Double Consolidation Technology for the Stabilization of Heavy Metal Ions in the Fly Ash Generated by the Incineration of Municipal Solid Waste

SUN JIA-YING*, YANG YI-FAN and ZHENG MING
Research Center of Green Building Material and Waste Resources Reuse, Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China

ABSTRACT: In this paper, a new consolidation technology is proposed for solidifying the fly ash from municipal solid waste; moreover, the safety of the solidified fly ash for practical applications is investigated. This approach aims to address the high levels of heavy metals, such as Pb and Zn, in the fly ash from municipal solid waste, which exceed the national emission standards for solid waste and water discharge in China. This consolidation method was found to increase the compressive strength (after 28 days) of fly ash concrete from municipal solid waste to values greater than 40 MPa. Furthermore, the asphalt mixture prepared with the fly ash concrete offered some excellent advantages, such as better residual Marshall Values and rutting resistance, which are beneficial when laying roads. Additionally, the leaching toxicity of the asphalt mixture was well within the limits prescribed by the national emission standards, which implies that the heavy metal ions were effectively bound in the asphalt mixture and the aggregate was stably solidified.

INTRODUCTION

The rapid increase in the rate of municipal solid waste (MSW) production, which is typically between 10–12% a year in countries like China, has necessitated the development of effective technologies for its disposal. At present, methods such as landfilling, incineration, composting and recycling are still the chief ways of treating and disposing of MSW. However, it has been seen over the past few decades that these waste disposal practices can be inefficient and cause pollution. Furthermore, each processing technology has its limitations, which cannot be ignored. For example: gases and leachates are generated by landfilling; incineration produces dioxins and furan and attracts mosquitoes; and the quality of the obtained compost is affected by the presence of glass and other impurities [1–2].

In order to make effective use of the existing treatment facilities and address the challenge of efficiently treating MSW, a novel technology, which combines incineration and double consolidation with inorganic gelling materials and asphalt, is proposed in this paper. Using this technology, the toxic hazardous substances in MSW, such as fly ash, and in particular the heavy metal ions, are effectively bound and stably solidified so that the resulting sludge is unpolluted by these substances. It is noteworthy that an asphalt mixture prepared by concentrating MSW fly ash offers excellent advantages, such as better mechanical properties than those of common asphalt mixtures and improved performance when used for laying roads. The stability imparted by the presence of heavy metal ions in the asphalt mixture, which was prepared by concentrating MSW fly ash, was evaluated using the toxicity characteristic leaching procedure (TCLP) and multilevel extraction technology to check whether it complies with the Chinese national emission standards, GB5086.2-1997 [3], and the United States (U.S.) Environmental Protection Agency (EPA) standards, SW-846.

EXPERIMENTAL METHODS

Raw Materials

The following raw materials were used in the experiments.

- Slag: The ground slag for the experiments was pro-
cured from New Building Materials Co. Ltd. Shanghai Baotian. The slag had a specific data of 460 m²/kg and its chemical composition is shown in Table 1.

- **Steel slag**: The ground steel slag for the experiments was procured from Shanghai BaoSteel Metallurgy Construction Company. The slag had a specific data of 500 m²/kg and its chemical composition is shown in Table 1.

- **Curing agent**: The curing agent used in the experiments was prepared in-house.

- **MSW fly ash**: The MSW fly ash produced by the solid waste incineration plant in Ningbo, China, was used in the experiments.

- **Asphalt**: Sinopec Asphalt70# was used in the experiments. The overall performance of the asphalt is shown in Table 2.

The results of the experimental AC-16I gradation of the asphalt mixture are shown in Table 3. The asphalt aggregate ratio was 4.8%.

### Method

After drying, the MSW fly ash was mixed with the curing agent in ratios of 1:2, 1:2.5, and 1:3. The size of each sample was 40 mm × 40 mm × 160 mm, and samples were kept in a standard curing room before their bending and compressive strengths were measured according to the GB/T50081-2002 standards. Subsequently, the samples were divided into 120 categories, and then the asphalt mixture was prepared by powder concretion with the MSW fly ash, or with limestone dust.

The mechanical properties of the asphalt mixtures obtained were evaluated using the Marshall test according to the JTJ052-2000 (T0709) standards; moreover, the results obtained for an asphalt mixture with MSW fly ash were compared with those obtained for the mixture with limestone dust. The influence of the different proportions of the MSW fly ash on the water solubility of the asphalt mixture was evaluated by performing a freeze-thaw splitting test according to the JTJ052-2000 (T0729) standards.

