

USER GUIDELINE FOR FOUNDRY SAND IN GREEN INFRASTRUCTURE CONSTRUCTION

by

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INTRODUCTION

Foundry sand is high-quality uniform silica sand that is used to make molds and cores for ferrous and nonferrous metal castings. The metal casting industry annually uses an estimated 100 million tons of foundry sand for production. Over time, foundry sands physically degrade until they are no longer suitable for molds. Consequently, 9 to 10 million tons of sand is discarded each year. However, the discarded foundry sands have remarkably consistent composition and are typically considered a higher quality material than typical bank run or natural sands used in construction. Currently, an estimated 28% of discarded sand is reused in primarily construction-related applications, while the remaining sand is disposed of in landfills (American Foundry Society 2007). Recycling of foundry sand can save energy, reduce the need to mine virgin materials, and may reduce costs for both producers and end users. Use of foundry sand as a fine aggregate in construction applications offers project managers the ability to enhance green sustainable construction by reducing their carbon footprint, while also qualifying for LEED credits. The USEPA recently estimated that at the current recycling level 20,000 tons of CO₂ emissions are prevented while 200 billion BTUs of energy are saved. Support for increased reuse of foundry sand has brought together the USEPA, the Federal Highway Administration, the US Department of Agriculture, the Recycled Materials Resource Center (RMRC), state environmental agencies, the foundry industry and end users to develop the tools and resources needed to increase foundry sand recycling to 50% by 2015.

This paper provides a comprehensive overview of the engineering and construction properties of foundry sand for use in Portland cement and concrete, hot mix asphalt, road subbase layers, embankments, and flowable fill. Recent studies addressing environmental concerns of using foundry sand, an industrial by-product, as a construction material are reviewed. Some case studies are presented to demonstrate successful applications of foundry sand. With the goal of advancing use of foundry sand in construction application, references to resources and tools, such as web-based training and a foundry locator map module, are made available.

GENERAL FOUNDRY SAND PROPERTIES

Foundry sands consist of green sand and resin sand. Green sands typically comprise of high-quality silica sand, 5-10 percent bentonite clay, 2 to 5 percent water and less than 5 percent sea coal. The green sand process constitutes upwards of 90 percent of the molding materials used. Resin sands are high-quality silica sand usually held together with organic binder in conjunction with catalysts and different hardening/setting procedures. Resin sands are most often used for "cores" that produce cavities that are not practical to produce by green sand molding operations, primarily due to strength issues.

Physical Properties

Physical properties for foundry sand from green sand systems are listed in Table 1. The grain size distribution of most foundry sand is very uniform, with approximately 85 to 95 percent of the material between 0.6 mm and 0.15 mm (No. 30 and No. 100) sieve sizes. Five to 12 percent of foundry sand can be expected to be smaller than 0.075 mm (No. 200 sieve). The particle shape is typically subangular to rounded.

Foundry sand has low absorption, although reported values of absorption were found to vary widely, which can be attributed to the presence of binders and additives (Javed and Lovell 1994ab). The content of organic impurities (particularly from sea coal binder systems) can vary widely (Emery 1993). The specific gravity of foundry sand has been found to vary from 2.39 to 2.70. This variability has been attributed to the amount of fines and additive contents in different samples (Federal Highway Administration 2004, Javed and Lovell 1994ab).

In general, foundry sands are dry, with moisture contents less than 2 percent. Clay lumps and friable particles are sometimes associated with the molded sand, and are easily broken up. The variation in hydraulic conductivity (Table 1) is a direct result of the fraction of fines in different foundry sands.

Mechanical Properties

Typical mechanical properties of foundry sand are listed in Table 3. Foundry sand has good durability characteristics as measured by low Micro-Deval abrasion (Ontario Ministry of Transportation, 1996) and magnesium sulfate soundness loss tests (ASTM C88-05). Studies have reported relatively high soundness loss, which is attributed to samples of bound sand loss and not a breakdown of individual sand particles. The internal friction angle of foundry sand has been reported to be in the range of 33 to 40 degrees, which is comparable to that of conventional sands (Javel and Lovell, 1994).

