Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements—A Guide to Best Practice

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16. Abstract
This document contains recommendations for best practices related to the use of air-cooled blast furnace slag (ACBFS) as coarse aggregate in concrete pavements. It is primarily based on the results of a review of available literature regarding the production and use of ACBFS as coarse aggregate in concrete pavements, information provided through interaction with the project's expert task group, and limited pavement field surveys and petrographic analysis of extracted cores from ACBFS concrete pavements.
This best practices document discusses the production, 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 and quality control practices applicable to ACBFS concrete. The document further provides design and construction recommendations for improving the quality of concrete pavement made using this material. Results from field inspections and laboratory evaluations of concrete pavements made with ACBFS coarse aggregate are discussed. Finally, the life-cycle and maintenance costs associated with concrete pavements incorporating ACBFS aggregate in the concrete are also discussed in the report.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1. INTRODUCTION

BACKGROUND

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). Michigan, in fact, cites extensive use of ACBFS in the Detroit Industrial Expressway system, placed in the 1940s through the 19 70s, as well as in many structures of that era and in a number of more recent highway construction projects (Oehler and Finney 1953; Staton 2006). It should be noted that ACBFS can also be used as feedstock for a granulator and the production of slag cement, and thus is a potentially valuable material that should not be considered as "waste."

By definition, blast furnace slag is the 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 predominately has a crystalline structure, which may contain some glassy and dense particles and which can be crushed to produce an angular and roughly cubical coarse aggregate for use in many aspects of highway construction including use in stabilized and unstabilized base courses, fill and embankments, hot-mix asphalt, and hydraulic cement concrete (simply referred to as concrete in this document).

Two key benefits associated with the use of ACBFS aggregate are resource conservation (reducing the need for natural aggregate) and reduction or elimination of solid waste. Although the environmental considerations are often of primary interest, there are often significant economic benefits as well, since the use of ACBFS aggregate reduces the need for natural aggregate and for landfill disposal (e.g., iron producers financially benefit from the sale of the material while avoiding disposal costs, and ready-mix concrete producers and contractors also financially benefit by obtaining a relatively low-priced reclaimed aggregate compared to natural aggregate materials). These benefits dovetail neatly with the recent focus on sustainability, which has been characterized as a balance between economic, environmental, and societal needs and impacts (Van Dam and Taylor 2009). Thus, the use of ACBFS can help meet sustainability needs in each of those three areas, and therefore can contribute to the sustainability of pavement construction projects provided that overall pavement performance is not compromised.

In that vein, it is important to recognize that ACBFS aggregates are distinct, unique materials, possessing a number of characteristics and properties that must be considered during the design and construction process to ensure long-term performance (Wang and Thompson 2011). For example, ACBFS typically exhibits the following characteristics when compared to natural aggregates (Chesner, Collins, and Mackay 1998; Rao 2006):

- Lower specific gravity.

- Higher porosity and absorption.
- Increased angularity.

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 compared to concrete pavements of similar construction but made with naturally derived aggregates. 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's) 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. This varied performance, which has led the Michigan DOT to discontinue the use of ACBFS coarse aggregates in concrete pavements, is discussed in detail in the project final report from which this guide has been developed (Morian, Van Dam, and Perera 2012). A number of the potential causes of the observed poor performance have been identified, some of which are linked to unique properties and characteristics of the ACBFS. 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.

PURPOSE AND SCOPE

Although there are potentially some limitations associated with the use of ACBFS coarse aggregate, the effective characterization of these materials during their production and throughout the design and construction process can help lead to their successful use and application. Therefore, this document has been developed to provide succinct "best practice" guidelines for using ACBFS coarse aggregate, drawing upon the experiences and practices of highway agencies to manage the risk posed in using ACBFS coarse aggregate in paving concrete. Adherence to these guidelines will help ensure the improved performance of concrete pavements constructed with ACBFS coarse aggregate.

DOCUMENT OVERVIEW

This guideline document consists of six chapters. In addition to this introductory chapter, chapter 2 provides a general overview of the production of ACBFS aggregate, describing some of the important chemical and physical properties of the material. Chapter 3 presents key pavement design considerations for concrete pavements that will be constructed using ACBFS aggregate. Chapter 4 presents key factors to consider in the mix design and proportioning of concrete with ACBFS, and also describes typical fresh and hardened concrete properties exhibited by ACBFS concrete. Chapter 5 provides specific recommendations for constructing concrete pavements containing ACBFS aggregate, including key items on concrete production, concrete placement and finishing, and quality control (QC) procedures. Finally, chapter 6 presents an overall summary of the document.

CHAPTER 2. ACBFS PRODUCTION AND PROPERTIES

INTRODUCTION

This chapter describes the production of ACBFS and how that production influences the resultant properties of the material. Typical chemical composition and properties of the ACBFS materials are presented, with emphasis on primary differences that exist between ACBFS aggregate and natural aggregate.

TYPES OF SLAG

Slag is the byproduct of metallurgical operations, typically containing gangue from the metal ore, flux material, and unburned fuel constituents. Slag is often classified into nonferrous and ferrous slags, where nonferrous slags include those derived from copper, lead-zinc, nickel, and phosphorus metallurgical operations, and ferrous slags are those derived from the production of iron and steel. Figure 1 illustrates slag classification based on origin, where ACBFS is shown as a byproduct of the production of pig iron from iron ore (Hammerling 1999).

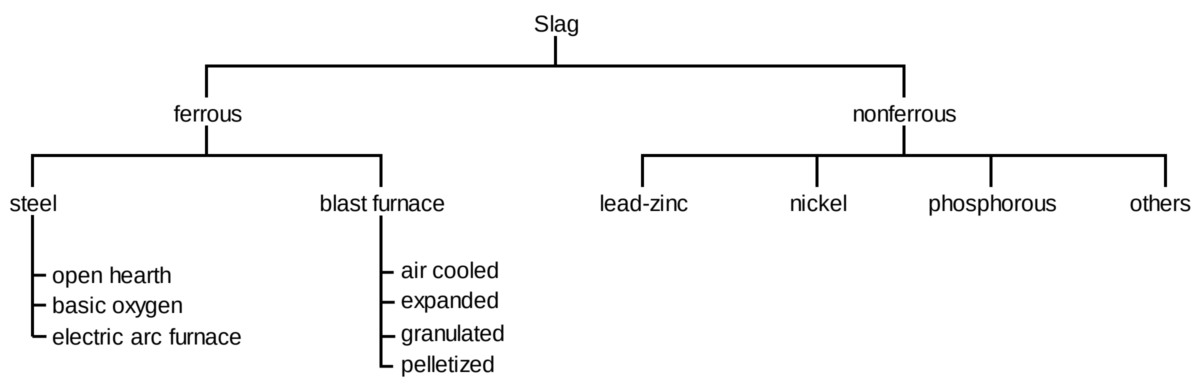

Figure 1. Types of slag classified based on origin.
(From D. M. Hammerling, *Calcium Sulfide in Blastfurnace Slag Used as Concrete Aggregate*, p. 4. © D. M. Hammerling 1999. Adapted with permission.)

