Engineering and Design Considerations for Steel Furnace Slag Aggregates in Concrete Pavements

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Abstract

The use of steel furnace slag (SFS) aggregates is limited in the United States and abroad, primarily because of the inherent expansion potential of the material, which results from the hydration of the free calcium and magnesium oxides present from the slagging process. When used in concrete, the literature presents contradictory findings, such as that the strength can increase or decrease with the addition of SFS aggregates. Microstructural investigations of the SFS aggregates as well as the interfacial transition zone (ITZ) in mortars revealed that the mechanical properties are strongly dependent on the SFS type and source. Certain SFS types can develop with a porous interior and/or a porous outer layer of different composition, both of which act as weaknesses in the bulk concrete. Depending on the SFS type, the ITZ may also be more porous, which can lead to further weakening of the concrete. Given the potential deleterious expansion of SFS, there are rapid screening protocols, which can quantify both the free lime content (complexometric titration) and expansion potential (autoclave index test) of the SFS. While the literature currently presents limits for the SFS to be used as a base material, no limits are defined for the use of SFS in bound applications, despite the fact that low expansion SFS aggregates are being used in several countries for certain applications.

Keywords: steel furnace slag, SFS, reclaimed asphalt pavement, RAP, expansion, autoclave expansion, mineralogy, basic oxygen furnace slag, BOF, electric arc furnace slag, EAF, free lime, free CaO

Introduction

Steel furnace slag (SFS) is an industrial by-product of the steel industry, commonly found in the United States as a product of basic oxygen furnace (BOF) or electric arc furnace (EAF) processes. In general, SFS are characterized as a hard, durable aggregate with exceptional friction qualities and thus, SFS aggregates are often used as aggregates in hot-mix asphalt (HMA) pavements (FHWA 1998), though it has also seen application as fill or railroad ballast and for snow and ice control (Collins and

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Ciesielski 1994). Rehabilitation and reconstruction projects are therefore producing a quantity of SFS reclaimed asphalt pavement (SFS RAP).

During production of SFS, the addition of fluxing agents (often calcite or dolomite) results in the formation of unassimilated free calcium oxide (CaO) and free magnesium oxide (MgO). The free CaO content can be on the order of 1-10% for BOF slags and 0-4% for EAF slags (Balcázar et al. 1999). The presence of free CaO and free MgO is problematic as these phases will react with water to form hydroxide phases; the formation of calcium hydroxide [$Ca(OH)_2$] and magnesium hydroxide [$Mg(OH)_2$] result in a volumetric expansions of 91.7% and119.6%, respectively (Erlin and Jana 2003). The resulting magnitude of expansion for unbound SFS aggregates can be upwards of 10% (Emery 1982). Because of this potential for deleterious expansion, SFS aggregates are not typically utilized in stabilized or bound applications, such as cement-treated bases or portland cement concrete.

The objective of this paper is to summarize the engineering and design considerations for using virgin SFS (or SFS RAP) aggregates in concrete pavements. A more rapid testing and aggregate screening protocol is suggested based on recent studies. The significance of this paper is to provide engineers, contractors, and material suppliers with the a summary of the effects of SFS on concrete properties, how SFS can be rapidly tested and screened, and how SFS aggregates can be effectively utilized in concrete pavement applications.

Literature Review

A summary of the effect of SFS aggregates on the concrete properties is shown in Table 1. The effect on concrete properties is somewhat variable, such as either increasing or decreasing the strength, modulus, and drying shrinkage. However, the majority of studies suggest that SFS aggregates can increase the concrete strength and modulus (Figure 1) with favorable effects on the concrete fracture properties, abrasion resistance, and freeze/thaw durability. Overall, the literature suggests that the addition of SFS aggregates to concrete can have favorable mechanical performance results.

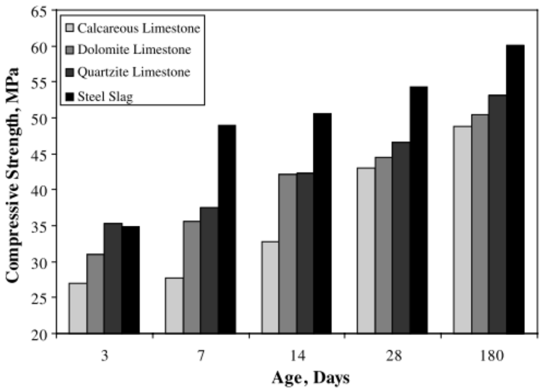
Despite the expansive nature of SFS aggregates, the literature has indicated suitable freeze/thaw resistance. Brand and Roesler (2015) found durability factors of 100% for mixtures with 100% BOF (3.4% free CaO) or EAF (0.1% free CaO) slag coarse aggregates in concrete after 300 freeze/thaw cycles. Similarly, Obratil et al. (2009) found durability factors of 100%, 96%, 76%, 100%, and 87% for concrete mixtures with 0%, 25%, 50%, 75%, and 100% replacements of aggregate with SFS, respectively, after 300 freeze/thaw cycles.