Additionally, the influence of the different proportions of MSW fly ash on the high-temperature stability of the asphalt mixture was evaluated by performing a wheel rutting resistance test according to the JTJ052-2000 (T0719) standards.

The toxicity level, i.e., the heavy metal content, in the asphalt mixture prepared with the MSW fly ash concrete was tested according to the GB5086.2-1997 national standards. Furthermore, the maximum leaching toxicity of heavy metals using the TCLP was also tested according to the US EPA standards, SW-846 [4].

### RESULTS AND DISCUSSION

#### The Leaching Toxicity of MSW Fly Ash Concrete

In order to understand the influence of the double consolidation technology on the safety of the asphalt mixture prepared with MSW fly ash concrete, the leaching toxicity of the mixture was measured. The experimental results are shown in Figure 1.

The leaching toxicity of the heavy metal ions in the asphalt mixture with the MSW fly ash, which was prepared using the double consolidation method, was tested using the fly ash level oscillation method. The leaching toxicity was found to be lower than the national emission standards for solid waste and water discharge. Furthermore, the maximum leaching toxicity of the heavy metal ions, as determined using the TCLP, was also lower than these national emission standards.
However, the leaching toxicity of the heavy metal ions in the MSW fly ash, when tested alone, was higher than these emission standards. The fractions of metal ions from the MSW fly ash remaining in the asphalt mixture were 98%, 99%, 97%, 99%, 98%, and 100% for Pb, Zn, Cd, Cr, Cu, and Ni, respectively. Therefore, the heavy metal ions present in the MSW fly ash were effectively stabilized in the asphalt mixture by the double consolidation method.

The Mechanisms for the Stabilization of Heavy Metal Ions in the Asphalt Mixture Prepared by the Concretion of MSW Fly Ash

The heavy metal ions of Pb, Zn, Cr, and Cd that were present in the asphalt mixture, which contained the MSW fly ash prepared using the double consolidation method, could be analyzed using a multistage extraction process. This experiment was carried out to confirm the long-term stability of the asphalt mixture prepared using the double consolidation method; the results are shown in Figure 2.

In the multistage extraction process, 10% of the Pb, as a representative heavy metal, was acid soluble and found in the form of heavy metal carbonates and hydroxides. The heavy metal ions of all types in this form leached readily; however the percentages remaining in the aqueous solution were less than 10%, which is below the national discharge standards prescribed. In addition, the amount of Pb present in the amorphous ferric oxide was 15%, and was mainly in the form of heavy metal sulfates and elemental heavy metals. The

Table 3. Experimental AC-16I Gradation of the Asphalt Mixture.

<table>
<thead>
<tr>
<th>Gradation</th>
<th>0.075</th>
<th>0.15</th>
<th>0.3</th>
<th>0.6</th>
<th>1.18</th>
<th>2.36</th>
<th>4.75</th>
<th>9.5</th>
<th>13.2</th>
<th>16.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit</td>
<td>8</td>
<td>15</td>
<td>21</td>
<td>28</td>
<td>37</td>
<td>50</td>
<td>63</td>
<td>78</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>Lower limit</td>
<td>4</td>
<td>7</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>32</td>
<td>42</td>
<td>58</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>Experimental gradation</td>
<td>3</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>29.5</td>
<td>41</td>
<td>52.5</td>
<td>68</td>
<td>82.5</td>
<td>97.5</td>
</tr>
</tbody>
</table>

Figure 1. The results of the toxicity testing to determine the heavy metal content in the asphalt mixture prepared with MSW fly ash.
heavy metal ions found in heavy metal sulfates, oxides, and chromates were hardly leached under these conditions, and the amount of Pb found in the crystalline ferric oxide was 52%. The remaining 18% of the Pb was retained as residuals owing to the minimal leaching of heavy metal ions in the silicate or aluminum silicate families, or in elemental or oxide forms. More than 88% of the Zn, Cd, and Cr in the asphalt mixture was in the form of bound organics, amorphous ferric oxides, crystalline ferric oxides, or residuals. This shows that the physical and chemical reactions triggered in the asphalt mixture during concretion produced stable mineral phases, such as heavy metal sulfates, elemental heavy metals, oxide or chromate salts, silicates, and aluminum silicates.

These heavy metal ions were hardly leached under the conditions prescribed by the national testing standards. Therefore, the double consolidation of the asphalt mixture prepared with MSW fly ash can be applied safely for practical purposes.

The Replacement of the Limestone Dust in a Common Asphalt Mixture Containing MSW Fly Ash Concrete and a Comparison of the Stability

The compositional analysis of the different asphalt mixtures indicated that the CaO content in the MSW fly ash concrete was much higher than that in the limestone dust mixture. Thus, the limestone dust was replaced with MSW fly ash concrete to improve the alkalinity and adhesion of the aggregate and the asphalt.

