TECHNICAL REPORT 5
RUGGEDNESS TESTING OF DISK-SHAPED COMPACT TESTION (DCT) TEST

In the month of September 2019, the research team finished the ruggedness testing of ASTM D7313-13: *Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry*, following ASTM E1169: *Standard Practice for Conducting Ruggedness Tests*. The following sections present detailed information about the Disk-Shaped Compact Tension (DCT) ruggedness test.

1. **Selection of Testing Factors and Their Levels**
   The seven factors and associated high and low levels for the DCT ruggedness testing are listed in Table 1.

Table 1. Factors and Levels for the DCT Ruggedness Testing.

No.	Factor	Standard Value	High Level (+)	Low Level (-)
A	Specimen thickness	50 mm	55 mm (Std.+5 mm)	45 mm (Std.-5 mm)
B	Notch depth	62 mm	65 mm (Std.+3 mm)	59 mm (Std.-3 mm)
C	Location of loading hole	25 mm from the notch	28 mm (Std.+3 mm)	22 mm (Std.-3 mm)
D	Air voids	7.0%	8.0% (Std.+1%)	6.0% (Std.-1%)
E	Crack Opening rate	1 mm/min	1.05 mm/min	0.95 mm/min
F	Test temperature	PG low +10 °C	PG low +11 °C	PG low +9 °C
G	Specimen conditioning time	8-16 hr	8 hr	2 hr

2. **Selection of Test Materials**
   The three asphalt mixtures used in this study are:
   - 12.5 mm virgin SMA with PG76-22 binder,
   - 12.5 mm virgin dense-graded Superpave mixture with PG64-22 binder, and
   - 9.5 mm dense-graded Superpave mixture with PG58-28 and 20% RAP binder replacement.

   Figure 1 shows the gradations for all three mixtures.

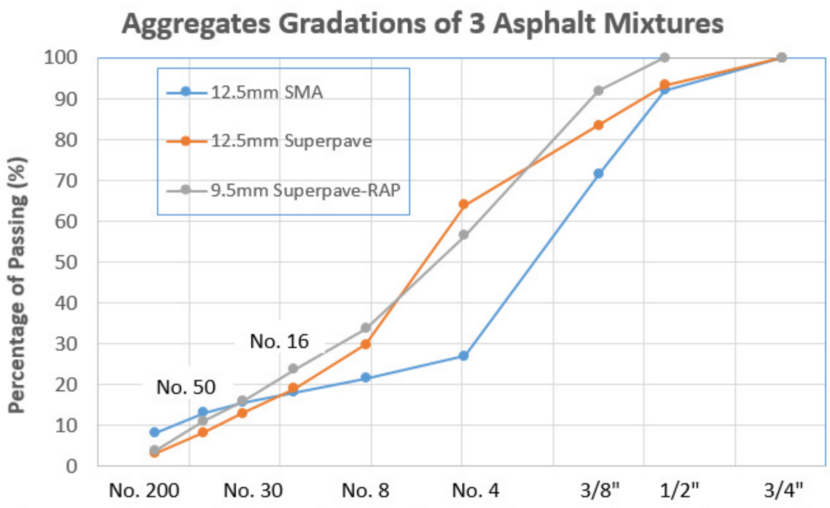

Figure 1. Aggregates Gradation for Each Asphalt Mixture.

3. PB Fractional Factorial Experimental Design

The experimental design used for this study is the Plackett-Burman (PB) fractional factorial design with two levels, seven factors, and eight runs (Table 2). The main effect refers to the difference between the average response of runs at the high level and the average response of runs at the low level. When the effect of a factor is the same regardless of the levels of other factors, then the main effect is the best estimate of the factor's effect.

Table 2. PB Experimental Design for Seven Factors.

PB Design Order	Actual Run Order	Testing Factors							Test Result	
		A	B	C	D	E	F	G	Replicate1	Replicate2
1		1	1	1	-1	1	-1	-1		
2		-1	1	1	1	-1	1	-1		
3		-1	-1	1	1	1	-1	1		
4		1	-1	-1	1	1	1	-1		
5		-1	1	-1	-1	1	1	1		
6		1	-1	1	-1	-1	1	1		
7		1	1	-1	1	-1	-1	1		
8		-1	-1	-1	-1	-1	-1	-1		
Ave +										
Ave -										
Main effect										

Note: A-specimen thickness, B-notch depth, C-location of loading hole, D-air voids, E-cracking opening rate, F-test temperature, and G-specimen conditioning time.

