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CHARACTERIZATION OF AGGREGATE RESISTANCE TO DEGRADATION IN STONE MATRIX ASPHALT MIXTURES

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16. Abstract

Stone Matrix Asphalt (SMA) mixtures rely on stone-on-stone contacts among particles to resist applied forces, and permanent deformation. Aggregates in SMA should resist degradation (fracture and abrasion) under high stresses at the contact points. This study utilizes conventional as well as advanced imaging techniques to evaluate aggregate characteristics, and their resistance to degradation. Aggregates from different sources and types with various shape characteristics were used in this study. The Micro-Deval test was used to measure aggregate resistance to abrasion. The aggregate imaging system (AIMS) was used to examine the changes in aggregate characteristics caused by abrasion forces in the Micro-Deval. The resistance of aggregates to degradation in the SMA was evaluated through the analysis of aggregate gradation before and after compaction using conventional mechanical sieve analysis, and the nondestructive X-ray computed tomography (CT). The findings of this study lead to the development of an approach for the evaluation of aggregate resistance to degradation in SMA. This approach measures aggregate degradation in terms of abrasion, breakage, and loss of texture.

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ROLE OF AGGREGATE CHARACTERISTICS IN RESISTANCE TO LOAD IN SMA

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INTRODUCTION

The use of Stone Matrix Asphalt (SMA) has steadily increased since its introduction in the United States in 1991. This mix provides engineers with another alternative in the search of a more rut-resistant and cost-effective asphalt mixture. Prior to its introduction in the U.S., it was originally developed in Germany to resist studded tire wear (*1*). However, it has also been used to successfully minimize rutting and lower maintenance costs in high traffic areas through out Europe (*2*).

Aggregate structure plays a significant role in the resistance of SMA to permanent deformation. This structure is dependant on stone-on-stone contacts of the coarse aggregate in the mixture (*1, 2)*, which places demands on aggregates that are different from those for previous conventional mixtures. Conventional dense-graded mixtures often allowed coarse aggregates to essentially “float” in a matrix of fine aggregates and asphalt binder, therefore, in these conventional mixes, strength properties of coarse aggregates were less important.

Evidence indicates that construction operations, particularly compaction of thin layers, plus subsequent traffic loadings can contribute to degradation of coarse aggregates at the contact points, which can significantly alter the original design gradation and create uncoated aggregate faces. Broken binder films can also provide inlets for water which, in concert with traffic loads, can exacerbate stripping. Therefore, strength properties of coarse aggregates are clearly more significant in SMA mixtures when compared with conventional mixtures.

It is imperative that the contribution of aggregate strength to the behavior of SMA mixes under loading is understood and that methods are developed to measure this contribution before significant problems are created. Recently, new methodologies to evaluate the aggregate structure in asphalt mixtures have been developed (*3-11*). Most of these studies focused on measuring stone-on-stone contact within an SMA specimen by analyzing the voids in the coarse aggregate (VCA) of the mixtures. Some of these studies incorporate imaging technology to measure aggregate properties, breakdown and aggregate contact in SMA mixtures *(7, 10)*.

SCOPE AND OBJECTIVES

The main objectives of this study are to characterize the resistance of aggregates to degradation (abrasion and fracture) in SMA mixtures, and recommend test methods to measure aggregate properties related to their resistance. These objectives will be achieved through the following tasks:

- Design SMA mixtures using different aggregate sources,
- Measure aggregate properties such as abrasion resistance, and physical characteristics,
- Quantify aggregate degradation due to compaction using different conventional and advanced methods such as X-ray Computed Tomography,
- Quantify aggregate degradation due to repeated dynamic loading, and
- Recommend an approach for the selection of aggregates in SMA.

MATERIALS AND MIX DESIGNS

Six coarse aggregates that were used in this study are shown in Table 1. Aggregates were selected to represent various types of mineralogy, and to exhibit different shape characteristics. The description of the shape characteristics in Table 1 was based on preliminary visual inspection, which was conducted to verify that these aggregates represent different characteristics. One 12.5 mm SMA mixture design using traprock was obtained from Texas Department of Transportation. The researchers replaced the coarse aggregate fraction of the original mixture design essentially keeping the same gradation in order to produce several mixture designs. In this study, the term “coarse aggregates” refers to particles larger than the 2.36 mm sieve. A total of six mixture designs were produced using the gradations in Table 2.

Table 1: Physical Characteristics of Coarse Aggregates Used in the Study.

Mixture #	Description of Aggregate	Characteristics		
		Cubical	Angular	Texture
1	Uncrushed River Gravel	H	L	L
2	Crushed Limestone 1	M	H	H
3	Crushed Glacial Gravel	H	M	M
4	Crushed Traprock	M	H	H
5	Crushed Granite	L-	M	M
6	Crushed Limestone 2	M	M	M
L-: Very low, L: Low, M: Medium, H: High.				

Table 2: SMA Aggregate Gradations Used in the Study.

Sieve Size inches (mm)	Cumulative Gradation for all Mixtures Except Glacial Gravel	Cumulative Gradation for Glacial Gravel
	% Passing	% Passing
3/4" (19.0)	100	100
1/2" (12.5)	89	89
3/8" (9.5)	60	60
#4 (4.75)	28	28
#8 (2.36)	18	18
#16 (1.18)	15	14
#30 (0.6)	12	11
#50 (0.3)	11	10
#100 (0.15)	10	9
#200 (0.075)	9.0	8.0
Pan	0	0

Fine aggregate fraction (particles smaller than 2.36 mm) was obtained from the same source for all six mixtures. Limestone screenings, filler (fly ash), and hydrated lime comprised the fine aggregate fraction. This allows a more direct examination of the SMA performance in relationship to coarse aggregate degradation. Fly ash was used as the mineral filler in all mixtures. Also, 0.3 percent cellulose fiber by weight of total mixture and 1.0 percent hydrated lime were used in the mixtures. SMA mixture designs require higher asphalt contents as opposed to dense-graded mixes (*1*). With the increase of asphalt in conjunction with the gap-graded mixture, additional filler is needed to prevent draindown in SMA (*1*, *9*). The mix design developed by Texas Department of Transportation originally used PG 76-22 asphalt, but a softer asphalt PG 64-22 was used instead to further emphasize the influence and interaction of coarse aggregates in SMA.

