The effect of type and particle size of industrial wastes filler on Indirect Tensile Stiffness and Fatigue performance of Stone Mastic Asphalt Mixtures

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Abstract: The purpose of this study is to evaluate the effect of type and particle size of industrial waste as filler on stiffness and fatigue performance of Stone Mastic Asphalt (SMA) Mixtures. In this study four types of industrial by-product wastes filler namely, limestone as reference filler, ceramic waste dust, coal fly ash, and steel slag dust with three size combination ratios, 100/0 passing the 0.075 mm, 50/50 passing 0.075 and 0.02, and 0/100 passing 0.02 mm sieve were used for direct comparison. The effect of different type and size of filler on the indirect tensile stiffness and fatigue properties of SMA bituminous mixtures was investigated. The Repeated Load Indirect Tensile Fatigue Test (ITFT) was carried out in accordance with British Standard DD ABF method Using Universal Testing Machine (UTM) on twelve SMA mixtures to establish fatigue failure criteria and to investigate the effect of waste fillers type and particle size on fatigue behavior of SMA mixtures. The parameters of fatigue functions for asphalt mixture with waste fillers are obtained and compared, and it confirms that the fatigue property of asphalt mixture can be improved especially at lower stress levels. Mixtures made with ceramic waste and coal fly ash with particle size ratio of 100/0, 50/50 respectively has resulted in increasing the fatigue life of SMA mixture. The only mixture that violated the increasing trend of fatigue damage resistance to cyclic loading was the mixture with steel slag dust.

Key words: SMA, Filler type and size, ITFT, Fatigue performance.

INTRODUCTION

With development of infrastructure and increasing transportation demands, the development of new modified paving materials and use them in construction results in high performance pavements to meet the needs of the communities. While developing these new modified paving materials, attention should be paid to using industrial and by product waste materials effectively in construction to address environmental and economic concerns. The vast amount of waste materials produced daily is one of the major worldwide problems in waste management. Developing countries like Malaysia produce a considerable amount of wastes from ceramic, steel industry and coal-fired power plants every year and this huge amount of waste creates a significant problem with respect to handling and storage, which are important both from the economic and environmental point of view.

Researchers have been investigating the use of waste materials in the construction industry, to enable better management of these important wastes and to improve the properties of construction materials. The use of industrial and by-products wastes as replacement of mineral fillers in asphalt mixtures to enhance the properties and performance of asphalt concrete pavements. Researchers are eager and devoted to select paving materials that minimize pavement distresses and to improve the performance of asphalt pavements. Fillers as one of the components in an asphalt mixture, play a major role in determining the properties and the behavior of the mixture, especially the binding and aggregate interlocking effects. The filler has the ability to increase the resistance of particle to move within the mix matrix and/or works as an active material when it interacts with the asphalt cement to change the properties of the mastic. Kim et al. (2003) investigated the effect of fillers and binders on the fatigue performance of asphalt mixes. They concluded that the filler type affected the fatigue behavior of asphalt binders and mastic. Fillers also stiffened the binders, and hydrated lime was more effective in stiffening binders than limestone fillers. Another conclusion was that even if the fillers stiffened the binders, they acted in such a way that they provided better resistance to microcracking and thus an increased fatigue life.

Tapkin et al. (2008) evaluated the effect of fly ash as a filler replacement on the mechanical properties of asphalt mixture and found that fly ash can be used effectively in a dense-graded wearing course as a filler replacement. Ahmed and Othman et al. (2006) investigated the effect of using waste cement dust as mineral filler on the mechanical properties of asphalt mixture, and the results indicated cement dust can totally replace limestone powder in asphalt paving mixture. Hwang et al. (2008) investigated the potential use of waste lime as mineral filler in asphalt mixture, and the results suggested that using waste lime as mineral filler can improve the permanent deformation characteristics, stiffness and fatigue endurance of asphalt mixture. Based on these
researches above, the use of such waste dusts as filler in asphalt mixture not only has no negative influence on asphalt mixture, but also can improve its engineering characteristics. Therefore, using wastes as filler for asphalt mixture may be an economic way in road and construction engineering, which can enlarge the application range and improve the utilization rate of waste.

