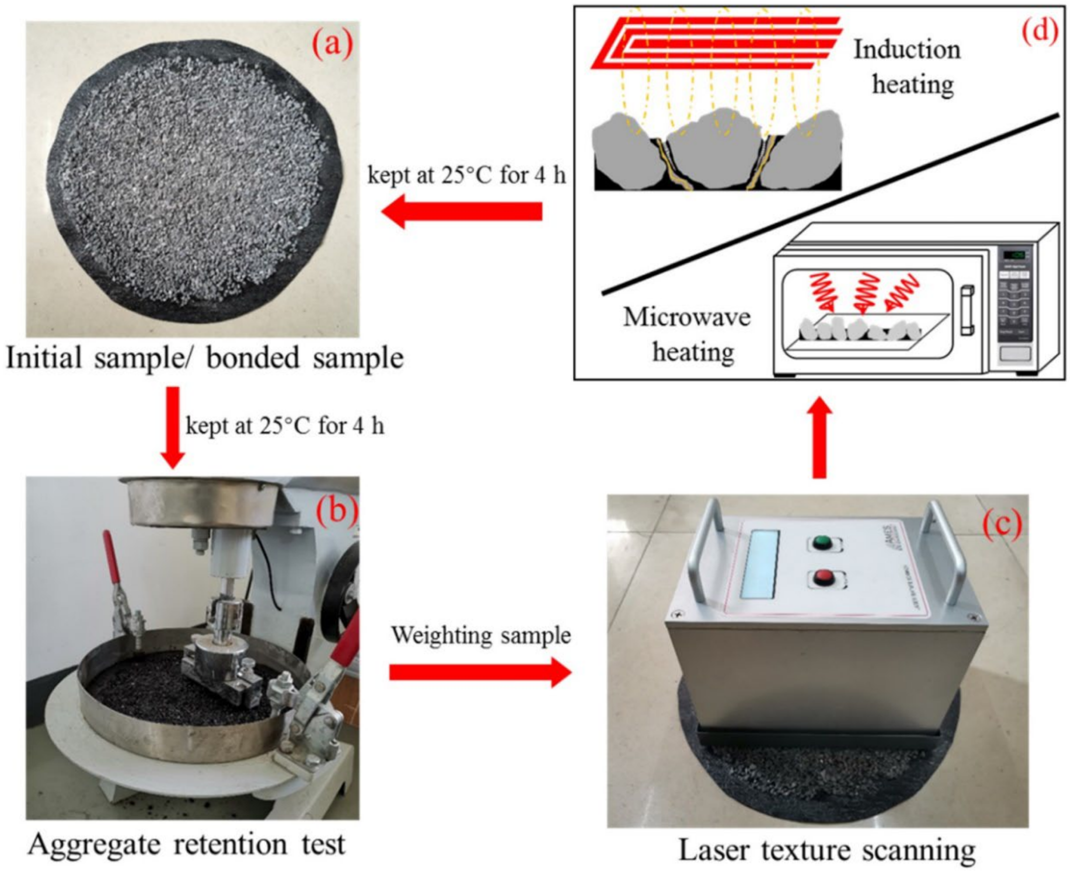


Figure B.14. Procedure to Evaluate Effect of Heating on Aggregate Retention (Cui et al. 2020).

Table B.5. Decrease in Mean Profile Depths (MPDs) after Aggregate Sweep Test (Cui et al. 2020).

Samples	Macro-MPD after IH cycles	Micro-MPD after IH cycles	Macro-MPD after MH cycles	Micro-MPD after MH cycles
BS-4%	0.63	0.08	0.67	0.09
SS-4%	0.27	0.03	0.20	0.02

