Recent Improvements in Quality of Steel Slag Aggregate

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Steel slag aggregate has been used in premium surface course hot-mix asphalt for Ontario highways since the early 1970s. Asphalt pavement performance problems led to the Ministry of Transportation imposing a moratorium on the use on steel slag aggregate in late 1991. The problem has been addressed from the steelmakers producing the slag to hot-mix design and production. Steel slag can serve as good aggregate for use in hot-mix asphalt if the volume expansion of the slag is controlled. Performance-based testing of steel slag aggregate, particularly volume stability, is recommended as a measure of the aggregate quality. Practices at the steelmaker and the slag processor were examined. The production of acceptable quality steel slag aggregate requires total quality management of all steps of production.

Steel slag has been used in Ontario as an aggregate in hot-mix asphalt since the early 1970s. The primary use of steel slag aggregate (SSA) has been in the premium surface, or wearing course, of asphalt pavement. The inherent physical properties of steel slag produced a hot-mix asphalt with high stability, good stripping resistance, and excellent skid resistance. A considerable amount of steel slag aggregate was produced in Ontario with some 488,000 tonnes used in hot-mix asphalt in 1990 (*1*).

The Ministry of Transportation of Ontario (MTO) expressed increasing concern in 1985 about pavement performance where steel slag aggregate was used after about 1980. The initial concerns of MTO were random map cracking, grey veining around cracks, "flushing" of asphalt cement to the pavement surface, and the general lack of SSA quality compared with natural aggregates.

The Ontario steel industry, aggregate producers, and paving industry worked on these and related concerns in 1985 and 1986, but did not resolve the problem to MTO's satisfaction. Continuing performance problems, particularly map cracking of dense friction course (DFC) mixes, led to a moratorium in December 1991 on the use of all steelmaking and blast furnace slags in hot-mix asphalt. The moratorium has prompted the steel industry to better understand steel slag as an aggregate and be able to produce that aggregate to an acceptable level of quality for use in hot-mix asphalt.

APPROACH TO PROBLEM

The problems with SSA are not limited to a single variable or step in processing. To fully understand the influence of production, processing, and use of SSA (Figure 1), a study team was assembled to represent the different groups concerned with the quality of the pavement containing SSA. The goal of the Steel Slag Technical Committee (Table 1) has been to make steel slag aggregate fully approved for use in hot-mix asphalt.

The bulk of the work was performed at Dofasco in Hamilton, Ontario. Dofasco's basic oxygen furnace (BOF) steelmaking slag is processed by Heckett, Plant No. 14. Additional work has been performed at Lasco in Whitby, Ontario, on electric arc furnace slag as processed by International Mill Services (IMS). MTO has mandated industry to solve the problems with SSA, with emphasis on the cause of random map cracking. Additional MTO concerns included consistency issues (gradation, density, absorption, moisture content), extractability of asphalt cement, oxidation of asphalt cement, and recyclability. An important part of the work has been close technical liaison with MTO to produce a quality SSA aggregate for Ontario's roads.

A two-phase approach has been taken to solve the problem. Phase 1 was to identify the problem and understand the variables affecting hot-mix asphalt containing SSA. Phase 2 was to implement the necessary changes identified in Phase 1 to demonstrate improved SSA quality. Phase 1 was completed in 1993, and Phase 2 is currently being implemented at Dofasco and Lasco.

- Phase 1: (a) identify the causes of poor pavement performance review literature and inspect and sample payments, (b) investigate steelmaking and slag processing practices, and (c) develop a preliminary aggregate quality specification.
- Phase 2: (a) produce acceptable quality SSA, (b) implement total quality management, and (c) evaluate pavement test strips.

RESULTS AND DISCUSSION OF RESULTS

Literature Review

A thorough review of SSA use was conducted, including technical literature, user agency contacts in 18 countries (including 7 Canadian provinces and 17 U.S. state agencies), and slag processor and steel industry surveys. There was consensus in the literature that steel slag can be used successfully as an aggregate in hot-mix asphalt. In addition, there was agreement that the principal problem associated with steel slag was volume expansion due to the hydration of free lime or magnesia that are common components of slag. Historically, the method of dealing with the free lime has been to age the slag or accelerate the hydration reaction with water or washing. There was no consensus that this approach was successful.

