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Re-use of steel slag as an aggregate to asphaltic road pavement surface

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Abstract: Electric arc Furnace steel slag produced from the ferrous smelting process in the manufacture of steel in Trinidad and Tobago presents disposal and environmental challenges. Research has demonstrated the possibility of overcoming these challenges by using this waste material as a substitute for sand and limestone aggregates for road surface course construction. The chemistry of the interaction of mineral aggregates with asphaltic materials determines the mechanical properties of the mixture and its suitability for engineering applications. Since the chemistry of asphaltic materials from different sources vary the properties of the mixtures cannot be generalized. The available literature on the utilization of slag as an aggregate with Trinidad and Tobago asphaltic materials for road construction is limited. This study investigated the influence of electric arc furnace steel slag (0–20% by weight of ¾ inch sized aggregates) using the Marshall stability of blends to determine the optimal slag content. Results revealed that, a slag content of 15% by mass of ¾ inch sized aggregates (or 2.25% of the total mass of aggregate) was optimal within Marshall stability and air void acceptability. Reuse of steel slag aggregate in this manner will result improvements in pavement performance and an environmentally friendly and more efficient management of this waste materials and preservation of environment.

Subjects: Materials Science; Transport & Vehicle Engineering; Civil, Environmental and Geotechnical Engineering

Keywords: slag; aggregate; bitumen; asphalt

1. Introduction

Trinidad and Tobago has been a steel producing nation for over three decades. As part of the thrust towards natural gas utilization, a mini-mill was constructed based on the Midrex® process and the electric arc furnace (EAF). The production of steel in the EAF generates significant quantities of EAF

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ABOUT THE AUTHORS

The authors in this study are part of a waste materials reuse research group who mission is to find reuse options for materials that are commonly disposed of. These include plastic products, slag, and automobile tyres.

PUBLIC INTEREST STATEMENT

Electric Arc Furnace (EAF) slag, a by-product from steel production, was investigated as a reuse option for natural aggregates in road pavement surface. An EAF steel slag aggregate (SSA) content with performance characteristics similar to the control (no EAF SSA addition) was obtained. Commercial application of the study can be immediately implemented. This reuse option is an alternative to disposal and will also reduce the impact of destructive quarrying to obtain natural aggregate otherwise.

steel slag as a waste product. This waste product presents disposal and environmental challenges. Research has demonstrated there is a possibility of utilization of this recycled raw material as a substitute for sand and limestone aggregates used in road construction.

Bitumen, is a black sticky substance obtained from natural asphalt deposits or from the refining of crude oil into petroleum products. In Trinidad and Tobago (T&T), asphalt also known as “pitch” is mined from the pitch lake at Brighton, La Brea. The pitch is heated to about 150 °C (300°F) for approximately 24–36 h to reduce the moisture and sulphur content. The residual pitch material termed Trinidad Lake Asphalt (TLA), is then strained and placed in barrels for local consumption and export. Trinidad Petroleum Bitumen (TPB) produced at the oil refinery is combined with TLA to produce asphalt cement for road pavements. Figure 1 reveals the compositions of different binder sources and highlights the uniqueness of the T&T asphaltic mixture.

According to the Highway Division of the Ministry of Works and Transport in T&T, road pavement comprises four (4) layers consisting of the sub–base, road base, binder course and surface course as shown in Figure 2. The base and sub-base utilize blue limestone, and sharp sand or natural gravel. The Binder Course layer is a load-bearing and strengthening layer and is usually composed of bitumen binder and aggregates such as ¾ inch blue limestone. The final surface (Surface Course), comprises Hot Mix Asphalt (HMA) made up of TPB, TLA and mineral aggregates such as porcellanite and blue limestone mixed together at a Batch Plant (Ragmoolie, 2015).