Table 1. Effect of SFS Aggregates on the Properties of Concrete Relative to Virgin Concrete

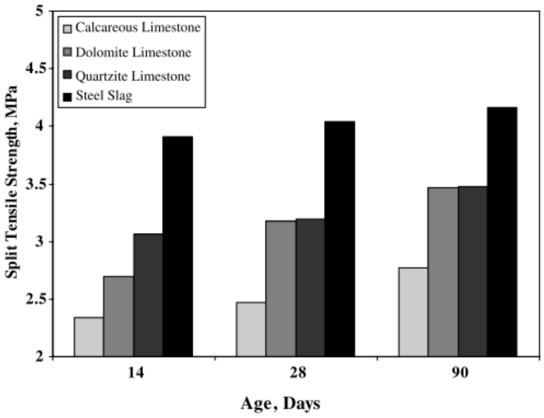
Property	*Effect Relative to Virgin Concrete*	*References*
Compressive Strength	Increase	(Sersale et al. 1986, Wang 1988, 1992, Akinmusuru 1991, Montgomery and Wang 1991, Madej et al. 1996, Vázquezramonich and Barra 2001, De Schutter et al. 2002, Maslehuddin et al. 2003, Alizadeh et al. 2003, Beshr et al. 2003, Almusallam et al. 2004, Mohammed et al. 2009, Pellegrino and Gaddo 2009, Qasrawi et al. 2009, Etxeberria et al. 2010, Papayianni and Anastasiou 2010a, 2011, Coppola et al. 2010, Liu et al. 2011, Qasrawi 2012, 2014, Adégoloyé et al. 2013, Pellegrino and Faleschini 2013, Pellegrino et al. 2013, San-José et al. 2014, Tarawneh et al. 2014, Anastasiou et al. 2014, Pang et al. 2015, Arribas et al. 2015, Brand and Roesler 2015, 2016a)
	Decrease	(Kawamura et al. 1983, Manso et al. 2004, Netinger et al. 2011, Ameri et al. 2012, Mathew et al. 2013, Brand and Roesler 2015, 2016a)
	Similar	(Al-Negheimish et al. 1997, Maslehuddin et al. 1999, Manso et al. 2006, Obratil et al. 2009, Tomasiello and Felitti 2010, González-Ortega et al. 2014)
Split Tensile Strength	Increase	(Montgomery and Wang 1991, Al-Negheimish et al. 1997, De Schutter et al. 2002, Alizadeh et al. 2003, Beshr et al. 2003, Almusallam et al. 2004, Pellegrino and Gaddo 2009, Papayianni and Anastasiou 2011, Coppola et al. 2010, Papayianni and Anastasiou 2010a, Qasrawi 2012, Pellegrino and Faleschini 2013, Pellegrino et al. 2013, Anastasiou et al. 2014, Brand and Roesler 2016a)
	Decrease	(Maslehuddin et al. 2003, Etxeberria et al. 2010, Mathew et al. 2013, Brand and Roesler 2015, 2016a)
	Similar	(Alizadeh et al. 2003, Obratil et al. 2009, San-José et al. 2014)
Flexural Strength	Increase	(Wang 1988, Montgomery and Wang 1991, Al-Negheimish et al. 1997, De Schutter et al. 2002, Alizadeh et al. 2003, Qasrawi et al. 2009, Mohammed et al. 2009, Coppola et al. 2010, Papayianni and Anastasiou 2010a, 2011, Ameri et al. 2012, Qasrawi 2014, Anastasiou et al. 2014)
	Decrease	(Maslehuddin et al. 1999, 2003, Liu et al. 2011, Netinger et al. 2011, Mathew et al. 2013)
	Similar	(Obratil et al. 2009)
Modulus of Elasticity	Increase	(Montgomery and Wang 1991, Al-Negheimish et al. 1997, Alizadeh et al. 2003, Beshr et al. 2003, Almusallam et al. 2004, Pellegrino and Gaddo 2009, Coppola et al. 2010, Papayianni and Anastasiou 2011, Pellegrino et al. 2013, Pellegrino and Faleschini 2013, Qasrawi 2014, Anastasiou et al. 2014, González-Ortega et al. 2014)
	Decrease	(Netinger et al. 2011)
	Similar	(Etxeberria et al. 2010, San-José et al. 2014, Arribas et al. 2015)
Dynamic Modulus	Increase	(Madej et al. 1996, Adégoloyé et al. 2013, Brand and Roesler 2016a)
Stress Intensity Factor	Increase	(Montgomery and Wang 1992, Brand and Roesler 2015)
Total Fracture Energy	Increase	(Papayianni and Anastasiou 2010a, Brand and Roesler 2015)