4. **Execution of the Experimental Design**
   Execution of the experimental runs in a random order is critical for the ruggedness testing to reduce the probability of encountering any potential effects of unknown, time-related factors. Table 3 lists the random run orders used for each of the three mixes.

   Sixteen specimens, as described in Table 3, were molded for each of the three mixtures: 12.5 mm SMA, 12.5 mm Superpave mixture, and 9.5 mm Superpave mixture. Note that the loose mixes were conditioned in the oven for 4 hrs at 135 °C before the molding. The DCT test was then conducted following the ASTM D7313-13 (see Appendix B) in the actual run order listed in Table 3. The DCT test results were fracture energy (G_f) values, tabulated in Tables 4, 5, and 6 for the 12.5 mm SMA, 12.5 mm Superpave mixture, and 9.5 mm Superpave mixture, respectively.

Table 3. Replicated Eight-Run in Random Order for the DCT Test with Seven Factors.

PB Design Order	Actual Run Order	Specimen Thickness	Notch Depth	Location of Loading Hole	Air Voids	Crack Opening Rate	Test Temperature	Specimen Conditioning Time
1	6	55 mm	65 mm	28 mm	6.0%	1.05 mm/min	PG low+9°C	2 hr
2	15	45 mm	65 mm	28 mm	8.0%	0.95 mm/min	PG low+11°C	2 hr
3	13	45 mm	59 mm	28 mm	8.0%	1.05 mm/min	PG low+9°C	8 hr
4	16	55 mm	59 mm	22 mm	8.0%	1.05 mm/min	PG low+11°C	2 hr
5	8	45 mm	65 mm	22 mm	6.0%	1.05 mm/min	PG low+11°C	8 hr
6	3	55 mm	59 mm	28 mm	6.0%	0.95 mm/min	PG low+11°C	8 hr
7	4	55 mm	65 mm	22 mm	8.0%	0.95 mm/min	PG low+9°C	8 hr
8	12	45 mm	59 mm	22 mm	6.0%	0.95 mm/min	PG low+9°C	2 hr
9	7	55 mm	65 mm	28 mm	6.0%	1.05 mm/min	PG low+9°C	2 hr
10	11	45 mm	65 mm	28 mm	8.0%	0.95 mm/min	PG low+11°C	2 hr
11	2	45 mm	59 mm	28 mm	8.0%	1.05 mm/min	PG low+9°C	8 hr
12	14	55 mm	59 mm	22 mm	8.0%	1.05 mm/min	PG low+11°C	2 hr
13	10	45 mm	65 mm	22 mm	6.0%	1.05 mm/min	PG low+11°C	8 hr
14	1	55 mm	59 mm	28 mm	6.0%	0.95 mm/min	PG low+11°C	8 hr
15	5	55 mm	65 mm	22 mm	8.0%	0.95 mm/min	PG low+9°C	8 hr
16	9	45 mm	59 mm	22 mm	6.0%	0.95 mm/min	PG low+9°C	2 hr

Table 4. DCT Test Results and Statistical Analysis for 12.5 mm SMA Mixture

PB Order	A: Specimen Thickness	B: Notch Depth	C: Location of Loading Hole	D: Air Voids	E: Crack Opening Rate	F: Test Temperature	G: Specimen Conditioning Time	Rep 1 G_f	Rep 2 G_f	Rep Ave G_f	Rep G_f Diff.
1	1	1	1	-1	1	-1	-1	841	880	861	39
2	-1	1	1	1	-1	1	-1	677	990	834	313
3	-1	-1	1	1	1	-1	1	729	473	601	-256
4	1	-1	-1	1	1	1	-1	787	991	889	204
5	-1	1	-1	-1	1	1	1	693	796	745	103
6	1	-1	1	-1	-1	1	1	1047	613	830	-434
7	1	1	-1	1	-1	-1	1	773	510	642	-263
8	-1	-1	-1	-1	-1	-1	-1	835	765	800	-70
Ave +	805.25	770.00	781.25	741.25	773.75	824.25	704.25			S_d	257.21
Ave -	744.75	780.00	768.75	808.75	776.25	725.75	845.75			S_r	181.88
Main Effect	60.50	-10.00	12.50	-67.50	-2.50	98.50	-141.50			S_{effect}	90.94