Asphaltic road pavement defects are mainly caused by moisture damage from harsh climatic conditions and excessive traffic loading. Defects include longitudinal cracking, transverse cracking, block cracking, alligator cracking, potholes and rutting (Aljassar, Metwali, & Ali, 2004; Asi & Khalayleh, 2011; Asi, Qasrawi, & Shalabi, 2007). Cementitious road pavements are an alternative to the asphaltic counterpart. When compared to asphaltic road pavements, concrete road pavements are more durable, have lower maintenance costs and vehicles consume less power as the pavement deflects significantly less under the vehicle wheels, especially with excessive loads. However, these are more expensive and can have less traction in wet conditions compared to asphaltic roads.

Studies have shown that incorporating industrial waste, including steel slag aggregate (SSA), fly ash, and crumb rubber from recycled tires improved the properties and performance of asphaltic pavements. Numerous researchers have found that, the rough textured surface, angular shape and high specific gravity of SSA provides high skid resistance, mechanical interlocking, better stability and rut resistance. (Hainin et al., 2012; Qian, Bai, Ju, & Huang, 2013; Skaf, Manso, Aragón, Fuente-Alonso, & Ortega-López, 2017; Ziari & Khabiri, 2007). SSA was found to also have properties to assist in deicing of the pavements (Gao, Sha, Wang, Tong, & Liu, 2017).

EAF steel slag is formed when a basic metal oxide such as calcium oxide reacts with molten silica at high temperatures. The slag protects the surface of the molten steel from the oxidizing environment as well as purifies the steel by removal of non-metallic impurities. SSA derived from this process is dark in colour and has a Swiss cheese appearance. The typical chemical composition of the EAF slag is shown in Table 1.

Figure 1. Compositions of different binder sources (Corbett, 1970; Maharaj, 2009).

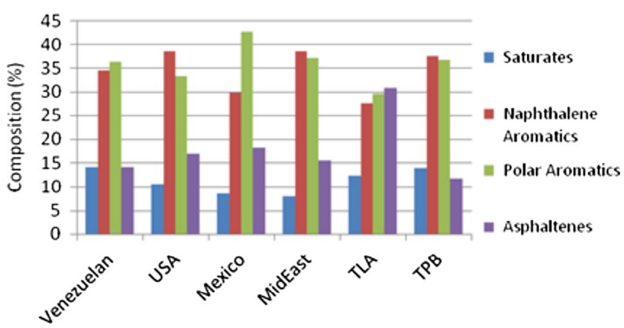

Figure 2. Layers of roadway construction (Ragmoolie, 2015).

Table 1. Typical chemical composition of EAF steel slag (White, 2003)

Chemical composition	EAF steel slag (%)
Calcium oxide	40–52
Iron oxide	10–40
Silicon dioxide	10–19
Magnesium oxide	5–10
Manganese dioxide	5–8
Aluminum oxide	1–3

It is noteworthy that EAF steel slag composition is dependent on the raw material source and its chemistry can vary from one batch to another. The rate of cooling from a molten liquid to a solid mainly affects the physical properties of SSA and as such, its chemical reactivity. Slag that is air-cooled is crystalline in nature and the Silica (SiO_2) is less acquiescent to initiating reactions with alkali when compared to the amorphous nature of glassy silica in water-cooled slag (Abd El. Aleem, 2004; Abd El-Aleem, Heikal, El. Didamony, & Abd-El-Aziz, 2005; Abd El-Aleem Mohamed, 2015; Abdel Gawwad, Khater, & Abd El-Aleem, 2016; El-Didamony, Abd El-Aleem Mohamed, & Gouda, 2015; Heikal, Abd El-Aleem, & Morsi, 2016; Sabrah, Abd El-Aleem, & Gouda, 2014). However, the higher density of air cooled slag render it more suitable for use as aggregate than water cooled slag. (White, 2003). Usually, SSA contains unreacted Calcium Oxide (CaO) or free lime, which undergoes volumetric expansion on exposure to moisture. This reaction must be completed through aging treatment before the slag can be utilized in the road industry (Kanda, Morisita, & Hamasaki, 2007). Natural aging takes approximately one year under humid conditions according to White (2003). Asi et al. (2007) state that, not all types of slags are suitable for processing into SSA as some types possess significant quantities of expansive free lime and free magnesium oxide. Overlooking these attributes can lead to pavement cracking (Ameri & Behnood, 2012). A comparison of some of the properties of steel slag with natural aggregate is shown in Table 2.

