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EFFECT OF SEGREGATION ON COARSE AGGREGATE STRUCTURE AND RUTTING POTENTIAL OF ASPHALT MIXTURES

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1 EXECUTIVE SUMMARY

Segregation of asphalt mixtures, which denotes the non-uniform distribution of coarse and fine aggregate components, either causes short term premature failures or affects the long term pavement performance. Since segregation may result in a significantly altered aggregate structure of an asphalt mixture, it may increase the potential for rutting, among all other distresses. In this study, the effect of segregation or change in aggregate gradation that may negatively influence the rutting potential of asphalt mixtures was evaluated. The Dominant Aggregate Size Range (DASR) gradation model and the DASR porosity parameter, which have previously been identified to be well correlated with rutting performance, were used to identify the potential degradation of rutting performance due to segregation. A total of four roadway sections with different severity levels of segregation were selected and evaluated. Evaluation of mixture gradations, volumetric properties, and DASR porosities indicated a significant shift in gradation for segregated mixtures, particularly for the coarse aggregate portion. Consequently, it was found that segregation of asphalt mixtures may significantly increase the potential for rutting.

2 INTRODUCTION

Segregation of asphalt mixtures, which denotes the non-uniform distribution of coarse and fine aggregate components, occurs due to the inappropriate handling of the material during the different stages of construction including asphalt production in the plant, hauling, placement, and compaction. In general, segregation yields an altered aggregate gradation with excessive coarse aggregates and insufficient fine aggregates in the finished asphalt mat. Due to its coarse-aggregate-rich nature, a segregated mixture exhibits increased air voids and decreased asphalt content when compared to a mixture free of segregation. Previous research studies have reported that such inconsistency caused by segregation either results in short term premature failures or reduces the long term pavement service life *(1-3)*.

Because segregation may result in a significant change in the aggregate structure of a mixture, segregated mixtures may show an increased potential for rutting or permanent deformation, among all other distresses. Rutting, a major distress encountered in asphalt pavements, is strongly related to the mixture's resistance to shear deformation. Previous studies have indicated that the shear resistance of an asphalt mixture is associated with the interlocking of the coarse aggregate particles *(4-5)*. More recently, studies conducted by Kim. et al. have introduced the concept of Dominant Aggregate Size Range (DASR) and the DASR porosity for characterizing the coarse aggregate structure of asphalt mixtures *(6-7)*. An Accelerated Pavement Testing (APT) study conducted by the Florida Department of Transportation (FDOT) validated that the DASR porosity correlates well with the rutting performance of asphalt mixtures, indicating that the characteristics of coarse aggregate structure may provide a great potential for evaluating the rutting performance of hot-mix asphalt *(8)*.

In this study, the DASR porosity was used as a parameter for evaluating the effect of segregation on the change in coarse aggregate structure that may influence the rutting potential of asphalt pavements.

3 CHARACTERIZATION OF COARSE AGGREGATE STRUCTURE AND INTERLOCKING OF ASPHALT MIXTURES

In this section of the report, the concept of DASR and DASR porosity is reviewed. The procedures for the calculation of DASR and its porosity are presented in detail.

3.1 Dominant Aggregate Size Range (DASR)

The DASR concept was first introduced by Kim et al. *(6-7)* who hypothesized that an interactive range of particle sizes exist that primarily contributes to interlocking of aggregates. The particles interacting with each other will form the primary structure of the asphalt mixture for resisting deformation and fracture, and the size of these particles is called the DASR. In other words, DASR is defined as the interactive range of particle size that forms the dominant structural network of aggregate.

Particles smaller than the DASR fill the voids between DASR particles which is called the Interstitial Volume (IV). The materials including the asphalt binder, aggregate, and air voids that exist within the interstices of the DASR structure are termed the Interstitial Components (IC). The IC aggregates combined with asphalt binder form a secondary structure in the mixture to help resist deformation and fracture, and are the primary source for adhesion and resistance to tension. Particle sizes larger than the DASR will simply float in the DASR matrix and will not play a major role in the aggregate structure. Figure 1 illustrates the concept of DASR and IC for asphalt mixtures.