Mineralogical and Chemical Properties

Foundry sand consists primarily of silica sand (>80% silicon dioxide), coated with a thin film of burnt carbon and residual binder (Du et al 2002). Loss on ignition in foundry sand has been reported by the American Foundrymen's Association (1991) to be around 5%.

Depending on the binder and type of metal being cast, the pH of foundry sand can vary from approximately 4 to 12 (Johnson, 1981, Emery 1992, Bhand and Lovell 1996, Dayton et al 2010). A pH of 5.5 or less in soil is considered a corrosive condition.

Environmental Considerations

Characterization of foundry sand: Foundry sand often contains trace metals and core material containing partially degraded binder. Foundry sand may contain trace amounts of leachable metals and phenols. As part of the national program to increase the utilization of non-hazardous industrial byproducts, the EPA undertook an extensive literature and data review on the environmental characteristics of foundry sand. In April of 2007, the EPA issued its first national foundry sand statement,

endorsing the use of foundry sand in bound and many unbound applications (EPA 2007).

Many studies have been conducted to characterize the constituents found in foundry sand. The metal type poured can significantly affect metal constituent levels. Foundry sand from brass or bronze foundries may contain high concentrations of metals including cadmium, lead, copper, nickel, and zinc (Javed and Lovell 1994ab). Therefore, unlike sands from ferrous and aluminum foundries, these sands are not typically well suited, nor are they designated for beneficial use in most applications. A study of 43 foundry sands from aluminum, iron, and steel foundries found the total metals concentration in the sand to be similar to the levels found in agricultural soil (Dungan and Dees 2007).

The resin binder system is the primary source of organic constituents in foundry sand. Green sand systems have been shown to have lower potential for leaching organic compounds. The primary organic constituents from foundry sand are acetone and 1,1,1-trichloroethane (EPA 2002a). Tikalski et al (2004) found that most organic compounds are burned out during the casting process. Studies have shown that foundry sands contain polyaromatic hydrocarbons (PAHs) and phenolic compounds (Ji et al 2001, Dungan 2006, Stehouwer et al. 2010). However, the majority of the foundry sands analyzed contained PAHs and phenolics below threshold levels established in state beneficial use regulations.

Evaluation of leaching: Multiple studies have concluded that constituents in leachate from most iron, steel, and aluminum foundry sands fall well below the regulatory limits for determining a hazardous waste (Fox and Mast 1997, Tikalsky et al 2004, Wang and Vipulanandan 2000, Dungan and Dees 2007). Sands from some leaded copper-base facilities, however, may be considered a hazardous waste under EPA rules due to metal content.

Examinations of the environmental effects of ferrous foundry sand have shown that foundry sand did not cause groundwater or surface water contamination and that the measured concentrations were below the U.S. EPA drinking water limits (Lovejoy et al 1996, Naik and Singh 2001, Guney et al 2006, Lee and Benson 2006). Several foundry sand leachate characterization studies suggest that foundry sand is generally safe to reuse in highway applications (Boyle and Ham 1979, Han and Boyle 1981, Ham et al 1993a, Ham et al 1993b).

A study on concentrations of metals in leachate beneath a foundry sand test plot found concentrations comparable to natural soils (Freber 1996). Dungan and Dees (2007) found that waste molding sands have a low metal leaching potential using SPLP and ASTM extraction tests with results falling below the national drinking water standards.

Leaching of metals from flowable fill is a long process due to the low permeability of the material. A study performed by Naik and Singh (2001) showed that

concentrations of iron, barium, magnesium, zinc, arsenic, chromium, lead, selenium, cadmium, mercury and chloride in leachate extracted from flowable fill materials containing up to 85% foundry sand were below the enforcement standards of the Wisconsin Department of Natural Resources ground-water quality standards and also met practically all the parameters of the drinking water standards

However, Lee and Benson (2002) and Coz et al (2004) had found leaching concentrations of zinc, lead, chromium, and iron in foundry sand to be above the U.S. EPA drinking water limits, although the difference was within 10 percent. Lee and Benson (2006) conducted water leach tests on 12 green sands from iron casting foundries. Concentrations of constituents of concern barely exceeded Wisconsin's maximum permissible concentrations. Similar concentrations are observed in reactive medium barrier material that is commonly placed below the groundwater table for remediation of contaminant plumes. Sauer et al (2005) performed a laboratory batch water leach test, column leach test, and below subbase lysimeter study to evaluate leachate from gray iron foundry sand. Peak selenium concentrations in the leachate from the field lysimeters exceeded Wisconsin groundwater standard. However, application of dilution factors reduces expected concentrations between the bottom of the pavement structure and the groundwater table. Concentrations would not exceed the groundwater quality standards if the foundry sand layer is at least 1 m above the groundwater table.