The present investigation assessed the influence of different type and size of waste materials as replacement of mineral filler on the structural integrity of SMA bituminous mixtures by performing indirect tensile fatigue (ITFT) and indirect tensile stiffness modulus (ITSM) tests. Based on these experimental results, the feasibility of waste materials as mineral filler in asphalt mixture is assessed comparing with control mixture using conventional limestone filler.

**Objective:**

This study aims to evaluate and to examine the deformation behavior under repeated loadings using UTM at define temperatures of the laboratory performance-based properties of Stone Mastics Asphalt (SMA) mixtures incorporating four different waste materials (limestone as reference (LSD), ceramic waste dust (CWD), coal fly ash (CFA), and steel slag dust (SSD)) as replacement of mineral fillers. The selected fraction of waste filler material (10% of the total weight of aggregate) was blended in three different proportions 100/0, 50/50, and 0/100 passing the 75 and 20 micron to determine and evaluate the effects of these waste fillers and their particle size on the stiffness and fatigue resistance of SMA mixtures.

**Experimental studies of fatigue cracking:**

**Materials:**

Mixture characteristics are directly dependent on the properties of the aggregate and bitumen that constitute the paving mixture. As the filler, in general, is an integral part of the aggregate used in bituminous mixtures, its characteristics and amount contained in the mix play an important role in modifying the mixture characteristics. The optimum bitumen content and air voids are influenced by the filler type, size, and amount and eventually all mechanical mixture characteristics are affected.

In this study one aggregate gradation was chosen such that it was within the master gradation band for a 12.5 mm Nominal Maximum Aggregate Size (NMAS) SMA. The crushed granite aggregate (coarse and fine) was blended to meet the gradation recommended by the National Asphalt Pavement Association (NAPA). The particle size distribution of the aggregates is shown in Table 1 and Figure 1 for (NMAS) SMA. The properties of coarse and fine aggregate were presented in Table 2.

**Table 1:** Granite aggregate gradation.

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>19.00</th>
<th>12.5</th>
<th>9.50</th>
<th>4.75</th>
<th>2.36</th>
<th>0.60</th>
<th>0.30</th>
<th>0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>% passing</td>
<td>100</td>
<td>85-95</td>
<td>Max. 75</td>
<td>20-28</td>
<td>16-24</td>
<td>12-16</td>
<td>12-15</td>
<td>8-10</td>
</tr>
<tr>
<td>% used</td>
<td>100</td>
<td>90</td>
<td>70</td>
<td>24</td>
<td>20</td>
<td>14</td>
<td>13</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig. 1:** Gradation graph of Granite Aggregate 12.5mm SMA mixture.

The Cellulose Oil Palm Fiber (COPF) used in this study is a University Putra Malaysia (UPM) initiated technology product.

In this study four waste fillers namely Limestone, Ceramic Waste, Coal Fly Ash, and Steel Slag with particle size proportion (passing 75µm / passing 20 µm) with three combination of filler 100/0, 50/50, and 0/100 were evaluated for direct comparison. Waste materials were crushed and ground to pass the standard sieve
size 0.075 mm and 0.02 mm. The particle size distributions of the waste materials are shown in Figure 2. It can be observed that the finest of these four samples is coal fly ash and the Steel slag dust is the coarsest.