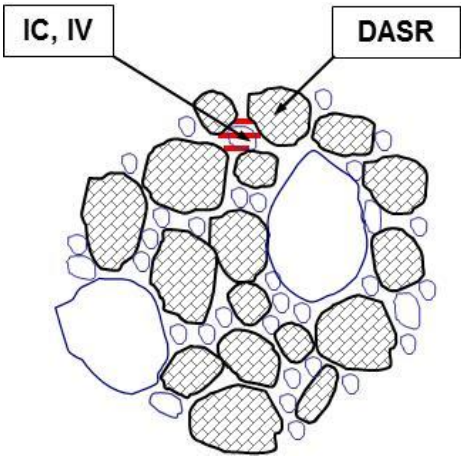


Figure 1. Schematic of DASR and IC concept (Kim et al. (6-7))

The DASR should consist of particles coarse enough to provide aggregate interlock and should include all contiguous particle sizes that are determined to be interactive. Based on packing theory, the pioneers of DASR determined that in order for particles of different sizes to provide adequate interaction, the relative proportion of particles from one of the two contiguous sieve sizes should be less than 70 percent and accordingly, the proportion from the other sieve greater than 30 percent. If this relative proportion exceeds the 70/30 threshold, the interaction capability between the particles is significantly disrupted. Therefore, the DASR should include all the interactive range of particle sizes determined by the interaction analysis based on the 70/30 relative proportion limit (*6-7*).

3.2 DASR Porosity

Porosity is a dimensionless parameter which has been widely used in the field of soil mechanics to indicate the relative ratio of voids to total volume. Research conducted by Kim et al. *(6-7)* showed that porosity can also be used for asphalt mixtures to establish a criterion which ensures contact between the DASR particles. They concluded that the porosity of DASR appeared to be a good tool for evaluating potential rutting performance as well as fracture resistance of asphalt mixtures.

The basic principles related to the calculation of DASR porosity are as follows. Referring to the phase diagram shown in Figure 2, the Voids in Mineral Aggregate (VMA) of an asphalt mixture, which indicates the volume of available space between aggregates in a compacted mixture, are comparable to the volume of voids in soil. Therefore, porosity can be calculated for any DASR by assuming that a mixture has certain effective asphalt content and air voids (i.e. VMA) for a given gradation. Finally, DASR porosity can be calculated using Equations (1) through (3):

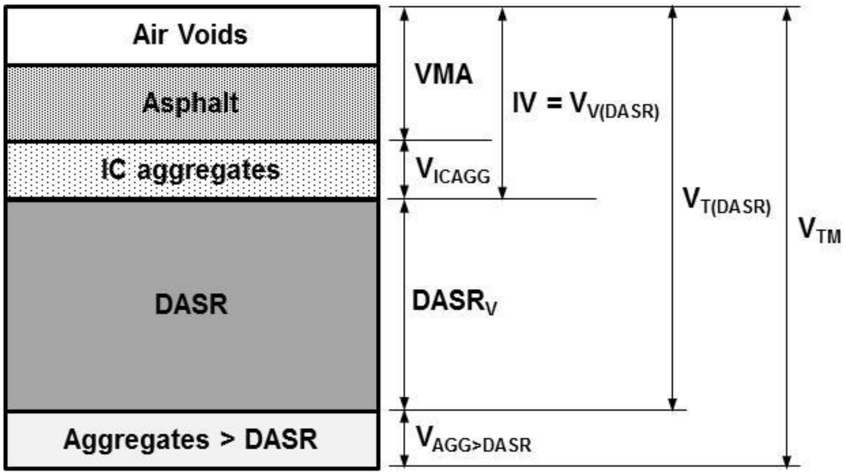


Figure 2. Mixture components for calculation of DASR porosity (Kim et al. (6-7))

$$V_{T(DASR)} = V_{TM} - V_{AGG>DASR} \quad (1)$$

$$V_{V(DASR)} = V_{ICAGG} + VMA \quad (2)$$

$$\eta_{DASR} = \frac{V_{V(DASR)}}{V_{T(DASR)}} = \frac{V_{ICAGG} + VMA}{V_{TM} - V_{AGG>DASR}} \quad (3)$$

Where, η_{DASR} = DASR porosity, $V_{V(DASR)}$ = volume of voids within DASR, $V_{T(DASR)}$ = total volume available for DASR particles, V_{ICAGG} = volume of IC aggregates, VMA = voids in mineral aggregate, V_{TM} = total volume of mixture, and $V_{AGG>DASR}$ = volume of particles bigger than DASR.

