Evaluation of The Effect of Gradation on Mechanical properties of Stone Mastic Asphalt Mixtures

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Abstract. For stone mastic asphalt (SMA) mixtures, the aggregate gradation is the significant requirement to achieve the best structural design. In this research, an attempt to evaluate the effect of nominal maximum aggregate size (NMAS) and gradation on SMA volumetric and mechanical properties. Samples for each mixture were designed and fabricated according to NAPA specifications. A total of 9 SMA mixtures with three NMASs, each with three different aggregate gradations, one asphalt binder (styrene butadiene styrene SBS) modified binder were studied. Volumetric analysis of specimens revealed that the voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) rise with a reduction in NMAS. SMA samples with higher NMAS have lower optimum asphalt than those of lower NMAS. From the laboratory study, SMA mixes fabricated utilizing the upper limit of gradation showed the highest mechanical properties in terms of Marshall Stability and indirect tensile strength. It was recorded also that the SMA mixtures with larger NMAS had higher ITS and Marshall stability contrasted to the others. This improvement could be because of the larger portion of coarse aggregate in the SMA mixture.

1. Introduction

As the volume of traffic continues to increase, the serviceability and service life of a normal hot mix asphalt (HMA) pavement is expected to decrease. This necessitates the specialists to search for alternative and cost-effective paving techniques to afford better endurance to induced paving problems. One of the mixtures that proved to fulfill these requirements is the stone matrix asphalt (SMA), which firstly began in Europe in the 1960s (Blazejowski, 2011). Lately, SMA gained some acceptance in the USA and Australia as it has continued to reveal excellent performing under harsh loading situations, with improved durability properties along the life span of the pavement in service. The Ministry of Communications in the Kingdom of Saudi Arabia recently introduced SMA in its road specification (Asi, 2006; Blazejowski, 2011; Tashman & Pearson, 2012; Hainin et al., 2013; Iskender, 2013).

It is known that the rut-resistant nature of SMA relies greatly on the solid mechanical entanglement of the overall aggregate skeleton by stone-on-stone aggregate contacts (Brown and Haddock 1997, Lynn 1999), providing reasonably high resistance to shear forces and an effective load distribution system that can bear relatively high traffic loads. The main dissimilarities between SMA and DGA are the structure of stones bearing the loads and the relatively higher content of asphalt binder (Gatchalian 2005; Prowell et al., 2009; Tashman & Pearson, 2012; Iskender, 2013; Hafeez et al., 2014).

The Stone matrix asphalt (SMA) is a gap-graded blend of two components, which includes a high coarse aggregate portion and a higher bitumen mortar content. Together, these two ingredients address distresses related to durability and stability of SMA mixtures. Bituminous mortar usually contains...
mineral filler, fine aggregate, asphalt binder, and a stabilizer, which is work to stop the drain-down of bitumen binder from the mix amid mixing, compaction processes (Sebaaly et al., 1997; Shankar et al., 2018). Therefore, it is vital that the SMA mix properly designed achieving an appropriately packed aggregate skeleton for stone-on-stone contact. This skeleton and mastic must meticulously meet the residual air voids volume of the coarse grains to ensure good cohesion of the aggregate skeleton (Qiu & Lum, 2006; Hainin et al., 2013; Mithanthaya et al., 2018; Miranda et al., 2019).

Some studies have been done to develop mix design approaches to assess the effect of stone-on-stone. The key approach is to evaluate the amount of bituminous mastic (bituminous material, fine aggregate, filler, and stabilizers) that must be less than the volume of airspace produced by the corresponding coarse particles (Voskuilen, 2000; Jacobs & Voskuilen, 2004; Chen & Wong, 2016).

The influence of NMAS and gradation on SMA mixture design is of great importance, and research was required to accurately evaluate the importance of NMAS in the general properties of SMA mixtures (Sridhar et al., 2007; Aodah et al., 2012; Liu et al., 2017). Xie et al. (2003) and Cooley and Hurley (2004) have conducted a study to investigate the SMA performance with different nominal maximum sizes for different aggregates (NMAS).