Test results have shown that, EAF steel slag is preferred in high stressed areas where conventional materials have failed (Kehagia, 2008). This is largely due to its advantageous technical properties which facilitates use not only for unbound layers like road bases and sub-bases, but also for surface layers (Ziari & Khabiri, 2007). Hainin et al. (2012) also noted that, SSAs have been reported to retain heat considerably longer than natural aggregates which can be advantageous for HMA construction.

Table 2. Comparison of some properties of steel slag with natural aggregates adapted from Ziari and Khabiri (2007)		
Characteristics	**Steel slag**	**Natural limestone aggregate**
Density, g/cm^3	3.30	2.73
Loose bulk density, g/cm^3	1.90	1.45
L. A. abrasion, %	13.2	23.0
Crushing value, %	12.1	15.6
Water absorption, %	1.29	1.08

This allows less energy to be utilized during the execution of asphaltic concrete works. Coarse EAF SSA aggregate was found to perform better than the fines counterpart since the fines appeared to worsen the water sensitivity of the mixes (Skaf et al., 2017). Masoudi, Abtahi, and Goli (2017) found that warm asphalt mixtures containing steel slag exhibited enhanced short-term and long-term performance as well as less aging.

According to Hainin et al. (2012) disposing of the slag will eventually become increasingly expensive for steel companies as the price of land for its disposal will be very costly. Additionally, the rise in steel production is accompanied by increased steel slag. Though non-hazardous, steel slag poses environmental, economic and technical problems (Marco Pasetto & Baldo, 2011). Utilizing SSA to supplement natural aggregate would also be beneficial because it will minimise depletion of natural resources such as limestone and sand. The continuous exploitation of these natural resources can result in environmental problems or high project costs (Hainin et al., 2012; Ziari & Khabiri, 2007). Due to the diminishing natural aggregate resources such as basalt, gravel, limestone and other processed rocks — researchers have tested the use of SSA in particular in many road construction activities (Hainin et al., 2012; Ziari & Khabiri, 2007).

Ziari and Khabiri (2007) conducted an investigation on the performance of asphalt concrete replacing some of the natural aggregates by crushed steel slag material from the Isfahan steel plant. A maximum slag particle size of 4.75 mm was used with limestone aggregate as the control sample. Refined bitumen of 60/70 penetration from the Tehran Bitumen Factory was used. Four steel slag samples of contents 0, 5, 10, 15 and 20% in terms of total aggregate weight were utilized. The binder content was 3.8% for all mixtures to allow comparisons. The strength and volume of the steel slag were investigated employing Marshall testing. The results revealed that, the control sample (0% slag) produced the highest Marshall stability and creep stiffness, followed by the 5% slag addition. Other researchers (Hainin et al., 2012; Pasetto & Baldo, 2012; Ziari & Khabiri, 2007) conducted similar tests with slag as a replacement/modifier and results are shown in Table 3.

Despite the existence of studies investigating the potential for the utilization of SSA as a supplement for aggregate materials in asphaltic based pavements, their findings especially with regards to the optimum dosages of added SSA to asphalt unfortunately, cannot be generalized for adoption in different countries (Zumrawi & Khalill, 2017). The literature demonstrates that most of the studies investigated the utilization of steel slag in HMA as coarse aggregate replacement with the optimal formulations of SSA slag content varied. Variations in formulations have been mainly associated with the fact that the source of the asphaltic base material plays a critical role on the eventual rheological and performance properties of the modified blends (Lesueur, 2008). Asphaltic materials from different sources naturally vary in their chemical composition and since the ultimate physical and performance properties of an asphaltic pavement is as a result of the intricate chemical interactions between the chemical functionalities between the asphaltic material, the aggregates and the additives (SSA), the optimum dosage for various additives to be incorporated in asphaltic systems may vary as demonstrated by the outcomes of previous studies incorporating various additives in TLA and TPB (Maynard, Maharaj, & Maharaj, 2015; Mohamed, Maharaj, & Ramjattan-Harry, 2016; Singh-Ackbarali, Maharaj, Ramjattan-Harry, & Mohamed, 2017). Studies comparing the chemical