Laboratory studies performed by Winkler and Bol'shakov (2000) indicate that organic compounds leach only at low concentrations. Johnson (1981), Emery (1993), and Ham et al (1989) report that with the presence of phenols in chemically bonded foundry sands, there is a possibility that leachate from stockpiles could result in phenol discharges.

Due to the general complexity in composition and character of foundry sand, appropriate leaching tests should be conducted on foundry sand from a particular source before reuse, although recent studies have suggested that it is not necessary to leach and measure the full spectrum of metallic elements in the sand (Tikalsky et al 2004). Foundries interested in beneficially using their sands should refer to their state's testing requirements.

Risk evaluations: In 2002, a national effort to establish the risks and benefits of using foundry sand from ferrous and aluminum foundries was initiated. Partners in the effort included the US Department of Agriculture-Agricultural Research Service, the Ohio State University, the Pennsylvania State University, and US EPA. Multiple samples of foundry sands from iron, steel and aluminum foundries were characterized for metals and organic constituents. Laboratory, greenhouse and field studies were conducted with foundry sand soil blends. The results were submitted to peer-reviewed journals.

Hindman et al (2008) conducted a greenhouse column experiment to evaluate the suitability of using foundry sand from ferrous and aluminum foundries in

manufactured soils by measuring plant growth, plant uptake and leaching of nutrients, trace metals, metalloids, and organics. They concluded that use of foundry sand from ferrous and aluminum foundries in blended soils will not increase risk of trace element or organic contaminant transport to surrounding soils or waters.

Dungan and Dees (2006) conducted a 28-day experiment with the earthworm *Eisenia fetida* and 6 different waste foundry sands to assess the bioavailability of metals in soil blends up to 50% foundry sands. Based upon the earthworm mortality and metal accumulation data, the study suggests that waste sands from the iron, aluminum and steel foundries do not pose an ecotoxicological or metal transfer risk. However, earthworms in soil blends using sands from a brass foundry suffered excessive mortality and metal uptake.

Using the metal and organic constituent levels from foundry sands from more than 30 iron, steel, and aluminum foundries, EPA modeled several exposure pathways associated with the use of foundry sands in a soil blend. Exposure pathways included: inhalation, groundwater ingestion, and ingestion of vegetables grown in a home gardener scenario. The draft study concluded that non-olivine sands from iron, steel, and aluminum foundries do not pose a threat to human health or the environment when used in roadway sub-base or as an ingredient in manufactured soils or soil-less media. The EPA study has been submitted for peer review and a final report is expected in late 2010.

Environmental Impact Modeling Tools: Models currently used to simulate leaching from pavement systems and potential impacts to groundwater include STUWMPP (Friend et al 2004), IMPACT (Hesse et al 2000), WiscLEACH (Li et al 2006), and IWEM (EPA 2002b). Examples of models in the public domain include WiscLEACH and IWEM. WiscLEACH combines three analytical solutions to the advection–dispersion–reaction equation to assess impacts to groundwater caused by leaching of trace elements from CCPs used in highway subgrade, subbase and base layers. WiscLEACH employs a user-friendly interface and readily available input data along with an analytical solution to produce conservative estimates of groundwater impact.

The U.S. EPA's Industrial Waste Management Evaluation Model (IWEM) can be used to determine whether leachate will negatively affect groundwater. IWEM inputs include site geology/hydrogeology, initial leachate concentration, metal parameters, and regional climate data. IWEM includes a roadway nodule that evaluates industrial material resources as a contaminant source. Given a length of time, the program will produce a leachate concentration at a control point that is a known distance from the source. Monte Carlo simulations can provide worst-case scenarios for situations where a parameter is unknown or unclear. Melton et al (2006) and Li and Benson (2009) compared IWEM to field lysimeter information and found that IWEM over predicted the leachate concentrations and could be considered conservative. Overall, IWEM performed satisfactorily in predicting groundwater and solute flow at points downstream from a source.