Table 5. DCT Test Results and Statistical Analysis for 12.5 mm Superpave Mixture

PB Order	A: Specimen Thickness	B: Notch Depth	C: Location of Loading Hole	D: Air Voids	E: Crack Opening Rate	F: Test Temperature	G: Specimen Conditioning Time	Rep 1 G_f	Rep 2 G_f	Rep Ave G_f	Rep G_f Diff.
1	1	1	1	-1	1	-1	-1	552	420	486	-132
2	-1	1	1	1	-1	1	-1	332	297	315	-35
3	-1	-1	1	1	1	-1	1	301	319	310	18
4	1	-1	-1	1	1	1	-1	507	529	518	22
5	-1	1	-1	-1	1	1	1	322	482	402	160
6	1	-1	1	-1	-1	1	1	332	457	395	125
7	1	1	-1	1	-1	-1	1	374	443	409	69
8	-1	-1	-1	-1	-1	-1	-1	303	383	343	80
Ave +	451.75	402.75	376.25	387.75	429.00	407.25	378.75			S_d	92.63
Ave -	342.38	391.38	417.88	406.38	365.13	386.88	415.38			S_r	65.50
Main Effect	109.38	11.38	-41.63	-18.63	63.88	20.38	-36.63			S_{effect}	32.75

Table 6. DCT Test Results and Statistical Analysis for 9.5 mm Superpave Mixture

PB Order	A: Specimen Thickness	B: Notch Depth	C: Location of Loading Hole	D: Air Voids	E: Crack Opening Rate	F: Test Temperature	G: Specimen Conditioning Time	Rep 1 G_f	Rep 2 G_f	Rep Ave G_f	Rep G_f Diff.
1	1	1	1	-1	1	-1	-1	325	293	309	-32
2	-1	1	1	1	-1	1	-1	271	383	327	112
3	-1	-1	1	1	1	-1	1	349	269	309	-80
4	1	-1	-1	1	1	1	-1	342	311	327	-31
5	-1	1	-1	-1	1	1	1	364	284	324	-80
6	1	-1	1	-1	-1	1	1	393	437	415	44
7	1	1	-1	1	-1	-1	1	276	286	281	10
8	-1	-1	-1	-1	-1	-1	-1	387	375	381	-12
Ave +	332.88	310.25	340.00	310.88	317.13	348.13	332.25			S_d	64.27
Ave -	335.25	357.88	328.13	357.25	351.00	320.00	335.88			S_r	45.45
Main Effect	-2.38	-47.63	11.88	-46.38	-33.88	28.13	-3.63			S_{effect}	22.72

5. **Statistical Analysis of Ruggedness Testing of the ASTM D7313-13 Test**

Following the procedures described in ASTM E 1169, the statistical analysis of ruggedness test was performed in the following steps for each mix tested in this study.

- *Factor Effects*

The main factor effects are the differences between average G_f values (Rep Ave) of each design factor for the two replicates. At the bottom of each column are the averages of the replicate averages corresponding to the (1) and the averages of the replicate averages corresponding to the (-1) signs in that column. For instance, the (Ave+) value for Factor A (specimen thickness) in Table 6 is the average of the G_f values corresponding to the (1= thickness 55 mm) signs in Column A: 309, 327, 415, and 281, which yield an average of 332.88. The (Ave-) value is the average of the G_f values corresponding to the (-1= thickness 45 mm) signs in Column A: 327, 309, 324, and 381, which yield an average of 335.25.

The effect row contains the difference [(Ave+)-(Ave-)] for that column, which is the result of changing Factor A (specimen thickness in this case) from low to high level. For Factor A (specimen thickness), since the Ave+ is 2.38 less than the Ave-, the effect is -2.38.

Similarly, all effects of the other six factors for each mix are calculated and presented in Tables 4, 5, and 6 for 12.5 mm SMA, 12.5 mm Superpave mixture, and 9.5 mm Superpave mixture, respectively.

- *Standard deviation of the difference, S_d*

  The standard error of effects from the dispersion of differences between replicates can be estimated through the standard deviation of the differences. For instance, in Table 6, the G_f values of the first pair of replicates are 325 and 293, and the difference between these two replicates (Rep2-Rep1) is -32. The remaining differences are 112, -80, -31, -80, 44, 10, and -12. The standard deviation of the differences (S_d) is 64.27 for the 9.5 mm Superpave mixture.

  Similarly, the standard deviation of the differences can be calculated and are listed in Tables 4, 5, and 6 for the 12.5 mm SMA, the 12.5 mm Superpave mixture, and the 9.5 mm Superpave mixture, respectively.