The asphalt content of each mixture was determined such that mixtures had 4.0 percent air voids at 100 gyrations. The values of the bulk specific gravities of the compacted specimens were determined using the vacuum sealed (Corelok®) system. The aggregate specific gravity, design asphalt content and voids in mineral aggregates (VMA) of the mixes are shown in Table 3. Some of VMA values were less than the minimum value of 17 percent recommended by AASHTO MP8-01 and PP41-01. The difference in VMA values among the mixes is caused primarily by the difference in aggregate shape, angularity and texture as well as aggregate crushing in some of the mixes as discussed later in this report. As shown in Table 2, the fine aggregate portion of the gradation for crushed glacial gravel mixture was slightly altered in order to meet the 4 percent air voids design requirement without altering the gradation of the coarse aggregate fraction.

Table 3: Mix Design Properties.

Aggregate Source	Aggregate Bulk Sp. Gravity	Asphalt Content	VMA
River Gravel	2.617	5.5	14.00
Limestone 1	2.655	5.0	14.64
Glacial Gravel	2.637	6.0	16.26
Traprock	2.966	6.5	19.71
Granite	2.621	7.5	19.25
Limestone 2	2.652	5.3	14.00

TEST METHODS AND RESULTS

Resistance to Abrasion Using the Micro-Deval Test and Imaging Techniques

Aggregates should exhibit resistance to abrasion in order to retain their shape characteristics as well as to resist fracture under construction operations and traffic. Typically, SMA mixture design requires the use of the Los Angeles Abrasion test (LAR) to determine the abrasion resistance of aggregate (*5*). However, recent studies have shown the Micro-Deval test is more suitable to evaluate aggregate resistance to abrasion, and hence it was used in this study.

The Micro-Deval Abrasion test was performed following AASHTO TP58. It induces abrasion on coarse aggregates by revolving them in the presence of steel spheres and water. Prior to the testing, the aggregate is saturated with water and washed to remove the fines (aggregate passing sieve #16). This test is similar to the LAR (AASHTO T96) as both tests measure the percent loss of the aggregate on certain sieve size; however, the LAR does not use water and the Micro-Deval test does not account for impact resistance. Results of the Micro-Deval test are listed in Table 4. The percentage in this table represents the aggregate weight loss passing sieve #16. Limestone 2 experienced the highest percent loss, while uncrushed river gravel experienced the lowest percent loss.

Table 4: Results for Degradation of Coarse Aggregate via Micro-Deval Abrasion.

Mixture #	Description	Micro-Deval Loss (%)
1	Uncrushed River Gravel	4.6
2	Limestone 1	12.6
3	Crushed Glacial Gravel	11.2
4	Traprock	11.3
5	Granite	5.6
6	Limestone 2	23.5

Recent advancements in aggregate shape measurement technology have led to a new methodology to classify aggregate characteristics (*12*). This methodology utilizes the Aggregate Imaging System (AIMS) to directly measure and analyze aggregate characteristics (texture, angularity and shape). AIMS consists primarily of a top lighting, back lighting, an auto-focus microscope, and associated software *(12, 13).* The analysis that AIMS performs for the three characteristics are briefly described in this report. More details concerning this system can be found in literature (*12*, *13*). Aggregate angularity is calculated using the gradient method. This method tracks the change of the gradient within a particle boundary. Higher value indicates more angular aggregate. Texture is measured using the wavelet method, in which a higher texture index indicates a rougher surface. AIMS has the ability to measure the three-dimensional shape of an aggregate. Shape is quantified using the sphericity index, which is equal to one for a particle with equal dimension. The sphericity index decreases as a particle becomes more flat and elongated.

AIMS was used to measure the angularity, texture, and shape of coarse aggregates before and after the Micro-Deval test in order to compute the change in physical characteristics of the aggregates due to the induced abrasion. The results of the AIMS analysis are shown on Figure 1. In this figure, the percent change is defined as difference in an aggregate characteristic before and after the Micro-Deval test divided by the shape index before Micro-Deval test. The percentages represented in Figure 1 are useful for describing the way by which the aggregate types have changed. Figure 1a shows the change in angularity. The negative change in angularity indicates that an aggregate became less angular after the Micro-Deval test. Figure 1b shows the change in aggregate sphericity, where the rounding of aggregate is denoted by the positive change and elongation of aggregate is represented by the negative change. In Figure 1c, negative changes mean that an aggregate lost some of its texture, and positive changes are indicative of increase in aggregate roughness.

The general trends illustrated by the figures show that after the Micro-Deval test, most of the aggregates became more polished and less angular. For the uncrushed river gravel, there was an increase in elongation and angularity after the Micro-Deval test. This finding suggests that that the Micro-Deval test caused some breakage in this aggregate leading to an increase in its angularity (Figure 1a). The glacial gravel, however, experienced a 30 percent reduction in angularity due to abrasion.

After the Micro-Deval test, four of the six aggregates became more elongated, which is denoted by the negative percent change in Figure 1b. Also in this figure, Limestone 1 exhibited a 70 percent increase in elongation of particles indicating that particles experienced breakage.

