Characteristics and Utilization of Steel Slag in Road Construction

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1.0 INTRODUCTION

Over the years, steel slag has been utilized in various construction activities. According to Godfrey and Nie [1], enormous quantity of steel slag was used for wall making and road construction during the period of Roman Empire. It was later used in the production of cement in the early 19th century. Its application as rail ballast and in bridges construction has been encouraging. Also, during that period blast furnace slag was used in the production of bricks and mortar and the production of slag wool Kalyoncu [2].

Steel slag is one of the by-products in metallurgical industry. In terms of pretreatment, it can be grouped as Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) and Ladle Refining (LF) slags [3]. According to the type of steel, steel slags can either be stainless steel slag or carbon steel slag. It can also be processed into aggregate (fine or coarse) which is useful in both dense and open graded hot mix asphalt concrete pavements [4-6]. Steel slag aggregate is also used in cold mix or surface treatment of pavement [7].

Currently, only BOF and EAF steel making process are predominant. Iron is converted into steel in the BOF steel making process while EAF process recycles mainly steel scraps. The steel from BOF and EAF can be processed into high grade steels, by passing them through a ladle refining unit. Different types of slags were produced from each of these processes. A flow chart that illustrates the kinds of slag produced for each process of iron and steelmaking is shown in Figure 1.

This paper critically examines utilization of steel slags for road construction in both developing and developed countries. Besides, characterization of steel slags in terms of mechanical, chemical and mineralogical properties was also examined. The problem and challenges associated with slag were also critically analyzed.

2.0 CHARACTERISTICS OF STEEL SLAG

2.1 Physical Properties

Unlike the chemical and mineralogical properties of steel slag, the available information on the physical properties of steel slags in the literature is very limited. Table 1 shows the physical properties of steel slag and the Malaysian specification for road works. Except for water absorption, the steel slag satisfies the requirements in terms of strength and shape. It was observed that the flakiness index value for slag was generally low, which can be attributed to the rounded shape of steel slags. The shape improved its interlocking properties when blended with bitumen compared to granite aggregates. The steel slag Los Angeles Abrasion...
Value (LAAV) and its Aggregate Crushing Value (ACV) were all within the aggregate standard specifications for Malaysian road works. This implied that the material possesses adequate strength for utilization as highway aggregate material. The excellent soundness results indicated that steel slag would not disintegrate under the destructive action of the nature. The stripping test results indicated no evidence of stripping indicating a strong bond strength the binder and steel slag aggregate.

2.2 Chemical Properties

The two major types of slag were produced during steel production. Thus, they are expected to have similar chemical composition. Tables 2a and 2b show the major chemical composition from different literatures of chemical composition of BOF and EAF slag respectively. The BOF slag has silica (SiO₂) content ranges from 8-22%. The iron oxide (FeO/Fe₂O₃) of the BOF slag has a high value of 35%; this can be described as the amount of iron that has been oxidized and cannot be recovered into the steel during its production from molten iron.

As noted in Table 2b, the compositions of both BOF EAF slags are quite similar. Due to its mode of production, its chemical composition depends mainly on the recycled steel properties. In view of this, both EAF and BOF slags differ in their basic chemical compositions. For example, the FeO, CaO, SiO₂ and Al₂O₃ values of EAF slags were 3.3-30%, 23-60%, 8-32.2% and 2-18% respectively.

2.3 Mineralogical Properties

Cooling rate and chemical composition determine slag crystallization. Steel slag samples subjected to X-ray diffraction analysis indicates a complex structure with various peaks overlapping showing the phases of crystalline that present in steel slag [9]. The types of mineral that were reported in the literature for slags were presented in Table 2c. The common mineral phases are olivine (2MgO.2FeO.SiO₂), β-C₃S (2CaO.SiO₂) α-C₃S, C₄AF (4CaO.Al₂O₃,FeO), C₆F(2CaO.Fe₂O₃).CaO (free lime), (3CaO.MgO.2SiO₂), FeO, MgO, C₃S (3CaO.SiO₂), RO phase and CaO-FeO-MgO-MnO [10].