Blast furnace slag is categorized based on how the molten slag is treated once it is removed from the furnace. The primary types of blast furnace slag are the following (Lewis 1982; Chesner, Collins, and Mackay 1998; Pulipaka, Parker, and Kohn 2007):

- ACBFS, which, as previously described, is the material resulting from the solidification of molten blast furnace slag under atmospheric conditions. The molten blast furnace slag is often dumped into a pit, and jets of water are sometimes sprayed onto the slag’s surface to accelerate cooling and facilitate expedited removal of the material so as not to inhibit the smelting process. The final product is then removed from the pit, transported to a crushing and screening facility, and then processed like conventional aggregate, except that magnetic separation is used to remove small pieces of pig iron.

- Expanded (or foamed) blast furnace slag results from the treatment of molten slag with controlled quantities of water (but less than that required for granulation). Expanded slags are more cellular and vesicular than air-cooled slags, and lighter in unit weight.

- Granulated blast furnace slag is created by quickly quenching molten slag with water to produce a glassy, granular product. When crushed or milled to very fine, cement-sized particles, this material has cementitious properties that make it a suitable partial replacement or additive to portland cement.

- Pelletized blast furnace slag is produced when the molten slag is cooled and solidified with water and air quenched in a spinning drum, resulting in the formation of pellets, rather than a solid mass. By controlling the process, the pellets can be made more crystalline, which is beneficial for aggregate use, or more vitrified (glassy), which is more desirable in cementitious applications.

Although some ACBFS may be sprayed with water to expedite processing, such as is done at the Ford Rouge River Complex in Detroit, Michigan, it is still broadly referred to as “air cooled.”

The focus of this Best Practice Guide is solely on the use of ACBFS as an aggregate in concrete pavements, so the specific production of ACBFS and its inherent properties and characteristics for that application are emphasized from this point forward.

ACBFS PRODUCTION

In the production of pig iron, the vertical shaft blast furnace is used to smelt iron from iron ore, which contains iron oxide and other minerals, and a fluxing agent (usually limestone, dolomite, or both). The primary fuel is coke, which is subjected to a continuous blast of air, resulting in a high rate of combustion. The fuel, ore, and fluxing agent are supplied continuously through the top of the furnace, while the air is blown into the bottom of the furnace. The smelting process, in which the ore containing iron oxide is converted to metallic iron through a reduction process, occurs as the material moves downward. The end products are the molten metal and the slag, each of which is tapped from the bottom of the blast furnace. Figure 2 presents a schematic of an iron blast furnace.

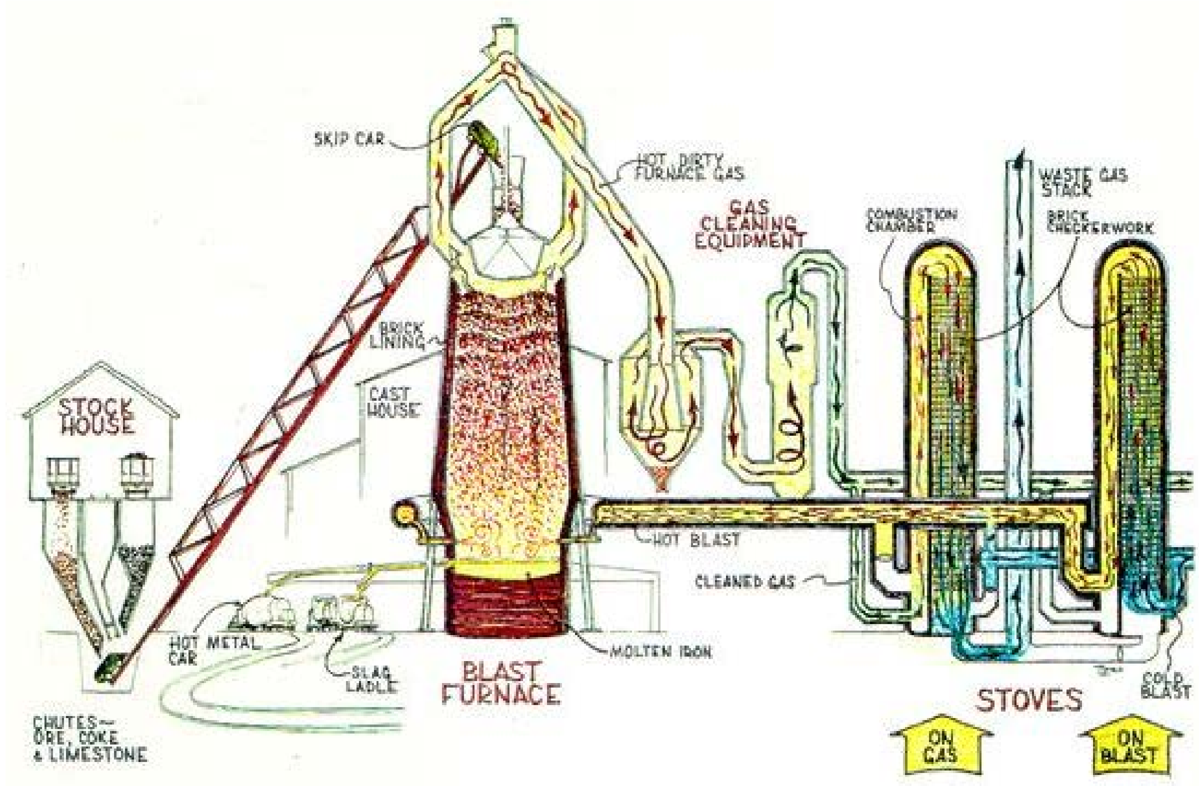

Figure 2. Schematic of iron blast furnace.
(Peacey and Davenport 1979, p. 2, figure 1.1; © Elsevier. Adapted with permission.)

CHEMICAL AND PHYSICAL PROPERTIES OF ACBFS

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), silicon (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, as shown in table 1 (Hammerling 1999). High magnesia content is generally attributed to the use of dolomite as a fluxing agent.

