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Steel Slag in the Mississippi Construction and Materials Market

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16. Abstract
This report assessed the viability of steel slag within Mississippi's construction market. After a review of potential applications to evaluate further, three areas were explored: 1) cement stabilized in-place recycled pavement bases; 2) unsurfaced applications such as roads, parking lots, and shoulders; and 3) stone matrix asphalt (SMA). Use of 15 to 30% non-expansive steel slag considerably improved elastic modulus derived per unit of unconfined compressive strength, which all other factors remaining equal allows reduced cement per unit modulus which should reduce potential for plastic shrinkage cracking and reduce embodied energy of the pavement layer. Laboratory testing and case studies of roadways in Noxubee county clearly concluded steel slag's viability for projects within reasonable trucking distances of steel mills. Successful use of steel slag was documented in SMA, though market factors (e.g. abundant chert gravel and a large expanse of unpaved roads and shoulders) are likely not to favor use in SMA to the same level in some other markets.

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CHAPTER 1 - INTRODUCTION

1.1 General and Background Information

As the name implies, steel slag is formed during the production of steel and over the years has progressively been more utilized in a variety of environmental and infrastructure applications. Steel can be produced in a basic-oxygen furnace (BOF), an electric arc furnace (EAF), in a ladle furnace (LF), or in a ladle metallurgy furnace (LMF). Steel slag produced via BOF or EAF is dependent on the reactions that take place during impurities removal as steel scrap is often used in this process. Steel produced by way of BOF or EAF processes can be further refined via a LF, with properties of the steel slag being dependent on the refinements that occur to the steel in the LF. It is important to understand that steel slag's properties can vary considerably as there are multiple potential processes that can be utilized. It is also important to understand that there are a variety of types of slag, and that this report focuses on slag formed during production of steel, not iron, as iron blast furnace slag can have different properties than steel slag.

The National Slag Association (NSA) was formed in 1918, and has been in existence for over 100 years. To celebrate NSA's 50th anniversary, a document was developed to highlight the state of practice for slag's use. Therein it was stated that more than 40 million tons of slag aggregates were produced in the late 1960's. Applications for various types of slag listed in the 1960's included as aggregate for built-up roofing, as railroad ballast, concrete for various purposes, asphalt paving, aggregate bases, turf improvement (due to micro nutrient additions, acid neutralization, and moisture retention), decorative building floors, as slag cement, as a liming agent to improve crop yields, and as a water purifier. This applications list would be comparable in present day and also include unpaved roads and unpaved roadway shoulders.

The previous paragraph pertains to slag as a whole and not just steel slag; more specific information is presented later in this chapter regarding steel slag applications. For reasons such as its widespread beneficial use potential, slag should not be viewed as an industrial waste. Some have suggested slag materials are more appropriately described as industrial co-products. ASTM recently adopted standard D8021-23: Standard Guide for Blast Furnace and Steel Furnace Slag as Produced During the Manufacture of Iron and Steel. This document is one resource that is providing useable guidance on slag product classification. Product Category Rules (PCRs) are another means by which construction materials are classified. PCRs are sets of guidelines for developing life cycle assessment and reporting findings in an Environmental Product Declaration (EPD) for one or more categories. Yzenas (2024) provides more information on PCRs. As documented in the remainder of this report, the steel slag available in the Mississippi market has beneficial use potential that is already being utilized, and there are possible applications beyond those employing the product at the present time.

1.2 Objectives and Scope

The primary objective of this report was to assess the viability of steel slag in the Mississippi construction market. To accomplish this objective, a review of steel slag applications and conditions under which applicability is most viable was first performed (Section 1.3). This applicability assessment was coupled with a review of steel slag available in the Mississippi marketplace during the 2017 to 2019 time frame that is provided in Section 1.4. Findings from these two sections ultimately led to this report investigating beyond literature and practice review three potential applications: 1) cement stabilized in-place recycled pavement base layers; 2) unsurfaced applications such as roads, parking lots, and pavement shoulders; and 3) stone matrix asphalt (SMA). Chapters 2 through 4 provide content specific to each of these areas where further literature review was performed alongside experiments and data analysis.

1.3 Review of Steel Slag Applications and Applicability

As with any material, positive and negative attributes of steel slag should be assessed and this assessment should dictate whether or not to employ steel slag in a given situation. Some of the desirable aspects of steel slag include that it is a co-product, it is often economical so long as trucking distances are not excessive, it can produce very high California Bearing Ratio (CBR) values (AASHTO T193), it often has low sulfate soundness (ASTM C88) values, it usually has low LA Abrasion (AASHTO T96) values, and it can be effective in some water treatment processes. Some of the potential challenges with use of steel slag are that availability is often regional due to formidable costs to truck the high specific gravity material, and expansion potential of some forms of steel slag. Expansion potential is one of the main obstacles for several applications, and as such the following sub-section deals exclusively with this subject. Expansion potential is not dealt with in any detail in this report beyond Section 1.3 other than to inform potential users of steel slag that expansion potential should be considered and properly accounted for prior to use. The remaining sub-sections within this section describe applications for steel slag that are not specifically evaluated in chapters 2 through 4; i.e. in place recycling, unpaved applications and shoulders, and asphalt are not discussed in this section and those literature reviews are provided in chapters 2 through 4.

1.3.1 Expansion Potential and Applicability

A first order factor to consider with steel slag for some applications is the potential for expansion. As mentioned earlier, there are several types of steel slag and properties can range considerably. BOF and EAF slag are typically chemically similar with regard to their primary components of calcium and iron oxide (Yildirim and Prezzi 2011). EAF slag is often more variable due to scrap metal usage. The chemical composition of ladle slag is more variable than EAF slag due to the use of various alloys and refining processes. Typically, the iron oxide content for ladle slag is lower while alumina and calcium oxide contents are higher (Yildirim and Prezzi 2011). Physical, chemical and mineralogical properties of steel slag differ depending on the steel type and slag handling after the separation from the steel melt, and Herrmann et al. (2007) provides a more extensive review of this subject.

The free lime (generally calcium oxide, or CaO) that can be in steel slag can hydrate and form low density portlandite that expands (Wang et al. 2010). Free lime contents for EAF are typically much lower than for BOF slag (Yildirim and Prezzi 2011). Magnesium oxide (MgO) can also be present and lead to meaningful expansion over time, albeit more slowly than free lime. Yildirim and Prezzi (2011) note that magnesium oxide is less common in modern byproducts and processes unless dolomite is utilized. Rojas and Rojas (2004) note that sulphur, sulphate, and chloride materials may also lead to some level of volume instability. Note that constituents such as free lime can be useful when mixing steel slag with clay as the lime can provide stabilization benefits provided expansion can be kept below acceptable levels.

Composition (e.g. free lime content) and aging (amount of time material has been exposed to moisture) are the primary factors affecting steel slag's volumetric stability. Several of the hydration reactions resulting in steel slag expansion may take considerable amounts of time. Controlling several of the expansive challenges of steel slag may be possible through pre-aging (Wang et al. 2014). There is risk in pre-aging if all of the particles are not exposed to sufficient moisture for sufficient amounts of time. Predictions exist for expansion based on, for example, available free lime (e.g. Wang et al. 2010), but testing representative samples for the actual project is the most reliable approach to controlling expansive problems. A few test methods are available to attempt to accelerate the rate at which expansion potential is manifested.

The standard test method to determine the volume expansion of hydrating aggregates is ASTM D4792. ASTM D2940 specifies that the recorded expansion of steel slag must be less than 0.50% at 7 days for the slag to meet requirements for use as a pavement base or subbase. ASTM C151 is the standard autoclave procedure to measure accelerated cement paste expansion due to hydration, where the autoclave provides high temperature and pressure conditions. Modifications to C151 have been explored to evaluate the hydration expansion of byproduct materials (Wang 2010, Brand and Roesler 2015). To capture longer term behaviors, some have employed autoclave environments to accelerate hydration of expansive oxides or extension of standard testing times (Brand and Roesler 2015; Manso et al. 2013). Manso et al. (2013) and Montenegro et al. (2012) tested long term expansion of soils stabilized with ground steel slag by prolonging test times to allow reactions to progress over extended durations.

A relatively simple test for steel slag expansion instability is the autoclave disruption test (Wang 2010). Disruption testing provides an idea of how prone the selected slag is to expansive cracking and may indicate potential problems for use in rigid systems. The method discussed by Wang (2010) accelerates hydration of a selected number of similar sized slag pieces (e.g. 100) through increased temperature and pressure and the percentage of particles damaged is disruption. Another disruption method is the Indiana Department of Transportation (INDOT) method ITM No. 219-09T. The INDOT method checks the change in mass passing a selected sieve instead of counting individual aggregates.

Recent efforts examining the feasibility of autoclave methods have used the standard autoclave test to provide a simple means to evaluate performance (Wang et al. 2014). Slag mixed mortar bars were tested by Wang et al. (2014) following the procedures outlined in ASTM C151. Brand and Roesler (2015) adapted the autoclave expansion test to measure expansion of compacted steel slag aggregates similar to D4792. This adapted method was based on internal testing practices of the Edw. C. Levy Company. A standard autoclave environment specified by ASTM C151 was applied to compacted aggregates in a mold consisting of a stem to hold a surcharge in place during a hour heating period. ASTM recently released another standard method for autoclave expansion; ASTM D8378-21: Potential Expansion of Steel Slag from Hydration Reactions by Autoclave.

1.3.2 Unbound Base Applications

The use of steel slag in road construction has considerable financial, environmental, and performance implications. These implications are described here as unbound base is one road construction application, though this content is applicable to a variety of road construction uses. When steel slag is used in place of other aggregates, not only is this material diverted from a landfill, it also enables the conservation of the natural resources that would be used otherwise.

As quarry materials have become scarce as a result of demand from the construction sectors and environmental regulations have become more stringent, meaningful attempts have been made to find alternative materials that can replace commonly used quarry aggregates in construction (Arulrajah et al. 2014).

For use as an unbound granular fill, the total system expansion, not the expansion of individual steel slag aggregates or particles, is the most important criteria. This is because the void space in granular systems allows the individual slag pieces to expand small amounts reducing the void space without expanding the systems volume. Wang et al. (2010) demonstrated that if there is sufficient void space to absorb the expansion with sufficient surcharge no system wide expansion will occur.

1.3.3 Environmental and Water Treatment Applications

Steel slag has been utilized in several environmental applications including wastewater treatment, ditch filtration systems, and streambank protection mainly due to its ability to absorb phosphorous. Phosphorous is most commonly the limiting agent in an ecosystem, and when in excess can cause major disturbance to the surroundings. Unnatural levels of phosphorous often enter waterways through agricultural and industrial wastewater, accelerating the growth of hydrophytes, diminishing water quality and eventually leading to eutrophication. Steel slag has been successfully utilized in filtering wastewater before it enters streams (Han et al. 2016). This process occurs through two main mechanisms. Many studies have found the key mechanism to phosphorous removal is in the precipitation between phosphates and calcium ions from the dissolution of steel slag (Barca et al. 2012, 2013; Bowden et al., 2009; Claveau-Mallet et al., 2012, 2013). Others have identified a key mechanism as the adsorption onto metal oxides or oxyhydroxides on steel slag surface (Jha et al., 2008; Pratt et al., 2007a,b; Xiong et al., 2008; Xue et al., 2009). Through these two mechanisms, steel slag is able to absorb phosphorous from water, making it a valuable material for wastewater treatment.

Many factors affect the phosphorous removal capacities (PRCs) of steel slag, which can vary greatly between 0.8 mg P/g to 89.9 mg P/g (Barca et al. 2012). Common factors include contact time between phosphorous and slag, pH, reaction temperature, phosphorous concentration and dosage, size and chemical compositions of steel slag. There has been a significant amount of research on the effect of pH on PRCs of steel slag due to its application in wastewater treatment. Claveau-Mallet et al. (2012, 2013) used column tests with EAF-slag as a filter substrate to show the strong positive relationship between high effluent pH and low effluent phosphorous concentration. Bowden et al. (2009) also confirmed this relationship through batch experiments. This is most likely due to the precipitation mechanism of steel slag. As pH increases, so does the precipitation of phosphates with calcium ions (Han et al. 2016). However, others have shown that the PRCs of BOF-slag actually decrease with an increase in pH. This is thought to be the result of the adsorption mechanism, in which higher pH causes the BOF-slag surface to become more negatively charged, repulsing the negatively charged phosphates in the water. Han et al. (2016) demonstrated the high PRCs of BOF-slag under acidic, neutral and alkaline conditions. Thus, while pH significantly affects the paths of phosphorous removal by BOF-slag, it does not affect the ability of BOF-slag to absorb phosphorous at varying levels of pH.

The main environmental concerns with using steel slag are based on the potential leaching of different elements within the slag such as chromium and vanadium and its tendency to increase the alkalinity of surrounding water. However, current research shows that the amount of leaching from steel slag (LFS and EAFS) utilized in road construction is in accordance with acceptable limits of EPA's drinking water standards (Maghool et al. 2016). Lind et al. (2001) also found no significant impact from steel slag (ferrochrome) on the soil, plants, or groundwater at their test sites, concluding that uptake by plants and spreading of dust seems to have the biggest impact on the environment and that there is a need for further research on the bioaccumulation of trace metals, namely chromium, by plants.

Thus, with minimal concern of the negative impacts of using steel slag in the environment, it can be implemented in many different scenarios for the benefit of not only its phosphorous absorbing capabilities but also for its neutralization potential. Steel slag contains aluminum and iron oxides that combine with a calcium base that can react to neutralize acidic water. The tendency for steel slag to increase the alkalinity of the surrounding environment can be used specifically to neutralize acidic waters such as in acid mine drainage. It can also be useful in more common situations such as neutralizing wastewater pH coming out of individual septic tank sewage disposal systems, making it an excellent backfill material. This idea is furthered in the next section.

