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Sensitivity Analysis on Semi-Circular Bending Tests Using the Plackett-Burman Matrix

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SENSITIVITY ANALYSIS ON SEMI-CIRCULAR BENDING TESTS USING THE PLACKETT-BURMAN MATRIX

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16. Abstract

Fatigue resistance of asphalt concrete (AC) is defined as the ability of the AC to resist repeated traffic loading without significant cracking or failure (Harvey et al. 1995). Fatigue cracking refers to primary distress in asphalt concrete due to repetitive stress and strain caused by traffic loading. Several fatigue tests were developed to investigate the fatigue resistance of AC. Fatigue cracking is often associated with loads that are too heavy for a pavement structure. It is also associated with many repetitions of a given load (Roberts et al. 2009).

There have been multiple standards and tests to make sure that asphalt concrete mixture can withstand traffic load. The Semi-Circular Bending (SCB) test is a standardized test accredited by ASTM to compare the cracking resistance of asphalt mixtures prepared with different binder grades and aggregate types.

The SCB test has plenty of parameters that affect its results. In this study, some of these parameters are examined to ascertain the impact of each of these parameters on SCB test results. Examining all these parameters would be cumbersome using traditional statistical techniques, as they require a significant number of samples. The Plackett-Burman (PB) technique was used to perform a sensitivity analysis. The PB method relies on a limited number of scenarios to study the effects of multiple parameters. Seven parameters have been examined and include, notch location, notch depth low, intermediate and high, air voids, loading rate, and span length. Even with the usage of the PB technique there have been 16 scenarios that need to be tested for each of the three notch depths; whereby the process requires plenty of time and material. In order to turn around this problem, a Discrete Element Method (DEM) is used to develop a model that will substitute the need for an actual lab test. Results showed that the most positively impactful parameters on the SCB test results were intermediate notch depth and notch location, while the most negatively impactful parameters were loading rates and air voids.

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EXECUTIVE SUMMARY

Fatigue resistance of asphalt concrete (AC) is defined as the ability of the AC to resist repeated traffic loading without significant cracking or failure (Harvey et al. 1995). Fatigue cracking refers to primary distress in asphalt concrete due to repetitive stress and strain caused by traffic loading. Several fatigue tests were developed to investigate the fatigue resistance of AC. Fatigue cracking is often associated with loads that are too heavy for a pavement structure. It is also associated with many repetitions of a given load (Roberts et al. 2009).

There have been multiple standards and tests to make sure that asphalt concrete mixture can withstand traffic load. The Semi-Circular Bending (SCB) test is a standardized test accredited by ASTM to compare the cracking resistance of asphalt mixtures prepared with different binder grades and aggregate types.

The SCB test has plenty of parameters that affect its results. In this study, some of these parameters are examined to ascertain the impact of each of these parameters on SCB test results. Examining all these parameters would be cumbersome using traditional statistical techniques, as they require a significant number of samples. The Plackett-Burman (PB) technique was used to perform a sensitivity analysis. The PB method relies on a limited number of scenarios to study the effects of multiple parameters. Seven parameters have been examined and include, notch location, notch depth low, intermediate and high, air voids, loading rate, and span length. Even with the usage of the PB technique there have been 16 scenarios that need to be tested for each of the three notch depths; whereby the process requires plenty of time and material. In order to turn around this problem, a Discrete Element Method (DEM) is used to develop a model that will substitute the need for an actual lab test.

Results showed that the most positively impactful parameters on the SCB test results were intermediate notch depth and notch location, while the most negatively impactful parameters were loading rates and air voids.

I. INTRODUCTION

Proper installation and rehabilitation could make asphalt pavement last up to 40 years. Asphalt concrete (AC) is a material mix commonly used in pavement design. AC is a mixture of binder, aggregates and air voids, the proportions of which affect AC characteristics. For example, increasing or decreasing air voids changes the durability of the AC mixture. Over the life of the pavement, it may undergo different surface and layer failures such as alligator cracking, potholes, upheaval, raveling, bleeding, rutting, shoving, stripping, and grade depressions. The AC layer can be the reason behind some of these failures, which is why there have been multiple standardized tests to study the durability of the mix in order to prevent these failures. In this study, we the authors, will study and analyze crack initiation and propagation in the Semi-Circular Bending test (SCB) based on a developed SCB model.

The American Society for Testing and Materials (ASTM) is an international standard organization that develops and publishes new test methods and specification to determine suitable material to use in its designated field. The Semi-Circular Bending test (SCB) was developed by Louisiana State University (LSU) and was later adopted by ASTM to evaluate or compare the cracking resistance of asphalt mixtures, different binder grades, and aggregate types. In the SCB test, a cylinder of the AC mixture is compacted with 57 mm thickness and 150 mm diameter. The sample is cut in half to resemble a semicircle, after that three semicircles are notched through the center to three different depths: 25 mm, 32 mm, and 38 mm (ASTM D8044, 2016).

Ever since simulation technology started to develop, the idea of modeling standardized tests to simulate these tests with computer programs has started to become a point of interest for plenty of researchers. Modeling these tests reduces the experiment duration and the material consumption used in the experimentation. One of the commonly used methods for asphalt modeling is the discrete element method (DEM). DEM was introduced by Cundall (1971) to study interactions between assembles of particles. Afterwards, DEM was extended to study rock mechanics, soils, granular materials, and asphalt mixes (Mahmoud et al. 2016).

Standardized test methods have been developed through mechanical equations, empirical experiments, or a combination of both. Due to the variability in empirical experiments, numerical or statistical approaches have been used to confirm the accuracy of that standardized test. The SCB test is a relatively new test, currently used to determine the resistance to cracks in asphalt mixtures. Even though it has been used as a standardized test, there has been controversy about its procedure along with its viability to predict its results under different temperatures. In this study, a sensitivity analysis will be performed on the following parameters of the SCB test (notch location, notch depth low, intermediate and high, air voids, loading rate, and span length) to investigate their effect on the test results.

Sensitivity analysis is a study that examines the changes in the results of a test based on variations in the inputs of that test. In this study, Plackett–Burman statistical analysis will be used to analyze the sensitivity of SCB test parameters.

II. LITERATURE REVIEW

The DEM has proven to be a suitable modeling approach to simulate the Semi-Circular Bending (SCB) test. Mahmoud et al. (2016) used homogenous 2D DEM H2DEM to predict the stiffening effect of Reclaimed Asphalt Pavement (RAP) asphalt mixtures. Their research, in particular, was able to predict the results accurately with different notch depths. Mahmoud et al. (2016) further used the DEM to model the fracture of asphalt mixtures in SCB. The authors used a bilinear cohesive zone bond to model the crack initiation in their study. To verify the model's prediction, an SCB test was done in a lab. Semi-circular samples used in the experiment were in three notch depths of 25.4, 31.8, and 38.0 mm.

Mahmoud et al. (2016) investigated the ability to use an H2DEM model to simulate the fracture of asphalt mixtures; the study was especially focused on RAP. Researchers conducted simulations to understand the effect of load on stiffness and contact bond strength for homogeneous models. They also calibrated a heterogeneous DEM model to study the same effects in RAP asphalt mixtures. In their final analysis, the authors found that the discrete element method has proven to be a suitable modeling approach to simulate the SCB test. Crack initiation and propagation were successfully simulated using the DEM model. Mahmoud's work demonstrates that it is possible to successfully predict the SCB results for any notch depth, after calibrating the DEM model (Mahmoud et al. 2016).

Saadeh et al. (2018) performed the SCB test numerical evaluation using DEM. Aggregates were taken from aggregate image measurement system (AIMS) which provided dimensions for the aggregates and the angularity. Aggregates passing No. 8 sieves were neglected since they have the ability to cause delays in simulation or unexpected results. In the mix, 4% air voids were used. The air particles in the model were generated as 1 mm diameter clumps and were randomly distributed in the model. PFC2D clumps were generated in a non-overlapping manner, that every new model had different aggregate and air locations, though still under the domain of normal distribution for the model.

To verify the suitability of the DEM model of the SCB test Saadeh et al. (2018) ran a total of 100 cases—50 for each of the mix combination. Two mix combinations were used: Superpave and coarse matrix high binder (CMHB). Their results indicated that the SCB test was affected by the following parameters: mix gradation; aggregate angularity; air voids location in the sample; and interface properties. High angularity aggregates increased peak forces for Superpave and CMHB. Changes in peak force was not noticed in low angularity mixtures. SCB tests, furthermore, can be considered a repeatable cracking test since the COV values obtained from the tests were less than 0.300.