The oxide compositions presented in table 1 represent their respective weight percentages.

Table 1. Typical Composition of ACBFS.
(From D. M. Hammerling 1999. © D. M. Hammerling 1999.
Adapted with permission.)

Component	**Percentage**
Major Components	*95*
Lime (CaO)	30–40
Silica (SiO_2)	28–42
Alumina (Al_2O_3)	5–22
Magnesia (MgO)	5–15
Minor Components	*5*
Sulfur (CaS, other sulphides, sulfates)	1–2
Iron (FeO, Fe_2O_3)	0.3–1.7
Manganese (MnO)	0.2–1
Rare Components	
$Na_2O + K_2O$	0–1
TiO_2	0–1
V_2O_5	0–1
Cr_2O_3	0–1

Depending on the composition of the raw material, the fusion temperature, and the cooling rate, a variety of minerals can form (see table 2). The glass content is mainly dependent on the cooling rate, with faster cooling resulting in more glass formation, whereas slower cooling allows more time for the formation of crystallized minerals. The cooling rate is very important, as glassy phases are chemically more reactive, and rapidly quenched granulated slag can be ground and used as cement. The most prevalent mineral found in ACBFS is melilite, which is a solid solution between the isomorphous minerals gehlenite ($2CaO{\cdot}MgO{\cdot}2SiO_2$) and akermanite ($2CaO{\cdot}Al_2O_3{\cdot}SiO_2$).

Table 2. Typical Minerals Found in ACBFS
(From D. M. Hammerling 1999, p. 15, table 2.2. © D. M. Hammerling. Adapted with permission.)

Mineral	Formula	Crystal System
Melilite	$(Ca,Na)_2(Mg,Al)(Si,Al)_2 0_7$	tetragonal
Wollastonite	$CaSiO_3$	triclinic
Oldhamite	CaS	cubic
Dicalcium silicate	$2CaO \cdot SiO_2$	
Rankinite	$3CaO \cdot 2SiO_2$	monoclinic
Merwinite	$3CaO \cdot MgO \cdot 2SiO_2$	monoclinic
Anorthite	$CaO \cdot Al_2O_3 \cdot 2SiO_2$	triclinic
Monticellite	$CaO \cdot MgO \cdot SiO_2$	orthorhombic
Spinel	$MgO \cdot Al_2O_3$	isotropic
Periclase	MgO	isotropic
Olivine	$(Fe,Mg)_2SiO_4$	orthorhombic
Glass	Variable	amorphous

A common mineral in ACBFS that potentially may affect its performance as a coarse aggregate in concrete is calcium sulfide (CaS), commonly referred to as oldhamite (Peterson et al. 1999; Hammerling 1999; Hammerling et al. 2000; MPA 2011). Calcium sulfide is soluble in the high-pH environment present in concrete, and if present in sufficient quantities, can result in the formation of secondary ettringite in nearby entrained air voids. Secondary ettringite does not have the expansive capability to cause fracturing of the concrete, but it has been speculated that substantial infilling may partially compromise the ability of the air-void system to protect the concrete against freeze–thaw damage. As documented elsewhere (Morian, Van Dam, and Perera 2012), other investigations have indicated that excessive dissolution of calcium sulfide might increase the risk of other materials-related distresses in concrete pavements.

Physical Properties

The physical properties of ACBFS are largely controlled by how it cools and solidifies. As previously described, crushed ACBFS used as coarse aggregate in concrete is angular and roughly cubical, with texture ranging from rough and vesicular (porous) to glassy (smooth) with conchoidal fractures (Rao 2006). Fine slag screenings are similar in density to natural sand, while the density of coarse aggregate particles is as much as 20 percent less than natural aggregates having the same gradation (Lewis 1982). Figure 3 provides a closeup view of an ACBFS particle.

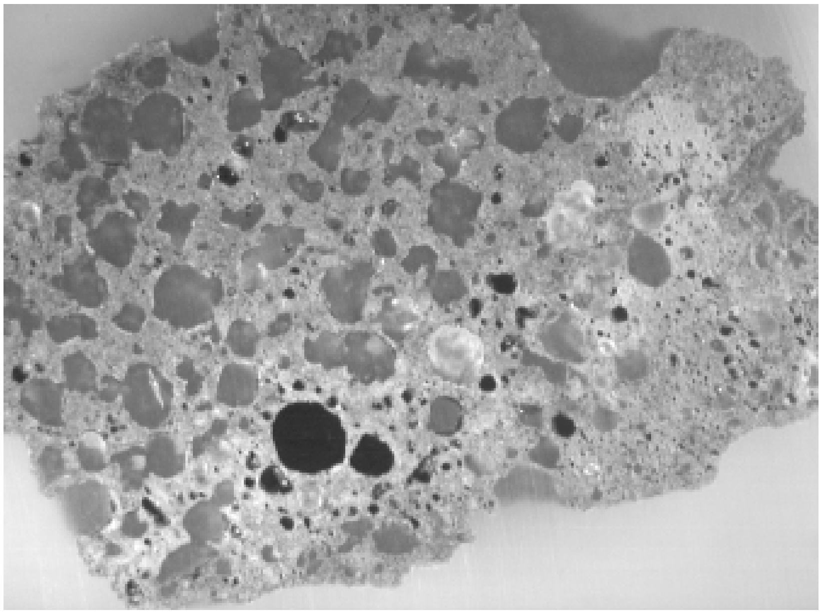

Figure 3. Closeup view of an ACBFS coarse aggregate particle.

Note: Horizontal field of view is 3 cm.
(From D. M. Hammerling 1999, p. 22, figure 2.12. © D. M. Hammerling 1999.
Reprinted with permission.)

Table 3 compares some of the typical ACBFS coarse aggregate properties with those of natural coarse aggregate. Some of the notable differences include the lower specific gravity of ACBFS (which can affect mix proportioning), the higher absorption of ACBFS (which can affect mix proportioning, workability, early-age shrinkage cracking, and later-age freeze–thaw performance), and the lower abrasion resistance of ACBFS (which can affect mechanical load transfer behavior at joints and cracks in concrete pavements).

The high absorption capacity of ACBFS is a particular concern in the proportioning, design, construction, and QC of concrete pavements. The higher absorption capacity is related to the intrinsic vesicular/porous nature of the larger ACBFS particles, but is also influenced by other factors including greater surface area and resistance to removal of water held in shallow surface voids.

