QUANTITATIVE EVALUATION IN THE BOX TEST AND EVALUATION OF FIELD MIXTURES BY THE TARANTULA CURVE

By

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Abstract: In this research project, a proposed evaluation technique of the surface voids concentrations in the Box Test was introduced. This was done by the development of a point count template that can allow critical surface voids to be identified and the evaluation to be more systematic. This method showed reliable results with low variability and can be considered as a useful tool in the Box Test surface voids assessment.

Vibrators consolidate the concrete by removing unwanted air voids from its matrix. Frequency of a vibrator is one of the key parameters that impacts the vibration effort. An investigation was made to determine the effect of changing the vibrator's frequency on the consolidation degree of concrete in terms of the amount of surface voids concentrations by the use of the Box Test. Results showed that a reduction in the frequency level could dramatically increase the surface voids concentrations at the sides of a Box Test sample.

Finally, the Tarantula Curve, which is a new aggregate gradation technique that gives recommendations of aggregate gradations used in designing concrete mixtures. Hundreds of field mixtures that were made and placed and utilized in different states were compared to the suggested recommendations. Results showed that there were high agreement between the evaluated aggregate gradations and the Tarantula limits.

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INTRODUCTION

Concrete has been broadly known and employed in various construction applications such as dams, bridges, residential and commercial buildings, and pavements. It can be cheap, strong, durable, and sustainable if it has a well design. The major compositions of concrete are Portland cement, water, rocks, and sand. Additionally, admixtures and cementitious materials are added to strengthen specific properties such as water reducer admixtures that influence the concrete’s workability.

Portland cement is the most indispensable material in a concrete matrix. It forms paste as water is added, which contributes to fresh and hardened concrete properties and acting as a binding material that combines the ingredients together. The content of the paste is determined by the water-cement ratio, which ranges between 0.38 to 0.6 depending on the concrete applications. Volume of the paste in a concrete mixture is very important because a high paste volume may lead to a high possibility of plastic shrinkage and drying shrinkage. Therefore, it is highly required to have enough paste in order to obtain satisfactory workable concrete with a desired performance.

Aggregate is a prime component in a concrete mixture. It contributes around three quarters to a concrete volume. Aggregate is highly beneficial in resisting the shrinkage that is happening due to the drying of fresh concrete. It is considered to be a filler material that reduces the paste content and makes the concrete more economical.

Aggregate plays a major role in determining the workability of fresh concrete, which arises from the amount of surface area and the space not occupied by aggregate that needs to be covered by paste. Physical properties of aggregates such as texture and angularity can impact the workability. In addition, flat and elongated aggregate would create poor packing and larger empty space that needs to be covered by paste.

Aggregate gradation can describe the distribution of different particle sizes of the aggregate and determine the density of a concrete matrix. Aggregate gradation has been widely utilized in aggregate proportioning. Standards provide practical specifications for both coarse and fine aggregate. These aggregates can then be combined to form a single gradation that can be evaluated by several gradation techniques such as the Power 45 chart, the Fineness Modulus, the Individual Percent Retained chart, and the Coarseness factor chart. The purpose of the aggregate evaluation is to minimize the empty space between the aggregate particles as much as possible and reduce the required paste content with sufficient workability. This process is called aggregate optimization.

The Box Test is a recently-introduced test to evaluate the workability of low slump mixtures. It simply measures the response of freshly mixed concrete mixtures to the applied vibration.

Pavement mixtures are normally consolidated by vibrators that are attached to a slip formed paver. The degree of consolidation is detected by the amount of air voids after consolidating the concrete. The Box Test investigates the surface voids concentrations resulting on the sides of a concrete box after vibration. A mixture can be accepted or rejected depending on the degree of the concentration of surface voids on the concrete sides. Chapter II provides a detail description about the Box Test in terms of usage and procedure. In addition, the object of this chapter is to introduce a new evaluation method of the Box Test that can make the surface voids resulting from a vibrated concrete box measurable.

Vibration is the prime factor in the mechanical consolidation of stiff mixtures. A vibrator transmits vibratory forces into the concrete, which cause its particles to be transformed from the solid to the fluid state. When paste is fluidized, it moves to surround aggregate particles and cover the empty space between them. In concrete vibration, there are parameters that determine its performance in concrete consolidation such as acceleration, frequency, and amplitude. In Chapter III, a demonstration of the vibration mechanism is provided. In addition, the aim of this chapter is to investigate the effects of the frequency change on the consolidation process of a concrete mixture via the Box Test.

Recently, an aggregate gradation technique was introduced to the field and showed a huge success in providing aggregate gradations that require lower paste content and remain workable enough to be placed and handled. This technique is called the Tarantula Curve. To obtain a desired aggregate gradation, recommendations were given for each sieve size in this curve. Chapter IV shows how the previous successfully placed and utilized pavement mixtures from Iowa, Minnesota, and Michigan meet the Tarantula recommendations. The goal of this chapter is to compare aggregate gradations of hundreds of different mixtures from different DOT agencies to the Tarantula Curve limits. Detailed charts and tables are provided in this chapter to evaluate the aggregate gradation performance in accordance to the Tarantula limits.

CHAPTER II

QUANTITATIVE EVALUATION IN THE BOX TEST

2.0 Introduction:

The Box Test is a new laboratory test that was developed in Oklahoma State University by Marllon D. COOK. It was introduced to satisfy the need for a laboratory test that investigates the workability of paving mixtures. This test tries to imitate the consolidation process of a slip formed paver and evaluate the ability of a mixture to respond to vibration [6].

The Box Test is a test that evaluates the performance of a mixture in terms of the response to a standard amount of vibration and to subsequently hold an edge after removing the forms [7]. Some common problems in the performance of concrete mixtures that are placed by slip formed pavers are the mixture's unresponsiveness to consolidation and edge slumping [6] [10]. Edge slumping is the deformation of an edge after the fresh concrete is placed, consolidated, and ejected from a slip formed paver [7]. The consolidation of fresh concrete depends on factors such as the mixture's workability, the dimensions of the region being consolidated, and the vibrator characteristics such as speed and power of the vibration [10].

In a slip formed paver, the main component that consolidates the concrete is the vibrator. Vibration affects the fresh concrete air system; therefore, to minimize this effect, the recommendation for the frequency of the slip formed vibrator is to be in the range of 5,000 to 8,000 vibrations per minute (vpm) with a speed below 36 inches per minute [6] [9]. The vibrators are placed toward the top surface of the concrete with a spacing between 12” to 16” and a head size of 2.25” [6] [10].

In the Box Test, the vibration energy is obtained by the use of a portable electric vibrator that is commonly utilized in concrete consolidation applications. In order to make the vibration energy of a slip formed paver and the portable vibrator comparable, the energy produced into a concrete section by a slip formed paver’s vibrator was calculated with a paver speed of 36 inches per minute and a spacing of 16”. Then for the Box Test, the concrete section, frequency of vibration, time of vibration, and the head size were modified to match the vibration energy of a paver [7]. Unlike the one-directional vibration path of a hydraulic vibrator of a slip formed paver, the vibration in the Box Test is completed as the vibrator is lowered and then removed from the concrete. Therefore, in order to achieve a similar energy to the hydraulic vibrator, the vibration time was adjusted so that the consolidation process can be comparable [7].

The Box Test is an easy and inexpensive test that comprises of a platform, two side-form, and clamps. The assembly of the Box Test is illustrated in Fig. 2.1.

Figure 2. 1: The Box Test components.

The wooden form consists of plywood with a thickness of 0.5” and it has a length, width, and height of 12”. Fig. 2.2 shows two L-brackets attaching two edges, and two 18” clamps attaching the remaining edges.

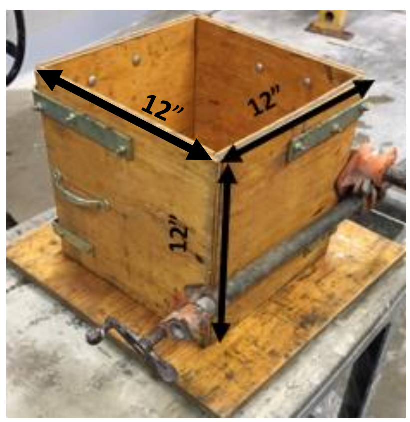


Figure 2. 2: The Box Test Sides dimensions.

The object of the Box Test is to measure the response of a mixture to vibration. This is done by assessing the surface voids concentration at the sides of the box. If the mixture responded well to vibration, the surface voids concentration should be low. In contrast, when the response to vibration was poor, there should be a high level of surface voids at the sides [6]. Currently, the Box Test assessment method is dependent on the visual observation and judgement of the operator. However, an attempt to improve the assessment method of the Box Test is addressed in this document. This new methodology aims to quantify the performance in the test by establishing criteria that help in assessing the surface voids accurately.

2.1 The overall visual assessment method:

The current assessment method for The Box Test, developed by Cook, is done by making an overall visual assessment of the surface voids based on the images shown in Fig 2.3. Each side of the box is observed visually and the average surface voids is estimated for the formed sides with a ranking number. This measurement is estimated by a comparison between the surface voids concentration of each side with pictures of surfaces with different amounts of surface voids. Finally, an overall average is calculated for a Box Test [6]. The comparative image criteria is illustrated in Fig 2.3.

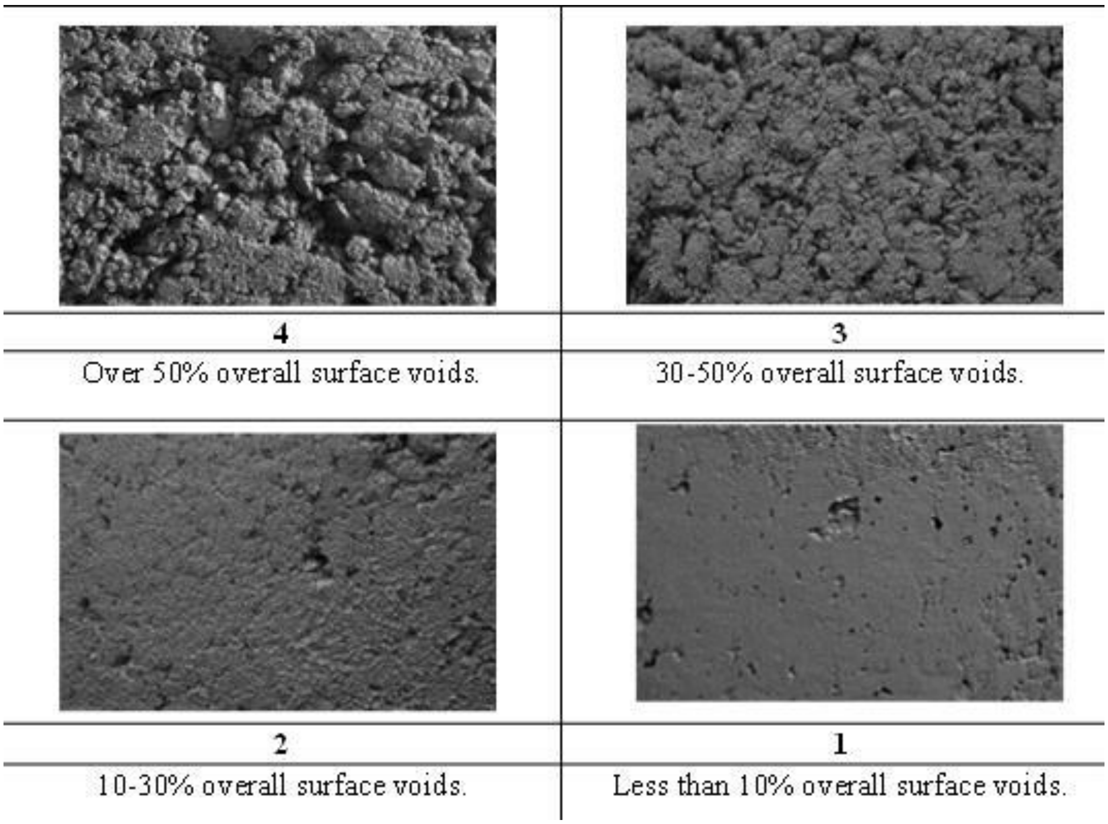


Figure 2. 3: The comparative image for the Box Test evaluation. (Adapted from [6]).

The average ranking should be two or below to be considered acceptable.

Finally, the top and bottom edge slump can be measured by placing a straightedge at a corner and by using a tape measure horizontally to find the length of the highest extruding point. The extruding distance should be less than ¼” [6].