1.3.4 Backfill and Drainage Applications

Steel slag has been proven to effectively treat phosphorous in subsurface drains (McDowell et al., 2008), ditch filters (Penn et al., 2012), direct submersion (McDowell et al., 2007), active filters (Shilton et al., 2006), and in laboratory flow through experiments (Stoner et al., 2012) (Wang et al. 2015). Using trench filters, Wang et al. (2015) indicated an 18.7% reduction in phosphorous after 14 precipitation events over a 7-mo period. McDowell et al. (2008) used subsurface drainage by filling in drainage channels containing drainage pipe with steel slag. After 12 drainage events over 2 years, they were able to reduce phosphorous levels by 60%. The slag in McDowell's study differed from the others in that it was not sieved. The amount of fine material on the steel slag increased the surface area and is most likely the reason for the large increase in phosphorous removal (Wang et al. 2015). Further conclusions in the Wang et al. (2015) study include no significant change in nitrogen concentration and an increase in pH after filtration. The PRCs, low cost, and abundant supply of steel slag make it an economical option for reducing phosphorous in surface waters through the use of filters and also makes it a great material for some backfill applications.

1.3.5 Concrete Applications

There have been a number of investigations involving steel slag in concrete systems (Arribas et al. 2015; Cook and Yzenas 2020). Expansion potential is a major concern for a relatively rigid material such as concrete, but successful uses have been documented for properly evaluated steel slag. Two examples follow. Qasrawi et al. (2009) used varying percentages of steel slag as fine aggregate in concrete where mixes had compressive strengths of 25 to 45 MPa. Sand fine aggregate was partially or totally replaced by steel slag in different mixes. The steel slag used had a low CaO content and no pozzolanic activity. Best results were 15 to 50% sand replacement ratios with steel slag depending on whether tensile or compressive strengths were of primary interest.

Manso et al. (2004) conditioned EAF steel slag with permanent wetting, homogenization, and periodic heap overturning with a minimum duration of 90 days. This conditioned steel slag was used as aggregate within laboratory concrete that produced compressive strengths in the 20 to 40 MPa range after 28 days of curing. Concrete containing steel slag had acceptable behavior in terms of fresh mixed properties, hardened mechanical properties, and integrity against aggressive environments.

1.3.6 Steel Slag Usage Summaries from Other Countries

The reclamation of steel slag is practiced in many countries throughout the world, utilized in numerous applications. For example, more than 24% of the produced steel slag in Germany (and 56% in USA) is used as sinter material (partially replacing commercial lime) when the CaO content is above 50% (Liu 1994; Jiang et al. 2002). Another common application of steel slag in other countries is hot metal dephosphorization and decarbonization. Nippon Steel Corporation, headquartered in Tokyo, Japan, has developed a process in which dephosphorization and decarbonization is carried out in the same converter, termed the Multi-Refining Converte (MURC) process (Matsumiya 2011). In China, Bao Steel was the first steel enterprise to successfully create a duplex process where slag is reused for desphosphorization (Zhang 2006). Steel slag is commonly used for erosion resistance due to its high strength and durability, and in Germany, 400,000 tons per year is used to stabilize river banks and river beds (Motz & Geiseler 2001). In 2008, The Nippon Slag Association in Japan published the Guide to using steel slag in port and harbor construction (Ozeki 1997). Another, possibly more imaginative, use of steel slag is in the creation of artificial reefs such as practiced by some in Japan. The incredible stability of steel slag in salt water is due to its $CaCO_3$ content, similar to shells and coral. Artificial reefs have been shown to increase breeding habitats for seaweeds and coral. In addition to this, China has successfully implemented steel slag in concrete armor blocks for sea coast reclamation projects (Xu 2010).

A large percentage of steel slag in other countries is used in roads. In Japan and European countries, approximately 60% of slag is used in roads, and 98% of that is used as aggregates of cement and bituminous pavement in UK. Steel slag is commonly used in both hot mix asphalt and cold mix recycling asphalt pavement. China has been utilizing steel slag in roads for many years, with the Ministry of Construction issuing the standard "Technical specification for construction of steel slag and lime mixture used as base course" in 1990 (Yi et al. 2012). In Germany, steel slag with free lime content up to 7% can be utilized in unbound layers and up to 4% in asphaltic layers. Leaching tests are conducted biannually on aggregates used in road construction and hydraulic structures to ensure minimal escape of Cr and Ni, typically from stainless slag, with Cr being limited to 3 mg/L (Motz & Geiseler 2001). Similar to studies in US, Zhang and Hong concluded that pollution risks of heavy metals contained in slag were very low, and as such can only be treated as common wastes, and not hazardous (2011). In addition to using slag as aggregate in roads, slag is also common for other countries to use it in the production of cement, which also occurs in the US.

The use of steel slag in glass ceramics has also been shown to be useful (Guo et al. 2011) (Khater 2002). Wuhan steel used slag in the production of colored pavior bricks and tiles and in 2012, the Chinese national standard was issued detailing the use of slag in concrete perforated brick and concrete pavior brick (Yi et al. 2012; Chen et al. 2010). In wastewater treatment, other countries have successfully shown the ability of steel slag to remove mercury, arsenic, copper, aqueous ammonium nitrogen, phosphorus, and phenol (Shi et al. 2011; Oh et al. 2012; Kim et al. 2008; Duan et al. 2012; Shilton et al. 2006; Gao et al. 2010). Research has also been conducted on the ability of steel slag to sequester carbon dioxide. The large amount of CaO contained in steel slag enables the storage of CO_2 in carbonate form using steel slag slurry with mild conditions of temperature and CO_2 pressure (Kunzler et al. 2001). Research has shown the use of steel slag in carbon capture is successful (Huijgen et al. 2007). In developed countries such as Germany, USA, France and Japan, slag is used to produce siliceous fertilizer, phosphorous fertilizer and micronutrient fertilizer (Wu et al. 2005). In fact, in 2011, the first steel slag fertilizer program began in China. For decades, steel slag has been used all over the world in many different applications. Ferreira et al. (2016) estimated around 50 million tonnes (i.e. metric tons) of steel slag were produced yearly worldwide. One metric ton (1,000 kg) is equivalent to 1.10231 English (or short tons – 2,000 lb), so there is an estimated 55 million short tons of steel slag produced annually worldwide.

1.4 Steel Slag in the Mississippi Market

The Mississippi market is primarily served by steel slag from Memphis Mill Service Co. in Memphis, TN (referred to hereafter as MMS) and by the Golden Triangle Mill Service Co in Columbus, MS (referred to hereafter as GTMS). Both of these mill services are owned by Edw C. Levy company. There is a third source of steel slag in the Jackson, MS area that is not owned or operated by Edw C. Levy company that produces less slag than either MMS or GTMS which is only casually referenced in this report.

Groups such as GTMS handle raw materials and steel slag for steel mills; for context GTMS had roughly 135 employees in the May of 2017 time frame. GTMS operates the steel scrap yard for Steel Dynamics, Inc. (SDI) in Columbus, MS, the owner of the steel scrap yard. GTMS also handles all steel slag from the mill. SDI sends three categories of slag to GTMS, which as of the time frame of this report were stored separately prior to processing, and are blended in some cases to produce products sent to market. The steel slag products are EAF (least expansive), LMF (intermediate expansion levels and often delivered back to SDI for their use in additional steel manufacturing and not sold to the construction market), and mill cleanup debris that informally referred to as *white slag* (highest expansion levels – is a major contributor to the expansion potential of a final product) that is generally smaller particles. The term *white slag* is also used to refer to products from ladle styled furnaces, while the term *black slag* is often used to refer to products from EAF furnaces.

Tables 1.1 and 1.2 summarize products from the MMS and GTMS mills as of the time frame of this report for general reference. Properties can vary over time, but the properties in Tables 1.1 and 1.2 would generally represent activities performed throughout this report. Of the products in Table 1.1, only Dura-Berm* contains *white slag*; this material was produced by blending 2 parts EAF with 1 part *white slag*. The smaller particles in Dura-Berm* are almost all *white slag*. Of the products in Table 1.2, two contain *white slag* and thus have notable expansion potential (1.5 in x 0 and 0.75 in x 0 both have 7 parts EAF to one part *white slag* where the EAF material is sized differently in the two products). The 2 in x 0.75 in Ballast in Table 1.2 is typically all EAF, and as such has the lowest possible expansion potential of the steel slag products from this mill represented in Table 1.2.

One reason for the product differences between MMS and GTMS is that MMS does not have a crusher but GTMS does have a crusher. MMS relies on impact only crushing from a ball dropped from a crane, whereas GTMS has similar capabilities plus a crusher, so products from this location can be of smaller sizes. In past years (prior to 2017), MMS supplied pure EAF steel slag to an asphalt paving contractor or contractors, who subsequently crushed the material into smaller sizes for use in stone matrix asphalt (SMA). For reasonable discussion purposes throughout this report, this material can be considered to have originated within a combination of the two EAF products shown in Table 1.1 at sizes of 1.5 to 8 inch when obtained by paving contractors. Of primary importance would be the origin of this material was only EAF and was absent any *white slag*.

Steel is one of the world's most recycled materials, capable of being reused an unlimited number of times without losing any quality. Over 1400 million tons of steel is produced around the world every year (Brooks et al. 2011). The steel mill that is served by GTMS produces on the order of 3 million tons of steel per year. As of 2019, approximately 125,000 tons of steel slag was available from MMS, and approximately 250,000 tons was available from GTMS. The steel mill in the Jackson area mentioned earlier in this section would produce at to less than 125,000 tons per year (specific data was not obtained), so a reasonable estimate of the steel slag supply in Mississippi as of the date of this report is 400,000 to 500,000 tons per year from three locations.

Table 1.1. Typical Properties from Memphis Mill Service Co.

Product	4 in x 1.5 in	8 in x 4 in	1.5 in x 0 Dura-Berm*
Type	EAF	EAF	Blend
γ_{DR} (lb/ft^3)	112.2	104.2	---
TCY	1.51	1.41	---
% Passing 5 in	100	30	100
% Passing 4 in	100	12	100
% Passing 3.5 in	84.6	---	100
% Passing 3 in	61.5	5	100
% Passing 2.5	53.4	---	100
% Passing 2 in	45.8	2	100
% Passing 1.5 in	28.7	---	100
% Passing 1 in	5.4	---	96
% Passing 0.75 in	---	---	81
% Passing 0.50 in	---	---	57
% Passing 0.38 in	---	---	40
% Passing No. 4	---	---	19
% Passing No. 8	---	---	14
% Passing No. 16	---	---	12
% Passing No. 30	---	---	10
% Passing No. 50	---	---	7
% Passing No. 100	---	---	6
% Passing No. 200	---	---	5

EAF = electric arc furnace
Blend = combination of EAF and *white slag*
γ_{DR} = dry rodded unit weight
TCY = tons per cubic yard
(*) was placed on MMS Dura-Berm to distinguish from GTMS Dura-Berm

Table 1.2. Typical Properties from Golden Triangle Mill Service Co.

Product	**0.75 in x 0 Commercial**	**1.5 in x 0 Dura-Berm**	**2 in x 0.75 in Ballast**
Type	Blend	Blend	EAF
γ_{DR} (lb/ft^3)	136	131 to 146 (avg of 138)	115 to 121 (avg of 118)
TCY	1.83	1.87	1.66
% Passing 2.5 in	---	---	100
% Passing 2 in	---	---	95 to 100
% Passing 1.5 in	---	100	77 to 98
% Passing 1 in	---	87 to 100	38 to 70
% Passing 0.75 in	100	78 to 96	17 to 41
% Passing 0.50 in	96.3	57 to 85	2 to 9
% Passing 0.38 in	83.6	46 to 76	1 to 5
% Passing No. 4	47.8	24 to 50	1 to 3
% Passing No. 8	24.9	14 to 32	---
% Passing No. 16	14.0	8 to 22	---
% Passing No. 30	8.3	4 to 16	---
% Passing No. 50	5.8	2 to 12	---
% Passing No. 100	3.6	1 to 6	---
% Passing No. 200	2.4	1 to 3	---
Autoclave Disruption (%)	---	---	0.2 to 2.3 (avg of 0.7)
Autoclave Expansion (%)	---	0.8 to 14.9 (avg of 5.8)	---
Bulk Specific Gravity	---	---	3.3 to 3.5 (avg of 3.4)
XRF – Al_2O_3 (%)	---	5.3 to 8.6 (avg of 7.2)	5.2 to 6.4 (avg of 5.8)
XRF – CaO (%)	---	30.2 to 34.9 (avg of 32.3)	30.2 to 33.1 (avg of 32.2)
XRF – Cr_2O_3 (%)	---	0.4 to 1.1 (avg of 0.8)	0.5 to 1.0 (avg of 0.9)
XRF – FeO (%)	---	29.7 to 36.3 (avg of 33.3)	32.2 to 35.5 (avg of 33.8)
XRF – MgO (%)	---	7.5 to 10.3 (avg of 8.9)	7.1 to 10.5 (avg of 9.5)
XRF – MnO (%)	---	1.7 to 6.0 (avg of 4.3)	4.7 to 5.9 (avg of 5.3)
XRF – SiO_2 (%)	---	8.2 to 13.6 (avg of 11.6)	11.2 to 15.4 (avg of 12.5)

Note that 1.5 in x 0 is Dura-Berm, which meets MDOT Gradation 825B, and that all properties shown are from the May 2017 time frame when materials were sampled for testing for this report.

EAF = electric arc furnace

γ_{DR} = dry rodded unit weight

TCY = tons per cubic yard

Blend = combination of EAF and *white slag*

CHAPTER 2 – IN-PLACE RECYCLING

2.1 In-Place Recycling Overview

In place recycling such as cold-in-place recycling (CIR) and full-depth reclamation (FDR) have been gaining interest in the paving community, and Mississippi is no exception. CIR can have a range of benefits when used properly. The Mississippi Department of Transportation (MDOT) has used portland cement as the only stabilization material for some CIR projects over the past few years where most or all of the material being stabilized is asphalt pavement. Areas such as Mississippi with limited virgin aggregate supply can benefit from as many aggregate options as possible in their paving market.