The purpose of this study is to investigate mechanical properties of SMA mixtures made using the local basalt aggregate blends for fine and coarse SMA mix with different maximum aggregate size and gradation changing through various laboratory tests such as Marshall properties, indirect tensile strength test, and drain-down test to satisfy the requirements as per NAPA specifications. All materials used in SMA blends make them very expensive. Therefore, the main objectives of this study was to replace the expensive traditional stabilizer with unconventional and locally available fibers such as waste palm date cellulose fiber (PDCF) to reduce cost, and to make the SMA blend cost-effective.

2. Research methodology and materials

The focal aim of this study was to evaluate the mechanical and volumetric properties of SMA mixtures changing the NMAS and gradation through a series of fundamental laboratory tests. In this research, the Marshall Mix design procedure was utilized to optimize the asphalt content for each mixture gradation. For SMA mixtures, the optimum bitumen content is usually designated as that corresponds to 4.0% air voids. The experimental study plan followed consisting of three main chores. The first task was to investigate the fundamental characterization of the materials used in this study. The second task was to optimize the SMA mixtures to ensure that they perform properly and to fabricate enough samples for the final stage using optimum asphalt content. The final task was to conduct a series of tests for comparison purposes. The mechanical testing consists of Marshall Stability, indirect tensile strength, and drain-down test.

2.1. Materials

The materials used in this study were one type of aggregate and two asphalt types and are described as follows:

2.1.1. Aggregate. Aggregates play an extremely vital task in providing strength to SMA Mix as they make up about 70-80% of the total mix. The proper quantity of the coarse aggregate in the mix creates a sort of skeleton arrangement giving an improved aggregate-to-aggregate interaction developing higher resistance to rutting, as well as better shear strength, and this is the crucial characteristic for SMA. This gradient should be designed in such a way that sufficient air voids and voids in the coarse aggregate are given (Brown and Haddock, 1997; Mithanthaya et al., 2018).

In this study, basalt type aggregate supplied from Al-nibaei quarry in the north of Baghdad was selected for its acceptable characteristics. This Basalt type aggregate has been confirmed to be suitable to be used in SMA, mostly due to its hardness. Consequently, this type of aggregate does not undergo an extreme break-down amid mixing and compaction processes. The physical properties for the Basalt type aggregate are illustrated in Table 1. Three aggregate gradations were selected for this study, namely 9.5, 12.5 and 19 mm NMAS, as illustrated in Figures 1-3. The aggregate gradation was designed based on the upper, mid and lower gradation limits according to the NAPA specification.
(NAPA 2002) for SMA. The purpose of selecting these gradations was to compare the mechanical properties of SMA using different aggregate gradations using locally available materials.

Table 1. Physical properties of aggregate.

| Property                           | Specification                  | Coarse aggregate | Fine aggregate |
|------------------------------------|--------------------------------|------------------|----------------|
| Relative density (SG)              | (ASTM C127-128-15)             | 2.625            | 2.653          |
| Apparent specific gravity          | (ASTM C127-128-15)             | 2.660            | 2.726          |
| % of absorption                    | (ASTM C127-128-15)             | 0.56             | 0.67           |
| Los Angeles abrasion                | (ASTM C131-14)                 | 19.8             | ……….          |
| % flat and elongated Particles, 10%| (ASTM D4791-10)                | 4                | ……….          |
| Fractured pieces %                 | (ASTM D5821-13)                | 96               | ……….          |
| Clay content % 45min               | (ASTM D2419-14)                | ……….           | 83             |
| Voids in course aggregate VCA      | (ASTM C29-03)                  | ……….           | ……….          |

Figure 1. Aggregate gradations of NMAS 19 mm mixture.

Figure 2. Aggregate gradations of NMAS 12.5 mm mixture.