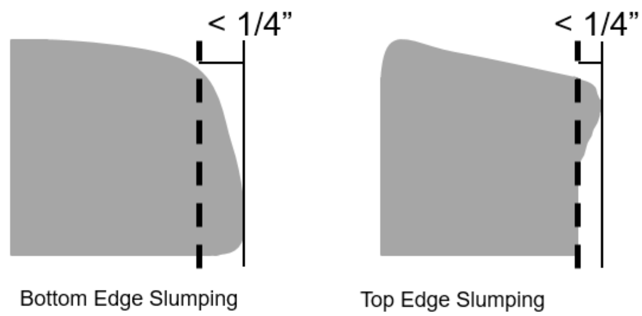


Figure 2. 4: An example of edge slump in the Box Test.

2.2 The Box Test point count template:

The proposed method to assess the concentration of critical surface voids on lateral sides of a concrete box is done with the use of a new tool called the point count template. It can allow a better way to quantify the measurements from the Box Test.

The point count template is a tool that is made of plexiglass with a square shape of 12” by 12” and a thickness of 0.5”. The point count template has two stands that are fixed at the bottom corners to support the plate and prevent it from falling. In addition, these stands limit left/right movement of the template when placing it in front of a concrete side in order to minimize the variation in measurements. Figure 2.5 illustrates the dimensions of the point count template and Fig. 2.6 shows the top view of the stands with its dimensions.

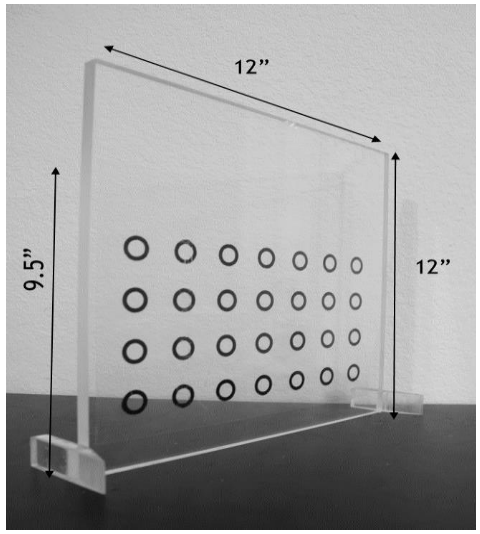


Figure 2. 5: The dimensions of the point count template.

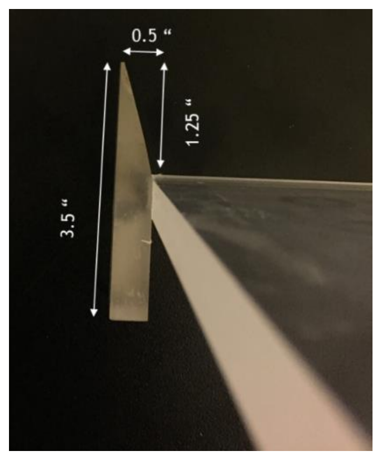
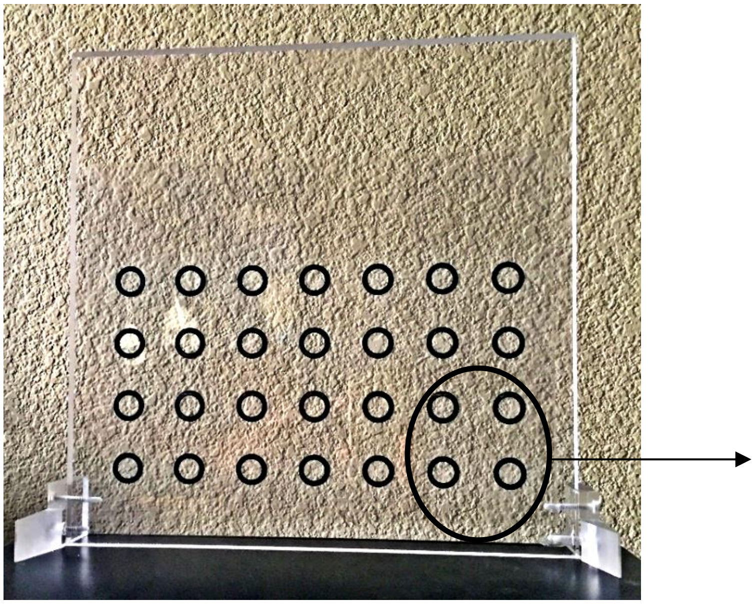


Figure 2. 6: The top view of the point count template and the stands.

Since the concrete may deform laterally after removing the box forms the width of the concrete box will sometimes be larger than 12”. Therefore, the point count template will not fit if the stands limit the width to the exact width of the template. Also, it is important to place the template near the surface of the concrete in order to allow the surface voids to be clearly observed through the circles. When the template is placed even 1” away from the concrete it will be more challenging to observe the voids on the surface of the concrete. This can affect the measurement of the surface voids. To accommodate the increase in the width of the concrete box, the stands have a triangular shape in the legs that are facing the concrete. This allows the template to be placed near the concrete face by increasing the width.

The point count template has 28 circles that are drawn on the side that is facing the concrete. These circles are distributed in four rows and seven columns. The spacing between each circle, center to center, is 1.5” in both horizontal and vertical directions. The distance from the bottom of the template to the outer edge of the bottom row of circles is 1.5”. The distance between the sides of the template and the adjacent circles’ center is 1.5”. Every circle has a diameter of 5/8” and a thickness of 1/8” (3 mm). This means that the inner diameter of the circle is 1/2”. The edge of the circle is black and the thickness of the circle is used as a comparative tool to evaluate the size of the voids within each circle. Figure 2.7 shows the point count template with the circles and the dimensions.



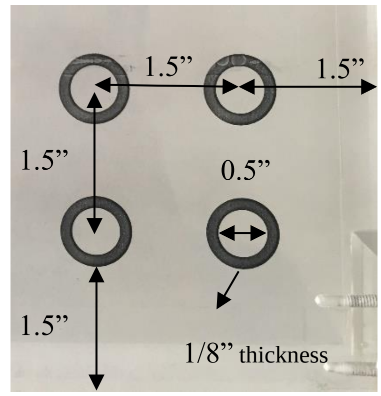


Figure 2. 7: The dimensions of the circles on the point count template.

The template can also be used to measure the edge slumping of a sample. Since it has a width of 12”, which is exactly the same width of a sample, the lateral displacement can be measured by comparing the template’s edge to the concrete with a measurement tape. Figure 2.8 shows an example of a sample’s edge slumping.

Figure 2. 8: The usage of the counting tool in edge slumping measurements.

2.3 Method

2.3.1 Materials:

The materials used in the investigated mixtures are :

- A Type I cement, satisfying ASTM C 150 [3].
- ASTM C 618 Class C fly ash, substituted 20% by mass of the cementitious materials. [5]
- A mid-range water reducer and a retarder were used [4].
- Three different types of crushed limestone (A, B, and C); and a river gravel D.

- Each aggregate has a maximum nominal aggregate size of 3/4" and an intermediate size of 3/8".
- A natural sand was used in each of the mixtures.

2.3.2 Material preparation:

Aggregates were brought in the lab and kept for at least 24 h at 72 °F. Then, a moisture correction was conducted for every type of aggregate by placing them individually in a mixing drum and spinning them for 3 minutes. After that, representative samples were taken. The samples were kept in an oven at 305 °F for at least 24 h. The weights of wet and dry were measured and the moisture content was obtained.

2.3.3 Mix Design:

The following Table illustrates the mixture design used.

Table 2. 1: The mixture design utilized in the Box Test investigation.

	Cement ***lb/yd3***	**Fly Ash** ***lb/yd3***	**Coarse** ***lb/yd3***	**Intermediate** ***lb/yd3***	**Fine** ***lb/yd3***	**Water** ***lb/yd3***
Pass	357.2	89.3	1756.6	511.5	1235.4	200.9
Fail	357.2	89.3	2000	200	1275	201

2.3.4 Mixing procedure:

All the aggregates were placed in a mixing drum with nearly two-thirds of the mixing water. The mixer was turned on to mix the materials for three minutes in order to blend the aggregates together and to reach the saturation surface dry state condition (SSD). After three minutes of mixing, the remaining water and the cementitious materials were added. Then, the whole mixture were mixed for three minutes. The mixer was turned off for two minutes to allow the contents to rest. During this time, the sides and paddles of the mixer were scraped. Finally, the concrete mixture was blended for another three minutes. Subsequently, the following tests were conducted: the slump test according to ASTM C143 [2], the unit weight according to ASTM C138 [1], and the Box Test.

2.3.5 The Box Test Procedure:

To perform the Box Test, the subsequent steps were followed. First, wooden forms were assembled above a platform and the internal sides were oiled. Then, concrete was hand scooped into the wooden box uniformly up to a height of 9.5”. Next, the concrete was consolidated with the help of a vibrator with a 1” square head at 12,500 vpm. The vibrator was inserted into the concrete vertically at the center of the box, and lowered down toward the bottom of the box for three seconds, without touching the platform. Then, the vibrator was raised upward for three seconds. Immediately, the clamps, or the forms holders, were removed as well as the side forms [7]. The Box Test Procedure is illustrated in the following figure.

Figure 2. 9: The Box Test Steps.

2.3.6 The proposed Box Test assessment methodology:

After mixing a concrete batch, filling and consolidating the concrete in the box form, and removing the side forms, the resulting concrete box was ready to be evaluated. The point count template was put adjacent to the concrete side, as close as possible without touching the concrete. An example is shown in Fig. 2.10. The evaluation of the surface voids at the face of the concrete was measured by looking at the voids contained in each of the circles.

Figure 2. 10: The point count template positioned in front of a concrete side.

The surface of the concrete commonly has voids. However, if there are too many large voids on the surface of the concrete then this is not desirable and suggests that the concrete was not consolidated properly. For this work it was decided that the voids of a critical size were any that have a dimension above 1/8”. This means that within the evaluated circle, any void with a dimension above 1/8” is considered a critical void. These voids may be completely contained within the circle or if they extend from inside the circle to the outside then they would also be considered a critical void. The thickness of the circle is also 1/8”. This was chosen so that it was easy for the operator to compare the thickness of the circle to the size of the void. Also, this means that any void that can be seen on both sides of the circle is greater than 1/8” and so this would be a critical void.

Examples of this method are given in Fig. 2.11, Fig. 2.12 and Fig. 2.13.

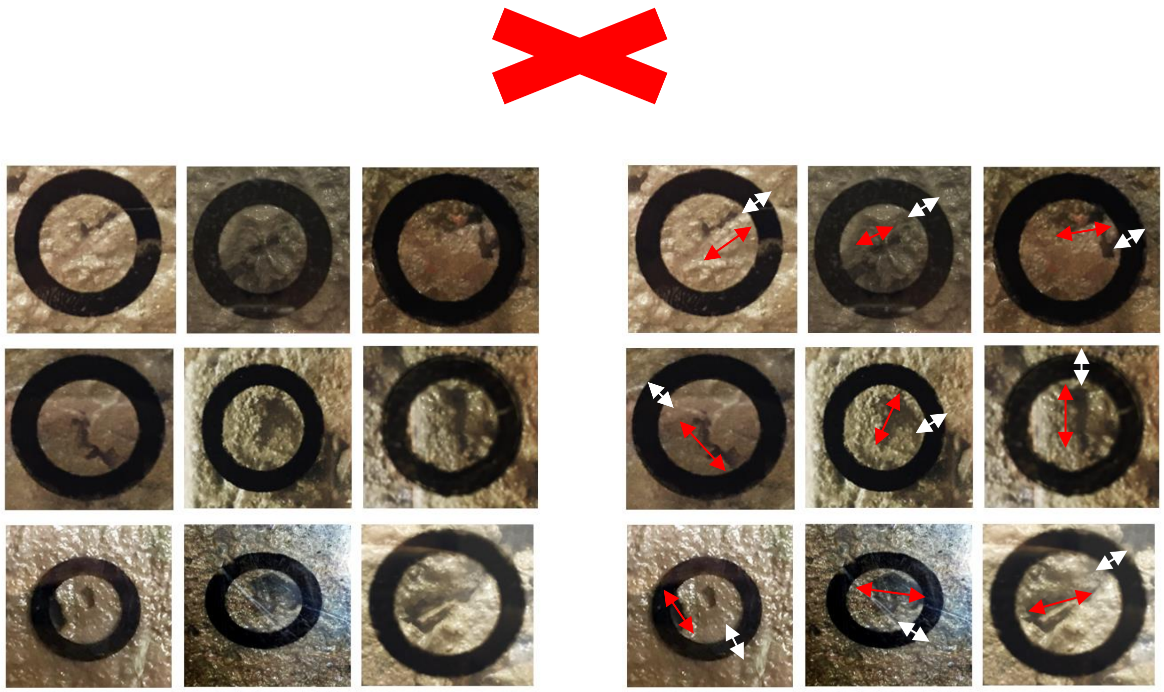


Figure 2. 11: Examples of critical surface voids contained within the circle.

