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TechBrief

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Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements

This TechBrief presents guidelines and recommendations for using air-cooled blast furnace slag (ACBFS) as a coarse aggregate in concrete pavements. It describes the physical and chemical properties of ACBFS aggregate, highlighting how this material differs from natural aggregates. It also discusses the properties of concrete produced with ACBFS coarse aggregate and identifies specific production issues applicable to ACBFS concrete. Furthermore, general design and construction recommendations are provided for improving the performance of concrete pavements that incorporate this material.

Introduction

Air-cooled blast furnace slag (ACBFS) has been used as a coarse aggregate in concrete pavements since at least the 1930s. The States of Michigan, Pennsylvania, New York, Indiana, and Ohio, among others, have had considerable experience with ACBFS in concrete pavement construction, with Michigan's usage significantly exceeding that of other highway agencies (Staton 2006). In Michigan, there was extensive use of ACBFS at the Detroit Industrial Expressway System placed in the 1940s through the 1970s, as well as in many structures of that era and in a number of more recent highway construction projects.

By definition, blast furnace slag is a nonmetallic product (consisting essentially of silicates and aluminosilicates of calcium and other bases) that is developed in a molten condition simultaneously with iron in a blast furnace. ACBFS is the material resulting from the solidification of molten blast furnace slag in a slag pit under atmospheric conditions with some spraying of water to accelerate cooling so the materials can be moved to the processing plant. Due to a relatively slow rate of cooling, the resulting ACBFS (see figure 1) predominately has a crystalline structure, and the resultant material can be crushed to produce an

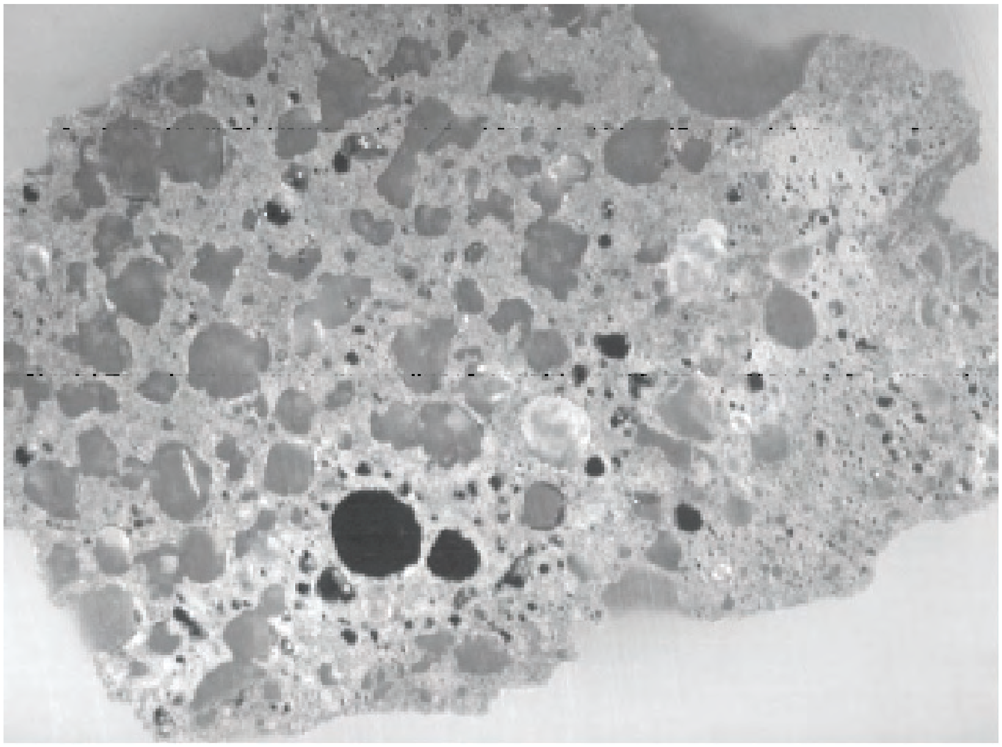

FIGURE 1. Closeup of ACBFS epoxy-impregnated coarse aggregate particle. (From D. M. Hammerling, *Calcium Sulfide in Blastfurnace Slag Used as Concrete Aggregate*, 1999, p. 22, figure 2.12. Photo © Karl Peterson. Reprinted with permission.)

angular and roughly cubical coarse aggregate for use in many segments of highway construction including base courses, fill and embankments, hot-mix asphalt, and hydraulic cement concrete.