### Table 2: Coarse and Fine Aggregate Properties

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard used</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles Abrasion (%)</td>
<td>ASTM C 131</td>
<td>22.3</td>
</tr>
<tr>
<td>Aggregate Impact Value</td>
<td>BS 812: Part 3</td>
<td>7.84%</td>
</tr>
<tr>
<td>Flakiness Index</td>
<td>ASTM D 4791, BS 812</td>
<td>14.89%</td>
</tr>
<tr>
<td>Elongation Index</td>
<td>ASTM D 4791, BS 812</td>
<td>1.55%</td>
</tr>
<tr>
<td>Coarse aggregate Angularity</td>
<td>Superpave Mix Design</td>
<td></td>
</tr>
<tr>
<td>One or more fractured face</td>
<td></td>
<td>97%</td>
</tr>
<tr>
<td>Two or more fractured face</td>
<td></td>
<td>93%</td>
</tr>
<tr>
<td>Fine aggregate Angularity, Air voids % (loose)</td>
<td>Superpave Mix Design</td>
<td>53%</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>AASHTO T 85</td>
<td>0.5</td>
</tr>
<tr>
<td>Specific Gravity of Coarse Aggregate</td>
<td>ASTM C 127</td>
<td>2.62</td>
</tr>
<tr>
<td>Specific Gravity of Fine Aggregate</td>
<td>ASTM C 128</td>
<td>2.58</td>
</tr>
</tbody>
</table>

The bitumen used in SMA mixtures is the 80/100 Penetration bitumen. Results of its properties are listed in Table 3.

### Table 3: Physical properties measured of bitumen

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Test method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity at 25°C, (g/cm³)</td>
<td>AASHTO T228</td>
<td>1.03</td>
</tr>
<tr>
<td>Penetration at 25°C, (0.1mm), 100 g, 5s</td>
<td>AASHTO T49</td>
<td>84</td>
</tr>
<tr>
<td>Softening point (R&amp;B), °C</td>
<td>AASHTO T53</td>
<td>48</td>
</tr>
<tr>
<td>Viscosity at 135°C, (centistokes)</td>
<td>AASHTO T201</td>
<td>413</td>
</tr>
<tr>
<td>Viscosity at 165°C, (centistokes)</td>
<td>AASHTO T201</td>
<td>100</td>
</tr>
<tr>
<td>Ductility at 25°C, (cm)</td>
<td>AASHTO T51</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

The composition of the 12.5mm nominal maximum aggregate size (NMAS) SMA mixture consists of:

- 76% coarse granite aggregate
- 14% fine aggregate
- 10% filler
- Cellulose fibers content of 0.3 kg per 100 kg aggregate
- Optimum (target) void content of 4.0%
- Asphalt binder at Optimum Asphalt Content (OAC)

### Specimens preparation:

The waste materials particle size combinations (passing 75/20 micron) were mixed at three different ratios, 100/0, 50/50, and 0/100, twelve mix designs were made with the same blend of coarse and fine aggregates to keep aggregate angularities and mineralogical characteristics constant. The only variable in the mixtures was the...
filler type and the filler particle size proportion. The twelve mix designs labeled, L10=LSD100/0, L5=LSD50/50, L0=LSD0/100, C10=CWD 100/0, C5=CWD 50/50, CO=CWDO/100, F10=CFA100/0, F5=CFA50/50, F0=CFA0/100, and S10=SSD100/0, S5=SSD50/50, S0=SSD0/100 represent four types of waste filler and three combinations of particle size to produce SMA mixes at established mixing and compacting temperatures. The twelve mixtures designed for this study are shown in Figure 3.

Aggregate (Granite) + Asphalt binder (80/100) + 10% Filler

- 100% passing 75 µm sieve [L10, C10, F10, S10]
- 50/50 % passing 75/20 µm sieve [L5, C5, F5, S5]
- 100 % passing 20 µm sieve [L0, C0, F0, S0]

Limestone Dust [L10, L5, L0]
Ceramic Waste Dust [C10, C5, C0]
Coal Fly Ash [F10, F5, F0]
Steel Slag Dust [S10, S5, S0]

Fig. 3: The Twelve Mixtures Designed for the Study.

The SMA slabs were prepared at optimum asphalt content. All the asphalt mixture testing was undertaken on 100mm diameter specimens that had been cored from 750mm by 600mm by 80mm slabs produced by means of a laboratory slab roller compactor (Turamesin) to compact the loose material with a segment of a roller that is said to allow the aggregate particles to move relative to one another and orientate themselves in a manner similar to in situ material. The precise depth of the slab can be preset, enabling a target density to be achieved as shown in Figure 4. Each mixture (slab) was subjected to the same number of passes and compaction effort in ensuring that engineering properties of laboratory prepared specimens are equivalent.