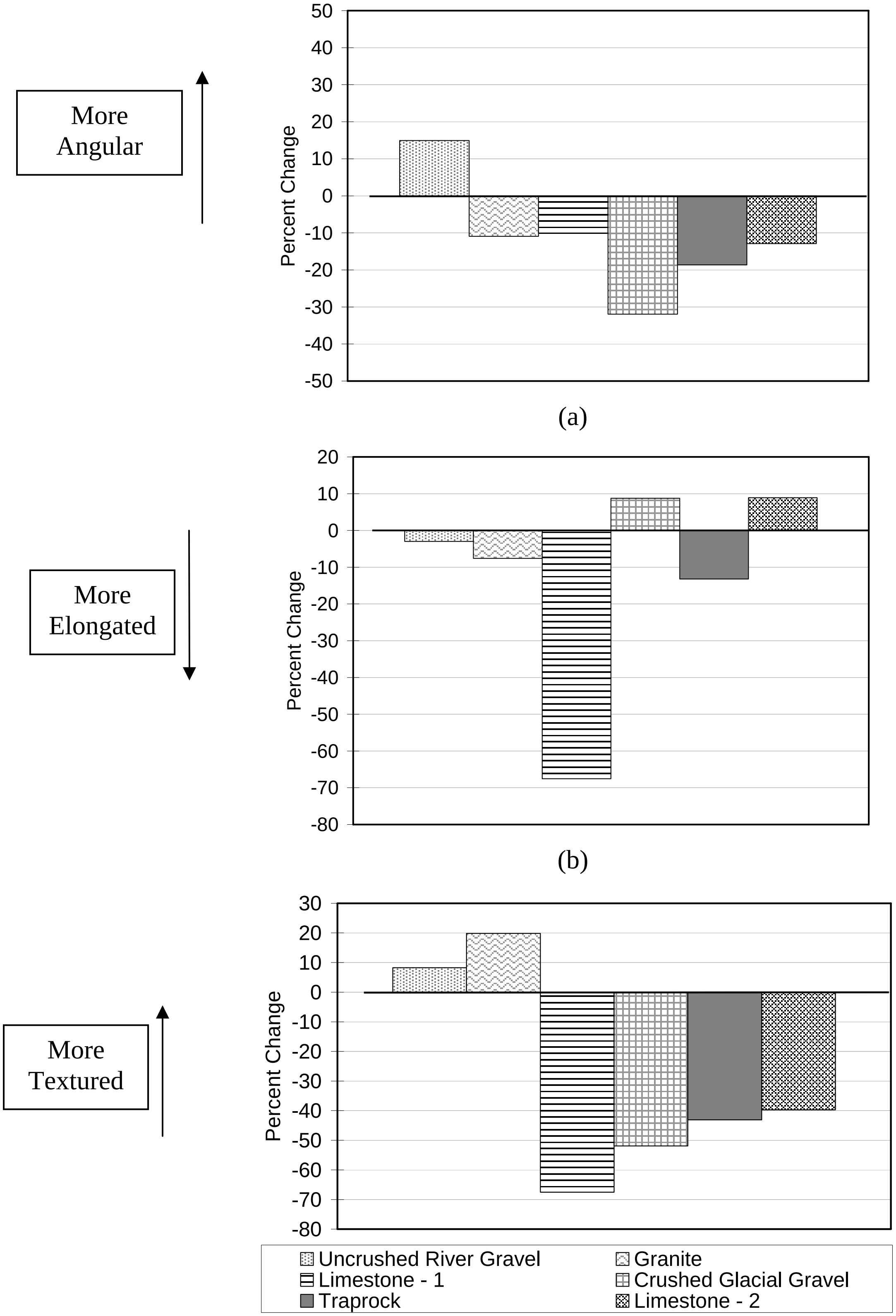
Granite and the river gravel exhibited less than 10 percent change in sphericity. However, the glacial gravel and Limestone 2 experienced an increase in sphericity most likely due to the abrasion of the sharp corners at the surface of these particles.

Figure 1c shows that four of the six aggregates became more polished. Limestone 1 experienced the most change compared to the other four aggregates. The texture results indicate that the river gravel exhibited a little increase in texture. This could be due to the exposure of textured surfaces when aggregates were crushed. The increase in texture of the granite could indicate that the abrasion in the Micro-Deval exposed surfaces with even more texture.

Aggregate Degradation Due to Compaction

Because the performance of SMA depends on aggregate quality and stone-on-stone contact, the breakdown of aggregate during compaction was also examined. In this study, the asphalt specimens were compacted using the Superpave gyratory compactor (SGC). For each of the six mixture designs, two specimens compacted to 100 gyrations and two specimens compacted to 250 gyrations were used in the analysis. The 100 gyration specimens had a target air void level of 4 percent. Dessouky et al. (*14*) found that volumetric change in a specimen decreases significantly after about 100 gyrations. They also suggested that specimens experience shear stresses among aggregate particles between 100 to 250 gyrations. It was not practical to compact specimens to more than 250 gyrations since specimens cooled down and stiffened making it harder to apply the compaction forces (vertical pressure and angle of gyration) in the SGC.

In this study, the changes in aggregate gradation of specimens compacted at 250 gyrations were compared with that of specimens compacted at 100 gyrations and uncompacted loose mixtures. Aggregate gradation was determined using mechanical aggregate size analysis and imaging techniques.



(a)

(b)

(c)

Figure 1: Results of AIMS Analysis for (a) Angularity (b) Sphericity (c) Texture

Mechanical Aggregate Size Analysis

The ignition oven was used to extract the asphalt and provide an aggregate sample. Gradation analysis was used to analyze the pair of 100 gyrated samples to the pair of 250 gyrated samples. Non-compacted mixtures that were put into the ignition oven were also used in the comparison. The purpose of these mixtures was to determine any change in gradation due to the aggregates exposure to extreme heat from the ignition oven. This comparison will show the aggregate breakdown due to the two compaction levels.

Very good repeatability was obtained from the analysis of replicates as evident in the example of gradation analysis shown in Figure 2. The results of the gradation analyses for all mixtures are shown on Figure 3. Ideally, a mix design gradation should not change after compaction from its design requirement. However, changes in gradations do occur to different extents after compaction. The graph shows the resultant change, with respect to the loose mix gradations, of the aggregates passing 12.5 mm sieve and retained on 9.5 mm sieve and aggregates passing 9.5 mm but retained on 4.75 mm sieve for the six mixtures. These two sieve sizes experienced most change when compared to the other sieve sizes. In fact, these two sizes comprise the most of the coarse aggregates. Limestone 1 mixture had the most change while granite mixture had the least. Limestone 2 followed Limestone 1 in terms of change in gradation. Each mixture showed a negative change in 12.5 – 9.5 mm aggregates and a small increase in the 9.5 - 4.75 mm aggregates at 250 gyrations.