Table 1 (continued). Effect of SFS Aggregates on the Properties of Concrete Relative to Virgin Concrete

Drying Shrinkage	Increase	(Coppola et al. 2010, Brand and Roesler 2015)
	Similar	(Netinger et al. 2011)
	Decrease	(Madej et al. 1996, Al-Negheimish et al. 1997, Liu et al. 2011)
Freeze/Thaw Durability	Acceptable	(Obratil et al. 2009, Papayianni and Anastasiou 2010a, Brand and Roesler 2015)
	Decrease in Strength	(Manso et al. 2006, Pellegrino and Gaddo 2009)
	Increase in Strength	(Pellegrino et al. 2013)
Abrasion Resistance	Improved	(Sersale et al. 1986, Papayianni and Anastasiou 2003, 2010a, 2011)
Water Penetration	Increase	(Manso et al. 2004, 2006, Anastasiou et al. 2014)
	Similar	(Papayianni and Anastasiou 2010a)
	Decrease	(Pacheco et al. 2010, San-José et al. 2014)
Sulfate Attack Resistance	Similar	(De Schutter et al. 2002, Ali et al. 2011)
Alkali-Aggregate Reactivity	Low Reactivity	(De Schutter et al. 2002, Manso et al. 2006)
Chloride Penetration Resistance	Increase	(Anastasiou et al. 2014)



(a)



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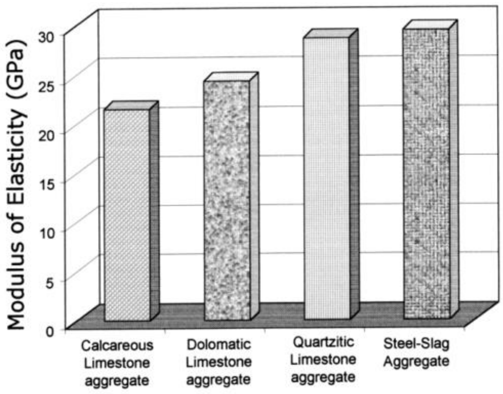


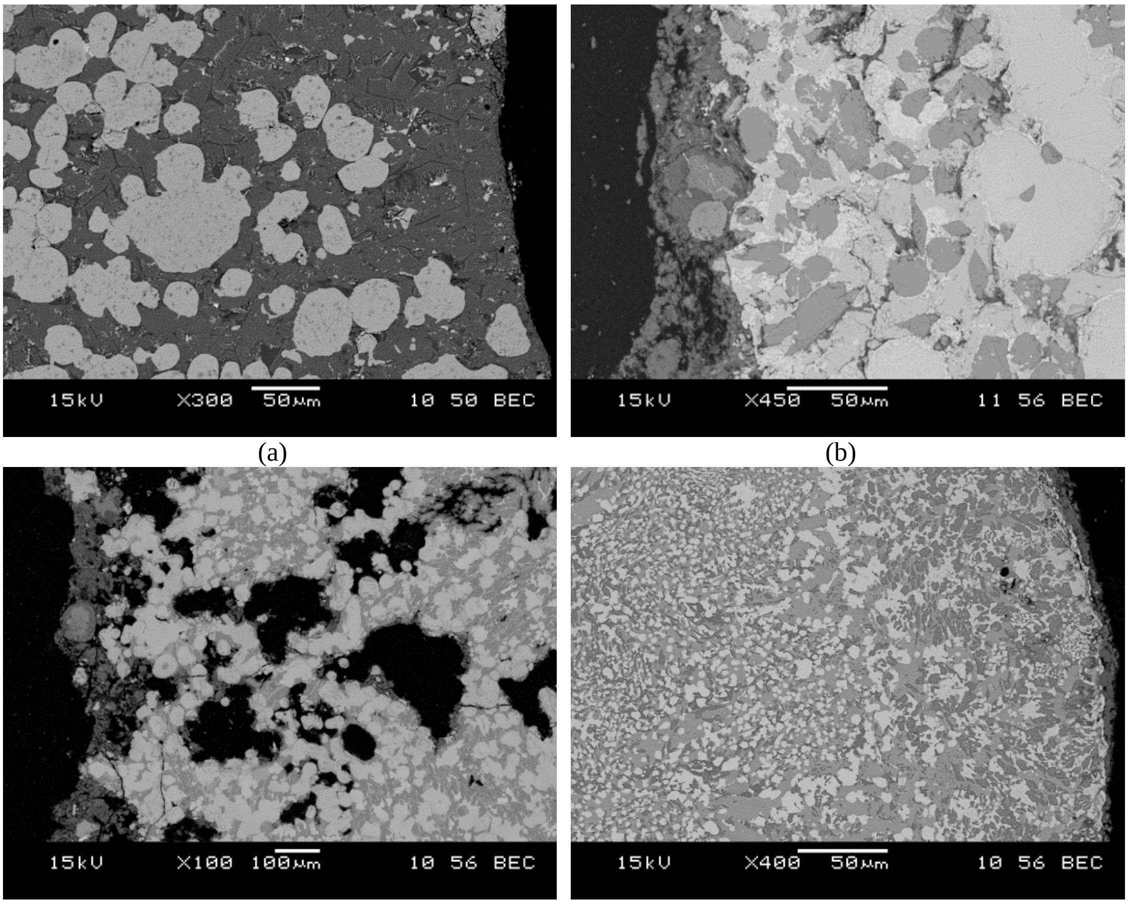
(c)

