Use of copper slag as construction material in bituminous pavements

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Copper Slag (CS) is produced as waste from roasting of copper, in which sulphur (as SO\textsubscript{2}) is eliminated. CS was used as fine aggregate (up to 30%) in the design of bituminous mixes like Bituminous Macadam, Dense Bituminous Macadam, Bituminous Concrete and Semi-Dense Bituminous Concrete. Mechanical properties of mix such as Marshall stability, Indirect Tensile Strength was determined. Addition of CS as fine aggregate in various bituminous mixes provides good interlocking and eventually improves volumetric and mechanical properties of bituminous mixes.

Keywords: Bitumen, Copper slag, Marshall mix design, Indirect tensile strength

Introduction

In India, there is great demand of aggregates mainly from civil engineering industry for road and concrete constructions. The construction of highways and development of several expressways for high-speed corridors exert tremendous pressure on natural resources. Many highway agencies, private organizations, and individuals are in the process of completing a wide variety of studies and research projects concerning the feasibility, environmental suitability, and performance of using waste industrial products in highway construction\textsuperscript{1-4}. These studies try to match society's need for safe and economic disposal of waste materials with the highway industry's need for better and more cost-effective construction materials.

This study aims to explore the potential use of copper slag (CS) as fine aggregate (up to 30%) in the design of bituminous mixes like Bituminous Macadam (BM), Dense Bituminous Macadam (DBM), Bituminous Concrete (BC) and Semi-Dense Bituminous Concrete (SDBC), which enhance the property of the bituminous mixes.

Non-ferrous Slag as Construction Material

Nonferrous slags are produced during the recovery and processing of nonferrous metal from natural ores. The slags are molten by-products of high temperature processes that are primarily used to separate the metal and nonmetal constituents contained in the bulk ore. When cooled, the molten slag converts to a rocklike or granular material.

The processing of most ores involves a series of standardized steps; after ining, the bulk ore is processed to remove any gangue. This processing typically consists of pulverizing the ore to a relatively fine state, followed by some form of gravity separation of the metals from the gangue, using a series of devices including cyclone separators, inclined vibratory tables, and flotation tanks. The refined ore is processed thermally to separate metal and nonmetal constituents, then further reduced to free metal. Since most of these metals are unsuitable for use in a pure state, they are subsequently combined with other elements and compounds to form alloys having the desired properties.

In preparation for metal ion reduction, some nonoxide minerals are often converted to oxides by heating at air temperatures below their melting point. Sulfide minerals, when present in copper, are converted to oxides. The reduction of metal ion to free metal is normally accomplished by smelting. In this process, a reducing agent, such as coke as impure carbon, along with CO and H\textsubscript{2}, is combined with the roasted product and melted in a siliceous flux. The metal is subsequently gravimetrically separated from the composite flux, leaving the residual slag.

CS is produced by (Fig. 1): (i) Roasting, in which sulfur in the ore is eliminated as sulfur dioxide (SO\textsubscript{2}); (ii) Smelting, in which the roasted product is melted in a siliceous flux and the metal is reduced; and (iii) Converting, where the melt is desulfurized with lime flux, iron ore, or a basic slag and then oxygen lanced to remove other impurities. CS derived by

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smelting of copper concentrates in a reverberatory furnace is referred to as reverberatory CS. Approx 4 million tons of CS are produced each year in the US while in India production is about 10 lakh tons/annum.

Laboratory Investigations

BM & DBM are base course layers, and BC & SDBC are the wearing courses of Flexible Pavement Construction. This investigation aims to use CS as construction material in bituminous road construction. In India, no mix design procedure is available till date for open graded mixes like BM, which has a tendency to crumble at 60ºC because of more open texture. Since, BM is used as a base course layer below the wearing course and it seems to be logical that the stability at temperature be lower than 60ºC. Therefore, the testing temperature was adopted at 60 ºC.

Marshall Method of Mix Design

The overall procedure for mixture design always begins with acceptance tests performed on the aggregates and bitumen considered for the design.

Aggregates

Stone aggregates, the major components of road structure, bear load due to particle interlocking and sustain wear and tear due to vehicular movement. The acceptability limits7-9 may vary depending upon the type of construction (Table 1). Delhi quartzite was used as coarse aggregate (20 mm and 10 mm), CS and stone dust as fine aggregate and hydrated lime as filler. CS is a black, glassy and vesicular matter (unit wt. 2800-3800 kg/m³, water absorption 0.3% having apparent specific gravity of 2.72). Its chemical composition is as follows: SiO₂, 36.6; FeO, 35.3;
Al$_2$O$_3$, 8.1; CaO, 2.0; S, 0.7; Cu, 0.4; and others (Fe$_2$O$_3$, MgO, PbO etc), 16.9%.