Aggregate Size Analysis Using Imaging Techniques

The X-Ray Computed Tomography is a non-destructive technique that captures the internal structure of an asphalt mix. Previous studies have been able to utilize the X-Ray CT to analyze stone-on-stone contacts, and air void distribution in HMA specimens (*10*). The focus of the X-Ray CT was to analyze the aggregate size distribution in specimens compacted at 100 gyrations and 250 gyrations. For this analysis, an additional two specimen were compacted to 100 gyrations and another two were compacted to 250 gyrations, for each SMA design. The specimens were then scanned with the X-Ray CT. Scanning yields images of the internal

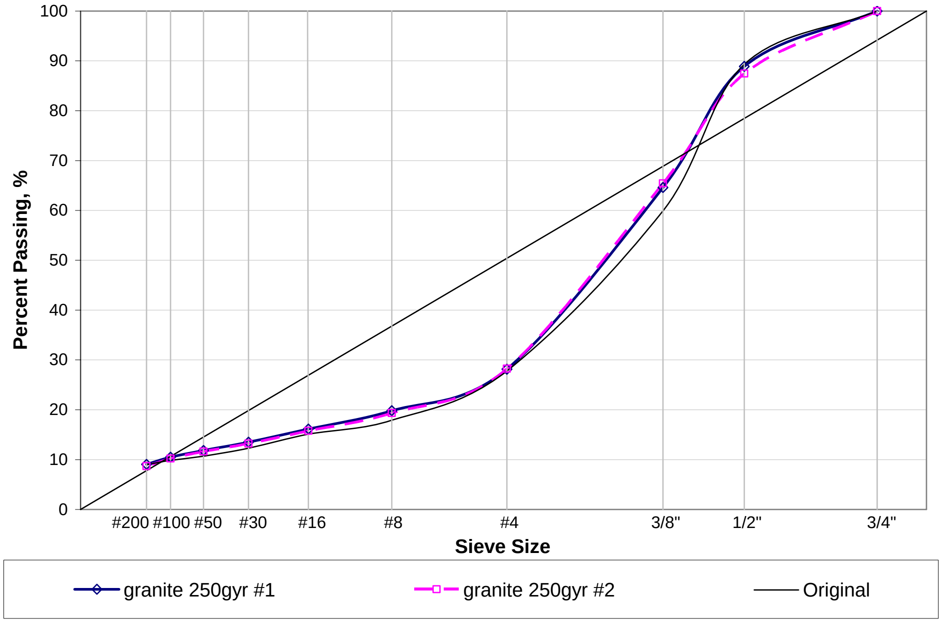


Figure 2: An Example of Aggregate Gradation before and after Compaction

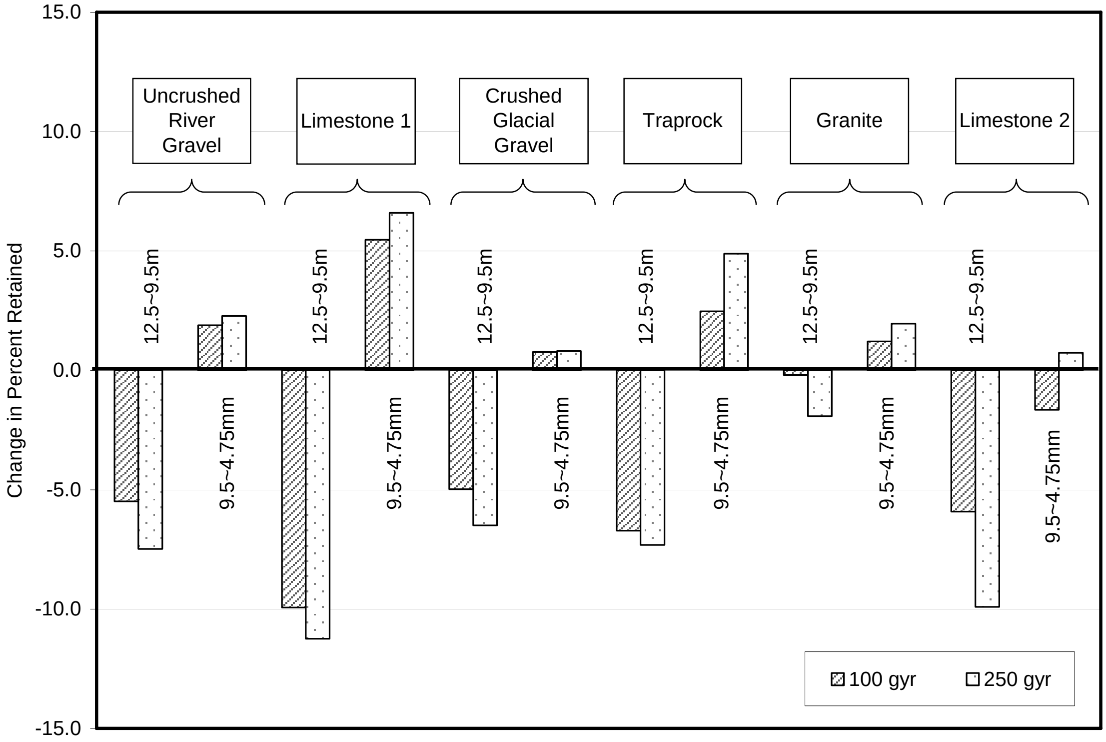


Figure 3: Percent Change in 9.5 mm and 4.75 mm Sieves Using Mechanical Sieve Analysis.

structure captured at incremental depths of one millimeter. An example of an image taken by the X-Ray CT is illustrated in Figure 4.

The software Image Pro® was used in the analysis of the X-Ray images. A macro was developed to analyze the size distribution of particles in X-ray CT images. In this macro, the method developed by Tashman et al. (*15*) was used to separate particles. Then, the diameter of each particle was determined, and percentages of aggregates in each of the coarse aggregate fractions in selected sieves were obtained for each image. The median (50th percentile) of the weight retained on each sieve size among all images was calculated, and the difference in the median between specimens compacted at 100 gyrations and 250 gyrations was then determined. The results are shown in Figure 5. The percentage of aggregates retained on 12.5 mm sieve was small and any change in size would exaggerate the percent change between the two sets of specimens. Therefore, this sieve was not included in the analysis. Negative changes mean the 250 gyration specimens yielded lower counts of aggregate for each respective sieve size. This is typically due to aggregates breaking down and being retained in a smaller sieve. A positive increase shows that the specimens exhibited a higher percentage in that particular size, which is due to larger aggregate breaking into sizes that fall into the respective sieve size.

Looking at the plots in Figure 5, five out of six aggregates showed negative changes. This is particularly the case for the aggregates retained on the 4.75 mm and 9.5 mm sizes. When focusing on the changes in the 9.5 mm, the results indicate that Limestone 2 experienced the most change, followed by Limestone 1, crushed glacial gravel, uncrushed river gravel, and then granite. The traprock mix, however, showed an increase in aggregate size. It was noticed that the traprock mix at 250 gyrations had more packed structure than the other mixes, which made it difficult to separate the particles in the X-ray CT images. Particles that are not separated at 250 gyrations are considered to be a larger particle by image analysis methods, which reduced the number of particles at this compaction level compared to the specimens at 100 gyrations.