Detailed information on assessing risk and protecting groundwater is available in EPA "Guide for Industrial Waste Management" which can be found at <http://www.epa.gov/epaoswer/non-hw/industd/guide/index.asp>.

DESIGN CONSIDERATIONS AND GUIDELINES

Highway Subbase

Laboratory and case studies have shown that with proper design and construction, compacted foundry sand provides adequate support as a working platform or subbase material in flexible pavement design (Kleven et al 2000, Edil et al 2000). Moreover, foundry sand-based subbase specimens have been shown to resist winter conditions better than specimens of reference materials (Guney et al 2006).

Highway Subbase Design Considerations: California Bearing Ratio percentages as well as regression coefficients for the power function model to calculate Resilient Modulus, MR, are shown in Table 3. Design charts for selecting the equivalent thickness of compacted foundry sand for working platforms are provided by Tanyu et al (2004). The methodology for including the structural contribution of working platforms made from foundry sand or other alternative material is presented by Tanyu et al (2005).

An increase in strength in highway subbase using foundry sand can be obtained in the field by compacting the foundry sand-based mixtures using higher compactive efforts. The subbase layer mixture should be compacted at dry of optimum for higher strength (Kleven et al 2000, Guney et al 2006).

Embankment

Several states have allowed full use of foundry sand as an embankment material with little or no restrictions, though the majority of states continue to place restrictions on foundry sand use and require some type of encapsulation.

Geotechnical performance of foundry sand has been found to be comparable to that of the natural sand. In an INDOT embankment project, foundry sand had acceptable strength and compressibility with standard penetration N-values ranging from 33 to 54 (Mast 1997). Leachate collected from a demonstration embankment indicated metal concentrations below regulatory reuse criteria and typically below drinking water standards, indicating that foundry sand would not have a negative impact on environmental quality (Partridge et al 1999). The embankment project saved an estimated \$145,000 as a result of using foundry sand (Fox and Mast 1998).

Embankment Design Considerations: Engineering properties important to embankment designs are summarized in Table 4. A draft AASHTO standard for incorporating foundry sand into embankment designs is currently being balloted.

For design with geosynthetics, interaction coefficients from pullout tests ranged from 0.2 and 1.7 in the normal stress range of 10 to 50 kPa or 209 to 1044 lb/ft² (Goodhue et al 2001). Recommended parameters for embankment design with foundry sand and geosynthetics can be found in Goodhue et al (2001).

Freeze-thaw tests conducted per ASTM D 560 show that the resistance of foundry sand to winter conditions was generally better than reference material (clayey gravel), except for lime amended mixtures, which were at the verge of disintegration after eight cycles. The hydraulic conductivity ratio ($K_r = K_n/K_i$) ranges from 2 to 24 with increasing values for higher cycles. The unconfined compressive ratio ($q_{ur} = q_{un}/q_{ui}$) remains nearly constant between the first and eighth cycle after losing 40 to 50 percent of their initial strength after the first cycle (Guney et al 2006).

Hot Mix Asphalt

The Federal Highway Administration (2004) reports that in the United States, asphalt concrete is used to cover over 2 million miles of roadway, accounting for over 94 percent of all pavements. Recycled foundry sand has successfully been used as a partial replacement for aggregate in hot mix asphalt (HMA) in Pennsylvania, Michigan, and Tennessee. Pennsylvania DOT allows the use of 8 to 10 percent foundry sand in asphalt mixtures. One asphalt producer in Michigan consistently supplies HMA with 10 to 20 percent recycled foundry sand to replace conventional aggregate. In Tennessee, HMA with 10 percent foundry sand had been reported to compact better and outperform HMA containing washed river sand. A hot mix producer in Ontario, Canada has also used foundry sand since 1994 in both foundation and surface HMA layers (Federal Highway Administration 2004). Superpave performance tests in Wisconsin found a potential for positive performance in using recycled foundry sand. In particular, the stability of mixes with recycled foundry sand can be higher than HMA with conventional sand; moisture resistance was higher than mixes with conventional sand; and some mixes demonstrated increased resistance to rutting (Delange et al 2001).