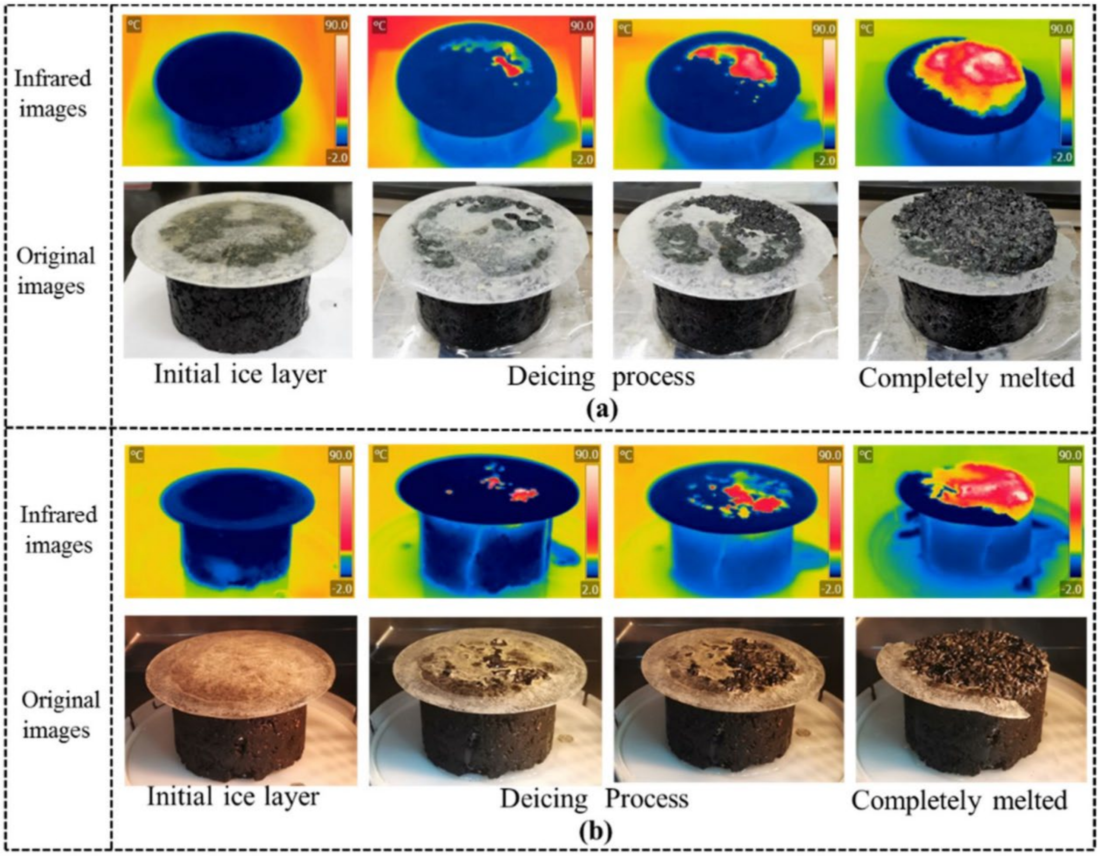


Figure B.15. procedure for Evaluating the Heating and De-icing Efficiencies of Chip Seal Samples (Cui et al. 2020).

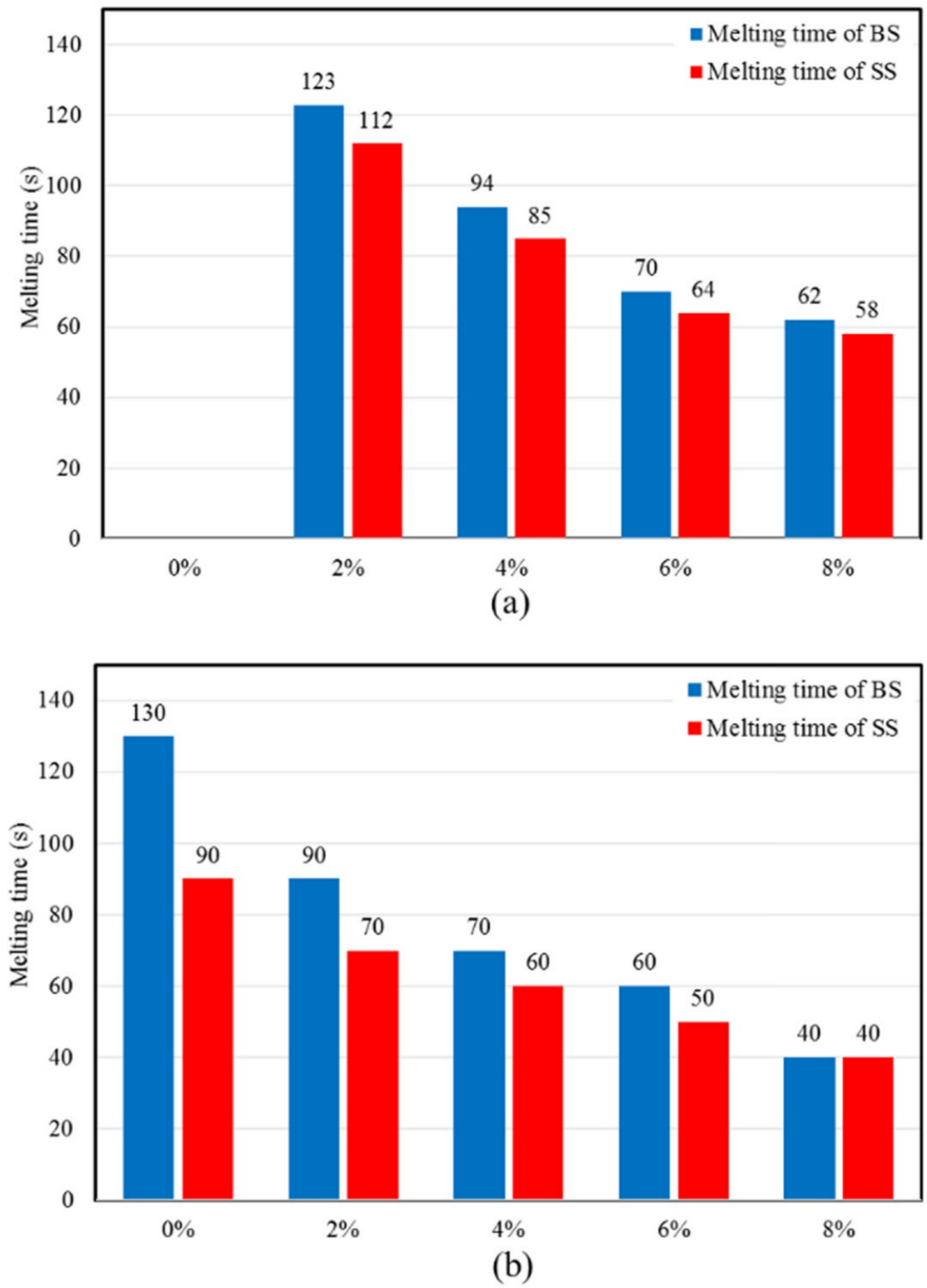


Figure B.16. Melting Time of Chip Seal Samples by (a) Induction Heating and (b) Microwave Heating (Cui et al. 2020).

Appendix C
Online Survey

C.1 Introduction

An online survey was conducted in this study to identify transportation agencies that have previously used or are currently using slag as a cover aggregate for chip seal treatments. Information was also sought about recommendations for best practices to improve the performance of chip seals with slag. A draft survey questionnaire was prepared by the research team and sent to the Technical Advisory Committee (TAC) for this project in April 2023. Modifications were made and some questions were deleted or added based on comments received from the advisory committee, and the revised survey was implemented by the research team in Qualtrics. Survey invitations were sent out in early May 2023 to state and local transportation agencies in Ohio and other states via the American Association of State Highway and Transportation Officials (AASHTO) Research Advisory Committee (RAC), the No Boundaries pooled fund project, and the Ohio Department of Transportation (ODOT) Local Technical Assistance Program (LTAP) contact lists. The due date for completing the survey was June 1, 2023.