3.0 UTILIZATION OF STEEL SLAG

The mineralogical composition of steel slags plays a significant role in its utilization for various construction purposes. Since steel consumption is proportional to slag production, the recent increase in the steel consumption has greatly increased slag volume which has a positive impact on developing various methods of steel slag utilization.

Unlike mined material, its production data for the globe are relatively unavailable. The ratios of iron and steel to slag output were used to estimate annual world iron and steel slag output. For instance, in Malaysia about 750 tons of steel were produced daily and approximately 7.5 tons of slag were produced. From the research carried out in the Asian country, approximately 10% of steel slag was produced from the production of steel.

<table>
<thead>
<tr>
<th>Property</th>
<th>Testing Aggregate Crushing Value</th>
<th>Granule Steel slag*</th>
<th>Steel slag**</th>
<th>JKR Specification</th>
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<tr>
<td>Aggregate abrasion Coefficient</td>
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<td>24.00%</td>
<td>&lt;30%</td>
<td></td>
</tr>
<tr>
<td>Aggregate Impact value</td>
<td>20.54%</td>
<td>23.00%</td>
<td>&lt;30%</td>
<td></td>
</tr>
<tr>
<td>Flakiness</td>
<td>19.00%</td>
<td>2.00%</td>
<td>&lt;30%</td>
<td></td>
</tr>
<tr>
<td>Soundness</td>
<td>5.20%</td>
<td>2.07%</td>
<td>&lt;18%</td>
<td></td>
</tr>
<tr>
<td>Polished stone value</td>
<td>52.70%</td>
<td>54.00%</td>
<td>&gt;40%</td>
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</tr>
<tr>
<td>Water absorption</td>
<td>0.51%</td>
<td>5.40%</td>
<td>&lt;2%</td>
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<tr>
<td>Stripping</td>
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<td>&gt;95%</td>
<td>&gt;95%</td>
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</table>

Table 2a Chemical composition of basic oxygen furnace slags

<table>
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<tr>
<th>References</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>P₂O₅</th>
<th>TiO₂</th>
<th>Free CaO</th>
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<td>Yi et al.[13]</td>
<td>45-60</td>
<td>1-5</td>
<td>10-15</td>
<td>3-13</td>
<td>3-9</td>
<td>7-20</td>
<td>2-6</td>
<td>1-4</td>
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<td>40-45</td>
<td>1-2</td>
<td>8-13</td>
<td>4-8</td>
<td>28-32</td>
<td>-</td>
<td>2-4</td>
<td>1-2</td>
<td>0.5-1</td>
<td>-</td>
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<td>Ameri et al.[15]</td>
<td>50-57</td>
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<td>40-58</td>
<td>2-3-4</td>
<td>12-16</td>
<td>6-9</td>
<td>17-28</td>
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<td>-</td>
<td>1.4-1-8</td>
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<td>41-43</td>
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<td>2.70</td>
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Table 2b Chemical composition of electric arc furnace slags

<table>
<thead>
<tr>
<th>References</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
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<td>Yi et al.[13]</td>
<td>30-50</td>
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<td>11-20</td>
<td>8-13</td>
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<td>8-22</td>
<td>5-10</td>
<td>2-5</td>
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<tr>
<td>Wang et al. [19]</td>
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<td>5.0</td>
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<td>Manso et al. [34]</td>
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<td>15.3</td>
<td>5.1</td>
<td>-</td>
<td>4.5</td>
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Table 2c Mineralogical phases of slags