Figure 3. Aggregate gradations of NMAS 9.5 mm mixture.
2.1.2. Mineral Filler. The mineral fillers have a noteworthy effect on the performance of SMA mixes. It is that fraction of materials that passing the sieve 0.075 mm. The selected mineral filler used in this work was Ordinary Portland Cement (Type I), produced by Mass Iraq company for cement industry, which is manufactured locally and available in the market. The mineral filler should be dry, clean and free from deleterious materials. Table 2 shows the physical properties of Ordinary Portland Cement.

Table 2. Physical properties of ordinary portland cement.

| Physical properties                  | Specification |
|--------------------------------------|---------------|
| % Passing sieve No. 200              | 97            |
| Bulk specific gravity                | 3.14          |
| Surface area (m²/kg)                 | 355           |
| Fineness (cm³/gm)                    | 3050          |

These tests were accomplished in the National Center for Construction Laboratories and Researches (Baghdad).

2.1.3. Asphalt binder. One type of asphalt cement was used in this study (SBS modified asphalt). The asphalt cement was obtained from a local petroleum refinery. Table 3 summarizes the physical properties of the asphalt used in this study.

Table 3. The physical properties of the SBS modified binder.

| Test                              | Unit                | Specification     | 5% SBS  |
|----------------------------------|---------------------|-------------------|---------|
| Penetration (25 ºC-100gm -5sec)  | l/10 mm             | (ASTM D5)         | 35      |
| Ductility (25 ºC, 5 cm/min)      | cm                  | (ASTM D113)       | 89      |
| Flash point (cleave land open cup)| ºC                  | (ASTM D92)        | 326     |
| Fire point                       | ºC                  | (ASTM D92)        | 368     |
| Softening point                  | ºC                  | (ASTM D36)        | 72      |
| Solubility in trichloroethylene  | %                   | (ASTM D2042-01)   | 99.3    |
| Rotational Viscosity at 135 ºC   | Pas.s               | (ASTM D4402)      | 0.83    |
| Rotational Viscosity at 165 ºC   |                     |                   | 0.32    |

2.1.4. Fiber Stabilization. One of the main difficulties that usually encountered in SMA mixes is the drainage during mixing, conveying and compaction. The fibers are traditionally used as stabilizers in the manufacturing of the stone asphalt pavements (SMA). The fiber used in this study was natural cellulose fiber extracted from palm fronds. This fiber was treated into industrial form locally, where it is used in making decorations. This type of fiber is abundant due to the abundance of palm trees in Iraq, therefore this fiber is economical to be used in paving projects. The Date Palm cellulose fiber was added at a rate of 0.3% by total weight of the mix, and homogeneously blended with the aggregate before the adding of bitumen binder (Cooley et al., 2000). This fiber was cut to achieve the length range of (5-10) mm before being added to the asphalt mixture. The performance of these mixtures was evaluated by conducting the test of drain-down. Table 4 shows the physical properties of date palm cellulose fiber (DPCF), while Figure 4 shows an image of the cellulose fiber used in this research.

Table 4. The physical properties of date palm cellulose fiber (DPCF).

| Physical properties                  | Specification |
|--------------------------------------|---------------|
| % Passing sieve No. 200              | 97            |
| Bulk specific gravity                | 3.14          |
| Surface area (m²/kg)                 | 355           |
| Fineness (cm³/gm)                    | 3050          |

These tests were accomplished in the National Center for Construction Laboratories and Researches (Baghdad).
Table 4. Physical properties of date palm cellulose fiber.

| Property                  | Value     |
|---------------------------|-----------|
| Bulk density (gm/cm$^3$)  | 0.5       |
| Average length (mm)       | (5-10)    |
| Thickness (mm)            | 0.1       |
| Breaking Elongation %     | 2.25      |
| Tensile strength (Mpa)    | 758       |
| Max tensile force (N)     | 8.1       |
| Moisture content (%)      | 2.6       |

Figure 4. Natural date palm cellulose fiber (DPCF).