C.2 Survey Organization

A copy of the survey questionnaire is provided below. The questionnaire included a total of 23 questions organized into nine sections. In the first section, respondents were asked to provide their contact information to be used for follow-up purposes (if needed) and indicate the type of agency that they work for. In the second section of the questionnaire, respondents were asked to indicate if their agency currently uses or had previously used slag as a cover aggregate for chip seal treatments. For respondents who indicated that their agency has never used slag as a cover aggregate for chip seal treatments, that was the end of the survey and the respondent was not required to answer the remaining questions. Respondents who indicated that their agency used slag as a cover aggregate for chip seal treatments in the past but no longer use it were asked to elaborate on why their agency stopped using slag for this purpose. Respondents who indicated that their agency currently uses chip seals with slag were directed to the next section in the survey. In the third section of the questionnaire, respondents were asked whether slag is used as a cover aggregate for all chip seal treatments or for some chip seal treatments in their jurisdiction, the centerline miles that are chip sealed with slag by their agency every year, how satisfied is their agency with the performance of chip seals with slag, the typical service life of chip seals with slag in their jurisdiction, whether the chip sealing with slag is performed by in-house crew and/or external contractors, and the typical cost of chip seals with slag. The survey proceeded to the next section, which solicited information about the binder type, binder application rate, method for determining the binder application rate, slag type, slag size, slag aggregate application rate, and method for determining the slag aggregate application rate. In addition, respondents were asked if their agency has any construction and material specifications for chip sealing with slag aggregates. The fifth section asked about the common issues that agencies encountered on roads chip sealed with slag in their jurisdiction. Recommendations for best practices to improve the performance of chip seals with slag were solicited from the respondents in the sixth section, and respondents were asked to highlight the advantages and disadvantages of using slag (instead of other aggregate types) for chip seal treatments in the seventh section. The eighth section asked for any additional thoughts or comments regarding chip sealing with slag and included contact information for the principal investigator for the project, should the respondents have any questions regarding the survey. The last section of the survey thanked the respondents for their time and asked for their permission to be contacted by the research team in the future regarding their responses.

District ROC Task 4 Chip Sealing with Slag

Start of Block: Introduction

Q1 Best Practices for using Slag in Chip Seal Treatments
This survey is conducted to identify best practices for using slag as a cover aggregate in chip seal treatments.
The survey should take less than 10 minutes to complete.
Please complete the survey even if your agency does not use slag as a cover aggregate in chip seal treatments. If your agency does not use chip seals with slag, the survey should take less than one minute to complete.
To view the survey questionnaire as a pdf file, please click: survey file.

For questions about this survey, please contact:

Dr. Ala R. Abbas
Department of Civil Engineering
The University of Akron
Email: abbas@uakron.edu

or:
Dr. Munir Nazzal Department of Civil and Architectural Engineering and Construction Management
The University of Cincinnati
Email: munir.nazzal@uc.edu

End of Block: Introduction

Start of Block: Contact Information

Q2 Contact information: *

◯ Name: (1) ____

◯ Position: (2) ____

◯ Agency: (3) ____

◯ State: (4) ____

◯ Email address: (5) ____

◯ Phone number: (6) ____

Q3 Type of agency: *

◯ Department of Transportation (DOT). Please specify (e.g., Central Office, District, County, etc.): (1) ____

◯ Local public agency. Please specify (e.g., County, City, Township, etc.): (2) ____

◯ Other. Please specify: (3) ____

End of Block: Contact Information

Start of Block: Chip Sealing with Slag?

Q4 Does your agency use **slag** as a cover aggregate for chip seal treatments? *

◯ Yes, we currently use slag as a cover aggregate for our chip seal treatments. (1)

◯ No, we used slag as a cover aggregate for our chip seal treatments in the past, but we no longer use it. (2)

◯ No, we have never used slag as a cover aggregate for our chip seal treatments. (3)

End of Block: Chip Sealing with Slag?

Start of Block: General Information

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q5 Does your agency use **slag** as a cover aggregate for all chip seal treatments in your jurisdiction or only for particular roads *

- ◯ Yes, slag is used for all chip seal treatments. (1)
- ◯ No, slag is not used for all chip seal treatments. Please elaborate on the selection criteria for roads chip sealed with slag: (2)

____

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q6 How many centerline miles of roads are chip sealed with **slag** annually in your jurisdiction?

- ◯ < 50 miles (1)
- ◯ Between 50 and 100 miles (2)
- ◯ Between 100 and 500 miles (4)
- ◯ More than 500 miles (5)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q7 How satisfied are you with the performance of chip seals with **slag** in your jurisdiction?

- ◯ Very satisfied (1)
- ◯ Somewhat satisfied (2)
- ◯ Not satisfied. Please elaborate on the reasons for dissatisfaction: (4)

____

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q8 What is the typical service life of chip seals with **slag** in your jurisdiction? *

- ◯ Less than three years (1)
- ◯ Three to five years (2)
- ◯ Five to seven years (4)
- ◯ More than seven years (6)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q9 Chip sealing with **slag** is performed by (check all that apply): *

- ▢ In-house crew. Percentage of the total performed by in-house crew: (1) ____
- ▢ External contractors. Percentage of the total performed by external contractors: (2) ____

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q10 What is the typical cost of chip seals with **slag** (e.g., $2.5 per square yard)? *

____

End of Block: General Information

Start of Block: Material Information and Application Rates

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q11 What type of binders are used for chip seals with **slag** in your jurisdiction (check all that apply)? *

☐ Performance-graded asphalt binder. Please specify type (e.g., PG 64-22) and source: (1) ____

☐ Asphalt emulsion. Please specify type (e.g., CRS-2P) and source: (2) ____

☐ Asphalt cutback. Please specify type (e.g., MC-3000) and source: (4) ____

☐ Other. Please specify type and source: (5) ____

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q12 What binder application rate is typically used for chip seals with **slag** in your jurisdiction? *

○ Please specify (e.g., 0.35 gallon/square yard): (1) ____

○ I don't know. (5)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q13 How do you determine the binder application rate for chip seal with **slag** in your jurisdiction (check all that apply)?