The Plackett–Burman sensitivity analysis (PBSA) technique allows for the concurrent consideration of numerous parameters. Beres and Hawkins (2001) presented an explanation on how to utilize the PB technique for sensitivity analysis for a multi-parameter model. In their research they illustrated that PBSA is not a one-at-a-time (OAAT) method making it require a smaller number of scenarios compared to OAAT methods. PBSA is not restricted by complicated conditions, thus making it easier to apply it on any model. Also, PBSA can be used on numerical and non-numerical parameters and does not require parameter limits to be identical. Moreover, it is possible to use this method to acquire information about how two parameters interact. Their results demonstrate that it is possible to use this method, despite its many drawbacks. The data, for example, might cause an aliasing among the interactions, and confusion when interpreting the data. In this research, PBSA will be used on SCB test parameters to determine the most effective parameters on the SCB test.

III. OBJECTIVE

In this study, the effect of the parameters (notch location and depth low, medium and high, air void content, loading rate, and span length) will be analyzed and their impact on the output of the SCB test results will be measured using the PBSA within the permitted upper and lower limits for these parameters. These limit values will be provided in the methodology section. In addition, crack initiation and propagation will be drawn and tracked through the SCB test sample.

IV. METHODOLOGY

DISCRETE ELEMENT METHOD (DEM)

The principle behind the DEM is based on applying laws of motion and force-displacements on small discrete elements. The discrete elements are connected by a bond between these elements to simulate a grid of the objective material. Bond characteristics are defined with limiting strength at contact points between the discrete elements to simulate a continuum solid, and once the forces at the contact exceed the specified strength, the bond breaks. Progressive breakage of bonds in the assembly represent the fracture behavior, i.e., crack initiation and propagation (PFC2D, 2018).

In this study, DEM modeling will be developed using PFC2D software. PFC2D is a commonly used software for developing the DEM model as seen in the literature. PFC2D uses different bond options depending on the material type that will be simulated, which simplifies the bonding calculations. The user can also create their own bond properties. PFC2Dcan also import images that resemble aggregates' gradation or angularity making the model more realistic.

TESTING FACTORIAL

The SCB test has many parameters that affect its output table. Table 1 shows the main parameters that will be tested on their impact on the SCB.

Table 1. SCB Test Factors

Test	Factor	Standard Level	High Level (+)	Low Level (-)
SCB test (ASTM D8044)	Notch location (mm)	Center of the specimen	3 mm to the right	3 mm to the left
	Low notch depth (mm)	25	26	24
	Intermediate notch depth (mm)	32	33	31
	High notch depth (mm)	38	39	37
	Air void (%)	7	8	6
	Loading rate (mm/min)	0.5	0.525	0.475
	Span (mm)	127	128	126

PLACKETT–BURMAN SENSITIVITY ANALYSIS

PBSA is a methodology that reduces the number of scenarios required to analyze a test's sensitivity output without reducing the number of input parameters. PBSA follows a simple mathematical idea, where instead of changing one parameter on its own and stabilizing the rest, we can change every parameter simultaneously. The change follows a matrix called the Plackett–Burman (PB) matrix. Since the matrix consists of different parameter values in each row, the result can be interpolated into the effect of each parameter on the whole test.

Parameters used in the matrix will have an upper value and a lower value (a maximum and a minimum); these values will be used in the matrix as (+) and (-). The number of rows in the matrix is determined by the number of parameters tested. Seven parameters will be studied in this research which means that the rows in the upper matrix will be at least the number of these parameters plus one row and then rounded to the closest highest multiplier of four, i.e., 4, 8, 12, 16, etc. Afterwards, the number of rows is multiplied by two in order to get the complete PB matrix. In this study, the number of parameters were seven, which means eight rows for the upper matrix and 16 for the PB matrix. Each row is a scenario that has to be tested or, in this case, simulated. The PB matrix is constructed based on the PB pattern, the pattern changes depending on the number of parameters that will be examined. The pattern changes for every four additional parameters starting by three parameters. Here, the following pattern (+ + + - + - -) will be utilized for the first row, based on the number of parameters to be examined. Furthermore, the pattern is shifted to the right for the next row until the 7th row in the matrix is completed. Then, the 8th row consists of negatives, as shown in Figure 1.

+	+	+	-	+	-	-
-	+	+	+	-	+	-
-	-	+	+	+	-	+
+	-	-	+	+	+	-
-	+	-	-	+	+	+
+	-	+	-	-	+	+
+	+	-	+	-	-	+
-	-	-	-	-	-	-

Figure 1. Upper PB Matrix for 7 Parameters

The upper matrix is used to get the complete matrix by reversing the signs of the eight rows in the upper matrix and adding them as the lower matrix Figure 2.

+	+	+	-	+	-	-
-	+	+	+	-	+	-
-	-	+	+	+	-	+
+	-	-	+	+	+	-
-	+	-	-	+	+	+
+	-	+	-	-	+	+
+	+	-	+	-	-	+
-	-	-	-	-	-	-
-	-	-	+	-	+	+
+	-	-	-	+	-	+
+	+	-	-	-	+	-
-	+	+	-	-	-	+
+	-	+	+	-	-	-
-	+	-	+	+	-	-
-	-	+	-	+	+	-
+	+	+	+	+	+	+

Figure 2. Complete PB Matrix for 7 Parameters

After that, the scenarios were applied based on the PB matrix as in Table 2.

Table 2. Scenarios of the Test Based on PB Matrix

Scenario's number	Notch location (mm)	Low notch depth (mm)	Intermediate notch depth (mm)	High notch depth (mm)	Air voids (%)	Loading rate (mm/min)	Span (mm)
Scenario 1	+1	26	33	37	8	0.475	126
Scenario 2	-1	26	33	39	6	0.525	126
Scenario 3	-1	24	33	39	8	0.475	128
Scenario 4	+1	24	31	39	8	0.525	126
Scenario 5	-1	26	31	37	8	0.525	128
Scenario 6	+1	24	33	37	6	0.525	128
Scenario 7	+1	26	31	39	6	0.475	128
Scenario 8	-1	24	31	37	6	0.475	126
Scenario 9	-1	24	31	39	6	0.525	128
Scenario 10	+1	24	31	37	8	0.475	128
Scenario 11	+1	26	31	37	6	0.525	126
Scenario 12	-1	26	33	37	6	0.475	128
Scenario 13	+1	24	33	39	6	0.475	126
Scenario 14	-1	26	31	39	8	0.475	126
Scenario 15	-1	24	33	37	8	0.525	126
Scenario 16	+1	26	33	39	8	0.525	128

The three notches cannot be examined in the same scenario, because every notch has its own model. Because of this, an alternative idea was established. Instead of making 16 scenarios for the three notches, we decided on 48 different scenarios. In other words, each notch will have 16 scenarios. This concludes the preparations of the scenarios and the start of modeling.

MATERIAL PROPERTIES

Materials modeled in this study are based on their properties in reality. Mixture used in the model are based on the CMHB mixture design. Aggregate angularity was extracted from AIMS. AIMS is an image capturing system designed to capture the angularity of the aggregates. 120 different aggregates images are used with low and high angularities. Figures 3 and 4 show the images for those aggregates, aggregates used in the modeling had the strength properties of granite. Aggregates gradation used in the model was based on the CMHB design gradation as seen in Table 3. After analyzing the model based on the previous mentioned gradation the aggregate that passed sieve #8 caused longer runs and unstable results. Because of this, aggregates passing #8 were removed and an adjusted gradation was established, as seen in Table 4.

Table 3. Gradation Test for CMHB Mixtures

Sieve #	Sieve size (mm)	% Retained
	25.40	0
	19.05	1
	12.70	21
	9.53	19
4	4.75	23
8	2.36	16
16	1.19	6

Table 4. Adjusted Gradation Test for CMHB Mixtures

Sieve #	Sieve size (mm)	% Retained
	25.40	0
	19.05	1
	12.70	26
	9.53	24
4	4.75	29
8	2.36	20
16	1.19	0

An asphalt binder was introduced as a linear bond in the program which meant it only had elastic properties without viscous properties. The density for the asphalt was assumed to be 1500 Kg/m^3 and the bond strength was assumed to be 33 KPa for tensile strength and 1.5 GPa for the shear strength, while the bond between asphalt and aggregates was 150 KPa for tensile strength and 1.5 GPa for the shear strength.