**Bitumen**

Bitumen (C, 80–87% by wt) is basically a hydrocarbon, less than 10 percent by weight is due to atoms of S, N and O, which are attached to hydrocarbon molecules. Three basic components of bitumen are (i) asphaltene, (ii) maltene, and (iii) carbene$^{10}$. Asphaltene is hard and aromatic. Maltene is a solvent and imparts viscoelasticity to bitumen. It is resin like intermediate molecule of hydrocarbon. Carbene is the fraction, which is insoluble in CCl$_4$. Bitumen as a material has drawn attention to the engineers since a long time because it is (i) water proof, (ii) durable, (iii) resistance to strong acids, and (iv) possesses good cementing properties.

At normal temperature, bitumen is a thermoplastic semi-solid cementing material and at higher temperature, bitumen behaves like a viscous liquid, whereas at a very low temperature bitumen is brittle as glass. Bitumen is believed to behave viscoelastically at the standard operating temperatures of highways. Penetration grade 60/70 bitumen has been used as binder (Table 2)$^{11,12}$.

**Proportion of Aggregates**

Aggregate gradation is one of the most important properties in bituminous mixture, which affects almost all the important properties like stability, durability, workability and resistance to moisture damage. Therefore, gradation is a primary consideration of bituminous mix design. The typical aggregate gradation taken for the design of BM, DBM, BC and SDBC are as per the MoRTH Specification$^9$ in order to explore the potential use of CS as fine aggregate in optimum level which enhances the property of the mixes to get the final grading (Tables 3 & 4).

**Determination of Optimum Binder Content**

At each grading, Marshall samples were prepared by varying the binder content and tested for its volumetric properties.

**Significance of Volumetric Parameters:** Bitumen holds the aggregates in position and the load is taken by the aggregate mass through the contact points. If all the voids are filled by bitumen, load is transmitted by hydrostatic pressure through bitumen, and strength of the mix, therefore, reduces. That is why stability of the mix starts reducing when bitumen content is increased beyond certain value. Also during summer season, bitumen melts and occupies the void space between aggregates and if the void space is not available, it causes bleeding. Thus, some amount of void is necessary in a bituminous mix, even after the

### Table 2 — Properties of 60/70 bitumen (AC-20)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Method of test</th>
<th>Test value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration at 25 °C</td>
<td>mm</td>
<td>IS 1203:1978</td>
<td>0.1</td>
</tr>
<tr>
<td>Softening Point, R&amp;B</td>
<td>°C</td>
<td>IS 1205:1978</td>
<td>87</td>
</tr>
<tr>
<td>Ductility at 25 °C</td>
<td>cm</td>
<td>IS 1208:1978</td>
<td>75+</td>
</tr>
<tr>
<td>Water content</td>
<td>% wt</td>
<td>IS 1211:1978</td>
<td>0.2</td>
</tr>
<tr>
<td>Viscosity at 60 °C</td>
<td>poise</td>
<td>IS 1206:1978</td>
<td>2600</td>
</tr>
<tr>
<td>Viscosity at 135 °C</td>
<td>poise</td>
<td>IS 1206:1978</td>
<td>410</td>
</tr>
<tr>
<td>Flash point, COC</td>
<td>°C</td>
<td>IS 1448</td>
<td>230</td>
</tr>
<tr>
<td>Specific gravity, at 27 °C</td>
<td>--</td>
<td>IS 1201:1978</td>
<td>0.99</td>
</tr>
</tbody>
</table>

### Table 3 — Copper slag used in different bituminous mixes

<table>
<thead>
<tr>
<th>Type of mixes</th>
<th>Size of aggregates</th>
<th>Copper slag</th>
<th>Stone dust</th>
<th>Lime</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>40 mm</td>
<td>17</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>DBM</td>
<td>30 mm</td>
<td>32</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>BC</td>
<td>33 mm</td>
<td>30</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>SDBC</td>
<td>23 mm</td>
<td>30</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 4 — Aggregate grading for bituminous mixes