Aggregate Degradation Due to Repeated Dynamic Loading

The flow number test captures fundamental material properties of an HMA mixture that correlate with rutting performance (*16*). In this test procedure, axial dynamic compressive stress is applied in a haversine waveform with a wavelength of 0.1 seconds followed by a rest period of

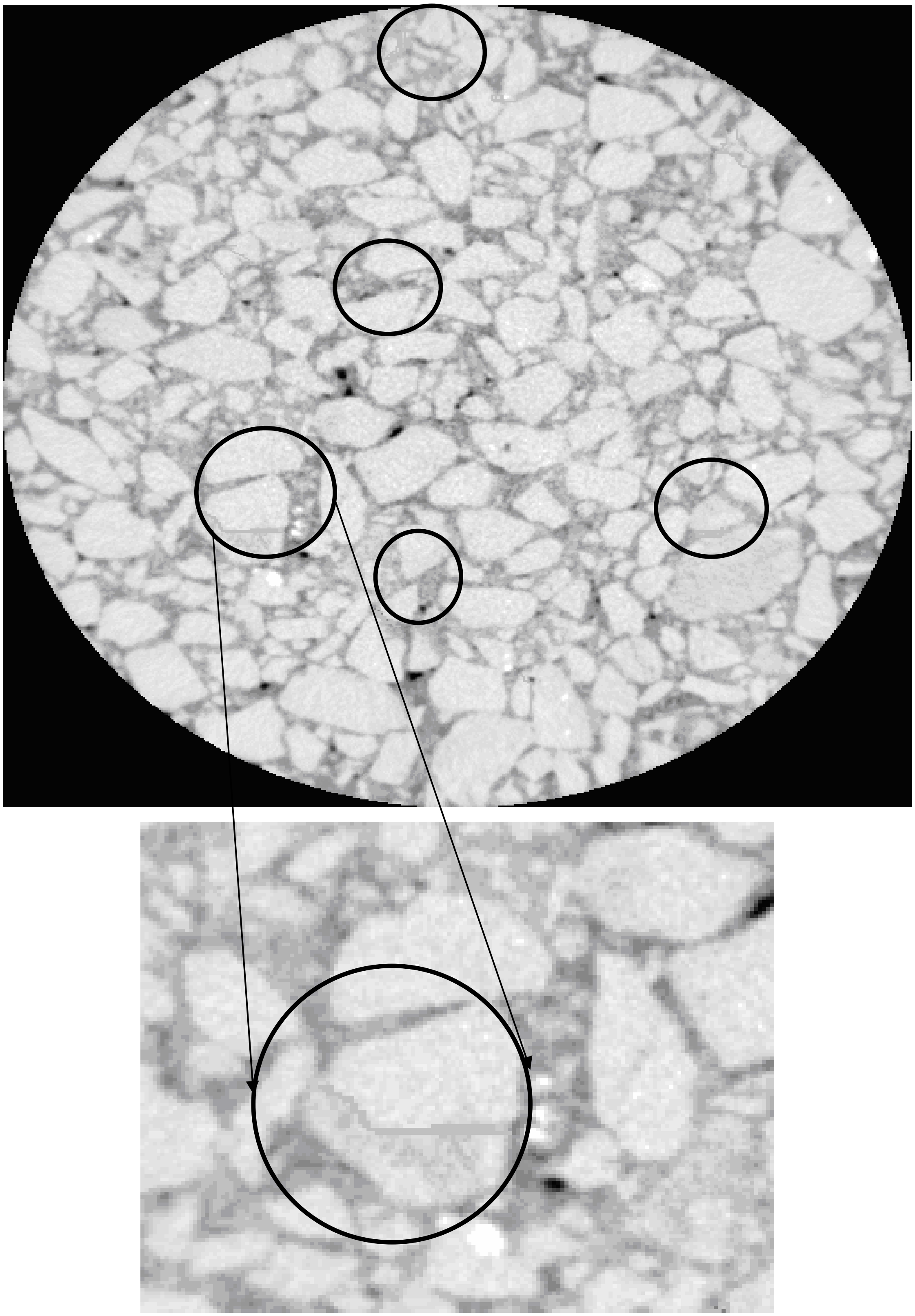


Figure 4: X-Ray Image of Limestone 1 at 250 Gyrations with Circles Highlighting Areas with Crushed Particles.

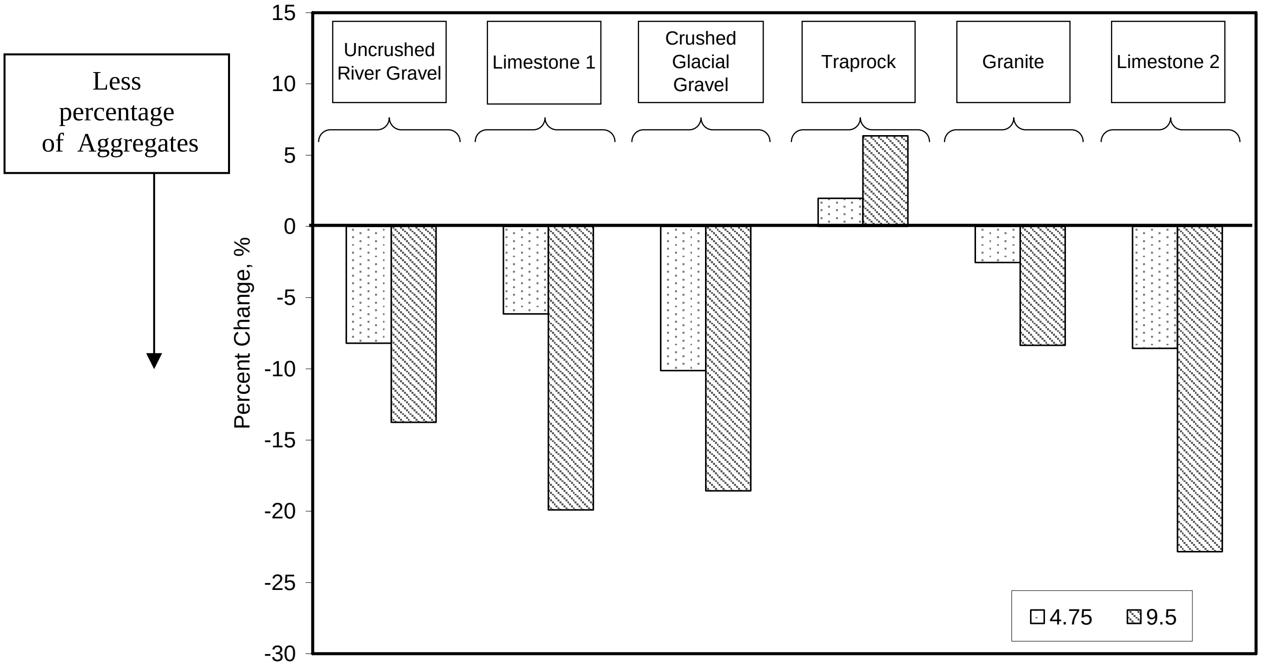


Figure 5: Results of Change in Gradation Using X-Ray CT Imaging.