Steel slag has not been comprehensively investigated in Mississippi for CIR (or similar stabilized soil applications), and this chapter documents pilot work in this area. Ayers and Howard (2020) is a peer-reviewed manuscript that also makes use of the information provided in this chapter and parallels the content contained in this chapter. The primary objective of these efforts was to evaluate compressive strength to elastic modulus relationships of cement stabilized CIR and determine if steel slag is beneficial in this regard.

2.2 Materials Tested

Figure 2.1 provides representative photos of pertinent materials tested. ASTM C150 Type I portland cement was used throughout, and 2 in by 0.75 in steel slag ballast (Table 1.2) was sampled in May of 2017. This material has the lowest expansion potential of the GTMS options. The potential for expansion was not directly considered in this chapter, but expansion potential must be considered and checked/verified to be acceptable for any use in bound pavement layers. For these experiments, particles retained on a 1.5 in sieve were discarded.

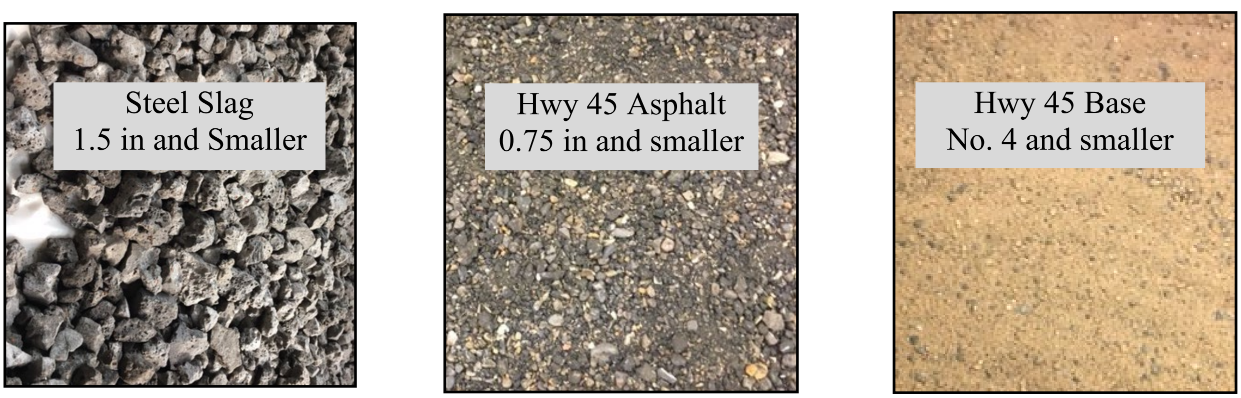


Figure 2.1. Aggregates Photos

Materials taken from a 2 mile in-place recycling project for MDOT on Hwy 45 (NH-0002-06(023) 107478-302000) were also utilized in addition to steel slag that was not part of the project itself. The reclaimed material consisted of roughly 6 inches of asphalt and 1.5 inches of sandy base taken in June of 2017 after pulverization but with no cement. Sampling occurred in layers and led to six parts asphalt to one part sandy base. The asphalt gradation as reclaimed had 99% passing the 1.5 inch sieve (retained material was discarded), 94% passing the 0.75 inch sieve, 44% passing the No. 4 sieve, 34% passing the No. 8 sieve, and 1% passing the No. 200 sieve. The Hwy 45 base all passed a No. 4 sieve.

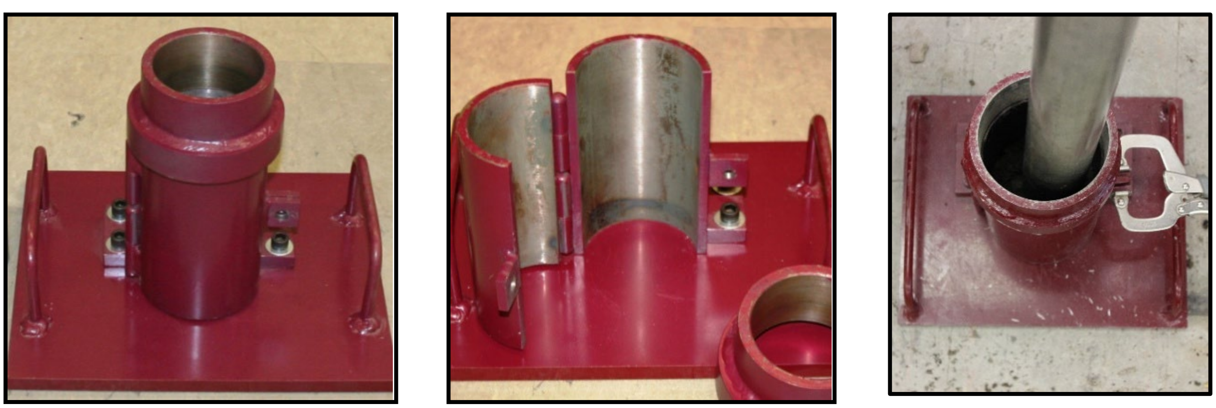
2.3 Specimen Preparation and Testing

Aggregates were air dried and after sampling to approximately 1% moisture, and thereafter they were fractionated and stored in buckets. Three aggregate blends were produced (Tab1e 2.1) where 0% steel slag represents the Hwy 45 project. These three blends were produced with either 4% or 5% cement on a dry mass basis. During the Hwy 45 project, four mix designs were performed leading to cement contents of 4.8 to 5.6% with an average of 5.2%. Therefore, 5% cement was believed to be a reasonable value to represent project conditions. The lower cement content (4%) was selected to assess whether addition of steel slag could compensate for some amount of cement in terms of mechanical properties.

Table 2.1. Blends Tested – Dry Aggregate Mass Basis

Steel Slag (%)	Hwy 45 Asphalt (%)	Hwy 45 Base (%)
0	86	14
15	73	12
30	60	10

Test specimens were produced in two manners. The first manner was standard Proctor testing generally in accordance with AASHTO T99 Method D and AASHTO T134 to determine Optimum Moisture Content (OMC) and Maximum Dry Density (γ_d). One notable difference was that particles up to 1.5 in (rather than 0.75 in) were included to match PM Device specimens. Each point was mixed individually, compacted within 20 minutes of mixing, and then discarded. The second specimen preparation manner used an AASHTO PP92 PM Device (Figure 2.2) that produced 10.2 by 20.4 cm sized specimens (95 total specimens). These specimens were compacted in 4 layers (scarified in between) by an AASHTO T180 hammer where the number of blows per layer (N_B) was recorded (5 to 17 blows per layer were used). Particles larger than 1.5 in were discarded.



a) PM Device Closed *b) PM Device Open* *c) PM and Proctor Hammer*

Figure 2.2. PM Device and Specimens Produced

Mixing was performed in a mechanical mixer that uses a paddle and trowel to mix materials inside a 5 gallon metal bucket (Figure 2.3). The entire mixing process took on the order of 3 to 4 minutes per specimen and mixing progression was evaluated by visual observation. Aggregates were added first, then cement was added and mixed. Thereafter, water was added and mixing continued to uniformity.

a) Bucket Mixer (19 L)

b) Mixing Tools

c) 15% Steel Slag Before Mixing

d) 15% Steel Slag After Mixing

Figure 2.3. Material Mixing

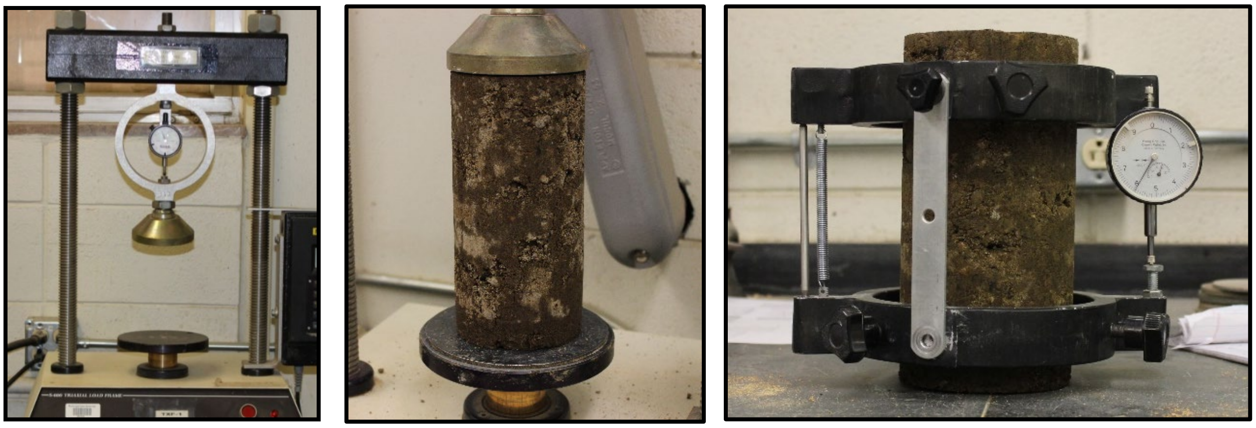
The majority of the PM Device specimens remained in their plastic molds for 24 hours on a lab bench before extraction, and immediately after extraction measurements were taken to allow dry density to be calculated. These specimens were then placed into a 100% humidity curing room (mean temperature of 73.9 ºF) shown in Figure 2.4 where they remained until testing at 7 or 28 days. Twelve PM Device specimens were oven dried for moisture content after compaction.

a) Curing Room

b) Curing Room Data Logger

Figure 2.4. Curing Room and Temperatures

After removal from curing, 83 specimens were tested for unconfined compressive strength (UCS), and some were tested for elastic modulus (E) in general accordance with ASTM C469 on a load frame at a rate of 0.05 in/min. Figure 2.5 summarizes testing.

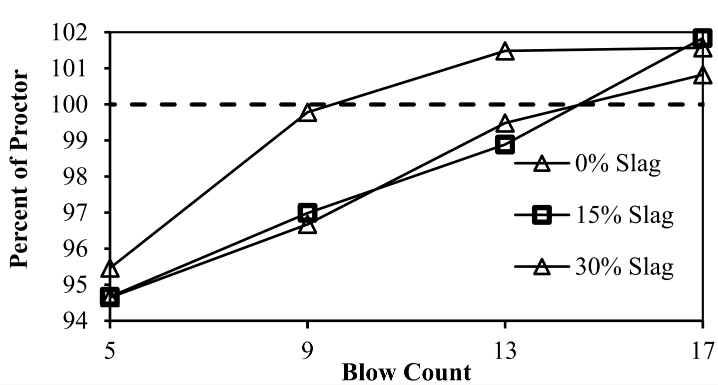


a) Load Frame *b) UCS* *c) Elastic Modulus*

Figure 2.5. Testing Photos

2.4 Test Results

Table 2.2 and Figure 2.6 summarize density test results. The plots in Figure 2.6 are from twelve specimens compacted at varying PM Device blow counts where the entire specimen was oven dried for moisture content determination. The 0% steel slag blend was the most compactable, and the PM Device was able to reasonable compact all the blends. Table 2.2 summarizes all 83 specimens tested for mechanical properties. Values from the Figure 2.6 curves are shown alongside each average (Avg) percent of Proctor value for a number of replicates (n).



Blend	γ_d (pcf)	OMC (%)
0% Slag	121	7.6
15% Slag	128	6.2
30% Slag	134	5.8

Figure 2.6. Proctor Compaction and PM Device vs. Blow Count Results

Table 2.2. PM Device Compaction Results for Mechanical Property Specimens

Steel Slag	Number of Blows (N_B)	Replicates (n)	Avg % Proctor	Range of % Proctor	Corresponding Figure 2.6 Value
0%	5	12	97.0	96.1-98.5	95.5
	9	12	99.7	98.3-101.1	99.8
15%	5	12	94.6	93.4-96.9	94.7
	7	3	96.7	96.6-96.8	95.8
	9	12	97.1	95.4-99.2	97.0
	11	3	98.5	97.8-99.5	98.0
	13	3	99.6	98.7-100.1	98.9
	15	2	99.3	99.1-99.4	100.4
30%	5	12	93.6	92.4-94.8	94.6
	9	12	96.5	95.6-98.7	96.7

Note: all specimens referenced Figure 2.6 irrespective of cement content

A total of 72 specimens were produced at two cure times (7, 28 days), two cement dosages (4, 5%), two compaction levels (N_B of 5 and 9), three blends (0, 15, and 30% steel slag), and three replicates. Ayers and Howard (2020) provide plots of UCS versus %γ_d where an additional eleven specimens were also utilized. UCS was influenced by density and regression was applied to select representative UCS values at 97% of γ_d (Table 2.3). Steel slag provided modest strength improvements, but mostly there were no compelling reasons to consider steel slag for a project such as Hwy 45 CIR based on UCS alone as the largest strength increase attributable to steel slag was 18%. This has potential meaning because UCS is the default evaluation mechanism by most agencies in present day, while elastic modulus is often more related to performance than UCS.

Table 2.3. UCS Results at 97% of Proctor

Steel Slag (%)	Cement (%)	UCS (psi) 7 Day	UCS (psi) 28 Day
0	4	230	226
	5	232	269
15	4	225	272
	5	268	318
30	4	230	265
	5	263	276

In 2010, MDOT conducted an in-place recycling project on US Highway 49 (US-49) that has been carefully documented (e.g. Howard and Cox 2016; Cox et al. 2016). A key finding was that in-place recycled cement stabilized materials had an elastic modulus to compressive strength relationship (E:UCS) of about 500:1, which is much lower than the 1200:1 to 4500:1 observed with MDOT's conventional soil-cement approach on Interstate 269 (Sullivan and Howard 2019). All factors being equal, higher modulus per unit strength is desirable for pavement performance.