Table 3. Optimum replacement slag contents from the work of other researchers

Study	Optimum slag replacement %based on highest Marshall quotient (MQ) or Marshall stability (MS) value	Range of slag content used (as a % of aggregate)	Highest MQ (daN/mm) or MS value (*N*)
Pasetto and Baldo (2012)	59	0, 26, 59, 100	381 MQ
Hainin et al. (2012)	0	0, 100	5,970 MQ
Ziari and Khabiri (2007)	0	0, 5, 10, 15, 20	13,760 MS

compositions of the two indigenous Trinidad asphaltic materials TLA and TPB showed a significant variation in their maltene contents as shown in Figure 1.

The studies using the ASTM D 4124-86 fractionation procedure show that TLA contains almost three times more asphaltenes than TPB and other typical refinery bitumen. Additionally, by utilizing XRD and XRF techniques, they also found that TLA contained 35.3% wt. inorganic material which was found to be kaolinitic in nature which is not present in TPB and other refinery bitumen. The presence of this kaolinitic has been shown to influence the particle size distribution of asphaltic materials by changing interfacial tension and colloidal properties by increasing aggregation and dispersion within the asphaltic system (Menon, Nikolov, & Wasan, 1988; Schramm & Hepler, 1994). Fractal studies conducted by Smith, Chatergoon, Whiting, Grierson, and Peters (1995) showed that the Korcak size distribution value, D, for TPB is much larger than that for TLA (1.60 compared to 1.13), suggesting that the range of particle sizes in TPB has a wider spread than that for TLA suggesting greater aggregation tendencies encountered in TLA. TLA was classified as a gel-type material while the TPB material, like other typical refinery bitumens, corresponded to a sol-type material. The presence of clays in asphaltic systems has been associated with improvements in rheological properties such as stability, resilient modulus, tensile strength, rutting and dynamic creep (Gelot, Friesen, & Hamza, 1984; Jahromi, Andalibizade, & Vossough, 2010; Yan & Masliyah, 1995; Zare-Shahabadi, Shokuhfar, & Ebrahimi-Nejad, 2010). TLA, due to its unique chemical composition has been internationally well established as a commercial product and a source of superior quality asphalt (Widyatmoko & Elliott, 2008). Another critical reason why the results of other studies involving the utilization of SSA cannot be adopted for usage within Trinidad asphaltic road pavements is because of the likelihood that the chemical composition of the slag itself will be different as the composition of this material depends on the procedure in which it was generated, the chemical composition of steel additives used in the process and the very type of steel being produced and the rate of cooling (Barišić, Dimter, & Netinger, 2010).

The construction of road pavements and infrastructure development in developing countries such as Trinidad and Tobago is an activity that demands a significant quantity of depleting natural resources. Large quantities of locally mined and imported natural materials, gravel, limestone and sand are built into kilometres of newly-built roads or in reconstruction of decrepit pavements. At the same time, the movement of Trinidad and Tobago towards sustainable development requires a more efficient management of waste materials and preservation of environment. The reuse and utilization of SSA as an aggregate supplement in Trinidad and Tobago in road paving provides an ideal opportunity to accomplish this goal. Unfortunately a survey of the literature has provided limited information and this lack of scientific studies investigating the influence of SSA on indigenous Trinidad and Tobago asphaltic materials TLA and TPB and presents a significant void of relevant information required towards reusing SSA as an aggregate substitute while also providing an environmentally friendly method of SSA disposal.