- ☐ Based on a test strip (1)
- ☐ Based on appearance during construction (13)
- ☐ Based on past experience (14)
- ☐ Based on external contractor recommendation (15)
- ☐ Using a design procedure. Please specify method (e.g., Kearby Method, McLeod Method, etc.): (16) ____
- ☐ Other. Please specify: (17) ____
- ☐ I don't know. (20)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q14 What type of **slag** is used in chip seal treatments in your jurisdiction (check all that apply)? *

- ▢ Air-cooled blast furnace (ACBF) slag (1)
- ▢ Electric arc furnace (EAF) slag (13)
- ▢ Basic oxygen furnace (BOF) slag (14)
- ▢ Open hearth (OH) slag (15)
- ▢ Granulated slag (GS) (16)
- ▢ Other. Please specify: (17) ____
- ▢ I don't know (20)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q15 What nominal maximum aggregate size (NMAS) is commonly used for **slag** aggregates in chip seal treatments (check all that apply)? *

☐ 1/2" (1)

☐ 3/8" (13)

☐ 1/4" (14)

☐ Other. Please specify: (17) ____

☐ I don't know (20)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q16 Do you have any material specifications for **slag** aggregates used in chip seal treatments (e.g., percent fractured faces, maximum % passing Sieve No. 200, maximum absorption, maximum Los Angeles abrasion loss, etc.)? *

○ Yes. Please send the aggregate specification information to Dr. Ala Abbas by email at abbas@uakron.edu. (1)

○ No (13)

○ I don't know (20)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q17 What aggregate application rate is typically used for chip seals with **slag** in your jurisdiction? *

○ Please specify (e.g., 25 pounds/square yard): (1) ____

○ I don't know. (5)

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q18 How do you determine the aggregate application rate for chip seal with **slag** in your jurisdiction (check all that apply)?

▢ Based on a test strip (1)

▢ Based on appearance during construction (13)

▢ Based on past experience (14)

▢ Based on external contractor recommendation (15)

▢ Using a design procedure. Please specify method (e.g., Kearby Method, McLeod Method, etc.): (16) ____

▢ Other. Please specify: (17) ____

▢ I don't know. (20)

End of Block: Material Information and Application Rates

Start of Block: Issues Encountered

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q19 How often are the following issues encountered on roads chip sealed with **slag** in your jurisdiction? *

	Often (7)	Sometimes (8)	Rarely (9)	Never (10)
Premature delamination (i.e., lack of bonding between binder material and pavement surface) (1)	○	○	○	○
Premature delamination at localized areas (e.g., patches, intersections, turning areas, etc.) (2)	○	○	○	○
Premature flushing/bleeding (7)	○	○	○	○
Premature flushing/bleeding at localized areas (e.g., patches, intersections, turning areas, etc.) (28)	○	○	○	○
Early loss of aggregates (29)	○	○	○	○
Early loss of aggregates at localized areas (e.g., patches, intersections, turning areas, etc.) (30)	○	○	○	○

Aggregate crushing (31)	○	○	○	○
Aggregate crushing at localized areas (e.g., patches, intersections, turning areas, etc.) (33)	○	○	○	○
Aggregate polishing (34)	○	○	○	○
Aggregate polishing at localized areas (e.g., patches, intersections, turning areas, etc.) (35)	○	○	○	○

End of Block: Issues Encountered

Start of Block: Recommendations for Best Practices

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q20 Any recommendations for best practices to improve the performance of chip seals with **slag** (in terms of binder type and properties, slag aggregate properties, binder and slag aggregate application rates, pre-existing pavement condition, pavement preparation, chip seal installation, snow plowing, etc.)? *

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End of Block: Recommendations for Best Practices

Start of Block: Advantages and Disadvantages of Chip Sealing with Slag

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q21 What are the advantages and disadvantages of using **slag** (instead of other aggregate types) for chip sealing?

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End of Block: Advantages and Disadvantages of Chip Sealing with Slag

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Start of Block: Final Comments

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = Yes, we currently use slag as a cover aggregate for our chip seal treatments.*

Q22 Any final thoughts or comments that you would like to provide that may benefit this research project?
Please send any documents that might be helpful to this project to Dr. Ala Abbas by email at abbas@uakron.edu.

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____

End of Block: Final Comments

Start of Block: Chip Sealing with Slag No Longer Used

Display This Question:

*If Does your agency use slag as a cover aggregate for chip seal treatments? * = No, we used slag as a cover aggregate for our chip seal treatments in the past, but we no longer use it.*

Q23 Please elaborate on why your agency stopped using chip seals with **slag** as a cover aggregate.

____

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____

End of Block: Chip Sealing with Slag No Longer Used

Start of Block: Permission to Contact

Q24 Do we have your permission to contact you in the future (if needed) for more information regarding your responses? *

○ Yes (1)

○ No (10)

End of Block: Permission to Contact

C.3 Summary of Responses

A total of 59 responses to the online survey were received. Of these, 32 responses were received from state department of transportation representatives, 6 responses were received from ODOT District representatives, 17 responses were received from Ohio local public agency (LPA) representatives, and four responses were received from LPA representatives outside Ohio.

