NCAT Report 13-09

EFFECT OF FRICTION AGGREGATE ON HOT MIX ASPHALT SURFACE FRICTION

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ABSTRACT

The objective of the study was to use a laboratory conditioning and testing protocol developed at the National Center for Asphalt Technology (NCAT) to better understand the influence of friction aggregate in a typical gravel-limestone 9.5 mm hot mix asphalt surface mixture and in an ultra-thin maintenance mixture placed by the Mississippi Department of Transportation. The agency used this laboratory study to quickly evaluate alternative friction aggregate sources by replacing a portion of the primary aggregate with an alternative friction aggregate source. The evaluation compared the friction performances of the mixtures with the alternative friction aggregates after identical conditioning (polishing) with the NCAT Three Wheel Polishing Device and testing with the Dynamic Friction Tester and Circular Texture Meter. The 9.5 mm mixture demonstrated better friction performance with either 33% or 60% slag added to the mixture in place of crushed gravel. The use of 60% granite made a marginal improvement, but the 33% granite did not improve the friction. The ultra-thin maintenance mixture demonstrated better friction performance with either 25% or 50% crushed gravel added to the mixture in place of limestone.

CHAPTER 1 BACKGROUND

The Mississippi Department of Transportation (MDOT) was looking for methods to improve surface friction without significantly increasing the cost of paving. The common approach requires building costly field test sections and an extended period of time to monitor the impact of traffic polishing. Agencies are then liable for exposing traffic to surfaces with deficient friction. The objective of this study was to use a laboratory conditioning and testing protocol developed at the National Center for Asphalt Technology (NCAT) to better understand the influence of type and amount of friction aggregate in a typical gravel-limestone 9.5 mm hot mix asphalt (HMA) surface mixture and in an ultra-thin maintenance mixture placed by MDOT. There are other characteristics of an asphalt mixture that can influence pavement surface safety, such as surface macro-texture, but are not a part of this study. MDOT can use the results of this laboratory study to quickly evaluate alternative friction aggregate sources based on the portion of the primary aggregate replaced with an alternative friction aggregate source. This evaluation will compare the friction performance of the mixtures with the alternative friction aggregates after identical conditioning (polishing) with the NCAT Three Wheel Polishing Device (TWPD). With a better understanding of the impact of friction aggregate on HMA surface friction, MDOT can confidently adopt surface mixture specifications that continue to maintain a high standard of friction performance using a cost-effective amount of required and costly friction aggregate.

The NCAT TWPD, shown in Figure 1, offers a practical and technically sound controlled evaluation of asphalt mixture surface friction performance. The test protocol with the TWPD provides a direct comparison of alternative aggregates and gradation proportions to a mixture with known friction performance, but the NCAT TWPD evaluation is not a true field traffic examination of performance.

FIGURE 1 NCAT Three Wheel Polishing Device

CHAPTER 2 WORK PLAN

The study was accomplished using the following series of tasks.

- Task 1 – Select Materials: MDOT provided NCAT with the aggregate sources and job-mix formula (JMF) of a 9.5 mm control mixture and an ultra-thin control mixture. MDOT also provided the source and gradation of two alternative friction aggregates, slag and granite. NCAT determined the amount of each aggregate required to build test slabs in Task 2. The study did not measure the properties of the aggregates or mixtures selected by MDOT.
- Task 2 – Prepare Test Slabs: NCAT used the two MDOT approved control mix designs to prepare eight mixtures. The combination of materials is described later in more detail. For the 9.5 mm control mixture, the study planned to substitute 30% and 60% of the coarse aggregate with a comparable proportion and gradation of the coarse aggregate from two alternative friction aggregate sources. For the ultra-thin control mixture, the study planned to substitute 30% and 60% of the total aggregate with a comparable proportion of one alternative aggregate source. The laboratory prepared three replicate slabs of each mix compacted to 7% air voids.
- Task 3 – Test Slabs: NCAT tested two replicate slabs of each mix with the dynamic friction tester (DFT) and circular texture meter (CTM) after conditioning (polishing) each slab with the NCAT TWPD to create a surface friction performance history curve for each mix. Tests were conducted at 0, 500, 1000, 2000, 5000, 10,000, 20,000, 40,000, 60,000 and 100,000 cumulative TWPD polishing cycles. The third replicate slab was retained as a referee test if the two slabs did not provide similar results.
- Task 4 – Analyze Results: NCAT analyzed the data for testing quality and determined the impact of the type and amount of friction aggregate on the friction performance of the mixture surface.

CHAPTER 3 RESEARCH APPROACH

Materials

The 9.5 mm control mixture (Mix 1) was a 9.5 mm NMAS gradation and the primary aggregate was crushed gravel. For this study, the portion of the crushed gravel defined as friction aggregate was selected to be the amount retained above the No. 8 sieve. The aggregate retained above the No. 8 sieve represents approximately 60% of the total aggregate weight and would be approximately 50% of the exposed aggregate surface. For Mix 1, 50% of the aggregate blend was crushed gravel retained above the No. 8 sieve.

The gradation of the alternate friction aggregates was modified to match the crushed gravel to avoid preparing a separate JMF for each mixture. After reviewing the modified gradation blends, the actual substitutions were 33% and 60% by weight of total aggregate. Specific to the friction aggregate, the substitution replaced 50% and 100% of the crushed gravel above the No. 8 sieve based on a volume substitution for the slag aggregate (Mix 1.1 and 1.2). Volume substitution was used to account for the higher aggregate specific gravity of the slag.

The substitution with granite applied the same 33% and 60% weight-based substitution (Mix 1.3 and 1.4) established for the substitution with the slag. Since the specific gravity of granite is similar to the specific gravity of gravel, the volume substitution was slightly different from the slag for the coarse crushed gravel.

The primary aggregate in the ultra-thin mix (Mix 2) was crushed limestone for this study, but other aggregate types are also used in the State. The aggregate substitution for the ultra-thin mix was based on total aggregate, not based on aggregate above the No. 8 sieve. The gradation of the alternative friction aggregate, crushed gravel, was not modified. For this study, 25% and 50% of the control limestone was replaced with the crushed gravel (Mix 2.1 and 2.2). There was no significant difference in a weight-based and volume-based substitution for this mixture because the aggregate specific gravities are similar.

Tables 1 and 2 show a summary of proportions of each aggregate blend. Figures 2, 3 and 4 show the mixture gradations.

The asphalt binder contents given in the JMFs for the 9.5 mm mix (5.5%) and ultra-thin mix (5.8%) were used for all mixtures prepared in this study. All mixes used a PG 67 -22 binder. Since this is a friction study, separate mix designs were not prepared for each mixture with alternative friction aggregate, as refining the binder content is not critical to the friction performance of each mixture.

TABLE 1 Summary of Mix 1 Components

	% of Mix (by total aggregate weight)				
Mix Designation	1.0	1.1	1.2	1.3	1.4
Material	Control	33% Slag	60% Slag	33% Granite	60% Granite
Cr GVL +#8 Sieve	50.4	22.5		22.5	
Cr GVL -#8 Sieve	14.8	13.2	11.9	13.2	11.9
LMS 820 +#8 Sieve	8.1	7.2	6.5	7.2	6.5
LMS 820 -#8 Sieve	15.7	14.0	12.7	14.0	12.7
Coarse Sand +#8 Sieve	0.5	0.5	0.4	0.5	0.4
Coarse Sand -#8 Sieve	9.5	8.5	7.7	8.5	7.7
Hyd. Lime	1.0	0.9	0.8	0.9	0.8
Slag +#8 Sieve		33.2	60.0		
GRN +#8 Sieve				33.2	60.0
	% of Mix (by total aggregate volume)				
Mix Designation	1.0	1.1	1.2	1.3	1.4
Material	Control	33% Slag	60% Slag	33% Granite	60% Granite
Cr GVL +#8 Sieve	51.6	25.8		23.5	
Cr GVL -#8 Sieve	15.1	15.1	15.1	13.7	12.6
LMS 820 +#8 Sieve	7.6	7.6	7.6	6.9	6.4
LMS 820 -#8 Sieve	14.7	14.7	14.7	13.4	12.3
Coarse Sand +#8 Sieve	0.5	0.5	0.5	0.5	0.4
Coarse Sand -#8 Sieve	9.4	9.4	9.4	8.5	7.8
Hyd. Lime	1.1	1.1	1.1	1.0	0.9
Slag +#8 Sieve		25.8	51.6		
GRN +#8 Sieve				32.5	59.6