Figure 1. The effect of SFS aggregate on the compressive (a) and split tensile (b) strengths and modulus of elasticity (c) of concrete relative to limestone aggregate. Source: Beshr et al. (2003) and Almusallam et al. (2004)

Microstructural Properties

Given that the literature had shown that the use of SFS aggregates can either increase or decrease the concrete hardened properties, Brand and Roesler (2016a) undertook a study to evaluate the interfacial transition zone (ITZ) and microstructure of mortar with SFS aggregates from different sources, including basic oxygen furnace (BOF), electric arc furnace (EAF), EAF/ladle metallurgy furnace (EAF/LMF). The study found that the mortar ITZ does vary, depending on the SFS type, particularly as a result of the changes in the microstructure of the SFS (Figure 2). Specifically, BOF slag has been shown to develop an exterior composition different from the interior (Coomarasamy and Walzak 1995, Brand and Roesler 2016a), and this exterior layer was found to be more porous and range in thickness from zero to ~1 mm. The EAF/LMF slag was also shown to exhibit the outer layer of different composition, but was also found to have interior sections of high porosity (Brand and Roesler 2016a). The outer layer composition is postulated to be calcium carbonate and/or other reaction products (Kawamura et al. 1983, Coomarasamy and Walzak 1995, Pang et al. 2015), likely to be another "weak link" in the resultant mortar or concrete, essentially being considered a second ITZ. In contrast, EAF slag was not found to exhibit an outer layer of different composition (Arribas et al. 2015, Brand and Roesler 2016a).

The strength of mortars with the different SFS aggregates is shown in Table 2, demonstrating that SFS aggregates can result in a statistically relevant increase in strength. Additionally, the ITZ composition in mortar with the different SFS aggregates is shown in Figure 3. In general, the ITZ properties were similar between mortars with and without SFS aggregates, with the exception of porosity. The BOF slag ITZ was found to be the most porous, followed by the EAF/LMF slag ITZ, and finally, the ITZs of dolomite and EAF slag were similar. The mean mortar strength was the lowest for the BOF slag, which had the highest ITZ porosity and a more porous SFS outer layer. In contrast, the EAF slag microstructure, which was the most uniform and least porous, had the greatest mortar strength and similar porosity to dolomite aggregate. Based on these findings, the SFS type and composition can greatly affect the concrete properties, primarily as a result of the ITZ composition and the SFS interior and outer microstructure and composition.



(c) (d)

Figure 2. Compositional BSE micrographs of the edge (exterior) of (a) EAF slag, (b) BOF slag, and (c-d) EAF/LMF slag aggregate particles (Brand and Roesler 2016a). The BOF and EAF/LMF slags (b-d) were found to have an outer layer of different composition from the interior of the particle. However, sections of EAF/LMF slag can be more porous (c) than other sections (d). The black colored phases are the epoxy and porosity, the white colored phases contain heavier elements (e.g., iron-containing phases), and the grey colored phases indicate the silicon-containing phases (e.g., larnite).

