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# Utilization of Sewage Sludge Molten Slag as Aggregate Substitute in Asphalt Mixtures

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**Graphical abstract**

**Abstract**

Sewage sludge is one of the final products from wastewater treatment processes. Handling and disposal of sewage sludge has become one of the major economic and environmental concerns. Instead of simply treating and disposing, high temperature melting treatment is considered as one of the effective alternative efforts to utilize sewage sludge as reusable materials. High temperature melting is defined as the method of melting sewage sludge at temperature of about 1500°C before cooling the molten sludge to become solidified materials, known as molten slag. Past studies have shown that high temperature melting treatment could convert sewage sludge into reusable products without adverse environmental effects. The objective of this study is to evaluate the possible utilization of sewage sludge molten slag as aggregate substitute in asphalt mixtures for pavement construction applications. The whole concept of this study was designed to assess the materials characteristics and suitability, and thus to evaluate the performance of asphalt mixtures with sewage sludge molten slag as aggregate substitute in terms of Marshall stability and flow tests. Based on the conducted study, it can be concluded that sewage sludge molten slag fulfilled almost all the standard requirements for aggregates in asphalt mixtures and can be utilized as partial replacement for aggregates. Sewage sludge molten slag has shown to be able to resist wear, polishing effect and weathering actions.

*Keywords*: Sewage sludge; thermal treatment, high temperature melting, asphalt mixtures, aggregates



## 1.0 INTRODUCTION

In recent decades, sewage sludge handling and disposal are of major economic and environmental concern. Sewage sludge, also known as bio solids is one of the final products from wastewater treatment processes. Today, wastewater treatment infrastructures have to deal with millions of tons of domestic sludge generated annually. In Malaysia, about four millions cubic meter of domestic sludge is being produced every year [1]. By the year 2015, Malaysia is expected to produce about 5.7 million cubic meters of domestic sludge and to be increased to about 6.6 million cubic meters by the year 2020 [2].

Due to increase in environmental awareness and stringent regulations governing the disposal set by environmental protection agencies, more effective measures for handling and disposal of sewage sludge need to be implemented. This is further compounded by the difficulty in securing reclaimed land in large urban areas, where land is not easily available for final disposal. Leachability of wastes to groundwater table also has been one of the problem if it is disposed in sanitary landfill [2]. The perception of society on sewage sludge is always bad, and therefore there is a large barrier on utilization of sewage sludge especially for agricultural use in Malaysia. Therefore, instead of simply treating and disposing sewage sludge, effective alternative efforts should be considered to utilize it as reusable materials.

Thermal treatment nowadays has become one of the major technologies for the sewage sludge treatment to produce secure final products. Thermal treatment processes including incinerating and high temperature melting are the latest advanced treatment processes in which safe, high, quality and non-leachable end products are achieved [3]. These final products can then be utilized in many applications such as in construction and building materials [3-4]. Thermal treatment is the control of heating and cooling of materials in solid states for the purposes of altering the material properties.

High temperature melting treatment of sewage sludge has been identified as an attractive method in terms of sludge-volume reduction and production of reusable by-products [5-6]. High temperature melting is defined as the method of melting sewage sludge at temperature of about 1500°C. Then the molten sludge is cooled to become solidified material, known as molten slag. High temperature melting treatment usually comprises of three important parameters, namely as heating temperature, holding time and cooling rate. Different heating temperature leads to different properties and microstructure of the end products. Holding time determines whether the desired temperature has reached the entire materials and thus allows changes to the entire microstructure of the sludge materials. Cooling rate affects the resulting microstructure and consequently the properties of the materials, and also affects the concentration of heavy metals in the leachate.

Molten slag produced by a slow cooling rate (less than 5°C per minutes) was found to exhibit the lowest heavy metals contents in the leachate [7]. Figure 1 shows the molten slag samples that have been produced from the high temperature melting treatment. Past studies have indicated that high temperature melting treatment could convert sewage sludge into products that can be either reused or land filled without adverse environmental effects [5]. This paper will focus on the possible utilization of sewage sludge molten slag as aggregate substitute in asphalt mixtures for pavement construction.

