NCAT Report 15-01

Comparing Friction Reducers for Use in AMPT Testing

By
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16. Abstract

The objective of this study was to evaluate methods of fabricating friction reducers for the flow number test to improve ease of fabrication and reduce variability of the test results. This study evaluated three two-layer latex friction reducers fabricated with paste silicone grease, dry-type silicone spray and wet-type silicone spray, each applied at two application rates, and a one-layer Teflon friction reducer. The results of this study showed that the Teflon friction reducer yielded statistically higher flow number test results than the two-layer latex friction reducers, except for the latex friction reducer using the Permatex wet type silicone spray applied at an application rate of 0.15 ± 0.02 g. The flow number test results for all the latex friction reducers using silicone lubricant were not statistically different. There was no specific trend indicating any effect of friction reducer silicone type or application rate on the variability (coefficient of variation) of flow number test results. In addition, the dynamic modulus testing conducted using the above latex and Teflon friction reducers showed that the effect of the friction reducers on the dynamic modulus test results was not statistically significant. It is recommended that only two-layer latex friction reducers be used for the flow number test as currently specified in AASHTO TP 79. The two latex layers can be greased using paste silicone, dry-type silicone spray and wet-type silicone spray at an application rate of 0.20 ± 0.05 g. As a result, the type of silicone used for the latex friction reducers (spray or paste) is a matter of preference of the technician running the test. The NCAT technician noted she preferred the paste silicone while preparing the specimens for this study. However, this was while attempting to control the silicone application to a tolerance of 0.02 grams. In addition, a friction reducer used for the dynamic modulus test can be made of latex or Teflon material as currently specified in AASHTO TP 79, except that the latex friction reducer can be lubricated with paste or spray silicone grease at an application rate of 0.20 ± 0.05 g.

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Final Report

By

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PROBLEM STATEMENT

An inter-laboratory study was conducted under NCHRP Project 09-29 (Bonaquist, 2011) to establish the precision statements for dynamic modulus and flow number tests using the Asphalt Mixture Performance Tester (AMPT). A key finding of the inter-laboratory study was that the variability of unconfined flow number tests was not suitable for the rutting resistance criteria developed in NCHRP Project 9-33 (AAT, 2011). The NCHRP Project 09-29 research team suggested that guidance for fabrication and use of friction reducers could be improved to reduce test variability (Bonaquist, 2011).

According to AASHTO TP79-13 Annex A, these friction reducers are currently fabricated using paste silicone grease at a specified application rate of 0.25 ± 0.05 g between two layers of latex membrane. This study was initiated to determine if friction reducers that were not fabricated according to the specification could be a source of test variability and if other materials could be used to improve both ease and uniformity of friction reducer fabrication.

OBJECTIVE

The objective of this study was to conduct an investigation into improved methods for fabricating the greased latex friction reducers and the viability of using a Teflon friction reducer, which could be made easier than a latex friction reducer using paste silicone grease, for flow number testing in accordance with AASHTO TP79-13. Specifically, this study investigated the effect of using (1) paste silicone, (2) spray silicone, and (3) Teflon friction reducers in addition to reusing paste silicone friction reducers on the flow number test results and the impact on test variability. Depending on their effect, appropriate friction reducers could be selected for the flow number test. In addition, dynamic modulus testing was conducted to confirm that the selected friction reducers would not have any adverse effects on the dynamic modulus test results.

TESTING PLAN

The mixture used in this study was a dense-graded asphalt mixture (with a design compaction effort of 60 gyrations) using a PG 67-22 binder. The mixture contained 20% reclaimed asphalt pavement (RAP) and was approved by the Alabama Department of Transportation for use in Alabama. The mix design is included in Appendix A. NCAT sampled this mixture as part of another study and had enough remaining material to fabricate AMPT specimens for this study. All of the specimens were prepared in accordance with AASHTO PP 60-13 to have target air voids of 7 ± 0.5%.

Two different sets of testing parameters (unconfined and confined) were originally planned for the evaluation. The unconfined testing would be performed in accordance with the recommended flow number testing parameters from NCHRP Project 09-33 (AAT, 2011). The confined testing parameters would be performed in accordance with the incremental Repeated Load Permanent Deformation (iRLPD) methodology (Azari and Mohseni, 2013), which has recently been recommended to the FHWA Asphalt Mixture Expert Task Group (ETG). However, the software for conducting the iRLPD testing in the AMPT was not made available to the project team for this study. Thus, only unconfined flow number testing according to the NCHRP 09-33 method was conducted. The testing parameters are summarized in Table 1. The test temperature of 60.5°C was selected because it is the LTPPBind v3.1 50%-reliability high temperature at a depth of 20mm in the pavement for the Dothan, Alabama area (the location where the mix used for this study was sampled).

The effects of the paste silicone latex, spray silicone latex, and Teflon friction reducers on flow number test results and test variability were evaluated in the NCAT laboratory in four steps using the same mix as summarized in Table 1. A total of eight friction reducers (based on the eight combinations of friction reducer types and application rates) were tested in this study. A description of each step follows.

1. The first step was to determine the "baseline" test variability for the flow number test using the currently specified greased latex friction reducers. These friction reducers were fabricated using the paste silicone lubricant in accordance with AASHTO TP 79-13 Annex A. The recommended application rate of the paste silicone lubricant for these friction reducers is 0.25 ± 0.05 g. For this study, the tolerance was changed from 0.05 g to 0.02 g to better evaluate the effect of application rate.
2. In the second step, another application rate was evaluated to determine the effect of the paste silicone on the test variability. Based on past experience at NCAT and through discussion with other laboratories, the specified application rate may be too high, so a lower application rate of 0.15 ± 0.02 g was evaluated.
3. The third step was to determine the effect of using a spray silicone lubricant on the flow number test results. Two different brands of spray silicone lubricant were tested at two application rates shown in Table 1 to determine the effect of lubricant type and application rate on the flow number test results. Originally, it was desired to test both of the spray applications at a target rate of 0.10 ± 0.02 g to create more separation between the high and low application rates. However, during testing the technician noted that it was not possible to achieve a uniform spray at the 0.10 ± 0.02 gram target with the Permatex Wet Type spray. Hence, the target rate for this material was adjusted to the original 0.15 ± 0.02 gram target. Before testing, an application procedure for spray silicone was prepared (see Appendix B) in a format similar to the procedure in AASHTO TP 79-13 Annex A and was followed consistently during testing.
4. The last step was to determine the effect of using single- and double-layer Teflon friction reducers on the flow number test results. The flow number test was conducted using friction reducers made of one and two layers of a 0.01-in. thick Teflon sheet, respectively.

In addition, to determine if reusing greased latex friction reducers may affect flow number test results, two sets of flow number test specimens were prepared and tested using the same procedure described in Table 1. The first set of test specimens was tested using a new set of greased latex friction reducers prepared at an application rate of 0.20 ± 0.02 g. Afterward, the friction reducers were kept in the laboratory at room temperature for two weeks and then used to test the second set of test specimens. The testing plan is summarized in Table 2.

Finally, since AASHTO TP79-13 encompasses both the dynamic modulus and flow number test, dynamic modulus testing was performed using the selected friction reducer types at their appropriate lubricant application rates to confirm that the selected friction reducers would not have adverse effects on the dynamic modulus test results.

For this testing, dynamic modulus testing with multiple friction reducer types was conducted on one set of three test specimens. Dynamic modulus testing was performed in accordance with the recommended test parameters from AASHTO PP61-13 (summarized in Table 3). Dynamic modulus testing was performed with seven different friction reducer applications, as shown in Table 3. A unique friction reducer was prepared for each individual dynamic modulus test. These applications were identical to those listed in Table 1, with the exception that a target application rate of 0.15 ± 0.02 g was used instead of 0.10 ± 0.02 g for the 3M dry type application, and that the double-layer Teflon friction reducer was not tested. Testing was performed in order of lowest temperature to highest temperature (all 4°C specimens were tested prior to testing all 20°C specimens and then all 40°C specimens). Within each temperature, the testing order (specimen ID and friction reducer application) was randomized. This prevented specimens and friction reducer types from being tested in the same order at each temperature and introducing bias into the results.

