Determination of Original Free Lime Content of Weathered Iron and Steel Slags by Thermogravimetric Analysis

William A. Kneller, Jiwan Gupta, Michelle Lea Borkowski, and David Dollimore

Iron and steel slags are often used as subbase materials in the construction of highways. Previous studies have suggested that the free lime (CaO) in these subbases is responsible for the deposition of calcium carbonate (tufa) in many highway drains. Clogging of these drains leads to the deterioration of highways. Previous work has shown that if the total original CaO in slags exceeds 1 percent, the slags will readily produce tufa. Therefore, to classify the tufa-producing potential of these slags, it is necessary to determine the total original CaO.

Thermogravimetry (TG) methods were employed and most of the TG plots indicated two major changes in weight loss—dehydroxylation of Ca(OH)₂ and dissociation of carbonates. From these changes in weight loss the percentage of CaO from the TG plot plus the results from the “sugar test” determine the total original percentage of CaO. Five groups are recognized according to the calculated total percentage of CaO: 0 percent, 3.5 to 5 percent, 8 to 9 percent, 10 to 12 percent, and 24 to 25 percent. Air-cooled blast furnace slag (0 percent CaO) is the only slag that should be used as a subbase in highway construction, whereas all others are considered to be harmful and could lead to the formation of tufa. TG methods and the sugar test are excellent and economical ways to characterize the original CaO in slags and the susceptibility of the slags to precipitate CaCO₃ in subdrains of highways.

Iron and steel slags from blast, open hearth, basic oxygen, and electric arc furnaces are often used as subbase materials in the construction of highways. Previous studies (1-3) suggest that the free lime (CaO) present in these subbase materials is responsible for the deposition of a chemical sedimentary rock composed of calcium carbonate called tufa. It is formed as a precipitate by the evaporation of water rich in dissolved calcium carbonate. This precipitate has been observed clogging many drains along highways in northeastern Ohio. Because the clogging of drains leads to highway deterioration, it is necessary to devise a rapid method to determine the total original CaO in these subbase materials.

PURPOSE AND SCOPE

The purpose of this study is to (a) characterize the slags, (b) determine the amount of “original” CaO in the weathered iron and steel slags, and (c) classify these slags according to their tufa-producing potential. The prepared samples were taken from stockpiles exposed to weathering for various lengths of time. Thermogravimetry (TG) analyses were performed on air-cooled blast furnace, basic oxygen furnace, open hearth, and electric arc furnace slags to determine the percent calcium hydroxide [Ca(OH)₂] and calcium carbonate (CaCO₃) in the samples. These percentages were added to the results from an extraction and titration method nicknamed the “sugar test” to determine the total original CaO—free CaO content at the time the slag was in a molten state or just poured from the ladle. After determination of the total original CaO content, the slags were clustered and classified according to the total original percentage of CaO.

IRON AND STEEL SLAGS

Slag is produced during the manufacture of iron and steel. It is formed by the combination of oxidized impurities and flux. Flux is used to purge the ores of impurities, lower the melting point of the slag, and remove sulfur from the smelted iron. The types of slags that are produced vary greatly according to the extraction or refining processes used.

Blast Furnace Slag

Blast furnace slag is a by-product of the iron industry. The process begins when iron ore, a limestone flux, and coke are heated in a blast furnace. The iron ore is a mixture of oxides of iron, silica, and alumina. Preheated air is then blown into the furnace, and the oxygen combines with the carbon from the coke to produce heat and carbon monoxide. The carbon monoxide reacts with the oxides of the iron ore to produce iron. The silica and alumina of the iron ore combine with the calcium of the limestone to form the slag. Air-cooled blast furnace (ACBF) slag is one that is allowed to solidify under normal atmospheric conditions. Water is sometimes sprayed on the slag to accelerate cooling and to induce cracks. Table 1 records the range of compositions for blast furnace slags.