2.2. Mix design methodology

The design of SMA mixtures was conducted according to the procedure developed for NAPA (NAPA, 2002). For each NMAS and gradation combination, three trial mixes were blended and compacted at the anticipated optimum binder content. The design best gradation was chosen based on the voids in the coarse aggregate (VCA) and the voids in the mineral aggregate (VMA).

The voids in coarse aggregate for the SMA mix ($VCA_{MIX}$) was determined and contrasted with the dry rodded voids in coarse aggregate ($VCA_{DRC}$) in order to assess the extent of packing achieved in the designed SMA mix. The $VCA_{DRC}$ is then computed based on equation (1) (Pasetto and Baldo, 2014):

$$VCA_{DRC} = \left(\frac{G_{CA} \times \gamma_w}{\gamma_s} - \frac{\gamma_s}{\gamma_w}\right) \times 100$$  \hspace{1cm} (1)

Where, the $G_{CA}$ is the bulk specific gravity of coarse aggregate, $\gamma_w$ is the unit-weight of water, and $\gamma_s$ is the unit-weight of coarse aggregate. The $VCA_{MIX}$ can be calculated according to equation (2):

$$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{CA}} \times P_{CA}\right)$$  \hspace{1cm} (2)

Where, $VCA_{MIX}$ is the voids in the coarse aggregate of the mixture, $G_{mb}$ is the bulk specific gravity of the compacted mixture, $G_{CA}$ is the bulk specific gravity of the coarse aggregate in the mixture, and $P_{CA}$ is the coarse aggregate percentage in the mixture. According to NAPA specifications (NAPA, 2002), the 4.75 mm sieve represents the breakpoint sieve for 19 and 12.5 mm NMAS, while the breakpoint sieve for 9.5 mm NMAS is 2.36 mm sieve.

PCA is determined according to equation (3):

$$P_{CA} = \frac{\%RBPS}{100} \times (1 - \frac{\%BC}{100})$$  \hspace{1cm} (3)
Where, BC is the Bitumen content, and %RBPS is the percentage of retained aggregate on the break-point sieve portion. The blend that fulfills the stone-on-stone contact condition in the mix with 17.5% VMA as a minimum, where VCADRC is larger or equal than VCA_{MIX} (Brown & Haddock, 1997; Watson et al., 2004; Pasetto and Baldo, 2014). After the selection of the best gradation, the asphalt binder proportion was changed for the determination of optimum asphalt content. The optimum binder content was chosen to rely on the targeted voids in the total mix (VTM) of 4%. The SMA mixes in this work were designed following the standard Marshall design approach to specifying the optimum binder content as per the ASTM specification (ASTM D 1559). The Marshall Samples of different NMAS of SMA (9.5, 12.5, and 19mm) mixtures were of 101.6 mm diameter and 63.5 mm height, and compacted utilizing 50 blows on each sample face. The determination of mixing and compaction temperatures was done using the viscosity-temperature relationship for the SBS modified binder which corresponded to the mixing and compaction viscosity of 0.17 and 0.28 Pa.s, respectively. It is observed that the mixing and compaction temperatures, as shown in Figure 5 are 185 and 170 °C, respectively. Three specimens of each asphalt content (5.5%, 6.0%, 6.5% and 7.0%) were prepared. A total of 108 specimens were tested for stability, flow, air voids, unit weight, voids in mineral aggregate, and voids filled with asphalt (VFA).