In traditional soil mechanics, it has been determined that the porosity of granular materials should be no greater than 50 % for particles to have contact with each other (i.e. to be interactive) *(9)*. However, such a distinct threshold for distinguishing potential rutting performance of asphalt mixtures is not practical. Instead, the DASR porosity of mixtures was categorized into three different groups with respect to their expected mixture rutting performance as follows *(6, 7, 10)*.

- Group I (Good): Mixtures with DASR porosity between 38 and 48 %. These mixtures are expected to show good rutting performance in the field.
- Group II (Marginal): Mixtures with DASR porosity between 48 and 52 %. This range was categorized as a marginal DASR porosity near the 50 % threshold. These mixtures can exhibit either good or bad field rutting performance.
- Group III (Bad): Mixtures with DASR porosity greater than 52 %. These mixtures are expected to show greater rutting potential than mixtures belong to the other groups.

4 RESEARCH APPROACH

According to the FDOT specification, a particular location is determined to be segregated if the average air voids from three 6-inch diameter roadway cores is greater than 10 percent *(11)*. For this study, a total of four segregated roadway sections were selected and evaluated. To comply with FDOT's existing specification, three 6-inch diameter roadway cores were retrieved from each segregated and non-segregated pavement area carefully identified based on visual inspection. Cut specimens were prepared from the surface mixtures of each core for gradation and volumetric tests. Bulk specific gravity (G_{mb}) tests were conducted on each cut specimen and air voids were calculated using the laboratory obtained G_{mb} and the design maximum specific gravity (G_{mm}). Also, the asphalt contents and in-place gradations were determined using the ignition oven method and sieve analysis. In addition, the DASR and its porosity were determined based on the gradation model described above, in order to evaluate the rutting potential of segregated and non-segregated mixtures.

5 LABORATORY TESTING AND DASR ANALYSIS RESULTS

As mentioned, four roadway sections with different severity levels of segregation were selected for evaluation in this study. All mixtures evaluated were designed using the Superpave mix design method and all pavements were less than four years old when the cores were obtained. For each project section, segregated and non-segregated areas were determined based on visual assessment and three field cores were obtained from each area for evaluation of volumetric properties in accordance with the standard specification used by FDOT *(11)*. Figure 3 shows an example of a segregated and non-segregated area identified through visual inspection for coring operation. Figure 4 shows the schematic of coring operation per location determined for both segregated and non-segregated areas. Detailed descriptions on the test sections, the results from the laboratory tests and DASR analysis are presented in the following section.

(a) Segregated area (b) Non-segregated area

Figure 3. Determination of segregated and non-segregated area by visual inspection