Steel Furnace Slags

In the steel-producing industry three types of furnaces are used: open hearth, basic oxygen, and electric arc. The actual heating and smelting methods are very similar for each type of furnace;
however, there are some minor differences between the steel furnaces. In open hearth (OH) furnaces the limestone is added along with the scrap steel. The OH furnace takes about 5 to 14 hr to produce 300 tons of steel, whereas it would take the basic oxygen furnace (BOF) only 45 min to produce an equivalent amount. In the BOF, oxygen is blown onto the top of the charge at supersonic speed before the flux is added. Another steel furnace is the electric arc furnace (EAF) in which graphite electrodes are used for the heating process. Table 2 gives a range of compositions for OH, BOF, and EAF slags.

CHEMISTRY AND MINERALOGY OF SLAG SAMPLES

The chemical analyses of the slag samples used in this study are shown in Table 3. The process involved heating the slag in a crucible over an open flame until dehydration was complete. The samples were analyzed for elemental and oxide content by X-ray fluorescence (XRF) methods. These analyses were normalized to include the hydroxyl water and CO₂ data gleaned from the TG studies.

X-ray powder diffraction analysis was used to determine the gross mineralogy of the slags (5). Search-and-match routines were used against the ICPDS data base for the identification of the resulting peaks. Many minerals typical of these slags were identified, but for brevity they are not listed here. Of importance to this study, however, is the identification of Ca(OH)₂ and CaCO₃ in all the slags except the ACBF sample (No. 1). These chemical species should not be present in an unweathered slag. They would have been dissociated to CaO because of the high temperature of the original molten slag. The presence of Ca(OH)₂ and CaCO₃ in the stockpiled slags is assumed to be due to weathering. Residual CaO is present because some of it is encapsulated by silicates. This encapsulation protects the CaO from the effect of CO₂-charged porewater.

THERMAL ANALYSIS

Thermal analysis is the study of chemical and physical changes in a given material due to changes in temperature. These temperature changes are usually linear with time. The changes in enthalpy that accompany chemical and physical changes can be observed and recorded. These enthalpic changes, either exothermic (+) or endothermic (−), are caused by phase transitions such as fusion, crystalline structural inversions, boiling, sublimation, and vaporization; dehydration reactions; dissociation or decomposition reactions; oxidation and reduction reactions; destruction of crystalline structures; and other chemical reactions. Generally, phase

TABLE 1 Range of Composition for Blast Furnace Slags (4)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Range Percent</th>
<th>Typical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>33-42</td>
<td>36.4</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10-16</td>
<td>12.8</td>
</tr>
<tr>
<td>CaO</td>
<td>36-45</td>
<td>41-43</td>
</tr>
<tr>
<td>MgO</td>
<td>3-12</td>
<td>5.8</td>
</tr>
<tr>
<td>FeO</td>
<td>0.3-2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>FeO + Fe₂O₃</td>
<td>0.2-1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>MnO</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Modified from T. Segal [4]

TABLE 2 Range of Composition for Steel Furnace Slags*

<table>
<thead>
<tr>
<th>Compound</th>
<th>OH Range</th>
<th>Typical Analysis</th>
<th>BOF Range</th>
<th>Typical Analysis</th>
<th>EAF Range</th>
<th>Typical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>16-19</td>
<td>18.4</td>
<td>7.2-18.2</td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2-3</td>
<td>2.5</td>
<td>0.42-3.0</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>40-55</td>
<td>45.0</td>
<td>36-49</td>
<td>48.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>5-7</td>
<td>5.9</td>
<td>5-12</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td></td>
<td>12.2</td>
<td>15-30</td>
<td>15.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td></td>
<td>5.4</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO + Fe₂O₃</td>
<td>10-23</td>
<td>15.6</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>5-6</td>
<td>8.6</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0-1</td>
<td></td>
<td>0.05-0.5</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td></td>
<td></td>
<td>0.03-0.9</td>
<td>0.88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Modified from T. Segal [4] and synthesized from 50 analyses furnished by J.M. Olle, Edward C. Levy Co. 8800 Dix Ave., Detroit, MI 48209
** From Olle, J.M., 1991, Personal correspondence
transitions, dehydration, reduction and some decomposition re-
actions produce endothermic effects, whereas crystallization, ox-
idation, and some decompositions produce exothermic effects. Re-
searchers (6-10) since the mid-century have made important con-
tributions to thermal analysis.