Asphalt Design Considerations: Asphalt mixes containing foundry sand can be designed using standard asphalt mix design methods. The amount of foundry sand used in an asphalt mixture depends largely on the amount of fines in the foundry sand. Studies have shown that foundry sand can be used to replace between 8 and 25 percent of the fine aggregate content in asphalt mixes (Federal Highway Administration 2004). The optimum asphalt content for HMA mixtures containing various amounts of foundry sand is comparable (5-6.2%) to the content of mixes not containing foundry sand (Miller et al 2001, Tikalsky et al 2004). HMA made with foundry sands have been shown to display good durability characteristics with resistance to weathering (Emery 1993).

Properties of foundry sand that are of particular interest when used in asphalt paving applications are summarized in Table 5. Generally foundry sand should be free of thick coatings of burnt carbon, binders, and mold additives. These constituents can inhibit adhesion of the asphalt cement binder to the foundry sand. Clay clumps can be

removed by screening and/or washing, while iron and rubbish can be removed with magnets and/or hand separation.

Although recycled foundry sand can be successfully incorporated into asphalt designs, large variability can exist between sands. Each sand should be treated as a unique source of aggregate (Tikalsky et al 2004). Foundry sand containing bentonite can be processed to reduce the fine content that affects performance

Conventional AASHTO pavement design methods are appropriate for asphalt paving incorporating foundry sand as fine aggregate. The same methods and equipment used for conventional HMA pavement are applicable to pavements containing foundry sand. If the foundry sand is dry (less than 5 percent moisture), the sand can be metered directly into a pugmill (batch plants only) or through a recycled asphalt feed (drum plants) where the sand can be further dried, by the already heated conventional aggregates (D'Allesandro et al 1990). The presence of bentonite and organic binder materials can increase the time required for drying and can increase the load on the hot mix plant dust collection system. Any coal and organic binders that are present are usually combusted in the process.

The same field-testing procedures used for conventional HMA mixes should be used for mixes containing foundry sand. Mixes should be sampled in accordance with AASHTO T 168 (AASHTO 2003c), and tested for specific gravity in accordance with ASTM D2726 and in-place density in accordance with ASTM D2950.

Flowable Fill

Natural sand is a major component of most flowable fill mixes. Foundry sand can be used as a replacement for natural fine aggregate because foundry sand consists of greater than 80 percent fine uniform silica sand. Foundry sand has been used in flowable fill in the states of New York, Pennsylvania, Ohio, Wisconsin, Tennessee, and Indiana (Smith 1996, Collins and Ciesielski 1994). Pennsylvania has reported successful use of foundry sand as a sand substitute in flowable fill, as well as Ohio where a field demonstration showed performance on par with conventional sand flowable fills (Smith 1996).

Flowable Fill Design Considerations: Some of the engineering properties of foundry sand that are of particular interest in flowable fill applications are summarized in Table 6.

Structural design procedures for cured flowable fill materials are no different than geotechnical design procedures for conventional earth backfill materials. The same methods and equipment used to mix, transport, and place flowable fill made with conventional aggregates may be used for flowable fill incorporating foundry sand. Additionally, flowable fill made with foundry sand can be produced at a central concrete mixing plant in accordance with ASTM C94 and delivered by concrete truck mixers or using a mobile, volumetric mixer for small jobs.

Portland Cement and Portland Cement Concrete

The use of foundry sand in Portland cement and Portland cement concrete mixtures is an emerging application area. Published research and case studies on this subject are limited. As such, the use of foundry sand for this application is not well documented, and any use of foundry sand in Portland cement should be considered somewhat experimental.

Portland cement concrete is a commonly used paving material that consists of approximately 45 percent coarse aggregate, 25 percent fine aggregate, 20 percent cement and 10 percent water (Federal Highway Administration 2004). Foundry sand has been shown to replace some fine aggregate portion of concrete mixtures (Federal Highway Administration 2004).