Fig. 4: Slab roller compactor (Turamesin).

The cylindrical specimens for the Performance Tests (Stiffness Modulus test and Repeated Load Indirect Tensile Fatigue test) were fabricated by coring 100 mm diameter by 80 mm high test specimens from the compacted slabs using a diamond-coated asphalt coring bit (100-mm inner diameter). The height of the specimen was then trimmed to 40± 1mm using a grinding machine. Specimens were grinded approximately equal from each end of the cored specimen to ensure the uniformity of the specimens and to obtain relatively flat, smooth and parallel ends which provided better bonding between the LVDT’s points and the specimen surface and to reduce the variation in the distribution of air voids in the specimen.
Once 100 mm diameter by 40 mm high cylindrical specimen was obtained it was checked that the sample-diameter had a parallel surface. Once all fabrication works are done and during the process of specimen preparation, if segregation on the specimen surface was observed, the specimen was discarded and additional specimens were made. Duplicate specimens were made from all the twelve mixtures for individual performance tests, a total of 120 specimens (5 loads x 2 specimens x 12 mix design) were used for determination of stiffness modulus and fatigue test (because of nondestructive nature of stiffness modulus testing, the same specimen can be used for fatigue tests) to evaluate the effects of the added filler type and particle size on the stiffness and fatigue life of SMA mixtures.

Methodology:
The two main tests that are undertaken with the use of Universal Testing Machine (UTM) are the measurement and assessment of the stiffness modulus (load bearing capacity) and one of the main pavement distress mechanisms which is fatigue cracking.

The key mechanical properties of a bituminous material are:
- Stiffness (load spreading ability)
- Fatigue resistance (resistance to cracking).
- Dynamic Modulus obtained from Fatigue data

Resilient Modulus Test:
The indirect tensile stiffness modulus (ITSM) test was used to determine the tensile properties of the asphalt concrete which can be further related to the cracking properties of the pavement. The ITSM test which is defined by BS DD 213 is a nondestructive test and has been identified as a potential means of measuring the stiffness properties and study effects of temperature and load rate. Under uniaxial loading the stiffness modulus is generally defined as the ratio between the maximum stress and the maximum strain. The ITSM (Sm) in MPa is calculated by the following equation:

\[
Sm = \frac{L(v + 0.27)}{D t} \quad \text{Eq.1}
\]

Where \( L \) is the peak value of the applied vertical load (N), \( D \) is the mean amplitude of the horizontal deformation obtained from 5 applications of the load pulse (mm), \( t \) is the mean thickness of the test specimen (mm), and \( v \) is the Poisson’s ratio (a value of 0.35 is normally used). The magnitude of the applied force conditioning pulses such that the specified target transient diametral deformation was achieved.

The Sm was determined from tests on cored specimens for each mixture at designed bitumen contents in the indirect tension mode. Constant test temperature was maintained using an environmental air chamber. Each specimen was placed inside the chamber at the set temperature for two hours before testing. All the 120 cored specimens were targeted to this test at temperature of 25 °C.

Repeated Load Indirect Tensile Fatigue Test (ITFT):
The fatigue performance of the asphalt mixtures was determined by means of the Indirect Tensile Fatigue Test (ITFT) with an experimental arrangement similar to that used for the Indirect Tensile Stiffness Modulus (ITSM) test but under repeated loading conditions using the Universal Testing System (UTS) developed by Industrial Process Control (IPC Global) limited. The indirect tensile test has been used in a number of asphalt mixture evaluations and pavement analyses. The test is simple to perform and is considered by some to be effective at characterizing materials in terms of their fundamental properties (Strategic Highway Research Program (SHRP) 1994). The test measures both the resilient and permanent deformations and strain in the horizontal and vertical axis of the specimen while applying up to one million loading cycles. This test is applicable to the British Standard – DD ABF method for determining the fatigue characteristics of bituminous mixtures. During the test, a pulsed diametral loading force is applied to the vertical axis of a specimen and the resulting total recoverable diametral deformation in the horizontal axis is then measured.