There are five basic categories or techniques of thermal analy-
sis: thermometry, differential thermal analysis (DTA), differential
scanning calorimetry (DSC), thermomechanical analysis and dil-
atometry (TMA), and thermogravimetry (TG). The last technique
was used in this study.

**THERMOGRAVIMETRY**

TG analysis measures the loss or gain of weight by a substance
as its temperature is raised or lowered at a constant rate. The
reactions that occur during the heating process are responsible
for the changes in weight. Knowing that certain reactions occur at
specific temperatures enables the identification of the constituents
of the sample. The data from the experiment are then recorded as
a TG plot of mass versus temperature or time. From the TG plots,
the composition of a sample can be determined. The physical-
chemical applications of thermogravimetry are given in Table 4
(10). Also from the TG plot, the first derivative can be calculated
with respect to either time or temperature; this is called derivative
thermogravimetry (DTG). The calculations can be done either by
the TG thermal balance or by a computer program. The derivative
is usually superimposed on the TG plot (see Figure 1). The DTG
plot is set up so that temperature or time is on the abscissa, in-
creasing from left to right, and the derivative values are on the
ordinate, increasing from bottom to top. The DTG plot is used to
help locate the start, peak, and end temperatures of a given reaction.

**METHOD OF ANALYSIS**

A high-temperature (1400°C) thermobalance was used to measure
weight gain or loss during heating. The sample and operational
parameters employed in this study are weight, 9 to 10 mg; grain
size, +325 mesh; atmosphere-nitrogen flow rate, 30 ml/min; heat-
ing rate, 20°C/min; and water flow rate, 300 ml/min. The instru-
ment was calibrated using melting and magnetic standards. In ad-
dition, a further check for accuracy was made by using a calcium
oxalate (CaC$_2$O$_4$·H$_2$O) standard. These calibrations were repeated
every 25 runs.

**DISCUSSION AND RESULTS**

Analysis of TG Plots

Most of the TG curves indicate two major changes in weight loss.
This doublet is evidence of a two-stage reaction that is character-
istic of OH, BOF, and EAF steel slags. All samples were pre-
heated to 350°C to drive off any chemiabsorbed water. The first-
stage reaction is caused by the evolution of hydroxyl water at
about 400°C and ending at about 460°C. The second stage of
decomposition is the evolution of carbon dioxide from the calcium
carbonate in the slag, which occurs at about 490°C and ends at
about 785°C. These reactions are detailed below:

$$\text{Ca(OH)}_2 + \text{heat} \rightarrow \text{CaO} + \text{H}_2\text{O} \uparrow$$

$$\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2 \uparrow$$

The first derivative of the TG curve, DTG, was superimposed on
each of the plots, excluding the ACBF sample (No. 1), for
which no reactions occurred throughout the heat. In this study
DTG was used to indicate the initial peak and final temperatures
of the reaction of the TG plots.

The first reaction, if present, is labeled 1 at the point at which
the reaction begins and 2 at the point at which the reaction ends.
These numbers were determined, as mentioned before, from the
first derivative. The temperature and percent weight loss for these
numbers are found in the box labeled POINT TABLE on the left
side of each plot. The value that is located between the numbers
1 and 2 on the curve is the extrapolated onset temperature, which
is determined from the computer program.