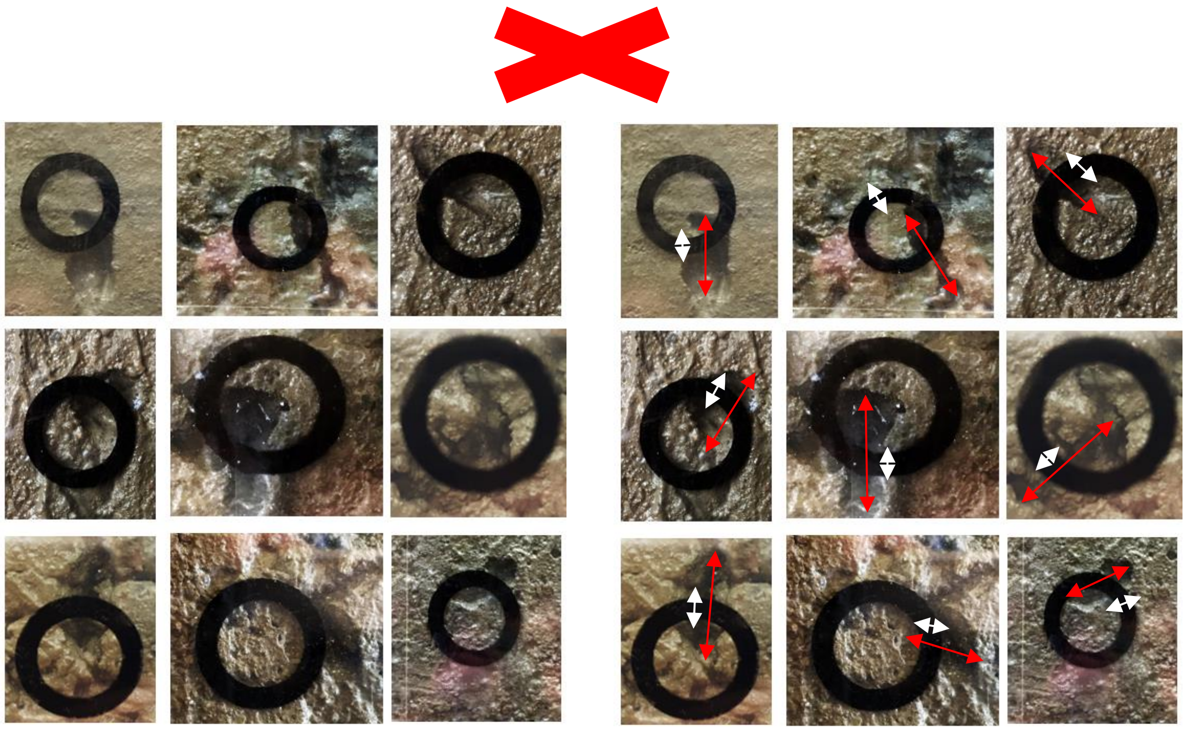


Figure 2. 12: Critical surface voids that are extended from inside the circle to the outside.

Figure 2. 13: Examples of circles that do not contain critical voids.

The total number of the critical voids for each side is counted. If the number is above 11 then that side does not pass the Box Test. If 11 voids are found per side then that corresponds to 40% surface voids. This matches the criteria established by the visual inspection and the usage of the comparative images. This method has the potential to be more quantitative than the visual inspection method because the evaluator is looking closely at a localized area and using a point counting technique similar to what is used in geology or the ASTM C 457 test method to evaluate air void volume and spacing.

One drawback of this technique is that it requires more equipment and time. The approximate time required per each side of a sample can be 30 s. This means that the visual inspection for all four sides could be completed in just over two minutes. Also, this technique only evaluates 5.8% of the surface area of the sample.

2.4 Results:

For this work, the total and average number of critical voids identified per side of the sample will be reported for each side of the specimen. This is done to show the repeatability of the method and make general comparison.

A number of variables were examined in order to validate the point count template technique in the Box Test evaluation. These variables include the repeatability of measurements of a single face by a single operator, the variability between multiple operators identifying the average number of critical voids per a single sample, and the repeatability of Box Test measurements per a single mixture by a single and multiple operators. Finally, the measurements of surface voids concentrations of a sample obtained from the point count method is compared to the visual inspection method to determine the relationships between them.

2.4.1 Repeatability of the measurements of a single face by a single operator:

To investigate the impact of the change in position of the point count template ten concrete mixtures were evaluated by a single operator. Each time the template was placed in front of the face of the concrete and evaluated. Surface void counts were evaluated three times per each side of a sample, and the average was taken and reported in Table 2.2. This table shows the average number of critical voids of a face computed from three rounds for each sample. The standard deviation (SD) and coefficient of variation (COV) between the measurements of the average critical voids per each side were included in the table.

Since the total numbers of critical voids identified per each side of a sample in the three rounds were almost always equal, this means that there is a SD of zero. The results showed that 71% of the samples had a SD of zero and 29% had a SD of less than 1 (average SD was 0.16 void). Furthermore, the COV was 1.52%. This means that there is very low variability of the measurement with the point count method from a single user.

Table 2. 2a: Ave. critical voids numbers identfied per each sample in 3 rounds.

Mix No.		Box faces	critical voids Ave. No.	S.D.	COV
Mix 3	Sample 1	face 1	14.67	0.47	3.21
		face 2	16.67	0.47	2.83
		face 3	17.00	0.00	0.00
		face 4	19.00	0.00	0.00
	Sample 2	face 1	13.33	0.47	3.54
		face 2	11.00	0.00	0.00
		face 3	12.67	0.47	3.72
		face 4	8.00	0.82	10.21
	Sample 3	face 1	7.00	0.00	0.00
		face 2	16.33	0.47	2.89
		face 3	9.00	0.00	0.00
		face 4	8.00	0.00	0.00
Mix 4	Sample 1	face 1	21.00	0.82	3.89
		face 2	11.00	0.00	0.00
		face 3	10.33	0.47	4.56
		face 4	15.67	0.47	3.01
	Sample 2	face 1	9.00	0.00	0.00
		face 2	13.00	0.00	0.00
		face 3	8.67	0.47	5.44
		face 4	15.67	0.47	3.01
	Sample 3	face 1	8.00	0.00	0.00
		face 2	14.67	0.47	3.21
		face 3	9.33	0.47	5.05
		face 4	15.00	0.00	0.00
Mix 5	Sample 1	face 1	17.67	0.47	2.67
		face 2	17.00	0.00	0.00
		face 3	13.00	0.00	0.00
		face 4	13.00	0.00	0.00
	Sample 2	face 1	10.00	0.00	0.00
		face 2	9.00	0.00	0.00
		face 3	11.00	0.00	0.00
		face 4	19.00	0.00	0.00
	Sample 3	face 1	7.67	1.25	16.27
		face 2	7.00	0.00	0.00
		face 3	5.00	0.00	0.00
		face 4	11.33	0.47	4.16

Mix No.		Box faces	critical voids Ave. No.	S.D.	COV
Mix 6	Sample 1	face 1	13.00	0.00	0.00
		face 2	17.00	0.00	0.00
		face 3	11.00	0.00	0.00
		face 4	19.33	0.47	2.44
	Sample 2	face 1	16.00	0.00	0.00
		face 2	10.00	0.00	0.00
		face 3	7.00	0.00	0.00
		face 4	14.00	0.00	0.00
	Sample 3	face 1	21.00	0.00	0.00
		face 2	25.00	0.00	0.00
		face 3	26.00	0.00	0.00
		face 4	27.00	0.00	0.00
Mix 7	Sample 1	face 1	12.00	0.00	0.00
		face 2	16.00	0.00	0.00
		face 3	9.00	0.00	0.00
		face 4	10.00	0.00	0.00
	Sample 2	face 1	14.67	0.47	3.21
		face 2	18.00	0.00	0.00
		face 3	14.00	0.00	0.00
		face 4	17.00	0.00	0.00
	Sample 3	face 1	26.00	0.00	0.00
		face 2	18.00	0.00	0.00
		face 3	20.00	0.00	0.00
		face 4	23.00	0.00	0.00
Mix 8	Sample 1	face 1	12.33	0.47	3.82
		face 2	12.00	0.00	0.00
		face 3	12.00	0.00	0.00
		face 4	14.00	0.00	0.00
	Sample 2	face 1	16.00	0.00	0.00
		face 2	17.00	0.00	0.00
		face 3	17.00	0.00	0.00
		face 4	13.00	0.00	0.00
	Sample 3	face 1	19.00	0.00	0.00
		face 2	23.00	0.00	0.00
		face 3	18.00	0.00	0.00
		face 4	23.00	0.00	0.00

Table 2. 2b: Ave. critical voids numbers identfied per each sample in 3 rounds.

Mix No.		Box faces	critical voids Ave. No.	S.D.	COV
Mix 9	Sample 1	face 1	10.00	0.00	0.00
		face 2	12.00	0.00	0.00
		face 3	8.67	1.25	14.39
		face 4	9.00	0.00	0.00
	Sample 2	face 1	12.00	0.00	0.00
		face 2	12.00	0.00	0.00
		face 3	15.00	0.00	0.00
		face 4	13.00	0.00	0.00
	Sample 3	face 1	16.00	0.00	0.00
		face 2	20.67	0.47	2.28
		face 3	24.00	0.00	0.00
		face 4	23.00	0.00	0.00
Mix 10	Sample 1	face 1	10.67	0.47	4.42
		face 2	4.00	0.00	0.00
		face 3	4.00	0.00	0.00
		face 4	12.33	0.47	3.82
	Sample 2	face 1	12.00	0.00	0.00
		face 2	14.33	0.47	3.29
		face 3	13.67	0.47	3.45
		face 4	13.00	0.00	0.00
	Sample 3	face 1	8.00	0.00	0.00
		face 2	12.00	0.00	0.00
		face 3	9.00	0.00	0.00
		face 4	4.00	0.00	0.00

Mix No.		Box faces	critical voids Ave. No.	S.D.	COV
Mix 11	Sample 1	face 1	4.67	0.47	10.10
		face 2	10.00	0.00	0.00
		face 3	7.00	0.00	0.00
		face 4	12.00	0.00	0.00
	Sample 2	face 1	6.67	0.47	7.07
		face 2	11.00	0.00	0.00
		face 3	8.67	0.47	5.44
		face 4	7.00	0.00	0.00
	Sample 3	face 1	14.00	0.00	0.00
		face 2	11.67	0.47	4.04
		face 3	8.33	0.47	5.66
		face 4	10.00	0.00	0.00
Mix 12	Sample 1	face 1	17.00	0.00	0.00
		face 2	11.00	0.00	0.00
		face 3	7.00	0.00	0.00
		face 4	7.33	0.47	6.43
	Sample 2	face 1	9.00	0.82	9.07
		face 2	12.00	0.00	0.00
		face 3	6.00	0.00	0.00
		face 4	13.33	0.47	3.54
	Sample 3	face 1	5.33	0.47	8.84
		face 2	7.00	0.00	0.00
		face 3	7.00	0.00	0.00
		face 4	12.33	0.47	3.82
			Average	**0.16**	**1.52**

2.4.2 Multiple operators comparison in identifying critical voids in a single sample:

The variation between multiple operators in identifying the average number of critical voids per a sample was investigated. Ten concrete mixtures were evaluated by the three operators. The operators evaluated the surface voids of three samples per each mixture. Every operator identified the critical voids per each side of a sample and the average critical voids counted per each sample was reported in Table 2.3. A comparison was made between the average identified numbers of critical voids by the operators. The SD and COV between the average critical void measurements taken by three operators for every sample was computed, and the overall average SD and COV is provided. It was shown that the average number of critical voids identified per a single sample by different operator could be repeatable with an average difference of one critical void and an average SD of 0.6. The average COV between the measurements of average critical voids identified by different operators in a single sample was 4.7%. These values are slightly higher than when the testing was completed by a single operator, but they are still acceptable.