The study will describe the basic characteristics of slag (SSA), present an overview of existing relevant research studies, and investigate the optimal formulation of SSA as an additive in Trinidad asphaltic paving materials and thus assess the possibility of the application of slag in road paving applications in Trinidad and Tobago. From Table 3, it is observed that the optimal formulation contained 0% SSA in 2 studies. Considering this information, the researchers in this study decided to limit the percentage of SSA to 3% of the total aggregate (or 20% by weight of the ¾ inch sized). This was an attempt to obtain a formulation that met or exceeded the properties of the 0% formulation.

2. Materials and methods

2.1. Slag composition and characteristic

The EAF SSA used in this study was obtained from Arcelor Mittal Point Lisas Limited, T&T. 60 kg (naturally aged for a minimum of 12 months) of EAF SSA passing through the 37.5 mm sieve was crushed and subsequently sieved to 20 mm. X-ray diffraction (XRD) and X-ray fluorescence (XRF) tests were conducted to determine chemical and elemental composition. XRD was conducted using CuK_α radiation in a Bruker Axis D5000 X-ray diffractometer operated at 40 kV and 50 mA. Scanning was done over 2θ angles 5–70°.The XRF test was carried out using a Bruker-AXS X-ray Spectrometer model SRS 3400.

EAF SSA as supplied by Arcelor Mittal Point Lisas Limited has slight variations in chemistry from batch to batch and samples taken from the stockpile can be derived from multiple batches. Consequently, no special grading/classification of the EAF SSA is carried out at source. The 20 mm EAF SSA exhibited a high degree of angularity and surface roughness with a high surface area.

2.2. Marshall stability test sample preparation

The procedure employed to execute the Marshall stability test was according to the Standard Practice for Preparation of Bituminous Specimens using Marshall Apparatus D6927 (ASTM International, 2015). The SSA was used as a modifier that was varied between 0 and 20% of the ¾ inch sized limestone aggregate as shown in Table 4. Values in the center column are quoted in this paper unless stated otherwise.

The mixture consisted of refined TLA, TPB 60/70 penetration, SSA, sharp sand and blue limestone (dust, ¾ inch, and $^3/_8$ inch sized aggregates).

Using a wet sieve for asphalt gradation, the aggregates (coarse, fine and filler) were proportioned according to the HMA2 requirements (Wearing course for Class A roads -Heavy traffic >7,500 vehicles per day) found in the T&T Hot Asphalt Mixture Requirements (Charles, 2013).

Table 4. Proportions of SSA modifier used in relation to the natural aggregate

Sample specimen	% Modifier used in the mixture (by weight of total ¾ inch sized aggregate)	% Modifier used in the mixture (by weight of total aggregate)
A	0	0.00
B	2	0.30
C	4	0.60
D	5	0.75
E	6	0.90
F	10	1.50
G	12	1.80
H	15	2.25
I	20	3.00

Table 5. Weights of aggregate, binder, and modifier used for testing

Sample	Binder (g)		Aggregates (g)					Total (g)
	TLA	TPB	Sharp sand	3/4″ gravel	3/8″ gravel	Stone dust	3/4″ Modifier SSA	
A	21	63	446.4	167.4	223.2	279	0	1,200
B	21	63	446.4	164.0	223.2	279	3.4	1,200
C	21	63	446.4	160.7	223.2	279	6.7	1,200
D	21	63	446.4	159.0	223.2	279	8.4	1,200
E	21	63	446.4	157.4	223.2	279	10.0	1,200
F	21	63	446.4	150.7	223.2	279	16.7	1,200
G	21	63	446.4	147.3	223.2	279	20.1	1,200
H	21	63	446.4	142.3	223.2	279	25.1	1,200
I	21	63	446.4	133.9	223.2	279	33.5	1,200

The total mixture comprised of 93% aggregate and 7% binder (75% was TPB 60/70 penetration, and 25% TLA) as is common practice in Trinidad and Tobago. Mix proportions are shown in Table 5.