**Figure 1** Sewage sludge molten slag from high temperature melting treatment [7]

## 2.0 MATERIALS AND METHODS

The overall concept of this study was designed to assess the materials characteristics and suitability of sewage sludge molten slag as aggregate substitute in asphalt mixtures. Also, this study was conducted in order to evaluate the performance of asphalt mixtures with sewage sludge molten slag as aggregate substitute in terms of Marshall stability and flow tests. Methods were conducted in to American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO) and British Standard (BS).

Median gradation based on the modified specification for aggregate gradation for Stone Mastic Asphalt (SMA) mixtures was selected [9] and presented in Figure 2. Conventional 60/70 penetration grade of bitumen was used as adhesive materials. The following tests were carried out in order to evaluate and confirm the properties of bitumen, namely penetration test and softening point test. All the test results for the physical properties of bitumen were conformed to the specification requirements.

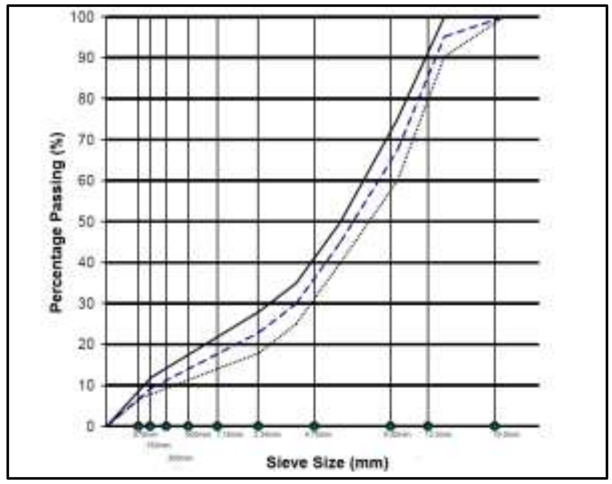


**Figure 2** Chart for aggregate gradation based on the modified specification for Stone Mastic Asphalt (SMA) mixtures [9]

### 2.1 Preparation of Sewage Sludge Molten Slag

A total of 60 kg of dewatered sewage sludge which was collected from sand drying beds in Damansara Regional Sewage Treatment Plant, Malaysia was introduced into electrical furnace (Model ELF 11/6 (201), CARBOLITE) at temperature of 900°C for a duration of three (3) hours for the purpose of drying and incinerating. The incinerated ash produced from these processes was then used as raw materials for the subsequent high temperature melting treatment, where the incinerated ash was grounded and placed in the porcelain crucible before being melted in the furnace. Temperature of the furnace was increased at a rate of 10°C per minutes until it reached 1450°C, then being hold for about 45 minutes before being cooled to a room temperature at a rate of 5°C per minutes. Molten slag was the final products from these processes. For duration of about five months, approximately 10 kg of sewage sludge molten slag samples had been produced by using high temperature melting processes.

### 2.2 Experimental Design

The plan of the study is outlined as follows.

1. Determination of the materials characteristics and suitability of sewage sludge molten slag as aggregate substitute in asphalt mixtures by valuating the physical properties as listed in Table 1.

**Table 1** Physical property tests for sewage sludge molten slag

| Test | Test Method | Significance of Test | Specification Requirements |
|---|---|---|---|
| Los Angeles Abrasion | ASTM C131-81 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregates by Abrasion and Impact in the Los Angeles Machine | Resistance to degradation and abrasion; quality in term of hardness | <30% |
| Aggregates Impact Value | BS 812 Testing Aggregates Part 112 Method for Determination of Aggregates Impact | Resistance to impact | <15% |
| Polished Stone Value | BS 812 Testing s Part 114 Method for Determination of Polished Stone Value | Resistance to polishing effect; skid and wear resistance | >40 |
| Soundness | ASTM C88-83 Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate | Resistance to freeze and thaw, and wet and dry | <20% |
| Flakiness and Elongation | BS 812 Testing Aggregates Part 105.1 Flakiness Index and Part 105.2 Elongation Index of Coarse Aggregates | Particle shape and surface texture | <20% (Flakiness) |
| Specific Gravity | ASTM C127-88 Standard Test Method for Specific Gravity and Absorption of Coarse Aggregates | Mix design analysis; porosity | - |