Table 2. 3: A comparison in counting critical voids per a single sample between three operators.

Ave. critical voids counted from a sample by 3 operators				
Mix No	Sample NO	Ave. critical voids	SD	COV
Mix R3	sample1	16.4	0.5	2.8
	sample2	11.7	0.4	3.2
	sample3	10.4	0.3	2.6
Mix R4	sample1	15.6	0.9	5.7
	sample2	12.2	0.8	6.6
	sample3	11.9	0.1	0.9
Mix R5	sample1	15.3	0.8	5.3
	sample2	12.3	0.1	0.6
	sample3	8.4	0.5	6.5
Mix R6	sample1	14.9	0.2	1.4
	sample2	10.9	0.7	6.6
	sample3	24.0	0.5	2.3
Mix R7	sample1	12.6	0.9	6.9
	sample2	16.1	0.5	3.3
	sample3	19.9	1.4	6.8
Mix R8	sample1	12.4	0.4	2.9
	sample2	14.5	1.1	7.8
	sample3	20.3	0.4	1.8
Mix R9	sample1	10.7	0.6	5.8
	sample2	13.1	0.1	0.6
	sample3	21.1	0.1	0.7
Mix R10	sample1	7.7	0.8	9.9
	sample2	12.1	1.2	9.6
	sample3	8.4	0.2	1.9
Mix R11	sample1	7.6	0.9	12.1
	sample2	8.1	0.4	4.9
	sample3	11.3	0.5	4.6
Mix R12	sample1	10.7	0.8	7.1
	sample2	10.1	0.5	5.4
	sample3	7.6	0.3	3.6
		Ave.	**0.6**	**4.7**

2.4.3 Repeatability of a Box Test in a single mixture by a single operator:

From a single mixture, three samples were evaluated with the Box Test and the point count template. In each side of a sample, the critical voids were identified and the average number of critical voids identified for the four sides was calculated and reported in Table 2.4. The SD and COV were computed to determine the variability in average the critical voids measurements between the samples. This was done to determine the repeatability of critical voids measurements in a single mixture by a single operator. While the variability has increased by using multiple mixtures, the results show a reasonable comparison as the average SD is 1.3 voids between three tests and the COV was 14.7%.

Table 2. 4: Repeatability of the average critical voids measurements in a mixture by a single operator.

Critical voids Ave. No. per sample				Mean	SD	COV %
Mix No.	**sample1**	**sample2**	**sample3**			
18	8	7	13	9	2.4	25.4
17	4	8	6	6	1.4	24.1
16	5	4	6	5	0.5	10.8
15	9	10	13	11	1.9	18.4
14	6	8	8	8	1.1	15.1
13	6	9	8	8	1.3	16.4
12	7	6	7	7	0.2	3.6
11	8	9	9	9	0.6	7.6
10	12	13	15	13	1.2	8.9
9	11	16	17	15	2.4	16.2
				Ave.	**1.3**	**14.7**

2.4.4 Repeatability of a Box Test in a single mixture by multiple operators:

Three different evaluators utilized the point count template to evaluate the surface voids concentration at the sides of the samples from ten mixtures. Three samples were prepared from each concrete mixture and evaluated by three operators. Each operator determined the number of critical voids for each side of the sample and the average of the four sides was calculated and reported in Table 2.5. The SD as well as COV were computed to determine the variability between the numbers of critical voids taken from the three samples for every operator. Finally, an overall average of the measurements taken by the operators were provided in the table. The variability of the results only slightly increased when multiple operators were used but the values are still quite reasonable as the SD is 2.8 voids with a COV of 21%.

Table 2.5: Repeatability of Box Test measurements in a single mixture by multiple operators.

Mix NO.	operator	Critical voids Ave. No. of a sample						Ave, critical voids per mix	Ave. SD	AVE. COV
		sample 1	**sample 2**	**sample 3**	**Ave.**	**SD**	**COV**			
Mix R3	op 1	17	11	10	12.7	2.9	23.2	12.8	2.6	20.0
	op 2	16	12	10	12.6	2.3	18.3			
	op 3	17	12	11	13.1	2.4	18.6			
Mix R4	op 1	15	12	12	12.6	1.3	10.6	13.2	1.7	13.0
	op 2	16	13	12	13.8	1.7	12.6			
	op 3	16	12	12	13.2	2.1	15.8			
Mix R5	op 1	15	12	8	11.7	3.1	26.0	12.0	2.8	23.4
	op 2	15	12	9	12.1	2.3	19.3			
	op 3	16	12	8	12.2	3.0	24.8			
Mix R6	op 1	15	12	25	17.2	5.5	32.1	16.6	5.5	33.1
	op 2	15	10	24	16.1	5.6	34.8			
	op 3	15	11	24	16.5	5.4	32.4			
Mix R7	op 1	12	16	22	16.5	4.1	24.9	16.2	3.0	18.7
	op 2	13	17	19	16.2	2.2	13.5			
	op 3	13	16	20	16.0	2.8	17.6			
Mix R8	op 1	13	16	21	16.4	3.4	20.5	15.8	3.4	21.4
	op 2	12	13	20	15.1	3.4	22.3			
	op 3	12	15	20	15.8	3.4	21.2			
Mix R9	op 1	10	13	21	14.6	4.6	31.7	15.0	4.5	29.9
	op 2	11	13	21	15.2	4.3	28.5			
	op 3	11	13	21	15.1	4.4	29.4			
Mix R10	op 1	8	13	8	9.8	2.5	25.5	9.4	1.9	20.1
	op 2	8	11	8	8.8	1.2	13.5			
	op 3	8	12	9	9.6	2.0	21.2			
Mix11	op 1	8	8	11	9.1	1.0	11.4	8.8	1.4	15.8
	op 2	7	9	10	8.6	1.2	14.3			
	op 3	7	8	11	8.7	1.9	21.6			
Mix R12	op 1	11	10	8	9.5	1.2	12.2	9.4	1.4	15.0
	op 2	10	11	8	9.4	1.4	14.8			
	op 3	11	9	7	9.3	1.7	17.9			
								Ave.	**2.8**	**21.0**

2.4.5 Point count method versus visual inspection method:

A comparison between the point count method and the visual inspection method was made by comparing ten mixtures. The average percentage of the total surface voids identified from both methods per each mixture were recorded. Table 2.6 shows a comparison of the overall average percentage of surface voids from both methods. The average absolute difference of the overall surface voids percentage of a sample would be approximately 5% with a SD of 2.7%. This again shows very good comparison between the two methods.

Table 2.6: A comparison between the point count method VS. the visual assessment method.

Mix No.	Template evaluation	Pass the test	Visual evaluation	Pass the test	Absolute difference	Percent difference
mix 18	29.5	YES	20	YES	9.5	38.24
mix 17	14.6	YES	13.5	YES	1.1	7.69
mix 16	17.9	YES	23.75	YES	5.9	28.33
mix 15	30.4	YES	27.5	YES	2.9	9.88
mix 14	21.1	YES	24	YES	2.9	12.74
mix 13	22.3	YES	26.75	YES	4.4	18.01
mix 12	32.4	YES	23.75	YES	8.7	30.93
mix 11	27.4	YES	26	YES	1.4	5.18
mix 9	28.3	YES	25	YES	5.2	19.36
Mix8	35.0	YES	28.75	YES	6.8	21.26
				Ave.	**4.9**	**19.16**
				SD	**2.7**	**10.23**

All numbers in percentages

2.5 Discussion:

2.5.1 Comparison between the results:

Table 2.7: Summary of the results from testing the variables of the point count method.

Variable tested	SD	COV
Repeatability of the measurements of a single face by a single operator	0.16	1.52 %
Multiple operators comparison in identifying critical voids in a single sample	0.6	4.7 %
Repeatability of a Box Test in a single mixture by a single operator	1.3	14.7 %
Repeatability of a Box Test in a single mixture by multiple operators:	2.8	21 %

Table 2.7 illustrates that the variance that can occur in the results of the point count method increased with multiple users and with multiple measurements. However, the results seem reasonable and show that this point count method is a repeatable method to complete the Box Test.

2.5.2 Causes of variance in the point count method:

One of the variables investigated in this chapter was the repeatability of the measurements by the proposed assessment method per each side of a sample in a Box Test. The variation in the results might happen because of the change in the point count template location when placing it in front of a concrete side. When the point count template is placed differently, there might be a chance that parts of a critical void will be included/excluded from the circle's area, especially for critical voids located at the edges of the circles as illustrated in Figure 2.14.

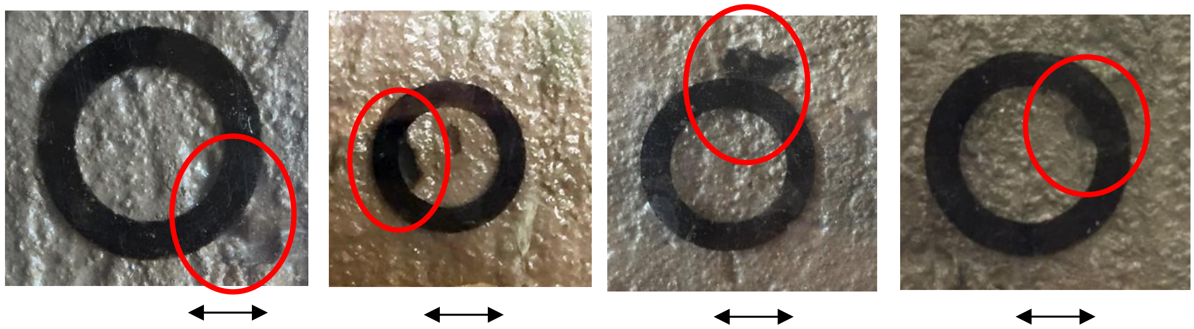


Figure 2.14: Examples of critical voids located at the edges of the circles.

Due to small shifts in location that might occur when placing the point count template, the number of the critical voids for each side of a sample can change. Based on the obtained results, the variation between the measurements taken per a single concrete side in three rounds was very low, in which 71% of the measurements from the four sides were repeatable with a zero SD. This means there is no variation between the measurements. The remaining measurements have a variation up to one critical void for each side of a sample, which represents the remaining 29% of the measurements. The COV due to the position change of the assessment tool was below 5%. This suggests that the measurements of the critical voids on the surface of the Box Test is very repeatable.

Another major cause for differences between operators was the roughness of the surface of concrete. It was occasionally challenging for the operators to identify if something was a void or just an imperfection in the surface. Sometimes, it was confusing when encountering an indentation at the concrete surface with a short depth, close to the surrounding surface. Figure 2.15 illustrates a rough surface that can cause the variation.

There are suggested approaches that can be followed in this situation. If an operator is able to see the bottom and edges of a surface void clearly as illustrated in Fig. 2.15 then the void is not critical. Another approach was the use of a flashlight. A flashlight was utilized and held on an angle, approximately 45°, to cast a shadow on a questionable void. For instance, the darker the shadow casted on the void in question, the more of a chance it was a void. The lighter the shadow casted on the void, the more likely it was a rough surface.

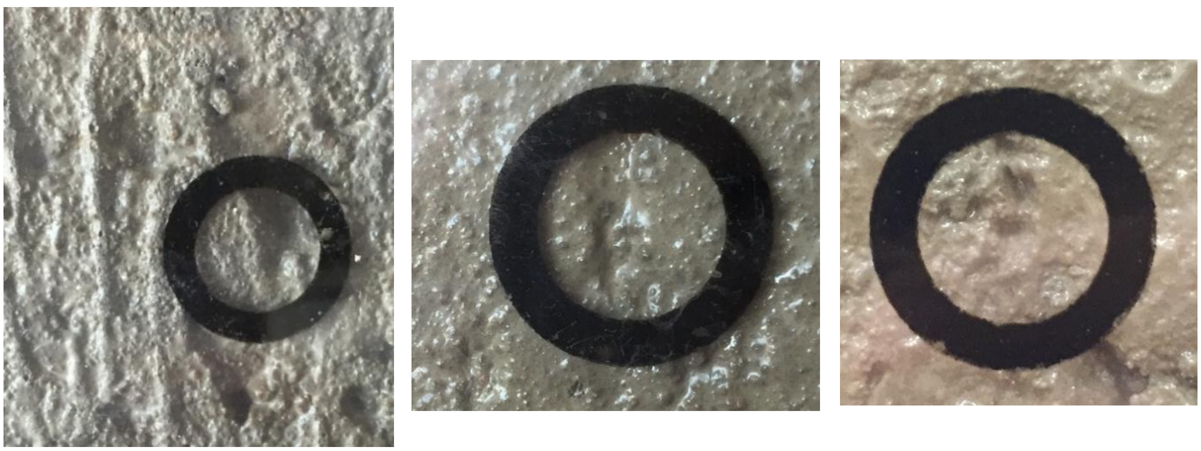


Figure 2.15: Examples of surface roughness inside a circle.