The initial and final temperatures and the percent weight loss
of the second reaction, if present, are labeled by the two-point
angle. Again, these points were determined from the DTG plot.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Type</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>FeO</th>
<th>MgO</th>
<th>Mn$_2$O$_3$</th>
<th>P$_2$O$_5$</th>
<th>K$_2$O</th>
<th>SiO$_2$</th>
<th>Na$_2$O</th>
<th>SO$_3$</th>
<th>(H$<em>2$O)$</em>{eq}$</th>
<th>CO$_2$</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACBF</td>
<td>8.52</td>
<td>40.09</td>
<td>0.85</td>
<td>10.80</td>
<td>0.71</td>
<td>&lt;0.02</td>
<td>0.24</td>
<td>38.09</td>
<td>0.23</td>
<td>0.24</td>
<td>0.04</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>OH</td>
<td>3.50</td>
<td>36.02</td>
<td>26.57</td>
<td>9.84</td>
<td>3.31</td>
<td>0.26</td>
<td>0.01</td>
<td>15.19</td>
<td>0.06</td>
<td>1.70</td>
<td>0.42</td>
<td>3.13</td>
<td>1.13</td>
</tr>
<tr>
<td>3</td>
<td>OH</td>
<td>3.57</td>
<td>40.76</td>
<td>23.81</td>
<td>7.81</td>
<td>5.26</td>
<td>0.10</td>
<td>&lt;0.01</td>
<td>13.73</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.78</td>
<td>1.51</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>OH</td>
<td>4.66</td>
<td>34.02</td>
<td>15.41</td>
<td>5.04</td>
<td>3.39</td>
<td>0.10</td>
<td>0.17</td>
<td>26.06</td>
<td>0.08</td>
<td>&lt;0.01</td>
<td>0.57</td>
<td>10.49</td>
<td>1.79</td>
</tr>
<tr>
<td>5</td>
<td>BOF</td>
<td>3.75</td>
<td>35.27</td>
<td>24.08</td>
<td>10.52</td>
<td>2.81</td>
<td>0.29</td>
<td>&lt;0.01</td>
<td>12.77</td>
<td>0.08</td>
<td>&lt;0.01</td>
<td>3.08</td>
<td>5.54</td>
<td>2.54</td>
</tr>
<tr>
<td>6</td>
<td>BOF</td>
<td>4.46</td>
<td>38.49</td>
<td>26.33</td>
<td>3.35</td>
<td>4.48</td>
<td>0.13</td>
<td>&lt;0.01</td>
<td>12.41</td>
<td>0.07</td>
<td>0.01</td>
<td>0.61</td>
<td>2.11</td>
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<tr>
<td>7</td>
<td>BOF</td>
<td>2.97</td>
<td>48.02</td>
<td>15.05</td>
<td>9.67</td>
<td>3.12</td>
<td>0.22</td>
<td>&lt;0.01</td>
<td>13.21</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>2.65</td>
<td>6.06</td>
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</tr>
<tr>
<td>8</td>
<td>BOF</td>
<td>3.01</td>
<td>50.81</td>
<td>15.62</td>
<td>5.32</td>
<td>3.56</td>
<td>0.30</td>
<td>&lt;0.01</td>
<td>15.04</td>
<td>&lt;0.01</td>
<td>0.04</td>
<td>2.88</td>
<td>3.40</td>
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</tr>
<tr>
<td>9</td>
<td>EAF</td>
<td>Oxides Not Determined</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.36</td>
</tr>
</tbody>
</table>

Others, commonly includes SrO, BaO, TiO$_2$, Cr$_2$O$_3$, and V$_2$O$_5$.
Dash (-) indicates not detected.
TABLE 4 Applications of Thermogravimetry

**Physical Changes**

- Sublimation
- Vaporization
- Absorption
- Adsorption
- Magnetic properties
- Curie temperature
- Magnetic susceptibility

**Chemical Changes**

**Solid → gas**

- Thermal decomposition of many organic and polymeric substances
- Pyrolysis of coal, petroleum, and wood
- Thermal oxidation degradation of polymeric materials
- Carbon gasification with oxygen, steam, or carbon monoxide

**Solid, → solid, + gas**

**Solid, + solid, → solid, + gas**

- Thermal decomposition of many inorganic materials
- Roasting and calcining of minerals
- Determination of moisture, volatiles, and ash contents
- Dehydration studies
- Dehydroxylation studies
- Decomposition of explosives
- Development of analytical procedures
- Kinetic studies (also applicable to solid → gas)