Two key benefits associated with the use of ACBFS aggregate are resource conservation (reducing the need for natural aggregate) and the reduction or elimination of solid waste. However, although ACBFS aggregate has been used in concrete pavement construction for more than 80 years, the performance of concrete pavements containing ACBFS has been mixed. In Ohio and Indiana, the performance of ACBFS aggregate in paving concrete has been reported to be acceptable. However, in Michigan, the use of ACBFS in paving concrete has been linked to poor performance of concrete pavements (Staton 2006). The Michigan Department of Transportation's (DOT) pavement management data collected over a period of more than 30 years indicate more frequent repairs and rehabilitation for pavements using concrete with ACBFS aggregate compared to comparable pavements using concrete with natural aggregate. The Michigan DOT data indicate that ACBFS pavements may have a higher life-cycle cost over their service life. It is therefore essential that engineers and contractors who use ACBFS in concrete be aware of the unique properties of ACBFS aggregate in order to better assess and predict the long-term performance of pavement structures.

This TechBrief presents a summary of recommendations for using ACBFS coarse aggregate in paving concrete. More detailed information on ACBFS aggregate properties and use in concrete pavements is given in two recently published reports available from FHWA:

1. *Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements—A Guide to Best Practice* (Smith, Morian, and Van Dam 2012).
2. *Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements* (Morian, Van Dam, and Perera 2012).

Properties and Characteristics of ACBFS Aggregate

ACBFS is one of several types of byproducts obtained during the production of iron in a blast furnace, with the other common materials being expanded blast furnace slag, granulated blast furnace slag, and pelletized blast furnace slag.

Chemical Composition

As a product of calcinated fluxstone and the alumina and silica phases present in iron ore, the four major oxide phases present in ACBFS are oxides of calcium (CaO), silica (SiO_2), aluminum (Al_2O_3), and magnesium (MgO). These oxides account for approximately 95 percent of the composition of ACBFS, with the remaining 5 percent consisting of sulfur, manganese, iron, titanium, fluorine, sodium, and potassium (Hammerling 1999).

It has long been known that the chemical properties of ACBFS must be taken into consideration when considering it for use in concrete. Two primary concerns are iron unsoundness and dicalcium silicate unsoundness. Iron unsoundness is considered to be very rare, arising only if partially reduced iron oxides in the slag oxidize, with the resulting expansive reaction causing the ACBFS particles to disintegrate. This is likely to occur when the slag contains more than 3 percent ferrous oxide and at least 1 percent total sulfur (S) (ASA 1997; JIS 2003).

Dicalcium silicate unsoundness is caused by an increase in volume due to a phase inversion from beta form to gamma form during cooling, which will weaken the ACBFS aggregate particles. This expansive phase inversion is completed within a few days as the slag cools to ambient temperatures, so it generally should not pose a future issue (Juckes 2002).

There are also concerns about the presence of calcium sulfide (also called oldhamite) in ACBFS, which forms as a result of the sulfur from the coke fuel reacting with calcium from the dolomite or limestone used as a flux. To some degree, the sulfide compounds found in ACBFS are soluble in concrete and may result in the formation of secondary ettringite in the air-void system, which can compromise the durability of the concrete. To control the amount of calcium sulfide dissolution, it is recommended that the maximum total sulfur content should be limited to 2.0 percent and the maximum total acid-soluble sulfates to 0.5 percent when tested in accordance with ASTM C114 (ASTM 2011). Testing for the sulfur content of the ACBFS is recommended for each run of the pig iron production.

Physical Properties

The physical properties of ACBFS are largely controlled by how it cools and solidifies. Table 1 compares some of the typical ACBFS coarse aggregate properties with those associated with natural coarse aggregate. Some of the notable differences between the two different aggregate types include:

- Greater angularity of ACBFS, which can affect mix proportioning.
- Lower specific gravity of ACBFS, which can affect mix proportioning.
- Higher absorption of ACBFS, which can affect mix proportioning, workability, and early-age shrinkage.