In this study a constant stress indirect tensile fatigue test was conducted by applying a cyclic constant load equal to 1.0, 1.5, 2.0, 2.5, and 3.0 kN, with a 0.2 sec loading followed by a 0.3 sec rest period was repeated until the specimen failed. A preconditioning program also was worked out, and that was keeping specimens inside the chamber at the testing temperature over a three-hour period before test begins. Pulse time was chosen 500 ms for very high trafficked volume roads and vehicle speeds were observed and 200 ms rise time for very low speed was used.

Deformation values were measured by two linear variable differential transformers (LVDT) attached to the specimen by pair of clamps at the center point of the specimen. A repeated dynamic compressive load was applied to specimens across the vertical cross section along the depth of the specimen using two loading strips 12.5 mm in width. The resulting total deformation was measured parallel with the applied force. The test was
terminated as soon as the specimen collapsed. The testing temperature chosen to characterize the fatigue lives of the mixtures was 20°C due to the fact that fatigue cracking is a pavement distress that typically occurs at intermediate temperatures. The horizontal deformation, parallel to the axis of tensile stress, was monitored and used to determine the failure of the specimens and the number of cycles that cause fatigue fracture is considered as the fatigue life.

Failure was considered to occur when the constant rate of increase of the horizontal deformations was replaced by a faster rate of increase of the deformations, as demonstrated in Figure 5. After that point, the microcracks present in the specimen were combined into macrocracks and the specimen was broken into two pieces as shown in Figure 6.

![Fatigue Failure Criterion for Controlled-Stress Fatigue Tests.](figure5)

![SMA test Specimen Before and After Fatigue Test.](figure6)

**Fig. 5:** Fatigue Failure Criterion for Controlled-Stress Fatigue Tests.

**Fig. 6:** SMA test Specimen Before and After Fatigue Test.

The ITFT tests were performed using the following test parameters (BSI, 1995):

- Test temperature: 20°C,
- Loading condition: controlled-stress,
- Loading rise-time: 200 ms,
- Load pulse rate: 500 ms between pulses, and
- Failure indication: 9mm vertical deformation.
- Waveform: haversine

The maximum tensile strain generated at the centre of the specimen is defined as:
\[ \varepsilon_{x, \text{max}} = \frac{\sigma_{x, \text{max}} (1 + 3\nu)}{S_m} \times 1000 \]  

Eq. 2

Where: \( \varepsilon_{x, \text{max}} \) is the maximum tensile horizontal strain at the centre of the specimen in micro-strain (µε), \( \sigma_{x, \text{max}} \) is the maximum tensile stress at the centre of the specimen in kPa, \( \nu \) is Poisson’s ratio and \( S_m \) is the indirect tensile stiffness modulus at \( \sigma_{x, \text{max}} \) in MPa. The maximum tensile stress at the centre of the specimen is defined as:

\[ \sigma_{x, \text{max}} = \frac{2L}{\pi d t} \]  

Eq. 3

Linear regression analysis of the ITFT results was used to determine fatigue functions for the asphalt mixtures using the following relationship:

\[ N_f = a (\varepsilon_0)^b \quad \text{OR} \quad N_f = a (\sigma)^b \]  

Eq. 4

Where: \( N_f \) is fatigue life (No. of cycles to failure), \( \varepsilon_0 \) is the initial tensile strain (microstrain) and \( \sigma \) is the stress (Newton) repeatedly applied; \( a, b \) are material coefficients associated with the laboratory test methodology and experimentally determined coefficients.

The Dynamic Modulus of the SMA mixtures was determined using the laboratory fatigue equations developed by the Asphalt Institute (AI, 1982) can be expresses as:

\[ N_f = 0.0432 C \varepsilon_t^{0.529 (E^\nu - 0.854)} \]  

Eq. 5

Where: \( C = 10^M \) is the correction factor and \( M = 4.84 [ (V_b / (V_a + V_b)) - 0.69] \) \( V_a \) and \( V_b \) are the percent of volume of air voids and the percent of volume of bitumen.