The mixture design outcomes of the nine SMA mixtures are illustrated in Table 5, in which optimum asphalt content, voids in the total mix (VTM), voids filled with asphalt (VFA), voids in mineral aggregate (VMA), drain-down, stability, and flow value are shown.

| Properties | 19UL | 19ML | 19LL | 12.5UL | 12.5ML | 12.5LL | 9.5UL | 9.5ML | 9.5LL |
|------------|------|------|------|--------|--------|--------|-------|-------|-------|
| Stability, kN | 8.1  | 7.8  | 4.5  | 8.5    | 8.1    | 8.7    | 9.6   | 8.7   | 5     |
| Flow, 1/10mm | 4.2  | 3    | 2.2  | 3.7    | 3      | 2.3    | 4.2   | 3.1   | 2     |
| Air voids, % | 17.8 | 18.5 | 19.9 | 19.6   | 20.7   | 22.1   | 22.1  | 22.8  | 24.5  |
| VMA, %       | 80.8 | 81.5 | 81.8 | 79.6   | 80.8   | 81.6   | 79.4  | 80.2  | 80.2  |
| VFA, %       | 2.330| 2.314| 2.262| 2.284  | 2.257  | 2.223  | 2.213 | 2.202 | 2.157 |
| Optimum binder content | 5.7 | 6.1  | 6.5  | 5.8    | 6.3    | 6.7    | 5.9   | 6.4   | 6.8   |
| Drain-down, % | 0.05 | 0.24 | 0.9  | 0.04   | 0.18   | 0.81   | 0.03  | 0.16  | 0.57  |

**Figure 5.** Viscosity-temperature relationship of SBS-modified binder.

2.3. Drain-down Test

The drain-down test is usually done following ASTM D 6390 (AASHTO T-305) utilizing a wire basket of standard sieve openings of 6.3 mm, at a temperature of 185 °C, the temperature related to the viscosity of about 0.17 Pa.s, as can be seen in Figure 5. A pre-weighted SMA mixture sample was set
and placed in the standard basket and was positioned in an oven stated at the test temperature. The mastic drained-down amid the testing time of 1 hr is stored in a plate and weighed. The ratio of the weight of mastic drained-down to the original weight of the mixture is taken as drain-down. The drain-down amounts were determined to be <0.3% as the maximum limit for SMA Mixtures (Sarang et al., 2015). The percentage of drained down materials was calculated using equation (4) (Kumar et al., 2007):

\[
\text{draindown} \% = \frac{(D-C)}{(B-A)} \times 100
\]  

(4)

where A is the empty wire basket mass (gm), B is the wire basket mass with the sample (gm), C is the catch plate mass (gm), and D is the catch plate with the drained mastic mass (gm).

2.4. Indirect Tensile Strength test
The ITS test was conducted following ASTM D-6931 (AASHTO T 283) through loading the Marshall specimen vertically along the diametral plane at a testing temperature of 25°C. The indirect tensile strength then was calculated using equation (5) (Aodah et al., 2012):

\[
\text{ITS} = \frac{2000P}{\pi dt}
\]  

(5)

where \(\text{ITS}\) is the indirect tensile strength (kPa), \(P\) is the applied load (N) at failure, \(d\) is the diameter of sample (mm), and \(t\) is the thickness of sample (mm).

3. Results and Discussions

3.1. Voids in the coarse aggregate
To assess the packing condition in the coarse aggregate of an SMA mixture, the voids in the coarse aggregate ratio (VCA\text{MIX}/VCA\text{DRC}) approach followed through comparing VCA values of the compacted SMA mixes (VCA\text{MIX}) with that of the dry rodded blend of coarse aggregate (VCA\text{DRC}). The VCA ratio is the criterion of the adequacy of the SMA mix, where it should be less than 1.0 for a particular mixture to be well packed (stone-on-stone contact) (Kandhal, 2002).

The results of the voids determined in the coarse aggregate and the compacted specimens are shown in Table 6. It may be noted that the contact of the stone-to-stone condition has been proven for all mixtures. For all SMA mixture samples, the values of VCA\text{MIX} were lower than the parallel VCA\text{DRC} values, and this ensures stone-to-stone contact between the coarse aggregate, thus ensuring improved stability.