Table 1 Testing Plan for Evaluating Effect of Friction Reducers on Flow Number Test Results

Test Procedure	Friction Reducer Type	Application Rate
• Unconfined Flow Number (NCHRP 09-33 Method): ○ Confinement: None ○ Deviator: 600kPa (87 psi) ○ Contact Stress: 30kPa (4.35 psi) ○ Temperature: 60.5°C	Paste Silicone Latex (DOW Corning 112 HP)	0.25 ± 0.02 g (baseline)
		0.15 ± 0.02 g
	Silicone Spray A Latex (3M Dry Type)	0.25 ± 0.02 g
		0.10 ± 0.02 g
	Silicone Spray B Latex (Permatex Wet Type)	0.25 ± 0.02 g
		0.15 ± 0.02 g
	Teflon	Single 0.01-in. Thick Sheet
		Double 0.01-in. Thick Sheets
Notes:		
1 Test Method x 8 Friction Reducers = 8 Sets of Flow Number Specimens		
4 Replicate Specimens Required per Flow Number Test.		

Table 2 Testing Plan for Evaluating Effect of Reusing Silicone-Greased Friction Reducers on Flow Number Test Results

Test Procedure	Friction Reducer	Application Rate
• As described in Table 1	New Set of Silicone-Greased Friction Reducers	Paste Silicone Latex @ 0.20 ± 0.02 g
	Same Set of Friction Reducers Reused in 2 Weeks	Paste Silicone Latex @ 0.20 ± 0.02 g
Notes:		
1 Test Method x 2 Sets of Friction Reducers = 2 Sets of Flow Number Specimens		
4 Replicate Specimens Required per Flow Number Test.		

Table 3 Testing Plan for Evaluating Effect of Friction Reducers on Dynamic Modulus Test Results

Test Temperature (°C)	Test Frequency (Hz)	Friction Reducer
4	10,1,0.1	Paste Silicone Latex @ 0.25 and 0.15 g Silicone Spray A Latex @ 0.25 and 0.15 g Silicone Spray B Latex @ 0.25 and 0.15 g Single Teflon 0.01-in. Thick Sheet
20	10,1,0.1	
40	10,1,0.1,0.01	

RESULTS AND ANALYSIS

Detailed results for the flow number and dynamic modulus tests are included in Appendices C and D, respectively. A discussion of these test results and analysis follows.

Effect of Friction Reducers on Flow Number Test Results

After specimens for flow number testing had been prepared, they were randomly grouped based on a stratified process to keep the average and variability of the air voids within each group similar to one another. Figure 1 compares the air voids of the eight sets of test specimens corresponding to the eight friction reducers shown in Table 1. A statistical analysis, included in Appendix E, showed no statistical difference between the air voids of the eight sets of test specimens. Thus, the effect of the specimen air voids would be negligible when comparing the flow number test results for the eight friction reducers.

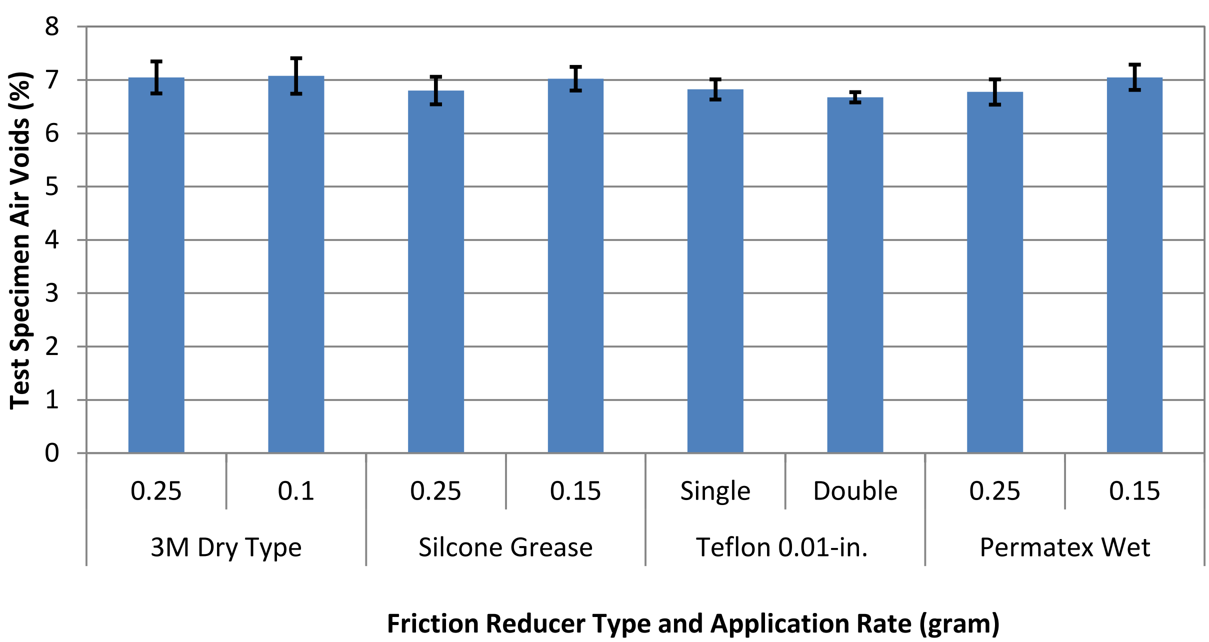

Figure 1 Comparing Air Voids of Eight Sets of Flow Number Test Specimens

Figure 2 compares the flow number test results for the eight friction reducers shown in Table 1. It appeared that the single-layer Teflon friction reducer yielded higher flow number test results.

A statistical analysis was then conducted to determine the effect of friction reducer type and application rate on the flow number test results. Results of this analysis are summarized in Table 4. Based on the analysis of variance (F-test) at a significance level of 0.05, the flow number test results were statistically different (p-value = 0.001 < 0.05). Further analysis using Tukey's pairwise comparison showed that the flow number test results for the single-layer Teflon friction reducer were statistically different from those of the other friction reducers. Furthermore, the flow number test results for all the latex and double-layer Teflon friction reducers were not statistically different from each other.

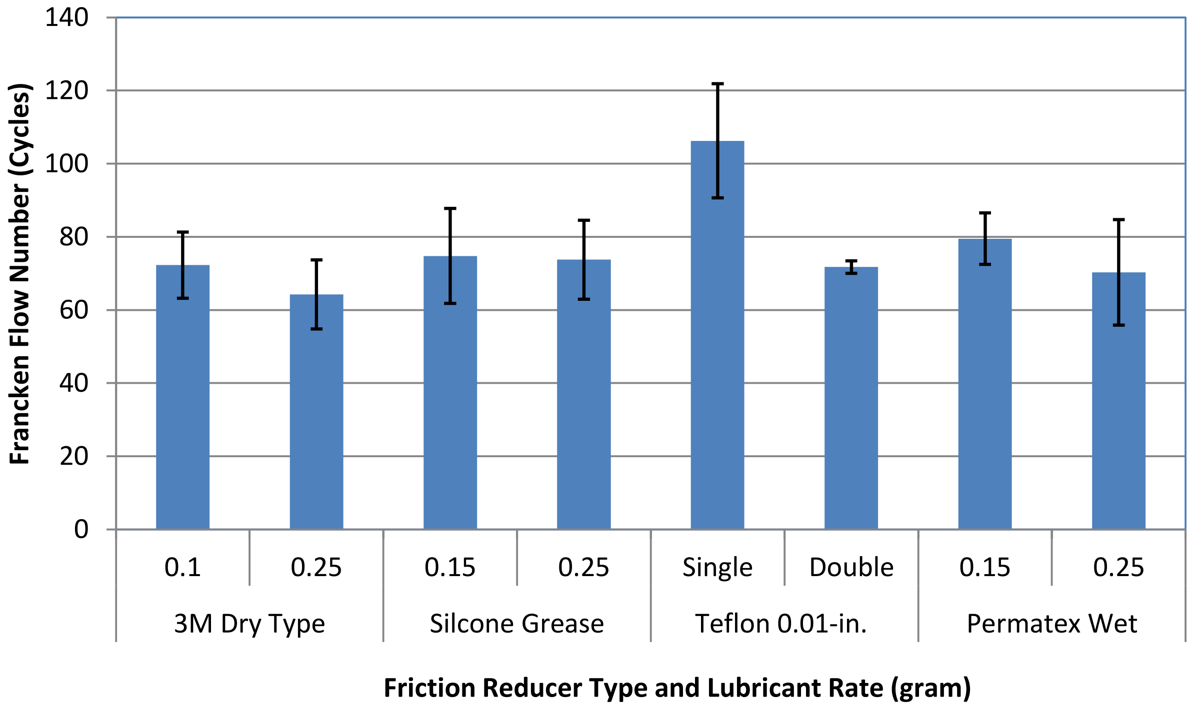

Figure 2 Comparing Flow Number Test Results for Seven Test Combinations

Additionally, flow number specimens are supposed to deform uniformly during the course of the test. As a specimen is compressed, its height will decrease and its diameter should increase uniformly (the volume of the specimen will remain constant). This constant deformation during the test was noted with all of the specimens produced using either the paste or the spray silicone. However, with the specimens tested using the single-layer and double-layer Teflon friction reducers, a 'bulging' effect was noted around the center of the specimens. Hence, both the single-layer and double-layer Teflon friction reducers may have negatively impacted how the flow number specimens deformed during the course of the test. Photos illustrating this behavior are shown in Figure 3.