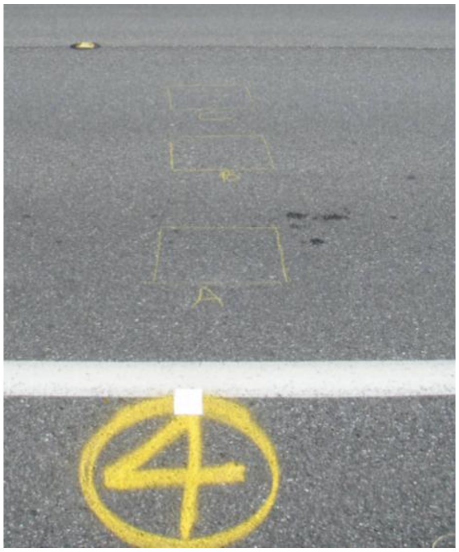


Figure 4. Schematic of coring operation for each location

5.1 Project Number 1

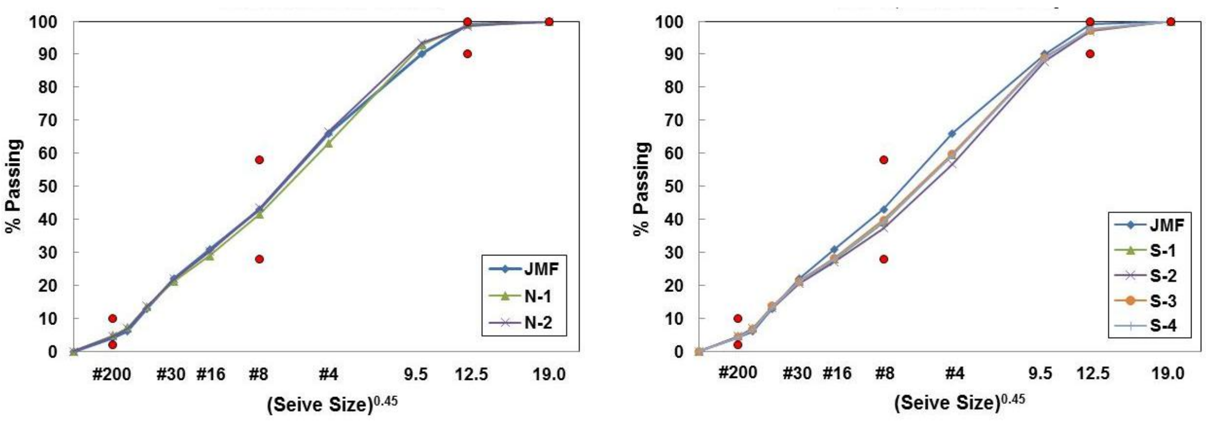
Project number 1 was constructed using a 12.5-mm Nominal Maximum Aggregate Size (NMAS) fine-graded Superpave mixture with granite aggregates and a PG 76-22 polymer modified binder. Based on visual assessment, this project was determined to exhibit low severity segregation.

The DASR, DASR porosity, air voids, and effective asphalt content were determined using the in-place gradations and mixture volumetric properties obtained from the field cores. The results are summarized in Table 1 which shows that the air voids obtained from the segregated cores averaged to be 12 percent, exceeding the 10 percent threshold established in FDOT's specification. It is also noted that the DASR determined from both the segregated and non-segregated cores is the same as that for the JMF. In addition, all cores showed the DASR porosity value of less than 48 percent (i.e., good rutting performance expected). Nonetheless, the DASR porosities of the segregated cores were higher than those of the non-segregated cores and were reaching the threshold for the marginal state (48 percent).

Table 1. Laboratory Test and DASR Analysis Results for Project Number 1

Mixture	Sample ID	DASR (mm)	DASR Porosity (%)	DASR Porosity Group	Air Void (%)	Effective Asphalt Content (%)
Control	**JMF**	**4.75 – 1.18**	**45.3**	**Good**	**4.0**	**4.8**
Non-Segregated	N-1	4.75 – 1.18	42.8	Good	5.6	4.5
	N-2	4.75 – 1.18	44.8	Good	7.2	4.6
	Average	**N/A**	**43.8**	**Good**	**6.4**	**4.5**
Segregated	S-1	4.75 – 1.18	46.1	Good	10.9	4.0
	S-2	4.75 – 1.18	45.9	Good	10.9	4.0
	S-3	4.75 – 1.18	47.9	Good	13.1	4.1
	S-4	4.75 – 1.18	47.9	Good	13.1	4.1
	Average	**N/A**	**47.0**	**Good**	**12.0**	**4.1**

Figure 5 includes the gradation charts for both the segregated and non-segregated cores. Figure 5(a) shows that the gradation of the non-segregated mixtures was in good agreement with the JMF. On the other hand, Figure 5(b) exhibits that the gradation of the segregated mixtures has been altered from the JMF, especially for sieve numbers 4, 8, and 16 (i.e., sieve sizes 4.75-mm, 2.36-mm, and 1.18-mm, respectively). These particle sizes also correspond to the DASR shown in Table 1.