2.5.3 The proposed evaluation method:

The assessment of the Box Test depends mainly on the visual observation, which may vary from one operator to another based on their experience. A comparison was made to determine if there were an agreement between the measurements of surface voids concentration. Based on Table 2.6, it can be noted that the evaluated mixtures passed the Box Test in both evaluation methods even though there were some differences in the overall surface voids percentages. Therefore, in both evaluation methods, an agreement was found in the decision of passing or rejecting a mixture in all evaluated mixtures. In addition, the average absolute difference in the overall surface voids percentage was 4.9% with a SD of 2.7%

2.5.4 Practical implication:

The point count template was developed to be a simple and fast evaluation technique in the Box Test. The aim of this method was to quantify the evaluation of surface voids at each side of a sample by providing a systematic way to count the critical voids. In addition, the point count template can facilitate the edge slump measurements in which an operator can use a measure tape or directly by looking at the edges of the template and record the measurements. The usefulness of the proposed evaluation method of the Box Test arises from the consistency in its results and the simple one rule that aids the decision of counting surface critical voids.

2.6 Conclusion:

A new evaluation technique was addressed in this work that has a potential to be more quantitative than the current evaluation in the Box Test. an attempt was made to develop an evaluation tool that can provide a systematic method to quantify the number of surface voids. The following findings were made:

- The new evaluation technique has repeatable results in which the variation of the measurements per each side of a sample can be within one critical void with a SD of 0.13 and a COV less than 5%. In fact, 71% of the measurements from the four sides were repeatable with no variation.

- The variation between three operators in determining the average critical voids per a sample was approximately one critical void with an average SD of 0.6 voids. The average COV between their measurements was 4.7%.
- Based on the single operator results from this document, the average critical voids identified per a sample can be repeatable in a single mixture. The average difference between the average critical voids numbers identified per three samples from the same mixture was one critical void with an average SD of 1.3 voids.
- However, the average difference between the average critical voids numbers identified per three samples from the same mixture by multiple operators was 2.5 critical voids with an average SD of 3 voids.
- When comparing the Box Test evaluation methods, it was found that both of them had an agreement in accepting/rejecting concrete mixtures. The average difference of the percentage of the surface voids concentrations reported from the two methods was 4.9% with an average SD of 2.7%.

To conclude, the proposed evaluation method provides a fast and inexpensive method with consistent results with the Box Test. Although the method requires additional equipment and an increase in the time required to complete the test, the results are more quantitative and this may be advantageous in some circumstances.

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CHAPTER III

CONCRETE VIBRATION AND THE FREQUENCY CHANGE EFFECT ON THE CONCRETE CONSOLIDATION

3.0 Introduction:

Concrete pavement mixtures commonly consist of paste and aggregate. The compositions of the paste are water, Portland cement, supplementary cementitious materials, and admixtures. The paste acts like a binding material that combines the aggregate together. It is known that the paste contains air voids that can be divided into two classifications: entrapped air voids with a size greater than 0.04 " (1 mm) and entrained air voids that have a size between 0.0004 to 0.04 " (10 µm to 1 mm) [17].

Slip formed pavements require concrete mixtures with enough stiffness to hold an edge after the placement by a paver, and, at the same time, have enough workability to achieve a satisfactory consolidation [11]. Commonly, the consolidation of pavement mixtures is obtained by removing entrapped air voids via mechanical methods. Typical mechanical methods used in fresh concrete consolidation are mechanical vibrators, which are the major element in a slip formed paver because the majority of the consolidation energy is contributed through them [11]. Vibration has a great influence on the air system of freshly mixed concrete. The highest concrete density needs a minimum amount of entrapped air, which can be achieved by comparing the vibrator characteristics with the properties of fresh concrete [1]. Therefore, it is essential to understand the behavior of fresh concrete under vibration.

3.1 Mechanisms of concrete vibration:

Generally, an internal vibrator consists of a poker that is connected to a bendable drive with a motor. An internal vibrator is immersed into the concrete and consolidates the plastic concrete directly by physical contact [17]. When concrete mass is vibrated, the vibration will transfer into the concrete through harmonic forces. These vibration forces can cause movements in the concrete particles and consolidate the concrete [17]. The vibration leads to the decrease in the yield stress of fresh concrete. This will cause the concrete to move under its own weight, Banfill et al. [7]. Chong quantified the previous observation and stated that during vibrating the concrete, the yield stress of the concrete is almost half the yield stress of the concrete with no vibration [9]. This temporary change in the performance of the concrete allows it to be easily consolidated.

3.1.1 Vibration motion:

An internal vibrator contains a rotational eccentric weight that is held and protected in an external housing. Due to the eccentric weight, the vibrator rotates in a circular orbit. The rotation of the eccentric weight of the vibrator generates circular compression waves into the concrete, which is characterized by sinusoidal waves, shown in Fig 3.1 & 3.2 [1] [17].

The size of the orbit, or the amplitude, relies on the vibrator weight, eccentric weight, vibrator frequency, and the moment of the eccentric weight [2] [3].

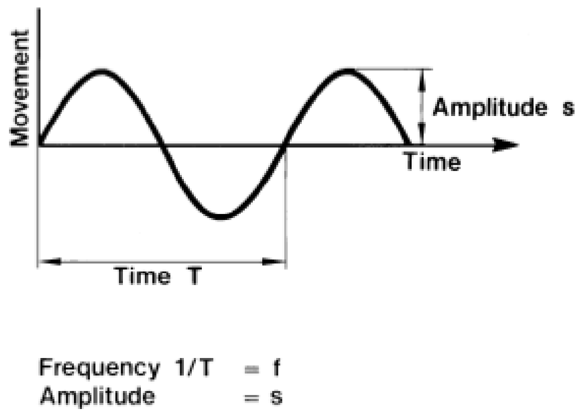
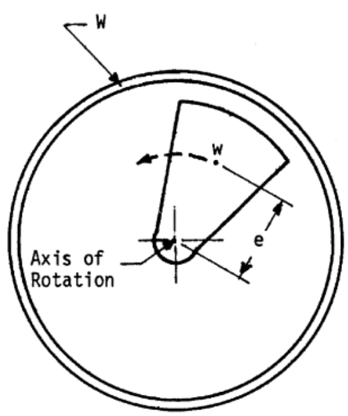


Figure 3. 1: The sinusoidal waves generated by a vibrator. (Adapted from [1]).



W	= weight of shell and other nonmoving parts, lb (kg)
w	= weight of eccentric, lb (kg)
$W+w$	= total weight of vibrator
e	= eccentricity, i.e., distance from center of gravity of eccentric to its center of rotation, in. (mm)
we	= eccentric moment, in.-lb (mm-kg)
n	= frequency, cycles per sec (Hz)
F	$= \frac{w}{g} 4\pi^2 n^2 e =$ centrifugal force, lb (kN)

Figure 3. 2: Circular compression waves generated due to the vibration. (Adapted from [4]).

3.1.2 Concrete vibration parameters:

- **Acceleration:**

Acceleration is a measurement of the intensity of vibration. Acceleration is a key factor in the consolidation process in which it starts at a minimum acceleration of approximately 0.5 g (4.9 m/s^2) [1]. The consolidation effectiveness increases linearly with the acceleration until it reaches an optimum acceleration in which any further increase in the acceleration will not affect the consolidation [1].

- **Frequency:**

The frequency of a vibrator can be defined as the number of rotations of the eccentric weight per minute. It can be simpler to say that the frequency is the number of times that the vibration forces happen in a time interval [21]. The vibrator's frequency has a huge influence on the fresh concrete consolidation, the air system, and the radius of action. In addition, it governs the vibration duration that is required to complete the consolidation process [1] [22].

- **Amplitude:**

The amplitude of a vibrator can be defined as a measurement of the maximum distance point that a vibrator head can travel from its original axis [10]. The amplitude is a function of the eccentric moment and the head mass [4] [22]. The amplitude has a great influence on the radius of action. The minimum required amplitude was found to be 0.0015 in (0.04 mm), proposed by Kolek [19].

- **Nominal maximum aggregate size:**

The nominal maximum aggregate size of a concrete mixture can be a major parameter for vibration effectiveness. The aggregate characteristics can have an impact on the vibration parameters. Based on Taylor's research results, the range of the accelerations recommended for vibrations should be from 100 to 200 g (980 to 1960 m/s2) for concrete mixtures with maximum aggregate sizes of 1-1/4, 3/4, and 3/8 in. (38, 19, and 10 mm) [1].

3.1.3 Vibration process:

Concrete pavements require low slump concrete in order to hold an edge after the placement by a slip formed paver. According to American Concrete Institute (ACI), low slump concrete that is not consolidated tends to have a percentage of entrapped air ranges from 5% to 20% [22]. Therefore, one of the effective methods to remove the entrapped air and consolidate the concrete is the vibration method. The vibration of a granular material will set its particles into motion. Thus, the internal friction can be eliminated [1]. L' Hermite and Tournon stated that when fresh concrete is under vibration, the internal friction is 0.15 psi; however, the internal friction when fresh concrete is in rest is 3 psi [20]. Therefore, there is a reduction in the internal friction of 95% while in motion. Walz reported that the primary reason for the decrease in the internal friction is the acceleration created during vibration [25].

The consolidation by vibration comprises two major stages. Kolek proposed that the first stage of the vibration process comprises the common slump of a loose mixture, which occur rapidly [19]. Due to the harmonic force, the behavior of the concrete particles can be close to fluids. This behavior happens because the internal friction between the particles in the concrete is reduced by the vibration. In this stage, the mix will become denser and flow like a viscous liquid and slump [22]. Subsequently, deaeration stage, or the removal of entrapped air, occurs [19]. Smalley and Ahmed theorized that air voids show a tendency of moving toward the surface depending on their buoyancy; in addition, air voids tend to move toward the vibrating object [23]. That is why excessive vibration should be avoided, especially for forms vibration [1].

Alexander studied the vibration process via the measurement of the mechanical impedance. It was found that when the vibratory motion level is low, the concrete is described as high damping and stiff; meaning that no resonant frequency is found. However, at higher intensities of vibratory motions, the impedance is largely decreased. After the concrete transforms to a fluid state, the vibratory motion is governed by the mass force, while the stiffness or damping has slight or no effect. This gave an indication that the concrete during vibration behaves as a fluid [5].

When the applied force intensity to vibrate the concrete is lower than the required level to make the concrete flow, the impedance will be high; it is a function of the mass, damping, and stiffness. When the induced force is raised to a higher level, the impedance drops down until the material changes from a solid to fluid state, and the mechanical properties change [1].

Different values for the wave velocity in fresh concrete have been reported. Halken reported that the wave velocity is about 150 ft/s (45 m/s) through the first stage of vibration. At vibration periods of 1 to 2 minutes, wave velocities were reported to be between 200 and 800 ft/s (60 and 250 m/s) [15].

3.1.4 Energy consumption:

During the first stage of the concrete consolidation by vibration, the rapid subsidence takes place. This rapid subsidence can be characterized as the plastic deformation, which consumes a large amount of energy, and the entire transmitted energy should be consumed to have complete consolidation [1].

In the final deaeration period, no extra energy is needed to keep the concrete mass in motion because the material is already behaving like a fluid. For ideal fluids, the energy consumption of the vibrators is hypothetically identical to air. In reality, there is a small internal friction and damping during deaeration stage, which requires a sufficient energy supply [1] [22]. In a homogenious fluid, the amplitude created around the vibrating head have the same vibrator amplitude. However, the concrete is not a homogenious material. Thus, during vibration, cement paste will move towards and surround the vibrator head. Consequently, a reduction in the energy transmision from the vibrator to the fresh concrete may occur, which can be determined empirically[1].