Table 4 Statistical Analysis to Evaluate Effect of Friction Reducers on Flow Number Results

Factor	Type	Levels	Values
Mix ID	Fixed	8	3M Dry Type - 0.15, 3M Dry Type - 0.25, Permatex Wet Type - 0.15, Permatex Wet Type - 0.25, Silicone Grease - 0.15, Silicone Grease - 0.25, Teflon - Double, Teflon - Single

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	7	4537	648.2	5.39	0.001
Error	24	2884	120.2		
Total	31	7422			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.9625	61.14%	49.80%	30.91%

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping	
Teflon - Single	4	106.25	A	
Permatex Wet Type - 0.15	4	79.50		B
Silicone Grease - 0.15	4	74.75		B
Silicone Grease - 0.25	4	73.75		B
3M Dry Type - 0.15	4	72.25		B
Teflon - Double	4	71.75		B
Permatex Wet Type - 0.25	4	70.25		B
3M Dry Type - 0.25	4	64.25		B

Means that do not share a letter are significantly different.

Figure 3 Comparison of (A) Untested Flow Number Specimens, (B) Specimen Tested Using Single-Layer Teflon, (C) Specimen Tested Using Spray Silicone, and (D) Specimen Tested Using Double-Layer Teflon

Figure 4 compares the coefficients of variation of flow number test results for the eight friction reducers. There was no specific trend indicating any effect of friction reducer type and application rate on the variability of flow number test results.

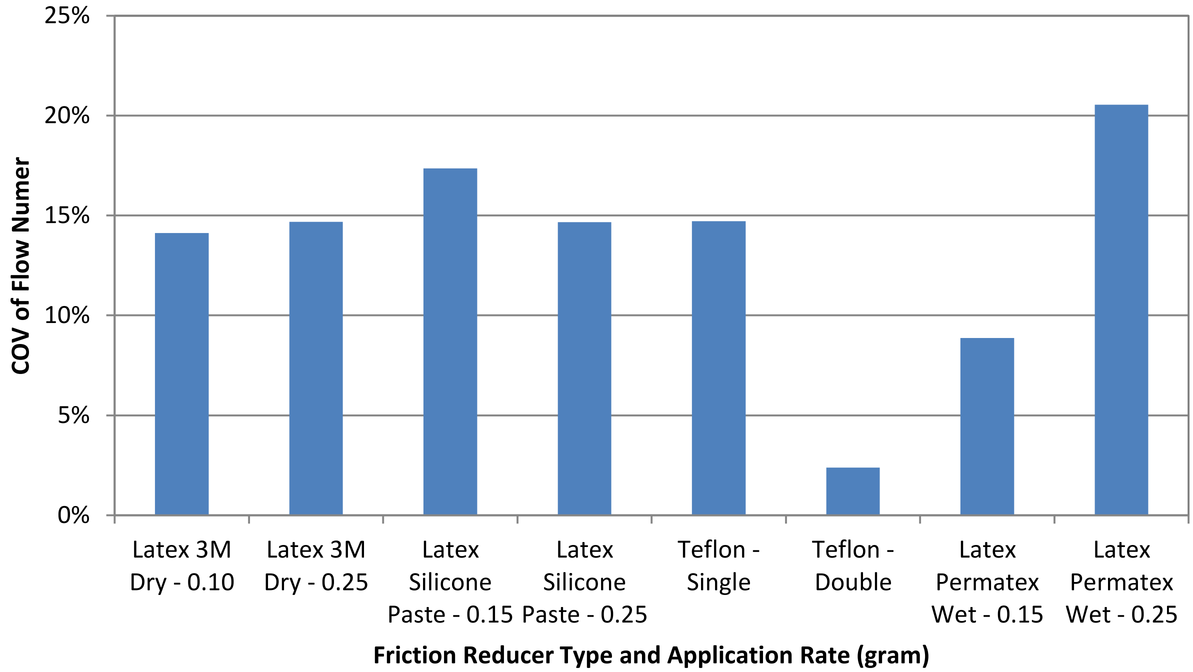

Figure 4 Comparing Coefficients of Variation of Flow Number Test Results for Eight Friction Reducers

Effect of Reusing Silicone-Greased Friction Reducers on Flow Number Test Results

An analysis similar to that presented in the previous section was conducted on the flow number test results performed according to the testing plan presented in Table 2 to determine the effect of reusing silicone-greased friction reducers. The first set of flow number specimens was conducted using a new set of silicone greased latex friction reducers, and the second set of specimens was conducted using the same set of friction reducers after they had been kept in the laboratory for two weeks.

As for the previous eight sets of test specimens, these two sets of test specimens were also randomly grouped based on a stratified process to keep the average and variability of the air voids within each group similar to one another. Figure 5(a) compares the air voids of the two sets of flow number specimens. A statistical analysis, included in Appendix E, showed no statistical difference between the air voids of the two sets of test specimens. Thus, the effect of the specimen air voids would be negligible when comparing the flow number test results.

Figure 5(b) shows similar flow number test results for the two sets. A statistical analysis shown in Table 5 confirmed that the flow number test results for the new and reused silicone greased latex friction reducers were not statistically different from each other at a significance level of 0.05 (p-value = 0.844 > 0.05).

Finally, Figure 5(c) compares the coefficients of variation of flow number test results for the new and reused friction reducers. The variability was similar for the two sets of flow number test results.

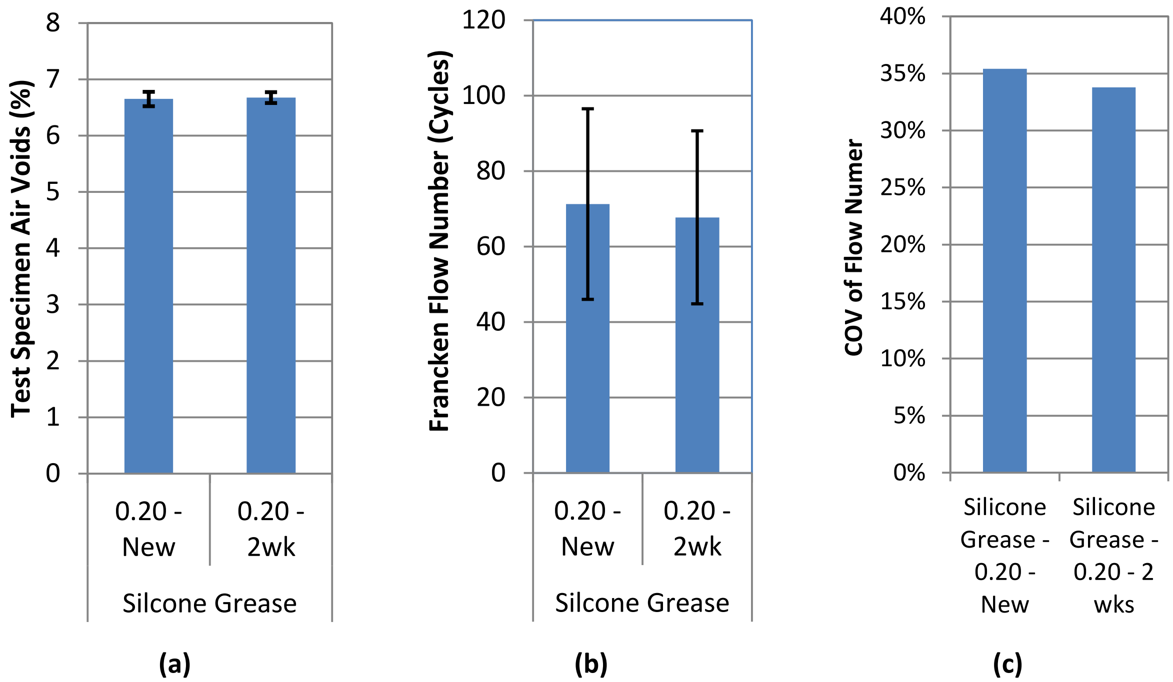

Figure 5 Comparison of (a) Specimen Air Voids, (b) Flow Number Test Results, and (c) Coefficient of Variation for Testing Plan Shown in Table 2

Table 5 Statistical Analysis to Evaluate Effect of Friction Reducers on Flow Number Results

Factor Information

Factor	Type	Levels	Values
Mix ID	Fixed	2	Silicone Grease - 0.20 - 2 Wk Age, Silicone Grease - 0.20 - New

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	1	24.50	24.50	0.04	0.844
Error	6	3483.50	580.58		
Total	7	3508.00			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
24.0953	0.70%	0.00%	0.00%

Dynamic Modulus Test Results

Based on the flow number test results, it was decided to conduct dynamic modulus testing using the same friction reducer types and application rates shown in Table 1 for flow number testing, except that the lower application rate for the 3M Dry Type silicone spray was at 0.15 ± 0.02 g instead of 0.10 ± 0.02 g and that double-layer Teflon friction reducer was not tested.