Table 3. Comparison of Typical ACBFS Coarse Aggregate Properties With Those of Natural Aggregate
(ASA 1997; Chesner, Collins, and Mackay 1998; Somayaji 2001; Rao 2006)

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 percent	0.5–4 percent
Angle of friction	40–45 degrees	30–45
Los Angeles abrasion test	35–45 percent	15–45 percent
California bearing ratio	> 100	80–100
Mohs scale of hardness	5–6	3–8

SUMMARY

ACBFS has unique chemical and physical properties that influence its behavior as an aggregate in concrete. The presence and dissolution of calcium sulfide is considered to be a chemical property that could affect the durability of concrete containing ACBFS, as the dissolution of calcium sulfide in aggregates may lead to freeze–thaw durability issues as well as contribute to other materials-related distress. The physical property of greatest concern is the high level of porosity compared to that present in naturally derived aggregates, which contributes to high absorption capacities. This is important during construction, as the moisture condition of the aggregate will impact workability and early-age, shrinkage-related cracking if the aggregate is not kept sufficiently moist prior to batching. It may also have long-term ramifications on inservice durability, depending on the level of saturation the aggregates are subjected to either at the bottom of the slabs or in the vicinity of joints and cracks. Therefore, as discussed later, an active QC program is needed to control, measure, and correct for free moisture on fine and coarse aggregate prior to batching concrete to control workability.

CHAPTER 3. CONCRETE MIXTURES INCORPORATING ACBFS COARSE AGGREGATES

INTRODUCTION

When used as a coarse aggregate in paving concrete, the unique characteristics of ACBFS described in chapter 2 can significantly affect the fresh and hardened properties of the concrete. Such effects are manageable if recognized and addressed during the mixture design and construction phases of the project. This chapter first describes the effects that ACBFS aggregate can have on resulting concrete mixtures and then presents typical properties of concrete incorporating ACBFS. Where appropriate, suggested mitigation measures or overall recommendations are provided for the development of effective ACBFS paving mixtures.

ACBFS CHARACTERISTICS THAT AFFECT CONCRETE MIXTURES

Effects of ACBFS Chemical Composition

Iron and Dicalcium Silicate Unsoundness

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) (ASA1997; JIS 2003). Although iron unsoundness is not typically observed in modern slag material, it may be of concern if older stockpiled slag material is used. Testing to detect iron unsoundness 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.

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. Juckes (2002) states that this expansive phase inversion is completed within a few days as the slag cools to ambient temperatures. In other words, the inversion is completed once the slag has cooled and should not pose a future issue.

Calcium Sulfide

As described in chapter 2, sulfides and sulfates make up 1 to 2 percent of ACBFS with the predominant occurrence in the form of calcium sulfide. Calcium sulfide (also called oldhamite) is present in ACBFS 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. Sufficient infilling with secondary ettringite may compromise the air-void system that protects the concrete from freeze–thaw damage. Additionally, some studies have indicated that dissolution of the calcium sulfide might lead to other types of materials-related distress (Morian, Van Dam, and Perera 2012).

To control the amount of calcium sulfide dissolution and ultimately the potential for freeze–thaw damage, it is recommended that a maximum limit of 2 percent be specified on the total sulfur content of ACBFS. Although damage from calcium sulfide dissolution is possible, it may only affect a small quantity of concrete. Therefore, it is recommended to test the total sulfur content of the ACBFS on a semiannual basis initially and to increase the testing frequency when high sulfur values are detected. The development of an effective air-void system is important for all paving concrete in freeze–thaw climates, but is of even greater importance when ACBFS aggregate is used due to the increased risk of the air voids infilling with secondary ettringite. In addition, the use of an appropriate supplementary cementitious material (SCM), such as AASHTO M 295 (ASTM C618) Class F fly ash or AASHTO M 302 (ASTM C989) slag cement, is effective in reducing the risk of deterioration due to materials-related distress, particularly in concrete made with high-alkali cements.

Effects of ACBFS Physical Properties

Texture

As described earlier, a dominant characteristic of ACBFS is the angular and rough surface texture of the aggregate particles. One result of this feature is that additional mortar (cementitious materials, water, and sand) is often needed when proportioning concrete containing ACBFS to overcome the high angular/vesicular surface area of the particles and maintain workability. The use of water-reducing admixtures can assist in this effort to some degree, but it has been observed that it is almost always necessary to have some additional mortar to “coat and fill” the irregular ACBFS surfaces to create a workable concrete mixture.

Absorption

The vesicular nature of the ACBFS aggregate creates a high water-absorption capacity, in some cases as high as 7 to 8 percent. It is known that if ACBFS aggregate is batched dry during concrete production, stiffening and poor workability issues may result. In addition, early-age shrinkage cracking may develop as water is absorbed from the paste by the aggregate.

The American Concrete Institute recommends saturation of porous aggregate (those with absorptions in excess of 2.5 percent (24-hour soaking method)) and proper wetting of aggregate stockpiles, including ACBFS, to minimize such absorption to avoid early-age shrinkage (ACI 2003). These practices are absolutely essential if ACBFS aggregate is to be used in paving concrete, as these mixtures are necessarily stiff (typically having a 0.5- to 1.5-in. (13 to 39 mm) slump), and absorption of even a small amount of mix water by the aggregate will result in an unworkable mixture that will be prone to early-age shrinkage cracking. Moreover, the ACBFS aggregate’s moisture content must be closely monitored during batching to ensure the desired water-to-cementitious materials ratio (w/cm). The practical consequence of this is that during construction, ACBFS stockpiles must be kept wet, requiring the contractor to maintain an extra level of stockpile management that is not required when most natural aggregates are used.

Specific Gravity

Specific gravity is a measure of the density of an aggregate relative to the density of water. As described in chapter 2, ACBFS aggregate generally has lower specific gravity values than natural materials, attributed to the vesicular nature of the material. Sufficient testing of the ACBFS should be performed to identify representative specific gravity values so that effective aggregate volumes can be developed in the concrete mixture proportioning stage. Allowable variation on the specific gravity of the ACBFS aggregate should be determined based on avoiding significant variations in overall yield; typical acceptable values may range from ± 0.07 to ± 0.10 percent.

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. Key properties of concrete containing ACBFS aggregate are summarized in the following sections.

Fresh Concrete Properties

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. A water-reducing admixture may help to some degree in maintaining adequate workability. The use of either a Class C or Class F fly ash is expected to lead to improved workability, but it should be recognized that Class F fly ash is typically more effective in mitigating potential alkali–silica reactivity if that risk is present.