RESULTS AND DISCUSSION

The aim of this study was to investigate the effect of different types and particle size of waste fillers on fatigue properties of SMA bituminous mixes. For the granite aggregate, four types of waste filler with three different particle size, and 80/100 penetration bitumen were used throughout the entire study, these specimens were tested to determine their fatigue lives.

Stiffness (Resilient) Modulus:

Results of stiffness modulus test at 25°C along with Optimum Asphalt Content for the twelve mixtures are presented in Table 4 and Figure 7 respectively for direct comparison between the three different fillers type and size and the reference mixture of limestone filler.

**Table 4: Stiffness modulus and OAC Test Results for SMA mixtures**

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>LSD</th>
<th>CWD</th>
<th>CFA</th>
<th>SSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>L10</td>
<td>3600</td>
<td>3672</td>
<td>3568</td>
<td>3679</td>
</tr>
<tr>
<td>L0</td>
<td>3679</td>
<td>3675</td>
<td>3679</td>
<td>3785</td>
</tr>
<tr>
<td>C10</td>
<td>3627</td>
<td>3140</td>
<td>3152</td>
<td>3075</td>
</tr>
<tr>
<td>C5</td>
<td>3140</td>
<td>3152</td>
<td>3075</td>
<td>3437</td>
</tr>
<tr>
<td>C0</td>
<td>3583</td>
<td>3498</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F10</td>
<td>S10</td>
<td>S5</td>
<td>S0</td>
<td></td>
</tr>
<tr>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The data presented are the mean value of two tested specimens for each of the four different types of waste filler SMA Mixtures. It was observed that the Stiffness Modulus values of paving mixtures increased when decreasing the particle size up to 50/50 ratio. Then Stiffness Modulus started to decrease again. It was observed also that the mixtures containing ceramic waste with 50/50 filler ratio are higher while the Stiffness Modulus values of paving mixtures containing coal fly ash and steel slag with 50/50 filler ratio are slightly lower as compared to paving mixtures comprising of limestone filler but still within the specification.

The Filler combination of 50/50 for all types of filler showed better response than other combinations and among the four types of filler, ceramic waste mixture exhibited superior Stiffness Modulus values compared to the other types as shown in Figure 7. It is also observed that the results of the four types and the three filler...
ratios specimens are consistent with a very small variation. This small variation could be due to the small variation in the percentage of air voids. Based on the Stiffness Modulus test results the ceramic waste with 50/50 particle size proportion has the average stiffness significantly higher than that of the other mixtures at the same test temperature and exhibited the best performance.

Fig. 7: Stiffness Modulus and OAC Test Results.

**Fatigue cracking:**

In the repeated load indirect fatigue test, the horizontal deformation, parallel to the axis of tensile stress, was monitored and used to determine the failure of the specimens. This was based on the concept that fatigue damage generally occurred when high levels of tensile strains at the bottom of the HMA layer created cracks that propagated upward towards the surface (Brown et al., 2001). Failure was considered to occur when the constant rate of increase of the horizontal deformations was replaced by a faster rate of increase of the deformations, as mentioned earlier.

The numbers of cycles to failure for SMA mixtures at each stress level and the horizontal deformation in mm are presented in Figure 8 through Figure 10.

Fig. 8: Cycle to failure vs Stress and horizontal deformation from ITFT for (L10, C10, F10, S10) SMA.

Fig. 9: Cycle to failure vs Stress and horizontal deformation from ITFT for (L5, C5, F5, S5) SMA.
The fatigue functions for the twelve SMA mixtures have been determined using equation (4) with a relatively high degree of accuracy (High correlation coefficient of determination, $R^2$, indicates the reliability of fatigue equations).

The fatigue performance of the asphalt mixtures was evaluated and ranking by determine the number of cycles at stress level of 1000N based on the fatigue functions obtained for the twelve mixtures. The fatigue functions together with their $R^2$ values, fatigue regression coefficients, and ranking are presented in Table 5. It can be observed that the values of regression coefficients (a, b) are all increased when compared with the reference filler L10.