(a) Gradation of non-segregated mixtures (b) Gradation of segregated mixtures

Figure 5. Gradation charts for project number 1

5.2 Project Number 2

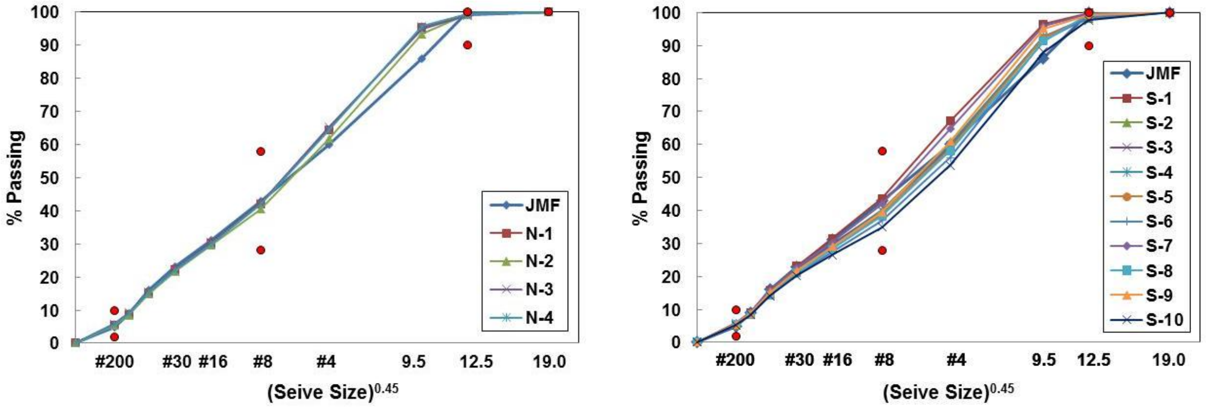
Project number 2 was also constructed with a 12.5-mm NMAS fine-graded Superpave mixture. The mixture included granite aggregates and a PG 76-22 polymer modified binder. Based on the visual assessment in the field, it was concluded that this project exhibited segregation of moderate severity.

The laboratory test and the DASR analysis results are summarized in Table 2. The average air void content obtained from the segregated cores was equal to 14.6 percent, which is noticeably higher than the 10 percent threshold. The effective asphalt content of the segregated cores averaged to be 3.6 percent, which is a significant reduction from the JMF value of 4.4 percent. The JMF for this project was determined to show a wide range of DASR from 1.18-mm to 9.5-mm. However, regardless of the presence of segregation, all the DASR determined from the field cores was limited to be between 1.18-mm and 4.75-mm, which indicates that the 9.5-mm aggregate was either missing or simply not interacting with smaller aggregates. It is also noted that the 1.18-mm aggregate was not included in the DASR for 3 of the 10 segregated samples showing increased porosity and hence higher potential for rutting. Based on the average DASR porosity, this project is expected to show marginal (i.e. either good or bad) rutting performance.

Table 2. Laboratory Test and DASR Analysis Results for Project Number 2

Mixture	Sample ID	DASR (mm)	DASR Porosity (%)	DASR Porosity Group	Air Void (%)	Effective Asphalt Content (%)
Control	**JMF**	**9.5 – 1.18**	**41.0**	**Good**	**4.0**	**4.4**
Non-Segregated	N-1	4.75 – 1.18	43.4	Good	6.5	4.2
	N-2	4.75 – 1.18	43.4	Good	6.5	4.2
	N-3	4.75 – 1.18	44.6	Good	7.8	4.3
	N-4	4.75 – 1.18	43.8	Good	7.8	4.3
	Average	**N/A**	**43.8**	**Good**	**7.1**	**4.3**
Segregated	S-1	4.75 – 1.18	48.3	Marginal	14.5	3.8
	S-2	4.75 – 1.18	48.1	Marginal	14.5	3.7
	S-3	4.75 – 1.18	48.2	Marginal	14.3	3.7
	S-4	4.75 – 1.18	47.8	Good	14.3	3.7
	S-5	4.75 – 1.18	47.6	Good	14.8	3.6
	S-6	4.75 – 2.36	54.9	Bad	15.0	3.5
	S-7	4.75 – 1.18	47.8	Good	15.0	3.7
	S-8	4.75 – 1.18	47.6	Good	14.6	3.6
	S-9	4.75 – 2.36	55.3	Bad	14.6	3.7
	S-10	4.75 – 2.36	54.1	Bad	14.2	3.5
	Average	**N/A**	**50.0**	**Marginal**	**14.6**	**3.6**

The gradation charts are shown in Figure 6. When compared to the JMF, the gradation of the non-segregated mixtures (Figure 6(a)) showed an increase in the percent passing of 9.5-mm sieve, indicating that the 9.5-mm aggregate is missing and hence not included in the DASR as shown in the above table. On the other hand, the segregated cores showed increased deviation from the JMF with decreased consistency (Figure 6(b)), which was somewhat expected based on the DASR results shown in Table 2.