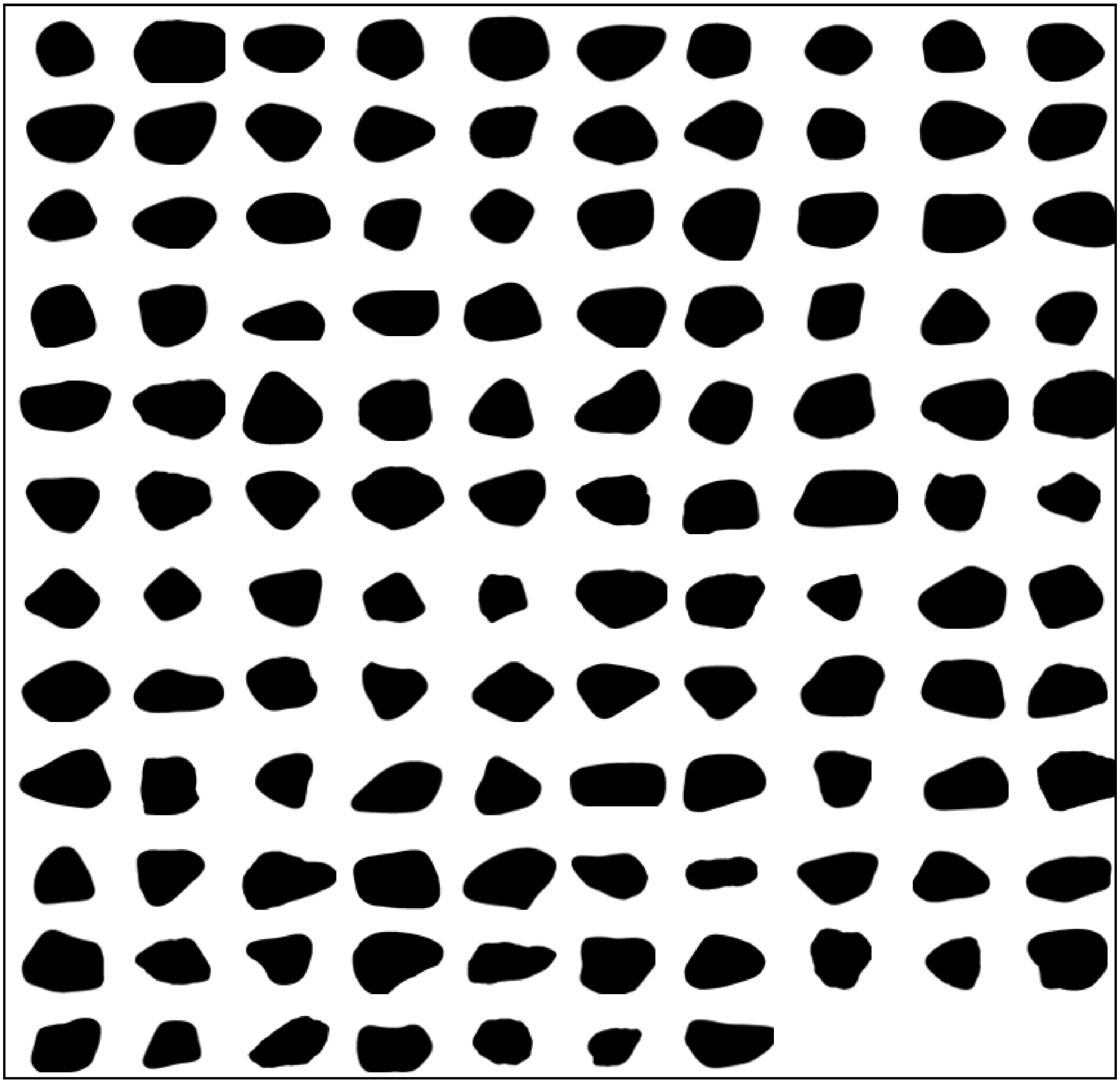

Figure 3. Low Angularity Aggregates

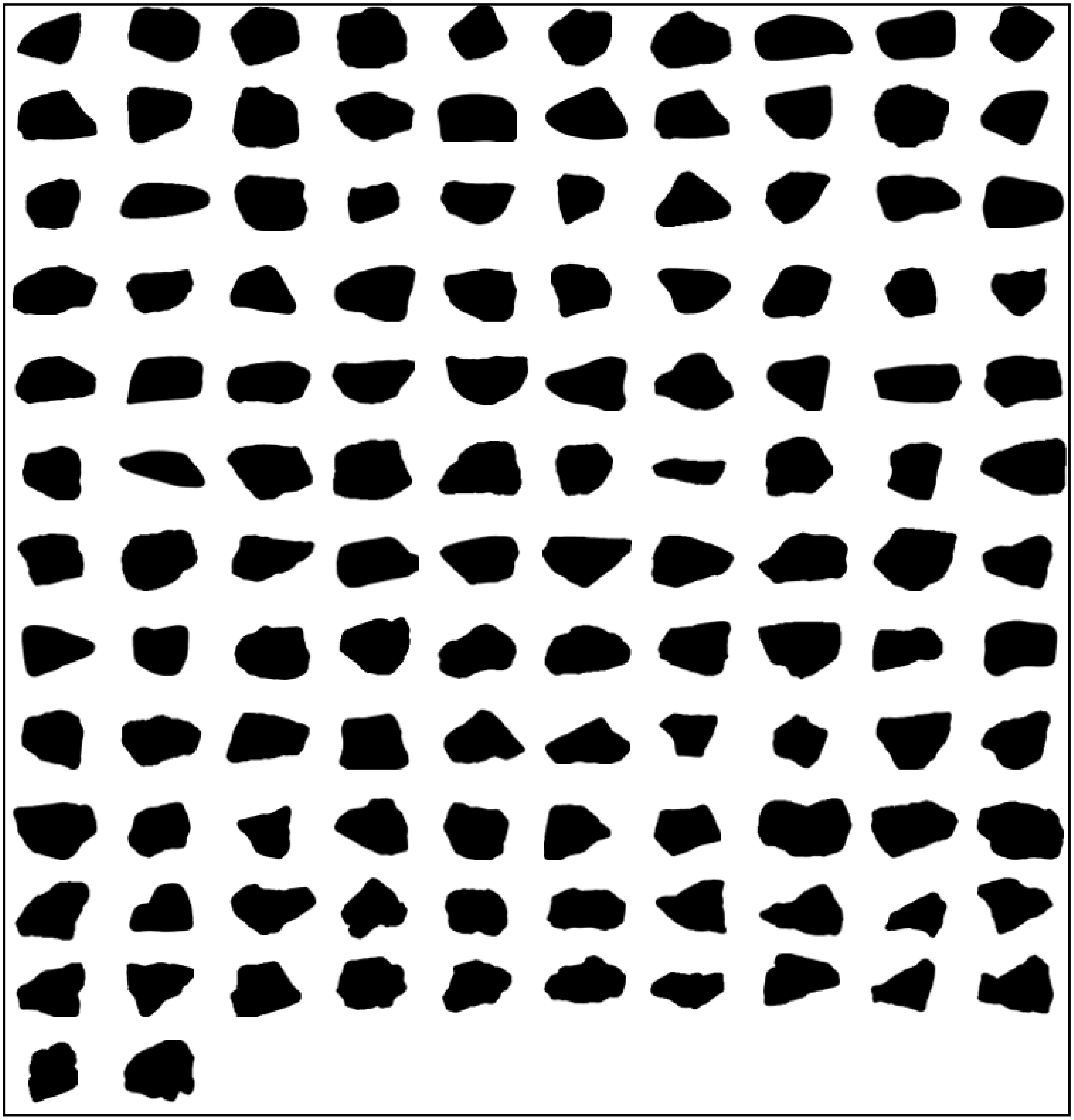

Figure 4. High Angularity Aggregates

MODELING

Models developed by PFC2D (2018) have three different body types, which consist of balls, walls, and clumps (Potyondy 2018). Each body has its own surface characteristics A ball is defined as a solid piece, while an assembly of balls resembles material that is usually the main focus of the model. A wall, or a facet, determines the shape of the sample and how it is constrained or formed. Finally, clumps, or pebbles, are similar to balls in regard to resembling material the difference between them is that clumps can overlap to make a bigger sized clump with a non-uniform shape while balls do not. Clumps are used usually when making a non-circular material shape, while balls are preferred in our case for circular shaped material. Figure 5 shows three body types and their interaction.