0.9 seconds on cylindrical HMA specimens until a tertiary deformation is observed. The number of load repetition to cause tertiary permanent deformation is termed as flow number. The primary purpose of the flow number test in this project was to induce aggregate crushing resultant from repeated dynamic loading.

This test was conducted following the procedure suggested by NCHRP Project 9-19 (*16*). All specimens were compacted to have a 150 mm diameter and 175 mm height. Mixtures were compacted to in order to obtain 7±0.5 percent air voids in the specimens after they were trimmed to final size. The final size of a test specimen was 100 mm in diameter and 150 mm in height. The test temperature was 37.8 °C, while the load peak was 310 kPa. Relatively lower temperature and higher stress were selected in order to induce permanent deformation caused primarily by aggregate degradation. Two specimens were tested for each mix design. Aggregates were extracted from the specimens using ignition oven after the flow number tests. Sieve analysis was performed on the recovered aggregates. The aggregate gradations after flow number test were compared to the gradations of control samples that were not tested with flow number test. Change in aggregate gradations due to dynamic loading is shown in Figure 6. The results revealed no significant change in gradations before and after the flow number test. Four of the specimens showed minor aggregate breaking in the 9.5 mm sieve while showing an increase on the 4.75 mm retained. Granite exhibited the most degradation in the test, while the Limestone 2 had the least. It was also found that the mixtures with a higher asphalt content yielded low flow number values.

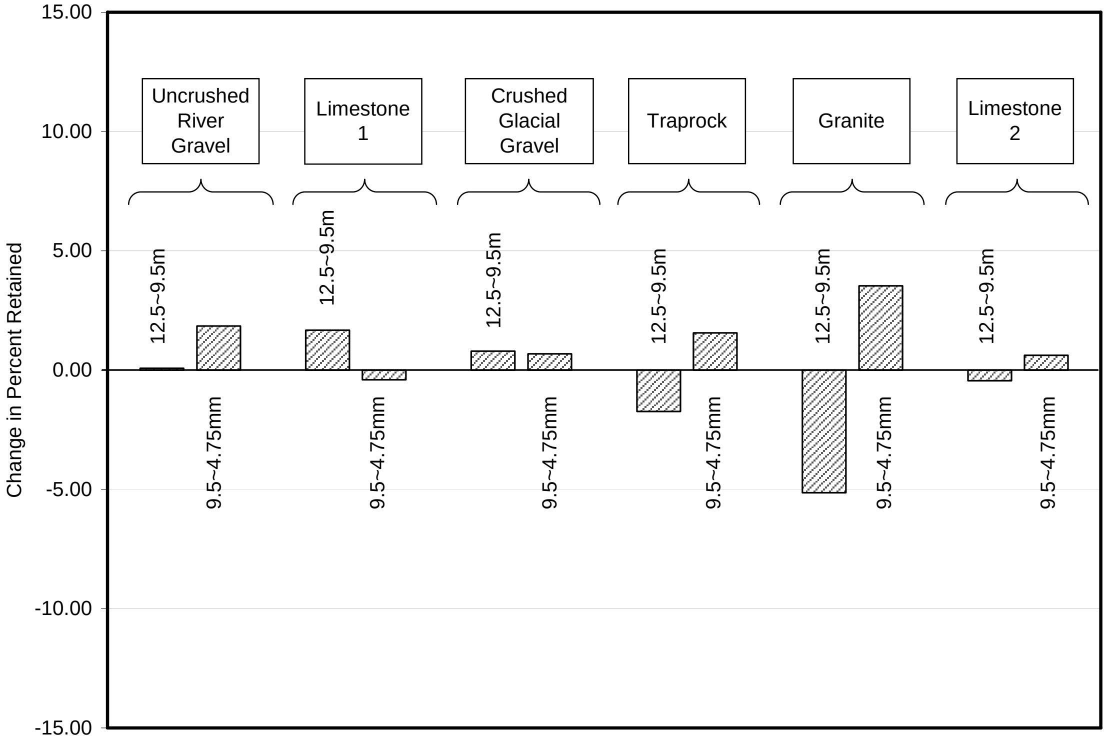


Figure 6: Percent Change in 9.5 mm and 4.75 mm Sieves for the Flow Number Test.

ANALYSIS OF RESULTS AND DISCUSSION

The results posted in the study provide interesting data that relate the quality of aggregate to the performance in SMA mixtures. The aggregate breakdown was evident in all mixtures to different levels. Aggregates of 12.5 mm to 9.5 mm fraction decreased as shown on Figure 3. All mixtures that exhibited breakdown in the 9.5 mm sieve showed that they were retained on the 4.75 mm sieve, which explains for the increase in some retained material. Out of the six mixtures, the Limestone 1 exhibited the greatest amount of aggregate breakdown in the 9.5 mm sieve, followed by limestone 2, glacial gravel, and then the river gravel (Figure 3). Granite mixture showed a change in gradation, but it was small compared to the other five mixtures. Figure 3 also shows that the gradations of the aggregates were affected by the increased gyrations from 100 to 250. Limestone 2 mixture was most affected by the increased gyrations.

The Micro-Deval test result showed that the two limestone samples exhibited the most percent loss (Table 4). These results support the findings from the change in gradation using both the mechanical sieving and imaging techniques. Also, the granite mixture’s post-compaction gradation correlated well with its Micro-Deval results. This mixture showed the least change in gradation due to compaction as well as the least percent loss in the Micro-Deval.