The literature review identified four agencies with significant experience with SSA and established testing requirements to deal with the volume expansion due to free lime (*2–5*). These agencies are listed in Table 2. There was agreement on the need to test the

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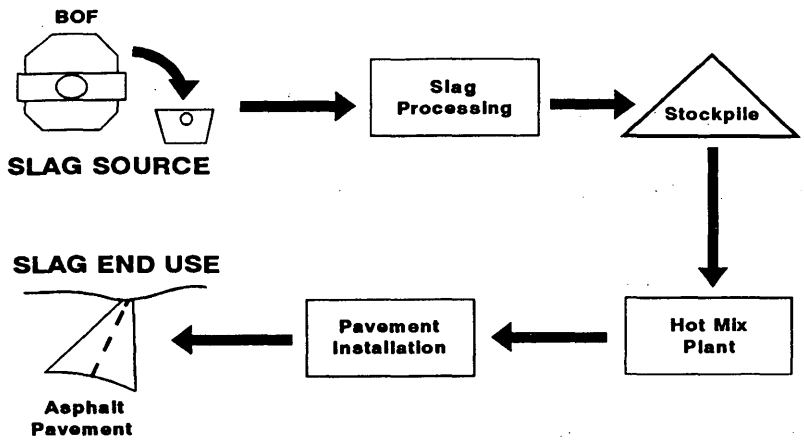

FIGURE 1 Overview of processing of SSA for use in hot-mix asphalt.

TABLE 1 Members of Steel Slag Technical Committee

Function	Company
Steelmaker	Dofasco Algoma
Slag/Aggregate Processor	Heckett International Mill Services
Asphalt Producer	Standard Aggregates
Technical Advisors	JEGEL* 'McMaster'**
Technical Liaison	Ministry of Transportation

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volume stability of the aggregate, with a water immersion test on the SSA and on a Marshall test briquette of the hot-mix asphalt (i.e., accelerated performance tests). Although the details of the stability testing may differ, the agreement on the need to test the volume stability was seen as a critical component for the current work in Ontario.

As a result of the literature review and experience, four tests have been recommended to measure the quality of SSA and hot-mix asphalt containing SSA (Table 3). These tests are in addition to the general tests required for hot-mix asphalt aggregates (e.g., gradation, bulk relative density, absorption, and moisture). The volume expansion test is based on the ASTM Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions (*6*).

These tests are considered to give a better indication of the performance of SSA in hot-mix asphalt. Previous testing relied on chemical analysis methods, such as free lime determination. These techniques are difficult to perform and give only an indirect measure of the SSA quality. Performance-based testing, particularly the volume expansion test, provides a direct measure of the aggregate, and it was the consensus of the key agencies identified in the literature review to use this type of testing.

Pavement Evaluation

A field program was completed to evaluate the performance of Ontario DFC and HL 1 pavements containing SSA (Table 4). Approximately 90 sections of pavement containing SSA were inspected. For comparison, several sections containing natural traprock aggregate were also examined. Each pavement section was inspected using the American Public Works Association PAVER procedure (*7*), which is similar to that used by MTO but provides additional surface condition information. A pavement condition index (PCI) ranging from 0 (very poor) to 100 (excellent)

TABLE 2 Aggregate Testing Requirements of Key Agencies Using SSA

Specification	Pennsylvania	Belgium	Germany	Japan
Free Lime	No	≤4.5%	No	No
Deleterious Constituents	No	No	Yes	No
Aging	>6 months	Yes	No	≥3 months
Volume Stability Test	Yes	Yes	Yes	Yes
Marshall Briquette Stability Test	Yes	Yes	Yes (free lime ≥4%)	Yes

TABLE 3 Recommended Tests for SSA Quality

Test	Purpose
1) Petrographic Examination	Simple examination for contamination by non-slag particles.
2) Autoclave Disruption	Accelerated 1 hour test to give quick information on the slag volume expansion.
3) Volume Expansion	Seven day water immersion test to measure SSA volume expansion.
4) Hot-Mix Asphalt Immersion	Test on final Marshall hot-mix asphalt briquette to assure stable hot-mix asphalt.