2. Mix design analysis which includes the determination of optimum asphalt contents (ASTM D1559-89 Standard Test Method for Resistance to Plastic Flow of Bituminous Mixture Using Marshall Apparatus) and performance of asphalt mixtures with sewage sludge molten slag as aggregate substitute in terms of Marshall stability and flow tests. A total of 15 specimens with asphalt contents ranging from 4.5% to 6.5% were prepared in order to determine the optimum asphalt contents value, before being subjected to Marshall stability and flow tests as per ASTM D1559-89. Stability of a specimen is the maximum load required to produce failure when the specimen was placed in the testing head and load was applied at a constant strain of 50.8 mm $min^{-1}$ (2 in $min^{-1}$). Flow rate is a general indication of potential for permanent deformation in asphalt mixtures. A high flow value (greater than 16) is usually considered as an indicator that the mixtures may be unstable under traffic [8-9].

## ■3.0 RESULTS AND DISCUSSIONS

Results of the study were presented in two sections, namely as physical property tests of sewage sludge molten slag and mix design analysis. In this study, sewage sludge molten slag was treated as aggregates and has been tested to determine the physical properties in accordance with the established method of testing and then was used as aggregate substitute in asphalt mixtures, before being subjected to Marshall stability and flow tests.

### 3.1 Physical Property Tests of Sewage Sludge Molten Slag

A total number of six tests have been carried out in order to obtain the physical properties of sewage sludge molten slag and thus to determine the suitability as aggregate substitute in asphalt mixtures. All the test results were conformed to the standard specification requirements. Based on the results, which were summarized in Table 2 with a comparison to the standard specification requirements, sewage sludge molten slag fulfilled almost all the specification requirements. Generally, sewage sludge molten slag has shown a positive sign on the utilization as aggregate substitute in asphalt mixtures.

Los Angeles abrasion test is the most commonly accepted method used to measure the hardness of aggregates for pavement constructions [8-9]. Based on the results of the physical property tests, the percent loss for the test was 16.71%, which is in acceptable range in accordance to the specification requirements. Aggregate impact value gives a relative measure of resistance of aggregates to sudden shock or impacts and the results obtained have shown that the sewage sludge molten slag can resist fracture under the impact of moving loads. Sewage sludge molten slag also has shown positive results in terms of polished stone value, which resulted in the values within the acceptable range of more than 40. Therefore, sewage sludge molten slag can provide sufficient resistance for skidding to permit normal turns and braking movements. Also, the sewage sludge molten slag can be said to have higher resistant due to weathering action which have been shown through the soundness test. This test measures the resistance of aggregates due to disintegration in a saturated solution of sodium sulfate which simulates the weathering of the aggregates in real nature [8-9]. However, sewage sludge molten slag has shown weakness in the flakiness and elongation index, in which about 24% of the molten slag was flaky in shape

**Table 2** Results of the physical property tests of sewage sludge molten slag

| Test | Results | Specification Requirements |
|---|---|---|
| Los Angeles Abrasion | 16.71 | <30% |
| Aggregates Impact Value | 12.44% | <15% |
| Polished Stone Value | 41.5 | >40 |
| Soundness | 11.61% | <20% |
| Flakiness and Elongation | 23.84% (Flakiness) and 5.26% (Elongation) | <20% (Flakiness) |
| Specific Gravity | 2.977 | - |

### 3.2 Mix Design Analysis

A total of 15 specimens with asphalt contents ranging from 4.5% to 6.5% by total mass of the mixtures were prepared in order to determine the optimum asphalt content value. The main purpose for mix design analysis was to obtain the optimum asphalt content value that would give the best performance of asphalt mixtures in terms of stability, rutting and fatigue cracking. Due to poor gradation and also the problems related to the flakiness and elongation, sewage sludge molten slag has to be mixed with conventional aggregates consisted of 14 mm nominal maximum aggregate size of Hanson granite and limestone as mineral filler, in order to result in the better gradation and properties of the aggregates. The ratio of the sewage sludge molten slag to conventional aggregates in the aggregate mixtures was one to five in terms of mass for each sieve size.