Table 2.4 summarizes E:UCS data and shows steel slag's value for CIR is more associated with modulus than with strength. Given that higher E:UCS ratios are desirable, Table 2.4 clearly demonstrates the value of steel slag in CIR. Ayers and Howard (2020) provide additional commentary and benchmark steel slag blends relative to other data in literature. Within the blocked set of experiments, four cases provided a direct assessment opportunity for reducing cement dosage by adding steel slag. These cases were 5 and 9 blows per layer specimens cured for 7 and 28 days. Approximately speaking, adding 15 to 30% steel slag allowed 1% cement reduction while still improving elastic modulus by 15 to 20%.

Table 2.4. E:UCS Results – Values Shown are Percentages of Occurrence

E:UCS	0% Steel Slag	15% Steel Slag	30% Steel Slag
<500	0	0	0
500 to 1200	0	0	6
1200 to 2500	94	48	6
2500 to 4500	6	48	69
>4500	0	4	19

2.5 Conclusions

The primary finding of this chapter is that use of 15 to 30% steel slag considerably improved the elastic modulus derived per unit of unconfined compressive strength for an in-place recycled material consisting mostly of reclaimed asphalt pavement with modest amounts of sandy base. Additional compactive effort is expected to achieve proper in-place density of a pavement layer containing steel slag, but there are clear durability benefits from steel slag's incorporation, and there are also environmental benefits from replacing cement with a co-product of steel production. Pavement designers are encouraged to consider use of non-expansive steel slag for in-place recycling projects to make modest reductions in cement dosages toward higher modulus pavement layers that reduce overall pavement deflections and also have less plastic shrinkage cracking.

CHAPTER 3 - UNPAVED SURFACES

3.1 Overview of Unpaved Surfaces

This chapter evaluates use of steel slag in paving applications absent a paved surface (e.g. an asphalt or concrete surface). A review of literature was first performed that was focused on environmental aspects and erosion potential as the experiments conducted later in this chapter did not directly consider these areas. A more comprehensive review of literature on steel slag use in unpaved applications could have been performed, but this review is planed for a future document. Findings from a laboratory testing program follow the literature review. With the controlled laboratory testing data serving as a benchmark, four routes were selected in Noxubee county Mississippi to serve as case studies for use of steel slag in unpaved roads. The collective information gained was used to discuss market potential of steel slag in unpaved applications in Mississippi.

3.2 Partial Literature Review of Steel Slag for Unpaved Surfaces

3.2.1 Environmental Impacts

A major environmental concern of using steel slag in road construction is heavy metal leaching. Leaching tests provide a glimpse of the potential for a solid to release harmful chemicals into the environment, as opposed to other methods which rely on measuring contaminant concentrations within a solid. Current perspectives are generally that total heavy metal content is not proportional to the leaching potential, and instead is contingent upon the material microstructure. Leaching potential is dependent on the way a metal is incorporated into an aggregate matrix (European Commission, 2014). Thus, leaching tests are required to determine the percentage of heavy metal content within slag that has the potential to be released into the environment. There are three prevailing leaching test method categories including pH dependence tests, percolation tests, and batch leaching tests. Heavy metals in relation to steel slag typically include Fe, Mn, Ti, Al, and Cr (Gomes & Pinto, 2006). The potential toxicity and leaching of harmful elements such as Cr and V depend on their chemical form or speciation (Chaurand et al., 2007).

While several studies made conclusions on the leachability of harmful chemicals within steel slag used in road construction, it is commonly agreed that there is a significant difference in laboratory and field studies and that it is difficult to correlate them (Barisic et al. 2017). Further research is necessary to fully understand how steel slag affects the environment over time. Chaurand et al. (2006 and 2007) concluded that despite the considerable leaching of chromium in BOF slag, it has a low impact on the environment, due to being in its less mobile and less toxic form. The leaching of vanadium is also significant; it can pose a serious risk if it is present in one of its most toxic forms (+4 oxidation state) and becomes oxidized to its most toxic form (pentavalent vanadium) during natural aging. However, Barisic et al. (2017) concluded that steel slag does not pose an environmental concern in terms of leaching either Cr or V according to drinking water standards. In addition, Van der Sloot et al. (1996) explain that current leaching tests are unrealistic and that without a comprehensive knowledge of release/retention mechanisms and long term leaching behavior, the effects of steel slag leachate on the environment will not be sufficiently understood.

Dissolved oxygen (DO) is an important environmental consideration due to its role in many chemical and biological reactions in water. If DO levels exceed 25 mg/L, eggs, small larvae, some fish, and aquatic invertebrates may suffer from "gas bubble disease," and if DO levels drop below 5 mg/L, aquatic life is stressed (Camas-Anzueto et al., 2015; Colt, 2006). DO levels vary seasonally in addition to geographically, but drastic alterations caused by steel slag leachate could be fatal for aquatic life. In the study performed by Barisic et al. (2017), DO levels in steel slag leachate were within the permissible range (5 mg/L < DO < 25 mg/L) and showed no potential risk to the environment.

Steel slag leachate is known to be alkaline, which is caused by the dissolution of calcium (Ca) silicates, oxides, and/or carbonates (Piatak et al., 2014). This can cause issues such as calcareous crystalline crust formation, which buries benthic macroinvertebrates and littoral aquatic habitats. It also reduces light penetration, raises pH which can harm fish populations, and increases chemical oxygen demand, among other issues (Mayes et al., 2006). Barisic et al. (2017) observed steel slag leachate pH values of 9.4 and 9.7, only slightly above the limit value of 9. Thus, according to Sakata (1987), through the interaction with acidic soils, alkaline leachate will be neutralized when used in road construction.

While comprehensive studies for the leaching of steel slag exist, there are few studies that analyze the direct effects that contaminated soil and water have on living organisms, which is a current knowledge gap. Ringelband (2001) studied the brackish water hydroid (Cordylophora capsica) and the toxicity effects of vanadium from slag used in riverbank reinforcements. The study concluded that steel slag had inhibitory effects on population growth which depended on water salinity (salinity and inhibition potential had a negative relationship). Asadpour et al. (2013) studied brine shrimps (Artemia urmiana and Artemia franciscana) and the effects of nickel and vanadium on their mortality and growth. After 24 hours of exposure, bioaccumulation and effects on growth were observed, with nickel being less toxic than vanadium. Wendling et al. (2012) showed that leachate was of low toxicity to algae (Chlorella sp.) and the marine bacterium Vibrio fischeri. However, the alkalinity of the material would have to be reduced before use in construction. Barisic et al. (2017), through conducting research on short term exposure to steel slag leachate, concluded that there was no adverse effect on earthworms and that because the enzymes that were measured are present in many different animals, it can be assumed to have similar effects on most animals.

3.2.2 Erosion Susceptibility

Erosion control is one of the biggest challenges for unpaved roads. Erosion is most commonly caused by water runoff and air turbulence caused by passing vehicles (Bilodeau et al. 2007). When shear energy in turbulent flows is not completely dissipated by friction, small particles erode and alter the gradation. Without sufficient fine particles, density and packing quality are hindered. The material is then more easily disturbed and more particles are carried away by turbulent flows and moved by the mechanical action of tires. Over time, this leads to ruts, potholes, and dust problems.

Water content and soil texture are intrinsic properties that influence erosion sensitivity (Sorial and Lacharite 1988). Texture is related to gradation, porosity, plasticity, and cohesion. The quantity of particles lost to runoff is a function of runoff velocity and turbulence. According to Henensal (1986) and Paige-Green (1999), soil erosion resistance factors can take multiple forms. They can be structural parameters (e.g. porosity, compacity, moisture content, permeability, soil cracking), physico-chemical parameters (e.g. clay content), and/or index parameters (e.g. gradation and plasticity). As Dudal (1980) states, cohesive soils are more erosion resistant than non-cohesive soils, but also are more susceptible to being carried away once they are detached from their surroundings. To achieve maximum stability in an aggregate blend, voids between aggregate particles should be filled with a sufficient quantity of fines (Barksdale 1991). Fines add cohesion to the blend and provide optimum compaction and erosion resistance.

Bilodeau et al. (2007) tested six gradation curves for three materials (basalt, limestone, and gneiss) under a concentrated turbulent flow. The gradation curves were chosen to study the effect of fine particles percentage, uniformity coefficient, packing characteristics, gradation of the sand fraction, dry density, and porosity. This study was conducted to determine the best gradation for resisting erosion during turbulent flows as well as what gradation related properties need to be controlled for good performance. The study found that the best gradation, regardless of material, consisted of 7% fines and that the uniformity coefficient was the best indicator for erosion sensitivity (higher uniformity coefficients were more desirable). The fundamental gradation recommendations of Bilodeau et al. (2007) serve as references for the case studies presented later in this chapter.

3.3 Laboratory Testing

3.3.1 Materials Tested

Four materials were evaluated: Dura-Berm, gravel, sand, and Reclaimed Asphalt Pavement (RAP). Dura-Berm steel slag was obtained from one source (GTMS) on May 11, 2017. Figure 3.1 is an example of the mill setup and Dura-Berm processing facility, and Figure 3.2 provides photos of the Dura-Berm sample tested. The sampled material was air dried under fans at room temperature to moisture content (MC) values on the order of 1%. Thereafter, the steel slag was sieved into four size fractions for more accurate batching: +0.75 in, -0.75 in to +No. 4, -No. 4 to +No. 30. and –No. 30. A large sample was taken in a manner where it could be assumed that the composite gradation of the sample matched the stockpile.

Figure 3.1. Steel Slag Manufacturing Process

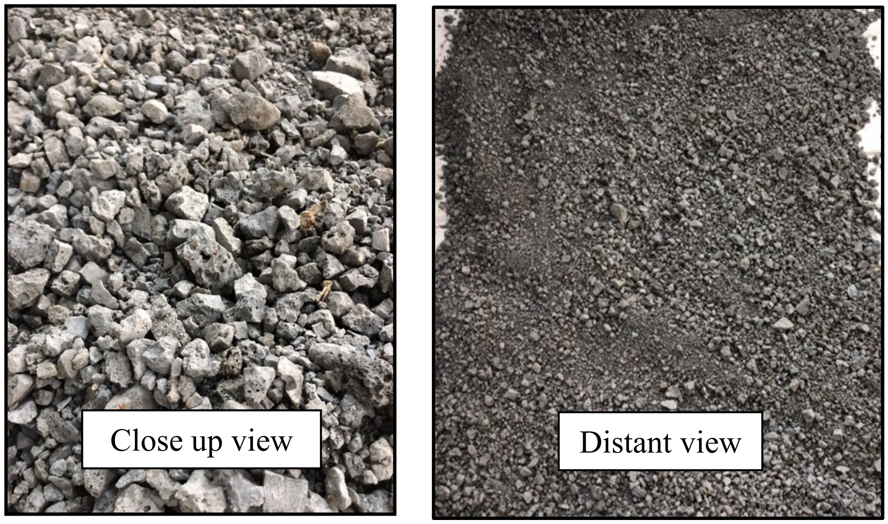


Figure 3.2. Photographs of Dura-Berm Tested

Gravel was sampled from activities occurring on part of Glenn Road, which is one of the case study routes evaluated later in this chapter. This material was air dried and sieved into four fractions in the same manner as Dura-Berm. A large sample was taken in a manner where it could be assumed that the composite gradation of the sample matched the stockpile. Figure 3.3 provides representative photos of the gravel tested.

Figure 3.3. Photographs of Gravel Tested

Sand was taken from a Mississippi Department of Transportation (MDOT) soil-cement project as this material is plentiful around the state. No cement was used for these experiments. The material was non-plastic, the AASHTO T88 clay content was 12, and the AASHTO soil classification was A2-4. The MDOT classification is 9B. The sand was processed and mixed in traditional manners when using this material for laboratory evaluations (it was not sieved into different fractions). Figure 3.4 provides photographs of the sand sample tested.

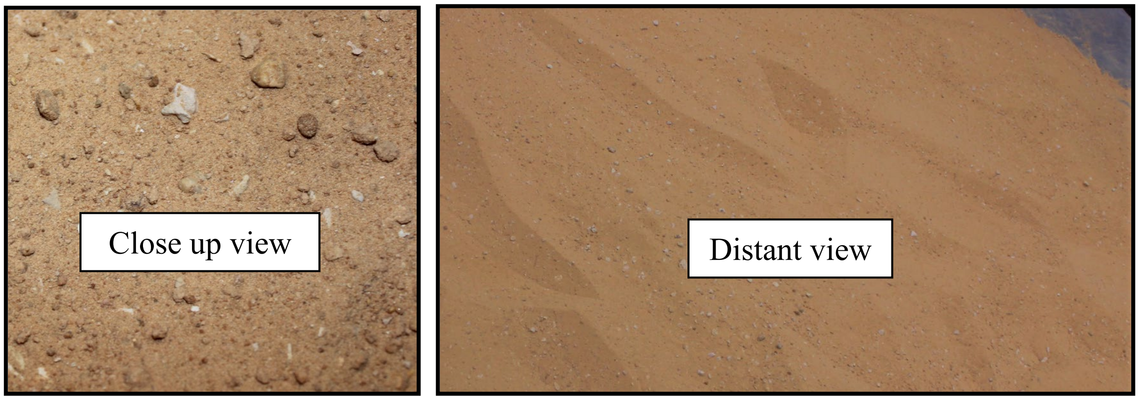


Figure 3.4. Photographs of Sand Tested

RAP was taken from APAC Mississippi's Columbus, MS asphalt plant. This material was air dried and sieved into fractions in the same manner as Dura-Berm. A large sample was taken in a manner where it could be assumed that the composite gradation of the sample matched the stockpile. Figure 3.5 provides representative photos of the RAP tested.