It is always important that sufficient moisture be present in the aggregates when batching concrete to prevent significant rapid absorption of concrete mixing water, which will result in reduced workability (as well as the potential for shrinkage cracking). Because of its vesicular nature, ACBFS aggregates should not be batched drier than the saturated surface dry (SSD) condition to prevent this problem. Free water should be maintained on both fine and coarse aggregates. The free water should be counted as part of the mix water and the concrete batch weights adjusted accordingly

Air Content

The development of a good entrained air-void system is important to the durability of all concrete exposed to freeze–thaw conditions. Current practice suggests that the entrained air content should be on the order of 5 to 7 percent, depending on the maximum aggregate size. Concrete containing ACBFS aggregates is no exception. Targeted air contents can be achieved for concrete containing ACBFS, but it is important to note that the relative lightweight nature of the ACBFS aggregate means that the pressure method for determining air contents (AASHTO T 152 or ASTM C231) will give erroneous results. Instead, the air content of freshly mixed ACBFS concrete should be measured by the volumetric method (AASHTO T 196 or ASTM C173), which has been an established standard practice for many years.

Unit Weight

Because of the lower specific gravity of ACBFS, it will produce concrete of a slightly lower unit weight than that of conventional concrete. The in-place unit weight of ACBFS concrete in Michigan has historically been reported to be between 135 and 140 lb/ft^3 (2,162 and 2,243 kg/m^3), compared to about 143 to 145 lb/ft^3 (2,291 to 2,323 kg/m^3) for natural aggregate. Measurement of unit weight is one simple QC test to help monitor mix uniformity over a period of production time.

Hardened Concrete Properties

Strength and Modulus Values

Over the years, a number of field and laboratory studies have evaluated the strength and stiffness properties of concrete made with ACBFS coarse aggregate. Taken as a whole, the results strongly suggest that ACBFS concrete displays strength and modulus values very similar to those exhibited by concrete made with natural aggregates. The results of these studies also indicate that the w/cm is of primary importance with regard to the strength of hardened concrete, with the importance of aggregate type secondary.

Concrete Coefficient of Thermal Expansion

A number of studies have measured the coefficient of thermal expansion (CTE) of concrete made with ACBFS, with a typical range reported to be between 5.1 and 5.9 x 10^{-6} in/in/°F (9.1 and 10.6 x 10^{-6} mm/mm/°C) (AASHTO 2008). This falls within the typical range of CTE values for concrete made with dolomite and sandstone, and is lower than that of concrete containing quartz sands and gravels and quartzite. For use with the new MEPDG pavement design procedure, it is recommended that the CTE of concrete made with ACBFS be determined using project-specific materials and the proposed concrete mixture.

Freeze–Thaw Durability

Although some concerns have been expressed that the vesicular nature of the ACBFS may lead to freeze–thaw durability issues for concrete incorporating ACBFS aggregate, several States (Illinois, Indiana, Ohio) and countries (Australia, Great Britain, Japan) have reported that ACBFS concrete exhibits excellent freeze–thaw durability (Morian, Van Dam, and Perera 2012). And, several field studies in Michigan on materials-related distress in concrete (which included several ACBFS concrete projects) did not identify coarse aggregate freeze–thaw durability as a cause of distress (Van Dam et al. 2002; Sutter, Van Dam, and Peterson 2009). Based on a review of all available data, no special recommendations are made with regard to the freeze–thaw durability of concrete made with ACBFS coarse aggregate. Hence, laboratory evaluation of ACBFS for freeze–thaw durability should follow the same testing procedures as used on natural materials.

Surface Friction

Concrete pavements constructed with ACBFS coarse aggregate are reported to exhibit good surface friction characteristics (Emery 1982). However, typical surface friction values are not available.

RECOMMENDATIONS: USING ACBFS IN CONCRETE PAVING MIXTURES

As presented in this chapter, there are a number of items to be addressed when using ACBFS in concrete paving mixtures. These key items are summarized below, along with other aspects of concrete mixture design and proportioning to help ensure good performance of the ACBFS concrete:

- For unproven sources of ACBFS, testing should be performed for iron unsoundness when the slag contains more than 3 percent ferrous oxide and at least 1 percent 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.

- Dicalcium silicate unsoundness is not thought to be a problem after the slag cooling process; that is, the phase inversion reaction does not occur at ambient temperatures.

- The potential for excessive calcium sulfide dissolution should be minimized by limiting the maximum total sulfur content to 2.0 percent and maximum percent of acid-soluble sulfates to 0.5 percent (ASTM C114, Section 6, HCl digestion). Testing on the sulfur content of the ACBFS is recommended to be performed on each source at least semi-annually.

- The control of moisture in the ACBFS aggregate is perhaps the most critical element in using it for concrete paving applications. The potential problem lies in the fact that the ACBFS aggregate when batched dry can lead to stiffening, poor workability, and early-age shrinkage cracking. Stockpiles of ACBFS should be watered immediately prior to shipping, using an agricultural type impact sprinkler (Levy undated). Additional moisture control is required at the concrete production facility to ensure that the ACBFS aggregate does not fall below a moisture level of SSD. The objective is to achieve a constant moisture level at or above SSD to prevent loss of mix water through absorption into the aggregate (Levy undated). The stockpiled ACBFS aggregate moisture content must be closely monitored during batching to maintain the desired w/cm. If the aggregate moisture content varies, appropriate adjustment in batch water or cement content may be required; the preferable method is to adjust batch water so the resulting concrete will maintain uniformity throughout the project.

  Achieving stockpile moisture control requires physical separation of aggregate stockpiles and regular watering to achieve and maintain uniform moisture throughout the stockpile. Good stockpile management techniques must be employed at all times.

- To achieve adequate workability of ACBFS concrete mixtures, additional mortar may be required during proportioning if adequate adjustment cannot be achieved by batch water adjustment. The addition of a water-reducing admixture may also provide some benefit in obtaining workability.

- The use of a suitable SCM, such as a Class F fly ash or slag cement, is highly encouraged to help ensure the durability of the resulting ACBFS concrete mixture.

- While air-entrainment is always important for the durability of concrete in a freeze–thaw environment, the quality of the entrained air-void system is especially critical when ACBFS aggregate is used. Air contents on ACBFS should be measured using the volumetric method (AASHTO T 196 or ASTM C173) and not by the pressure method. Targeted air contents should be based on the exposure condition and maximum aggregate size, but will typically range from 5 to 7 percent.

- Mix proportioning can be done using conventional methods, but the specific gravity of the ACBFS aggregate must be determined and used in developing initial quantities. Highly variable specific gravity values, along with variable absorption levels, can make the mix proportioning process very difficult. Trial batches should be prepared to ensure that the desired properties are obtained. The specific gravity of ACBFS aggregate relates closely to aggregate gradation. Good control of aggregate gradation will help reduce variability in specific gravity.