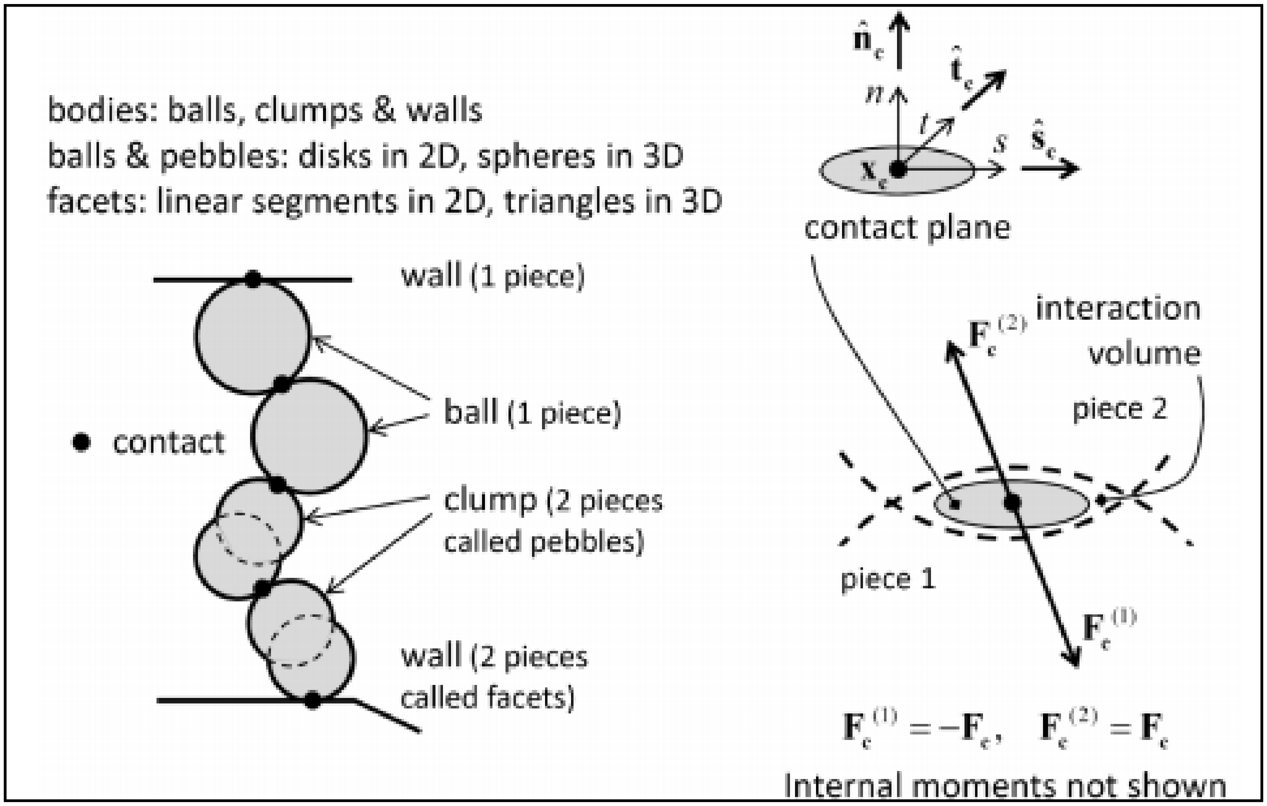

Figure 5. PFC2D Body Types (Potyondy, 2018)

The models developed in this study were built over five stages. Starting with stage one, the shape of the model was constructed using three different walls: one for the circular shape, another to cut the circle into a semi-circle and the last to shape the notch as seen in Figure 6.

Modeling started with the making of a circular shape containing homogeneous particles resembling the shape of the circular sample depending on its parameter. Later on, a wall was introduced to resemble the cut that makes a semi-circular shaped model. After that, a rectangular-shaped hollow was added in the middle to mimic the shape of the notch in the model, generating a homogeneous semicircular notched model in Figure 7.

After that, aggregates and air voids were generated in a different model. Aggregates angularities and shapes were imported from the AIMS and were defined as clumps to resemble how aggregates function in AC mixtures. Aggregates were randomly generated within the semi-circular model and, air voids were randomly generated as clumps between the aggregates with area percentage as specified by the scenarios table mentioned above. Figure 8 shows an example of this step.