Tables 3 to 4 and Figure 3 summarize the mix design analysis conducted based on Universiti Putra Malaysia's method, which was adopted from Asphalt Institute. The optimum asphalt content was calculated by averaging the asphalt content corresponding to 4% air voids and maximum value of bulk density, resilient modulus and corrected Marshall stability [7], as shown in Figure 2. Based on Asphalt Institute Method, the optimum asphalt content was determined by averaging the asphalt content corresponding to only 4% air voids and maximum value of bulk density, and corrected Marshall stability [10]. The inclusion of resilient modulus as one of the parameters in determining the optimum asphalt content based on the Universiti Putra Malaysia's method was based on the emphasis that being placed on the measurement of fundamental properties of stiffness modulus and simplicity of the test procedure. Since Marshall stability test was regarded as empirical and not highly correlated to pavement performance [11], improved methods for determining the optimum asphalt content are needed and the inclusion of resilient modulus seems to be reasonable to provide a more accurate measure of the value.

**Table 3** Results of mix design analysis

| Percentage Binder (%) | Bulk Density (g/cm$^3$) | Theoretical Maximum Density (g/cm$^3$) | Air Voids (%) | Corrected Marshall Stability (kN) | Resilient Modulus (MPa) | Flow (mm) |
|---|---|---|---|---|---|---|
| 4.5 | 2.535 | 2.680 | 5.46 | 15.47 | 1234.40 | 2.31 |
| 5.0 | 2.537 | 2.660 | 4.57 | 16.12 | 1230.95 | 3.08 |
| 5.5 | 2.538 | 2.640 | 3.76 | 17.99 | 1409.55 | 3.70 |
| 6.0 | 2.535 | 2.620 | 3.07 | 12.28 | 1096.80 | 3.44 |
| 6.5 | 2.531 | 2.590 | 2.43 | 13.57 | 1163.75 | 4.15 |

**Table 4** Calculation of optimum asphalt content based on Universiti Putra Malaysia's method

| Parameter | Percentage Binder (%) |
|---|---|
| Bulk Density | 5.26 |
| Air Voids @ 4% | 5.32 |
| Corrected Marshall Stability | 5.09 |
| Resilient Modulus | 5.25 |
| Optimum Asphalt Content | 5.23 |