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>BM</th>
<th>DBM</th>
<th>BC</th>
<th>SDBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>26.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>13.2</td>
<td>67</td>
<td>75</td>
<td>73</td>
<td>81</td>
</tr>
<tr>
<td>9.5</td>
<td>59</td>
<td>69</td>
<td>67</td>
<td>76</td>
</tr>
<tr>
<td>4.75</td>
<td>25</td>
<td>43</td>
<td>49</td>
<td>46</td>
</tr>
<tr>
<td>2.36</td>
<td>18</td>
<td>36</td>
<td>42</td>
<td>37</td>
</tr>
<tr>
<td>1.18</td>
<td>11</td>
<td>22</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>0.600</td>
<td>5</td>
<td>12</td>
<td>14</td>
<td>--</td>
</tr>
<tr>
<td>0.300</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>0.150</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>--</td>
</tr>
<tr>
<td>0.075</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 2 — Properties of BM mix at different binder content

Fig. 3 — The property of DBM Mix at different binder content

Fig. 4 — Properties of BC mix at different binder content
For determination of optimum binder content (OBC), the values of bulk density, stability and air voids are plotted against the binder contents (Figs 2-5).

Selection of Optimum Bitumen Content (OBC)

OBC is a delicate balancing act in which there are a number of variables - like voids in mineral aggregate (VMA), air voids (VA), and voids filled with bitumen (VFB). A balance is to be maintained such that all the specification limits recommended in the code of practice are simultaneously satisfied. OBC for different mixes was found as follows (Table 5): BM, 3.5; DBM, 5.3; BC, 5.9; and SDBC, 5.9%.

Computation of Moisture Sensitivity

For Moisture sensitivity test as per AASHTO T 283, samples were tested for dry and wet strength conditions at OBC. The dry set was stored at 25°C in an environmental chamber for 2 h before testing. The wet set was first placed in water bath maintained at 60°C for 24 h and then placed in an environmental chamber at 25°C for 2 h. The load was applied at the rate of 50 mm/min by loading a Marshall specimen with compressive load acting parallel to and along the vertical diametric loading plane (Fig. 6). The moisture sensitivity is determined as a ratio of the average tensile strengths of the wet and dry tensile strength of the specimens. The Indirect Tensile Strength (ITS) is calculated from the equation given below:

\[ S_t = \frac{2P}{\pi dt} \]

where, \( P = \) load (kg), \( d = \) diam of specimen (cm), \( t = \) thickness of specimen (cm).

Results and Discussion

By addition of CS, the density of mixes at OBC are as follows: BM, 2.273; DBM, 2.540; BC, 2.594; and SDBC, 2.541 g/cc (Fig. 7). The higher densities are because of the good interlocking developed by the incorporation of CS as fine aggregate in the

<table>
<thead>
<tr>
<th>Property</th>
<th>BM</th>
<th>DBM</th>
<th>BC</th>
<th>SDBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder, % by aggregate</td>
<td>3.5</td>
<td>5.3</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Binder, % by mix</td>
<td>3.38</td>
<td>5.03</td>
<td>5.57</td>
<td>5.57</td>
</tr>
<tr>
<td>Bulk density, g/cc</td>
<td>2.273</td>
<td>2.540</td>
<td>2.594</td>
<td>2.541</td>
</tr>
<tr>
<td>Air voids, %</td>
<td>10</td>
<td>5</td>
<td>4.5</td>
<td>4.2</td>
</tr>
<tr>
<td>VMA, %</td>
<td>27</td>
<td>20</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>VFB, %</td>
<td>29</td>
<td>72</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Stability, kg</td>
<td>1287</td>
<td>1228</td>
<td>1880</td>
<td>1429</td>
</tr>
<tr>
<td>Flow, mm</td>
<td>5</td>
<td>3.2</td>
<td>3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
bituminous mixes. The Marshall stability is a measure of structural strength of a bituminous mixes. Higher the stability of the mix, greater will be the strength of surfacing. Stability values of BM at 40° C and that of other bituminous mixes like DBM, BC and SDBC at 60° C are 1287, 1228, 1880, and 1429 kg respectively at OBC (Fig. 8).

Moisture sensitivity test on bituminous mix provides information to evaluate the effects of moisture and stripping potential of bituminous mixes (Fig. 9). TSR values (> 90 %) of all the bituminous mixes improve the moisture susceptibility criteria (Table 6).

Conclusions

Addition of copper slag as fine aggregate in various bituminous mixes improves good interlocking and eventually improved the volumetric properties as well as the mechanical properties of the mixes. Because of the improved property by the incorporation of copper slag, it can be used as a fine aggregate in bituminous mixes as the substitute of crusher dust as fine aggregate, which normally used in the conventional bituminous mixes. A field study may be undertaken at different climatic / traffic conditions on national/state highways.

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References