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<tr>
<th>Reference</th>
<th>Type</th>
<th>Mineralogical Phases</th>
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<tr>
<td>Gahan et al. [37]</td>
<td>EAF</td>
<td>CaFe₂O₃, Ca₂MgO₄Fe₂O₆Si₂O₅, Ca₅SiO₄, FeO</td>
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<tr>
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<td>BOF</td>
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<tr>
<td>Tsakiridis et al. [33]</td>
<td>EAF</td>
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<td>Tossavainen et al. [29]</td>
<td>EAF</td>
<td>Ca₂Mg(SiO₄)₂, (CaFe₂O₃) (SiO₂) (Cr₂O₃), FeO, MgO</td>
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<td>B-Ca₂SiO₄, FeO-MnO-MgO, CaO</td>
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<td>Nicolae [24]</td>
<td>BOF</td>
<td>2CaOAl₂O₃, SiO₂, Fe₂O₃, CaO</td>
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<td>BOF</td>
<td>MnO, Fe₂O₃, SiO₂, Fe₂O₃</td>
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<td>Reddy et al. [28]</td>
<td>BOF</td>
<td>2CaOFe₂O₃, 2CaOFe₂O₃, SiO₂, CaO</td>
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<td>Belhadj [14]</td>
<td>BOF</td>
<td>Ca₂SiO₄, C₅S, C₆S, CaO, FeO, Fe₂O₃, SiO₂, MgO</td>
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<tr>
<td>Qian et al.[10]</td>
<td>EAF</td>
<td>Y₂Ca₂SiO₆, CMS, CMS, Fe₂O₃, MnO-MgO, Fe₂O₃</td>
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</table>

Table 3 shows the estimated slag generated in recent years while Figure 2 shows the various applications of steel slag for a particular year, 2006.

Globally, steel slag has been extensively used in the following areas of Civil Engineering works:
3.1 Asphalt Aggregates

Provided adequate quality control measures were put in place during the production of steel slag, it can perform credibly well as asphaltic aggregates. Many research works have proved it to be a high quality aggregates for asphaltic concrete. There is a natural temperature dependent viscosity for each grade of bitumen. Thus it will become soft and flow beyond a given temperature and become brittle and crack under load below a given temperature [38]. In view of this the tropical climates binders need to be stiffer at a given temperature. Tropical climate countries like Singapore had utilized steel slag as asphalt aggregates.

Ahmedzade and Sengoz [39] researched on the influences of steel slag utilization as coarse aggregate on hot mix asphaltic concrete properties. The incorporation of steel slag into the mixes produced better Marshall Stability and flow test results than mixtures with limestone. This implies that using steel slag as a coarse aggregate in asphaltic concrete mixtures reduces flow values and increased stability which indicates resistance to permanent deformation and high stiffness.

Table 3 Slag generation [40, 41]

<table>
<thead>
<tr>
<th>Year</th>
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<th>World Output</th>
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<tr>
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<td>9-14Mt</td>
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<tr>
<td>1995</td>
<td>9-14Mt</td>
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<td>2010</td>
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<td>141-201Mt</td>
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</table>

Figure 2 Use of steel slag in 2006 [40]

3.2 Cement Stabilization

Cement stabilization is one of the methods used in building pavement layers. Steel slag can be mixed effectively with other by product materials to produce an excellent cement stabilization product. BOF slag has been successfully mixed with Blast Furnace Slag and Fly ash to produce a semi rigid structure; it does not deform under traffic load and not flexible enough to resist cracking.

The major chemical composition of cement (C₃S, C₅S and C₆AF) that presents in steel slag qualifies it as cementitious materials. The basicity of steel slag generally increased with its cementitious properties. In view of this powdery steel slag can be used as concrete admixtures and cement additives [42]. Research carried out by Arabani and Azarhoosh [43] where a mixture of powdered steel slag, cement clinker and fly ash were used to prepare composite cement and it was observed that quantity of steel slag admixture present in cement can improve pore distribution, enhance the consistency of cement and also reduce the porosity. Altum, et al. [44] confirmed that 30% powdered steel slag added to the cement satisfied the Turkish Portland Cement standard requirements.
3.3 Sub base

Steel slag has very good internal friction, free draining ability and good compactability. Besides, it will not pump from the high water table due to its low water absorption. These qualities qualify it as a good sub base material. It has been used in Chile for decades under reinforced concrete roads as a sub base material and its long term performance has been sustained.

The study carried out by Pasetto and Baldo [45] on evaluating the performance of base course and road base asphaltic concrete incorporating electric arc furnace steel slags shown that EAF slags exhibits substantially equivalent physical and mechanical characteristics to those of natural aggregates normally used in pavement layers construction. Without violation of workability and densification of the mixes, mix designs with EAF slags gave good values of Marshall quotient and Marshall stability. Mixes with EAF slags also exhibit low water damage thereby showing a good durability application. All the mixes with EAF slags satisfied the conditions for acceptance of the Italian road standards and thus suitable for road construction.