3.1.5 Radius of action:

The radius of action is defined as the distance from the immersed vibrator head to the ultimate point for the vibrator to deliver enough force in order to consolidate the surrounding concrete. Usually, the radius of action increases as the vibrator's frequency increases, until it reaches the optimum frequency [1] [22]. Bergstorm and Linderholms, and Forssbald made the measurements of the radii of action of vibrators at different intervals of time based on the surface concrete images [8] [14]. Consequently, relationships were developed between frequency, radius of action, and amplitude for an internal vibrator with 2-1/2" head and a vibration period of 10 s and 30 s, as shown in Fig. 3.3. At all frequencies, an increase in the vibrator amplitude led to an increase in the radius of action.

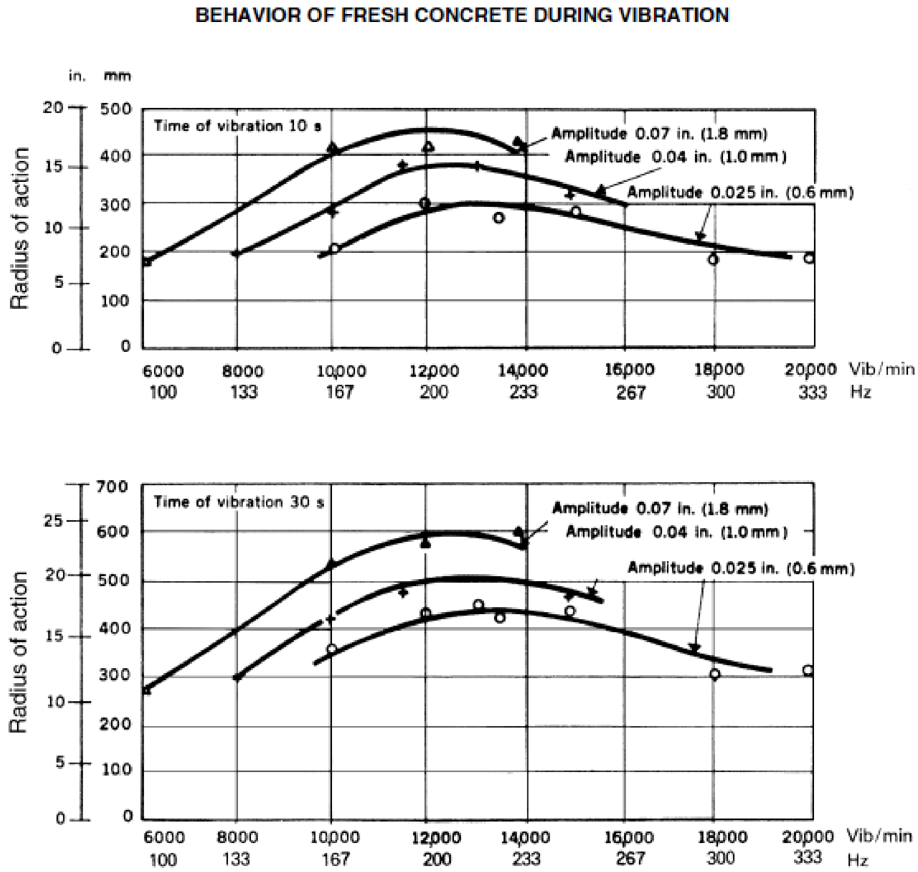


Figure 3. 3: A relationship between frequency, radius of action, and amplitude for an internal vibrator (2-1/2 in head size). (Adapted from [1])

According to Fig 3.3, the optimum frequency at which the largest radius of action occur at approximately 12,000 vpm and it was confirmed by Taylor [24]. Forssbald used photographs of concrete surfaces to determine the radius of action, and Hover made measurements of the radius of action of internal vibrators at different frequencies, amplitudes, vibration durations, and mixture consistencies [14] [16]. It was found that the frequency of a vibrator is a significant factor for consolidating fresh concrete. At too low frequencies, the vibrator can not provide a proper consolidation for the concrete. On the other hand, at too high frequencies, entrained air content of the concrete can be affected;

the volume of entrained air can be lowered by high frequencies, which makes it less resistible to freeze-thaw cycles [1].

Dessoff theorized that the amplitude decreases with the increase in the distance from the vibrator. This reduction in the amplitude is primarily caused by geometric energy distribution due to the radial generation of compression waves. In addition, damping is minor factor in the amplitude reduction. Damping could be a result of the small residual internal friction in the fresh concrete [12].

Finally, based on Erosy, the consolidation effectiveness can be determined primarily by the eccentric moment and the frequency of a vibrator [13]. Kirkham found that the degree of consolidation is affected by factors such as the frequency, the vibratory force, and the amplitude of vibration [18]. Taylor showed that the most important parameters on the effectiveness of internal vibrators are acceleration and amplitude in which gamma ray scanning was utilized to measure the density of concrete and the vibrator's radius of action [24]. Alexander proposed a prototype method that can be used in the field to determine the consolidation degree by measuring the electrical impedance of the concrete; relationships between the electrical impedance and the air voids types and magnitude were made [6].

3.1.6 Object:

In the Box Test, the consolidation of fresh concrete is done by the use of an internal vibrator. The type of vibrator used was Wyco Sure Speed vibrator. This vibrator has a motor that operates at constant frequency despite the shaft length, head size, and concrete slump. An internal vibrator that operates in air would have the same specified frequency, but when operating in concrete, a reduction in the frequency would occur [4]. The reduction can be between 20 to 25 percent from the original frequency of the vibrator [21]. In addition, the shaft length can have an impact on the frequency due to the friction loss creation [10]. An analysis was made to investigate the influence of the frequency change of an internal vibrator on the consolidation of fresh concrete in the Box Test. In addition, the Box Test was utilized to evaluate the effect of the change of the frequency on the radius of action resulting from an internal vibration.

3.2 Method:

3.2.1 Material and The Box Test procedure:

The Box Test was used to evaluate the effect of changing the frequency of vibration on fresh concrete. The materials, mixture preparation, and the Box Test procedure were discussed earlier in chapter II.

3.2.2 Consolidation method by an internal vibrator with different frequencies:

After preparing a concrete batch and mixing it, two samples were prepared and examined simultaneously by the Box Test by following the procedure described in Chapter II. This would ensure that both samples had the same concrete material characteristics and the only difference between the samples was the vibration frequency. For the first sample, the vibration frequency utilized was 12,500 vpm (high frequency), and for the second sample, the frequency of the vibrator was 10,000 vpm (medium frequency).

The Box Test assessment was conducted on both concrete boxes to investigate the concrete's response to vibration by evaluating the surface voids concentration at each side of concrete. Moreover, the radii of action at the top concrete surfaces were observed.

3.3 Results:

3.3.1 Effect of the vibration frequency on the critical voids:

Seven mixtures were made to investigate the variation of the concrete response to vibration when the vibration frequency is changed. From a single mixture, tow samples were prepared, vibrated with their specified frequencies, and evaluated by the Box Test; this sequence was repeated three times. Then, an average was calculated for each set of the critical voids measurements. The average Box Test measurements for each mixture is displayed in Table 3.1. The Table shows the average number of the critical voids per each concrete side of a sample.

Table 3. 1: The average results of critical voids per each side of a sample in a mixture.

Mix NO.	Box face	No. Of critical voids					
		High frequency	**medium frequency**	Ave.	Absolute difference	percent difference	
Mix F 18	face 1	10	17	13.61	7.45	54.70%	
	face 2	9	14	11.94	5.00	41.86%	
	face 3	8	16	12.17	7.45	61.21%	
	face 4	10	16	12.94	5.67	43.78%	
Mix F 17	face 1	5	16	10.56	11.11	105.26%	
	face 2	7	18	12.78	10.67	83.49%	
	face 3	6	19	12.28	13.22	107.70%	
	face 4	6	16	10.89	10.00	91.83%	
Mix F 16	face 1	4	12	7.89	7.78	98.67%	
	face 2	6	15	10.34	8.89	86.02%	
	face 3	5	14	9.89	9.11	92.13%	
	face 4	5	14	9.72	9.44	97.14%	
Mix F 15	face 1	9	14	11.44	4.67	40.78%	
	face 2	11	18	14.39	6.33	43.99%	
	face 3	11	18	14.06	7.00	49.83%	
	face 4	11	15	13.28	3.89	29.30%	
Mix F 14	face 1	9	11	10.33	2.23	21.55%	
	face 2	8	15	11.28	7.23	64.09%	
	face 3	6	15	10.56	8.67	82.14%	
	face 4	7	13	9.83	5.67	57.63%	
Mix F 13	face 1	8	13	10.56	5.33	50.52%	
	face 2	9	17	13.39	7.89	58.93%	
	face 3	8	15	11.39	7.22	63.39%	
	face 4	7	14	10.22	6.67	65.21%	
Mix F 12	face 1	6	9	7.61	2.78	36.48%	
	face 2	6	17	11.83	11.22	94.82%	
	face 3	5	16	10.50	11.44	108.97%	
	face 4	5	10	7.50	5.89	78.49%	
					7.50	68%	Ave
					2.64	25%	SD.

3.3.2 Observation of the radius of action:

The radii of action resulting from the high and medium frequencies were observed. Images were taken of the top surface of the concrete after vibration. Figures 3.4 through 3.10 illustrate the differences in the radii of action due to the change in the vibrating frequency.