(a) Gradation of non-segregated mixtures (b) Gradation of segregated mixtures

Figure 6. Gradation charts for project number 2

5.3 Project Number 3

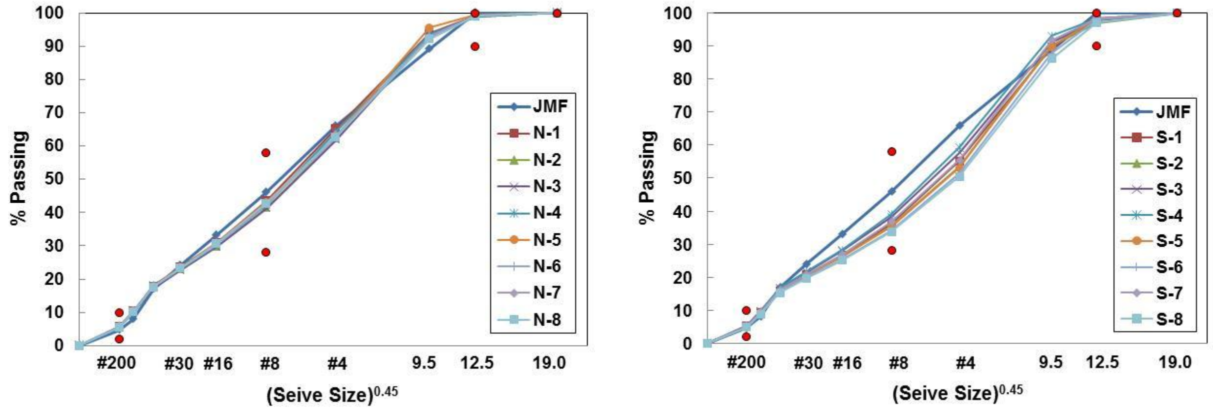
Project number 3 was constructed with 12.5-mm NMAS fine-graded Superpave mixture. Granite aggregate was used along with a PG 76-22 polymer modified binder. Visual observation in the field has indicated that the segregation on this roadway was more severe than project numbers 1 and 2.

Table 3 shows the laboratory test results. The average air void obtained from the segregated mixtures was determined to be 13.1 percent, again exceeding the 10 percent threshold but not as high as what was observed from Project number 2. The average effective asphalt content for the segregated mixtures was found to be 4.0 percent which was slightly lower than 4.2 percent of the JMF. However, the DASR of the segregated mixtures were inconsistent and the porosities were, in general, higher and more variable when compared to the previous projects. The average DASR porosity was determined to be 57.7 percent, indicating that the roadway is subject to significantly increased potential for rutting.

Figure 7 shows the gradation charts for both the segregated and non-segregated mixtures. Although the gradation of the non-segregated mixtures is relatively in good agreement with the JMF, the gradation of the segregated mixtures showed a significant departure from the JMF, especially for the sieve numbers 4, 8, and 16 (i.e., sieve sizes 4.75-mm, 2.36-mm, and 1.18-mm, respectively), which explains the inconsistent DASR results shown in Table 3.