Limestone 2 is softer than Limestone 1, which is supported by the Micro-Deval results. However, Figure 3 shows that breakdown of Limestone 2 was less than that of Limestone 1 when compacted to 100 gyrations. Limestone 2 had nearly the same amount of change in the 9.5 mm sieve as limestone 1 when compacted to 250 gyrations. The imaging results in Figure 5 support the mechanical sieve analysis finding as the difference between the two limestone mixes was very small. It is evident that the difference between these two aggregates in the Micro-Deval did not translate into gradation analysis. Micro-Deval result is determined by the weight loss through the 1.18 mm (#16) sieve. Breakdown may alter the distribution of aggregates used in the Micro-Deval test; but the breakdown may be limited to sizes higher than 1.18 mm. This would be the case for the Limestone 1. In comparison to Limestone 2, abrasion caused large percentage of aggregates to pass sieve #16.

The AIMS results can be used to help explaining the findings from the Micro-Deval test and gradation analysis. Limestone 1 experienced a small change in angularity (Figure 1a), while the change in sphericity was significant. Past experience with the AIMS results have shown that the change in sphericity is an indication of particles' breakage, while the change in angularity indicates loss of angular elements on the surface which tend to be smaller than those produced due to breakage. The change in texture is not indicative of weight loss, as texture is measured at very high resolution (*12*), and its changes correspond to the loss of a very small amount of fine particles that are typically pass sieve #200. These AIMS results indicate that Limestone 1 experienced breakage to relatively large pieces rather than abrasion that would produce particles passing sieve #16. However, Limestone 2 became less elongated after Micro-Deval due to the abrasion of its surface.

The remaining four aggregates (uncrushed river gravel, crushed glacial river gravel, traprock and granite) experienced some aggregate breakdown as indicated in Figures 3 and 5. However, the small changes in Micro-Deval loss (less than 12 percent) along with the small changes in sphericity (Figure 1b) indicate that these changes are not significant.

When the results from compaction analysis were compared to the results of the flow number test, no correlation could be established. There was no significant change in gradation as a result of the specimens subjected to dynamic loading. Possible explanation could be that the applied stress (310 kPa) was not high enough to cause aggregate breakdown. Moreover, the tests were conducted in unconfined condition for simplification. In unconfined condition, the permanent deformation of SMA specimen was probably mostly due to the plastic flow of mastic with relatively soft asphalt.

APPROACH FOR THE ANALYSIS OF AGGREGATE BREAKAGE AND ABRASION

This section presents an approach for the analysis of aggregate breakage and abrasion. The limits that are included herein need to be further examined in future studies based on the relationship of aggregate abrasion and fracture or breakage to SMA performance. Nonetheless, this approach is presented here to set the framework for the development of this linkage.

Figure 7 shows the relationship between percent of change in weight retained on the aggregate size smaller than the NMAS versus weight loss in the Micro-Deval. Only small percentage of aggregate is retained on the NMAS, and consequently, evaluating weight loss on the NMAS would exaggerate the percent change due to compaction. Aggregates in region A exhibit small change in gradation and small Micro-Deval loss; these aggregates are expected to resist degradation in SMA. Aggregates in region B experience change in gradation due to compaction, but they have small loss in Micro-Deval. These types of aggregates could be susceptible to fracture under compaction, but they resist surface abrasion and loss of angularity. It is recommended that mix design engineers conduct an evaluation of aggregate gradation even on those that meet the Micro-Deval requirements to ensure aggregate resistance to degradation. Aggregates in region C have high Micro-Deval loss, and they susceptible to degradation in SMA. Aggregates that would fall in region D are those that have high Micro-Deval loss, but HMA can be designed such that aggregate degradation is minimized (low change in gradation). Even if aggregates do not meet the allowable weight loss requirements in the Micro-Deval, they can still be used if the change in gradation is minimized to acceptable limits.

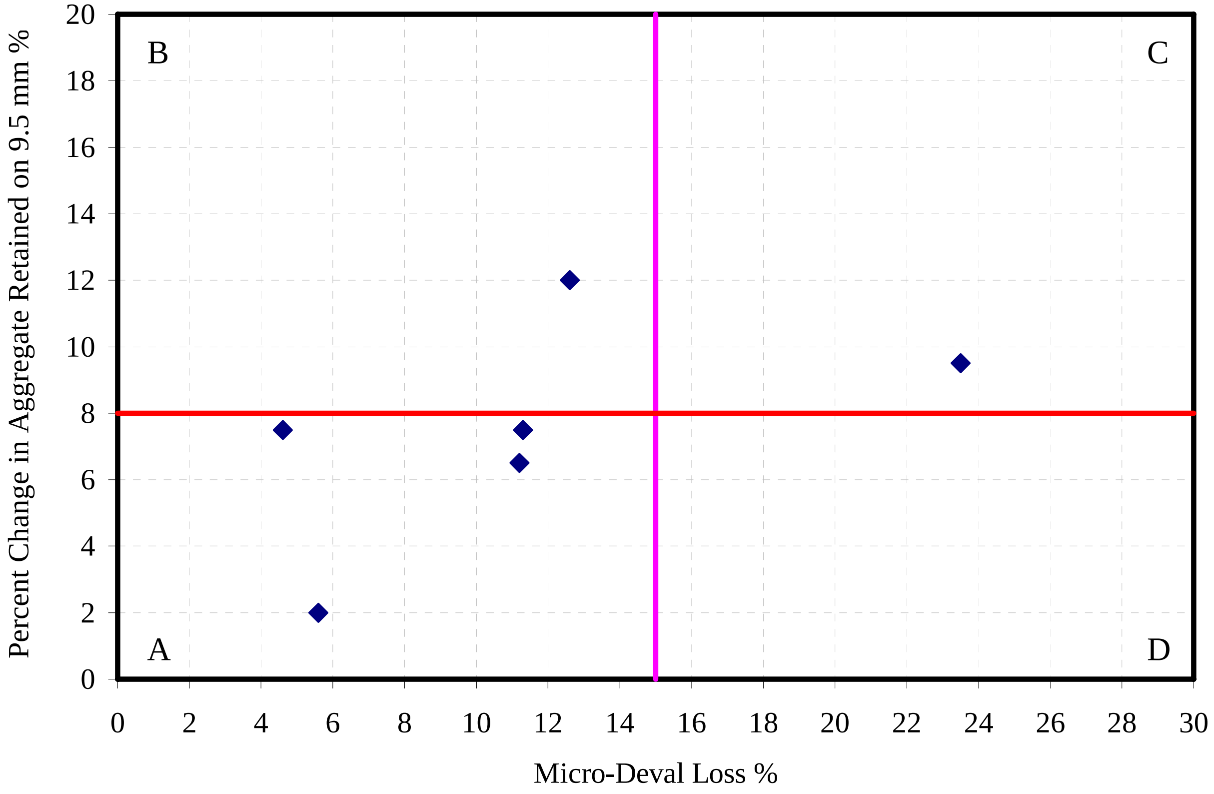


Figure 7: The Relationship between Change in Aggregate Gradation and Micro-Deval Loss.