- *Estimate of the standard deviation of the test results, S_r*

  For replicated PB design, S_r is equal to $S_d/\sqrt{2}$. The calculated S_r for each of the three mixtures is listed in Tables 4, 5, and 6, respectively.

- *Estimate of the standard error of an effect*

  For an effect with 8 runs and 2 replicates PB design, the estimate of the standard error of an effect is calculated in Equation 1.

$$S_{effect} = \sqrt{\frac{4{S_r}^2}{8\times 2}} \tag{1}$$

  where S_{effect} is the estimate of the standard error of an effect with degrees of freedom of 7 [=(8-1)×(2-1)], and S_r is the estimated standard deviation of the test results.

  The estimated standard error of an effect for each of the three mixtures is calculated and displayed in Table 4, 5, and 6. For example, the S_{effect} value of the 9.5 mm Superpave mixture (Table 6) is 22.72.

- *Statistical Analysis to Identify Statistically Significant Effects*

  Statistical significance of the factor effects and half normal values for the half-normal plot are shown in Tables 7, 8, and 9 for the 12.5 mm SMA, 12.5 mm Superpave mixture, and 9.5 mm Superpave mixture, respectively.

  - Student's *t* test

    Dividing the effect by S_{effect} provides a Student's *t*-value, which has 7 degrees of freedom for this study. For example, the *t*-value for Effect A (specimen thickness) of the 9.5 mm Superpave mixture (Table 9) is $|-2.38|/22.72=0.1048$. The corresponding *p*-value is 0.920 (larger than 0.05). Thus, Effect A is not statistically significant factor in this case. Similarly, it can be determined whether or not all other factors for each mixture are statistically significant, as displayed in Tables 7, 8, and 9, respectively.

- Half-Normal plot

  The half-normal plots for the 12.5 mm SMA, 12.5 mm Superpave mixture, and 9.5 mm Superpave mixture are shown in Figures 2, 3, and 4, respectively. In each plot, a line for comparison of factor effects is plotted with slope determined by $1/S_{effect}$. Potentially significant effects are those which fall farthest to the right of the line. For example, in Figure 3 the significant factor for the 12.5 mm Superpave mixture is Factor A: *Specimen Thickness*. The corresponding p value for Factor A in Table 8 is 0.012 which is smaller than the significant level of 0.05. The other factors do not appear to be significant and their p values are all larger than 0.05.

  Similarly, no factor is found to be significant in either Figure 2 (the 12.5 mm SMA) or Figure 4 (the 9.5 mm Superpave mixture), and their p values are all larger than 0.05 (see Tables 7 and 9). Although Factor A (Specimen Thickness) is significant for the 12.5 mm Superpave mixture, it is not significant for the other two mixtures. Therefore, the conclusion is that no factor is considered to have significant effect on G_f values for the given factor ranges used in this DCT ruggedness testing

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Table 7. Statistical Significance of Effects for DCT Ruggedness Test: 12. 5 mm SMA

Effect Order	Factor	| Effect|	Students's *t*	*p*-value	Half-Normal
4	A (Specimen thickness)	60.50	0.67	0.527	0.674
2	B (Notch depth)	10.00	0.11	0.916	0.272
3	C (Location of loading hole)	12.50	0.14	0.895	0.464
5	D (Air voids)	67.50	0.74	0.482	0.921
1	E (Crack opening rate)	2.50	0.03	0.979	0.09
6	F (Test temperature)	98.50	1.08	0.315	1.242
7	G (Specimen conditioning time)	141.50	1.56	0.164	1.803

Table 8. Statistical Significance of Effects for DCT Ruggedness Test: 12. 5 mm Superpave Mixture

Effect Order	Factor	| Effect|	Students's t	p-value	Half-Normal
7	A (Specimen thickness)	109.38	3.34	0.012	1.803
1	B (Notch depth)	11.38	0.35	0.739	0.09
5	C (Location of loading hole)	41.63	1.27	0.244	0.921
2	D (Air voids)	18.63	0.57	0.587	0.272
6	E (Crack opening rate)	63.88	1.95	0.092	1.242
3	F (Test temperature)	20.38	0.62	0.554	0.464
4	G (Specimen conditioning time)	36.63	1.12	0.300	0.674

Table 9. Statistical Significance of Effects for DCT Ruggedness Test: 9. 5 mm Superpave Mixture