3. Results

3.1. Slag composition

The XRF results for the slag are shown in Table 6. The XRD analysis indicated that the slag contained Calcium Silicate (Ca_2O_4Si), Kirschsteinite ($CaFeSiO_4$), Merwinite [$Ca_3Mg(SiO_4)_2$] and SiO_2.

3.2. Marshall stability test

The gradation results are shown in Figure 3 and the Marshall stability test results are shown in Table 7.

From tests performed, the 0% slag had the lowest air voids at 1.97% and the 6% slag had the highest void of 4.28%. However, T&T hot asphalt mixture requirements specifies that the air voids

Table 6. XRF results on the EAF slag used in this study

Elements	Percentage composition by weight (%)
Oxygen	43.60
Iron	18.28
Calcium	16.63
Silicon	9.21
Magnesium	7.87
Aluminum	2.80
Titanium	0.54
Manganese	0.37
Phosphorus	0.23
Chromium	0.13
Carbon	0.09
Vanadium	0.05
Sulphur	<0.05
Copper	<0.05
Zirconium	<0.05
Strontium	<0.05

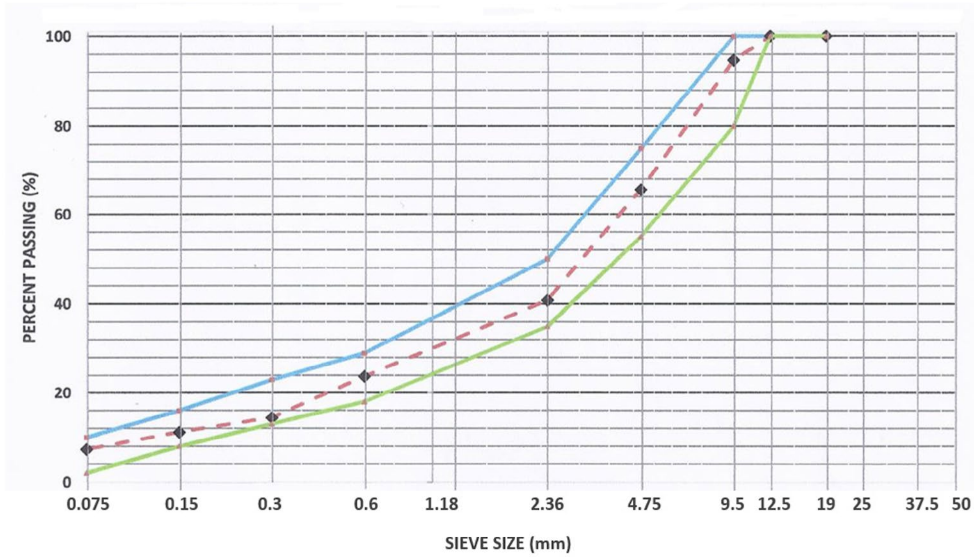

Figure 3. Percent passing (%) against sieve (mm) with upper and lower limits shown.

Table 7. Marshall test results

SSA %	Bulk density (g/cm³)	Stability (kN)	Flow (mm)	Marshall quotient (N/mm)	Air voids (%)	VMA (%)	Specific gravity
0	2.38	9.36	3.30	2,836 ± 471	1.97	17.6	2.43
2	2.38	8.64	3.23	2,679 ± 570	2.46	17.7	2.44
4	2.38	8.85	3.12	2,833 ± 283	2.09	17.6	2.44
5	2.37	8.33	3.38	2,464 ± 429	2.87	18.2	2.44
6	2.37	7.69	3.30	2,329 ± 289	4.28	18.1	2.48
10	2.37	8.03	3.30	2,432 ± 238	3.85	18.1	2.47
12	2.38	8.46	3.48	2,430 ± 233	3.34	18.1	2.46
15	2.38	8.58	3.30	2,597 ± 205	3.37	18.0	2.46
20	2.39	8.30	3.56	2,335 ± 173	2.37	17.7	2.45
Acceptance criteria		8.00 min	2.00 to 4.00		3.00–5.00	15.0 min	

should be within 3 to 5% (Charles, 2013). Only specimens containing 6–15% SSA were in the acceptable range.