Both the Micro-Deval test and aggregate gradation analysis cannot capture the change in texture, which is an important aspect of aggregate degradation in SMA. Therefore, the Aggregate Imaging System (AIMS) can also be used to evaluate this aspect of aggregate degradation. For example, the Limestone 1 aggregate experienced the highest loss of texture as evident in Figure 1c. Current research is focusing on establishing the limits in this approach based on evaluation of aggregate gradation in cores from asphalt pavements, and SMA laboratory and field performance.

CONCLUSIONS AND RECOMMENDATIONS

It is recommended to use the weight loss in the Micro-Deval, the change in aggregate shape characteristics, and the change in gradation to evaluate the resistance of aggregate particles to degradation in SMA mixes. The following are the main conclusions of this study:

- The measurement of weight loss in the Micro-Deval combined with the change in gradation due to compaction can be very valuable procedure to evaluate the resistance of aggregates to degradation. Even if aggregates do not meet the allowable weight loss requirements in the Micro-Deval, they can still be used if the change in gradation is minimized to acceptable limits. On the other hand, aggregates that exhibit small weight loss should be evaluated for possible degradation in the mix, and should be avoided if proven to be susceptible for breakage.

- The Aggregate Imaging System (AIMS) can be used to supplement the Micro-Deval results. A decrease in sphericity indicates that the aggregate has the potential to experience particle breakage. AIMS results can also be used to set maximum values for loss of texture in order for the mix to have the necessary friction between particles.

- X-Ray Computed Tomography (CT) is a research tool that was used in this study to confirm the findings from the mechanical analysis of aggregate gradation after compaction. In general, the findings from X-ray CT were consistent with those from the mechanical sieve analysis.

- The Flow number test is a destructive test that measures the number of dynamic loads applied to an asphalt mixture that causes tertiary permanent deformation. However, it may not be an efficient means to test for aggregate degradation. Future research is needed to determine if the Flow number test is capable of testing SMA specimens in both an unconfined and confined condition. Also further study is needed to see if the high asphalt content of SMA specimens has an affect on the result of the flow number.

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REFERENCES

1. Lynn., T.A. Evaluations of Aggregate Size Characteristics in Stone Matrix Asphalt (SMA) and Superpave Design Mixtures. Ph.D Dissertation. Auburn University, 2002
2. Brown, E.R. Experience with Stone Matrix Asphalt in the United States. NCAT Report No. 93-4. National Center for Asphalt Technology, Auburn University, Auburn, Ala., 1993.
3. Xie, H. and D.E. Watson. Determining Air Voids Content of Compacted Stone Matrix Asphalt Mixtures. In Transportation Research Record: Journal of the Transportation Research Board, No. 1891, TRB, National Research Council, Washington D.C., 2004, pp.203-211.
4. Xie, H. and D.E. Watson. Lab Study on Degradation of Stone Matrix Asphalt (SMA) Mixtures. A Paper presented at the 83rd Annual Meeting of the Transportation Research Board, TRB, National Research Council, Washington D.C., 2004.
5. Brown, E.R., J.E. Haddock, R.B. Mallick, and T.A. Lynn. Development of a Mixture Design Procedure for Stone Matrix Asphalt (SMA). NCAT Report No. 97-3. National Center for Asphalt Technology, Auburn University, Auburn, Ala., 1997.

6. Brown, E.R. and J.E. Haddock (1997). A Method to Ensure Stone-on-Stone Contact In Stone Matrix Asphalt Paving Mixtures, NCAT Report No. 97-2. National Center for Asphalt Technology, Auburn University, Auburn, Ala., 1997.
7. Watson, D., E. Masad, K.A. Moore, K. Williams, and L.A. Cooley. Verification of VCA Testing to Determine Stone-On-Stone Contact of HMA Mixtures. In Transportation Research Record: Journal of the Transportation Research Board,, No. 1891 TRB, National Research Council, Washington D.C., 2004, pp. 182-190.
8. Brown, E.R., and R.B. Mallick. Stone Matrix Asphalt-Properties Related to Mixture Design. NCAT Report No. 94-2. National Center for Asphalt Technology, Auburn University, Auburn, Ala., 1994.
9. Brown, E.R., and R.B. Mallick. Laboratory Study on Draindown of Asphalt Cement in Stone Matrix Asphalt. In Transportation Research Record: Journal of the Transportation Research Board, No. 1513, TRB, National Research Council, Washington D.C., 1995, pp.25-38.
10. Masad, E. (2004). X-Ray Computed Tomography of Aggregates and Asphalt Mixes. In Materials Evaluations Journal, Vol. 62, No. 7, 2004, pp.775 – 783.
11. AASHTO Provisional Standards. American Association of State Highway and Transportation Officials, Washington D.C., 2001
12. Al-Rousan, A., E. Masad, L. Myers, and C. Speigelman. A New Methodology for Shape Classification of Aggregates. In Transportation Research Record: Journal of the Transportation Research Board, TRB, National Research Council, Washington D.C., (Accepted for Publication, 2005).
13. Masad, E. The Development of a Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties. *NCHRP-IDEA Project 77 Final Report*, Transportation Research Board, Washington, D.C.2003.
14. Dessouky, S., E. Masad, and F. Bayomy. Prediction of Hot Mix Asphalt Stability Using the Superpave Gyratory Compactor. In Journal of Materials in Civil Engineering, ASCE, Vol. 16, No. 6, 2004, pp. 578 – 587.
15. Tashman, L., E. Masad, B. Peterson, and H. Saleh. Internal Structure Analysis of Asphalt Mixes to Improve the Simulation of Superpave Gyratory Compaction to Field Conditions. In Journal of the Association of Asphalt Paving Technologists, Vol. 70, 2001 pp.605-645.

16. Witczak, M.W., K. Kaloush, T. Peillinen, M.E. Basyouny, and H.V. Quintus. Simple Performance Test for Superpave Mix Design, NCHRP Report No. 465, 2002.