Effect Order	**Factor**	**| Effect|**	**Students's t**	**p-value**	**Half-Normal**
1	A (Specimen thickness)	2.38	0.10	0.920	0.09
7	B (Notch depth)	47.63	2.10	0.074	1.803
3	C (Location of loading hole)	11.88	0.52	0.617	0.464
6	D (Air voids)	46.38	2.04	0.081	1.242
5	E (Crack opening rate)	33.88	1.49	0.180	0.921
4	F (Test temperature)	28.13	1.24	0.256	0.674
2	G (Specimen conditioning time)	3.63	0.16	0.878	0.272

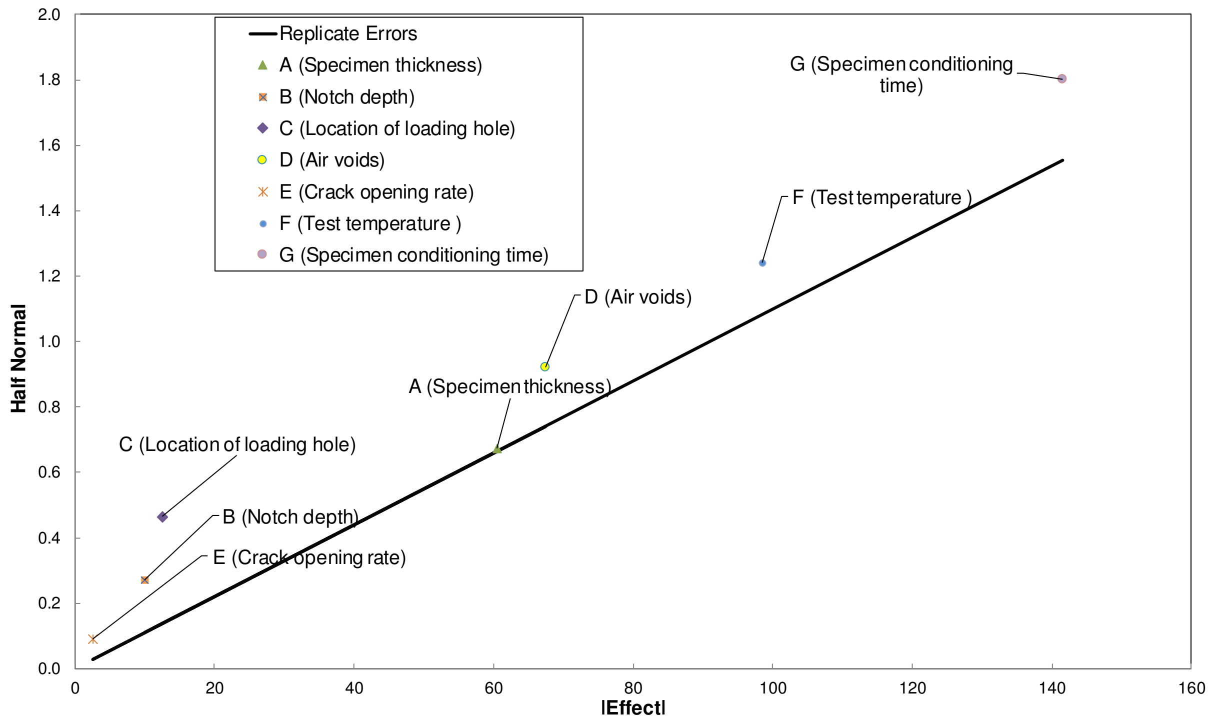

Figure 2. Half-Normal Plot: DCT Ruggedness Test with the 12.5 mm SMA.