Table 2. 28-Day Strength of Mortars with SFS Aggregates (Brand and Roesler 2016a)

Mix	Split Tensile Strength (psi)		Compressive Strength (psi)	
	Average	Standard Deviation	Average	Standard Deviation
Control (Dolomite)	647.2	59.0	5960.9	317.1
BOF Slag	617.1	97.0	5587.4	157.2
EAF Slag	737.6	88.4	7229.9*	314.7
EAF/LMF Slag	740.1	44.8	6236.8	619.0

*Means are statistically different from the control (95% confidence)

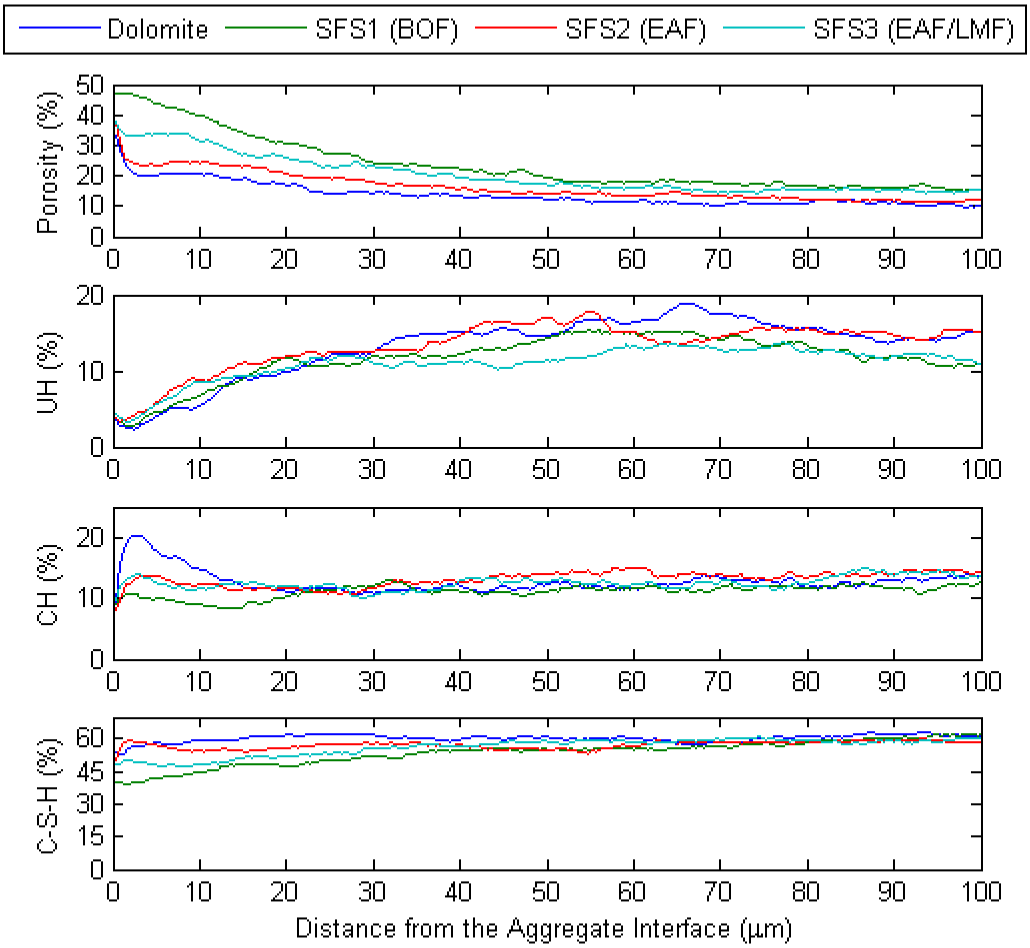


Figure 3. Detectable porosity, unhydrated cement (UH), and calcium hydroxide (CH) and estimated calcium silicate hydrate (C-S-H) at 28 days for mortars with dolomite and SFS (Brand and Roesler 2016a). Note: for additional information and details on how the ITZ composition was determined, see Brand (2015) and Brand and Roesler (2016b, 2016c).

Rapid Test Methods and Screening Protocol

The expansion limits for unbound SFS aggregates are commonly dictated by the results of ASTM D4792, which can take multiple weeks to complete. Brand and Roesler (2015, 2016d) proposed a suite of tests for the rapid testing and screening of SFS and SFS RAP sources, which included tests for mineralogy and composition, free CaO content, and an index test for potential expansion.