Table 5: Fatigue relationship for SMA Mixtures

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Regression Coefficients</th>
<th>$R^2$</th>
<th>Fatigue Function</th>
<th>No. of cycles @ 1000 N</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>L10</td>
<td>$2 \times 10^{13}$</td>
<td>2.758</td>
<td>0.6819</td>
<td>$N_f = 2 \times 10^{13} (\varepsilon)^{-2.758}$</td>
<td>106,422.00</td>
</tr>
<tr>
<td>L5</td>
<td>$9 \times 10^{19}$</td>
<td>4.906</td>
<td>0.9029</td>
<td>$N_f = 9 \times 10^{19} (\varepsilon)^{-4.906}$</td>
<td>172,283.00</td>
</tr>
<tr>
<td>L0</td>
<td>$9 \times 10^{16}$</td>
<td>3.882</td>
<td>0.8247</td>
<td>$N_f = 9 \times 10^{16} (\varepsilon)^{-3.882}$</td>
<td>203,349.00</td>
</tr>
<tr>
<td>C10</td>
<td>$2 \times 10^{22}$</td>
<td>5.687</td>
<td>0.9039</td>
<td>$N_f = 2 \times 10^{22} (\varepsilon)^{-5.687}$</td>
<td>173,792.00</td>
</tr>
<tr>
<td>C5</td>
<td>$6 \times 10^{16}$</td>
<td>4.027</td>
<td>0.9559</td>
<td>$N_f = 6 \times 10^{16} (\varepsilon)^{-4.027}$</td>
<td>49,791.00</td>
</tr>
<tr>
<td>C0</td>
<td>$3 \times 10^{20}$</td>
<td>5.165</td>
<td>0.9918</td>
<td>$N_f = 3 \times 10^{20} (\varepsilon)^{-5.165}$</td>
<td>95,966.00</td>
</tr>
<tr>
<td>F10</td>
<td>$7 \times 10^{18}$</td>
<td>4.678</td>
<td>0.9994</td>
<td>$N_f = 7 \times 10^{18} (\varepsilon)^{-4.678}$</td>
<td>64,729.00</td>
</tr>
<tr>
<td>F5</td>
<td>$1 \times 10^{20}$</td>
<td>4.984</td>
<td>0.9973</td>
<td>$N_f = 1 \times 10^{20} (\varepsilon)^{-4.984}$</td>
<td>111,686.00</td>
</tr>
<tr>
<td>F0</td>
<td>$4 \times 10^{15}$</td>
<td>3.509</td>
<td>0.9915</td>
<td>$N_f = 4 \times 10^{15} (\varepsilon)^{-3.509}$</td>
<td>39,360.00</td>
</tr>
<tr>
<td>F10</td>
<td>$3 \times 10^{15}$</td>
<td>3.669</td>
<td>0.9822</td>
<td>$N_f = 3 \times 10^{15} (\varepsilon)^{-3.669}$</td>
<td>43,149.00</td>
</tr>
</tbody>
</table>

The fatigue functions being established from a large fatigue raw data set for stress level of 1000N as well as the dynamic modulus using equation (5) are shown in Figure 11 through Figure 13.
In terms of the fatigue performance of the different SMA mixtures, the fatigue functions (no. of cycles to failure) in Figure 8-10 and the fatigue parameters for all the asphalt mixtures in Table 5 (based on type) confirm the superior fatigue performance of the SMA mixtures containing limestone waste filler (has the longest fatigue life) followed by ceramic waste and coal fly ash. The only mixture that violated the increasing trend of fatigue damage resistance to cyclic loading was the mixture with steel slag dust.

In terms of the overall fatigue performance based on the asphalt mixture rankings and particle size given in Table 5 and the number of cycles to failure, the proprietary L0, C10, F5, and S0 showed the best performance while the other proprietary showed a similar level of actual performance. Furthermore, it was noted that the fatigue lives of the remaining mixtures and control SMA mixtures showed a range of different performance and appear to be similar at 20,000 to 50,000 cycle’s range which gave nearly the same strain level.