The majority of the respondents indicated that their agencies have never used slag as a cover aggregate for chip seal treatments. This includes departments of transportation (DOTs) in Arkansas, Alaska, California, Connecticut, Delaware, Florida, Georgia, Idaho, Indiana, Kansas, Kentucky, Louisiana, Massachusetts, Maryland, Minnesota, Mississippi, Nebraska, New Jersey, Nevada, Ohio, Oregon, Rhode Island, South Carolina, Texas, Virginia, Vermont, and Wyoming. In addition, representatives from Tuscarawas County, Scioto County, Defiance County, Coshocton County, Putnam County as well as ODOT Districts 2, 9, and 10 indicated that their agencies have never used slag as a cover aggregate for chip seal treatments.

Five respondents indicated that their agencies have used slag as a cover aggregate for chip seal treatments in the past but no longer use it. Table C.1 provides a summary of the reasons provided by the respondents on why their agencies stopped using slag with chip seal treatments.

Table C.1. Reason for Stopping the Use of Slag with Chip Seal Treatments.

Agency	Reason
Carroll County, OH	Availability of the material, also the cost in times that it is/was available.
Williams County, OH	We were using both slag and limestone at the time. Our box was an older model and when we switched to slag the belts would drag. I assume because of the weight difference. For production it was easier to stay consistent with the limestone. We have a newer box but have not tried slag again. We have tried naturals because of access which is a good material.
Carlisle Township, OH	Mostly availability, but cost plays a part in our decision to go to limestone.
Winneshiek County, IA	The aggregate was too expensive to haul compared to local aggregates.
North Carolina DOT	It's been decades since our DOT has used it, so I do not have an answer as to why.

Responses to the online survey indicated that slag is more commonly used as a cover aggregate for chip seal treatments by local transportation agencies than by state DOTs. Only two representatives from state DOTs (South Carolina and Utah) indicated that their agencies use or allow using slag as a cover aggregate for chip seal treatments. The two respondents reported that slag is not commonly used for this purpose in their states due to high cost and/or lack of availability.

Several local public agencies reported using slag as a cover aggregate for chip seal treatments, including Medina County, Portage County, Lake County, Stark County, City of Canton, City of Chagrin, City of Toledo, and Beaver Township in Ohio as well as Louisa County in Iowa and Boone County in Indiana. The Wisconsin Transportation Information Center at the University of Wisconsin-Madison also reported that slag is used as a cover aggregate for chip seal treatments by local public agencies in Wisconsin.

Follow-up interviews were conducted with selected LPAs in Ohio and other states that use chip seal with slag to obtain additional information about the testing and specifications used by the agency to ensure the quality of the slag; the distance between the slag source and the LPA's location; shipping, handling, and stockpiling of slag when chip seal is installed by in-house crews; recommended best practices when using slag as opposed to other natural aggregates with chip seal treatments; effect of snow plowing on chip seal performance; and potential damage to vehicles.

Below is a summary of the information provided – in response to the online survey or as part of the follow-up interviews – by the agencies that reported using slag as a cover aggregate for chip seal treatments:

- Medina County, Ohio
  - Slag is used for all chip seal treatments.
  - External contractors
  - Cost: $28,000/Mile ($2.40/SY)
  - Emulsion and cutback at 0.45 gallons/SY
  - No. 8 ACBF Slag @ 20 lb/SY
  - Largest concern is clean aggregate.
  - Slag has a darker appearance than limestone and provides better visibility with center line and edge lines painted on.

- Portage County, Ohio
  - Slag is used for all chip seal treatments.
  - In-house crew. Bid out for township roads.
  - Avg. bid price: $2.35/SY
  - CRS-2 and CRS-2P at 0.42 gallons/SY
  - No. 8 ACBF Slag @ 21 lb/SY
  - We have found using CRS-2P on high ADT roads has worked better than CRS-2. CRS-2 is specified on low traffic roads especially with shaded areas.
  - Advantage is durability and skid resistance along with dust control. Disadvantage is cost and availability.
- Lake County, Ohio
  - Slag is used for all chip seal treatments.
  - External contractors
  - Avg. bid price: $3.25/SY
  - Emulsion at 0.35 gallons/SY
  - No. 8 ACBF Slag @ 18 to 25 lb/SY
  - We use a fog seal to lock in the chip seal treatment.
  - Limestone can break down more easily than slag. The slag treatments last longer than a limestone treatment.
- Stark County, Ohio
  - Slag is used for all chip seal treatments.
  - In-house crew. Bid out for township roads.
  - Avg. bid price: $2.10/SY
  - CRS-2P at 0.43 gallons/SY
  - No. 8 ACBF Slag @ 22 lb/SY
  - Less dust, better riding surface.
- City of Canton, Ohio
  - Slag is used for all chip seal treatments.
  - External contractors.

- ACBF slag is significantly less dusty than crushed limestone during installation. It is also harder than limestone.

- City of Chagrin, Ohio
  - No information was provided.
- City of Toledo, Ohio
  - Chip seal with EAF slag was used by the city on unimproved roads from 2000 until 2016 when the city discontinued its chip sealing program.
  - Slag was used for all chip seal treatments.
  - In-house crew.
  - Estimated price (including installation): $3.81/SY
  - The determining factor is not the cost of slag but the cost of mobilization. Logistics plays the largest factor.
  - CRS-TR at 0.20 gallons/SY (less emulsion is needed when using EAF slag than limestone)
  - No. 8 EAF Slag from Delta @ 6 lb/SY
  - Distance to slag source is approximately 25 miles.
  - Steel slag is a great improvement over limestone. With proper roadway drainage, a chip seal program can last 10 to 20 years.
  - Pay close attention to application rates of distributor and chipper. We use test pads and a portable scale on the back of a pickup truck.
  - Our biggest problem in our area is lack of drainage. Need to reintroduce crowns in roadway and swales. Ponding causes premature raveling and bleeding.
  - Too much slag kicks up and causes damage to windshields.
- Beaver Township, Ohio
  - Slag is used for all chip seal treatments.
  - External contractors
  - Cost: $5.50/SY
  - CRS-2P at an average of 0.35 gallons/SY
  - No. 8 ACBF Slag @ 30 lb/SY
  - I have used slag and limestone. I feel the slag holds better and wears better with a longer life span.