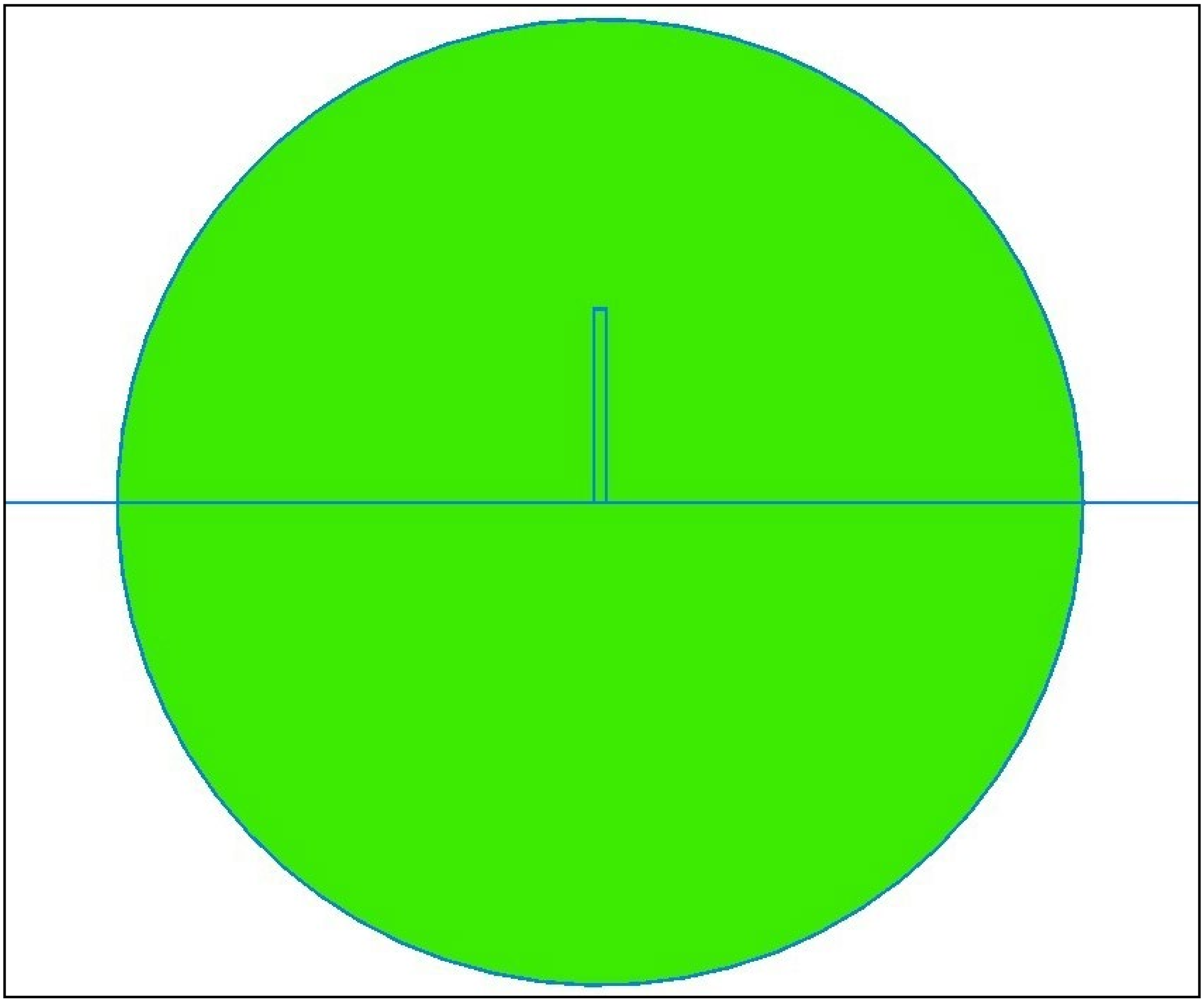

Figure 6. SCB Model Geometry

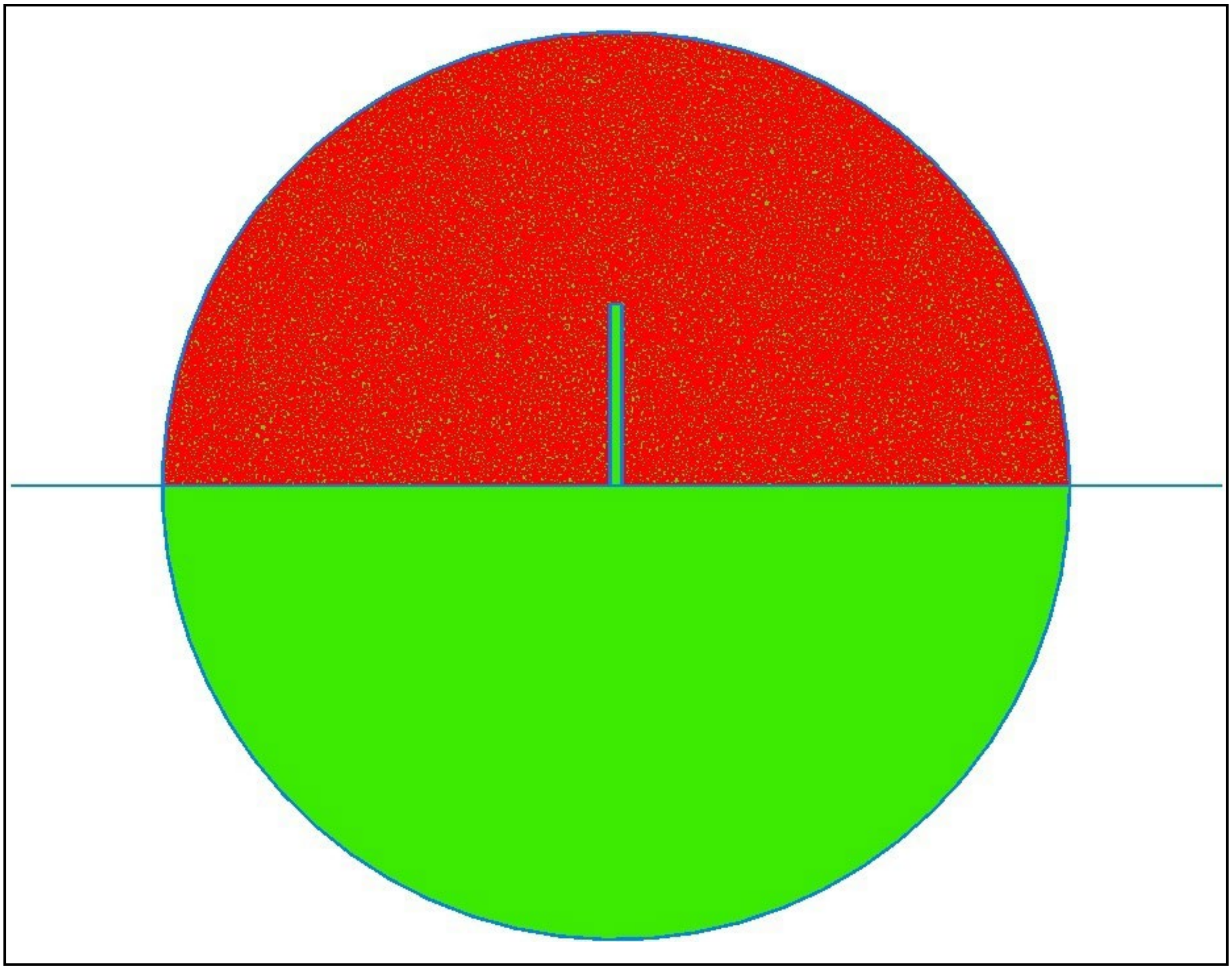

Figure 7. Homogeneous SCB Model

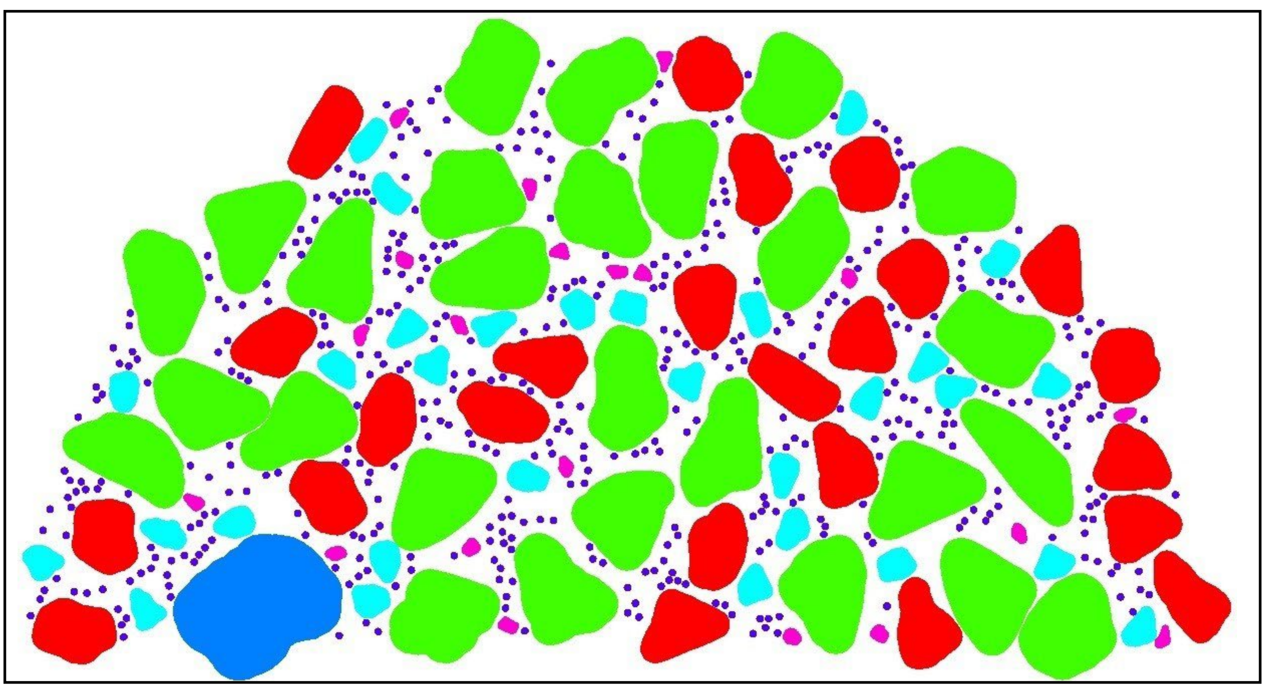

Figure 8. Aggregates and Air Voids Model

The aggregate and air voids model in Figure 8 was used to overlay the homogeneous model in Figure 7. The aggregate shapes overlapping the homogeneous model were defined as aggregates. Aggregates and air voids were defined next. Figure 9 shows the overlapping results in a model from the 12th scenario, i.e., the highest depth notch. Afterwards, air voids were then deleted and bonds were created between the aggregates and the mastic (mixture between oil, or binder, and fine aggregates) to simulate bonds contained in HMA. It is also worth mentioning that the location of the supports were selected to get the span length based on the scenarios table mentioned above. Finally, the excess particles were deleted and the loading rate was established. This, in turn, made the model ready to start the simulation; the result of this step is seen in the Figure 10.