Figure 11-13 show the dynamic modulus isotherms and the viscoelastic response characteristics of the twelve SMA mixtures. In general, it was noticed that, the number of repetitions to failure decreases with the increase in the $|E^\ast|$ values for all mixtures and the $|E^\ast|$ isotherms maintained the pattern of inclined straight-line, which indicated that the mixture behavior was in the linear viscoelastic region.

The presence of ceramic waste limestone generally increased the dynamic modulus values, the proprietary C10, L5, and L0 showed the best of all mixtures. However, C5 and F5 mixtures obtained good $|E^\ast|$ values, whereas mixture with steel slag filler achieved the lowest $|E^\ast|$ values in all the three groups.

**Correlation between Fatigue Life and Stiffness Modulus:**

Figure 14 and 15 showed that fatigue life have good correlation with stiffness modulus properties of the mixes containing coal fly ash and ceramic waste filler, with correlation factor $R^2 = 0.863$ and $R^2 = 0.979$, respectively, while mixtures containing steel slag filler showed fair correlation with $R^2 = 0.473$ and very poor correlation for the reference filler (limestone) with $R^2 = 0.396$. The fatigue life of the specimens showed a proportional correlation with stiffness properties of the mixes containing coal fly ash, while there was an inverse correlation between the fatigue life and stiffness properties of the mixes containing limestone, ceramic waste, and steel slag filler.

**Conclusions:**

Based on the results of laboratory experiments and analyses of Stiffness Modulus and Repeated Load Indirect Tensile tests the following conclusions can be summarized and concluded:

1. It was observed that the waste filler improve the Resilient Modulus values of paving mixtures and Resilient (Stiffness) Modulus values increased when decreasing the particle size up to 50/50 ratio. Then Resilient Modulus started to decrease again.
2. The Filler combination of 50/50 for all types of waste fillers showed better response than other combinations as compared to the reference mix and among the four types of waste, ceramic waste mixture exhibited superior Resilient Modulus values compared to the other types.

3. It was observed that different types of waste fillers show quite different patterns with respect to their fatigue lives. The fatigue life and dynamic modulus values of SMA specimens containing ceramic waste and coal fly ash is relatively high when compared with the fatigue life of the mix containing steel slag filler but perform less compared to the medium size of limestone. Therefore, these waste fillers are considered to improve the fatigue cracking resistance and the dynamic modulus values of SMA asphalt mixtures at temperature (20°C).

4. It is also found that the number of load cycles to failure decreases as the filler particle size decreases up to 50/50 proportion then start to increase again for ceramic waste dust and steel slag. On the other hand, the number of load cycles to failure increases with the particle size decreases for coal fly ash up to 50/50 proportion then decreases again.

5. Results from performance tests confirm that, there is a good relationship between resilient modulus and fatigue performance of the SMA mixtures as demonstrated by ceramic waste and coal fly ash filler mixtures. This is a very promising performance results that can be explained mainly by the stiffening and void-filling effects of these fillers acting as a bitumen extender in the asphalt-aggregate mixture.

6. Based on the above findings of the experimental results and as compared with the limestone filler, it can be concluded that using waste materials as replacement of mineral filler in SMA asphalt mixture is feasible and improve the resilient, dynamic modulus, and the fatigue life of SMA asphalt mixtures especially the large to medium size particle.

7. The use of these wastes as replacement of mineral filler were promising in mitigating fatigue cracking and will draw the interest of pavement engineers as utilization of these wastes is an important problem both from an economic and environmental point of view. Since these wastes can be obtained easily with little cost and the addition of these waste to the asphalt-aggregate mixtures does not need any specialized equipment or skilled workmanship.

Fig. 14: Fatigue Life vs Stiffness Modulus for limestone and coal fly ash dust.

Fig. 15: Fatigue Life vs Stiffness Modulus for ceramic waste and steel slag dust.

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