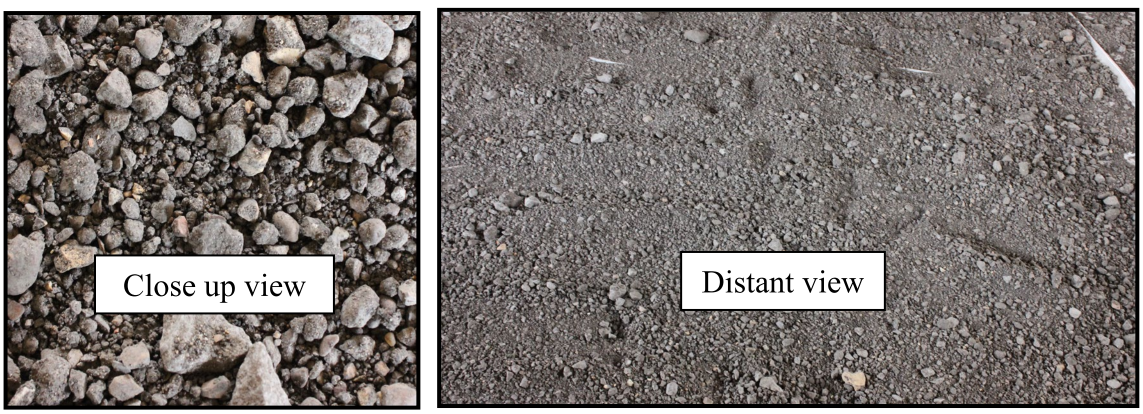


Figure 3.5. Photographs of RAP Tested

3.3.2 Specimen Preparation and Testing

Sixteen blends were created from the Section 3.3.1 materials and these blends were evaluated with AASHTO T99 Method D Proctor compaction testing and AASHTO T193 California Bearing Ratio (CBR) testing; some deviations to T193 were also evaluated as described later in this section. Specimens were labeled according to their blend percentages as follows: A/B/C/D where A= Dura-Berm percentage; B = Gravel percentage; C = Sand percentage; and D = RAP percentage. For example, 75/0/25/0 has 75% Dura-Berm and 25% sand by mass.

Table 3.1 provides bulk gradations of all four materials. Bulk gradations were determined from representatively obtained large samples where material was sieved into fractions for more accurate laboratory batching. Note that the Dura-Berm gradation shown in Table 3.1 is very coarse relative to the values shown in Table 1.2. The No. 4 and 30 sieves evaluated were on the coarsest side of the range of values shown in Table 1.2 as typical values of the time frame. The implications of this observation are that the test results shown in this section with Dura-Berm are believed to be conservative for CBR since finer particles in the steel slag are believed to be useful for unpaved applications.

All materials larger than 0.75 in were discarded, with batching accounting for this material following typical MDOT practices where material larger than 0.75 in was discarded. In accordance with AASHTO T99 Method D, material was limited to particles passing a 0.75 inch sieve. Particles larger than 0.75 inches were labeled as oversized and omitted. Materials smaller than 0.75 inches were batched in accordance with typical MDOT practices.

Table 3.1. As Received Gradations – Percent Passing

Sieve	Dura-Berm	Gravel	Sand	RAP
0.75 in	89	87	100	93
No. 4	24	8	92	56
No. 30	4	1	81	15
No. 200	1.6	0.2	17.7	1.4

Note: RAP gradation was measured on conglomerates received; no solvents were used to extract actual particles as this would increase the amount of No. 200 particles but does not represent use in unpaved roads.

Materials were batched to the desired gradation and placed in plastic buckets prior to mixing and compaction (Figure 3.6a). Materials were mixed in 5-gallon metal buckets with concave bottoms (Figure 3.6b). A paddle and trowel were used to assist with mixing uniformity (Figure 3.6c). Mixing began with dry ingredients, and once they were mixed for a few seconds, water was gradually added until the proper amount had been added and all ingredients were uniformly mixed (3 to 4 minutes of mixing was typical).

Mixed material was compacted to produce Proctor specimens as per AASHTO T99 or CBR specimens as per AASHTO T193. An automatic Proctor hammer was used dropping a 5.5 lb hammer a distance of 12 in. Proctor molds were 6 in inside diameter, and 3 layers were compacted with 56 blows per layer. Between each layer, the specimen was scarified to ensure uniformity and prevent stratification. Compacted specimens were stuck off level with the tops of specimen molds, weighed, then a moisture content was taken from specimen centers. Proctor testing determined maximum dry density (γ_d) and optimum moisture content (OMC).

a) Batched Material Awaiting Mixing

b) Bucket Mixing

c) Mixing Tools

Figure 3.6. Photos of Pre-Batched Specimens and Mixing

The same amount of compaction, scarification (e.g. Figure 3.7a), and similar was applied to CBR specimens as was applied to Proctor specimens. CBR specimens were produced at OMC with 56 blows (B) per lift. CBR molds are approximately 2.4 in taller than Proctor molds to allow room for a spacer disk that is placed in the bottom of the mold during compaction. Once compacted, the CBR specimen was flipped, the spacer removed, and the cavity has a stem for surcharge weights to be placed for the soaking period. Due to the granular nature of several of the tested mixtures, the entire CBR mold needed to be flipped as a whole with another base plate located on the top of the struck off material. To facilitate this process, a hole was drilled into the bottom of a CBR spacer disk, that allowed a bolt to be threaded into the disk once the base plate was removed so the spacer could be lifted vertically from the mold (Figure 3.7b). The granular nature of several of the blends tested damaged filter paper, and as such filter paper was withheld during compaction and placed after the specimen was flipped and the spacer was removed. Dry density of compacted CBR specimens was determined from the fully compacted specimen total mass, dimensions of a fully compacted specimen, and a moisture content taken from the fully mixed material just prior to compaction. The dry density of CBR specimens was reported as a percentage of AASHTO T99 density (%-γ_d).

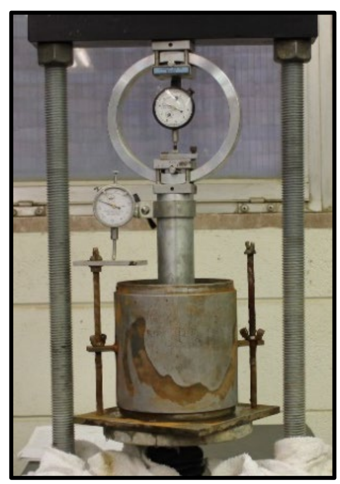
a) Scarification

b) CBR Spacer and Removal Accessories

c) Soaking

d) CBR Load Frame

e) 15 Minute Draining Period



f) CBR Test

Figure 3.7. CBR Specimen Preparation and Testing

After CBR compaction, a stem plate was placed directly on the specimen, and two surcharge weights (total 10 lbs) were placed on top of the stem plate. This configuration was placed in the bottom of a tank filled with water that was maintained at least 1 in above the specimen. A dial gage was placed on the specimen to record shrink/swell (denoted Δh and reported alongside time of submersion as a percent of original specimen height where positive values are swell). Specimens were kept underwater for either 4 days as specified in T193 (denoted CBR_{4D}) or 90 days (denoted CBR_{90D}) to assess any bonding potential from free lime or other potentially reactive products within the steel slag. Figure 3.7c shows specimens soaking with dial gages in place.

CBR testing occurred within 10,000 lb capacity load frames (e.g. Figure 3.7d). Load rates were calibrated with gage blocks at 1.27 mm/min (0.05 in/min). Just prior to removal from water submersion, a final Δh value was recorded. Specimens were placed on top of a CBR collar and drained for 15 minutes while covered with a damp towel to minimize surface evaporation (Figure 3.7e). At the end of drainage, specimens were weighed a final time and tested (Figure 3.7f). For specimens that approached the load ring capacity, tests were halted and data recorded was up to the point of the tests being stopped. This was done in accordance with AASHTO T193. After CBR testing, specimens were removed and a sample was extracted from them to measure as tested moisture content ($w_{AT\%}$).

One additional small experiment was performed with the Plastic Mold compaction device (i.e. PM Device) currently specified in AASHTO PP 92-19 and described in several references (e.g. Sullivan et al., 2015; Sullivan and Howard 2017; Sullivan and Howard 2019, Sullivan et al., 2020). A blend of 50% gravel and 50% Dura-Berm was compacted and moist cured for 14 days to see if any evidence of particle bonding occurred. At the end of 14 days, the compacted specimen was removed from its mold and visually evaluated.

3.4 Laboratory Test Results

Tables 3.2 to 3.5 summarize all laboratory results for the sixteen blends tested. Note that the Proctor (T99) column repeats in each table. Also note that %-γ_d, Δh, and $w_{AT\%}$ are organized according to a corresponding CBR test set. For example, blend 100/0/0/0 had an average CBR after a traditional soaking period of 4 days of 43 (i.e. CBR_{4D} in the first row of Table 3.2 had an average of 43 from five replicate tests). The average %-γ_d value of 101.2 in Table 3.3 is for these same five replicate tests of blend 100/0/0/0.

Figure 3.8 is a visual of select blends in the CBR mold after testing. A yellow circle shows the approximate area penetrated by the CBR loading piston. These images are to highlight the considerably different surface texture of the blends, and to a secondary extent to show the failures in the vicinity of the CBR loading piston. Figure 3.9 provides additional visual representation of select blends surface texture after compaction, but prior to testing.

There was very little to no evidence of reactivity within blends containing steel slag. Blend 100/0/0/0 (i.e. all steel slag) had effectively the same CBR after 4 days of submerged curing (43) as after 90 days of submerged curing (37). Visually, there was some very modest evidence of particle bonding in the all steel slag blend (Figure 3.10), but overall this is not compelling when CBR values were not meaningfully different after soaking for 86 additional days. The five blends tested after submerged curing for 4 days and also after submerged curing for 90 days were not meaningfully different. Also, the PM compacted specimen shown in Figure 3.10 displayed no evidence of particle bonding.

Table 3.2. Laboratory Test Results – 1 of 4 – CBR

Blend	Proctor (T99)		CBR_{4D-56B} (T193)			$CBR_{90D-56B}$		
	γ_D (lb/ft^3)	OMC (%)	n	R	Avg	n	R	Avg
100/0/0/0	140.0	6.8	5	37-49	43	6	28-42	37
0/100/0/0	101.5	5.5	5	28-45	37	6	31-61	50
0/0/100/0	109.9	12.4	5	18-32	24	---	---	---
0/0/0/100	117.9	7.3	5	17-21	20	---	---	---
75/25/0/0	131.0	4.0	5	36-63	49	6	43-62	49
50/50/0/0	119.5	4.0	5	34-50	44	6	30-62	45
25/75/0/0	109.5	5.3	5	24-43	35	6	32-40	37
87.5/0/12.5/0	165.3	8.3	5	118-201	169	---	---	---
75/0/25/0	160.0	6.7	5	189-288	228	---	---	---
62.5/0/37.5/0	152.3	8.0	5	160-204	176	---	---	---
50/0/50/0	141.9	8.6	5	79-120	106	---	---	---
37.5/0/62.5/0	134.9	7.9	5	66-70	68	---	---	---
25/0/75/0	124.6	9.7	5	34-51	43	---	---	---
75/0/0/25	151.5	7.8	3	22-26	24	---	---	---
50/0/0/50	140.2	6.7	4	27-38	33	---	---	---
25/0/0/75	132.7	7.0	5	23-26	25	---	---	---

n = number of replicate tests
R = range of all replicate test results
Avg = average of all replicate test results

Table 3.3. Laboratory Test Results – 2 of 4 – Compaction

Blend	Proctor (T99)		%-γ_d of CBR_{4D-56B}			%-γ_d of $CBR_{90D-56B}$		
	γ_D (lb/ft^3)	OMC (%)	n	R	Avg	n	R	Avg
100/0/0/0	140.0	6.8	5	100.2-103.6	101.2	6	98.0-101.3	99.7
0/100/0/0	101.5	5.5	5	98.8-102.6	100.6	6	94.4-100.1	97.8
0/0/100/0	109.9	12.4	5	97.0-101.4	99.1	---	---	---
0/0/0/100	117.9	7.3	5	99.0-99.9	99.3	---	---	---
75/25/0/0	131.0	4.0	5	99.9-103.5	100.0	6	98.5-103.0	100.2
50/50/0/0	119.5	4.0	5	99.1-100.9	100.2	6	97.4-102.3	99.8
25/75/0/0	109.5	5.3	5	99.7-104.1	100.7	6	98.9-101.3	100.4
87.5/0/12.5/0	165.3	8.3	5	101.1-102.8	101.8	---	---	---
75/0/25/0	160.0	6.7	5	98.9-100.9	100.1	---	---	---
62.5/0/37.5/0	152.3	8.0	5	99.0-100.4	99.9	---	---	---
50/0/50/0	141.9	8.6	5	97.2-100.0	98.6	---	---	---
37.5/0/62.5/0	134.9	7.9	5	98.0-99.5	98.8	---	---	---
25/0/75/0	124.6	9.7	5	95.8-100.3	98.1	---	---	---
75/0/0/25	151.5	7.8	3	89.9-94.0	91.8	---	---	---
50/0/0/50	140.2	6.7	4	94.6-97.3	95.7	---	---	---
25/0/0/75	132.7	7.0	5	93.2-95.6	94.3	---	---	---

n = number of replicate tests
R = range of all replicate test results
Avg = average of all replicate test results