It is clear from Table 6 that the stone-to-stone contact of coarse aggregate is ideally developed when the VCA ratio is closer to the maximum value of 1.0. After that, a more amount of finer aggregates will likely be contained within the coarse aggregate structure preventing the full stone-on-stone contact. At the same time, VCA\text{MIX} values steadily reduced as stone-to-stone contact decreased. When good packing between aggregate particles happens, the coarse aggregates could not move any closer, providing a more stable and stiffer SMA mixture. Generally, it was noticed that the VCA was greater for the SMA mixes that have a larger aggregate proportion.

Table 6. Comparison of the VCA values.

| NMAS (mm) | Aggregate gradation | VCA\text{MIX} (%) | VCA\text{DRC} (%) | VCA\text{MIX} < VCA\text{DRC} | VCA Ratio |
|-----------|---------------------|-------------------|-------------------|-------------------------------|-----------|
| 9.5       | U                   | 40.10             | 42.3              | yes                           | 0.948     |
|           | M                   | 37.09             | 41.3              | yes                           | 0.898     |
|           | L                   | 35.13             | 42.1              | yes                           | 0.834     |
|           | U                   | 38.18             | 41.6              | yes                           | 0.918     |
| 12.5      | M                   | 35.51             | 41.7              | yes                           | 0.851     |
|           | L                   | 33.14             | 41.4              | yes                           | 0.795     |
3.2. Volumetric properties
The theoretical maximum specific gravity ($G_{MM}$) was measured for each SMA mixture in uncompressed form, according to ASTM D 2041. Marshall Compactor was used to prepare cylindrical SMA samples. The weights and dimensions were determined in order to calculate the volumetric properties like voids filled with asphalt (VFB), voids in mineral aggregates (VMA), and bulk specific gravity ($G_{MB}$). VMA was found to be above 17.5% for all mixtures and VFA was in the range of 79.4-81.8%.

![Figure 6. VMA, VFA, and $G_{mb}$ for SMA mixtures.](image)

3.3. Marshall Stability
To check the diversity in Marshall Stability of the SMA mixtures, Marshall Stability values for each mixture were obtained after 30 min of water immersion at 60°C. Figure 7 shows the test results of Marshall Stability for all mixtures. A clear trend was observed, where with a decrease in NMAS, the stability of the SMA mixtures increased, while the mixtures prepared with the upper gradation of aggregates (finer) has higher stability, (8.1 kN) for 19mm NMAS, (8.5 kN) for 12.5mm NMAS, and (9.6 kN) for 9.5mm NMAS than mixes prepared with mid and lower gradation (coarser). This could be justified by the stone-to-stone contact of the coarse aggregate, where, as the coarse aggregate volume grows, stone-to-stone contact is developed and the internal strength of SMA mixture increases.
3.4. *Indirect tensile strength (ITS)*

The indirect tensile strength (ITS) test is useful in forecasting the potential of SMA mixtures for cracking. The results are presented in Figure 8. The SMA mixtures with higher NMAS have lower tensile strength. On the other hand, the mixes made with the upper aggregate gradation level (finer) had higher ITS, (1250 kPa) for 19mm NMAS, (1310 kPa) for 12.5mm NMAS, and (1710 kPa) for 9.5mm NMAS than mixtures done with mid and lower aggregate gradation (coarser).

3.5. *Drain-down test*

Polymer-modified bitumen (SBS) was used as the binder material in combination with date palm cellulose fiber (DPCF) as a stabilizing additive. Therefore, it was expected for the drain-down to be within the acceptable limits for SMA mixtures. However, for the coarser mixture in each NMAS, the Drain-down present was out of acceptable limits. This most likely means that the percentage of voids between the grains of aggregate was more than the permissible, and thus the possibility of the asphalt material escaping or flowing out of the asphalt mixture was greater, as can be seen in Figure 9.
Conclusions
The mechanical and volumetric properties of stone mastic asphalt mixtures with three NMAS at three aggregate gradations (Upper, middle, and lower levels) and one asphalt binder type are evaluated using different tests. The following conclusion can be drawn from the results:

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