Mineralogy. Powder x-ray diffraction (XRD) can provide details about the mineralogical composition of the SFS. If the free CaO content is high enough, it may be detected by XRD, allowing for determination of the total free CaO content by quantitative XRD (e.g., Rietveld analysis), although the XRD patterns for SFS are often very noisy because of the multiple peaks for larnite (β-dicalcium silicate). Therefore, the best method for free CaO determination is by complexometric titration discussed below. XRD will provide additional details about the type of SFS, as certain phases are specific to the SFS type; for example, a review of the literature revealed that srebrodolskite (dicalcium ferrite) is primarily found in BOF slags while gehlenite and merwinite are specific to EAF slags (Brand and Roesler 2014). Finally, XRD can also identify possible phases that formed upon reaction of the free oxides, such as $Ca(OH)_2$, $Mg(OH)_2$, $CaCO_3$, etc.

Free CaO Content. The free CaO content is a critical value to know for a given SFS source or stockpile because CaO will react quickly with water to expand and thus, the free CaO content provides a comparative metric for expansion potential. The free CaO content of SFS can be determined with the use of complexometric titration by ethylene glycol extraction. Ethylene glycol complexes with both free CaO and $Ca(OH)_2$, so the value needs to be refined by determining the approximate $Ca(OH)_2$ content through thermal analysis (e.g., thermogravimetry) (Thomas 1983, Kneller et al. 1994, Gumieri et al. 2004, Lun et al. 2008, Waligora et al. 2010, Papayianni and Anastasiou 2011, Belhadj et al. 2012, Brand and Roesler 2015). Some recommended applications for SFS are based on the free CaO content; for example, Verhasselt and Choquet (1989) recommended that SFS could be used in an unbound base or subbase if the free CaO content is <4.5%.

The suggested testing procedure recommends that about one gram of powdered SFS is stirred in 50 mL of hot 95-100°C (203-212°F) ethylene glycol for 30 minutes. The free CaO and $Ca(OH)_2$ in the SFS forms a complex with ethylene glycol, which changes the pH of the solution, as is detected by adding a few drops of phenolphthalein indicator. Titration with hydrochloric acid (HCl) is then used to evaluate the ethylene glycol number (EGN), see Equation 1, which represents the total CaO from free CaO and $Ca(OH)_2$. The EGN is determined as a function of initial mass (m, in grams) of the powdered sample, the normality of the HCl (N_{HCl}), the volume in mL of the HCl consumed during titration (V_{HCl}), the correction for the volume (in mL) of HCl titrated in a blank ethylene glycol sample (V_{blank}), and an equivalency factor (F). The equivalency factor F for this method and equation formulation is 28 (Javellana and Jawed 1982).

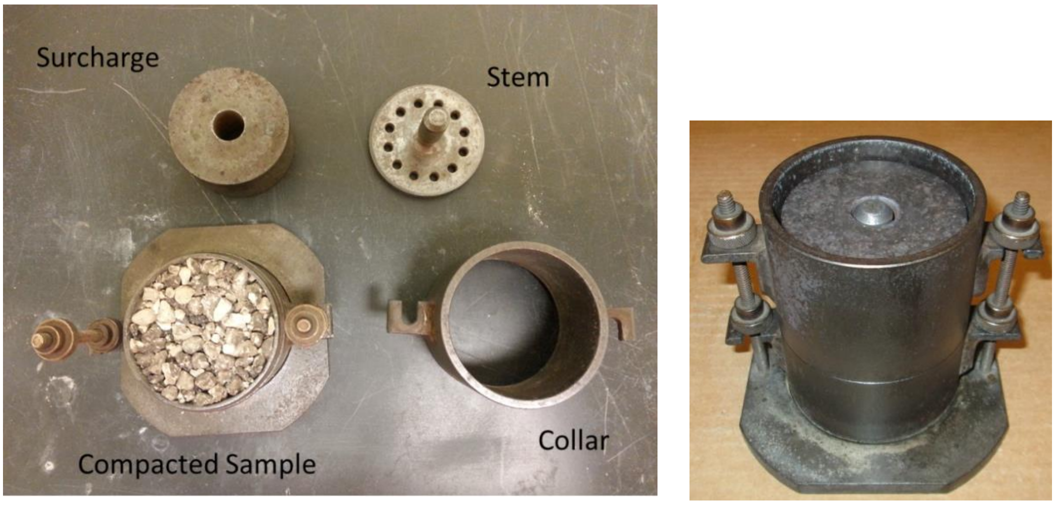
$$EGN = F\left[\frac{N_{HCl}(V_{HCl} - V_{blank})}{10\, m}\right] \qquad (1)$$

From thermal analysis, such as thermogravimetry, the stoichiometric amount of CaO in the $Ca(OH)_2$ present in the SFS sample is subtracted from the EGN value to refine the total free CaO estimate, as exampled in Table 3.