Table 3.4. Laboratory Test Results – 3 of 4 – Shrink/Swell

Blend	Proctor (T99)		Δh (%) of CBR_{4D-56B}			Δh (%) of $CBR_{90D-56B}$		
	γ_D (lb/ft^3)	OMC (%)	n	R	Avg	n	R	Avg
100/0/0/0	140.0	6.8	5	-0.01-0.00	0.00	6	-0.17-0.00	-0.03
0/100/0/0	101.5	5.5	5	-0.02-0.01	-0.01	6	-0.10-0.05	-0.04
0/0/100/0	109.9	12.4	5	0.09-0.34	0.20	---	---	---
0/0/0/100	117.9	7.3	5	-0.28-0.00	-0.16	---	---	---
75/25/0/0	131.0	4.0	5	-0.01-0.00	0.00	6	-0.10-0.02	-0.04
50/50/0/0	119.5	4.0	5	-0.02-0.00	0.00	6	-0.11-0.00	-0.03
25/75/0/0	109.5	5.3	5	-0.01-0.00	0.00	6	-0.14-0.24	-0.01
87.5/0/12.5/0	165.3	8.3	5	0.00-0.01	0.00	---	---	---
75/0/25/0	160.0	6.7	5	-0.01-0.01	0.00	---	---	---
62.5/0/37.5/0	152.3	8.0	5	0.00-0.02	0.01	---	---	---
50/0/50/0	141.9	8.6	5	-0.03-0.13	0.01	---	---	---
37.5/0/62.5/0	134.9	7.9	5	0.03-0.07	0.05	---	---	---
25/0/75/0	124.6	9.7	5	0.02-0.20	0.10	---	---	---
75/0/0/25	151.5	7.8	3	-0.08-0.00	-0.03	---	---	---
50/0/0/50	140.2	6.7	4	-0.22- -0.05	-0.11	---	---	---
25/0/0/75	132.7	7.0	5	-0.24- -0.04	-0.11	---	---	---

n = number of replicate tests
R = range of all replicate test results
Avg = average of all replicate test results

Table 3.5. Laboratory Test Results – 4 of 4 – Moisture Content

Blend	Proctor (T99)		WAT% of CBR_{4D-56B}			WAT% of $CBR_{90D-56B}$		
	γ_D (lb/ft^3)	OMC (%)	n	R	Avg	n	R	Avg
100/0/0/0	140.0	6.8	5	2.5-4.3	3.5	6	4.4-7.5	5.8
0/100/0/0	101.5	5.5	5	5.0-5.5	5.2	6	5.7-6.0	5.8
0/0/100/0	109.9	12.4	5	13.8-16.7	15.3	---	---	---
0/0/0/100	117.9	7.3	5	8.0-9.4	8.8	---	---	---
75/25/0/0	131.0	4.0	5	3.4-3.7	3.5	6	4.0-5.1	4.7
50/50/0/0	119.5	4.0	5	3.9-4.1	4.0	6	4.2-5.4	4.8
25/75/0/0	109.5	5.3	5	4.2-4.6	4.4	6	4.8-5.5	5.2
87.5/0/12.5/0	165.3	8.3	5	6.8-7.1	6.9	---	---	---
75/0/25/0	160.0	6.7	5	6.7-7.3	6.9	---	---	---
62.5/0/37.5/0	152.3	8.0	5	7.2-7.9	7.7	---	---	---
50/0/50/0	141.9	8.6	5	8.7-10.2	9.5	---	---	---
37.5/0/62.5/0	134.9	7.9	5	9.9-10.4	10.2	---	---	---
25/0/75/0	124.6	9.7	5	11.1-14.2	12.6	---	---	---
75/0/0/25	151.5	7.8	3	5.9-6.7	6.1	---	---	---
50/0/0/50	140.2	6.7	4	6.7-8.0	7.3	---	---	---
25/0/0/75	132.7	7.0	5	7.6-8.3	8.0	---	---	---

n = number of replicate tests
R = range of all replicate test results
Avg = average of all replicate test results

a) 100% Dura-Berm

b) 100% Gravel

c) 100% Sand

d) 100% RAP

e) 75% Dura-Berm, 25% Gravel

f) 75% Dura-Berm, 25% Sand

g) 75% Dura-Berm, 25% RAP

h) 50% Dura-Berm, 50% Sand

Figure 3.8. Photographs of Specimens Post CBR Testing

a) 75% Dura-Berm, 25% Sand *b) 25% Dura-Berm, 75% Gravel* *c) 75% Dura-Berm, 25% Gravel*

Figure 3.9. Select Specimens After Compaction

The most compelling observation in Table 3.2 is that average CBR values are below 50 for all blends except those containing a blend of steel slag and sand, and in those cases as long as half or more of the blend is steel slag, the average CBR is above 100. The optimal blend was 75% steel slag and 25% sand, which produced an average CBR of 228. This finding is somewhat intuitive in that a proper gradation is needed for stability of an unpaved road, but these findings also highlight the importance of product evaluation that represents the condition of interest. The 100/0/0/0 blend should not be taken as the anticipated behavior of steel slag within an unpaved roadway as come might suggest, rather, the steel slag when blended with existing roadway materials at the approximate gradation and ingredients percentages is a more appropriate behavior indicator.

50% Dura-Berm, 50% Gravel – PM Device Compacted –14 day cure – no evidence of particles bonding together

100% Dura-Berm – CBR – 90 day soak – evidence of a few semi-bonded particles

Figure 3.10. Photographs of Particle Interactions Over Time

With regard to compaction, most achieved an average %-γ_d of 98 to 102%, which provides reasonable means to directly compare CBR values. The notable exception was the three steel slag and RAP blends in the bottom three rows of Tables 3.2 to 3.5 where average %-γ_d values were 92 to 96%. The reason for the %-γ_d of these blends differing by a considerable amount from the 98 to 102% range is not known, but it is likely due to variability in the RAP materials utilized. Very little care was taken with the RAP materials utilized other than to have a consistent bulk gradation. The CBR specimens from these three blends were tested later in the program. Given their very low CBR values (33 or less), there was believed to be no need to investigate further as a repeat experiment where the Proctor and CBR specimens were produced with a uniform sample of RAP at this gradation were believed to be likely to lead to CBR values of 50 or less. Overall, the authors believed the most likely explanation for the low %-γ_d from these three blends was RAP material variability between the Proctor and CBR specimens, and that the CBR specimens were reasonably compacted.

CBR swell (Δh) values (Table 3.4) showed average values were 0.2% or less, where the all sand blend (0/0/100/0) swelled an average of 0.2% and the all steel slag blend (100/0/0/0) had no measurable swell. For reference, Netterberg and Paige-Green (1988) and Paige-Green et al. (2015) summarized laterite and lateritic soil base specifications in the Brazilian market as having CBR swell of generally below 0.2 to 0.5% and fines contents of at least 5% when a surface treatment to up to 2 inches of asphalt was to be applied. Lateritic materials have high iron oxide and aluminum contents but also have a meaningful clay content. As an additional reference, Amadi (2014) studied the effects of modifying subgrade soils with quarry fines and cement kiln dust and used CBR swell measurements as part of their assessment. Amadi (2014) referenced the Transport Scotland standard HA 74/07 (2007) where an average swell from CBR testing that exceeds 5 mm (4.3%) is a failing result for a pavement subgrade. The materials tested ranged from roughly 5.5% to less than 1%. Overall, the swell values measured for the materials evaluated in this report were manageable to negligible.

As tested moisture contents (Table 3.5) were fairly inconsistent relative to OMC. The draining period allowed blends that were mostly to all steel slag to discharge water and be tested at a moisture content below OMC. On the other hand, blends with meaningful amounts of sand, had moisture contents above OMC, even after the draining period. Blends where RAP or gravel were the primary material were tested as moisture contents closer to OMC. Given the nature of these materials, the as tested moisture content results were not surprising.

3.5 Noxubee County Case Studies

Four routes in Noxubee County, MS were selected for evaluation as case studies. This section provides fundamental information collected from these case studies, alongside basic observations. A more detailed evaluation of the data collected is planned for a future manuscript focused exclusively on unpaved applications for steel slag.

Figure 3.11 highlights locations of the four routes evaluated, all of which reside in District 5 in the northern portion of Noxubee County. Noxubee county is divided into 5 districts (denoted with gold letters in Figure 3.11), and each district has a supervisor. Noxubee County has been using steel slag as a part of their unpaved road program for some time, and a site visit occurred on November 13, 2019 where their overall program and concepts for effective use of slag were discussed. On this visit, Noxubee County officials estimated they have 10 roads in their district that utilize steel slag.

Glenn Road was a topic of conversation during the November of 2019 site visit. The steel slag on this route is roughly 3 inches deep and was placed in two lifts. The top of Glenn Road has tightened over time as grading operations blade and pull material in from the shoulders; gradation improvements as documented earlier are a likely explanation. Typical operations in Noxubee County District 5, as of November 2019, were to loosen and shape the existing roadway surface, and while the existing material is loose to end dump steel slag over this material from trucks. A second layer of steel slag is then placed. No additional blending occurs prior to adding water if needed and roller compacting.

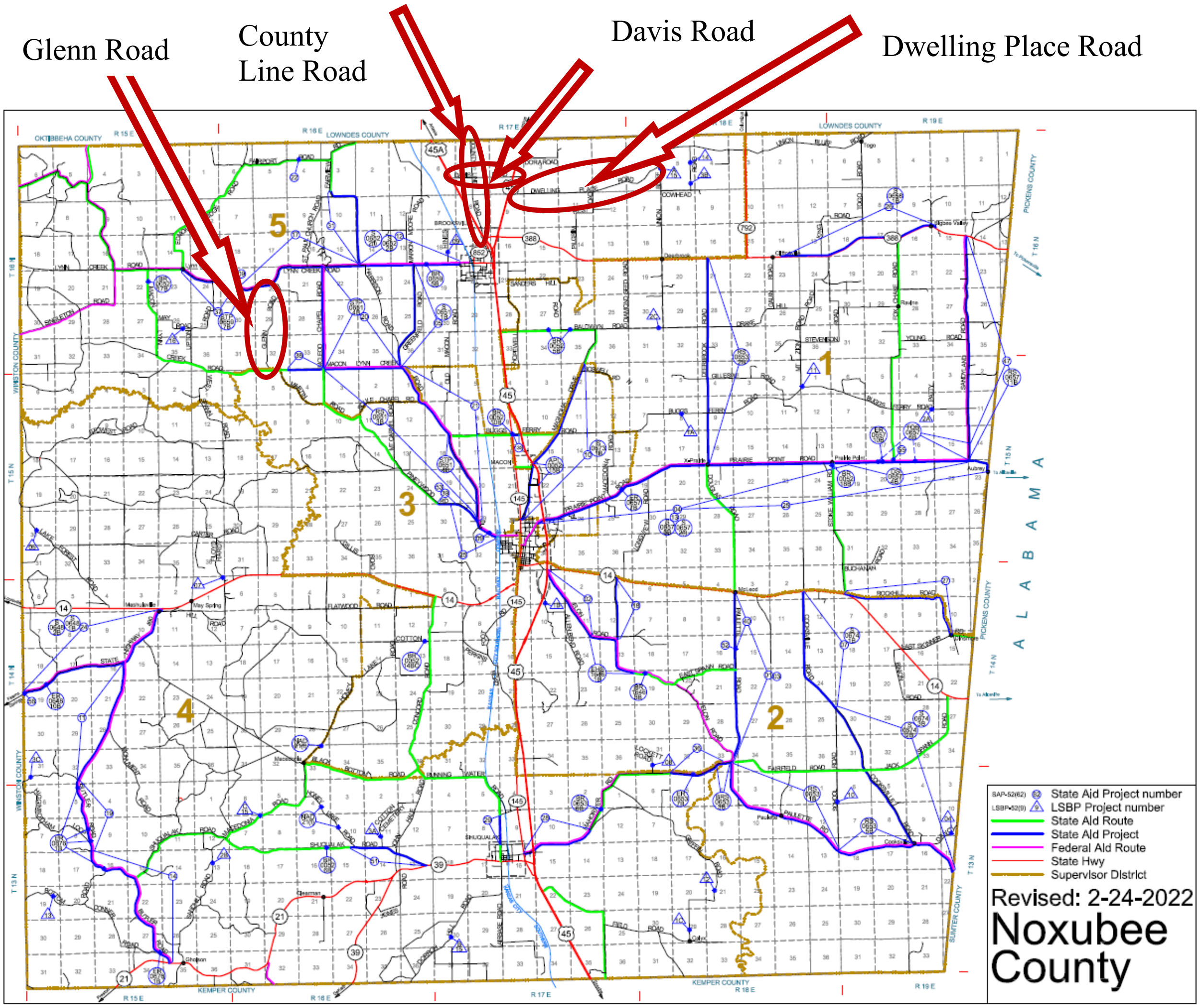


Figure 3.11. Noxubee County Routes Evaluated

On January 20, 2020, all four routes were sampled for laboratory evaluation. Figure 3.12 provides relevant photographs. Samples were taken from rectangular areas that were approximately 17 to 21 inches on a given side with hole depths of roughly 2.5 to 4 in, but mostly on the order of 3 in deep. Any loose material at a sampling location was incorporated into the sample. Figure 3.13 shows laboratory processing of the samples. A No. 4 screen, mortar/pestle, and hand work was used to dislodge any particle conglomerates.

Once material was processed (Figures 3.14a to 3.14d show processed materials), an appropriately sized sample was used to perform a washed sieve analysis as per ASTM C117 to remove particles passing a No. 200 sieve (– No. 200). Thereafter, washed particles were split over a No. 8 sieve for visual examination (Figure 3.14). Particles that retained on the No. 8 sieve were further divided into six fractions (+0.75 in, +0.50 in, +0.38 in, +0.25 in, +No. 4, +No. 8) and visually sorted into steel slag and non-steel slag particles (Figures 3.14e to 3.14h). In each of the images in Figures 3.14e to 3.14h, there are twelve slices for steel slag and non-steel slag particles in each of the six size fractions.