- Overall hardened properties of ACBFS concrete should be very similar to those obtained for conventional concrete. Slightly lower unit weights are expected for ACBFS, as compared with concrete containing natural aggregates.

CHAPTER 4. DESIGN CONSIDERATIONS FOR CONCRETE PAVEMENTS CONSTRUCTED WITH ACBFS COARSE AGGREGATE

INTRODUCTION

The nature and inherent properties of ACBFS coarse aggregate can have a strong effect on the performance of concrete pavements that incorporate ACBFS. As noted by the Michigan DOT, concrete pavements they have constructed using ACBFS aggregate have exhibited inconsistent levels of performance, with many pavements rehabilitated after only about 10 years of service and a few achieving service lives of 30 years or more (Staton 2006). A review of the data in Michigan's Pavement Management System indicates that, for a service life of about 30 years, the ACBFS pavements required approximately twice the maintenance expenditures than pavements constructed with natural aggregate (Staton 2006). The specific role played by ACBFS in the observed poor performance in Michigan was not conclusively determined, but a key characteristic of ACBFS cited as a contributing factor with regard to design is the poor shear (load transfer) performance across joints and cracks in concrete made with ACBFS aggregates.

This finding gives rise to the need for identifying critical aspects of the concrete pavement design that will help contribute to the performance of concrete pavements incorporating ACBFS. Some of these general recommendations are presented in this chapter.

APPLICABLE CONCRETE PAVEMENT TYPES

Load transfer across joints and cracks in concrete pavements is a critical design element. Load transfer at transverse joints is provided in a number of ways, including through the use of mechanical devices (dowel bars), aggregate interlock of abutting joint faces, and base/subgrade support. Effective load transfer helps reduce critical slab stresses and deflections under loading.

Aggregate interlock load transfer is effectively lost once the joint (or crack) opens about 0.035 in. (0.889 mm) and the abutting crack faces are no longer in contact with one another. That loss of contact, along with the fact that the crack face in concrete containing ACBFS aggregate is relatively smooth (with the crack passing through and not around the aggregates), results in unreliable aggregate interlock load transfer. Consequently, ACBFS coarse aggregate should be used only in those pavement designs where more positive methods of load transfer are employed, namely mechanical devices such as dowel bars. This effectively limits the use of ACBFS coarse aggregate to jointed plain concrete pavement (JPCP) designs that contain dowel bars at the transverse joints. Other concrete pavement designs—including undoweled JPCP, continuously reinforced concrete pavement, and jointed reinforced concrete pavement—are not recommended for concrete made with ACBFS coarse aggregate because of the reliance on aggregate interlock for load transfer in those pavements.

PAVEMENT DESIGN DETAILS

Because of the characteristics associated with the ACBFS aggregate, several key factors should be carefully considered when designing a concrete pavement incorporating ACBFS aggregate:

- *Slab thickness.* Slab thickness for a concrete pavement using ACBFS can be determined using an agency's accepted design procedures, but mechanistic analysis tools, which can better characterize some of the unique characteristics of the ACBFS concrete, will likely produce more reliable results. The new Mechanistic-Empirical Pavement Design Guide (AASHTOWare DARWin-ME^{TM} software), for example, may be more appropriate in that it can directly account for the unique effects of ACBFS on concrete properties. It is important that mix-specific parameters (such as coefficient of thermal expansion and other thermal properties and direct measurements of flexural strength (i.e., not derived from a general compressive–flexural strength relationship)) be used to characterize the ACBFS concrete mix. DARWin-ME also allows for the direct consideration of base support characteristics and joint spacing in the slab thickness design.

- *Base support.* Because of the potential for poor load transfer through aggregate interlock, it is recommended that ACBFS concrete pavements be constructed on a relatively strong, stiff support. This suggests the use of stabilized base courses, such as a cement-treated or asphalt-treated base, especially for high-traffic applications. Another approach that has proven successful is to use a combination of layers to create relatively thick, stiff support such as a permeable aggregate layer 3 in. (76 mm) thick on a dense-graded aggregate base layer 6 in. (152 mm) thick; stabilized subgrade may also be included. These support layer configurations provide higher levels of support to the slab and reduce the magnitude of critical deflections.

- *Joint spacing.* The use of shorter joint spacing should be considered in JPCP designs, especially those incorporating ACBFS aggregate, as shorter joint spacing reduces joint openings, helping to maintain some degree of aggregate interlock load transfer at the joints. Shorter joint spacing also reduces the magnitude of thermal curling stresses in the slab, which can be higher when slabs are constructed on stiff bases. For most highway-type concrete pavements (typically 10 to 12 in. (250 to 300 mm) thick), a maximum transverse joint spacing of 15 ft (4.6 m) is recommended, but slightly shorter joint spacing (but not less than 12 ft (3.7 m)) may be justified for ACBFS concrete, particularly if it is placed on a stiff, stabilized base course. DARWin is one design tool that takes these factors into consideration when establishing optimal joint spacing.

- *Load transfer design.* All concrete pavements containing ACBFS should include dowel bars at the transverse joints for load transfer. Typically, a minimum 1.25-in. (31.75 mm) diameter bar is recommended for slabs less than 10 in. thick, and a minimum 1.50-in. (38.10 mm) diameter bar is recommended for slabs 10 in. (250 mm) and thicker. However, ACBFS concrete may be more susceptible to dowel "socketing," which occurs when the concrete surrounding the dowel bar is crushed under the high stresses generated as the dowel bar bears against the concrete. This socketing leads to poor support of the dowel bars and, consequently, faulting and perhaps even cracking in the vicinity of the joint. Thus, consideration may be given to the use of a dowel bar that is slightly larger in diameter to help reduce the magnitude of the dowel bearing stresses. As with all concrete pavements, dowel bars should be epoxy-coated for protection against corrosion; alternatively, some agencies allow the use of noncorrodible dowel bar materials or claddings.

- *Drainage.* Subsurface drainage features should be incorporated into the concrete pavement design as dictated by local practices and the experiences of the highway agency.

- *Early-age cracking treatment*. Because of the poor aggregate interlock characteristic of ACBFS concrete, any early-age transverse cracking should be addressed either through a full-depth repair or by using the dowel bar retrofit technique to ensure adequate load transfer at these cracks.

SUMMARY OF PAVEMENT DESIGN RECOMMENDATIONS

Figure 4 provides a cross section of a pavement, highlighting features that are recommended for concrete pavements constructed with ACBFS coarse aggregate.