TABLE 4 Hot-Mix Asphalt Mix Designs Containing SSA for Use on High Traffic Volume Highways

Mix Design	Description
DFC	A dense graded premium surface course mix with high frictional resistance using coarse and fine aggregates (all steel slag or all natural aggregate only).
HL 1	A dense graded surface course mix with premium quality coarse aggregate. Excellent wear and frictional properties.

was determined for each section. The results are compared with the normal rate of deterioration expected for a typical flexible pavement.

The inspection results clearly show that DFC pavement containing SSA has deteriorated at an accelerated rate compared to the normal rate (Figure 2). However, it should be noted that the traprock sections exhibit a similar rate of deterioration. The deterioration was characterized by moderate to severe random cracking with some wheelpath flushing. These results are similar to MTO findings in earlier and parallel pavement condition monitoring studies (*8*). The HL 1 pavement containing SSA was acceptable (Figure 3), which was consistent with MTO study results (*9*). The mix design also appears to affect the pavement performance.

Further investigation of the pavement was completed using representative core samples taken for testing in the laboratory. Standard pavement testing was performed on the samples (e.g., gradation, petrography, asphalt cement content, and Marshall properties). Examination of the samples showed soft, deleterious particles at the crack faces. The presence of these non-slag particles pointed to the need to closely examine the steelmaking and slag processing practices.

Steelmaking Practice

Steel in Ontario is made in either a BOF or an electric arc furnace. Most steel slag is produced by the BOF. At Dofasco, a variation of the BOF, called a KOBM, is used. The KOBM has oxygen and powered lime injected through bottom tuyeres in addition to a top lance. Each steelmaking shop has unique equipment and practices that affect the quality of steel slag. Each shop must therefore be considered a separate source when evaluating the quality of SSA. For this reason, it is important that the specific findings of this study not be extended to other steel slags.

The flux and slag practices of Dofasco's KOBM furnace were closely examined. Different practices were implemented on a trial basis to assess the effect on SSA quality. Figure 4 shows the sig-

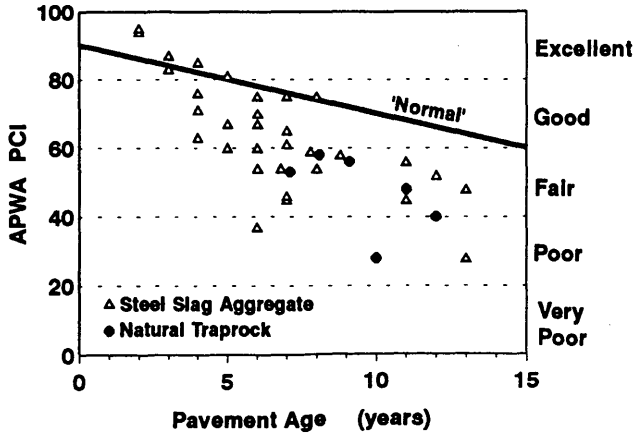

FIGURE 2 DFC pavement performance.

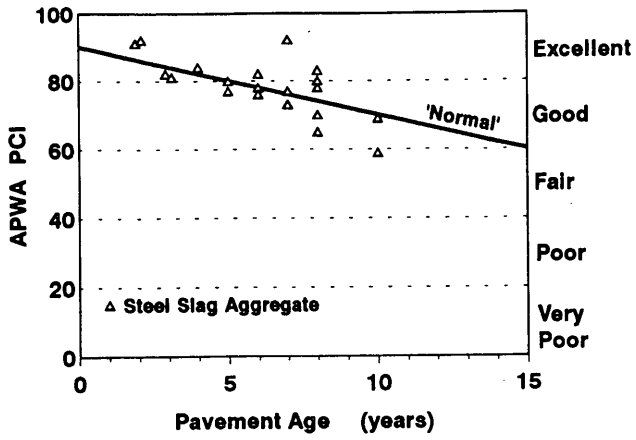

FIGURE 3 HL 1 pavement performance.

nificant difference that flux and slag practice can have on SSA volume expansion. Flux Practice A resulted in slag that was contaminated with lime or dolime and exhibited greater volume expansion as compared with Practice B. An SSA sample from Australia of known good hot-mix asphalt performance was obtained for comparison. The very low volume expansion of the Australian sample again highlights the effect that slag source can have on the quality of SSA.