TABLE 1. Typical ACBFS Coarse Aggregate and Natural Aggregate Properties (Smith, Morian, and Van Dam 2012)

Property	ACBFS Aggregate	Natural Aggregate
Particle shape and texture	Angular and roughly cubical with rough to glassy texture	Well-rounded, smooth (gravels) to angular and rough (crushed stone)
Specific gravity	2.0–2.5	2.4–2.9
Absorption capacity	1–8%	0.5–4.0%
Angle of friction	40–45 degrees	30–45 degrees
Los Angeles abrasion test	35–45%	15–45%
California bearing ratio	>100	80–100
Mohs hardness	5–6	3–8

- Lower abrasion resistance of ACBFS, which can affect mechanical load transfer behavior at joints and cracks in concrete pavements.
- Highly vesicular aggregates that have low fracture energy/toughness, which leads to poor aggregate interlock at joints and cracks.

Typical Properties of Concrete Constructed With ACBFS

In general, most of the properties of concrete containing ACBFS are similar to those exhibited by concrete produced with natural aggregate. Some of the specific characteristics and properties of concrete containing ACBFS aggregate are summarized below.

- *Workability*. Because of the vesicular nature of ACBFS, workability requirements may dictate the need for slightly more mortar (cementitious material, sand, and water) during proportioning. As with concrete made with natural aggregates, water-reducing admixtures and/or Class F fly ash or slag cement may also be used to improve workability of ACBFS concrete. It is always important that sufficient moisture be present in the aggregates when batching concrete to prevent significant rapid absorption of concrete mixing water; ACBFS aggregates should not be batched drier than saturated surface dry (SSD) condition.
- *Unit weight*. Concrete made with ACBFS will exhibit a slightly lower unit weight because of the lower specific gravity of the ACBFS. The in-place unit weight of ACBFS concrete in Michigan has been reported to be between 135 and 140 lb/ft^3 (2,160 and 2,240 kg/m^3), compared to about 143 to 145 lb/ft^3 (2,290 to 2,320 kg/m^3) for natural aggregate.
- *Strength and modulus values*. Generally speaking, ACBFS concrete displays strength and modulus values very similar to those exhibited by concrete made with natural aggregates.
- *Coefficient of thermal expansion* (CTE). A typical range for the CTE of concrete made with ACBFS is reported to be between 5.1 and 5.9 x 10^{-6} in/in/°F (2.8 and 3.2 x 10^{-6} in/in/°C). This falls within the typical range of CTE values for concrete made with dolomite and sandstone.
- *Freeze–thaw durability*. Although some concerns have been expressed that the vesicular nature of the ACBFS may lead to freeze–thaw durability issues, several States (Illinois, Indiana, Ohio) and countries (Australia, Great Britain, Japan) have reported that ACBFS con-

crete exhibits excellent freeze–thaw durability (Morian, Van Dam, and Perera 2012). It is recommended that the laboratory evaluation of ACBFS for freeze–thaw durability should follow the same testing procedures as are used on natural materials.

Recommendations for Incorporating ACBFS Into Concrete Pavements

Table 2 presents a listing of recommendations for incorporating ACBFS into concrete pavements, based largely on the unique characteristics and properties of the material. These recommendations cut across all phases of a pavement construction project, from aggregate production to mix design and proportioning and from pavement design to construction and placement. In addition, recommendations are provided for the long-term monitoring of concrete pavements constructed with ACBFS aggregate. It should be noted that if a State DOT has a pavement management system that it uses to monitor the performance of its pavement network, the DOT should be able to determine the performance of its ACBFS pavements relative to pavements with natural aggregate concrete. This would allow the DOT to determine *where it would be satisfactory or unsatisfactory* to use ACBFS aggregates in its concrete pavement construction program.