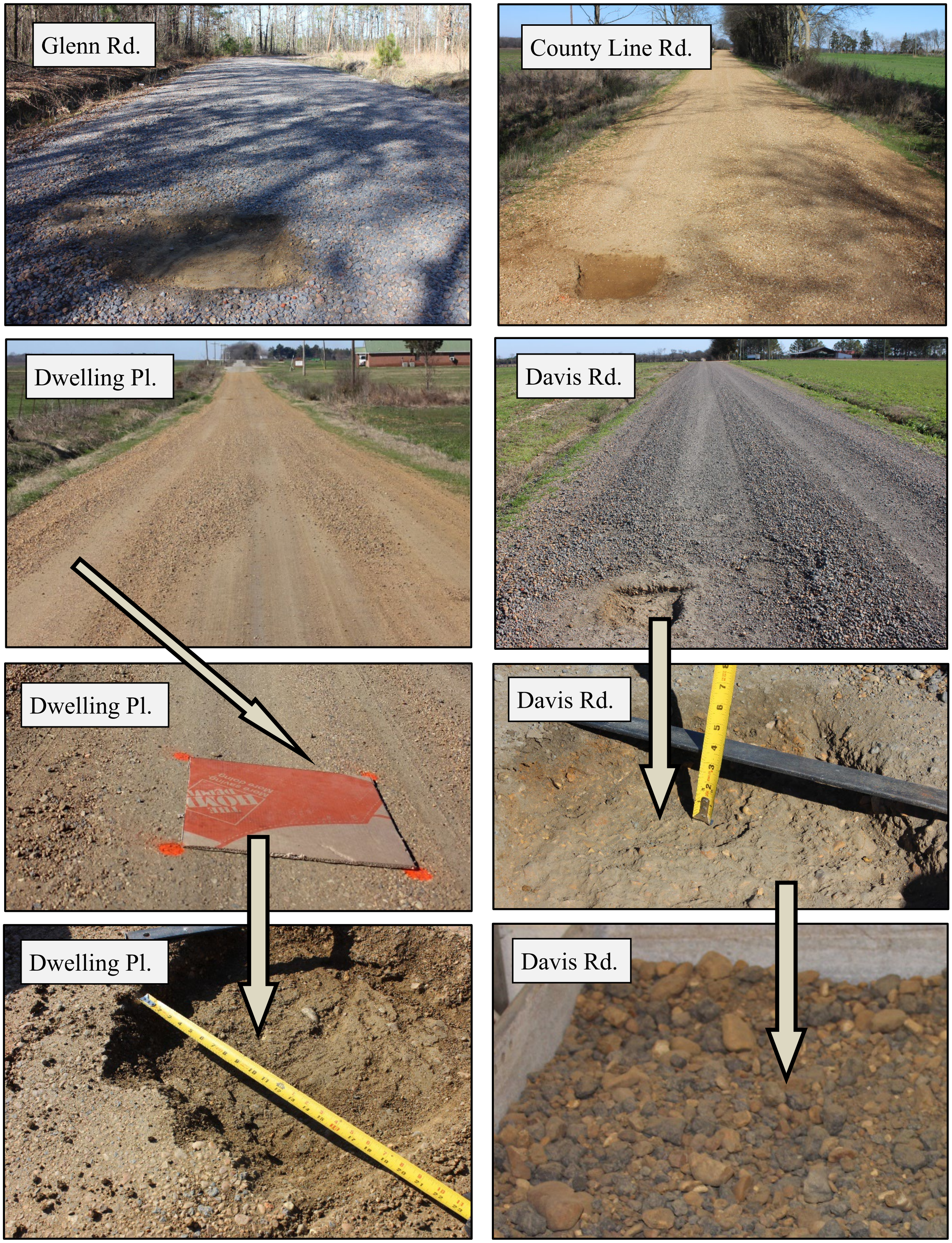
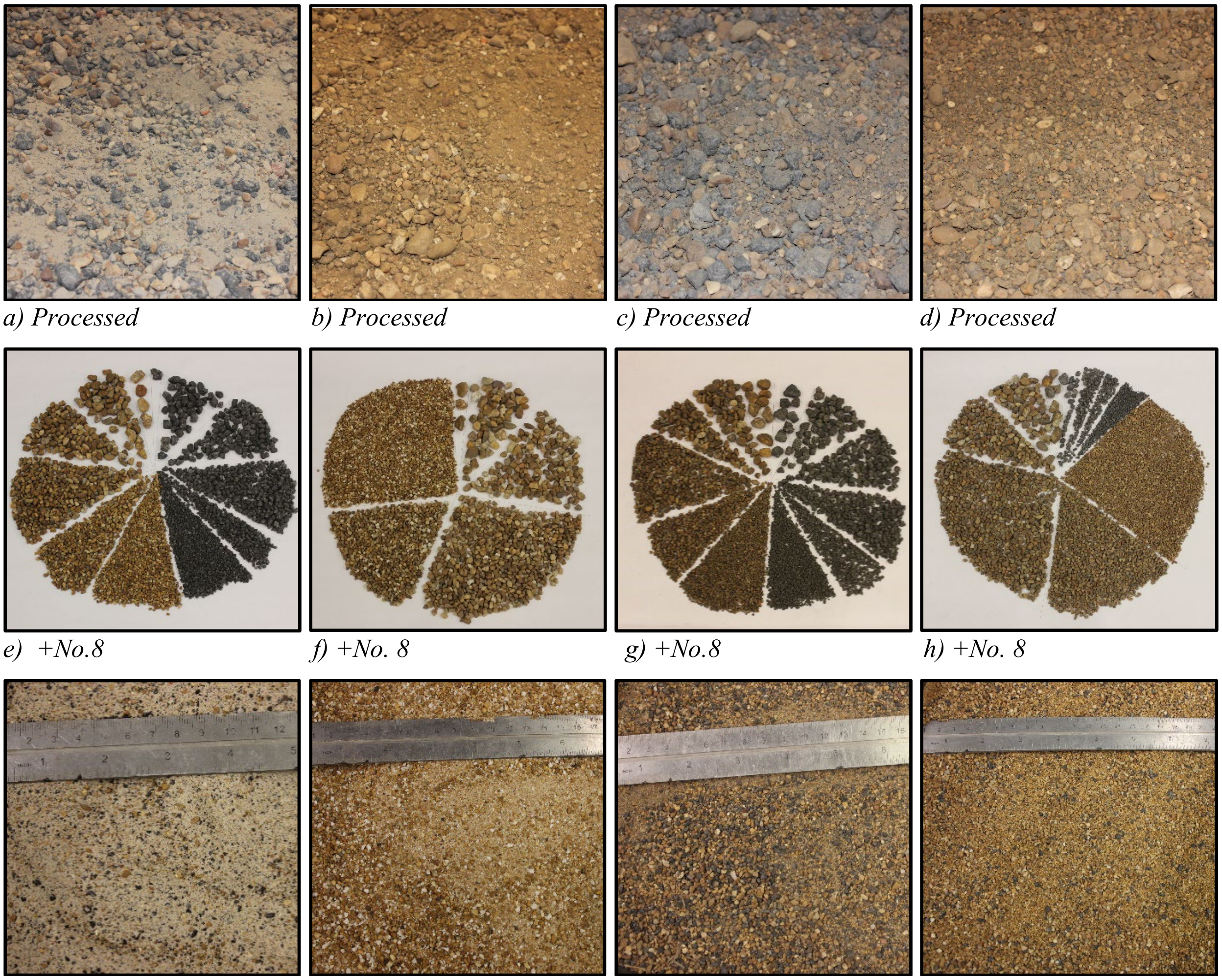


Figure 3.12. Photos of Roadways and Materials Sampling

Figure 3.13. Material Processing

Once photographed, the samples evaluated in Figures 3.14e to 3.14h were used to estimate the amount of steel slag by mass retained on the No. 8 sieve. The – No. 8 particles were not sorted, but are shown visually in Figures 3.14i to 3.14l. Once photographs were taken, a gradation was performed on the full + No. 200 sample (steel slag and non-steel slag) according to ASTM C136 to produce a full gradation curve when combined with results from ASTM C117, where results are shown in Table 3.6.



a) Processed *b) Processed* *c) Processed* *d) Processed*

e) +No.8 *f) +No. 8* *g) +No.8* *h) +No. 8*

i) –No.8 and + No. 200 *j) –No. 8 and + No. 200* *k) –No.8 and + No. 200* *l) –No. 8 and + No. 200*

Glenn Rd. *County Line Rd.* *Davis Rd.* *Dwelling Place*

Figure 3.14. Visuals of Aggregates and Particle Distributions

Table 3.6 summarizes all test results from the Noxubee county projects. Atterberg limits were measured as per ASTM D4318, and Proctor specimens were measured as per AASHTO T99. CBR specimens followed AASHTO T193 in one set of specimens, and omitted the 4 day soak period for another set of specimens (T193+). CBR terminology was the same as was used in Section 3.3. Due to limited amounts of material, a specimen was prepared and tested absent a soaking period (i.e. $CBR_{0D\text{-}56B}$), the area surrounding the piston was removed from the mold and discarded, and the remaining material was remixed and used to produce a T 193 specimen.

Table 3.6. Summary of Noxubee County Project Properties

	Glenn Rd	Davis Rd	Dwelling Place Rd	County Line Rd
Road Identification Number	4	2	1	3
Estimated Steel Slag +No. 8 (%)[1]	50	50	10	0
Time of Steel Slag Service (years)[2]	2.75	1.0	3.0	---
Liquid Limit (%)	16	34	39	17
Plastic Limit (%)	13	19	19	16
Plasticity Index (%)	3	15	20	1
γ_d (pcf)	152	147	129	133
OMC (%)	6.0	7.8	9.8	7.3
Passing 0.75 in Sieve (%)	98	92	97	99
Passing 0.50 in Sieve (%)	87	78	91	93
Passing 0.38 in Sieve (%)	74	66	82	86
Passing 0.25 in Sieve (%)	58	50	64	71
Passing No. 4 Sieve (%)	50	43	52	62
Passing No. 8 Sieve (%)	40	33	34	47
Passing No. 16 Sieve (%)	36	27	27	39
Passing No. 30 Sieve (%)	34	24	23	34
Passing No. 40 Sieve (%)	33	22	21	31
Passing No. 50 Sieve (%)	31	20	20	28
Passing No. 100 Sieve (%)	23	17	18	19
Passing No. 200 Sieve (%)	14	15	16	12
$CBR_{4D\text{-}56B}$ (T193)	134, 225, 228, 255 {211}	168, 185, 190 {181}[3]	9, 10 {10}	28, 84, 107 {73}
$CBR_{0D\text{-}56B}$ (T193+)	129, 158, 190, 195 {168}	120, 170, 208, 213 {178}	5, 7 {6}	24, 30, 91 {48}
$\%S_{4D\text{-}56B}$ (T193)	0.00	0.15 to 0.18	0.16 to 0.17	0.00 to 0.11

AASHTO T99 protocols were used to measure γ_d and OMC. During data collection, Davis Rd and County Line Rd CBR data was recorded opposite to what is shown in this report. An internal investigation led to these data being reversed after several items fully supported this change and that the original recording was a laboratory error.

1: Steel slag percentage is for particles retained on a No. 8 sieve.

2: Approximate time that slag was in service as of January 2020.

3: Fourth replicate couldn't achieve 0.1 inch reading level with correction applied.

For purposes of this report, Table 3.6 clearly shows the benefits of steel slag when used within unpaved roads where the steel slag percentages are high enough to produce meaningful CBR improvements. Glenn Rd had a low plasticity index, a high CBR value, and no measurable swell. Figure 3.15 provides visuals of Gleen Road condition over time. Additional assessment of this data is planned for a future document.

In September of 2020, Edw C. Levy representatives engaged Noxubee County District 5 representatives about their unpaved roads. This engagement was intentionally held until after MSU had finished their testing and preliminary assessment of the site visit data collected. An overall assessment of all their District 5 routes was that portions of their road network containing steel slag have reduced maintenance and grading relative to routes without steel slag. An estimate was grading was reduced by 50 to 75% by way of steel slag use, which is largely in comparison to use of clay gravel. This 50 to 75% reduced grading is a holistic assessment of any areas in their network that use a modest amount of steel slag. Also, representatives noted no failures have been observed in portions of their unpaved road network containing steel slag. Overall, drivers, farmers, and homeowners were favorable to steel slag's use on unpaved roads.

Figure 3.15. Glenn Road Photos Over Time

Glenn Road (50% slag) was reported to have no visible aggregate accumulation in adjacent ditches, reduced mud, reduced dust, and the portion of the roadway with steel slag has been reported as performing very well for the traveling public and for maintenance. The aforementioned assessments were for the portion of Glenn Road that uses steel slag; clay gravel is also used on a portion of Glenn Road. Davis Road (50% slag) was reported to have a firmer base for farmers and heavy equipment, shoulders that hold up well, and aggregate stays on roadway driving surface and does not excessively migrate into adjacent ditches. Glenn and Davis roads were reported to be the best performing routes.

Dwelling Place (10% slag) was reported to have a firmer base and the route has been reported favorable for heavy farm equipment. County Line Road (0% slag) had visible aggregate accumulation in the vicinity of material sampling for these experiments. This route has steel slag on the south end of the roadway away from where the sample was taken. The south end of County Line Road has been reported as favorable by farmers with favorableness decreasing on the northern section where steel slag isn't used.

3.6 Discussion of Mississippi Market Potential

The data collected and presented in this chapter provides clear evidence of steel slag's viability for unpaved roads in the vicinity of the GTMS facility. Any location where trucking costs are not prohibitive should be considered a candidate for Dura-Berm from GTMS (or a comparable material from GTMS or another source). For reference, a local contractor provided aggregates trucking costs in 20 to 25 ton loads in the Golden Triangle regional market in the fall of 2019. Haul distances up to 20 miles were estimated at $4/ton, and thereafter an additional $0.20/ton mile should be added (i.e. 30 miles is $6/ton). This report did not directly consider Dura-Berm* in the Memphis, TN market. Edw C. Levy did, however, report that Dura-Berm* is very commonly used in the unpaved surface market and that the overall user satisfaction and performance is directly comparable to that for the Dura-Berm from GTMS that is the focus of this chapter.