There was no apparent difference between the seven master curves of dynamic modulus using the seven friction reducers, as shown in Figure 6. A statistical analysis was conducted on the dynamic modulus test results at each combination of test temperature and frequency, and results of this analysis are summarized in Table 6. Based on a significance level of 0.05, the effect of the seven friction reducers on the dynamic modulus test results was not statistically significant (all p-values were greater than the significance level of 0.05).

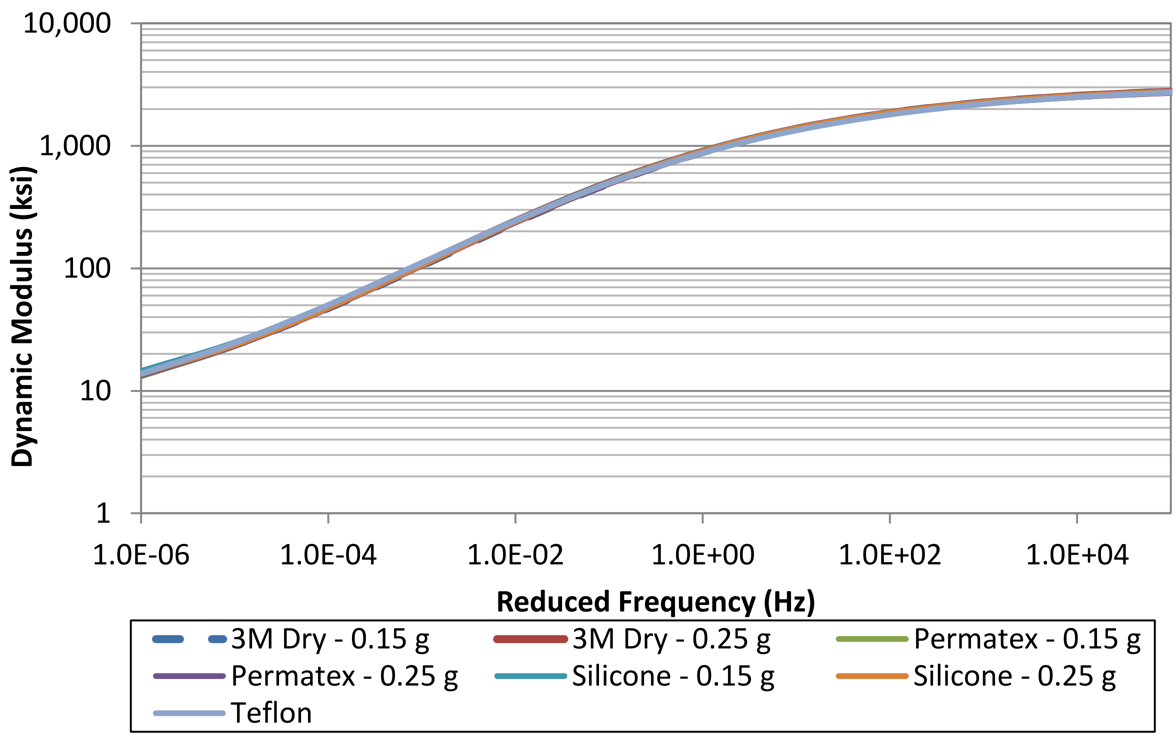

Figure 6 Comparing Dynamic Modulus Master Curves for Seven Friction Reducers

Table 6 Statistical Analysis: Effect of Friction Reducer on Dynamic Modulus at Each Temperature and Frequency Combination

Test Temperature (°C)	Test Frequency (Hz)	p-Value
4	10	0.419
4	1	0.553
4	0.1	0.743
20	10	0.710
20	1	0.892
20	0.1	0.887
40	10	0.856
40	1	0.880
40	0.1	0.864
40	0.01	0.512

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to determine (1) if other types of lubricant and materials can be used to fabricate friction reducers for the flow number test to improve ease of fabricating friction reducers and reduce test result variability; and (2) if reusing latex reducers may affect the flow number test results. This study evaluated the following friction reducers:

- Two-layer latex friction reducers with a paste silicone grease applied at two application rates (0.25 ± 0.02 and 0.15 ± 0.02 g)
- Two-layer latex friction reducers with a dry-type silicone spray applied at two application rates (0.25 ± 0.02 and 0.10 ± 0.02 g)
- Two-layer latex friction reducers with a wet-type silicone spray applied at two application rates (0.25 ± 0.02 and 0.15 ± 0.02 g)
- One-layer and two-layer Teflon friction reducers cut from 0.01-in. thick sheet
- New latex friction reducers (with a paste silicone grease applied at 0.20 ± 0.02 g) and reused latex friction reducers after being kept in the laboratory for two weeks

Based on the results of this study, the following conclusions can be offered:

- The results of this study showed that the single-layer Teflon friction reducer yielded statistically higher flow number test results than the two-layer latex and two-layer Teflon friction reducers. In addition, the flow number test results for all the silicone latex and double-layer Teflon friction reducers were not statistically different.
- However, the specimens tested using both the single-layer and double-layer Teflon friction reducers showed a 'bulging' effect around the center of the specimens. As a specimen with frictionless ends is compressed, its height will decrease and its diameter should increase uniformly (the volume of the specimen will remain constant). Hence, both the single-layer and double-layer Teflon friction reducers may have negatively impacted how the flow number specimens deformed during the course of the test.
- There was no specific trend indicating any effect of friction reducer silicone type or application rate on the variability (coefficient of variation) of flow number test results.
- Reusing the same set of silicone latex friction reducers once did not statistically affect the flow number test results.
- In addition, the dynamic modulus testing conducted using the silicone latex and single-layer Teflon friction reducers showed that the effect of these friction reducers on the dynamic modulus test results was not statistically significant.

Based on the results of this study, it is recommended that:

1. Only two-layer latex friction reducers be used for the flow number test, as currently specified in AASHTO TP 79-13. The two latex layers can be greased using paste silicone, dry-type silicone spray, and wet-type silicone spray at an application rate of 0.20 ± 0.05 g. As a result, the type of silicone used for the latex friction reducers (spray or paste) is a matter of preference of the technician running the test. The NCAT technician noted she preferred the paste silicone while preparing the specimens for this study. However, this was while attempting to control the silicone application to a tolerance of 0.02 grams.

2. A friction reducer used for the dynamic modulus test be made of latex or Teflon material as currently specified in AASHTO TP 79-13, except that the latex friction reducer can be lubricated with paste or spray silicone grease at an application rate of 0.20 ± 0.05 g.
3. A study be conducted to determine if the same set of silicone latex friction reducers can be used to test a set of four flow number test specimens and/or a set of three dynamic modulus test specimens. Findings of this study can potentially reduce the numbers of friction reducers prepared for the flow number and dynamic modulus tests.