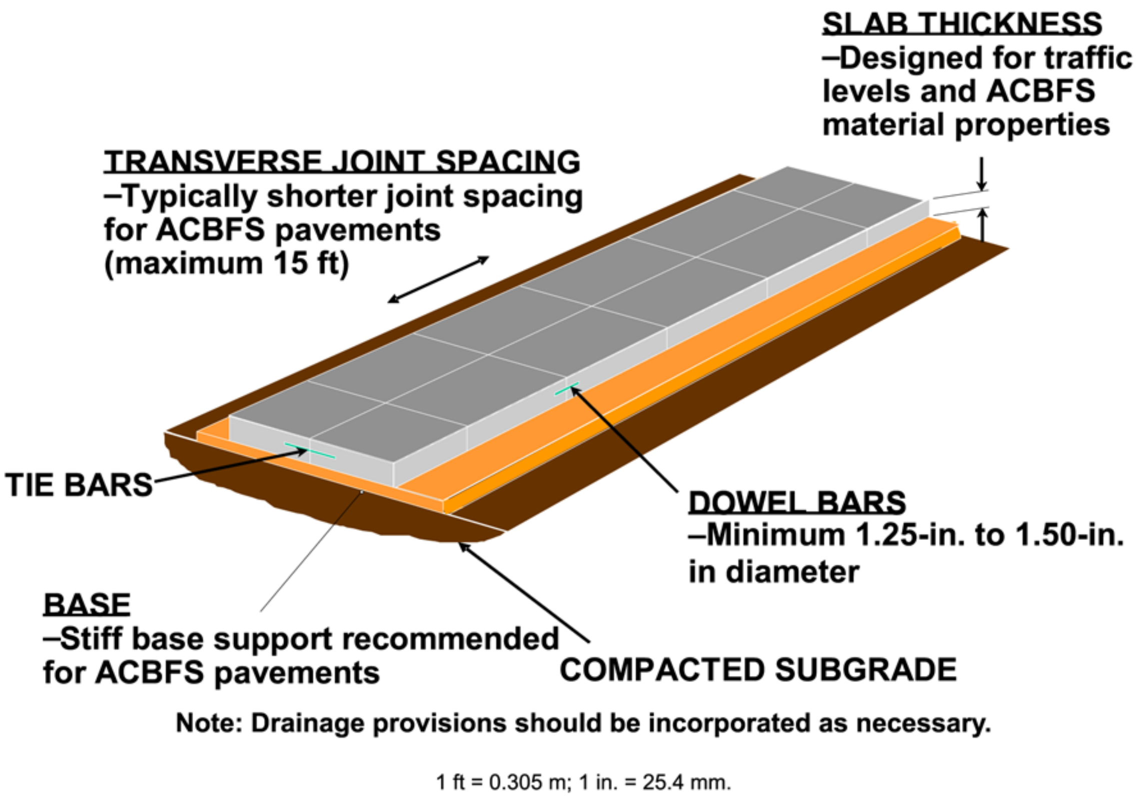

Figure 4. Recommended features for concrete pavements incorporating ACBFS aggregate.

CHAPTER 5. PRODUCTION AND PLACEMENT OF CONCRETE MADE WITH ACBFS

INTRODUCTION

Understanding the properties and characteristics of ACBFS coarse aggregate and accounting for those properties and characteristics during the mixture and pavement design stages are the first steps to effectively using ACBFS in concrete paving. The final step is to ensure that concrete incorporating ACBFS is effectively produced and placed during the construction phase. Although most conventional practices are applicable, this chapter highlights only aspects of concrete production and placement that are unique to the use of ACBFS as a coarse aggregate in paving concrete.

CONCRETE PRODUCTION

Concrete production consists of blending the cement, SCMs if applicable, aggregate, water, and any admixtures. The overall goal in this process is to produce a uniform, consistent concrete suitable for placement, while meeting the production requirements of the project.

When using ACBFS coarse aggregate, conventional concrete production procedures and methods are employed, but special attention must be given to the management of the ACBFS stockpile. As described throughout this document, the higher absorption of ACBFS (and its potentially high variability) can significantly affect the workability and early-age setting behavior of concrete pavements. Thus, it is recommended that ACBFS aggregate should be stockpiled in moist condition at or above SSD condition prior to use; this is accomplished using sprinklers that are set up to provide uniform coverage of the entire stockpile. In many situations, applying a predetermined volume of water on a daily basis can maintain the ACBFS stockpile in a saturated condition, although additional moisture conditioning may be needed to keep the ACBFS aggregate particles wet at the time of concrete batching. This is a particular concern during hot weather conditions. The objective is to achieve a constant moisture level at or above SSD to prevent loss of mix water through absorption into the aggregate.

Routine monitoring of the stockpiled ACBFS aggregate should be performed at least once per day during production, with a general recommended testing frequency of once per 1,000 yd^3 (765 m^3) of ACBFS (Fick 2008). General experience has shown that manual testing methods (AASHTO T 85, *Specific Gravity and Absorption of Coarse Aggregate* (see also ASTM C127), and AASHTO T 255, *Total Moisture Content of Aggregate by Drying* (see also ASTM C566)) are effective in monitoring and maintaining stockpile moisture. Care should also be exercised to ensure that dried ACBFS aggregate is not left in the feed hopper during long periods of nonproduction. If variation in moisture content is present as the aggregate is batched into the concrete, it may be necessary to adjust batch water to maintain a consistent w/cm and ensure concrete consistency from batch to batch.

Similar to conventional aggregates, it is important to minimize segregation in stockpiled ACBFS. The specific gravity is closely linked to the size of individual particles, so as the grading becomes finer, the specific gravity increases (and as the grading becomes more coarse, the specific gravity decreases). Therefore, the aggregate grading has a large impact on the volume of aggregate being proportioned for a given mass, which affects both concrete consistency and yield. As a result, the ACBFS aggregate grading must be closely controlled during batching to ensure proper proportioning. Reducing segregation is achieved by, among other things, minimizing free-fall heights of aggregates, building the stockpile in layers of uniform thickness, minimizing crushing of the aggregate by the loader, and adequately separating adjacent stockpiles from one another (Taylor et al. 2006).

CONCRETE PLACEMENT, CURING, AND JOINT SAWING

Placement

The placement of concrete incorporating ACBFS aggregate follows conventional procedures. The entire cycle of mixing, discharging, transporting, and depositing concrete must be coordinated for the specific mixing plant capacity, hauling equipment, hauling distance, and spreader and paving machine capabilities (Taylor et al. 2006).