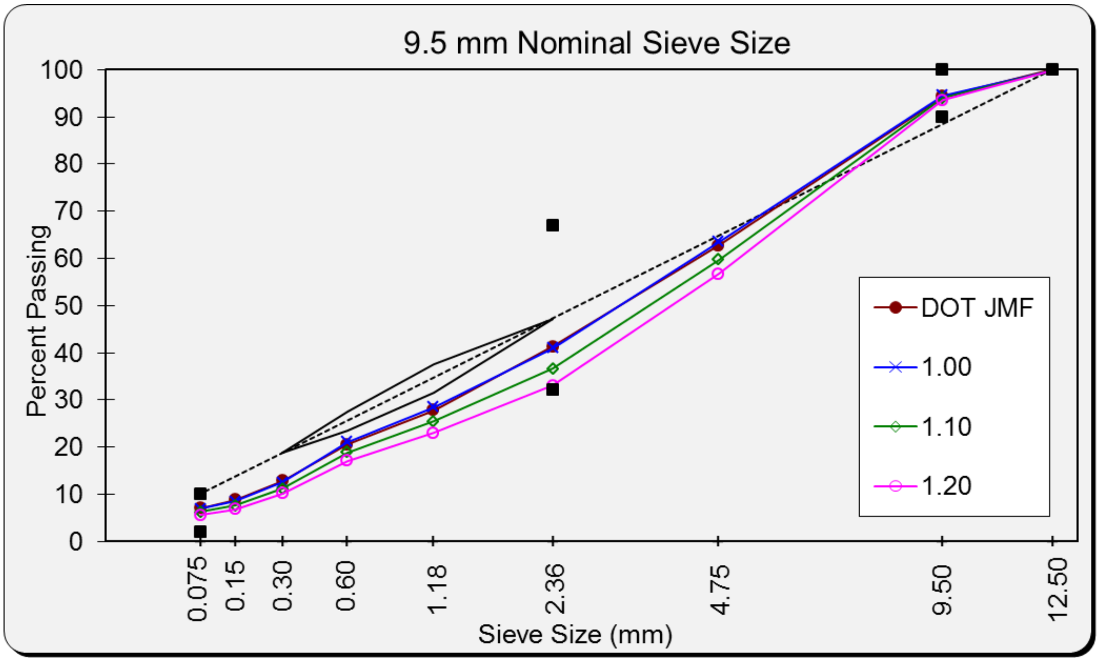


FIGURE 2 9.5 mm mixture gradations with slag substitution

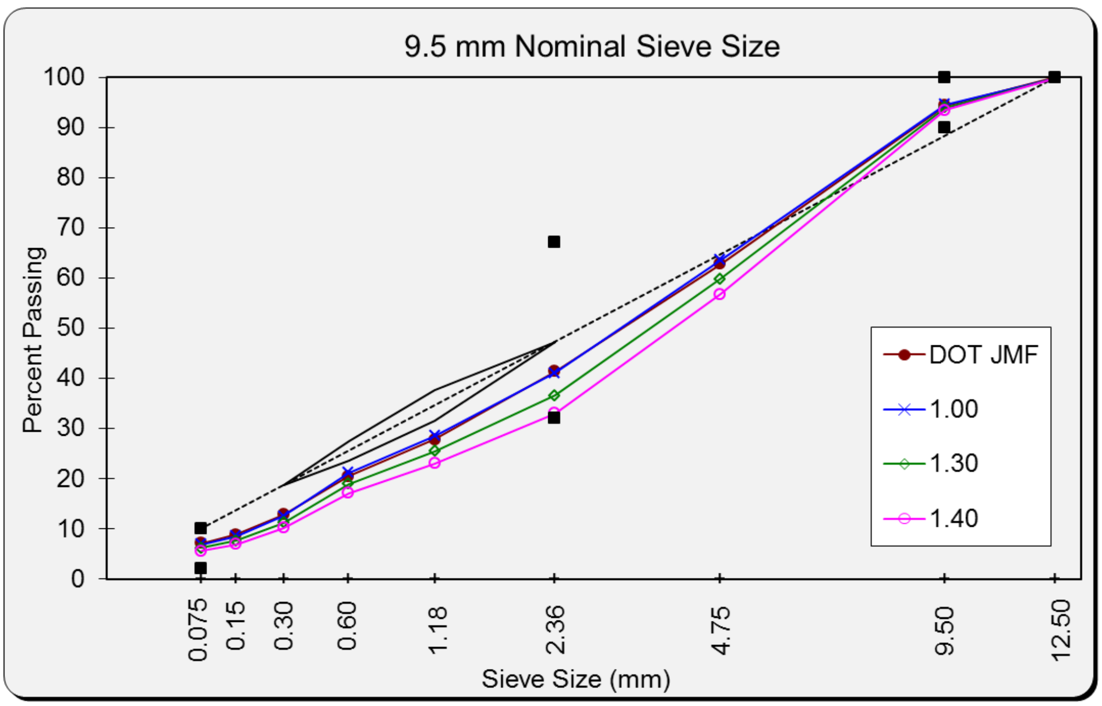


FIGURE 3 9.5 mm mixture gradations with granite substitution

TABLE 2 Summary of Mix 2 Components

	% of Mix (by total weight of aggregate)		
Mix Designation	2.0	2.1	2.2
Material	Control	25% Cr. Gravel	50% Cr. Gravel
810 LMS	56.0	45.0	20.0
89 LMS	14.0	0.0	0.0
Coarse Sand	10.0	10.0	10.0
Manuf. Sand	19.0	19.0	19.0
Hydrated Lime	1.0	1.0	1.0
-1/2 Cr. Gravel		25.0	50.0
	% of Mix (by total volume of aggregate)		
Mix Designation	2.0	2.1	2.2
Material	Control	25% Cr. Gravel	50% Cr. Gravel
810 LMS	56.3	44.1	19.2
89 LMS	13.6	0.0	0.0
Coarse Sand	10.2	9.9	9.7
Manuf. Sand	18.7	18.2	17.8
Hydrated Lime	1.2	1.2	1.1
-1/2 Cr. Gravel		26.6	52.1

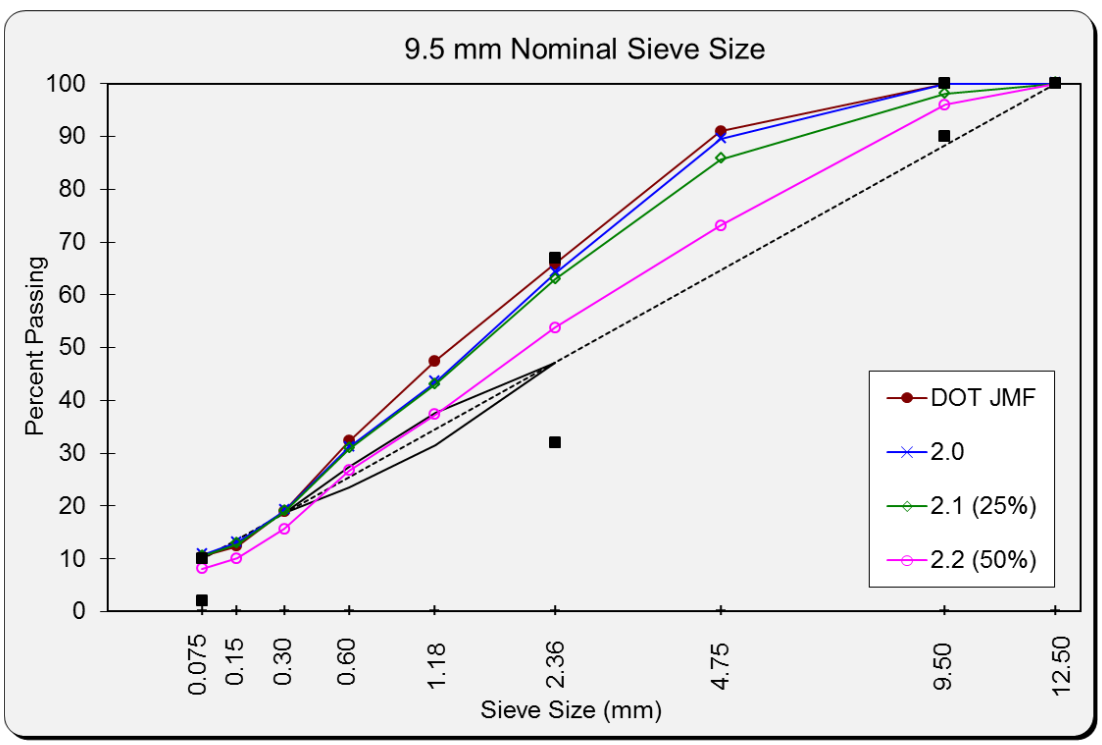


FIGURE 4 Ultra-thin maintenance mixture gradations with crushed gravel substitution

Test Protocol

The test slabs used for this laboratory study were prepared at the NCAT laboratory. Three replicate slabs were made for each of the eight mixtures. Using the measured maximum specific gravity (G_{mm}) of each mixture, the lab prepared the correct amount of mixture to achieve a 2-inch thick slab at 7% air voids. A slab compactor was used to compact each slab independently. The bottom of the slab had a smooth surface which was used for friction testing. The top of the slab had a slight undulating surface from the steel plates used as part of the compaction process and is not suitable for friction testing. These surface characteristics are consistent with slabs prepared with the slab compaction process.

The laboratory protocol for the NCAT TWPD is a developing procedure. The NCAT TWPD was developed at NCAT in a 2004-2006 study[1]. A second study to refine the test parameters and correlate the laboratory results to field testing was completed in 2010[2]. The TWPD is designed to uniformly condition (polish) the surface of the test slab using three rubber tires that rotate on a wet surface at 60 rpm with 50 psi tire pressure and 91-lb gross carriage weight. The conditioned surface is tested for friction resistance after various numbers of polishing cycles using ASTM test methods E 1911 and E 2157, commonly called the Dynamic Friction Tester (DFT) and Circular Texture Meter (CTM), respectively.

The DFT is a small portable device that measures friction with three rubber pads placed on the bottom of a rotating disk. The device measures the change in friction resistance as the pads slide on top of the asphalt mixture surface. A friction value (Fn) is a unitless value of force resisting movement related to the total force applied. Friction values are recorded for moving speeds of 20, 40 and 60 kph and reported as DFT(20), DFT(40) and DFT(60), respectively. There is no accepted correlation between DFT values and conventional skid trailer (ASTM E 274) measurements, but a general approximation for comparing these values is DFT(60) x 100 = SN40R, where SN40R denotes skid number measured at 40 mph with a ribbed tire. One NCAT study using results from the NCAT Pavement Test Track showed a correlation of SN64R (metric) = -19.43 + (1.36 x DFT(60) x 100).

The CTM is a small portable device that measures the texture of the surface with a laser mounted on a rotating arm. The device measures the profile of the asphalt surface along a circular path (same path as the DFT) to within 0.01 mm height. The recorded measurement is the mean profile depth (MPD) which is the average difference between the peaks and valleys of the surface texture. This is comparable to the MPD measured by the sand patch method (ASTM E 965).

For the evaluation of the Mississippi surface mixtures, the following test protocol was used.

[1] Vollor, T., and D. Hanson. *Development of Laboratory Procedure for Measuring Friction of HMA Mixtures Phase I*. NCAT Report 06-06, National Center for Asphalt Technology, Auburn, Alabama, 2006.
[2] Erukulla, S. *Refining a Laboratory Procedure to Characterize Change in Hot-Mix Asphalt Surface Friction*. MS Thesis. Auburn University, Auburn, Alabama, 2011.

- For each set of materials being evaluated, three replicate slabs were created. Two of the three slabs were selected for testing and randomly assigned to one of two TWPD devices located in the NCAT laboratory. After testing, the results were checked to determine if the measurements were consistent. If the measurements were found to be consistent, then the third slab was not tested.
- The TWPD tires were replaced at the beginning of the study. The tires are inspected after each round of testing, but no excessive wear was observed over the course of the study.
- Each CTM test included five replicate measurements of MPD.
- Each DFT test included three replicate friction measurements. DFT rubber slider pads were replaced after 45 measurements. Each set of rubber slider pads was used for more than the twelve measurements specified by the ASTM standard based on minimal wear during the testing cycles.
- The sequence of DFT-CTM testing and NCAT TWPD conditioning was as follows:
    1. Six ultra-thin maintenance mixture slabs were divided between the two TWPD devices and randomly ordered.
    2. Initial CTM and DFT testing was performed on each slab.
    3. Each slab was conditioned for 500 cycles.
    4. CTM and DFT testing was performed on the group of conditioned slabs.
    5. TWPD conditioning was continued for a total of 100,000 cycles. CTM and DFT tests were performed after 1,000, 2,000, 5,000, 10,000, 20,000, 40,000, 60,000 and 100,000 cycles. The slabs were randomly re-ordered for each cycle of conditioning and testing.
    6. The process was repeated for the ten 9.5 mm mixture slabs.

CHAPTER 4 TEST RESULTS

The measured DFT and CTM results of the laboratory study are presented as graphs in the appendix of this report. Each page of the appendix represents the result for testing two slabs of each test mixture. The results of the two sets of mixes (9.5 mm and ultra-thin maintenance) are discussed independently, as described in the objectives for this study.

Analysis – Mix 1 (9.5 mm)

The laboratory testing for Mix 1 consisted of 100 sets of DFT and CTM measurements (10 cycle periods x 2 slabs x 5 mixtures). Only the Fn recorded as DFT(20), DFT(40) and DFT(60) were considered in the analysis. The DFT(0) and DFT(80) results were not used in the analysis as they typically have much higher variability than the intermediate speeds.

The first level of data quality analysis examined the three replicates of DFT measurements to make sure that the replicate friction values for each slab were providing repeatable numbers. The histogram of DFT three-replicate ranges ($DFT(kph)_{high}$ – $DFT(kph)_{low}$) for all 300 recorded DFT data sets is shown in Figure 5. The ASTM E1911 standard precision states that DFT results have a standard deviation of 0.044 to 0.038 for eight replicate tests for the recorded friction at 30 km/h and 60 km/h, respectively. Testing for this study was based on three replicates (not eight replicates), so the allowable range between replicate tests would be greater than 0.12 (3 standard deviations x 0.040). Figure 5 shows that 83% of the replicate tests for Mix 1 had range values below 0.040 and 97% of the range values fell below 0.12. Eight test results had ranges exceeding the 0.12 limit with the two largest range values being 0.331 and 0.247. All eight ranges that exceeded the allowable limit were DFT(20) tests measured at 0 TWPD cycles. The first replicate test at 0 TWPD was substantially higher than the other two replicates. These values were not removed from the data because they do not impact the analysis regarding long-term friction performance.