Table 3. Laboratory Test and DASR Analysis Results for Project Number 3

Mixture	Sample ID	DASR (mm)	DASR Porosity (%)	DASR Porosity Group	Air Void (%)	Effective Asphalt Content (%)
Control	**JMF**	**4.75 – 1.18**	**46.8**	**Good**	**4.0**	**4.2**
Non-Segregated	N-1	4.75 – 1.18	43.7	Good	5.2	4.2
	N-2	4.75 – 1.18	42.5	Good	5.2	4.1
	N-3	4.75 – 1.18	43.1	Good	5.9	4.2
	N-4	4.75 – 1.18	43.5	Good	5.9	4.2
	N-5	4.75 – 1.18	41.8	Good	3.6	4.2
	N-6	4.75 – 1.18	42.4	Good	3.6	4.2
	N-7	4.75 – 1.18	44.3	Good	5.9	4.2
	N-8	4.75 – 1.18	44.4	Good	5.9	4.2
	Average	**N/A**	**43.2**	**Good**	**5.1**	**4.2**
Segregated	S-1	4.75 – 2.36	54.2	Bad	12.8	4.0
	S-2	2.36 – 1.18	66.1	Bad	12.8	4.0
	S-3	4.75 – 1.18	47.7	Good	14.3	4.0
	S-4	4.75 – 1.18	47.2	Good	14.3	4.1
	S-5	2.36 – 1.18	66.6	Bad	12.7	4.0
	S-6	2.36 – 1.18	66.9	Bad	12.7	3.9
	S-7	4.75 – 1.18	45.4	Good	12.6	4.0
	S-8	2.36 – 1.18	67.1	Bad	12.6	3.9
	Average	**N/A**	**57.7**	**Bad**	**13.1**	**4.0**



(a) Gradation of non-segregated mixtures

(b) Gradation of segregated mixtures

Figure 7. Gradation charts for project number 3

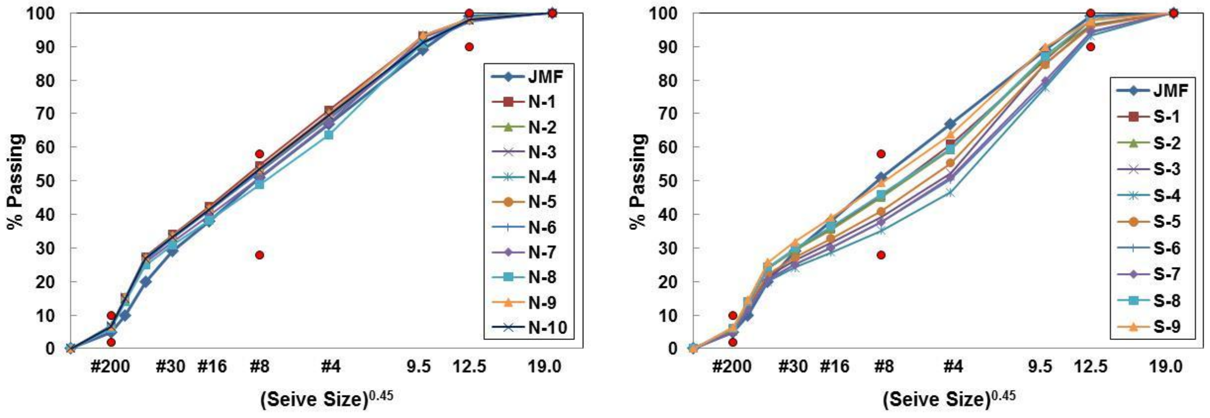
5.4 Project Number 4

Project number 4 was constructed with 12.5-mm NMAS fine-graded mixture which included granite aggregates, 20 percent Reclaimed Asphalt Pavement (RAP), and a binder with a recycling agent. Based on visual inspection, it was determined that the segregation in this project was more severe than the other projects presented earlier.

The laboratory test and DASR analysis results are summarized in Table 4 and the gradation charts are shown in Figure 8. It should be noted that the DASR porosities of the JMF and the non-segregated mixtures for the previous projects were all less than 48 percent (i.e., expected to show good rutting performance). However, the JMF of this project was found to have marginal DASR porosity. As a result, the DASR porosities were varied in the marginal and bad range even though the mixtures were not segregated and their gradation was only slightly altered from the JMF (Figure 8(a)). Furthermore, as expected from the significantly altered gradation shown in Figure 8(b), it was found that the segregated mixtures exhibited excessively high DASR porosities with an average of 68.5 percent, indicating the potential gradation deficiencies associated with the coarse aggregate structure or interlocking that may influence the rutting resistance.