Consolidation of the placed concrete is important to achieving good density and eliminating air pockets and honeycombing. The suitable paving rate and associated vibrator frequency should be established early in the construction of the project. If the moisture content is allowed to vary, ACBFS concrete may be more susceptible to honeycombing, an eventuality that must be avoided. If the mix is found to be harsh and difficult to place, construction should be halted and adjustments made to correct the problem.

Curing

Concrete curing describes those activities conducted to maintain moisture and temperature regimes in fresh concrete after paving. Effective curing is essential to the long-term durability and performance of all concrete pavements, and those constructed with ACBFS coarse aggregate are no exception. Poor or improper curing can lead to a number of issues, such as cracking due to drying shrinkage, poor strength gain, and reduced durability.

There is some speculation that the highly absorptive ACBFS aggregate can provide a significant benefit to concrete during the curing process as the abundance of water in the aggregate pores could act as an internal source of cure water, promoting cement hydration beyond the normal curing period (Grove, Bektas, and Gieselman 2006). It should be noted that most work on internal curing is based almost exclusively on the use of porous, lightweight, fine aggregate (and not coarse aggregate), so this potential advantage is only speculative at this time.

Joint Sawing

Timely and effective joint sawing is needed to ensure the proper formation of transverse and longitudinal joints and prevent the development of random cracking. A number of factors influence the joint sawcutting “window,” several of which may make the sawcut timing more critical for concrete pavements constructed with ACBFS aggregate, such as the following (Taylor et al. 2006):

- Concrete mixtures with high water demand.
- Concrete mixtures that exhibit rapid early strength.
- High friction or bond between the concrete slab and the base (such as when a stiff/stabilized base is used).

In essence, the surface condition of the pavement must be continually monitored, and sawing should commence just as soon as possible.

CONSTRUCTION QUALITY CONTROL

Construction QC embodies a variety of activities that are performed by the material suppliers, by the contractor at the concrete plant, and during the paving process to ensure that the desired product is being delivered, and to preempt any potential problems or variations. Generally, conventional concrete pavement QC procedures may be adequate for concrete pavement incorporating ACBFS, but there are several items that should receive special emphasis. These are summarized in table 4.

One QC-related tool that can be useful in predicting the early-age behavior of concrete pavements is the HIPERPAV® (HIgh PERformance Concrete PAVing) software (Xu et al. 2009). This software predicts the development of strength and stresses in the concrete using a set of inputs that consider the pavement design, type of materials used in the concrete, mix design information, construction information (e.g., temperature of concrete, curing method), concrete properties, environmental conditions, and so on. Based on the predicted strength and stresses, the software predicts the risk of random pavement cracking. The user can modify the various input parameters, including mixture design parameters and environmental conditions, to evaluate the effect of strength and stress development on the potential for cracking to occur once the pavement has been placed. Moreover, if a risk of cracking is identified, HIPERPAV can be used to evaluate strategies for preventing cracking.

The most recent version of this software is HIPERPAV® III, which supports several types of coarse aggregates: basalt, granite/gneiss, limestone, sandstone, and siliceous gravel. At this time, a version of the software is under development that incorporates ACBFS, and it should be available within the year.

SUMMARY

This chapter presents important information regarding the construction of concrete pavements incorporating ACBFS coarse aggregate. While most generally accepted practices for concrete paving apply, there are several key areas that require emphasis when using ACBFS, and these are highlighted in this chapter, including critical QC activities.

Table 4. Recommended Quality Control Activities for Concrete Incorporating ACBFS

Responsible Party	QC Activity or Test Method

Blast Furnace Slag Coarse Aggregate Supplier	• Test for iron unsoundness when ferrous oxide >3% and total sulfur $\geq$1% (JIS 2003).
	  – Conduct when a new source is being approved.
	• Monitor sulfur contents of ACBFS.
	  – 2 to 3 times per season.
	  – Limit maximum total sulfur (S) content to 2.0% and maximum percent of acid-soluble sulfates to 0.5 %.
	  – (per ASTM C114, Section 6. HCl digestion)
	• Monitor ACBFS stockpile moisture contents prior to shipping.
	  – Every 1,000 yd^3 (minimum 1 per day).
	• Monitor aggregate grading.
	  – Every 1,000 yd^3 (minimum 1 per day).
	• Test for ACBFS unit weight/specific gravity.
	  – Every 1,000 yd^3 (minimum 1 per day).

Concrete Producer (Paving Contractor)	• Monitor ACBFS stockpile moisture contents.
	  – Every 1,000 yd^3 (minimum 1 per day).
	• Determine aggregate grading.
	  – Every 1,000 yd^3 (minimum 1 per day).
	• Test for ACBFS unit weight/specific gravity.
	  – Every 1,000 yd^3 (minimum 1 per day).
	• Make adjustments during mix proportioning as necessary to maintain mix uniformity.

Paving Contractor	• Use the slump test as a measure of consistency of delivered concrete.
	  – Perform in accordance with ASTM C143.
	  – Test frequency as specified.
	• Determine air content of concrete as delivered.
	  – Use volumetric method (AASHTO T 196 or ASTM C173) and not the pressure method.
	  – Test frequency as specified.
	• Measure unit weight of concrete as delivered.
	  – Perform in accordance with ASTM C138.
	  – Test frequency as specified.
	• Measure temperature of concrete as delivered.
	  – Perform in accordance with ASTM C1064.
	  – Record whenever strength specimens are fabricated or when concrete temperatures are approaching limits (commonly 90 ^oF max and 40 ^oF min).

1 yd^3 = 0.765 m^3. (^oF-32)/1.8=^oC.

CHAPTER 6. SUMMARY

This document presents recommended best practices for using ACBFS coarse aggregate in concrete paving mixtures. 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. Table 5, on the following pages, provides a summary of key points and recommendations for successfully using ACBFS in concrete pavement.

The recommendations presented herein are expected to contribute to improved performance from concrete pavements incorporating ACBFS coarse aggregate. Nevertheless, they are subject to further development and refinement as more definitive long-term studies of ACBFS concrete pavement performance become available. It should be noted that if a State DOT has a pavement management system (PMS) 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 either satisfactory or unsatisfactory* to use ACBFS aggregates in its concrete pavement construction program. Finally, 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.

Table 5. 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 to assist in achieving adequate workability. • Maintain water-to-cementitious materials ratio during concrete batching to maintain mix uniformity, adjusting batch water added 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.
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 the 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 is 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.

Table 5 (continued). Summary of recommendations for incorporating ACBFS into concrete pavements.

Phase of ACBFS Aggregate Use	**Recommended Activities**
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.

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