The CTM MPD measurements were also examined to determine if the five replicate results for each slab met repeatability requirements. The histogram of ranges for all of the data sets is shown in Figure 6. The ASTM E2157 standard precision states that the CTM MPD has a standard deviation of 0.03 for eight replicate tests. Testing for this study was based on five replicates, so the measurement precision would have an allowable range of 0.117 based on ASTM C670 criteria. Figure 6 shows that 98% of the tests had a range of 0.12 or below and only two of the ranges were above 0.12 with values of 0.13 and 0.15. The five replicate values for all of the data sets were within two standard deviations of the mean, so there were no outliers.

A second level of quality control analysis determined if the two TWPDs generated similar results. If the results were not similar, or if there was a bias found between the two devices, the results were analyzed for potential influence on the results. For this analysis, the two TWPD devices were designated Round-1 (new TWPD) and Round-2 (old TWPD). The average DFT(40) results from each test cycle of TWPD in Round-1 testing were compared to the same results of Round-2 testing. The differences between the devices (Round-1 values minus Round-2 value) were combined into a histogram in Figure 7 to show the distribution of slab test differences for DFT(40). Overall, the average difference was a DFT(40) delta of -0.011 with a standard deviation of 0.039. Only one difference value was greater than two standard deviations from the average difference. Figure 7 shows that the difference values are normally distributed around 0.0, with no bias to the positive or negative. The histograms for DFT(20) and DFT(60) are not shown, but were found to be similar to those of DFT(40). This analysis was sufficient to conclude there was no bias between the slabs tested in Round-1 and Round-2 and that DFT testing the third slab was not necessary.

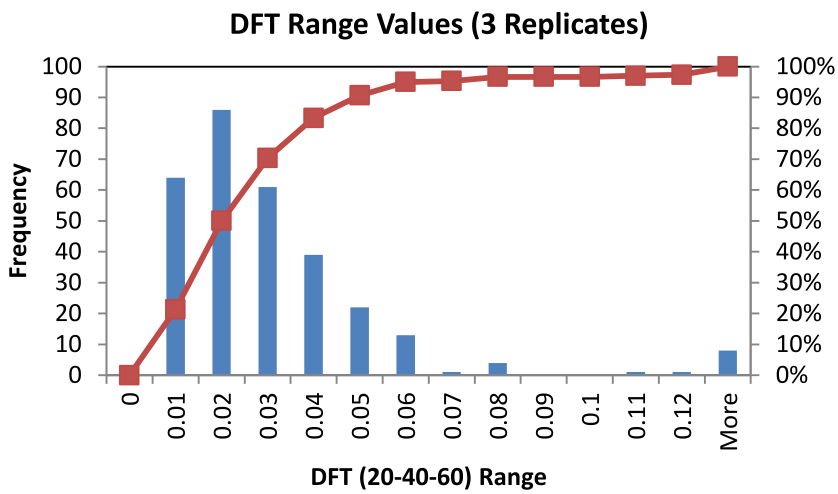


FIGURE 5 DFT data quality control for Mix 1

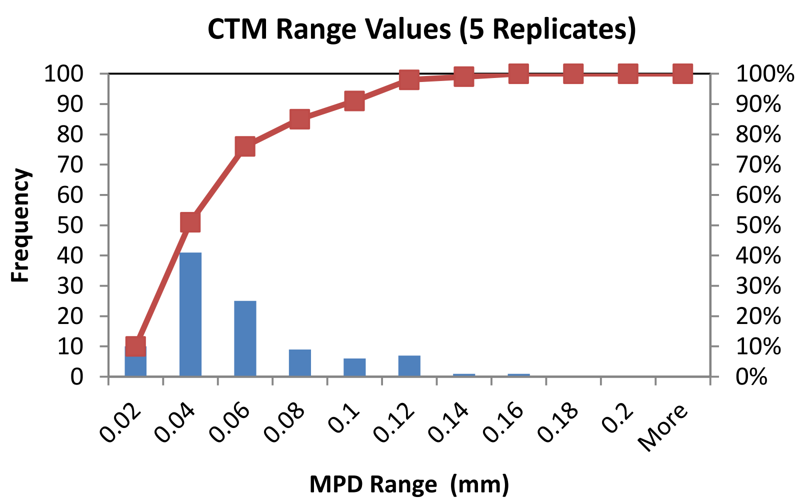


FIGURE 6 CTM data quality control for Mix 1

A similar analysis was done for CTM MPD test results between the two TWPD with results shown in Figure 8. The MPD values were more variable than the DFT results and showed only slight bias between devices, with the Round-2 TWPD giving higher MPD values than the Round-1 TWPD. The bias is most likely related to the surface texture created during the fabrication of each slab. While the MPD differences are not normally distributed, the actual differences are relatively small and did not appear to influence the friction values.

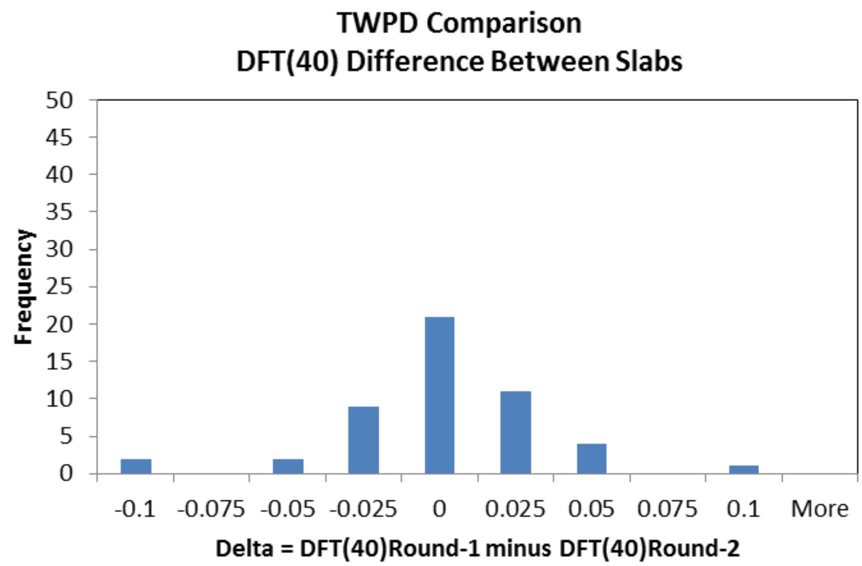


FIGURE 7 Mix 1 slab replicate comparison for DFT(40) values

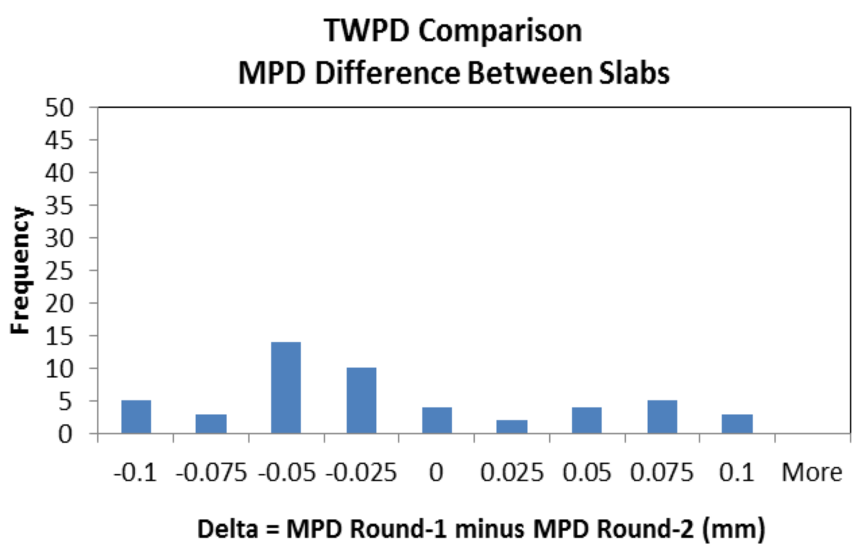


FIGURE 8 Mix 1 slab replicate comparison for CTM MPD

The use of the TWPD and DFT/CTM for surface friction comparisons is a developing test protocol. There are no "standards" or thresholds for CTM and DFT values. This test protocol provides the ability to make relative comparisons of the performance between different surfaces. It will be the responsibility of the governing agency to determine what an acceptable threshold should be. This study compared a control mixture and four alternative mixtures using the laboratory friction performance histories. Figures 9 and 10 show the change in DFT(40) friction number and CTM MPD compared to the control mix for each of the four alternative mixtures evaluated. Each data point is the average of the replicate test measurements. Table 3 shows a numerical comparison of the Fn and MPD results at 2,000, 40,000, and 100,000 cycles.

Figure 9 shows that DFT(40) values for all of the alternative mixtures, except for the 60% slag mix, showed a small improvement over the control mix in early conditioning cycles. The 60% slag mix showed a slight reduction in early conditioning. After 100,000 cycles of polishing, three of the four alternative mixtures showed improvement in Fn relative to the control. The 60% slag mix had the highest terminal Fn. Only the 33% crushed granite mix showed a slight decrease in Fn after 100,000 cycles compared to the control mix. The results for DFT(20) and DFT(60) were similar to DFT(40) and therefore are not shown.

In Figure 10, the control mix slabs and the 60% slag slabs both showed a sharp increase in MPD at 100,000 cycles as compared to previous cycles. The 33% slag slabs had a similar increase at 60,000 cycles. This behavior is not typical and may indicate a testing error or higher test variation. For example, looking back at the raw MPD test data for the control slab after TWPD Round-2 100,000 cycle conditioning appears to be a testing error, but 33% slag data shows normal testing variation. These values are shown on the plots using open markers instead of the filled markers to indicate that they are suspicious values. In general, the CTM MPD values shown in Figure 10 ranked the materials in relation to the coarseness of the gradation. As the gradation got coarser, the MPD measurements increased. This is the expected trend in test results.