**Solid, + gas → solid,**

---

**TABLE**

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>SLAG</th>
<th>GASES</th>
<th>NITROGEN</th>
<th>SOURCE</th>
<th>O.H.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN ID</td>
<td># 3</td>
<td>SIZE</td>
<td>10.008 mg</td>
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<tr>
<td>METHOD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Start</td>
<td>Final Ramp</td>
<td>Iso</td>
<td>Gas</td>
<td></td>
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<tr>
<td>1</td>
<td>25</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>1.0 sec/pt</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**FIGURE 1** TG plot of sample No. 3, OH slag.
TABLE 5 Data from Thermogravimetric Analysis

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dehydroxylation of Ca(OH)₂</th>
<th>Dissociation of CaCO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I.T.¹</td>
<td>O.T.¹</td>
</tr>
<tr>
<td>1 (ACBF)</td>
<td>416.07</td>
<td>430.85</td>
</tr>
<tr>
<td>2 (OH)</td>
<td>397.77</td>
<td>427.18</td>
</tr>
<tr>
<td>3 (OH)</td>
<td>Reaction not measurable</td>
<td></td>
</tr>
<tr>
<td>4 (OH)</td>
<td>408.78</td>
<td>441.81</td>
</tr>
<tr>
<td>5 (BOF)</td>
<td>402.60</td>
<td>418.77</td>
</tr>
<tr>
<td>6 (BOF)</td>
<td>404.61</td>
<td>435.13</td>
</tr>
<tr>
<td>7 (BOF)</td>
<td>408.80</td>
<td>430.54</td>
</tr>
<tr>
<td>8 (BOF)</td>
<td>424.31</td>
<td>448.49</td>
</tr>
</tbody>
</table>

1 Initial temperature. 2 Onset temperature. 3 Peak temperature. 4 Final temperature.

These temperatures and percentages were determined from the TG and DTG curves.

The extrapolated onset temperature is located to the right of the reaction. The plot for sample No. 3 is shown in Figure 1 and illustrates the double reaction, point table, and the first derivative. The TG curve in Figure 1 is labeled as mentioned above, with the residue located at the end of the curve. The peak temperatures for the two reactions are labeled on the derivative. All values for the reactions that occurred in the samples are given in Table 5, which also records the percent weight loss for (OH)₂ and CO₂ for the nine slag samples.

Method Used To Determine Total Original Percentage CaO

The total original percentage of CaO is calculated by addition of the results from the sugar test, calculated percentage of CaO due to dehydroxylation of Ca(OH)₂ (first reaction), and the calculated percentage of CaO due to dissociation of CaCO₃ (second reaction).

The sugar test (II) determined the CaO in the slag aggregates by dissolution and extraction of the CaO by hot (60 to 70°C) anhydrous ethylene glycol. The CaO is determined by titration with 0.05 N HCl and phenolphthalein as the indicator (see Table 6). The CaO percentages are calculated by using the values for sample No. 3 from Table 5, such as percent hydroxyl water loss, 0.54; percent CO₂ loss, 1.51; and by using the mole weights from the reaction. As stated previously, the reactions that occur are

Ca(OH)₂ + heat → CaO + H₂O ↑
CaCO₃ + heat → CaO + CO₂ ↑

The mole weights for each of the components are as follows:

CaO = 56.079 = 56; H₂O = 17.99 = 18; Ca(OH)₂ = 74.096 = 74;
CaCO₃ = 100.088 = 100; and CO₂ = 44.079 = 44.