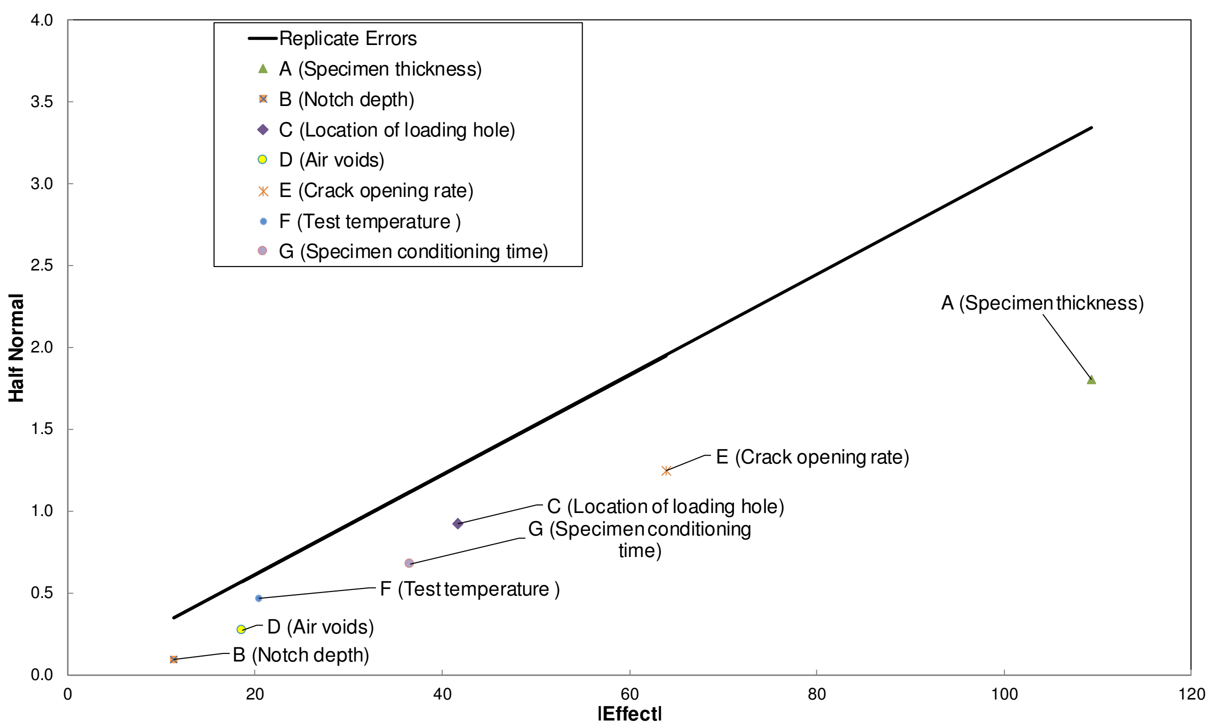

Figure 3. Half-Normal Plot: DCT Ruggedness Test with the 12.5 mm Superpave Mixture.