This report did not directly consider placing a wearing surface over unpaved roads after they have been in place for some time so they have densified with depth, though this is an area of potential. For example, a sub-division in a rural area might consider making use of unpaved roads with steel-slag during construction, and thereafter adjust the on-site gradation (if needed) to one comparable to Glenn Road, compacting the material to typical construction standards, then placing a chip or fog seal over the top of the road.

A third application with promise is use of steel slag for highway shoulders. No work of this nature was performed specifically for this project, but the Mississippi Department of Transportation (MDOT) initiated a test section on State Route 388 in the summer of 2019 where a steel slag test section is present as shoulder aggregate alongside eight other test sections. Findings from this MDOT study should be referred to for viability as a shoulder aggregate.

CHAPTER 4 - PLANT MIXED ASPHALT

4.1 Overview of Plant Mixed Asphalt

Plant mixed asphalt has successfully used steel slag in several markets over an extended period of time. Mississippi has used steel slag in asphalt mixes, and this chapter documents use in Mississippi within stone matrix asphalt (SMA). Plant mixed asphalt was of secondary interest in this investigation, due largely to Mississippi having an abundant supply of very hard and polish resistant gravel aggregates. A common use of steel slag is for polish/skid resistance of surface mixtures, and in the Mississippi market, alternatives exist for polish resistance. There are numerous references about EAF steel slag improving skid resistance and overall roadway safety (e.g. Liapis and Likoydis 2012).

The late Dr. Rebecca McDaniel performed some of the most state-of-the-art investigations into aggregates and polish resistance. Key references include: McDaniel and Coree (2003); McDaniel and Shah (2012); McDaniel et al. (2015); Kowalski et al. (2008); Kowalski et al. (2009); Kowalski et al. (2010). Collectively, this work, as it pertains to this report, shows steel slag to be a high friction aggregate. Friction resistance is key for markets where limestone, in particular polish prone limestone, is abundant and used as a paving material. Mississippi tends to use locally available crushed gravel aggregates for surfaces mixtures, often in conjunction with limestone.

A comprehensive literature review of steel slag use in plant mixed asphalt was not performed. A few references were selected to highlight successful use of steel slag in asphalt mixtures, and/or what attributes were sought from steel slag use. Wu et al. (2007) evaluated Marshall designed SMA mixtures and reported steel slag improved high temperature properties and resistance to low temperature cracking compared to a mixture with basalt aggregates. It is noteworthy that an additional 0.2% binder was present in the mixture containing steel slag. Field observations reported excellent roughness performance and British Pendulum surface coefficients.

Another reason cited in literature for use of steel slag is positive environmental impact. Ferreira et al. (2016) assessed the environmental impact of EAF slag (lime content of roughly 22%) by way of life cycle assessments. Their assessment concluded important environmental benefits could be obtained from EAF slag in the context of carbon footprint, abiotic depletion, ozone layer depletion, and photochemical oxidation.

Eldin (2002) performed an exhaustive environmental investigation of road construction materials from the perspective of their effect on the surrounding environment and adjacent water bodies. This study reported that steel slag was one of the ten most repurposed materials used by state agencies and that 15 states used this material as of roughly twenty years ago. Eldin (2002) employed a toxicity-based approach where test elutriates were prepared in a very conservative manner; i.e. toxicity conditions that could never duplicate in normal field conditions. When materials were incorporated into an asphalt mixture, less extreme results were obtained, and for reference, when materials were mixed into soil, reductions beyond asphalt were achieved. Steel slag's results were comparable toxicity wise to several other materials that are readily used in roadway construction.

Hansen and Copeland (2017) reports results from the National Asphalt Pavement Association (NAPA) 2016 construction season survey on recycled materials usage within plant mixed asphalt. A total of 229 companies and 1,146 production plants are represented; 4

of these companies and 22 of these plants were from Mississippi. Nationwide, it was estimated that 41.5% of all tons produced in 2016 were represented, and for Mississippi, the 2.69 million tons reported were estimated to be 57% of the total tons produced (4.72 million). The NAPA survey had steel slag listed within a category of "other recycled materials", and 53 companies responded with information in this category.

The NAPA recycled materials survey began tracking steel slag in 2012 and from 2012 to 2016, twelve states have reported steel slag use, including Mississippi. In 2015, Mississippi reported 3,000 tons of steel slag used, and in 2016, 500 tons were reported. Over this five year period, the total steel slag use from these twelve states ranged from 167,000 to 716,000 tons.

Blast furnace slag was also documented, and Mississippi did not report use of blast furnace slag. National reported blast furnace slag usage from 2012 to 2016 ranged from 444,000 to 741,000 tons. Hansen and Copeland (2017) cited the National Slag Association (NSA) as estimating more than 20 million tons of slag (steel or blast furnace) produced and marketed annually, and that 2016 usage in plant mixed asphalt accounted for about 3.7% of the total slag available.

4.2 Steel Slag for Asphalt in Mississippi

Informal discussions with Mississippi paving practitioners revealed use of slags from various sources for many years. As an example, in the 1980's a Chromium foundry was operational in Millington, TN and the resulting slag was fairly consistent with a specific gravity of around 3.1 with relatively low water absorption. This material was readily used in the paving market until around 1990 when the foundry closed. Challenges existed with crushing this material, and use of this material accelerated wear on paver screeds, plant drums, crusher belts, and similar. Overall, even with a higher specific gravity (i.e. lower volume per unit trucking cost), crushing challenges, and accelerated equipment wear, economics were favorably for the total in-place cost of plant mixed asphalt in the 1980's in the vicinity of Millington, TN when using this foundry slag.

Roughly ten years ago, a regional paving contractor began taking three different sizes of steel slag from Nucor's Memphis facility that was managed by Edw C. Levy. This operation was referred to as Memphis Mill Service (MMS) in Chapter 1. The contractor received a specified quantity of material where roughly 20% was sized 4 to 8 inches, roughly 30% was sized 1.0 to 1.5 inches, and roughly 50% was 0.75 inches and smaller. Their intended use was surface mixes. Over time this balance of material tended more to the 4 to 8 inch sized material. Crushing a material of this nature to a ¾ x 0 product (i.e. smaller than 0.75 inches) could generally be estimated to cost $15 to $20 per ton in the 2019 time frame.

Also roughly ten years ago, steel slag from the Golden Triangle Mill Service Co in Columbus, MS (referred to as GTMS in Chapter 1) was used to pave a small parking lot. Placement and performance were favorable. As of 2019, this lot was reported to be in good condition and during paving the appearance, workability, and stability were favorable.

In the spring of 2017 time frame, some paving contractors were using some EAF steel slag out of Nucor-Memphis, but in this time frame the decision was made to suspend production of this material in lieu of producing other steel slag products. Contractors purchased the remaining EAF steel slag and stockpiled it for future use. Generally speaking, contractors were purchasing a considerable percentage of large steel slag particles and using their own crushers to reduce the steel slag to sizes that are suitable for asphalt paving mixtures. Overall, the assessment of steel slag as a paving aggregate is favorable performance wise. Supply and crushing economics seem to be the most formidable factors in a paving market where crushed gravel can meet surface friction requirements.

4.3 Interstate 22 Asphalt Mixture Containing Steel Slag

In August of 2019, APAC-Mississippi, Inc. placed SMA containing steel slag onto Interstate 22 (I-22) near Tupelo, MS. This mixture was produced from their Auburn Road (south Tupelo) facility where the average mixture temperature (as measured by thermometers in buckets of sampled material) was approximately 345 ^{o}F. This mixture's primary purpose was evaluation of mixing temperature effects within Mississippi Department of Transportation (MDOT) specifications. This mixture is also part of a long term aging experiment at the Columbus Parking Lot (CPL) where it was given identification M60, or mix 60. For purposes of this report, the primary objective was to document successful use of steel slag in plant mixed asphalt in Mississippi.

The mixture produced contained the following aggregates: 28% limestone, 8% agricultural lime, 34% crushed gravel, 4% fly ash, 10% RAP, 1% hydrated lime, and 15% EAF steel slag from Nucor-Memphis (described in the previous section). The mixture also contained 6.3% PG 76-22 binder by mixture mass, and 0.3% fibers. Figure 4.1 is a close up view of the steel slag on the day of mixture production alongside its corresponding gradation. Water absorption (*Abs*) of this material was 1.3%, and bulk specific gravity in a dry condition (G_{sb}) was 3.525.

Sieve	Passing (%)
0.50 in	100
0.38 in	87
No. 4	46
No. 8	22
No. 16	10
No. 30	9
No. 50	8
No. 100	3
No. 200	2.3

Figure 4.1. I-22 EAF Steel Slag From Nucor-Memphis

Figure 4.2 shows photos of this mixture during production, placement, and sampling of plant mixed material for subsequent use in laboratory and field aging activities. Figure 4.3 shows representative photos of laboratory and field activities to measure Cantabro Mass Loss (CML) values as produced (i.e. unaged) and after one and two years of field aging. Average CML values unaged, after one year of field aging, and after two years of field aging were 20.0%, 24.0%, and 22.7% for general reference. The CPL field aging site is described in other publications (e.g. Smith and Howard 2019), as is CML testing (e.g. AASHTO T401, Cox et al. 2017).

Figure 4.2. I-22 Plant, Paving, and Mixture Sampling Operations

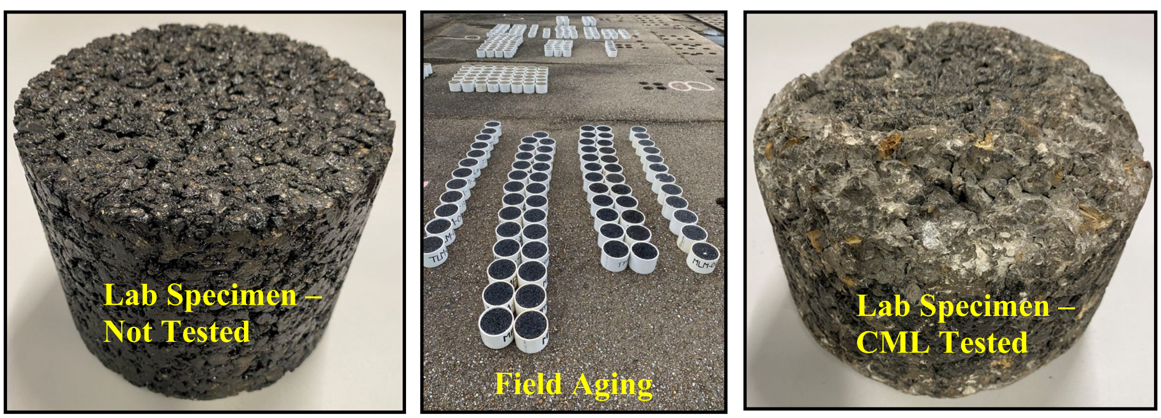


Figure 4.3. I-22 Laboratory Testing, Field Aging, and Cantabro Testing

4.4 Summary of Steel Slag in Plant Mixed Asphalt

This chapter documents successful placement of plant mixed asphalt containing steel slag in Mississippi. This chapter also documents key market factors that are likely to make unpaved applications, as discussed in Chapter 3, more viable in the majority of situations over time. Steel slag is typically used in surface mixtures, and performance wise, high friction is often the most desirable characteristic. Crushed chert gravel, abundant in Mississippi, can also provide desirable friction properties, which makes supply consistency and economics (crushing being a major factor) seemingly driving factors for selection on a given project.

CHAPTER 5 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

This report assessed the viability of steel slag within Mississippi's construction market. After a review of potential applications to evaluate further, three areas were explored: 1) cement stabilized in-place recycled pavement bases; 2) unsurfaced applications such as roads, parking lots, and shoulders; and 3) stone matrix asphalt (SMA). Each topic was explored within its own chapter and the most relevant findings are described in the following section.

5.2 Conclusions

1. *Cement stabilized In-Place Recycling:* Use of 15 to 30% non-expansive steel slag considerably improved elastic modulus derived per unit of unconfined compressive strength, which all other factors remaining equal allows reduced cement per unit modulus which should reduce potential for plastic shrinkage cracking and reduce embodied energy of the pavement layer.
2. *Unpaved Roads:* Laboratory testing and case studies of roadways in Noxubee county clearly concluded steel slag's viability for projects within reasonable trucking distances of steel mills. It was concluded that any location where trucking costs were not prohibitive should be considered a candidate for Dura-Berm from the Golden Triangle Mill Service (or a comparable material from this or other source).
3. *Stone Matrix Asphalt:* Successful use of steel slag was documented in SMA, though market factors (e.g. abundant chert gravel and a large expanse of unpaved roads and shoulders) are likely not to favor use in SMA to the same level in some other markets.

5.3 Recommendations

1. Use the AASHTO PP92 (final designation to be R120) PM Device to evaluate in-place recycling (with emphasis herein on steel slag) so unconfined compressive strength and elastic modulus can be simultaneously measured.
2. Consider evaluating the merits of a wearing surface (e.g. chip seal) over a mature unpaved road containing a reasonable percentage of steel slag after correcting surface irregularities. This report did not perform any work in this regard, but the positive findings for unsurfaced unpaved roads led to this as a recommendation for the future.
3. Consider steel slag for use on unpaved shoulders. No work of this nature was performed specifically for this project, but the Mississippi Department of Transportation (MDOT) initiated a test section on State Route 388 in the summer of 2019 where a steel slag test section is present as shoulder aggregate alongside eight other test sections. Findings from this MDOT study should be referred to for viability as a shoulder aggregate.
4. Users of Dura-Berm in the GTMS market are encouraged to consider on-site blending of a small amount of sandy material (e.g. MDOT Class 9B or 9C) when economically viable as data in this report showed the likelihood of meaningfully enhanced stability.

CHAPTER 6 - REFERENCES

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