Table 3. Estimated Total Free CaO Content in SFS Aggregate (Brand and Roesler 2015)

Sample	EGN Value from Titration	$Ca(OH)_2$ Content from TGA	Stoichiometric CaO Content in $Ca(OH)_2$	Estimated Free CaO Content
BOF	4.4%	1.3%	1.0%	3.4%
EAF	0.1%	0.0%	0.0%	0.1%
EAF/LMF	0.5%	0.2%	0.1%	0.4%

Expansion Test. A rapid expansion test can be conducted with an autoclave. This test measures the linear (vertical) expansion of a compacted aggregate sample (Figure 4) subjected to steam at 300 psi (2.1 MPa) and 420°F (216°C) for three hours and has been shown to be a viable test for the expansion of compacted samples of virgin SFS and SFS RAP aggregates (Brand and Roesler 2015, 2016d). The test may react (hydrate) all of the available free oxides, allowing for the backcalculation of the initial free MgO content (Brand and Roesler 2015). While further testing and characterization is required, the autoclave expansion limits proposed by Edw. C. Levy Co. are the following: 0-5%, suitable for pavement base applications; 5-10%, marginal material, additional weathering necessary; ≥10%, reject material, not for use in confined applications.



(a) (b)

Figure 4. Components (a) and completed assembly (b) of the autoclave expansion mold (Brand and Roesler 2015).

Protocol Discussion. Utilizing these various testing protocols, which takes one to two days to complete, engineers can rapidly screen a given stockpile for use in bound or unbound applications. However, there are still no acceptable limits set or standards for autoclave expansion and free CaO or MgO contents. At present, SFS RAP is an excellent candidate for use in unbound base applications, given that the presence of the asphalt coating greatly reduces the expansion (Senior et al. 1994, Deniz et al. 2010, Dayioglu et al. 2014, Brand and Roesler 2016d), and the autoclave expansion test can be used on samples with and without the asphalt coating to evaluate the current and potential long-term expansions.

Field Studies of SFS Aggregates in Concrete

Given the expansive nature of SFS aggregates, the literature contains a number of case studies of successes and failures. As of a 2009 survey, the applications of SFS aggregates in the United States is limited, with allowable usages in hot-mix asphalt (13 states), in non-structural pavement surface treatments (4 states), as embankment material (3 states), and in concrete pavements (2 states) (NCHRP 2013).

Understandably, engineers are hesitant to use SFS aggregates in concrete and other bound applications for future liability of the expansive potential, but Geiseler (1996) presented that, through careful material characterization, certain SFS aggregates can be used in Austria in concrete pavements and concrete floors.

In the United States, early failures with SFS aggregates halted further usage in concrete and other bound applications. These failures occurred when SFS aggregates were used in econocrete on I-75 in Tampa, Florida, and at the Tampa International Airport (Armaghani et al. 1988, Bosela et al. 2012); crack openings of up to two inches were reported as a result of the SFS expansion. Miller and Collins (1976) reported a failure in Pennsylvania when the open hearth furnace slag aggregate expanded that was used in cement-treated base and in subbase applications. In both cases, it is unclear if screening protocols were used prior to construction to measure the risk of expansion.

Despite these reported failures, a number of successful case studies have been reported in Europe. In Greece, a concrete pavement test section that contained EAF slag aggregates was surveyed after 10 years in service and indicated comparable to better performance to the control section (Papayianni and Anastasiou 2010b). An experimental self-consolidating concrete test section with EAF slag fine aggregates has also been constructed in Greece (Lykoudis and Liapis 2010). Stainless steel EAF slag aggregates have been used in Belgium in roller-compacted concrete and cement-treated base applications (De Bock and Van den Bergh 2004). A cement-stabilized base test section has been constructed in Spain using EAF slag aggregates (Vázquez et al. 2010).

Other successful uses of SFS aggregates in concrete have been reported in Europe. In the United Kingdom, BOF slag aggregates have been used in armour stones for sea defense barriers, with no distresses reported after 18 months of wetting/drying cycles in the field (Dunster 2002). In Madrid, Spain, the Labein-Tecnalia Kubik Building was constructed with the basement wall and floor slab concrete containing 100% coarse and fine EAF slag aggregate and the foundation walls and slab concrete containing up to 75% EAF slag aggregate (of the total aggregate) (Arribas et al. 2010).