Table 4. Laboratory Test and DASR Analysis Results for Project Number 4

Mixture	Sample ID	DASR (mm)	DASR Porosity (%)	DASR Porosity Group	Air Void (%)	Effective Asphalt Content (%)
Control	**JMF**	**4.75 – 1.18**	**51.7**	**Marginal**	**4.0**	**4.5**
Non-Segregated	N-1	4.75 – 1.18	54.3	Bad	5.4	4.5
	N-2	4.75 – 1.18	54.4	Bad	5.4	4.5
	N-3	4.75 – 1.18	53.8	Bad	4.3	4.5
	N-4	4.75 – 1.18	53.1	Bad	4.3	4.5
	N-5	4.75 – 1.18	55.5	Bad	7.8	4.5
	N-6	4.75 – 1.18	55.5	Bad	7.8	4.5
	N-7	4.75 – 1.18	52.3	Bad	5.6	4.4
	N-8	4.75 – 1.18	51.6	Marginal	5.6	4.4
	N-9	4.75 – 1.18	54.9	Bad	7.7	4.5
	N-10	4.75 – 1.18	55.5	Bad	7.7	4.5
	Average	**N/A**	**54.1**	**Bad**	**6.2**	**4.5**
Segregated	S-1	4.75 – 1.18	55.1	Bad	11.3	4.3
	S-2	4.75 – 1.18	54.5	Bad	11.3	4.3
	S-3	2.36 – 1.18	74.0	Bad	13.3	4.1
	S-4	2.36 – 1.18	76.0	Bad	13.3	4.1
	S-5	2.36 – 1.18	75.0	Bad	17.8	4.1
	S-6	2.36 – 1.18	74.5	Bad	14.5	4.1
	S-7	2.36 – 1.18	74.0	Bad	14.5	4.1
	S-8	2.36 – 1.18	74.7	Bad	15.5	4.3
	S-9	4.75 – 1.18	58.3	Bad	15.5	4.4
	Average	**N/A**	**68.5**	**Bad**	**14.1**	**4.2**



(a) Gradation of non-segregated mixtures (b) Gradation of segregated mixtures

Figure 8. Gradation charts for project number 4

5.5 Summary of Observations

The DASR porosity results indicated that segregation may cause the coarse aggregate structure within the asphalt mixture to be altered significantly such that it may negatively influence the rutting potential of mixtures. The increase in DASR porosity due to segregation was more pronounced for Project numbers 3 and 4 than it was for Project numbers 1 and 2. In particular, some of segregated mixtures from Project numbers 3 and 4 exhibited unusually high DASR porosities (i.e. higher than 65.0 percent and up to 75.0 percent), which appears to be associated with a higher degree of segregation than the other two sections. This observation is also consistent with the severity of segregation determined from the visual inspection and the shift in the gradation curves.

6 CONCLUSIONS AND RECOMMENDATIONS

In this study, the effect of segregation or aggregate gradation changes that may negatively influence the rutting potential of asphalt mixtures was evaluated. The concept of Dominant Aggregate Size Range (DASR) and the DASR porosity parameter, that were previously identified to be well correlated with rutting performance, have been used to identify the potential degradation of rutting performance due to segregation. A summary of findings and conclusions is presented as follows.

- Significant gradation shifts were clearly identified from segregated mixtures, especially for the coarse aggregate portion of the mixture. The in-place gradation of segregated mixtures deviated from those of non-segregated mixtures and from JMF.
- Increased amount of coarse aggregates in segregated mixtures may result in significantly altered volumetric properties such as reduced asphalt content and increased air voids when compared to non-segregated mixtures.
- Analysis of the DASR porosities indicated that segregation of asphalt mixtures may increase the potential for rutting.

Although the field sections evaluated using the DASR gradation model indicated that segregation resulted in increased rutting potential, the long-term field performance data is not available as of this writing for verification of the DASR analysis results. Therefore, work is planned for long-term monitoring of the projects evaluated in this study as well as additional projects with segregation that may be identified in the future.

7 ACKNOWLEDGEMENTS

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8 DISCLAIMER

The content of this report reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Florida Department of Transportation. This report does not constitute a standard, specification, or regulation. In addition, the above listed agency assumes no liability for its contents or use thereof.

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