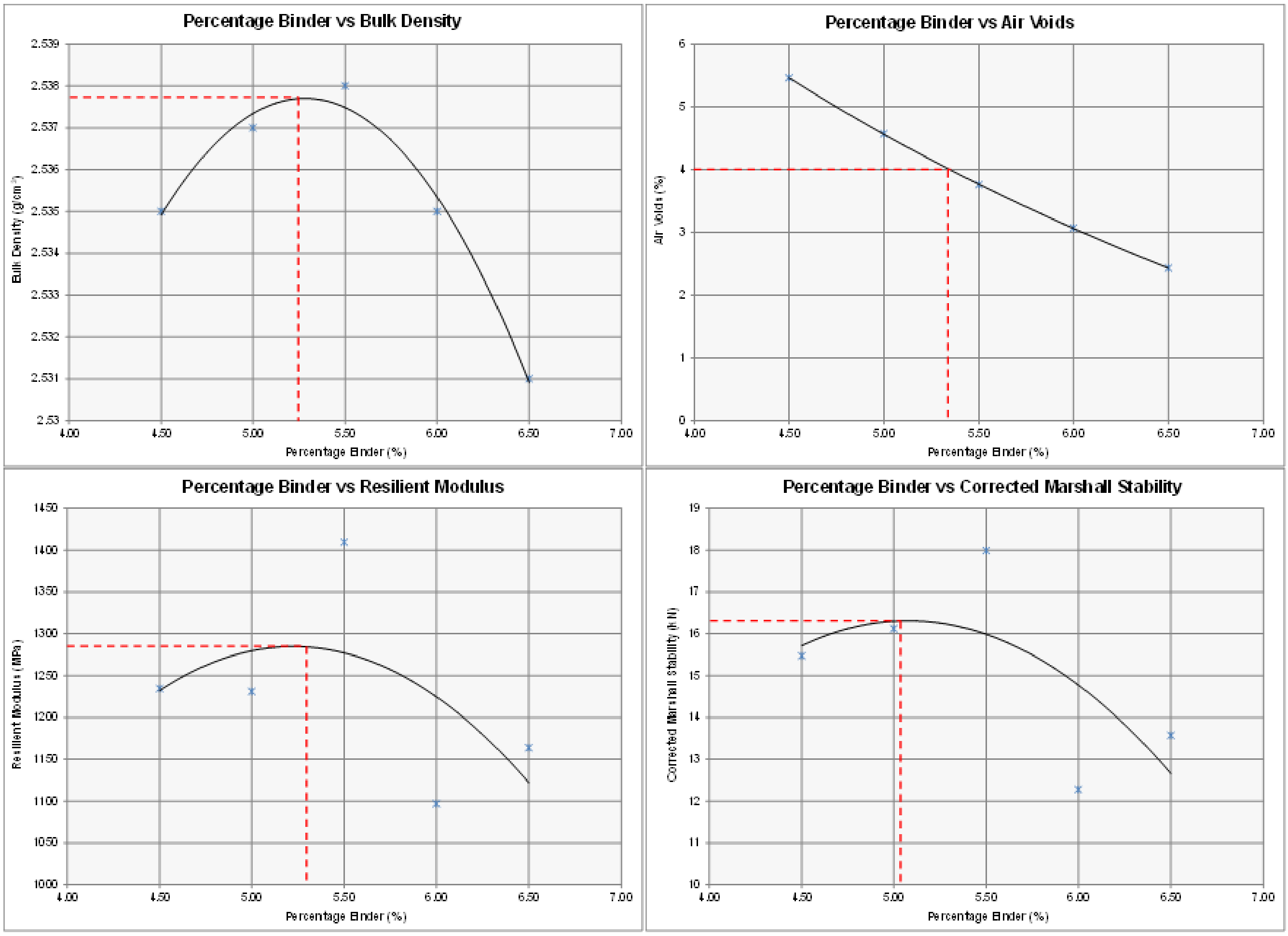


**Figure 3** Plots for determination of optimum asphalt content

The optimum asphalt contents value from the mix design analysis was found to be 5.23%. Comparing the optimum asphalt contents value of 5.23% with the typical asphalt contents for Stone Mastic Asphalt (SMA) mixtures which is ranging from 5% to 8%, the resulted value of the optimum asphalt content with sewage sludge molten slag as aggregate substitute seems to meet the standard specification requirements. Also, based on the controlled Stone Mastic Asphalt (SMA) mixtures using the same conventional aggregates of 14 mm nominal maximum aggregate size of Hanson granite and limestone as mineral filler (i.e. without the sewage sludge molten slag as aggregate substitute), the optimum asphalt contents value was found to be comparable. The optimum asphalt contents value from the controlled Stone Mastic Asphalt (SMA) mixtures is 5.77% [9].

## 3.3 Performance Tests

Based on the obtained optimum asphalt contents value of 5.23% for the Stone Mastic Asphalt (SMA) mixtures with sewage sludge molten slag as aggregate substitute, a total of 10 specimens were further prepared and tested for various performance tests. These tests were conducted in order to evaluate the performance in terms of Marshall stability and flow tests as well as resilient modulus in comparison with the controlled Stone Mastic Asphalt (SMA) mixtures using the
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same asphalt mixtures materials (i.e. conventional aggregates of 14 mm nominal maximum aggregate size of Hanson granite, limestone as mineral filler and conventional 60/70 penetration grade of bitumen). Results for the controlled Stone Mastic Asphalt (SMA) mixtures were obtained from previous study [9]. Table 5 summarizes the data of the test results. Based on the data of the test results, the average values for the Marshall stability and flow tests as well as resilient modulus between Stone Mastic Asphalt (SMA) mixtures with sewage sludge molten slag as aggregate substitute and controlled Stone Mastic Asphalt (SMA) mixtures were found to be close to each other.