Slag Processing

Liquid slag from the steelmaking furnace is dumped, cooled, and processed to recover the metallics in the slag. The slag fraction is further crushed and screened to produce SSA. Slag processors may handle a variety of materials, such as steel slag, ladle slag, used refractory and pit slag, to recover steel metallics. These materials must be source separated, and well-defined handling practices must be in place to avoid contamination of the SSA. The slag processor must also be aware of general aggregate requirements of the end user (i.e., hot-mix producer and specifying agency). Aggregate requirements, such as gradation, moisture content, and material handling practices to avoid segregation, must be satisfied before delivery of a quality aggregate to the hot-mix plant.

A trial was conducted at Heckett using a fine mineral jig to process the steel slag. The jig used wet gravity separation in an attempt to eliminate the less dense, lime-rich particles from the slag. The resulting material had a clean washed appearance. However, testing of the aggregate showed volume expansion of 3.9 percent for the coarse size fraction and 4.5 percent for the fine. Later investigation showed that this was attributed to the effect of the steelmaking flux practice on the quality of the aggregate. The slag processor cannot work in isolation to produce good aggregate if the steelmaker is producing slag contaminated with lime or dolime.

Total Quality Management

In the past, there has been minimal quality control in the production of SSA in Ontario. The principal focus of the steelmakers was steel, and steel slag was treated as a by-product for disposal. The recent problems with SSA pavement and the resulting moratorium has forced the steel industry to change this view. In addition, rising costs and decreasing capacity at landfills have practically eliminated disposal as an option. The recent work of the Steel Slag Technical Committee has led to a proposed SSA specification and quality control outline. A site specific quality control practice must be established at each source of SSA including the steelmaker and slag processor. The purpose of these controls is to ensure that an aggregate of suitable quality is produced for use in hot-mix asphalt.

CONCLUSIONS

- Steel slag of suitable quality and consistency can be used to produce good aggregate for use in hot-mix asphalt.

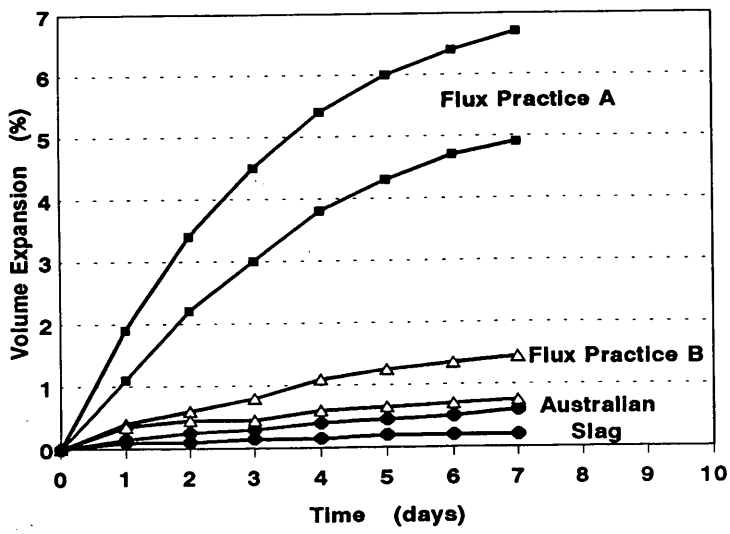

FIGURE 4 Effect of steelmaking source and flux practice on volume expansion of SSA.

- Volume expansion of the steel slag aggregate is a problem that must be controlled before the aggregate can be used in hot-mix asphalt.
- Steelmaking flux and slag practices must be compatible with making low volume expansion slag aggregate.
- Performance-based testing should be used to measure the volume expansion of the steel slag aggregate.
- Total quality management is necessary to cover all aspects of SSA production to ensure an aggregate of suitable quality is delivered to the end user.

ACKNOWLEDGMENTS

The authors thank the Steel Slag Technical Committee and Dofasco for permission to publish this work. Many groups and individuals have contributed to this ongoing project over the past 2½ years. The authors thank G. Kennepohl and C. Rogers of MTO, D. Milberger of IMS, B. Crann of Standard Aggregates, R. Wallace of Heckett, K. Fulcher of Dofasco, M. MacKay of JEGEL, and B. Strathdee of McMaster.

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Publication of this paper sponsored by Committee on Mineral Aggregates.