Portland Cement and Concrete Design Considerations: Various characteristics of foundry sand can affect the quality of concrete produced. Because foundry sand properties vary depending on the source from which the foundry sand was produced, it is important that adequate testing of the sand is performed. The material characteristics that are most relevant in Portland cement applications are summarized in Table 7.

Prior to reuse, foundry sand should be screened and crushed to obtain the desired gradation, and magnetic particles should be separated. These processes will remove deleterious materials preventing technical problems when mixing the cement components.

Foundry sand from green sand molding is black or gray and may cause finished concrete to have a slightly darker grayish/black tint. A 15 percent or less fine aggregate replacement with foundry sand typically produces a minimal color change.

Foundry sand can be used in combination with all types of cementitious materials including mixes containing chemical admixtures (Zirschky and Piznar 1988). Retarders and water reducers are compatible with most foundry sands. As with natural sands, any organic material in the foundry sand may affect the dosage and effectiveness of air entraining agents. Sodium silicate binder systems are not desirable in Portland cement. Trial mixtures should be examined for any potential compatibility problems.

END USER RESOURCES

Several resources are available to end users interested in incorporating foundry sand into construction applications. The American Foundry Society and Foundry Industry Recycling Starts Today (AFS-FIRST) website contains the most up-to-date information on foundry sand recycling, including technical documents, case studies, recent news, and links to companion organizations. AFS-FIRST can be accessed at www.foundrysand.org or directly at <http://www.afsinc.org/content/view/791/264/>.

State regulations of foundry sand reuse are guided by the concept of ensuring the protection of human health and the environment. Rules guiding foundry sand reuse vary from state to state. The USEPA maintains a “Foundry Sand State Reuse Resource Locator” that can be accessed directly at <http://www.envcap.org/statetools/fsand/> or via the AFS-FIRST website, under the Environmental page.

Regulations guiding the reuse of foundry sand in ten example states including: Illinois, Indiana, Louisiana, Maine, Michigan, New York, Pennsylvania, Texas, West Virginia, and Wisconsin, can also be found in the State Toolkit for Developing Beneficial Reuse Programs for Foundry Sand published by EPA (2006). The toolkit is found at <http://www.epa.gov/sectors/sectorinfo/sectorprofiles/metalcasting/foundry.html>.

Currently, there are around 2000 active foundry operations in the United States that generate over 9 million tons of foundry sand per year (American Foundry Society 2007). Foundry sand is commonly obtained directly from foundries, many of which are located in the Great Lakes region. Other states with a large concentration of foundries include: Alabama, California, Louisiana, Tennessee, and Texas (EPA 2002a). An easy-to-use mapping tool developed by the American Foundry Society is available at http://www.afsinc.org/component/option,com_wrapper/Itemid,254 to assist end users in locating foundries near construction projects.

The Recycled Materials Resource Center (RMRC) website contains a foundry sand portal that includes information on standards, links, publications, case studies, and webinars related to using foundry sand in construction applications. An elaboration on the user guidelines presented in this paper is also available. The RMRC website can be accessed at www.recycledmaterials.org. The Foundry Sand Portal is available under the “Materials” tab.

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Table 1. Typical physical properties of spent green foundry sand.

Property	Results	Test Method
Specific Gravity ^(1,2,3)	2.39 - 270	ASTM D854-06
Bulk Relative Density, lb/ft ³ ⁽⁴⁾	160	AASHTO T 084
Absorption, % ⁽¹⁾	0.76 - 6.20	ASTM C128-07a
Moisture Content, % ^(1,2,3)	0.1 - 15.0	ASTM D2216-05
Clay Lumps and Friable Particles, % ^(3,5)	1-44	ASTM C142-97
		AASHTO T 112
Hydraulic Conductivity (cm/sec) ^(1,6,7,8)	10 ⁻³ - 10 ⁻⁹	ASTM D2434-68
		ASTM D5084-03
		AASHTO T 215
Plastic Index ^(2,3)	Nonplastic to 12	ASTM D4318-05
		AASHTO T 090

⁽¹⁾ Federal Highway Administration (2004), ⁽²⁾ Goodhue et al (2001), ⁽³⁾ Javed and Lovell (1994ab),

⁽⁴⁾ Johnson (1981), ⁽⁵⁾ American Foundrymen's Society (1991), ⁽⁶⁾ Abichou and Benson (2000),

⁽⁷⁾ Abichou et al (2002), ⁽⁸⁾Dungan et al (2007)

Table 2. Typical mechanical properties of spent foundry sand.