- Louisa County, Iowa
  - We use slag on all new and rural roads. We may use stone when the work is within an incorporated community if the City requests it.
  - External contractors.
  - Avg. bid price: $3.10/SY
  - We buy the slag chips from a nearby mill and hire a local trucking outfit to haul to the site. We then bid out the oil and labor to a couple regional contractors.
  - MC-3000 at 0.3 for 3/8" chips
  - 3/8" EAF Slag @ 35 lb/SY
  - The surface is only as good as what is under it therefore you must repair or treat the base in order for these projects to succeed.
  - The aggregates do not crush like rock. Slag is cheaper than rock. The appearance is black or dark gray which looks like asphalt and more consistent than river rock chip seal. The public prefers the look. Black surface does provide some limited snow melting assisted (though don't plan on it).
- Boone County, Indiana
  - We started experimenting with chip seal with EAF slag in 2018. We liked the slag more than limestone aggregates. Therefore, more sections were constructed recently on roads with heavier traffic.
  - In-house crew.
  - EAF slag is less expensive than limestone aggregates ($10 per ton for EAF slag versus $15 to $16 per ton for limestone aggregates).
  - Distance to slag source is approximately 25 miles.
  - No. 11 (smaller than 3/8") EAF slag at 17.5 to 18.5 lb/SY
  - AE-90S emulsion at 0.45 to 0.5 gallons/SY
  - Advantages: Lower cost than chip sealing with limestone, EAF slag is easier to compact and has better chip retention, better skid resistance, better marking visibility, and better public perception.

- Disadvantages: EAF slag is heavy for the aggregate spreader. Cannot chip seal 20 ft roads in one pass. Need to chip seal each lane separately. Snow plowing might pull aggregates from joint along the centerline.
- Suggestion: visual inspection to avoid dirty slag.
- No fog seal is used.

- Wisconsin Transportation Information Center
  - No information was provided.
- Utah DOT
  - Slag is not used for all chip seal treatments. In areas of Utah where they are able to get Utelite on contract they use that product which is slag for aggregate. The selection to use slag isn't based on anything other than availability i.e. is on contract in a certain area.
  - 80% in-house crews and 20% external contractors
  - Cost: $2.25/SY
- South Carolina DOT
  - We allow slag in our specifications. However, it is not commonly used by our contractors in designs.
  - It's too expensive and is not readily available.
  - The granite we use is typically between $2.50 - $3.00 per sq yd. Slag is more expensive than this.
  - CRS-2P at 0.28 to 0.35 gallons/SY + 15% when using slag
  - ACBF Slag at 15 to 20 lb/SY for #789 aggregate
  - Cons: Lack of cleanliness. More absorption of binder, which will increase cost.
  - Pros: Localized if not having to ship, but other than that none.

Appendix D
Available Specifications for Chip Sealing with Slag

D.1 Introduction

As discussed in Appendix C, state transportation agencies in South Carolina and Utah reported using or allowing the use of slag as a cover aggregate for chip seal (also called seal coat by some agencies) treatments. A thorough review of chip seal construction and material specifications used by other state transportation agencies also revealed that slag is allowed to be used as a cover aggregate by Michigan, Indiana, and Louisiana DOTs. A summary of these specifications is provided in the following pages with emphasis on information relevant to chip sealing with slag.

D.2 South Carolina DOT Chip Seal Specifications

Below is a summary of South Carolina DOT's chip seal specifications:

- Section 406 – Asphalt Surface Treatment / Single Treatment
  - Slag type: ACBFS
  - Aggregate size: No. 89M (Max. 3/8") and No. 789 (Max. 1/2")
  - Percentages of fines: ≤ 2%
  - LA abrasion: ≤ 45% (60% for natural aggregates)
  - Bulk weight: ≥ 75 lb/ft^3
  - Free from soft, thin or elongated pieces, disintegrated particles, vegetation, or other deleterious substances.
  - Aggregate application rate: 12 to 15 lb/yd^2 for No. 89M and 15 to 20 lb/yd^2 for No. 789.
  - Emulsion rate: 0.28 to 0.35 gallon/yd^2 + 15% when using slag.

SCDOT Coarse Aggregate Gradation Specifications											
	Stone								Graded Aggregate Base		
Sieve	CR-14	5	57	67	6M	8M	789	89M	Macadam	MLBC	RPCC
2"	100								100	100	100
1 1/2"	95-100	100	100						95-100	95-100	95-100
1"	70-100	90-100	95-100	100	100				70-100	70-100	70-100
3/4"		20-55		90-100	90-100	100	100				
1/2"	35-65	0-10	25-60			95-100	95-100	100	48-75	50-85	48-75
3/8"		0-5		20-55	0-20	75-100	80-100	98-100			
No. 4	10-40		0-10	0-10	0-5	10-35	20-50	20-70	30-60	30-60	30-60
No. 8			0-5	0-5				2-20			
No. 16						0-5	0-6				
No. 30									11-30	17-38	11-30
No. 100						0-2	0-2	0-3			
No. 200									0-12	0-20	0-12
LL									25 Max	25 Max	25 Max
PI									6 Max	6 Max	6 Max

D.3 Utah DOT Chip Seal Specifications

Below is a summary of Utah DOT's chip seal specifications:

- Section 02785 – Chip Seal Coat
  - Use crusher processed virgin aggregate consisting of natural stone, gravel, or slag for standard chips.
  - Slag type: ACBFS (bulk unit weight ≤ 100 lb/ft^3).
  - Aggregate application rate adjusted based on unit weight of chip aggregates.