The MSW fly ash concrete produced for the experiments was fully ground to pass through a 0.0075 mm standard test sieve. The grade of the asphalt mixture was at the medium level, according AC-16I. In the common asphalt mixture, the ratio of limestone dust is 6%, and in the experiments in this paper 25%, 50%, 75%, or 100% of this limestone dust was replaced by MSW fly ash concrete. The performance index of the asphalt mixture after the replacement was determined by the Marshall Stability test. The results of this sta-

![Figure 2. The results of the multilevel extraction.](image-url)
Double Consolidation Technology for the Stabilization of Heavy Metal Ions in the Fly Ash

These results show that replacing the limestone dust with MSW fly ash concrete can improve the stability of the aggregate and the asphalt. As the amount of the MSW fly ash concrete increased, the stability and its residual stability gradually increased, with the stability being maximized when 75% of the limestone dust was replaced with the MSW fly ash. However, when the amount of fly ash was increased further, the stability decreased marginally.

According to the chemical reaction theory, the alkalinity of the MSW fly ash concrete is higher than that of the limestone dust. Therefore, the acidic materials in the asphalt reacted completely with the alkaline MSW fly ash concrete, which could improve the adhesion between the asphalt and the aggregate. The maximum stability obtained when 75% of the limestone dust was replaced with the MSW fly ash. However, when the amount of fly ash was increased further, the stability decreased marginally.

According to the chemical reaction theory, the alkalinity of the MSW fly ash concrete is higher than that of the limestone dust. Therefore, the acidic materials in the asphalt reacted completely with the alkaline MSW fly ash concrete, which could improve the adhesion between the asphalt and the aggregate. The maximum stability obtained when 75% of the limestone dust was replaced with the MSW fly ash. However, when the amount of fly ash was increased further, the stability decreased marginally.


Fresh water, seawater, and sulfate liquor with 5% of Na₂SO₄ were employed in the freeze-thaw splitting tests, with the test results displayed in Figures 4(a) and 4(b).

The test results show that the addition of MSW fly ash concrete improved the water stability of the asphalt mixture; this was due to the alkaline nature of the fly ash. The asphalt, which contained carboxylic acid and sulfoxides, acted as a weak acid. Therefore, when the MSW fly ash concrete was evenly distributed in the asphalt mixture, the compounds reacted to form neutral and stable products. These products adhered to the surface of the aggregate and were difficult to remove, thus improving the water stability of the asphalt mixture.

Furthermore, the test results also show that the water stability of the asphalt mixture prepared with MSW fly ash concrete significantly differed depending on the...
test medium employed. The stability of the asphalt mixture was more pronounced in fresh water, for which the test results (TSR) exceeded 75%. The TSR in seawater was also high, while the minimum TSR was observed in sulfate liquor.

The High-temperature Stability of Asphalt Mixture Containing MSW Fly Ash Concrete Prepared by Double Consolidation

The results of the wheel rutting test of the asphalt mixture are shown in Figure 5, where it can be seen that the dynamic stability of the asphalt mixture increased significantly by increasing the MSW fly ash content. However, the increase in the dynamic stability of the asphalt mixture was not very significant when more than 75% of the limestone dust was replaced with the MSW fly ash concrete.

CONCLUSIONS

The following conclusions can be drawn from this study.

- The heavy ions present in MSW fly ash concrete were stabilized in the asphalt mixture during the double consolidation, which included the addition of the curing agent and asphalt. The leaching toxicity of heavy metal ions, as tested using the flat oscillation method or the TCLP, in the asphalt mixture prepared with the MSW fly ash concrete was far less than the limits prescribed by the national solid waste emission standards. Furthermore, because the binding between the heavy metals and the MSW fly ash concrete was significantly strengthened, the leaching toxicity of the heavy metals decreased.
- The multilevel extraction experiments demonstrated...
that the heavy metal ions in the MSW fly ash concrete were stable in the asphalt mixture. The stabilization of the heavy metal ions during the preparation of the asphalt mixture is attributed to a combination of chemical bonding and physical encapsulation.

- The results of the freeze-thaw splitting tests and wheel rutting tests of the asphalt mixtures, which were produced using the double consolidation technology, showed that the water stability and rutting resistance of the MSW fly ash concrete were better than those of common asphalt mixtures. Thus, the MSW fly ash subjected to the double consolidation method could be used to prepare asphalt mixtures that can be used safely for practical purposes.

REFERENCES