Property	Results	Relevant Test Method
Micro-Deval Abrasion Loss, % ⁽¹⁾	< 2	ASTM D6928-06
Magnesium Sulfate Soundness Loss, % ^(2,3)	5-15	ASTM C88-05
Internal friction angle (drained) ^(1,4,5,6)	33° - 43°	ASTM D4767-04
		ASTM D 3080
Cohesion intercept (drained), lb/ft ² ^(1,4,5,6)	145-585	ASTM D4767-04
		ASTM D 3080
Unconfined compressive strength, lb/ft ² ⁽⁷⁾	482-3968	ASTM D 2166
California Bearing Ratio, % ^(5,7)	4 - 20 average 20	ASTM D1883-05
Resilient Modulus (M _R) Regression Coefficients ⁽⁷⁾	K ₁ = 122,000 – 248,000 lb/ft ²	AASHTO T-294- 94
	K ₂ = 0.44 - 0.56	

⁽¹⁾ Goodhue et al (2001), ⁽²⁾ American Foundrymen's Society (1991), ⁽³⁾ Emery (1992), ⁽⁴⁾ Winkler

and Bol'shakov (2000), ⁽⁵⁾ Javed and Lovell (1994ab), ⁽⁶⁾ Goodhue et al (1998), ⁽⁷⁾ Kleven et al

(2000)

Table 3. Design parameters for foundry sand in subbase applications.

Design Parameter	Foundry Sand Performance	Relevant Test Method	Considerations
California Bearing Ratio, % ^(1,2)	4 - 20 average 20	ASTM D1883-05	
Unconfined Compressive Strength, lb/ft ² ⁽²⁾	482-3968	ASTM D 2166	Guney et al (2006) reported the addition of lime or cement will increase the unconfined compression and CBR of fully hydrated specimens.
Resilient Modulus (M _R) Regression Coefficients	K ₁ = 122,000 – 248,000 lb/ft ²	AASHTO T-294-94	
	K ₂ = 0.44 - 0.56		

⁽¹⁾ Javed and Lovell (1994ab), ⁽²⁾ Kleven et al (2000)

Table 4. Design parameters for foundry sand in embankment applications.

Design Parameter	Foundry Sand Performance	Relevant Test Method
Specific Gravity ^(1,2,3)	2.39 – 2.70	ASTM D854-06
Bulk Relative Density, lb/ft ³ ⁽⁴⁾	160	AASHTO T 084
Standard Proctor Max Dry Density, lb/ft ³ ^(3,5)	109	AASHTO T 085
Optimum Moisture Content, % ^(3,5)	~ 12%	ASTM D2216-05
Hydraulic Conductivity (cm/sec) ^(1,6,7,10)	10 ⁻³ - 10 ⁻⁹	ASTM D2434-68
		ASTM D5084-03
		AASHTO T 215
Plastic Index ^(2,3)	Nonplastic to 12	ASTM D4318-05
		AASHTO T 090
Internal friction angle (drained) ^(2,3,8,9)	33° - 43°	ASTM D4767-04
		ASTM D 3080
Cohesion intercept (drained), lb/ft ² ^(2,3,8,9)	145-585	ASTM D4767-04
		ASTM D 3080

⁽¹⁾ Federal Highway Administration (2004), ⁽²⁾ Goodhue et al (2001), ⁽³⁾ Javed and Lovell (1994ab)⁽⁴⁾ Johnson (1981), ⁽⁵⁾ Guney et al (2006), ⁽⁶⁾ Abichou and Benson (2000), ⁽⁷⁾ Abichou et al (2002), ⁽⁸⁾ Winkler and Bol'shakov (2000), ⁽⁹⁾ Goodhue et al (1998), ⁽¹⁰⁾ Dungan et al (2007)