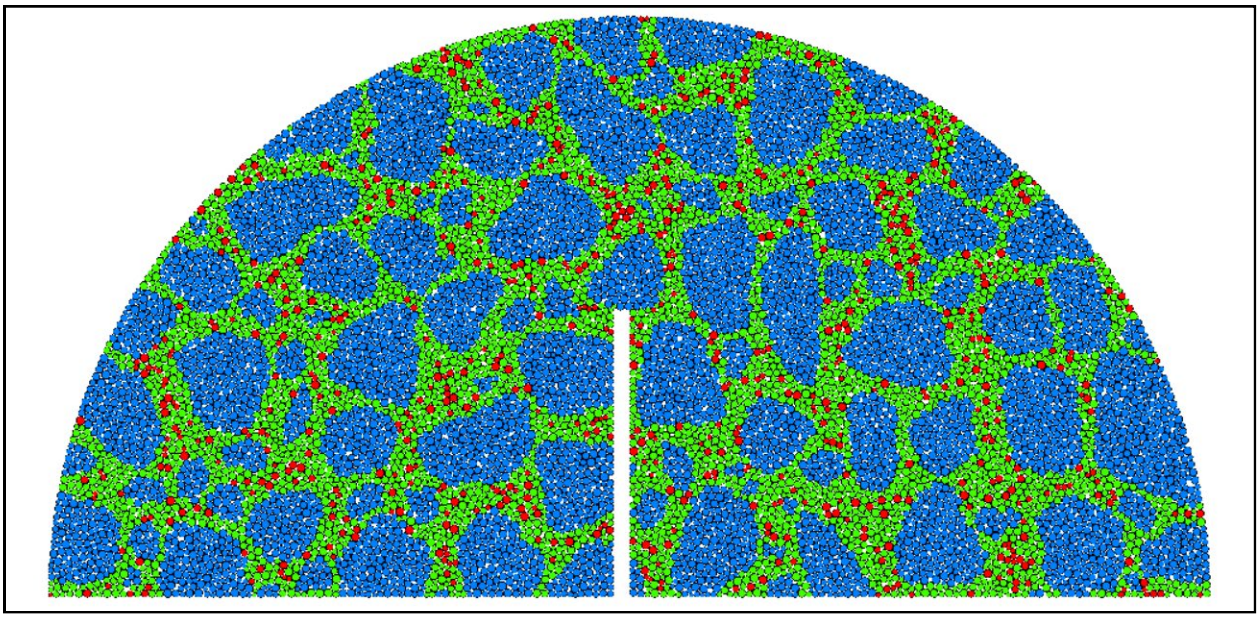

Figure 9. Overlapped SCB Model with Air Voids

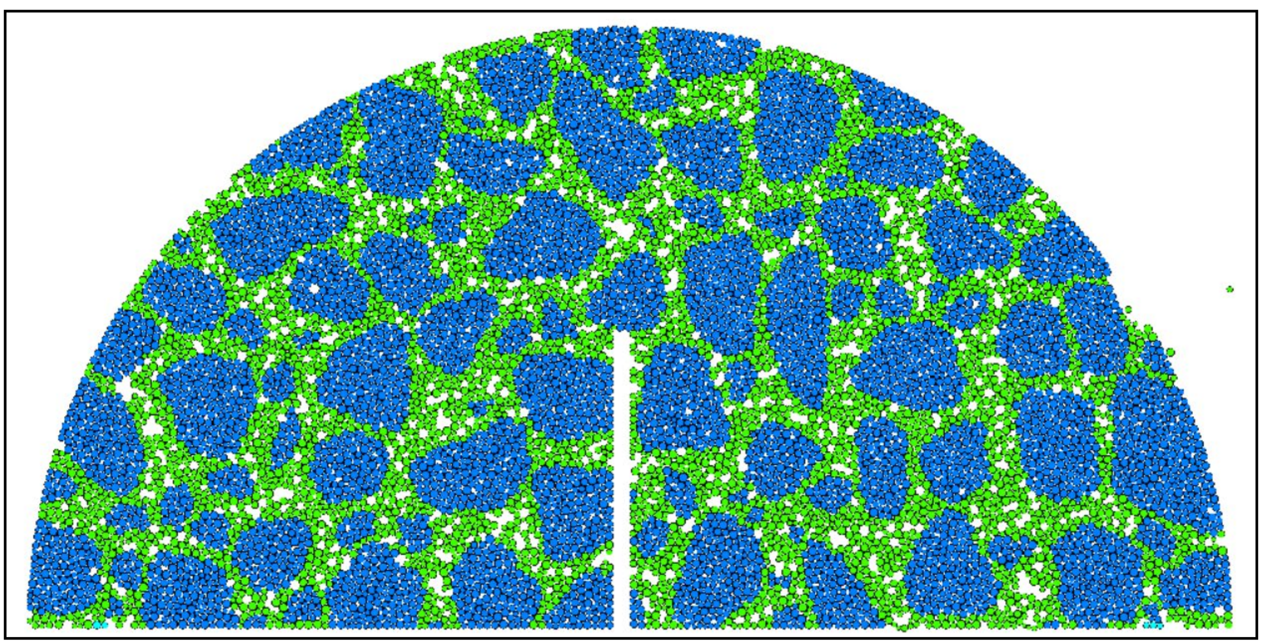

Figure 10. Finalized SCB Model with Supports Locations

V. RESULTS AND DATA ANALYSIS

This study introduces an analysis for the SCB test based on a theoretical model made using the DEM. In addition, crack initiation and propagation were measured as seen in Figure 11.

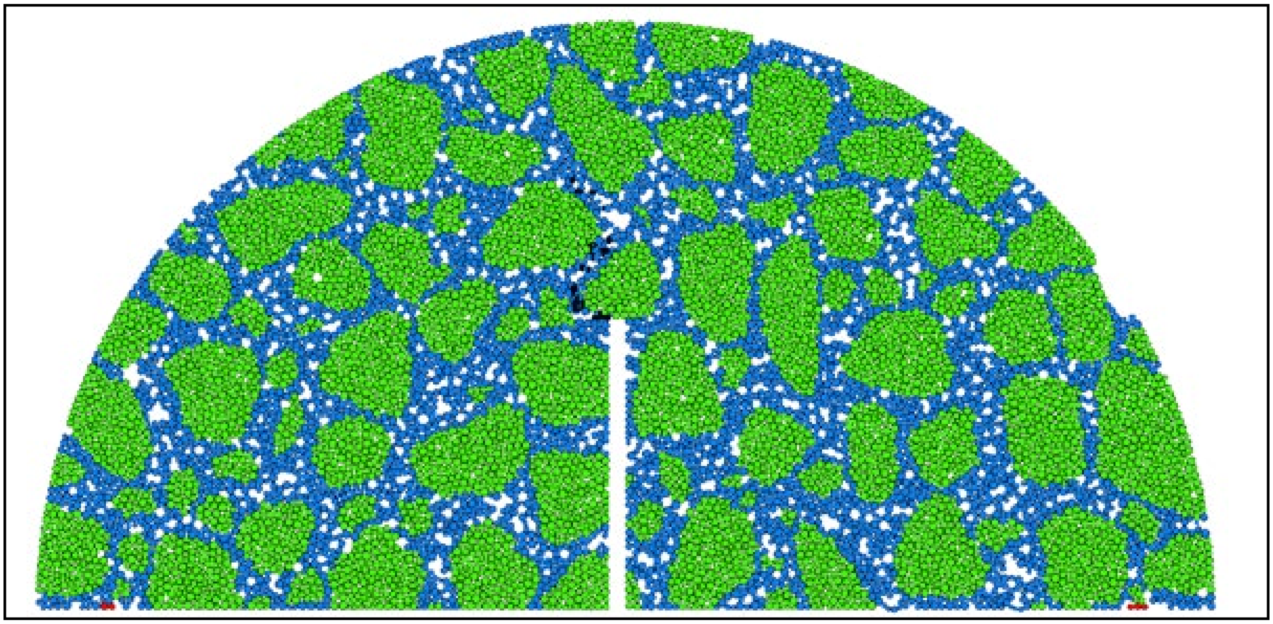

Figure 11. Crack Initiation and Propagation

In addition, contact force was measured and can be seen in Figure 12.