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APPENDIX A DESIGN OF ASPHALT MIXTURE USED IN THE STUDY

Alabama Department of Transportation

Sampled By: Vinson, Jackie
Sample ID: 375274

Project Manager: ALEX MURPHREE
Sample Date: 04/20/2011

County: HOUSTON
Date Tested: 05/03/2011

Producer: GULF COAST DIV OF APAC - DOTHAN
Sample Test Number: 352G-11

Intended Use: SURFACE/PATCH, LEVEL, WIDEN
Division: 07

GYRATORY COMPACTOR (HMA4302B)

Contractor's Address: APAC MID-SOUTH, INC.
P.O. BOX 8888
DOTHAN, AL 36304

Date: 5/3/11
Producer: APAC MID-SOUTH, INC.
Plant: DOTHAN

Section/ESAL Category: 424 A/B, C/D
Max. Size Aggregate: 1/2" THRU RESTRICTED ZONE
Metric Size Aggregate: 12.5MM THRU RESTRICTED ZONE

Intended Use: SURFACE/PATCH,LEVEL,WIDEN
Binder Grade: PG 67-22 BLACKLIDGE
Specific Gravity of AC: 1.034

% (Approx)	Description	I.D.#	Source	BPN
				-9
18	#89 LIMESTONE	1405-G	MM-O'NEIL; SAGINAW, AL	26
12	#8910 LIMESTONE SCRN'S	1405-G	MM-O'NEIL; SAGINAW, AL	26
15	#810 GRANITE SCRN'S	1723	VMC-NOTASULGA QUARRY; LOACHAPOKA, AL	
20	SHOT GRAVEL	0261	MM-PINKSTON PIT; SHORTER, AL	
15	SAND	1642-F	COUCH; HILTON, GA	
20	RAP		STOCKPILE #10-7-2	

Job Mix:

Sieves	% Passing
1 1/2"... (37.5 mm)	
1"........ (25.0 mm)	
3/4"..... (19.0 mm)	
1/2"...... (12.5 mm)	100
3/8"..... (9.5 mm)	97
#4....... (4.75 mm)	72
#8....... (2.36 mm)	48
#16.... (1.18 mm)	37
#30...... (600 µm)	27
#50...... (300 µm)	14
#100... (150 µm)	8
#200.... (75 µm)	5.8

Other Information:

% AC Required................	5.50*	
AC Reqd/Ton,lbs/MT,kg....	110.0	55.0
Max. Sp. Gr. Mix..............	2.467	
Wt., lbs/Mass, kg/m³	147.3	2360.0
TSR................................	0.84	
Anti-Strip.........................	.25	
ADHERE 1500		
Effective AC.....................	5.22	
Dust/Asphalt Ratio............	1.11	
Coarse Agg. Angularity....	96/92	
Fine Agg. Angularity.........	46	
Agg Bulk SG....................	2.663	
% VMA............................	15.8	

Note:

*4.38% PG 67-22 must be added to the mix. The remaining 1.12% comes from the RAP. comes from RAS.

\# Gyrations: 60 % Gmm: 96.1

Additional Notes:

MIXING TEMP 325°F ST-352-G-11

Hot-Mix Asphalt Engineer

Standard Remarks: This material has been tested in accordance with ALDOT specifications.

Print:

Signature:

Authorized By: cato2437
Authorized Date: 05/05/2011

5/5/2011

Page 1 of 1

APPENDIX B PROCEDURE FOR APPLYING SILICONE SPRAY

The following steps should be followed when applying silicone spray for Flow Number and Dynamic Modulus testing:

1. Cut out four latex membrane rounds per sample (two for the top and two for the bottom).
   a. 16 rounds are needed for each set of four flow number specimens, and 12 rounds are required for each set of three dynamic modulus specimens.
   b. A hole may be cut in the bottom membranes to keep the valve in the bottom platen uncovered.
2. Place one of the top membranes on a high resolution scale.
   a. Tare the membrane <u>inside a large tin</u>. This is to ensure an accurate scale reading.
3. Remove the membrane from the scale and apply a silicone spray (using the spray can).
4. After the grease is sprayed, re-weigh the membrane.
   a. Target for these membranes is 0.15 ± 0.02 g or 0.25 ± 0.02 g.
   b. Adjust the amount of grease on the membranes as necessary.
      i. A uniform spray is needed, but care should be taken to not go over the target amount.
      ii. If the target is exceeded, a small amount may be removed using a Popsicle stick or similar apparatus. If this is done, care should be taken to spread the grease in the affected area back into a uniform layer.
   c. Add the other top membrane to the membrane with the grease. Press together to eliminate any air pockets.
5. Record the weight of the grease on a data form.
6. Repeat the process for the bottom friction reducers.
7. Eight friction reducers are needed for each set of four flow number specimens, and six friction reducers are needed for each set of three dynamic modulus specimens
   a. Record the amount of silicone grease on each friction reducer.

APPENDIX C FLOW NUMBER TEST RESULTS

Mix ID	Application Type	Target Application Rate (g)	Measured Silicone Top Reducer (g)	Measured Silicone Bottom Reducer (g)	Spcm ID	Sample Air Voids (%)	Francken Flow Number	Francken Microstrain
Silicone Grease - 0.25	Silcone Grease	0.25 +/- 0.02	0.2507	0.2517	7	6.9	87	22776
Silicone Grease - 0.25	Silcone Grease	0.25 +/- 0.02	0.2501	0.2518	15	6.7	71	18183
Silicone Grease - 0.25	Silcone Grease	0.25 +/- 0.02	0.2519	0.25	25	7.1	61	19778
Silicone Grease - 0.25	Silcone Grease	0.25 +/- 0.02	0.2498	0.2514	27	6.5	76	18881
Silicone Grease - 0.15	Silcone Grease	0.15 +/- 0.02	0.1513	0.15	8	6.9	90	19888
Silicone Grease - 0.15	Silcone Grease	0.15 +/- 0.02	0.1517	0.1514	17	7.3	63	19183
Silicone Grease - 0.15	Silcone Grease	0.15 +/- 0.02	0.1508	0.1498	26	7.1	65	18899
Silicone Grease - 0.15	Silcone Grease	0.15 +/- 0.02	0.1563	0.1538	45	6.8	81	18807
Teflon - Single	0.01-in. thick	Single	0	0	10	6.8	124	19609
Teflon - Single	0.01-in. thick	Single	0	0	18	6.7	109	20628
Teflon - Single	0.01-in. thick	Single	0	0	43	7.1	86	18536
Teflon - Single	0.01-in. thick	Single	0	0	46	6.7	106	19995
Teflon - Double	0.01-in. thick	Double	0	0	52	6.7	74	17323
Teflon - Double	0.01-in. thick	Double	0	0	53	6.6	70	17527
Teflon - Double	0.01-in. thick	Double	0	0	54	6.8	71	19434
Teflon - Double	0.01-in. thick	Double	0	0	57	6.6	72	17171
3M Dry Type - 0.15	3M Dry Type	0.15 +/- 0.02	0.0986	0.1009	11	6.7	74	20559
3M Dry Type - 0.15	3M Dry Type	0.15 +/- 0.02	0.1042	0.0935	19	7.5	61	19171
3M Dry Type - 0.15	3M Dry Type	0.15 +/- 0.02	0.0928	0.0973	28	7.1	71	19274
3M Dry Type - 0.15	3M Dry Type	0.15 +/- 0.02	0.1074	0.0983	35	7	83	19920
3M Dry Type - 0.25	3M Dry Type	0.25 +/- 0.02	0.2483	0.2507	13	6.8	65	19310
3M Dry Type - 0.25	3M Dry Type	0.25 +/- 0.02	0.248	0.2536	23	7.4	65	18450
3M Dry Type - 0.25	3M Dry Type	0.25 +/- 0.02	0.255	0.2513	30	7.2	52	19608
3M Dry Type - 0.25	3M Dry Type	0.25 +/- 0.02	0.2501	0.248	38	6.8	75	18202
Permatex Wet Type - 0.15	Permatex Wet Type	0.15 +/- 0.02	0.1507	0.1575	12	6.9	81	19658
Permatex Wet Type - 0.15	Permatex Wet Type	0.15 +/- 0.02	0.1687	0.1677	21	7.4	78	19299
Permatex Wet Type - 0.15	Permatex Wet Type	0.15 +/- 0.02	0.169	0.169	29	6.9	88	18995