TABLE 2. Summary of Recommendations for Incorporating ACBFS Into Concrete Pavements

Phase of ACBFS Aggregate Use	Recommended Activities
ACBFS Aggregate Production	• Test for iron unsoundness when the slag contains more than 3% ferrous oxide and at least 1% total sulfur. Testing is conducted by immersing pieces of slag in water for a period of 14 days and observing whether any of the particles crack or disintegrate. • Minimize the potential for calcium sulfide dissolution by limiting total sulfur content to a maximum of 2.0% and total acid-soluble sulfates to a maximum of 0.5%. • Monitor and maintain the moisture content of ACBFS stockpiles above saturated surface dry (SSD). • Regularly test for unit weight/specific gravity.
Mix Design, Proportioning, and Concrete Production	• Monitor and maintain the moisture content of ACBFS stockpiles above SSD. • Work to minimize segregation in ACBFS stockpiles. • Regularly test for unit weight/specific gravity and aggregate grading, and use appropriate values in determining mix proportions. • Perform trial batches to ensure that the desired concrete properties are obtained. • Consider the addition of a water-reducing admixture and/or Class F fly ash or slag cement to assist in achieving adequate workability. • Maintain water-to-cementitious materials ratio during concrete batching to maintain mix uniformity, adjusting batch water as necessary. • Employ conventional concrete aggregate gradations, but consider any effect of particle size on the specific gravity of the ACBFS during mix design. • Consider the use of Class F fly ash or slag cement in minimizing potential mixture durability problems. • Use good quality-control procedures for both aggregate and concrete production, including careful monitoring of the ACBFS aggregates.

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TABLE 2 (continued). Summary of Recommendations for Incorporating ACBFS Into Concrete Pavements

Phase of ACBFS Aggregate Use	Recommended Activities
Pavement Design	• Use ACBFS only in doweled jointed plain concrete pavements. Include appropriately sized dowel bars for load transfer at the transverse joints and make sure they are corrosion resistant. • Use the DARWin-ME™ (AASHTOWare® pavement design software) for slab thickness design because it can directly account for the properties of ACBFS aggregate. Use mix-specific parameters reflective of the ACBFS mixture (specifically the coefficient of thermal expansion and the flexural strength) in the design process. • Use shorter transverse joint spacing (maximum 15 ft (4.6 m) and minimum 12 ft (3.7 m)) for most highway pavement applications) to help improve performance. • Use permeable asphalt-treated or cement-treated base to ensure adequate support and positive subsurface drainage. The Michigan experience indicates that ACBFS pavements must be well-drained.
Construction and Placement	• Employ established construction practices and exercise good quality control throughout the project. • Monitor air content using the volumetric method. • Monitor concrete mixture uniformity throughout the project. • Perform adequate consolidation to remove entrapped air. Make sure that internal vibration is effectively applied and that vibrating frequencies are matched to the paving speeds and the mixture. • Perform finishing and texturing as per local or prevailing specifications. • Provide adequate curing using an effective curing compound. • Saw joints as soon as practical to prevent random cracking. • Avoid construction under extreme weather conditions. • Use HIPERPAV® software to identify critical concrete pavement issues.
Performance Monitoring and Feedback	• Monitor performance of ACBFS concrete pavements (that are reflective of modern designs) using the agency's major concrete pavement performance indicators (e.g., cracking, faulting, roughness). • Document maintenance and rehabilitation expenditures associated with ACBFS concrete pavements. • Develop performance curves for ACBFS concrete pavements for comparison with those developed for concrete pavements constructed with natural aggregates.

Summary

This document presents overall recommendations for using ACBFS coarse aggregate in concrete pavements. An overview of the properties and characteristics of ACBFS aggregate is first presented so that users understand some of the inherent differences that exist between ACBFS and natural aggregates and thus why certain handling requirements or design or construction modifications may be needed to achieve a comparably performing pavement. This overview is followed by specific recommendations for incorporating ACBFS into paving concrete, from the production of the aggregate, to its use in a concrete mixture, to the consideration of pavement design attributes, and finally to the production of the concrete and the construction of the pavement itself. The recommendations presented herein are expected to contribute to improved performance from concrete pavements incorporating ACBFS coarse aggregate. It must be emphasized that it is very important to ensure that the moisture content of the ACBFS aggregate stockpiles at the concrete plant site is monitored regularly and appropriate adjustments are made in the batch water during concrete production.

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