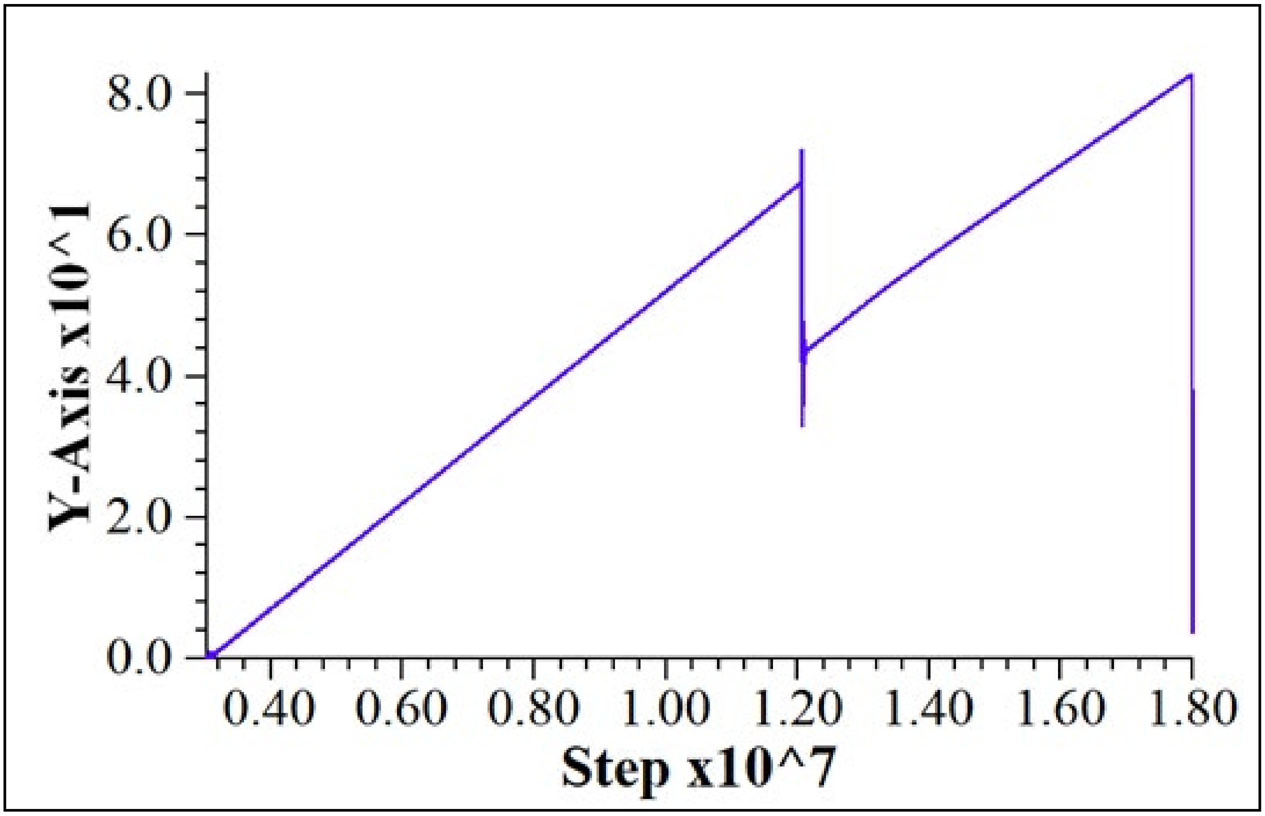

Figure 12. Contact Force (Y-Axis) vs. Time (X-Axis)

Based on the number of scenarios that have been determined in this study, the number of models that were tested were 48 samples. The results for the maximum peak load applied for each sample is shown in Table 5. The load and displacement were taken from the simulations readings and will be used to determine the strain energy U and the critical strain energy J_c for the SCB test. In order to calculate the energy J_c per scenario, the following equation must be used:

$$J_c = \frac{-1}{b}\left(\frac{dU}{da}\right) \qquad \text{Equation (1)}$$

J_c = critical strain energy release rate.

b = sample thickness (assumed to be 57 mm).

U = strain energy to failure.

a = Notch depth (mm).

= change of strain energy with notch depth (slope of the regression line).

The load displacement curves for Scenario 1 are presented in Figure 13.

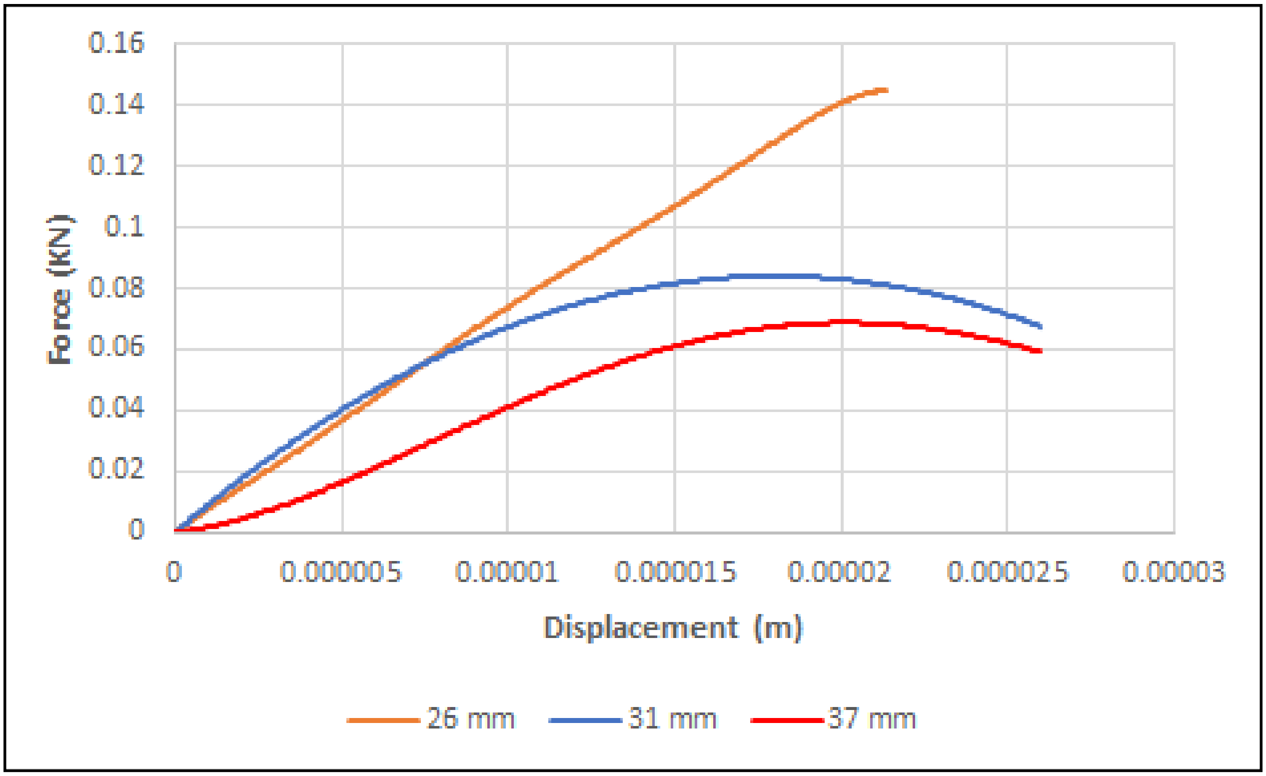

Figure 13. Load Displacement Curves for Scenario 1

Table 5. Peak Load and Strain Energy

Scenario's Number	Peak Load for Low Notch (N)	Displacement at Peak Load Low Notch (μm)	Peak Load for Intermediate Notch (N)	Displacement at Peak Load Mid Notch (μm)	Peak Load for High Notch	Displacement at Peak Load High Notch (μm)
Scenario 1	152.04	25.62036	81.38	16.78826	61.51	17.16365
Scenario 2	105.88	20.1974	103.66	16.09994	83.13	23.6825
Scenario 3	143.18	27.36947	98.15	18.13872	88.73	14.60386
Scenario 4	142.22	15.07464	169.97	34.66284	79.69	16.89276
Scenario 5	81.38	15.47325	62.94	21.09993	61.13	13.89998
Scenario 6	161.33	28.05728	129.71	18.59797	56.28	8.354919
Scenario 7	174.43	39.20685	170.01	32.39988	112.76	22.50949
Scenario 8	114.53	15.0666	54.60	17.27041	98.31	14.01737
Scenario 9	125.06	16.94381	125.89	17.59995	97.85	18.82499
Scenario 10	139.70	19.19284	92.13	15.19996	112.50	24.10016
Scenario 11	150.32	21.29709	115.30	19.77051	85.41	20.96411
Scenario 12	170.71	22.22682	140.08	30.90771	82.82	19.70417
Scenario 13	171.74	31.76717	195.15	25.00809	61.14	17.6243
Scenario 14	144.15	18.41755	84.39	17.29091	81.47	25.04753
Scenario 15	194.83	23.32011	172.95	27.99888	56.15	11.7871
Scenario 16	160.03	17.23149	55.83	18.4552	46.46	12.5999

The strain energy (U) that is calculated from the displacement and peak load rate will be used with the different notch depths to calculate the $J_{c.}$ Table 6 further demonstrates the strain energy (U) per notch depth and critical strain energy J_c.