Mix ID	Application Type	Target Application Rate (g)	Measured Silicone		Spcm ID	Sample Air Voids (%)	Francken Flow Number	Francken Microstrain
			Top Reducer (g)	Bottom Reducer (g)				
Permatex Wet Type - 0.15	Permatex Wet Type	0.15 +/- 0.02	0.1598	0.1689	36	7	71	19143
Permatex Wet Type - 0.25	Permatex Wet Type	0.25 +/- 0.02	0.2479	0.2524	14	6.6	59	18651
Permatex Wet Type - 0.25	Permatex Wet Type	0.25 +/- 0.02	0.2625	0.258	24	7.1	60	18556
Permatex Wet Type - 0.25	Permatex Wet Type	0.25 +/- 0.02	0.2601	0.2479	41	6.8	72	20249
Permatex Wet Type - 0.25	Permatex Wet Type	0.25 +/- 0.02	0.2605	0.2459	39	6.6	90	20163
Silicone Grease - 0.20	Silicone Grease	0.20 +/- 0.02	0.2001	0.2015	47	6.8	109	19253
Silicone Grease - 0.20	Silicone Grease	0.20 +/- 0.02	0.1992	0.1999	58	6.5	60	20155
Silicone Grease - 0.20	Silicone Grease	0.20 +/- 0.02	0.1999	0.2013	60	6.6	60	19370
Silicone Grease - 0.20	Silicone Grease	0.20 +/- 0.02	0.2003	0.2001	61	6.7	56	17461
Silicone Grease - 0.20 - 2 Wk Age	Silicone Grease - 2 wk	0.20 +/- 0.02	0.1999	0.2001	48	6.7	102	17761
Silicone Grease - 0.20 - 2 Wk Age	Silicone Grease - 2 wk	0.20 +/- 0.02	0.2003	0.2013	51	6.6	54	17659
Silicone Grease - 0.20 - 2 Wk Age	Silicone Grease - 2 wk	0.20 +/- 0.02	0.1992	0.1999	55	6.6	57	17773
Silicone Grease - 0.20 - 2 Wk Age	Silicone Grease - 2 wk	0.20 +/- 0.02	0.2001	0.2015	59	6.8	58	18364

APPENDIX D DYNAMIC MODULUS TEST RESULTS

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
3M Dry - 0.15 g	37	6.9	4	10	16212	8.1
3M Dry - 0.15 g	37	6.9	4	1	12955	10.3
3M Dry - 0.15 g	37	6.9	4	0.1	9749	13.4
3M Dry - 0.15 g	37	6.9	20	10	8621	15.7
3M Dry - 0.15 g	37	6.9	20	1	5631	20.5
3M Dry - 0.15 g	37	6.9	20	0.1	3342	25.4
3M Dry - 0.15 g	37	6.9	40	10	3004	27.7
3M Dry - 0.15 g	37	6.9	40	1	1453	30.7
3M Dry - 0.15 g	37	6.9	40	0.1	642	30.2
3M Dry - 0.15 g	37	6.9	40	0.01	275	27.2
3M Dry - 0.15 g	40	7.3	4	10	17092	8.2
3M Dry - 0.15 g	40	7.3	4	1	13603	10.6
3M Dry - 0.15 g	40	7.3	4	0.1	10167	13.8
3M Dry - 0.15 g	40	7.3	20	10	8553	16.2
3M Dry - 0.15 g	40	7.3	20	1	5500	21.1
3M Dry - 0.15 g	40	7.3	20	0.1	3199	26.1
3M Dry - 0.15 g	40	7.3	40	10	2814	28.6
3M Dry - 0.15 g	40	7.3	40	1	1328	31.5
3M Dry - 0.15 g	40	7.3	40	0.1	580	30.7
3M Dry - 0.15 g	40	7.3	40	0.01	254	26.6
3M Dry - 0.15 g	42	7.0	4	10	17495	8.0
3M Dry - 0.15 g	42	7.0	4	1	13955	10.4
3M Dry - 0.15 g	42	7.0	4	0.1	10454	13.7
3M Dry - 0.15 g	42	7.0	20	10	9016	16.2
3M Dry - 0.15 g	42	7.0	20	1	5821	21.1
3M Dry - 0.15 g	42	7.0	20	0.1	3418	26.0
3M Dry - 0.15 g	42	7.0	40	10	3021	28.4
3M Dry - 0.15 g	42	7.0	40	1	1434	31.0
3M Dry - 0.15 g	42	7.0	40	0.1	630	29.8
3M Dry - 0.15 g	42	7.0	40	0.01	277	25.5
3M Dry - 0.25 g	37	6.9	4	10	16124	8.0
3M Dry - 0.25 g	37	6.9	4	1	12885	10.3
3M Dry - 0.25 g	37	6.9	4	0.1	9682	13.5
3M Dry - 0.25 g	37	6.9	20	10	8810	15.7
3M Dry - 0.25 g	37	6.9	20	1	5734	20.4
3M Dry - 0.25 g	37	6.9	20	0.1	3389	25.3
3M Dry - 0.25 g	37	6.9	40	10	2945	28.2
3M Dry - 0.25 g	37	6.9	40	1	1412	31.2
3M Dry - 0.25 g	37	6.9	40	0.1	625	30.5

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
3M Dry - 0.25 g	37	6.9	40	0.01	275	26.6
3M Dry - 0.25 g	40	7.3	4	10	16869	8.2
3M Dry - 0.25 g	40	7.3	4	1	13496	10.5
3M Dry - 0.25 g	40	7.3	4	0.1	10101	13.8
3M Dry - 0.25 g	40	7.3	20	10	8783	16.5
3M Dry - 0.25 g	40	7.3	20	1	5670	21.3
3M Dry - 0.25 g	40	7.3	20	0.1	3341	25.8
3M Dry - 0.25 g	40	7.3	40	10	2816	29.1
3M Dry - 0.25 g	40	7.3	40	1	1323	32.3
3M Dry - 0.25 g	40	7.3	40	0.1	585	31.5
3M Dry - 0.25 g	40	7.3	40	0.01	260	26.8
3M Dry - 0.25 g	42	7.0	4	10	17469	8.0
3M Dry - 0.25 g	42	7.0	4	1	13958	10.3
3M Dry - 0.25 g	42	7.0	4	0.1	10508	13.5
3M Dry - 0.25 g	42	7.0	20	10	9064	16.2
3M Dry - 0.25 g	42	7.0	20	1	5887	20.9
3M Dry - 0.25 g	42	7.0	20	0.1	3490	25.3
3M Dry - 0.25 g	42	7.0	40	10	2911	28.2
3M Dry - 0.25 g	42	7.0	40	1	1374	30.8
3M Dry - 0.25 g	42	7.0	40	0.1	595	29.8
3M Dry - 0.25 g	42	7.0	40	0.01	258	25.7
Permatex - 0.15 g	37	6.9	4	10	16157	7.7
Permatex - 0.15 g	37	6.9	4	1	12988	9.9
Permatex - 0.15 g	37	6.9	4	0.1	9814	13.0
Permatex - 0.15 g	37	6.9	20	10	8620	15.4
Permatex - 0.15 g	37	6.9	20	1	5649	20.2
Permatex - 0.15 g	37	6.9	20	0.1	3347	25.5
Permatex - 0.15 g	37	6.9	40	10	2966	28.2
Permatex - 0.15 g	37	6.9	40	1	1430	31.4
Permatex - 0.15 g	37	6.9	40	0.1	637	31.1
Permatex - 0.15 g	37	6.9	40	0.01	279	27.7
Permatex - 0.15 g	40	7.3	4	10	16577	8.6
Permatex - 0.15 g	40	7.3	4	1	13093	11.0
Permatex - 0.15 g	40	7.3	4	0.1	9706	14.3
Permatex - 0.15 g	40	7.3	20	10	8861	16.1
Permatex - 0.15 g	40	7.3	20	1	5705	21.0
Permatex - 0.15 g	40	7.3	20	0.1	3325	26.0
Permatex - 0.15 g	40	7.3	40	10	2791	28.3
Permatex - 0.15 g	40	7.3	40	1	1311	31.0
Permatex - 0.15 g	40	7.3	40	0.1	570	29.9