TABLE 6 Total Original Percentage of CaO by TGA

<table>
<thead>
<tr>
<th>Sample #</th>
<th>% CaO*</th>
<th>% CaO(OH)₂**</th>
<th>% CaO(CO₃)**</th>
<th>Total % CaO</th>
<th>Rank/Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (ACBF)</td>
<td>0</td>
<td>N/D</td>
<td>N/D</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2 (OH)</td>
<td>0.237</td>
<td>0.622</td>
<td>4.047</td>
<td>4.906</td>
<td>2</td>
</tr>
<tr>
<td>3 (OH)</td>
<td>0.123</td>
<td>1.692</td>
<td>1.922</td>
<td>3.745</td>
<td>3</td>
</tr>
<tr>
<td>4 (OH)</td>
<td>0.044</td>
<td>N/D</td>
<td>8.464</td>
<td>8.508</td>
<td>3</td>
</tr>
<tr>
<td>5 (BOF)</td>
<td>0.604</td>
<td>2.971</td>
<td>7.064</td>
<td>10.639</td>
<td>4</td>
</tr>
<tr>
<td>6 (BOF)</td>
<td>1.051</td>
<td>0.992</td>
<td>2.685</td>
<td>4.728</td>
<td>2</td>
</tr>
<tr>
<td>7 (BOF)</td>
<td>0.691</td>
<td>2.775</td>
<td>7.840</td>
<td>11.306</td>
<td>4</td>
</tr>
<tr>
<td>8 (BOF)</td>
<td>1.064</td>
<td>2.700</td>
<td>4.480</td>
<td>6.244</td>
<td>3</td>
</tr>
<tr>
<td>9 (EAF)</td>
<td>0.602</td>
<td>2.340</td>
<td>21.891</td>
<td>24.833</td>
<td>5</td>
</tr>
</tbody>
</table>

N/D = Not Determinable
* Data derived from anhydrous ethylene glycol, ‘sugar test’
** Calculation of % CaO due to dehydroxylation of Portlandite (Ca(OH)₂)
*** Calculation of % CaO due to dissociation of carbonates
The equations are set up as follows to calculate the percentage of CaO:

\[
\frac{\text{CaO}}{56} = \frac{\text{H}_2\text{O \ delta wt. loss}}{18} \quad (1)
\]

\[
\frac{\text{CaO}}{56} = \frac{\text{CO}_2 \delta \text{t wt. loss}}{44} \quad (2)
\]

Now the percentage of CaO is easily calculated, that is, using the values 0.54 and 1.51 (from Table 5 for sample No. 3) and cross-multiplying, as shown below:

\[
\frac{\text{CaO}}{56} = \frac{0.54}{18} = 1.692 \text{ percent CaO} \quad (3)
\]

\[
\frac{\text{CaO}}{56} = \frac{1.51}{44} = 1.922 \text{ percent CaO} \quad (4)
\]

The final step in determining the total original percentage of CaO is to add the three percentages of CaO together as shown in Table 6.

From the studies by Narita et al. (12), weathering slag is related to the amount, distribution, and characteristics of the CaO. If the unweathered slag contains less than 1 percent CaO, it should be volumetrically stable and should not produce tufa. If, however, the original amount of CaO is in excess of 1 percent, the slag should readily produce tufa in subdrains of highways. All slag samples are grouped in Table 6 according to their range of total original percent CaO. Five groups are recognized: 0 percent, 3.5 to 5 percent, 8 to 9 percent, 10 to 12 percent, and 24 to 25 percent. ACBF slag (0 percent CaO) is the only one that can be used as a subbase in highway construction; all others are considered to be harmful and could lead to the formation of tufa.

**CONCLUSIONS**

Previous work (12) has shown that if the percentage of total original CaO in a slag exceeds 1 percent, the slag could readily precipitate CaCO₃. The results from the TG plots showed two major changes in weight loss—dehydration and dissociation of carbonates. From these changes in weight loss, the percentage of CaO can be calculated. These calculated percentages of CaO from plots plus the results from the sugar test determine the maximum original percentage of CaO. ACBF slag (0 percent CaO) is the only one that can be used as a subbase in highway construction; all others are considered to be potentially deleterious and could lead to pavement failure. The TG method together with the sugar test are excellent and economical ways to determine the maximum original CaO in slags and the tendency of the slags to precipitate CaCO₃ in the subdrains of highways.

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**REFERENCES**


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