VMA refers to the voids in mineral aggregate and is defined as the volume occupied by air voids and the amount of binder not absorbed into the pores of the aggregate (ASTM International, 2016). According to T&T requirements, the minimum VMA should be 15%. All samples met this requirement.

The most important performance attributes with respect to the Marshall test are the Stability and Flow values. The stability measures the maximum load carried by a compacted specimen at a standard test temperature of 60 °C. This test resulted in values ranging from 7.69 to 9.36 kN with the 6% slag having the lowest load and the 0% having the highest load. All results except the 6% met the T&T Standard minimum requirement of 8 kN.

The flow measures the deformation between no load and maximum load carried by the specimen during the stability test (ASTM International, 2015). Values ranging from 3.124 to 3.556 mm were achieved with the 4% slag having the lowest deformation and the 20% having the highest deformation.

With respect to the Marshall quotient (Marshall stability divided into Marshall flow values), the 0% SSA and the 4% SSA were the highest and similar in value when referenced to the stated standard error values. A higher Marshall quotient value is considered better. However, the 0% SSA and the 4% SSA are not acceptable with respect to air voids. The optimal formulation when considering air void acceptability and high Marshall quotient is 15% SSA formulation.

4. Discussion

Like the name, the composition of this material depends on the procedure in which it was generated, composition of steel additives and the very type of steel being produced and the cooling speed. In this study, the four major elements present in the SSA are: Oxygen (O), Iron (Fe), Calcium (Ca) and Silicon (Si). These are mainly chemically bonded in the minerals Ca_2O_4Si, $CaFeSiO_4$, $Ca_3Mg(SiO_4)_2$ and SiO_2. However, free oxides of Ca and Magnesium (Mg) do exist within SSA. These can have adverse effects if the SSA is used without proper ageing because of the tendency to react with moisture. This tendency accounts for the limited usage of this material in road building as the steel slag is very expansive (volume can change by as much as 10% due to the reaction of the oxides of calcium and magnesium with moisture resulting in changes of volume) (Barišić et al., 2010). A common and successful mitigation step involves slag weathering in atmospheric conditions which can eliminate this adverse property. The presence of free calcium oxide also presents a negative factor as it reacts with moisture forming calcium hydroxide, $Ca(OH)_2$, which reacts with carbon dioxide and carbon monoxide in the atmosphere resulting in the formation of calcium carbonate. This material is responsible for drainage problems and water retention which can result in adverse consequences in the case of freezing. This does not present an issue in Tropical climates and can be tolerated. Fe and Iron Oxide (Fe_2O_3) are also present in SSA. Figure 4 shows a piece of Fe embedded in SSA. Large pieces of Fe can be removed by magnetic separation. The small pieces such as shown in Figure 4 are not expected to be problematic due to the microscopic size.

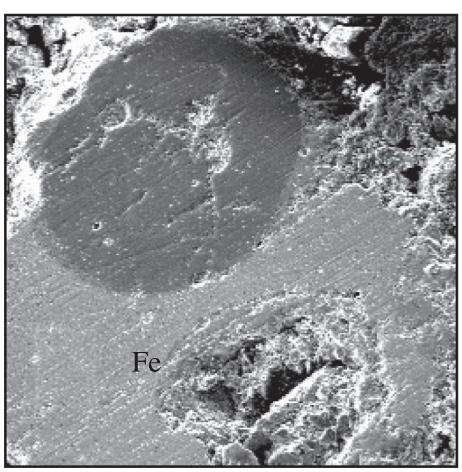

Figure 4. Electron micrograph of an electric arc furnace steel slag aggregate showing a piece of embedded iron (Fe).