Chip Seal Cover Material Properties			
Test	**Test Method**	**Standard Chip Seal Type I & II**	**Lightweight Chip Seal Type I &II**
*Unit Weight	AASHTO T 19	100 lb/ft^3, max	60 lb/ft^3, max
One Fractured Face	AASHTO T 335	95% minimum	N/A
Two Fractured Faces	AASHTO T 335	90% minimum	N/A
*LA wear	AASHTO T 96	30% maximum	30% maximum
*Soundness	AASHTO T 104	10% maximum	10% maximum
Flakiness Index	Materials MOI 933	17 maximum	25 maximum
*Stripping	Materials MOI 945	10% maximum	10% maximum
*Polishing	AASHTO T 278, T 279	31 minimum	31 minimum

* This requirement may be waived if the aggregates have proven acceptable through successful past performance as determined by the Engineer.

Gradation Limits				
Sieve Size	**Percent Passing**			
	Standard Aggregate		**Lightweight Aggregate**	
	Type I	**Type II**	**Type I**	**Type II**
½ in		100 - 98	100	100 - 90
⅜ in	100	69 - 91	80 - 100	55 - 80
No. 4	0 - 15	0 - 11	5 - 40	0 - 10
No. 8		0 - 6	0 - 20	0 - 3
No. 16			0 - 10	
No. 200	0 - 1	0 - 1.5		0 - 2

	Approximate Spread Rates	
	Unit Weight lbs/ft^3	Application Rate lbs/yd^2
Lightweight Type I Chip Seal	45 - 50	9.6
	50 - 55	10.6
	55 - 60	11.6
Lightweight Type II Chip Seal	45 - 50	11.8
	50 - 55	13.1
	55 - 60	14.3
Standard Chip Seal	60 - 65	17.0
	65 - 70	18.4
	70 - 75	19.8
	75 - 80	20.7
	80 - 85	22.1
	85 - 90	23.5
	90 - 95	24.9
	95 - 100	25.8

D.4 Michigan DOT Chip Seal Specifications

Below is a summary of Michigan DOT's chip seal specifications:

- Section 505 – Chip Seals
  - Slag type: ACBFS
  - Aggregate size: 34CS for single chip seals (Max. 1/2")
  - Percentages of fines: ≤ 2%
  - LA abrasion: ≤ 45% (35% for natural aggregates)
  - Flat and elongated: ≤ 15% (for single chip seals)
  - Aggregate wear index (AWI): ≤ 260 for ADT > 4,000 and ≤ 220 for ADT < 4,000
  - Percentages of soft particles: ≤ 3.5%
  - Aggregate application rate: 20 to 24 lbs/yd^2
  - Emulsion application rate: 0.39 to 0.46 gallons/yd^2

Table 902-7:
Capital Preventive Maintenance Final Aggregate Blend Gradation Requirements

	Mechanical Analysis, Total % Passing										
Material	**¾ inch**	**½ inch**	**⅜ inch**	**¼ inch**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200[(a)]**
27SS	100	85–100	55–80	—	22–38	19–32	15–24	11–18	8–14	5–10	4–7[(b)]
30SS	—	100	85–100	—	22–38	19–32	15–24	11–18	8–14	5–10	4–7[(b)]
34CS[(c)]	100	100	90–100	—	0–15	0–5	—	—	—	—	≤2
CS-T[(c)]	100	100	100	85–100	—	0–15	—	—	—	—	≤2
2FA	—	—	100	—	90–100	65–90	45–70	30–50	18–30	10–21	5–15[(b)]
3FA	—	—	100	—	70–90	45–70	28–50	19–34	12–25	7–18	5–15[(b)]

(a) Includes mineral filler.
(b) No. 200 limits are significant to the nearest whole percent.
(c) All aggregate must be washed.

D.5 Indiana DOT Chip Seal Specifications

Below is a summary of Indiana DOT's chip seal specifications:

- Section 404 – Seal Coat
  - Slag type: ACBFS and steel slag
  - Aggregate size: 9, 11, SC 11, 12, SC 12, 16, SC 16 (Coarse), and 23, 24 (Fine)
  - Angularity: SC aggregates shall have 85% one and 80% two crushed faces. Non-SC aggregates shall have a minimum crushed particle percentage of 70% (by weight).
  - Flakiness index: ≤ 25% for SC aggregates.
  - Adjust aggregate application rate when slag is used based on specific gravity (× SG/2.6).

Type (see Note 1)	Application	Cover Aggregate Size No. and Course	Rates of Application per sq yd	
			Aggregate, lb	Asphalt Material, Gal. at 60°F
1 or 1P (see Note 2)	Single	23, 24	12 - 15	0.12 - 0.16
2 or 2P	Single	12, SC 12	14 - 17	0.29 - 0.33
3 or 3P	Single	11, SC 11, SC 16	16 - 20	0.36 - 0.40
4 or 4P	Single	9	28 - 32	0.63 - 0.68
5 or 5P	Double	Top: 12, SC 12 Bottom: 11, SC 11, SC 16	16 - 19 16 - 20	0.41 - 0.46 0.28 - 0.31
6 or 6P	Double	Top: 11, SC 11, SC 16 Bottom: 9	18 - 22 28 - 32	0.62 - 0.68 0.42 - 0.46
7 or 7P	Double	Top: 11, SC 11, SC 16 Bottom: 8	18 - 22 28 - 32	0.62 - 0.68 0.42 - 0.46

Note 1 – AE-90S and SC aggregates shall be used for Type P seal coats, except SC aggregate requirement will not apply to seal coat used on shoulders.
Note 2 – HFRS-2 shall not be used with Type 1 seal coat.