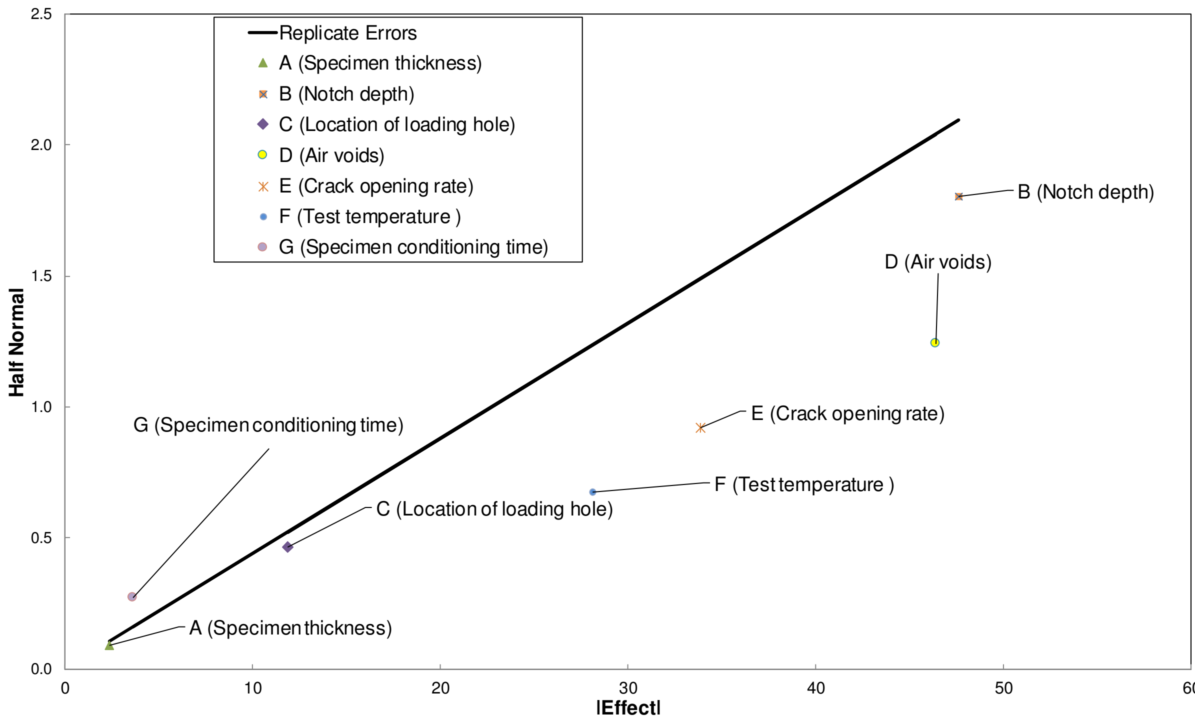

Figure 4. Half-Normal Plot: DCT Ruggedness Test with the 9.5 mm Superpave Mixture.

6. Estimating Non-significance Intervals for Significant Factors

As identified previously, only one factor is significant for the 12.5 mm Superpave mixture. When a factor has a significant effect on the test result, one can estimate its tolerance with the following equations:

$$\left[-\frac{|X_{(1)}-X_{(-1)}|E_{critical}}{2|E_X|}, +\frac{|X_{(1)}-X_{(-1)}|E_{critical}}{2|E_X|}\right] \tag{2}$$

where $X_{(1)}$ and $X_{(-1)}$ are the real values of factor X for the High (+) and Low (-) Level respectively (as seen in Table 1); E_x is the effect of the factor; and $E_{critical}$ is the critical effect, which can be determined by the following equation:

$$E_{critical} = t_{critical} \times S_{effect} \tag{3}$$

where S_{effect} is the estimate of the standard error (same in Equation 2), and $t_{critical}$ is the two-tailed inverse of the Student's *t*-distribution which equals 2.3646 when calculated at a significance level of 0.05 with degrees of freedom of 7.

Table 10 shows the estimated tolerance of Factor A (Specimen Thickness) for the 12.5 mm Superpave mixture.

Table 10. Estimated Tolerance of Factor A (Specimen Thickness) for the 12.5 mm Superpave Mixture

Factor	Tolerance
A (Specimen Thickness), mm	±3.5

7. **Revision of the ASTM D7313-13 Test Method**

   Table 11 lists the seven factors used in this study and associated tolerance for each factor specified in ASTM D7313-13. Although only one factor is identified as significant factor for the 12.5 mm Superpave mixture alone, the revision of the ASTM D7313-13 DCT test method should be considered, as it may be necessary to relax some specific requirements of those non-significant factors. Therefore, all seven factors are discussed below:

   - *Specimen Thickness*
     As shown in Table 10, the tolerance for the specimen thickness for the 12.5 mm Superpave mixture is ±3.5 mm. The current tolerance for the specimen thickness in ASTM D7313-13 is ±5 mm. The research team recommends changing the tolerance of the specimen thickness to ±3.5 mm to be conservative.
   - *Notch Depth*

     According to the notch depth and location described in ASTM D7313-13, "Fig. 3 DCT Specimen Dimensions", current tolerance of the notch depth is ±2.5 mm. The tolerance of the notch depth (Factor B) used in this study is ±3 mm, and Factor B was not found to be significant for all three mixtures. Since there is not a big difference between ±2.5 mm and ±3.0 mm, and it will not matter to specimen preparation if the tolerance is increased to ±3.0 mm, the tolerance of the notch depth is kept the same as it is in the current method: ±2.5 mm.
   - *Location of Loading Hole*

     According to "Fig. 3 DCT Specimen Dimensions" in ASTM D7313-13, the tolerance of the location of the loading hole is ±2.5 mm (from the center of the hole to the center of the notch). The tolerance of the location of loading hole (Factor C) used in this study was ±3 mm, and it was found non-significant for all three mixtures. Similar to the notch depth, the tolerance of the location of loading hole is kept the same as it is in the current test method: ±2.5 mm.
   - *Air Voids*

     Air void tolerance of DCT specimens is not required in current ASTM D7313-13. The tolerance of the air voids (Factor D) used in this study was ±1%. Although Factor D, the air voids of DCT specimens, was found non-significant for all three mixtures, the air void content has always been a critical variable for preparing test specimens. Thus, the research team believes that it is important to have some guidance for specimen preparation. The recommendation is to add a subsection for the air void requirement of test specimens in ASTM D7313-13, as described below:

6.2.2 *Specimen Air Void — The air void of the disk-shape specimens with a thickness of 50±3.5 mm, before notching and drilling holes, shall be 7±1%.*