The particle size distribution of the Aggregate used fell well within the limits established in the requirements for Hot Mixed Asphalt in Trinidad and Tobago, as seen in Figure 4. The bulk density and Specific gravity of the mixes ranged between 2.37 and 2.39×10^3 g cm^{-3} and 2.43 and 2.48 respectively. It must be stressed that apart from a high and favorable bulk density, the grains of the material are pointed, with a rough surface, characteristics particularly suitable for use in asphalt blends as they increase friction between the particles of the material and ultimately increase adhesiveness between the pavement and the wheels of vehicles. Steel slag has a large angle of internal friction (40–45°) which contributes to significant stability of materials better than other natural aggregates. It is well suited for applications where great wear resistance and good adhesiveness of pavement is required, such as roads in industrial installations, parking spaces exposed to heavy freight vehicles and junctions (National Slag Association, 2013).

The absence of variation in the bulk density readings show that the bulk density of the SSA and ¾″ limestone aggregate is quite similar. The specific gravity data can be similarly explained. The closeness of the values of bulk density and the values of the specific gravity indicate the air void content is low as formulated below:

$$\text{Air Void }(\%) = \left(\frac{\text{Theoretical Specific Gravity} - \text{Bulk Specific Gravity}}{\text{Theoretical Specific Gravity}}\right) \times 100$$

Low air voids between 3 and 5% ensure well compacted roads that are durable and resist the ingression of water better than improperly compacted roads with high air voids. Additionally, roads would deform minimally under heavy loads and thus resist raveling and fatigue. An air void content lower than 3% results from mixes that are too rich in asphaltic binder, and are susceptible to bleeding as there are insufficient voids to tolerate the expansion of the binder on very hot days. Additionally, too low an air void content results in rutting, thereby reducing the service life of the pavement.

Voids in Mineral aggregate for all the specimens consistently fell within the acceptable range, and had marginal variations between the mixes, due to the fact that the samples had similar, well graded particle size distribution. A higher VMA means that the aggregate can accept a greater quantity of binder rendering the pavement more impermeable and hence durable. An SSA content between 5 and 15% marginally increased the VMA over the control.

The mixes met the minimum Marshall stability requirement, with no noticeable relationship between slag content and Marshall stability. The 6% SSA had the lowest stability of 7.69 kN, whilst the control had the highest stability of 9.36 kN. SSA additions in general marginally reduced Stability within the allowable range. There is a variation of about 14% in Marshall flow of 3.12 mm and 4% SSA for the smallest to flow of 3.56 mm to 20% SSA for the largest.

The Marshall quotient varied from 2329 kN·mm^{-1} for 6% SSA to 2836kN·mm^{-1} for the control. Since the mix regime followed is prescribed for use in Trinidad and Tobago, the 15% SSA at 2597 kN·mm^{-1} specimen is considered optimal as it met air void specifications.

5. Conclusions

In this study, the natural aggregate used in road paving in Trinidad and Tobago was replaced by SSA, a waste material from the steel industry. The effectiveness of substituting the natural aggregate by SSA was measured by changes the physical and mechanical properties attributes of the various blends. The physical properties of SSA basically satisfy the requirements of Marshall Specification for design of HMA at the 15% SSA addition which offered similar properties to the 0% formulation. The amount of binder used could be varied for the SSA modified formulation to determine its optimal content. The SSA improved the porous surface in comparison to the natural aggregate. Under these conditions, SSA appears to be especially beneficial for aggregate substitution for road paving applications in Trinidad and Tobago. From the economic point of view, utilizing SSA reduces the dependency on naturally occurring aggregate and reduces the cost of extracting and processing naturally occurring aggregates. It will also result in a reduction of the cost for treating and disposing the huge number of steel slag stockpiles. If implemented such a strategy for the reuse of SSA will foster the movement of Trinidad and Tobago towards sustainable development that will result in a more efficient management of waste materials and preservation of environment.

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