Sieve Sizes	Coarse Aggregate Sizes (Percent Passing)									
	Coarse Graded									
	2	5	8	9	11, SC 11[5]	12, SC 12[5]	SC 16[5]	43[1]	91	93PG[6]
4 in. (100 mm)										
3 1/2 in. (90 mm)										
2 1/2 in. (63 mm)	100									
2 in. (50 mm)	80 - 100									
1 1/2 in. (37.5 mm)		100						100		
1 in. (25 mm)	0 - 25	85 - 98	100					70 - 90	100	
3/4 in. (19 mm)	0 - 10	60 - 85	75 - 95	100				50 - 70		
1/2 in. (12.5 mm)	0 - 7	30 - 60	40 - 70	60 - 85	100	100	100	35 - 50		98 - 100
3/8 in. (9.5 mm)		15 - 45	20 - 50	30 - 60	75 - 95	95 - 100	94 - 100			75 - 100
No. 4 (4.75 mm)		0 - 15	0 - 15	0 - 15	10 - 30	50 - 80	15 - 45	20 - 40		10 - 60
No. 8 (2.36 mm)		0 - 10	0 - 10	0 - 10	0 - 10	0 - 35		15 - 35		0 - 15
No. 16 (1.18 mm)							0 - 4			
No. 30 (600 µm)						0 - 4		5 - 20		0 - 5
No. 200 (75 µm)[2]								0 - 6.0		
Decant (PCC)[3]		0 - 1.5	0 - 1.5	0 - 1.5	0 - 1.5	0 - 1.5			0 - 1.5	
Decant (Non-PCC)	0 - 2.5	0 - 2.5	0 - 3.0	0 - 2.5	0 - 2.5	0 - 2.0			0 - 2.5	0 -2.0
Decant (SC)					0 - 1.5	0 - 1.5	0 - 1.5			

(h) Sizes of Fine Aggregates

	Sizes (Percent Passing)					
Sieve Sizes	23	24	15	16	PP	S&I
3/8 in. (9.5 mm)	100	100				100
No. 4 (4.75 mm)	95 - 100	95 - 100			100	
No. 6 (3.35 mm)			100			
No. 8 (2.36 mm)	80 - 100	70 - 100	90 - 100		85 - 95	
No. 16 (1.18 mm)	50 - 85	40 - 80				
No. 30 (600 µm)	25 - 60	20 - 60	50 - 75	100	50 - 65	
No. 50 (300 µm)	5 - 30	7 - 40	15 - 40		15 - 25	0 - 30
No. 80 (180 µm)				95 - 100		
No. 100 (150 µm)	0 - 10	1 - 20	0 - 10		0 - 10	
No. 200 (75 µm)	0 - 3	0 - 6	0 - 3	65 - 100		0 - 7

D.6 Louisiana DOT Chip Seal Specifications

Below is a summary of Louisiana DOT's chip seal specifications:

- Section 507 – Asphalt Surface Treatment
  - Slag type not specified.
  - No adjustments for the use of slag.
  - Percentages of fines: ≤ 2%

Table 507-1
Asphalt Surface Treatment (AST) Requirements
(Cold Application)

	Course No.	AST TYPE A		AST TYPE B		AST TYPE C	AST TYPE D			AST TYPE E (Interlayer)
Aggregate		Lightweight, Crushed Stone		Lightweight, Crushed Stone		Lightweight, Crushed Stone	Lightweight, Crushed Stone, Crushed Gravel			Crushed Stone, Crushed Gravel
Agg. Friction Rating		I, II		I, II, III		I, II, III	I, II, III, IV			I, II, III, IV
Asphalt Emulsion		CRS-2P		CRS-2P		CRS-2P	CRS-2P			CRS-2P
Application Temp. Minimum		160°F		160°F		160°F	160°F			160°F
Maximum		175°F		175°F		175°F	175°F			175°F
Number of Applications		2	1	2	1	1	3	2	1	2
Asphalt Emulsion[1] Application Rates Per Course	1	0.39	0.41	0.39	0.31	0.41	0.46	0.39	0.31	0.39
	2	0.29	—	0.29	—	—	0.36	0.29	—	0.29
	3	—	—	—	—	—	0.26	—	—	—
Aggregate size and Application Rates Per Course[2]	1	S2-0.0111	S2-0.0111	S2-0.0111	S3-0.0075	S2-0.0111	S1-0.0200	S2-0.0111	S3-0.0075	S2-0.0111
	2	S3-0.0075	—	S3-0.0075	—	—	S2-0.0111	S3-0.0075	—	S3-0.0075
	3	—	—	—	—	—	S3-0.0075	—	—	—

[1]Application rates are in gallons of asphalt emulsion per square yard of AST.
[2]Size aggregate and application rates. For example, S2 is Size 2 aggregate and 0.0111 is the application rate in cubic yards of aggregate per square yard of AST. S1A may be used in lieu of S1. Aggregate sizes for AST are shown in Table 1003-15.

Table 1003-15
Gradation for Asphalt Surface Treatment

		Size 1		Size 1A	Size 2	Size 3
U. S. Sieve	Metric Sieve	Slag or Stone Aggregate (Size No. 5)	Crushed Gravel[1] or Lightweight Aggregate	Slag or Stone Aggregate	All Aggregate	All Aggregate
1 1/2 inch	37.5 mm	100	100	100	—	—
1 inch	25.0 mm	90-100	95-100	100	—	—
3/4 inch	19.0 mm	20-55	60-90	85-100	100	—
1/2 inch	12.5 mm	0-10	—	25-40	95-100	100
3/8 inch	9.5 mm	0-5	0-15	5-15	60- 80	95-100
No. 4	4.75 mm	—	0-5	—	0-5	20-50
No. 8	2.36 mm	—	—	—	0-2	0-2
No. 200[2]	75 µm[2]	0-1	0-1	0-1	—	—

[1] Uncrushed gravel may be used for Size 1 aggregate if more than one application of Asphalt Surface Treatment is required.
[2] If the material passing the No. 200 (75 µm) sieve consists of only dust from crushing and handling, and is essentially free of clay, then the percentage passing the No. 200 (75 µm) sieve shall be 0 - 2 percent.