- *Crack Opening Rate*

ASTM D7313-13 indirectly specifies a tolerance of ±0.00034 mm/s (±0.000013 in./s) under Section 8.1.4 which is ±2% of the specified loading rate and may be overly strict. The tolerance of the crack opening rate (Factor E) used in this study is ±0.0008 mm/s (±5% of the specified loading rate). As presented previously, the crack opening rate is not a significant factor. Thus, the research team recommends increasing the tolerance to ±5% of the specified loading rate. The recommended change to ASTM D7313-13 is noted below:

"8.1.4 *For a valid test, the rate (a_1) shall be within 5 % of the expected rate defined in 7.3 (±0.0008 mm/s (±0.00003 in./s)).*"

- *Test Temperature*

Section 7.1 of ASTM D7313-13 currently requires that "*The temperature shall be within ±0.2°C (±0.4°F) throughout the conditioning and testing times*." There are two issues with this requirement: (1) It is very strict and difficult to meet for most conditioning temperature chambers; and (2) It does not specify the temperature of test specimen or air temperature of the testing chamber or conditioning chamber. Note that the test specimen temperature could be much different from the air temperature of the testing chamber. For example, this could happen when one moves a DCT specimen out of a conditioning chamber to the DCT test machine and then inserts the specimen into the loading fixture. This process may take 2-5 min. During this testing setup period, the testing chamber lid (or door) has to be kept open. Consequently, both test specimen temperature and the air temperature of the testing chamber become much higher than the desired testing temperature. After closing the testing chamber lid (or door), the air temperature of the testing chamber starts dropping, but the specimen temperature may still rise and then drop after a while. Thus, it is necessary to clarify the temperature issue.

This study employed a dummy specimen instrumented with a temperature probe to monitor the temperature variation during the period of specimen setting up in the testing chamber. Thus, a total of three temperatures are involved in this study: air temperature of the conditioning chamber, dummy specimen temperature within the testing chamber, and air temperature of the testing chamber. As expected, the dummy specimen temperature rose significantly when the testing chamber lid (or door) was open in order to insert a DCT specimen into the fixture. Furthermore, the dummy specimen temperature continued rising even after closing the lid (or door) of the testing chamber. It took approximately 1 hour for the dummy specimen to restore its original temperature and to maintain it within ±0.2°C (±0.4°F) throughout the testing time.

Meanwhile, this study evaluated the effect of temperature variation: ± 1°C with actual test temperatures of -11 °C and -13 °C. As shown previously, the test temperature is not a significant factor for all three mixtures. Thus, it is unnecessary to have such strict tolerance of the test temperature. Considering the fact that the standard temperature accuracy (or tolerance) for most temperature chambers is ±0.5°C, the research team recommends changing the temperature tolerance from ±0.2°C to ±0.5°C. Furthermore, it is necessary to wait for the test specimen temperature to stabilize within ±0.5°C of the desired test temperature. After this, DCT test may be performed as described in Section 7.3.

- *Specimen Conditioning Time*

  ASTM D7313-13 requires that "*The specimens shall be placed in a temperature-controlled chamber for a minimum of 8 h and a maximum of 16 h at the desired test temperature*" under Section 7.1. It is obvious that this requirement makes the DCT test very impractical to conduct on a daily basis. This study evaluated two specimen conditioning times: 2 h and 8 h with a goal of identifying the minimum conditioning time. As shown previously, the specimen condition time was found non-significant for all three mixtures. In order to make the DCT test more practical, the research team recommends revising the conditioning time to "*a minimum of 2 h and a maximum of 16 h at the desired test temperature*" under Section 7.1.

In summary, the research team recommends changes to the current version of ASTM D7313-13, as listed in Table 11. A revised D7313-13 is documented in Appendix B (in a separated file).

Table 11. Recommended Tolerances for the Seven Factors of the DCT Test

Factor	Tolerance used in NCHRP 9-57A	Current Requirement in ASTM D7313-13	Recommended Tolerance
A (Specimen thickness), mm	±5	±5	±3.5
B (Notch depth), mm	±3	±2.5	±2.5
C (Location of loading hole), mm	±3	±2.5	±2.5
D (Air voids), %	±1.0	None	± 1.0
E (Crack opening rate), mm/min	±0.05	±0.02	±0.05
F (Test temperature), °C	±1.0	±0.2	±0.5
G (Specimen conditioning time), hr	2-8	8-16	2-16