Table 6. Critical Strain Energy

Scenario's number	Low notch strain energy U (N.m)	Intermediate notch strain energy (N.m)	High notch strain energy (N.m)	Critical strain energy (N/m)
Scenario 1	0.00187	0.000657	0.000505	2.2720
Scenario 2	0.00108	0.000882	0.000895	0.2549
Scenario 3	0.00214	0.000921	0.000536	1.9206
Scenario 4	0.00109	0.00303	0.000725	0.5382
Scenario 5	0.00066	0.000715	0.000426	0.3844
Scenario 6	0.00222	0.001138	0.000233	2.5864
Scenario 7	0.00355	0.00278	0.00120	3.1929
Scenario 8	0.000863	0.000508	0.000650	0.3048
Scenario 9	0.000969	0.00105	0.000854	0.1424
Scenario 10	0.00136	0.000727	0.00132	0.0945
Scenario 11	0.00163	0.00119	0.000861	1.2176
Scenario 12	0.00214	0.00186	0.000893	1.8358
Scenario 13	0.00318	0.00245	0.000451	3.0468
Scenario 14	0.00131	0.000725	0.00111	0.1623
Scenario 15	0.00208	0.00183	0.000358	2.0192
Scenario 16	0.00136	0.000556	0.000219	1.5549

Given the PBSA matrix and the Critical strain for the SCB, the impact of the parameters can be measured. In order to measure the sensitivity of the SCB test, the following will apply. First the J_c values will be substituted in the PBSA matrix with its corresponding sign. Second, values will be added by taking negative signs as a subtraction, whereby the sum will be divided by the rank of the PB matrix—eight in this case. Finally, the value provided will be the impact of that parameter on the SCB output. Table 7 shows the results for these calculations; the parameters' effect on the SCB results are shown in the last row. In addition, Table 8 shows the order of the most impactful parameters, in order of the most impactful to the least.

Table 7. SCB Results Implemented in PB Matrix

Scenario's number	Notch location (mm)	Low notch depth (mm)	Intermediate notch depth (mm)	High notch depth (mm)	Air voids (%)	Loading rate (mm/min)	Span (mm)
Scenario 1	2.2720	2.2720	2.2720	-2.2720	2.2720	-2.2720	-2.2720
Scenario 2	-0.2549	0.2549	0.2549	0.2549	-0.2549	0.2549	-0.2549
Scenario 3	-1.9206	-1.9206	1.9206	1.9206	1.9206	-1.9206	1.9206
Scenario 4	0.5382	-0.5382	-0.5382	0.5382	0.5382	0.5382	-0.5382
Scenario 5	-0.3844	0.3844	-0.3844	-0.3844	0.3844	0.3844	0.3844
Scenario 6	2.5864	-2.5864	2.5864	-2.5864	-2.5864	2.5864	2.5864
Scenario 7	3.1929	3.1929	-3.1929	3.1929	-3.1929	-3.1929	3.1929
Scenario 8	-0.3048	-0.3048	-0.3048	-0.3048	-0.3048	-0.3048	-0.3048
Scenario 9	-0.1424	-0.1424	-0.1424	0.1424	-0.1424	0.1424	0.1424
Scenario 10	0.0945	-0.0945	-0.0945	-0.0945	0.0945	-0.0945	0.0945
Scenario 11	1.2176	1.2176	-1.2176	-1.2176	-1.2176	1.2176	-1.2176
Scenario 12	-1.8358	1.8358	1.8358	-1.8358	-1.8358	-1.8358	1.8358
Scenario 13	3.0468	-3.0468	3.0468	3.0468	-3.0468	-3.0468	-3.0468
Scenario 14	-0.1623	0.1623	-0.1623	0.1623	0.1623	-0.1623	-0.1623
Scenario 15	-2.0192	-2.0192	2.0192	-2.0192	2.0192	2.0192	-2.0192
Scenario 16	1.5549	1.5549	1.5549	1.5549	1.5549	1.5549	1.5549
Parameters effect	0.9349	0.0277	1.1817	0.0123	-0.4544	-0.5164	0.2370

Table 8. Parameters Order of Impact

Parameter	Parameter's effect on SCB output
Intermediate notch depth	1.18167254
Notch location	0.93486954
Span Length	0.23699507
Low notch depth	0.02773073
High notch depth	0.01227974
Air voids	-0.45443303
Loading rate	-0.51644848

CONCLUSION AND FUTURE WORK

The SCB test is a standardized test that is used to evaluate fatigue resistance and it can measure crack initiation and propagation in AC mixtures. In this study, SCB sensitivity was analyzed in order to determine the impact that the imputed parameters have on the output results of the SCB. In order to achieve that PBSA was used to verify the sensitivity of the SCB, but it required plenty of materials and time. The DEM model has been used to reduce the required material and time to complete the study. The SCB test has many parameters that may affect its outcome results significantly. This study focused on the most important seven parameters that can be examined with the current capabilities and limitations. After completing the analysis, the following conclusions were attained:

- Intermediate notch depth had the most impact on the J_c Value. As seen in Table 8, intermediate notch depth had the highest absolute value of all parameters, thus making it the most critical to the output of the SCB.

- Notch location unexpectedly had the second highest impact on the J_c Value, a 1 mm misplacement of the blade from the center would cause the results of the SCB to significantly change.

- Loading rate and air voids had a negative impact on the J_c Value. In other words, an increase in the values of these two parameters caused the SCB results to decrease, their impact is also significant when compared to the other parameters.

- Low and high notch depths appeared to be the least impactful on the J_c Value. Low and high notch depths have only 1% to 2% impact when compared with the intermediate notch depth.

- PBSA is rarely used in transportation related research. With more research that involves using PBSA, the reliability of using the PBSA method will increase. In addition, using a different sensitivity analysis method on the same parameters will also increase PBSA’s credibility.

- Due to the limitations of the 2D model, a 3D SCB model would give more reliable results. Also, other parameters can be examined, such as specimen thickness and load inclination.

ABBREVIATIONS AND ACRONYMS

AC	Asphalt Concrete
AIMS	Aggregate Image Measurement System
ASTM	American Society for Testing and Materials
CMHB	Coarse Matrix High Binder
DEM	Discrete Element Method
HMA	Hot Mix Asphalt
PBSA	Plackett–Burman Sensitivity Analysis
PFC2D	Particle Flow Code 2 Dimensions
SCB	Semi-Circular Bending test

BIBLIOGRAPHY

ASTM D8044-16, Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures, ASTM International, West Conshohocken, PA, 2016, www.astm.org.

Beres, D. L., & Hawkins, D. M. (2001). Plackett-Burman technique for sensitivity analysis of many-parametered models. Ecological Modelling, 141(1-3), pp. 171–183. Cundall, P.A. and Strack, Q.D.L. (1971) A Discrete Numerical Model for Granular Assemblies. Geotechnique, 29, pp. 47–65.

Harvey, J.T., J.A. Deacon, B.W. Tsai, and C.L. Monismith. (1995). "Fatigue performance of asphalt concrete mixes and its relationship to asphalt concrete pavement performance in California." Asphalt Research Program: Institute of Transportation Studies, University of California, Berkeley.

Mahmoud, E. and Saadeh, S. and Yanz, R. (2016). "Feasibility of Discrete Element to Simulate RAP Asphalt Mixtures Fracture Behavior", ASCE Geotechnical Special Publication, v 2016-January, n 270 GSP, pp. 577–587.

Potyondy, D. (2018). "Material-Modeling Support in PFC [fistPkg6.1]," Itasca Consulting Group, Inc., Technical Memorandum ICG7766-L, Minneapolis, Minnesota. Roberts, F., Kandhal, P., Brown, E., Lee, D., Kennedy, T. (2009) "Hot mix asphalt materials, mixture design and construction." National Center for Asphalt Technology.

Saadeh, S., Renteria, D., Mahmoud, E., Eljairi, O. (June 1, 2018). "NumericalEvaluation of Semi-Circular Bending Test Variability." ASCE Journal of Materials in Civil Engineering, v 30, n 6.

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