In unbound applications, case studies of SFS aggregates have reported successes and failures as well. An Australian pavement test section with a BOF slag aggregate base indicated no expansion after two years (Heaton 1989). Additional Australian test sections have used blast furnace slag as a cementitious binder along with SFS aggregates (Heaton 1993, 1996, Heaton *et al.* 1996). Base test sections have also been constructed in the United Kingdom and Germany (Thomas 1983, Motz and Geiseler 2000). However, a number of case studies have also highlighted failures when expansive SFS aggregates were used as backfill (Crawford and Burn 1969, 1971, Bailey and Reitz 1970, Gnaedinger and Gnaedinger 1970, Gray and Salver 1970, Ritchie 1970, Spanovich and Fewell 1970, Gnaedinger 1987, Glass 2003, da Silveira et al. 2005).

Discussion of Design Considerations

It is a fact that failures have occurred when SFS aggregates have been used in unbound or bound applications with many not screening the aggregates for deleterious expansion. However, the literature equally supports that, when properly designed, certain SFS aggregates can be utilized and achieve the expected performance. Given that the yearly world output of SFS is on the order of 150-230 million tons (van Oss 2013), this by-product material should be more effectively utilized in infrastructure applications with the proper testing protocols. While the SFS aggregate expansion can be high – up to 10% (Emery 1982) – not all SFS types and sources are highly expansive or contain high free CaO contents. While BOF slag can contain 1-10% free CaO, EAF slag can contain 0-4% free CaO (Balcázar et al. 1999). Brand and Roesler (2015, 2016a) studied one EAF slag source that contained low free CaO and MgO contents at 0.1% and 0.2%, respectively, exhibited relatively low autoclave expansion at 0.1%, and demonstrated superior mechanical and fracture properties as well as good freeze/thaw durability.

Through material characterization and screening, it is possible to identify stockpiles or specific sources of SFS aggregate that would be suitable for use in concrete. The proposed rapid screening protocol from the literature recommends mineralogical characterization by x-ray diffraction, free CaO content determination by complexometric titration and thermal analysis, and expansion potential by the autoclave index test. Additional evaluation of the SFS microstructure can be conducted using compositional backscattered electron microscopy of polished cross-sections, which can identify the SFS stockpiles or sources whose particles have a porous outer layer of different composition that may act as another "weak link" in the concrete microstructure. Still, further research is required to evaluate the long-term expansion of concrete with SFS aggregates, particularly with regard to developing acceptable limits for the free CaO and MgO contents.

Assuming that a suitable, low expansion SFS aggregate source is identified, there is, as of yet, no concrete pavement design methodology in place. Based on the suitable to superior fracture properties obtained in concretes with SFS aggregates, it is possible that the flexural capacity of concrete slabs with SFS aggregates will be at least similar, if not better than, concrete slabs with virgin aggregates, based on the findings by Brand et al. (2014). Based on the increased strength, modulus, and fracture properties when certain SFS aggregates are used, it may be even possible to design a thinner concrete slab.

Summary

Steel furnace slag (SFS), an industrial by-product of steel manufacture, is often overlooked as a candidate aggregate for cement-based composites, primarily because of its inherent expansion potential as a result of containing free calcium and magnesium oxides, which expand when hydrated. However, with the prospect of low expansion SFS aggregate sources, its use as an aggregate in concrete is quite viable, especially since SFS aggregates are often shown to increase the concrete strength, modulus, and fracture properties while retaining suitable freeze/thaw durability.

A number of SFS types are available, which can dramatically impact the concrete properties and performance. Certain SFS types can form with areas of interior porosity and/or develop an outer layer of different composition that may be more porous, both of which can act as weaknesses in the concrete microstructure. In general, electric arc furnace (EAF) slag has been shown to contain low free oxide contents (i.e., exhibit low expansion potential) and give the most favorable microstructure for concrete materials in terms of ITZ properties and aggregate microstructure. As expected then, EAF aggregates have resulted in statistical increases in the concrete mechanical and fracture properties.

To evaluate the suitability of a given SFS stockpile or source, a suite of tests, including mineralogical composition by x-ray diffraction, free CaO content determination by complexometric titration and thermal analysis, and expansion potential by the autoclave index test should be conducted. While further research is necessary to more conclusively define the limits on free CaO or autoclave expansion such that the SFS aggregate could be used in bound applications, the current proposed limits from the literature for free CaO content and autoclave expansion to use as an unbound base material are ≤4.5% and ≤5%, respectively.

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