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Permatex - 0.15 g	40	7.3	40	0.01	249	25.9
Permatex - 0.15 g	42	7.0	4	10	17318	8.0
Permatex - 0.15 g	42	7.0	4	1	13874	10.3
Permatex - 0.15 g	42	7.0	4	0.1	10415	13.5
Permatex - 0.15 g	42	7.0	20	10	9121	15.9
Permatex - 0.15 g	42	7.0	20	1	5928	20.8
Permatex - 0.15 g	42	7.0	20	0.1	3488	25.8
Permatex - 0.15 g	42	7.0	40	10	2823	28.9
Permatex - 0.15 g	42	7.0	40	1	1320	32.1
Permatex - 0.15 g	42	7.0	40	0.1	574	31.4
Permatex - 0.15 g	42	7.0	40	0.01	252	27.1
Permatex - 0.25 g	37	6.9	4	10	16995	7.8
Permatex - 0.25 g	37	6.9	4	1	13672	10.1
Permatex - 0.25 g	37	6.9	4	0.1	10345	13.1
Permatex - 0.25 g	37	6.9	20	10	8729	15.7
Permatex - 0.25 g	37	6.9	20	1	5684	20.6
Permatex - 0.25 g	37	6.9	20	0.1	3353	25.6
Permatex - 0.25 g	37	6.9	40	10	2882	28.3
Permatex - 0.25 g	37	6.9	40	1	1384	31.5
Permatex - 0.25 g	37	6.9	40	0.1	613	31.1
Permatex - 0.25 g	37	6.9	40	0.01	268	27.6
Permatex - 0.25 g	40	7.3	4	10	16371	8.6
Permatex - 0.25 g	40	7.3	4	1	12946	11.0
Permatex - 0.25 g	40	7.3	4	0.1	9629	14.3
Permatex - 0.25 g	40	7.3	20	10	8690	16.4
Permatex - 0.25 g	40	7.3	20	1	5565	21.2
Permatex - 0.25 g	40	7.3	20	0.1	3248	25.8
Permatex - 0.25 g	40	7.3	40	10	2776	28.3
Permatex - 0.25 g	40	7.3	40	1	1304	31.2
Permatex - 0.25 g	40	7.3	40	0.1	565	30.4
Permatex - 0.25 g	40	7.3	40	0.01	247	26.3
Permatex - 0.25 g	42	7.0	4	10	17099	7.9
Permatex - 0.25 g	42	7.0	4	1	13749	10.1
Permatex - 0.25 g	42	7.0	4	0.1	10373	13.2
Permatex - 0.25 g	42	7.0	20	10	9009	16.3
Permatex - 0.25 g	42	7.0	20	1	5831	21.1
Permatex - 0.25 g	42	7.0	20	0.1	3436	25.7
Permatex - 0.25 g	42	7.0	40	10	2930	28.7
Permatex - 0.25 g	42	7.0	40	1	1384	31.7
Permatex - 0.25 g	42	7.0	40	0.1	603	30.8

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Permatex - 0.25 g	42	7.0	40	0.01	263	26.5
Silicone - 0.15 g	37	6.9	4	10	16483	8.0
Silicone - 0.15 g	37	6.9	4	1	13179	10.2
Silicone - 0.15 g	37	6.9	4	0.1	9919	13.3
Silicone - 0.15 g	37	6.9	20	10	8925	15.8
Silicone - 0.15 g	37	6.9	20	1	5828	20.7
Silicone - 0.15 g	37	6.9	20	0.1	3459	25.6
Silicone - 0.15 g	37	6.9	40	10	2950	28.4
Silicone - 0.15 g	37	6.9	40	1	1421	31.6
Silicone - 0.15 g	37	6.9	40	0.1	633	31.2
Silicone - 0.15 g	37	6.9	40	0.01	276	27.5
Silicone - 0.15 g	40	7.3	4	10	17392	8.1
Silicone - 0.15 g	40	7.3	4	1	13914	10.4
Silicone - 0.15 g	40	7.3	4	0.1	10395	13.7
Silicone - 0.15 g	40	7.3	20	10	8802	16.5
Silicone - 0.15 g	40	7.3	20	1	5681	21.0
Silicone - 0.15 g	40	7.3	20	0.1	3338	25.5
Silicone - 0.15 g	40	7.3	40	10	2892	28.5
Silicone - 0.15 g	40	7.3	40	1	1365	31.5
Silicone - 0.15 g	40	7.3	40	0.1	599	30.7
Silicone - 0.15 g	40	7.3	40	0.01	264	26.1
Silicone - 0.15 g	42	7.0	4	10	17629	7.8
Silicone - 0.15 g	42	7.0	4	1	14158	10.2
Silicone - 0.15 g	42	7.0	4	0.1	10659	13.3
Silicone - 0.15 g	42	7.0	20	10	8931	16.1
Silicone - 0.15 g	42	7.0	20	1	5800	20.9
Silicone - 0.15 g	42	7.0	20	0.1	3437	25.5
Silicone - 0.15 g	42	7.0	40	10	3020	28.2
Silicone - 0.15 g	42	7.0	40	1	1435	30.6
Silicone - 0.15 g	42	7.0	40	0.1	632	29.3
Silicone - 0.15 g	42	7.0	40	0.01	281	25.0
Silicone - 0.25 g	37	6.9	4	10	16701	7.7
Silicone - 0.25 g	37	6.9	4	1	13522	9.8
Silicone - 0.25 g	37	6.9	4	0.1	10269	12.8
Silicone - 0.25 g	37	6.9	20	10	8690	15.9
Silicone - 0.25 g	37	6.9	20	1	5652	20.7
Silicone - 0.25 g	37	6.9	20	0.1	3335	25.7
Silicone - 0.25 g	37	6.9	40	10	3077	27.5
Silicone - 0.25 g	37	6.9	40	1	1494	30.6
Silicone - 0.25 g	37	6.9	40	0.1	661	30.3

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Silicone - 0.25 g	37	6.9	40	0.01	283	26.9
Silicone - 0.25 g	40	7.3	4	10	16653	8.7
Silicone - 0.25 g	40	7.3	4	1	13110	11.3
Silicone - 0.25 g	40	7.3	4	0.1	9667	14.5
Silicone - 0.25 g	40	7.3	20	10	8804	16.3
Silicone - 0.25 g	40	7.3	20	1	5666	21.0
Silicone - 0.25 g	40	7.3	20	0.1	3318	25.7
Silicone - 0.25 g	40	7.3	40	10	2789	28.4
Silicone - 0.25 g	40	7.3	40	1	1310	31.2
Silicone - 0.25 g	40	7.3	40	0.1	570	30.4
Silicone - 0.25 g	40	7.3	40	0.01	253	25.8
Silicone - 0.25 g	42	7.0	4	10	17455	8.2
Silicone - 0.25 g	42	7.0	4	1	13853	10.6
Silicone - 0.25 g	42	7.0	4	0.1	10344	13.8
Silicone - 0.25 g	42	7.0	20	10	9361	15.9
Silicone - 0.25 g	42	7.0	20	1	6039	20.8
Silicone - 0.25 g	42	7.0	20	0.1	3529	26.0
Silicone - 0.25 g	42	7.0	40	10	2933	29.0
Silicone - 0.25 g	42	7.0	40	1	1377	32.1
Silicone - 0.25 g	42	7.0	40	0.1	602	31.5
Silicone - 0.25 g	42	7.0	40	0.01	266	27.1
Teflon - Single	37	6.9	4	10	15786	7.9
Teflon - Single	37	6.9	4	1	12792	10.0
Teflon - Single	37	6.9	4	0.1	9852	13.0
Teflon - Single	37	6.9	20	10	8520	15.4
Teflon - Single	37	6.9	20	1	5697	20.2
Teflon - Single	37	6.9	20	0.1	3385	25.6
Teflon - Single	37	6.9	40	10	3005	28.3
Teflon - Single	37	6.9	40	1	1455	31.8
Teflon - Single	37	6.9	40	0.1	650	31.8
Teflon - Single	37	6.9	40	0.01	290	27.8
Teflon - Single	40	7.3	4	10	15930	8.4
Teflon - Single	40	7.3	4	1	12775	10.9
Teflon - Single	40	7.3	4	0.1	9538	14.2
Teflon - Single	40	7.3	20	10	8593	15.9
Teflon - Single	40	7.3	20	1	5578	20.7
Teflon - Single	40	7.3	20	0.1	3276	26.0
Teflon - Single	40	7.3	40	10	2752	28.3
Teflon - Single	40	7.3	40	1	1317	31.0
Teflon - Single	40	7.3	40	0.1	579	30.2

Friction Reducer	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Teflon - Single	40	7.3	40	0.01	263	25.0
Teflon - Single	42	7.0	4	10	16607	8.3
Teflon - Single	42	7.0	4	1	13285	10.6
Teflon - Single	42	7.0	4	0.1	9985	13.8
Teflon - Single	42	7.0	20	10	8867	16.0
Teflon - Single	42	7.0	20	1	5827	20.5
Teflon - Single	42	7.0	20	0.1	3489	25.0
Teflon - Single	42	7.0	40	10	2944	28.2
Teflon - Single	42	7.0	40	1	1419	30.8
Teflon - Single	42	7.0	40	0.1	627	29.8
Teflon - Single	42	7.0	40	0.01	282	24.9