Coefficient of variation was calculated for each parameter based on the total of 10 specimens for each mixture (i.e. Stone Mastic Asphalt (SMA) mixtures with sewage sludge molten slag as aggregate substitute and controlled Stone Mastic Asphalt (SMA) mixtures). Coefficient of variation was used to evaluate and compare the variation between data sets and calculated as in Equation 1. Based on the literature found in the pavement related areas, which had used the coefficient of variation as part of the data analysis, the selection of 7% as cutoff value to indicate the consistency level of the data sets seems to be reasonable [13]. Hence, small percentage of coefficient of variation of 4% to 6% as compared to the predefined cut-off value of 7% indicates the excellent uniformity between data sets of Stone Mastic Asphalt (SMA) mixtures with sewage sludge molten slag as aggregate substitute and controlled Stone Mastic Asphalt (SMA) mixtures.

**Table 5** Results of performance tests

| | Average Bulk Density (g/cm$^3$) | Coefficient of Variation (%) | Average Corrected Marshall Stability (kN) | Coefficient of Variation (%) | Average Resilient Modulus (MPa) | Coefficient of Variation (%) | Average Flow (mm) | Coefficient of Variation (%) |
|---|---|---|---|---|---|---|---|---|
| SMA mixtures with sewage sludge molten slag | 2.537 | 5 | 15.89 | 6 | 1337.42 | 5 | 3.78 | 6 |
| Controlled SMA mixtures | 2.417 | 4 | 13.21 | 7 | 1576.32 | 4 | 4.21 | 6 |

## ■4.0 CONCLUSIONS AND RECOMMENDATIONS

Aggregates constitute about 94% to 95% by weight of asphalt mixtures. Therefore, the properties of aggregates are very important to the performance of pavement system in which asphalt mixtures are used [12]. Suitability of the aggregates is usually determined by grading, resistance to abrasion, soundness, shape and texture properties and specific gravity. Based on the results of the physical property tests, sewage sludge molten slag fulfilled almost all the standard requirements. Sewage sludge molten slag has shown the ability to resist wear, polishing effect and weathering actions. Also, sewage sludge molten slag can be classified as hard materials, the most important properties for aggregates used for pavement constructions.

However, sewage sludge molten slag has shown weakness in the flakiness and elongation index, in which about 24% of the aggregate particles was found to be flaky in shape. Based on past studies, flaky aggregates are normally not very suitable for pavement constructions due to difficulty for compaction and workability. Sewage sludge molten slag also shown poor aggregates gradation in which the proportions of aggregate particles largely consist of a size higher than 2 mm. This criteria can results in porous mixtures and lack of tensile strength when mix with asphalt materials. Therefore, to overcome problems due to high flakiness index and poor aggregates gradation, it is recommended for sewage sludge molten slag to be mixed with conventional aggregates from natural sources. In addition, the amount of sewage sludge molten slag that can be produced is quite limited due to the large volume and weight reduction after the high temperature melting treatment which can be considered as time consuming and cost-effective processes. Therefore this suggestion seems reasonable and efficient, since a great amount of aggregates is required for pavement constructions.

The value for the optimum asphalt content for asphalt mixtures with sewage sludge molten slag as partial aggregate substitute is 5.23%, which lies in the standard requirements range of 5.0% to 8.0% for Stone Mastic Asphalt (SMA) mixtures. In terms of the performance, asphalt mixtures with sewage sludge molten slag was found to produce comparable properties in relation with the controlled mixtures. Therefore, it can be concluded that sewage sludge molten slag can be utilized as partial replacement for aggregates in asphalt mixtures. The mixtures of the sewage sludge molten slag and conventional aggregates from natural sources in the ratio of one to five has satisfied all the properties required for asphalt mixtures and produced expected mix design properties in accordance with the standard specification requirements. However, future works should be conducted to further evaluate the performance of sewage sludge molten slag as aggregate substitute in asphalt mixtures, which can be extended in the detailed determination of asphalt mixtures properties such as wheel tracking test (rutting), fatigue cracking and moisture damage.

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