TABLE 3 Numerical Comparison of Results for Mix 1

	DFT(40) Fn			CTM MPD, mm		
Mix 1	2,000 Cycles	40,000 Cycles	100,000 Cycles	2,000 Cycles	40,000 Cycles	100,000 Cycles
Control	0.48	0.39	0.36	0.30	0.33	*0.41**
33% Slag	0.50	0.43	0.40	0.40	0.39	0.43
60% Slag	0.47	0.43	0.42	0.45	0.48	0.50
33% Granite	0.50	0.40	0.35	0.41	0.39	0.39
60% Granite	0.50	0.42	0.39	0.49	0.53	0.53

*Suspect data

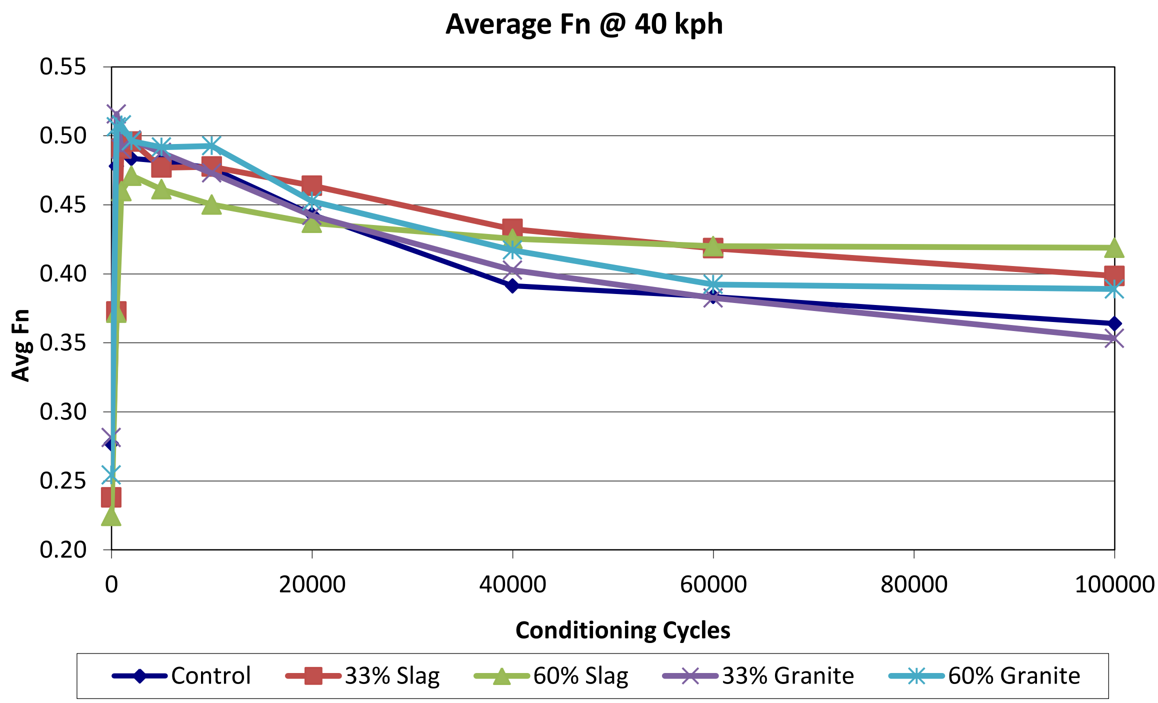


FIGURE 9 Average Fn at DFT(40) for Mix 1

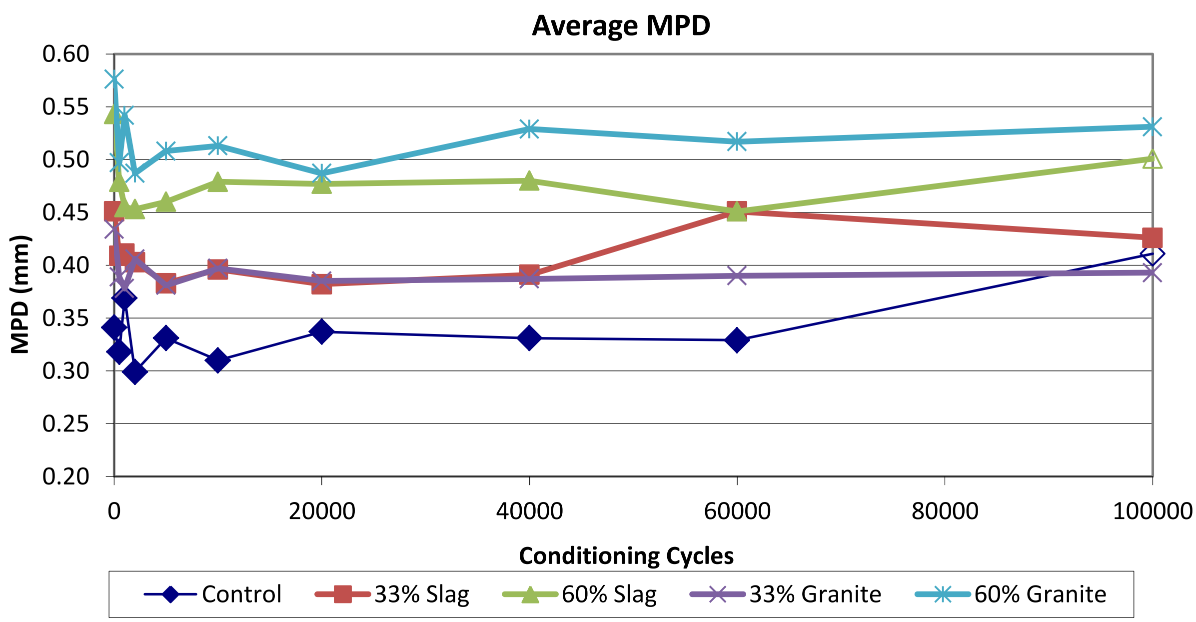


FIGURE 10 Average MPD for Mix 1

Analysis – Mix 2 (Ultra-thin maintenance)

The laboratory testing for Mix 2 consisted of 60 sets of DFT and CTM tests (10 cycle periods x 2 slabs x 3 mixtures). As before, only the DFT measurement speeds of 20, 40, and 60 kph were used in the analysis. Figure 11 shows the histogram of DFT three-replicate measurement ranges from all 180 recorded DFT measurements. Using the same maximum allowable range as for Mix 1, the figure shows that 89% of the DFT ranges fell below 0.04 while 97% of the range values fell below 0.12. Six DFT range values were greater than 0.12 with the largest two values being 0.308 and 0.327. Similar to Mix 1, all of the range values that exceeded the allowable range were due to the first replicate result for the DFT(20) at 0 TWPD cycles.

Figure 12 shows the histogram of ranges for all of the replicate CTM measurements. 98% of the replicate measurements had range values less than the allowable 0.12 range. Only one range value (0.13) exceeded the allowable range. This value was not considered to be an outlier as it was within two standard deviations of the mean value.

The slabs for this mix were also evaluated to determine if the two TWPD gave similar results. In Figure 13 the frequency distribution is plotted for the difference in DFT values among the two slabs. Likewise, the histogram in Figure 14 represents the differences in CTM results for the two slabs. Both sets of test results show a bias in the data, with the Round-1 TWPD giving higher DFT and CTM results than the Round-2 device. Since the Mix 1 CTM results showed only a very slight bias toward the Round-2 TWPD, the implied bias in the rate of polishing between the devices for Mix 2 is more likely a reflection of differences in slab preparation. Since this is an ultra-thin mixture with a low surface texture (less than 0.30 mm MPD), these small differences in macro-texture (delta MPD less than 0.1 mm) of the surface are not a critical factor. All values are typical of fine dense-graded mixtures.

Figures 15 and 16 show the DFT friction histories and CTM MPD histories for each of the three mixtures evaluated. Each data point is the average of the replicate test measurements. Table 4 shows the numerical comparison of the alternative mixtures to the control. For Mix 2, the crushed gravel at both percentages improved the Fn of the alternative mixtures compared to the control. The improvement was slightly more pronounced at the higher gravel content. The CTM results for this mix had a similar increase in MPD with increased coarseness of the gradation. Overall, the 25% crushed gravel gradation was similar to the control and measured similar MPD values. The 50% crushed gravel was significantly coarser and reflected higher MPD values.