APPENDIX E STATISTICAL ANALYSIS OF AIR VOIDS RESULTS FOR FLOW NUMBER TEST

Statistical Analysis of Air Voids Results for Eight Sets of Flow Number Specimens for Evaluating Effect of Friction Reducer Types

General Linear Model: Sample Air Voids (%) versus Mix ID

Factor Information

Factor	Type	Levels	Values
Mix ID	Fixed	8	3M Dry Type - 0.15, 3M Dry Type - 0.25, Permatex Wet Type - 0.15, Permatex Wet Type - 0.25, Silicone Grease - 0.15, Silicone Grease - 0.25, Teflon - Double, Teflon - Single

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	7	0.6897	0.09853	1.67	0.165
Error	24	1.4175	0.05906		
Total	31	2.1072			

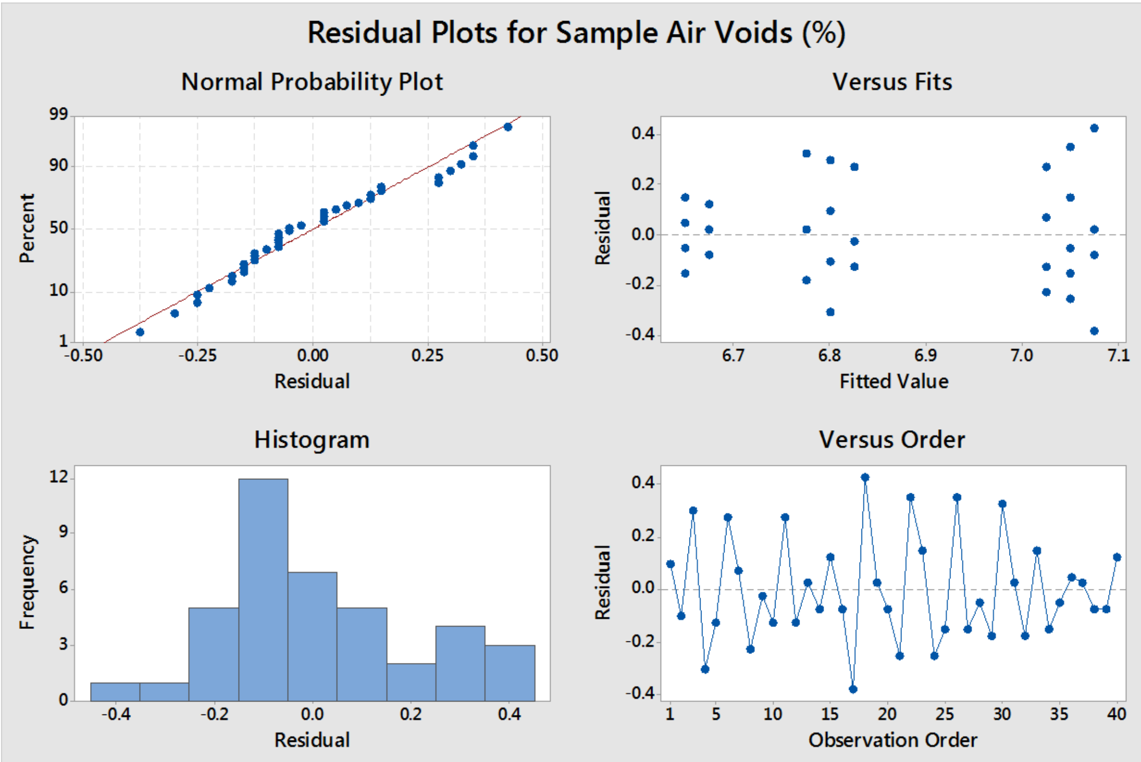
Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.243028	32.73%	13.11%	0.00%

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
3M Dry Type - 0.15	4	7.075	A
3M Dry Type - 0.25	4	7.050	A
Permatex Wet Type - 0.15	4	7.050	A
Silicone Grease - 0.15	4	7.025	A
Teflon - Single	4	6.825	A
Silicone Grease - 0.25	4	6.800	A
Permatex Wet Type - 0.25	4	6.775	A
Teflon - Double	4	6.675	A

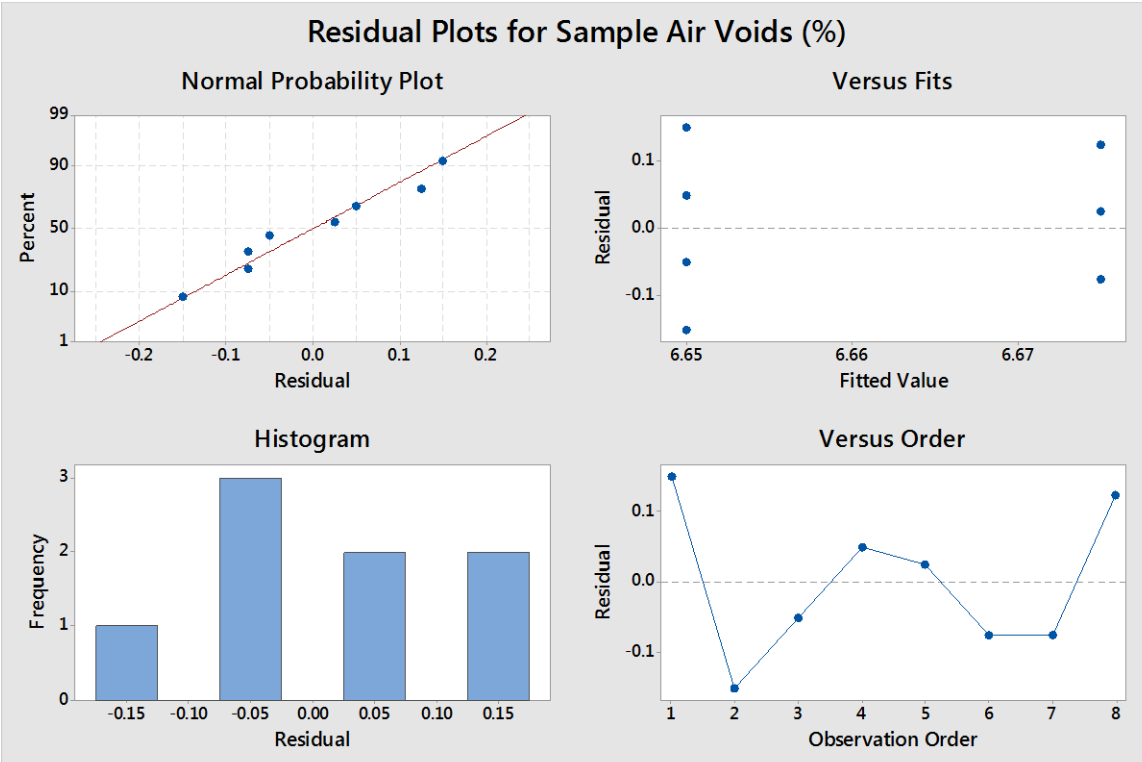
Means that do not share a letter are significantly different.



Statistical Analysis of Air Voids Results for Two Sets of Flow Number Specimens for Evaluating Effect of Reusing Latex Friction Reducers

General Linear Model: Sample Air Voids (%) versus Mix ID

```
Factor Information

Factor  Type   Levels  Values
Mix ID  Fixed       2  Silicone Grease - 0.20 - 2 Wk Age, Silicone Grease -
                       0.20 - New

Analysis of Variance

Source     DF    Adj SS    Adj MS  F-Value  P-Value
  Mix ID    1  0.001250  0.001250     0.10    0.766
Error       6  0.077500  0.012917
Total       7  0.078750

Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.113652  1.59%      0.00%       0.00%


Grouping Information Using the Tukey Method and 95% Confidence

Mix ID                             N   Mean  Grouping
Silicone Grease - 0.20 - 2 Wk Age  4  6.675  A
Silicone Grease - 0.20 - New       4  6.650  A

Means that do not share a letter are significantly different.
```


Residual Plots for Sample Air Voids (%)
Normal Probability Plot
Percent
99
90
50
10
1
-0.2
-0.1
0.0
0.1
0.2
Residual
Versus Fits
Residual
0.1
0.0
-0.1
6.65
6.66
6.67
Fitted Value
Histogram
Frequency
3
2
1
0
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
Residual
Versus Order
Residual
0.1
0.0
-0.1
1
2
3
4
5
6
7
8
Observation Order