3.4 Ground Improvement

It can be successfully used in swampy and water logged areas as filling materials because of its low water absorption and free draining ability. When it is compacted it remains stable and can be placed easily in wet environments. Besides, it is not susceptible to frost action; high percentage of coarse aggregates and its special chemical composition make it suitable for road foundations in cold areas like North America [38]. Besides, high resistance to crushing, angular shape, dense, inert, durable and polishing under the action of all kinds of traffic qualifies it for good road construction. It also provides better skid resistance surface than natural aggregates.

3.5 Miscellaneous

Aside from the enumerated applications, it is also useful as railway ballast, filter media, chippings etc. The products must conform to relevant specifications before use. A Vibro-flotation and stone column application is the latest application of steel slag [38]. Steel slag with high content of quicklime, CaO can be used as sinter ore fluxing agent. It has been proved that addition of slag can reduce the cost of sinter, decrease fuel consumption as a result of Fe liberation and oxidation reaction of FeO. In the advanced nations like USA and Germany, steel slag that have been used as sinter material exceeded 56% and 24% respectively [46]. Some steel rolling mills in China like Baoshan Iron and Steel Group and Lianyuan Iron and Steel Company have been using steel slag for sintering purposes since 1996. Due to its physical, mechanical and chemical properties of steel slag, it has many environmental applications as showed in Table 4.

5.0 CONCLUSIONS

This paper has reviewed the utilization of steel slag and its characterization. Also, the problems associated with its use were also examined. The assessment of this review work results in the following recommendations:

Microstructure analysis should be conducted for steel slag to identify any harmful components present in it. Slag should be stored in an open space for a period at least 3 months before use. The volumetric stability of steel slag should be ascertained by conducting volumetric swelling test. There is a need of standard methods to assess its suitability as highway construction material. Field performance data should be made available to assess its performance on surface treatment.
Table 4 Typical uses of iron and steel slag [47]

<table>
<thead>
<tr>
<th>Iron and steel slag uses</th>
<th>Environmental applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Applied to land surface</td>
</tr>
<tr>
<td>Aggregate in bitumen mixes</td>
<td></td>
</tr>
<tr>
<td>Concrete aggregate and as a cement ingredient</td>
<td>x</td>
</tr>
<tr>
<td>Antiskid aggregate (snow and ice control)</td>
<td>x</td>
</tr>
<tr>
<td>Surfacing stabilized shoulders, banks and other select material</td>
<td>x</td>
</tr>
<tr>
<td>Bank stabilization (erosion control aggregate)</td>
<td></td>
</tr>
<tr>
<td>Gabions and riprap</td>
<td>x</td>
</tr>
<tr>
<td>Aggregate base courses and sub-bases</td>
<td></td>
</tr>
<tr>
<td>Unpaved driveways, surface roads and walkways</td>
<td>x</td>
</tr>
<tr>
<td>Railroad ballast</td>
<td></td>
</tr>
<tr>
<td>Neutralization of mine grainage and industrial discharge</td>
<td></td>
</tr>
<tr>
<td>Agricultural uses</td>
<td></td>
</tr>
<tr>
<td>Controlled, granular fills, such as those required for unpaved parking areas and storage areas</td>
<td>x</td>
</tr>
<tr>
<td>Fluxing agents</td>
<td></td>
</tr>
<tr>
<td>Landfills</td>
<td></td>
</tr>
<tr>
<td>Landscape aggregate</td>
<td></td>
</tr>
<tr>
<td>Trench aggregate/drain fields</td>
<td></td>
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<tr>
<td>Sand blast grit</td>
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<tr>
<td>Roofing granules</td>
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<tr>
<td>Bulk fillers e.g. paints, adhesives</td>
<td></td>
</tr>
<tr>
<td>Mineral wool (home and appliance insulation)</td>
<td></td>
</tr>
<tr>
<td>Fill</td>
<td>x</td>
</tr>
</tbody>
</table>

References