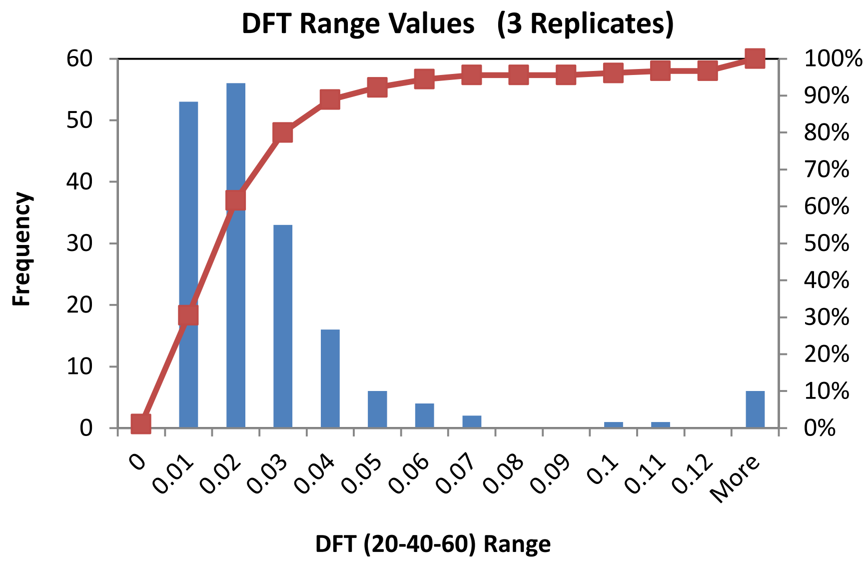


FIGURE 11 DFT data quality control for Mix 2

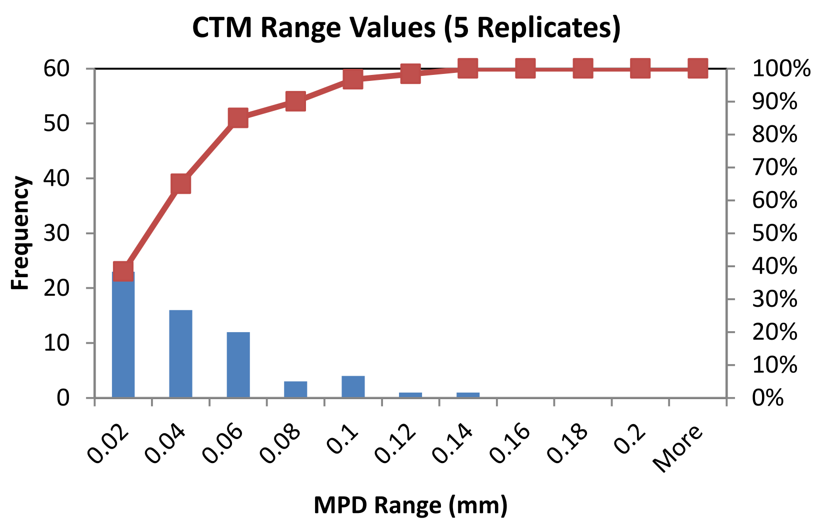


FIGURE 12 CTM data quality control for Mix 2

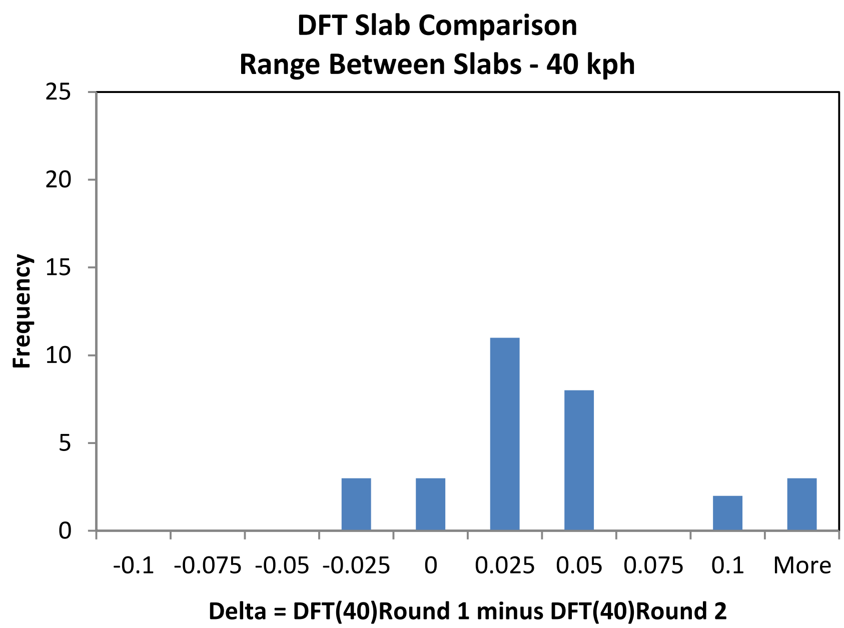


FIGURE 13 Mix 2 slab replicate comparison for DFT(40) values

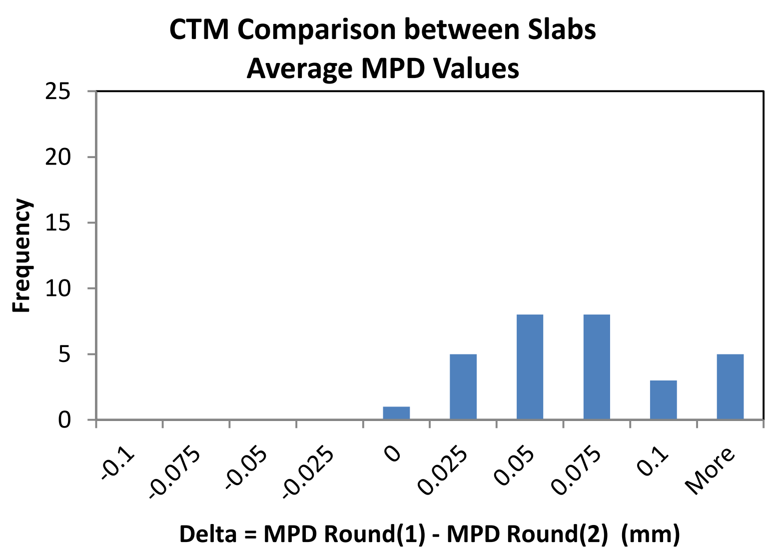


FIGURE 14 Mix 2 slab replicate comparison for CTM MPD

TABLE 4 Numerical Comparison of Results for Mix 2

	DFT(40) Fn			CTM MPD, mm		
HFS	2,000 Cycles	40,000 Cycles	100,000 Cycles	2,000 Cycles	40,000 Cycles	100,000 Cycles
Control	0.40	0.31	0.27	0.21	0.21	0.22
25% Crushed Gravel	0.43	0.36	0.31	0.23	0.20	0.24
50% Crushed Gravel	0.46	0.38	0.34	0.28	0.26	0.28

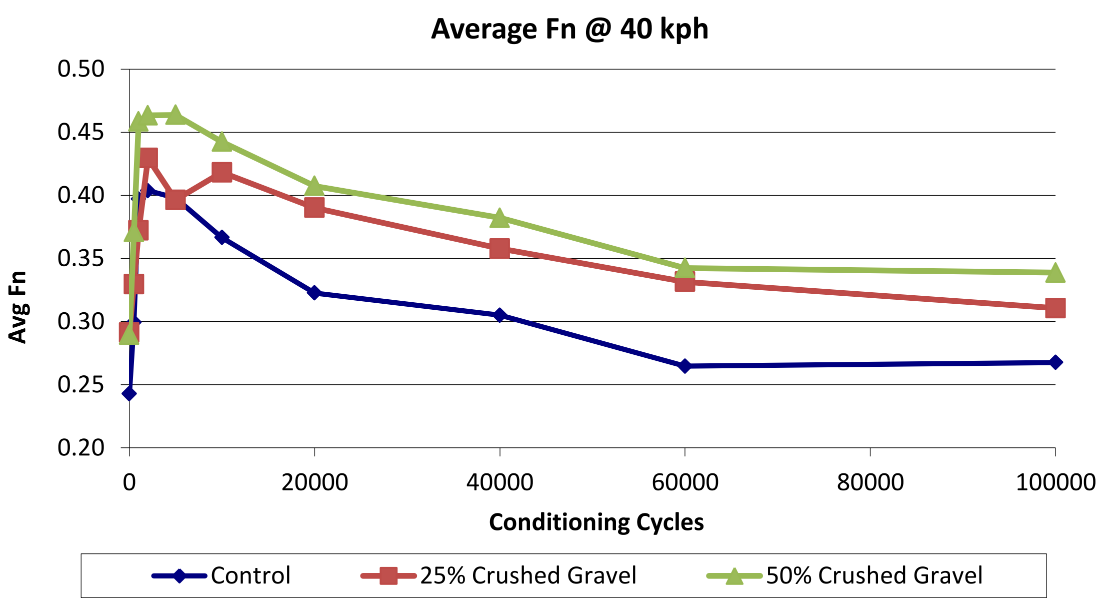


FIGURE 15 Average Fn @ 40 kph for Mix 2

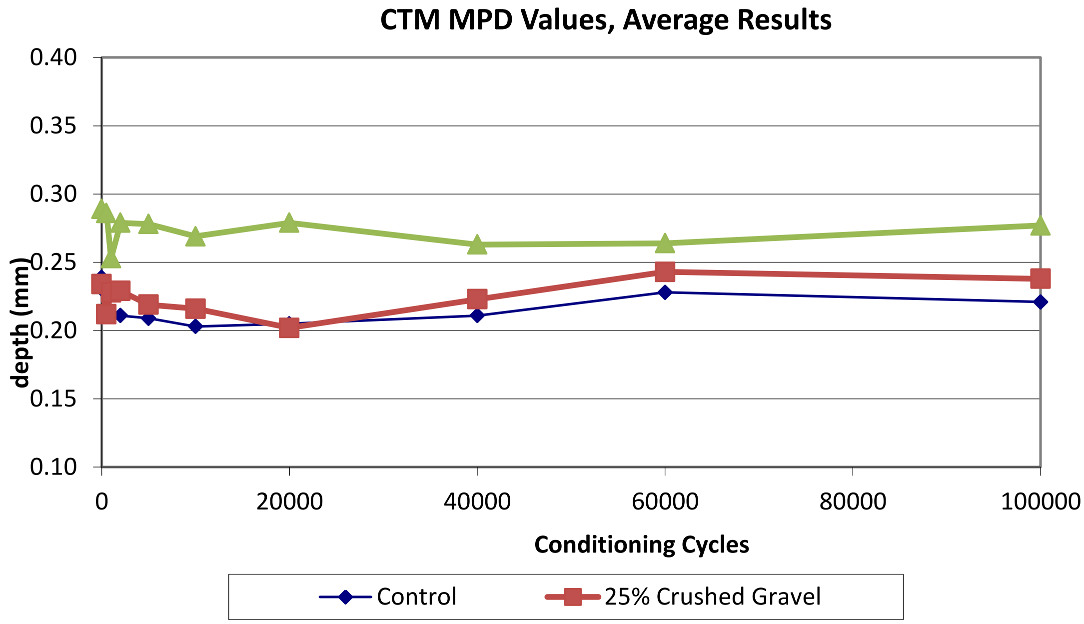


FIGURE 16 Average MPD for Mix 2

CHAPTER 5 CONCLUSIONS AND SUMMARY

Conclusions

The following conclusions are based on the results of the NCAT TWPD laboratory study of two Mississippi DOT control surface mixtures compared to study mixtures with alternative friction aggregate.

1. The gradations for the mixtures with the alternative friction aggregates are slightly coarser than the control mixture. The CTM results show a marginal increase in macrotexture, which would have a very small influence on DFT friction measurements.
2. The replicate DFT and CTM test data for all mixes was of acceptable quality. The range of replicate testing met or exceeded the precision of the test methods.
3. The 9.5 mm mixture (Mix 1) results showed no bias in DFT results between TWPD devices and only a slight bias in CTM with the Round-2 device giving slightly higher MPD results than the Round-1 device. The ultra-thin maintenance mixture (Mix 2) results showed a definite bias with higher DFT and CTM values from the Round-1 TWPD. The DFT bias follows the difference in surface texture MPD. In all cases the DFT and CTM values ranked the same between mixtures, so the average of the paired slabs is a valid comparison.
4. For the 9.5 mm mixture, the long-term friction performance was improved by replacing a portion of the aggregate with 33% slag and 60% slag. After 100,000 cycles, the 60% slag mix retained the highest DFT Fn of all the alternative materials. The CTM MPD results correlated with the change in the gradation. As the gradation became coarser, the MPD values increased. There was no change in MPD as the amount of TWPD conditioning increased.
5. For the 9.5 mm mixture, the substitution of 60% crushed granite improved the long-term friction performance compared to the control. The 33% crushed granite slabs had performance similar to the control. The 60% crushed granite retained higher Fn values than the control throughout the test. The CTM MPD results correlated with the change in the gradation. As the gradation became coarser, the MPD values increased. There was no change in MPD as the amount of TWPD conditioning increased.
6. For the ultra-thin maintenance mixture, the crushed gravel gave improved DFT Fn values compared to the control. The 50% crushed gravel improvement was greater than the 25% crushed gravel. The CTM MPD results correlated with the change in the gradation. As the gradation became coarser, the MPD values increased. Specifically, the 50% crushed gravel mixture was coarse compared to the control and 25% gravel mixes. There was no change in MPD as the amount of TWPD conditioning increased.

Summary

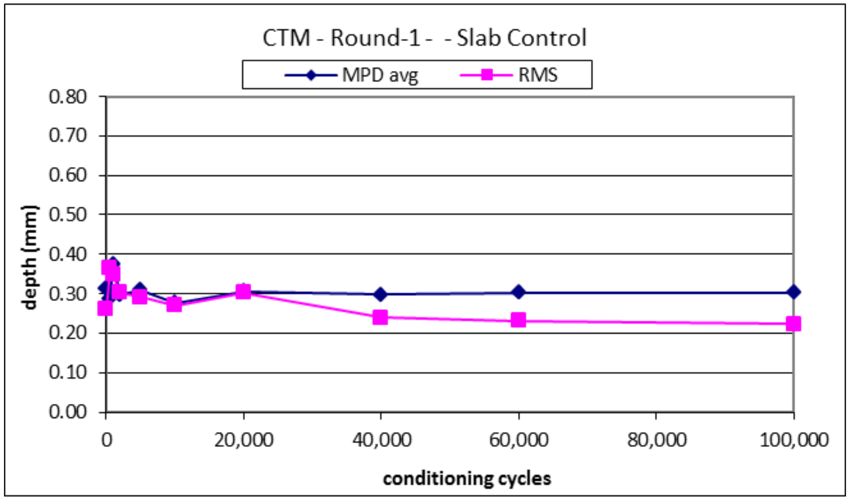
The following summary can be made based on the laboratory friction performance of the mixtures studied. The 9.5 mm mixture demonstrated better friction performance with either 33% or 60% slag added to the mixture in place of crushed gravel. The use of 60% granite made a marginal improvement, but the 33% granite did not improve the friction. The ultra-thin maintenance mixture demonstrated better friction performance with either 25% or 50% crushed gravel added to the mixture in place of limestone.

Laboratory testing with the CTM and DFT does not create a standard or threshold. This test protocol provides a relative comparison between different surfaces. It is the responsibility of the highway agency to determine what an acceptable level of friction should be.

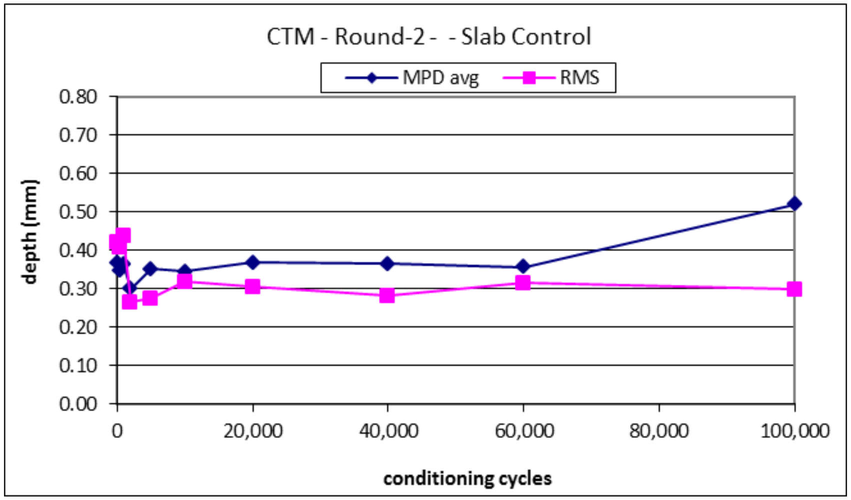
APPENDIX – Test Results

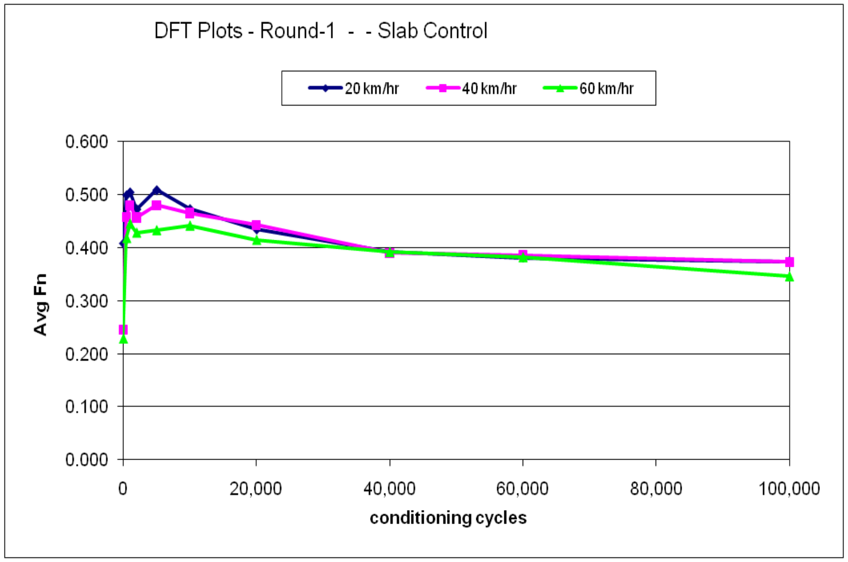
The test results for each slab are provided in the following figures. Each data point is an average of the replicate test measurements.

ROUND-1



ROUND-2





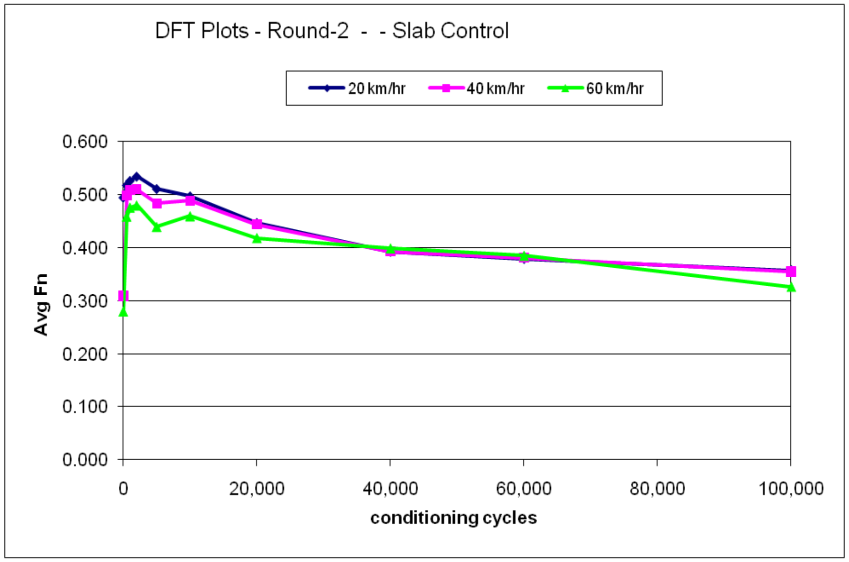


FIGURE A-1 Mix 1.0 control results

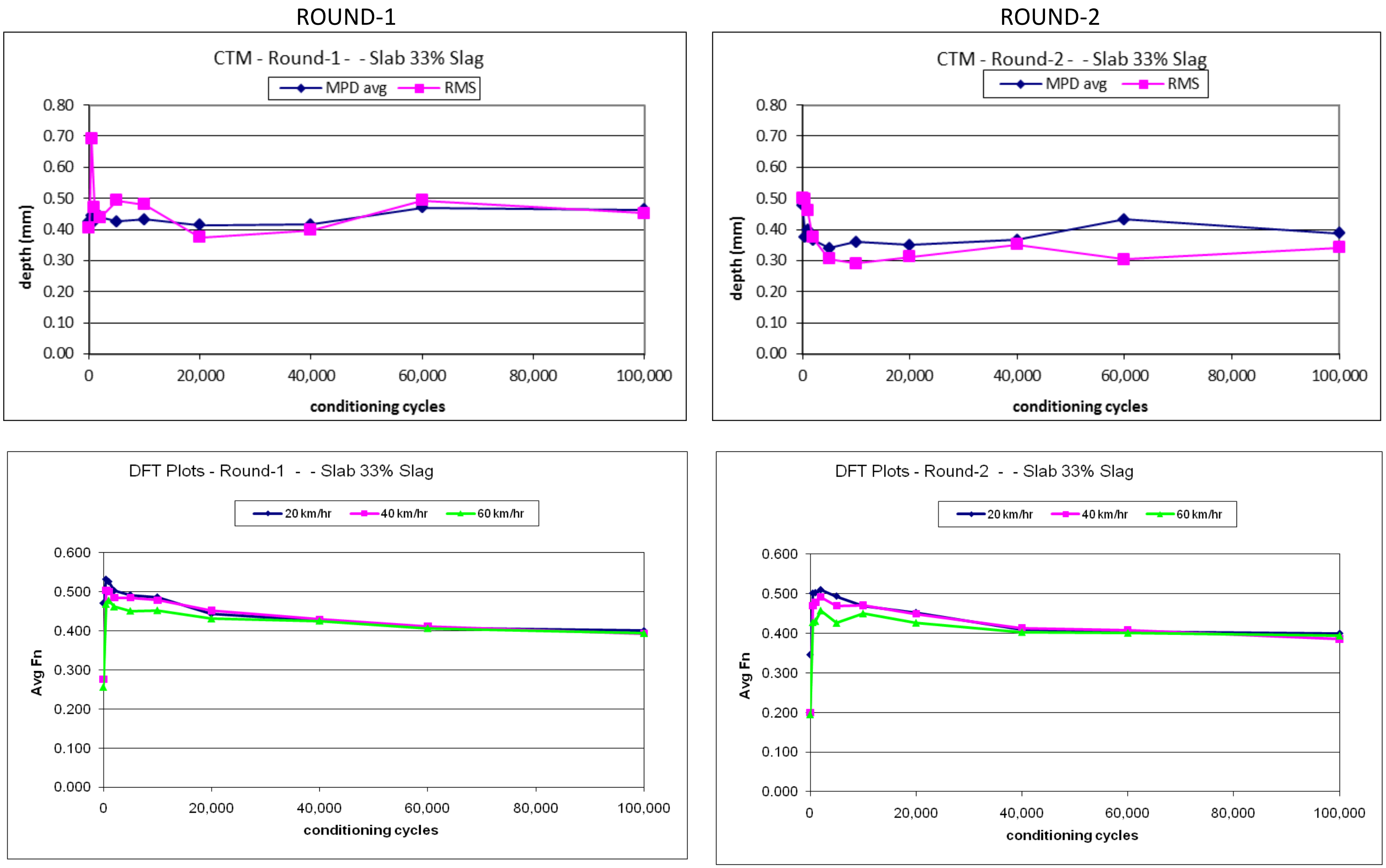


FIGURE A-2 Mix 1.1 33% slag results

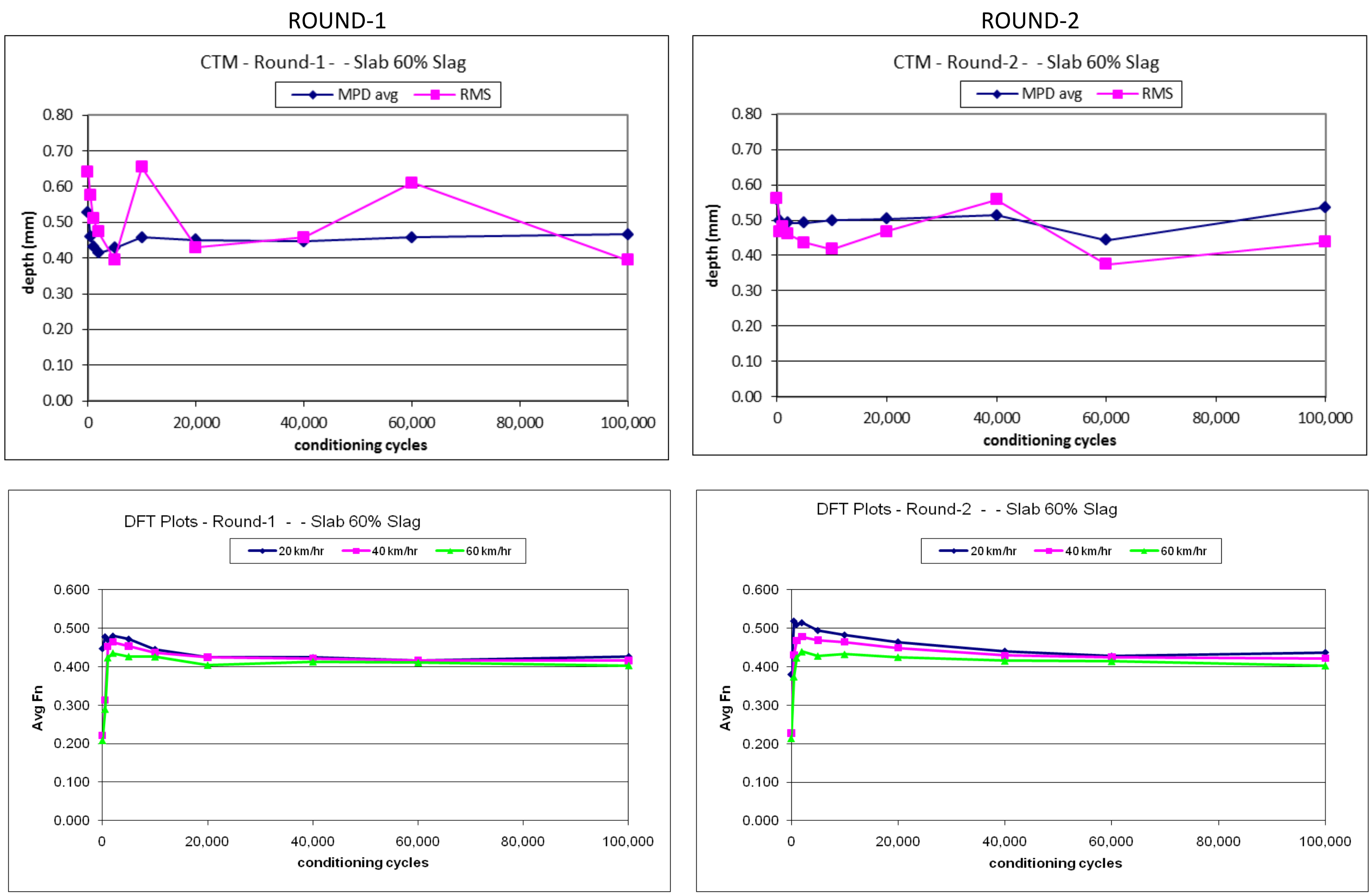
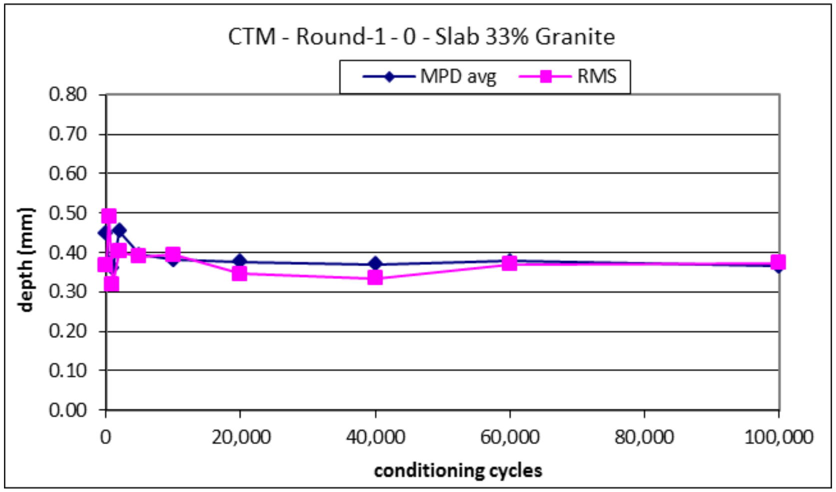
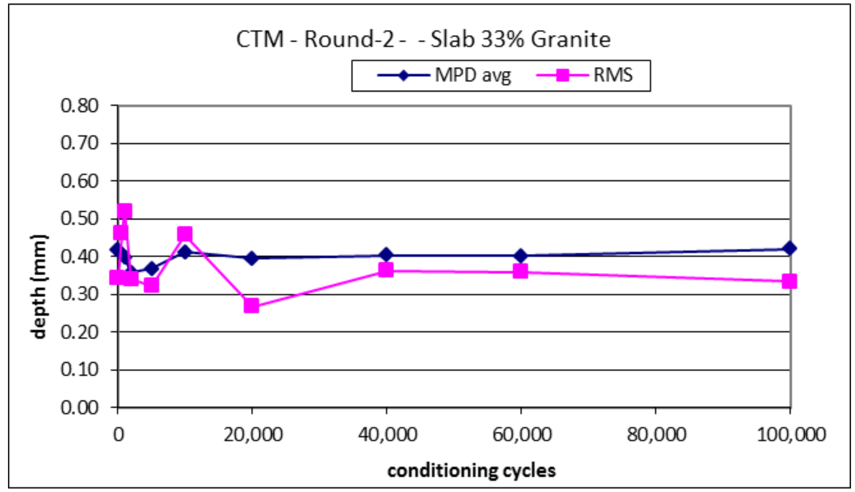


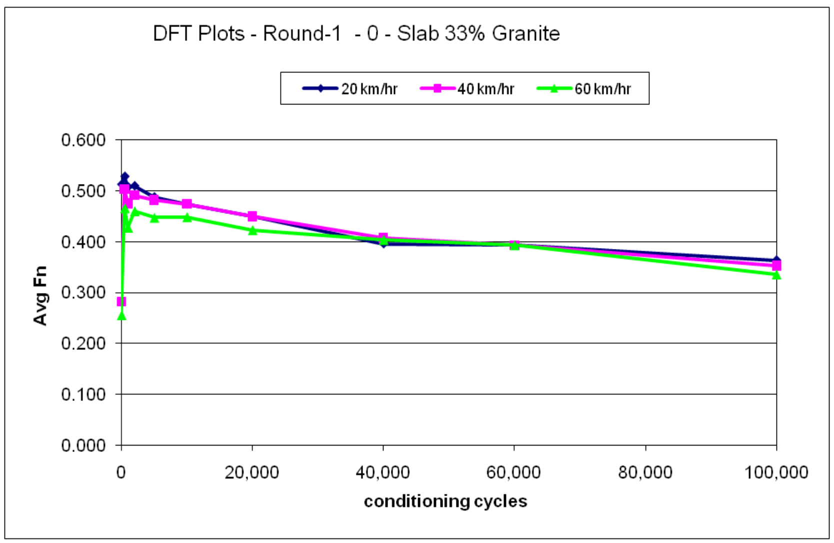
FIGURE A-3 Mix 1.2 60% slag results

ROUND-1



ROUND-2





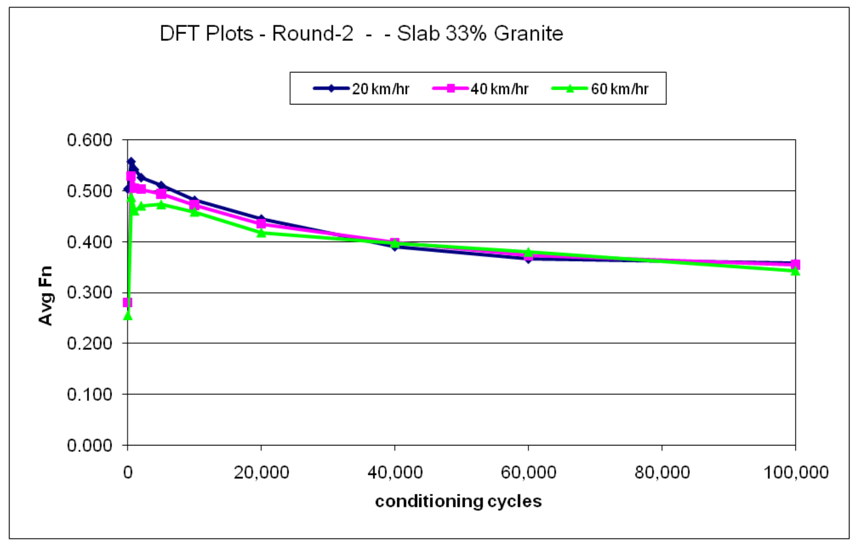


FIGURE A-4 Mix 1.3 33% granite results

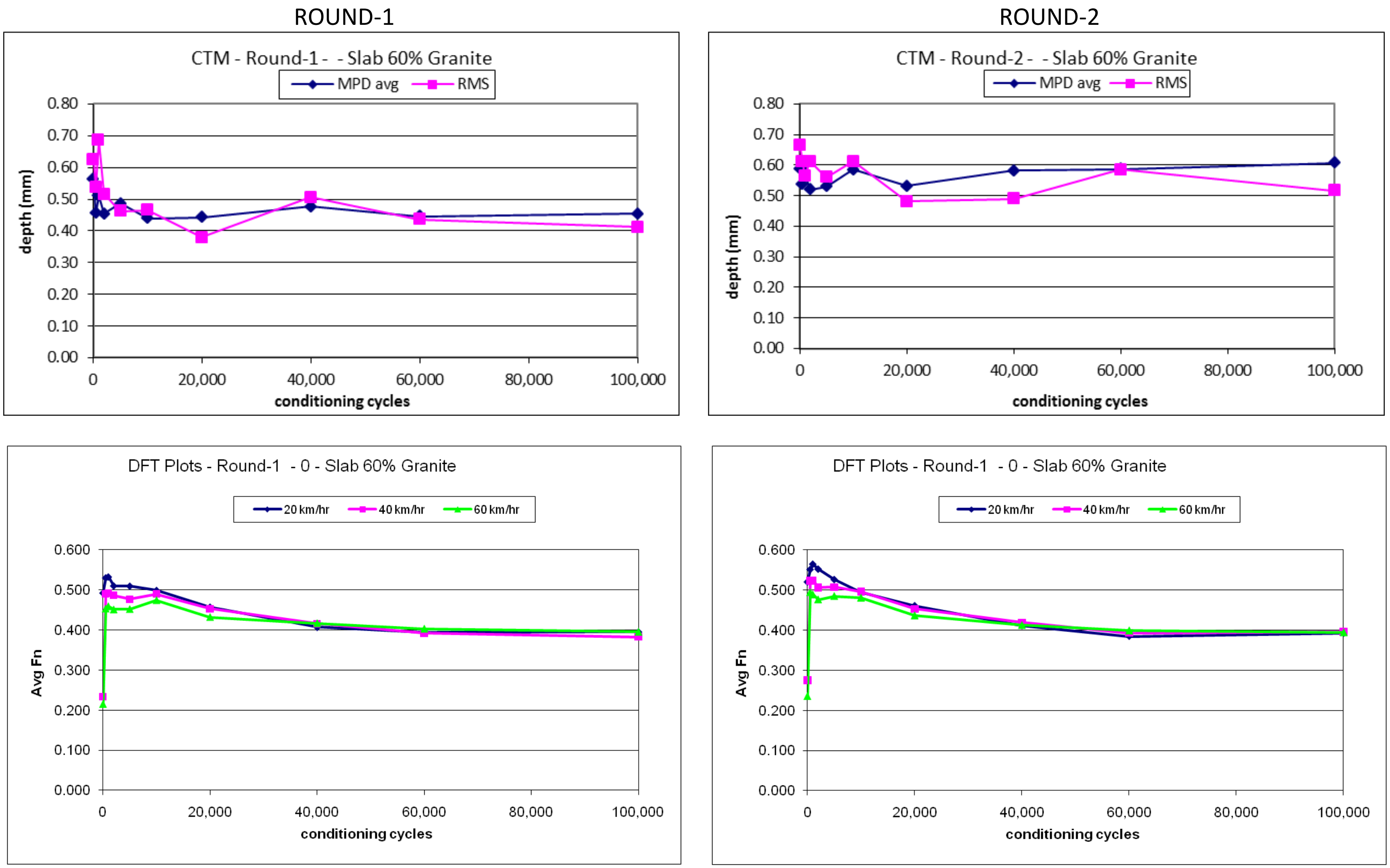


FIGURE A-5 Mix 1.4 60% granite results

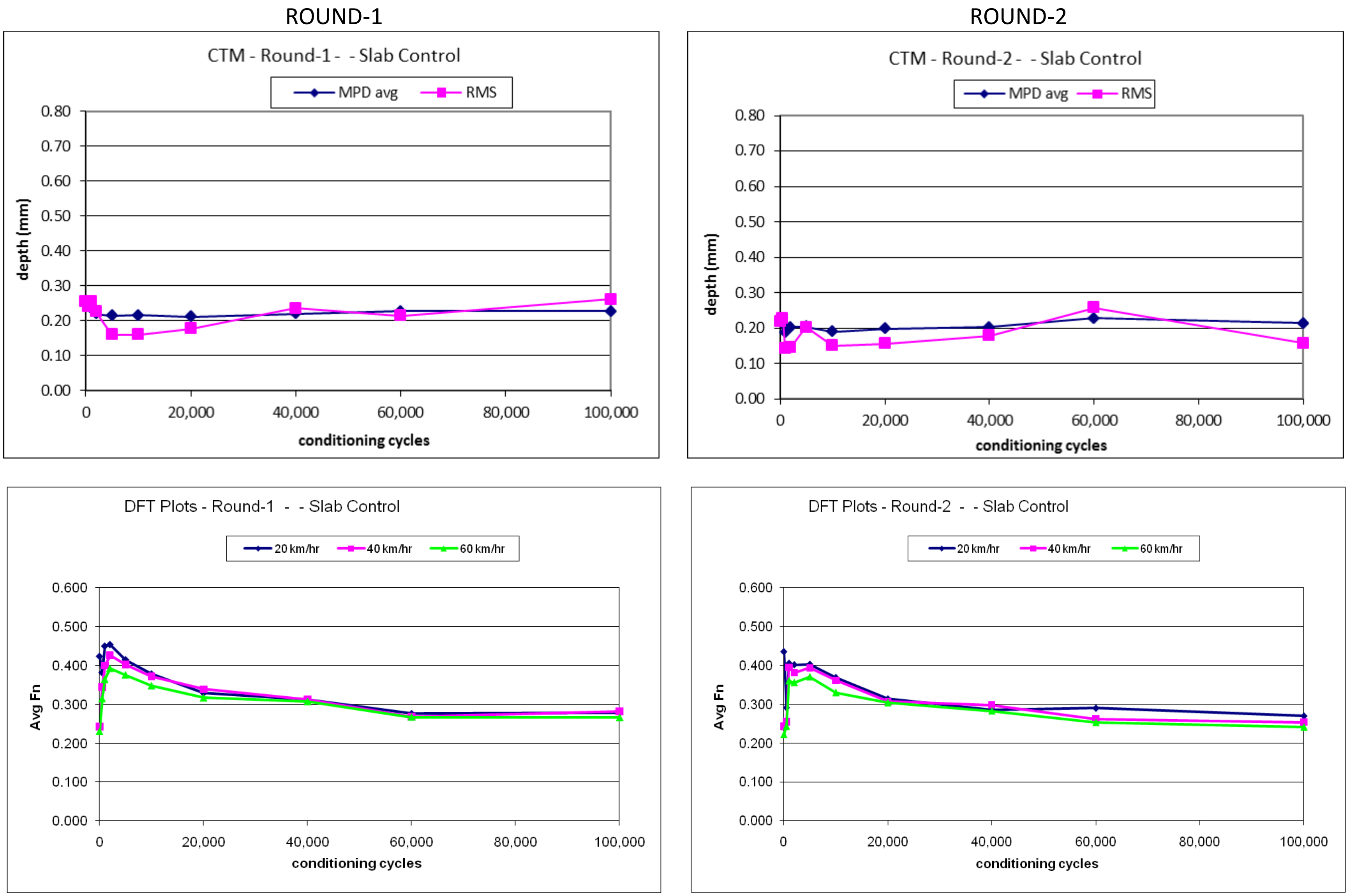


FIGURE A-6 Mix 2.0 control results

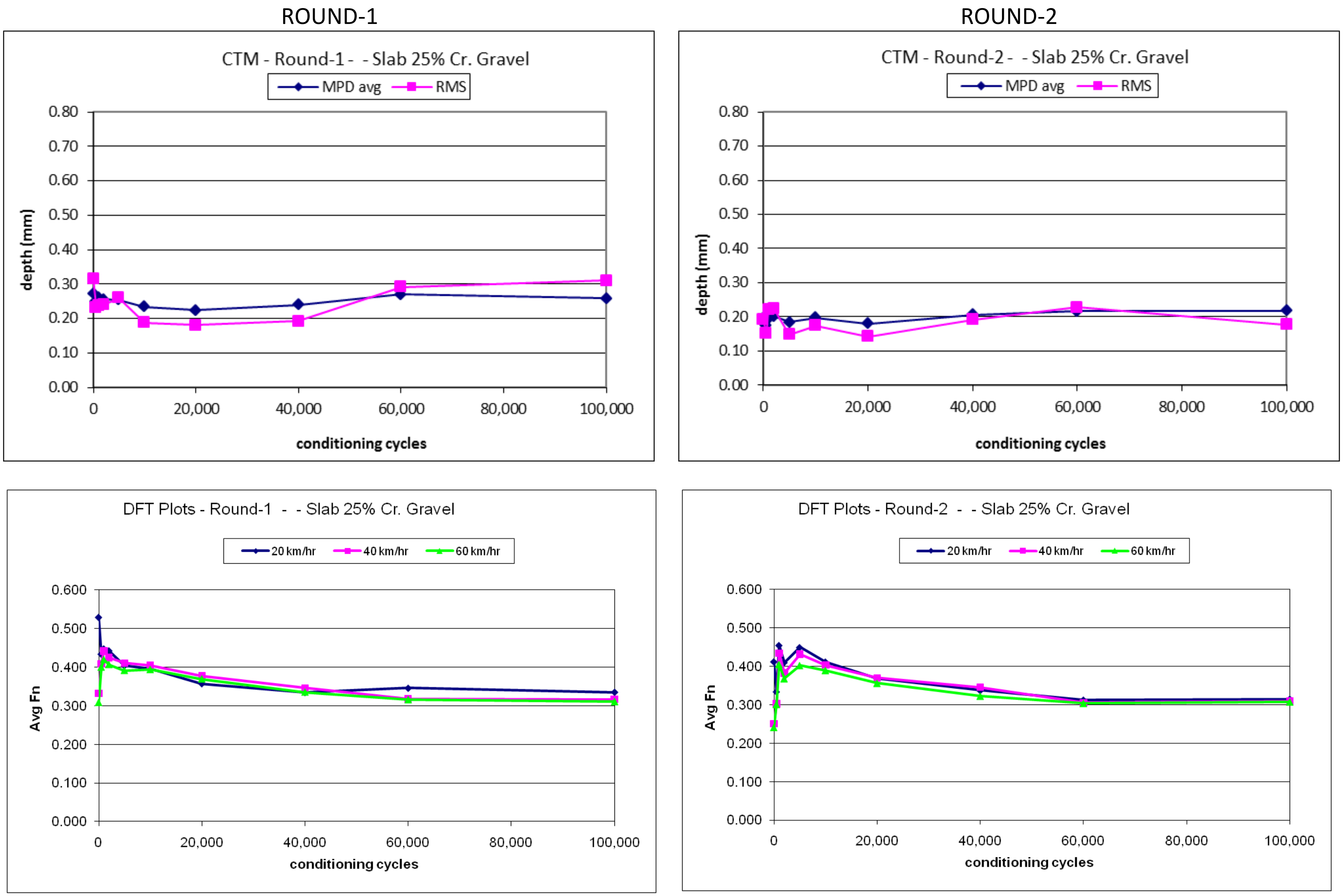


FIGURE A-7 Mix 2.1 25% crushed gravel results

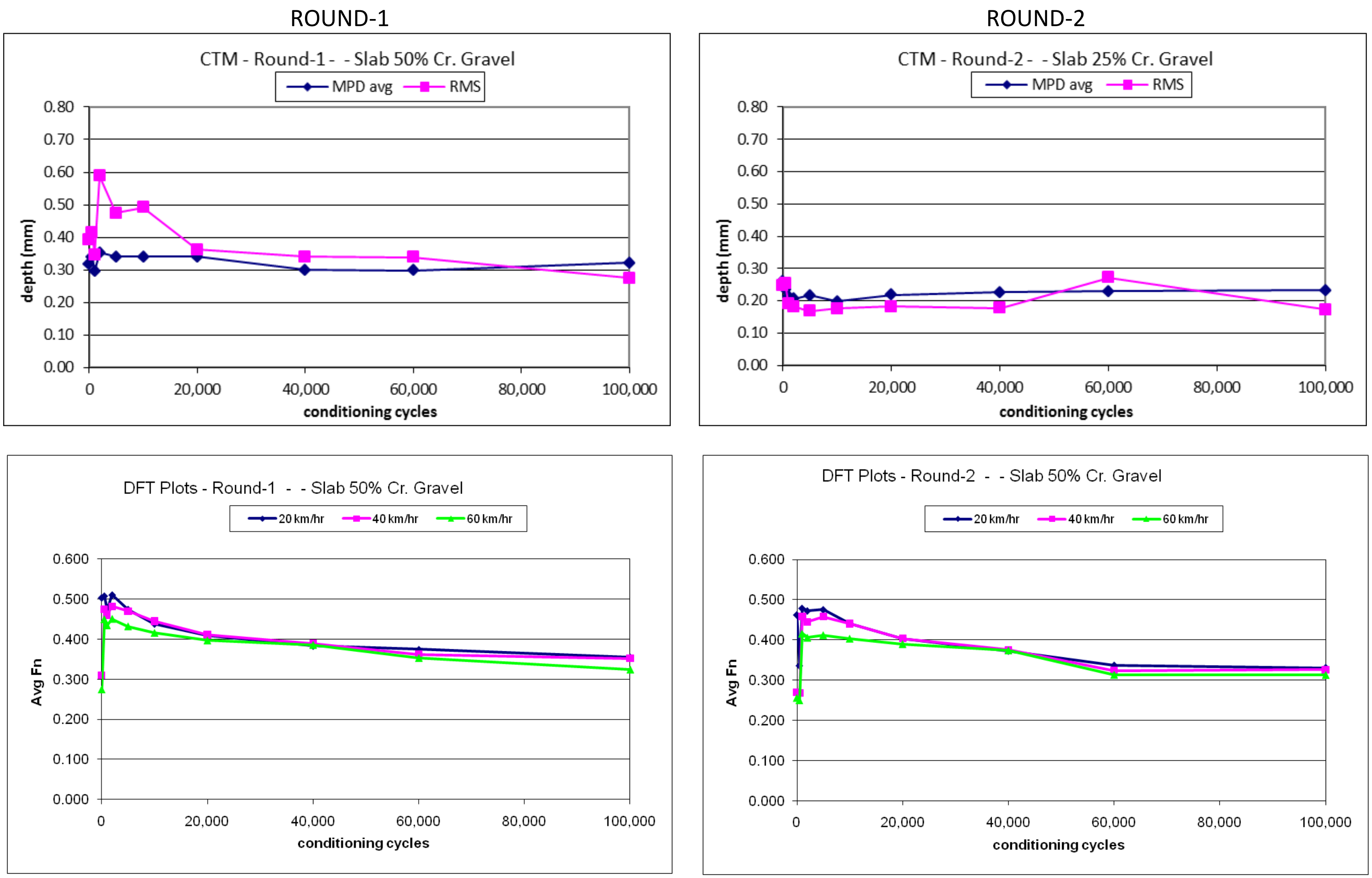


FIGURE A-8 Mix 2.2 50% crushed gravel results