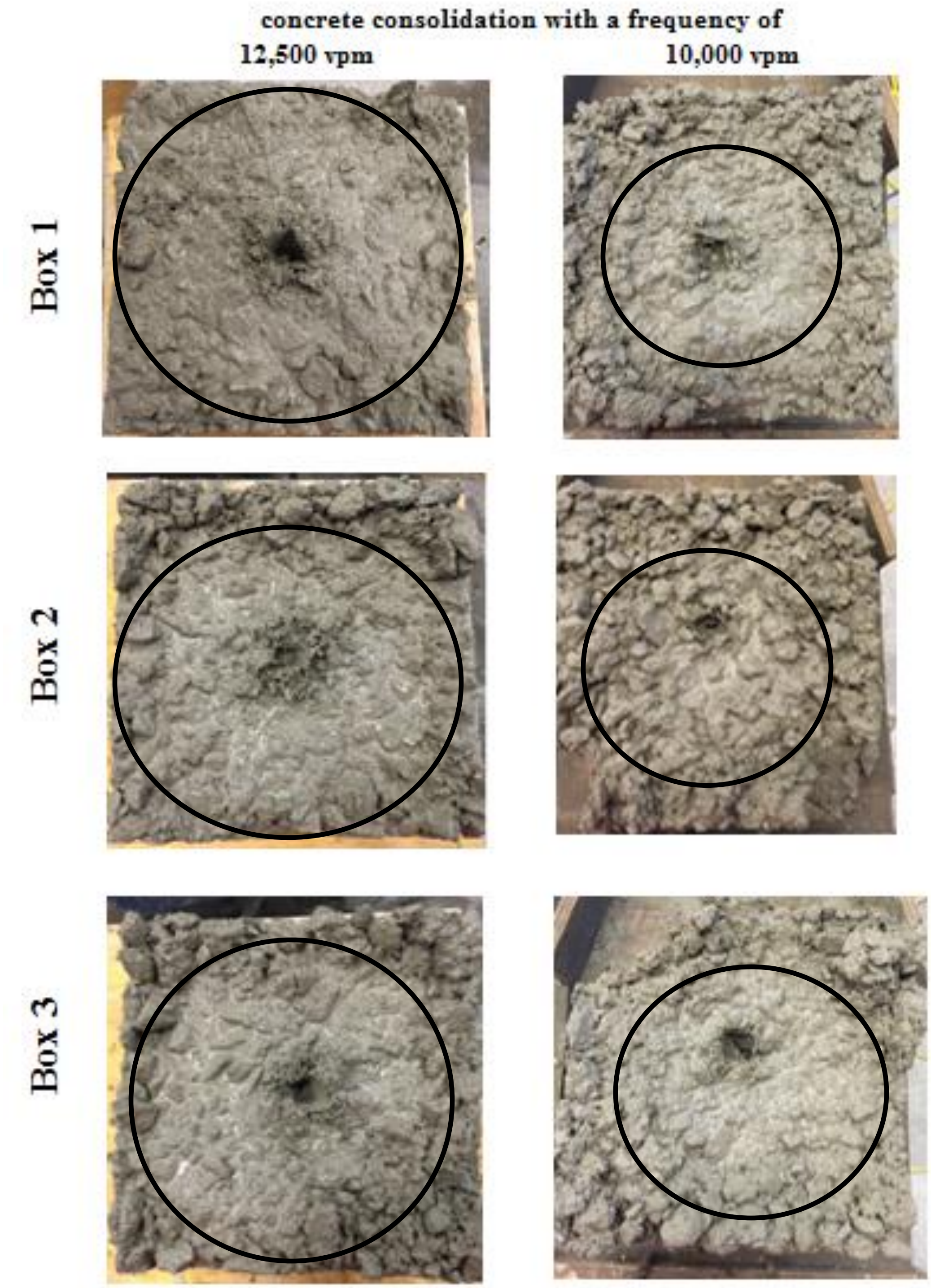


Figure 3. 4: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F12

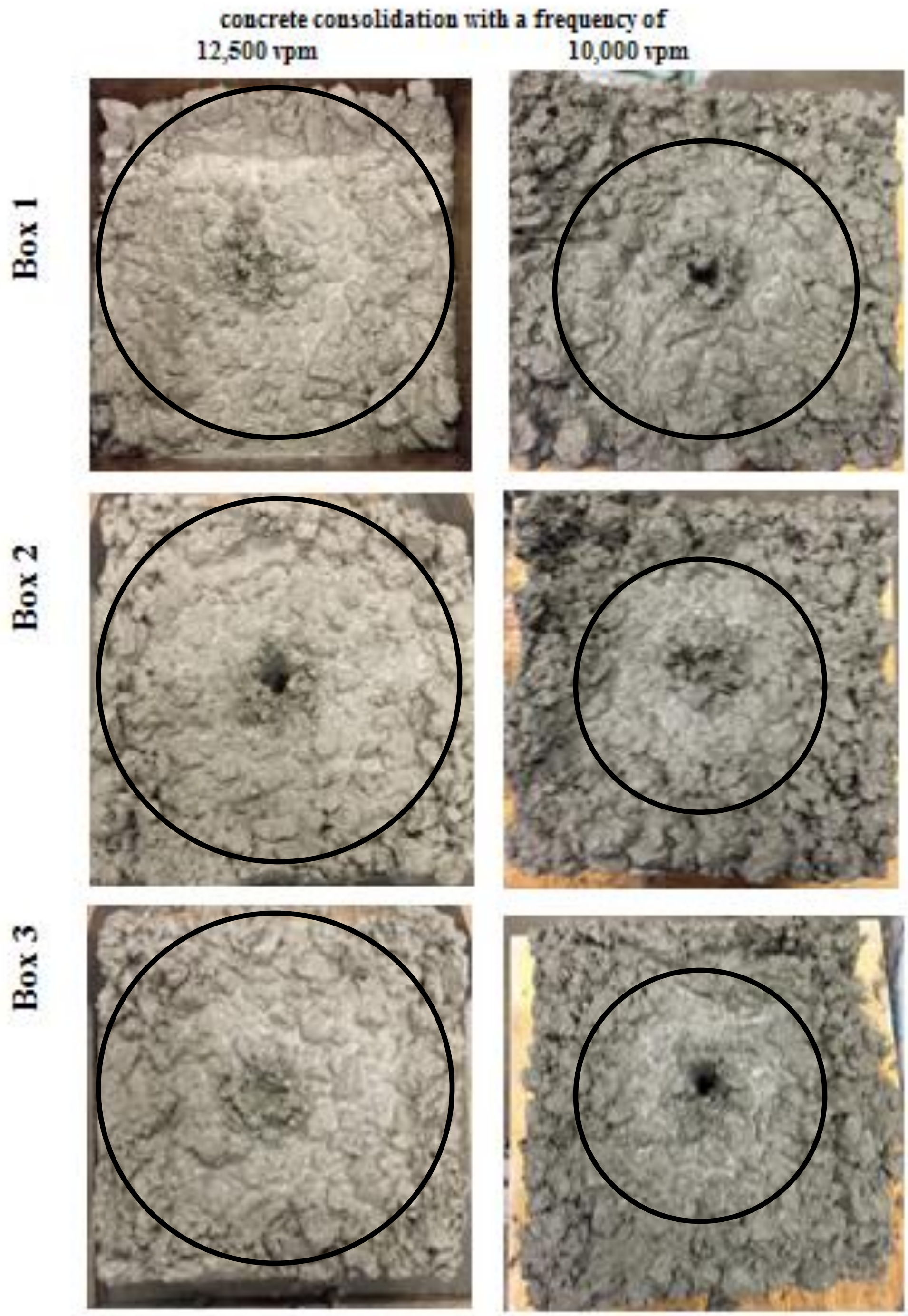


Figure 3. 5: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F13

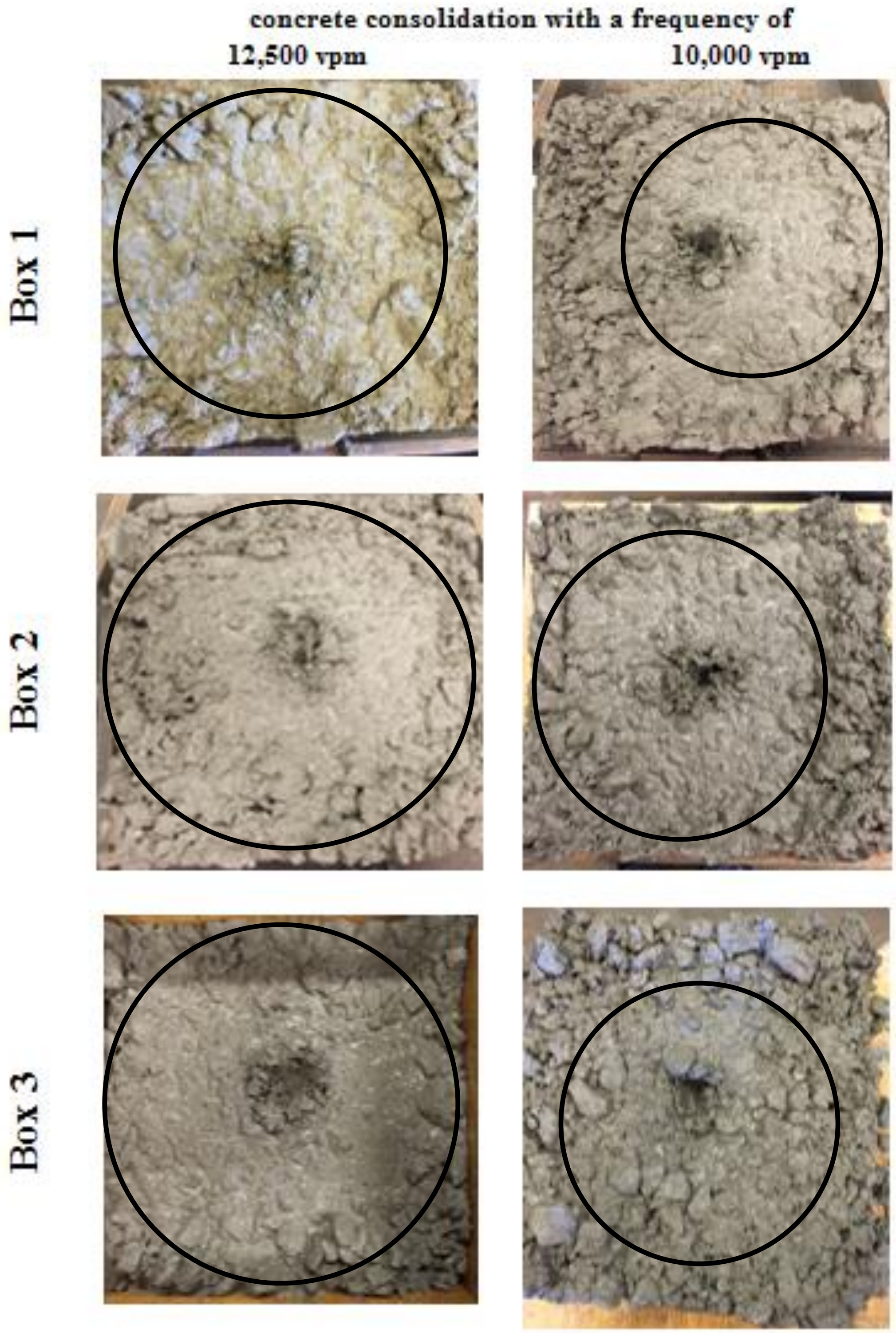


Figure 3. 6: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F14

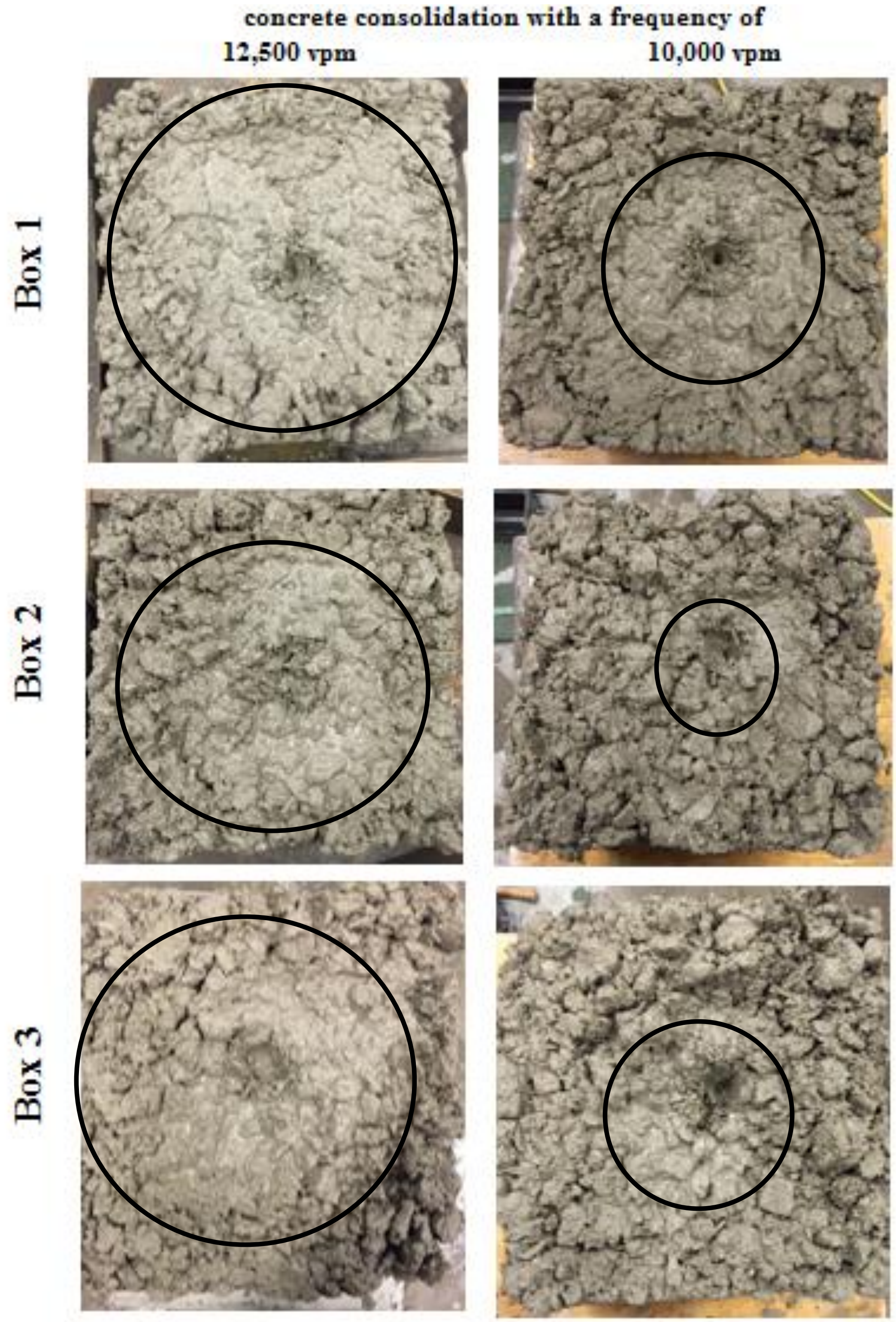


Figure 3. 7: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F15

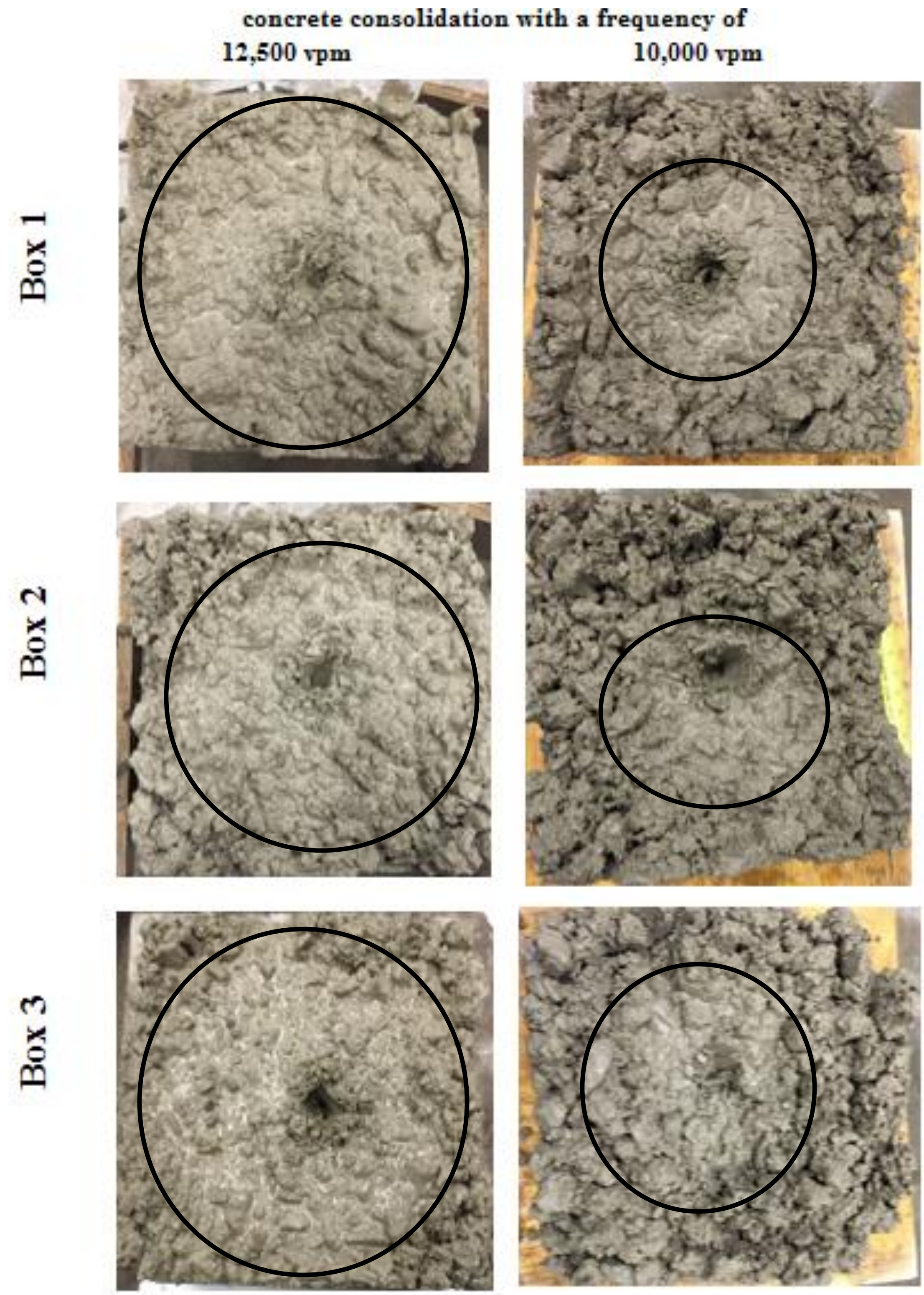


Figure 3. 8: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F16

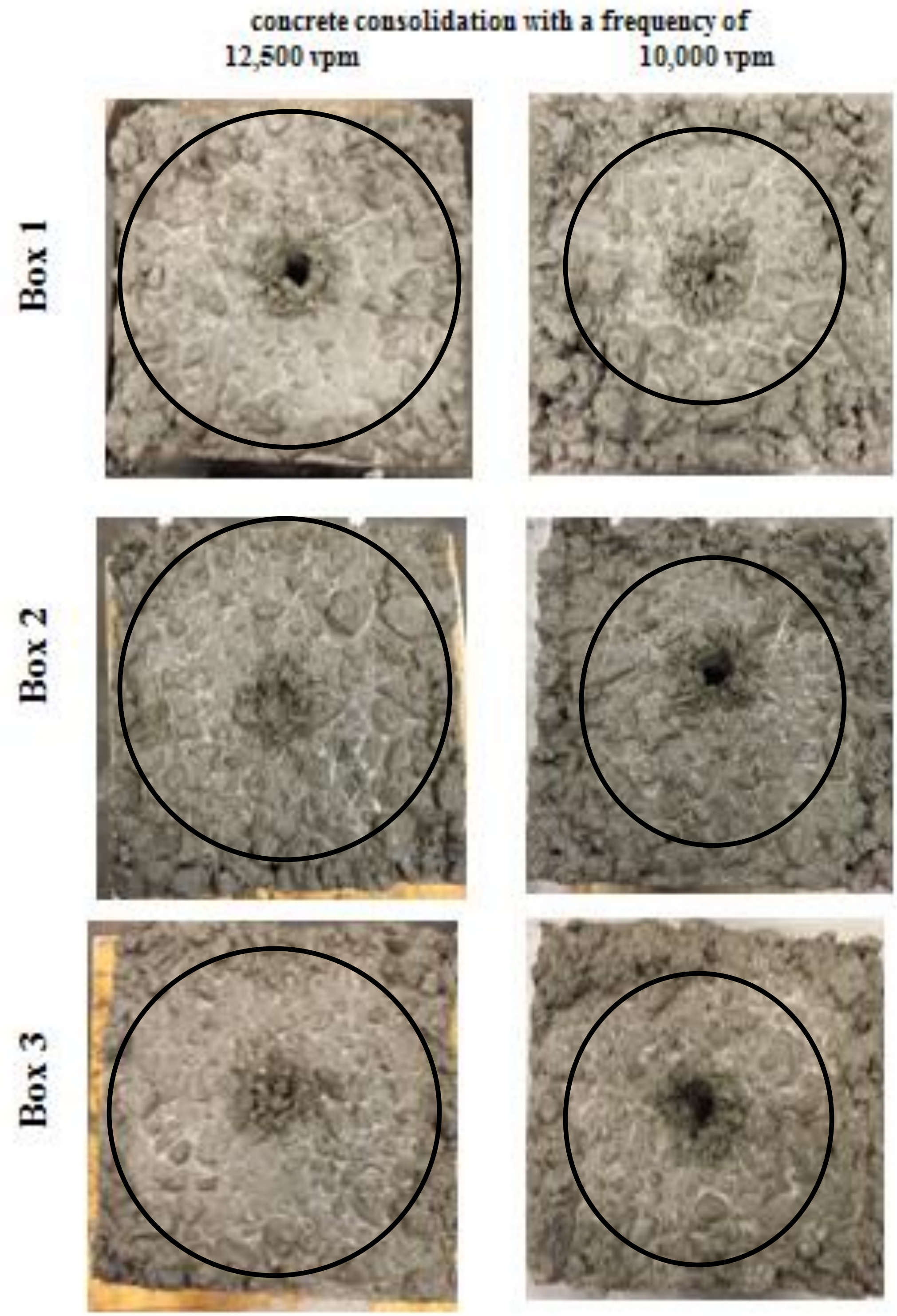


Figure 3. 9: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F17

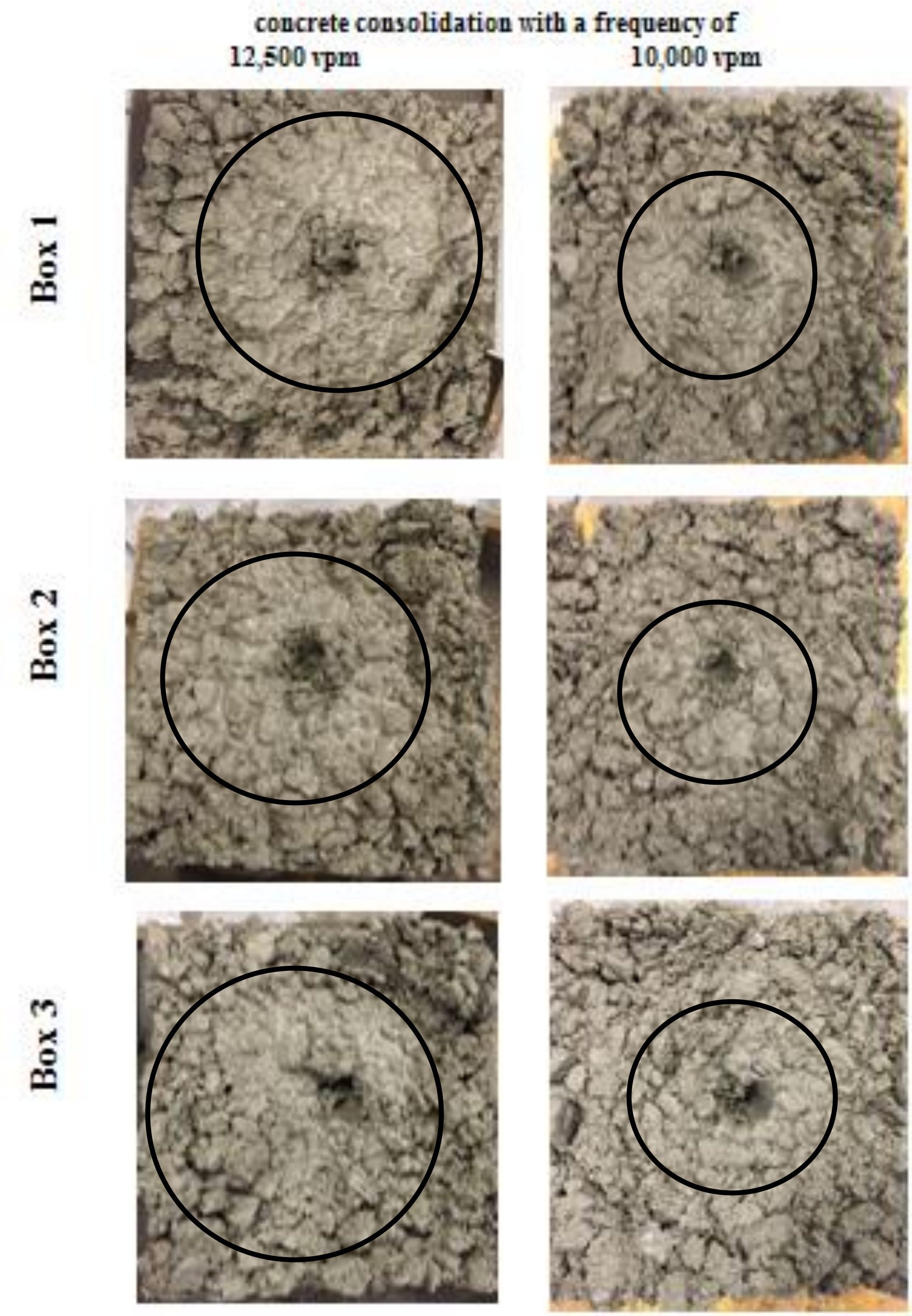


Figure 3. 10: The radius of action resulted from the consolidating the Box Test at different frequencies.

Mixture F18

3.4 Discussion:

3.4.1 Frequency effect on critical circles:

The frequency of the vibrator utilized in the Box Test can have a great impact on the amount of critical voids identified per each side of a sample. To prove that, from a single mixture, two samples were made to ensure that the concrete materials and characteristics would be the same for both of them. The only difference between the samples was the vibrating frequency in which sample 1 was vibrated with a high frequency and sample 2 was vibrated with a medium frequency. Via the Box Test, a measurement of the critical voids was made for each side of the samples and a comparison between the measurements was made. Based on Table 3.1, it can be noticed that the number of critical voids per each side of a sample was lower when the high frequency was utilized. The concrete deemed a good response to vibration and passed the Box Test. However, when the frequency was reduced to the medium level, the number of critical voids increased dramatically and the concrete was granted a poor response to vibration. The absolute difference between the critical voids identified per a side was between 2 and 13 with an average of 7.5 critical voids and an average SD of 2.64 critical voids. The average percent difference in the counted critical voids was found to be 68% with an average SD of 25%.

A combination of amplitude and frequency of a vibrator imparts a vibratory force into the concrete [21]. The centrifugal force of a vibrator is a measure of the capability of moving a concrete mix depending on the rotation speed, and the eccentric rotor and its size. As more force is applied, the higher movement of the concrete is achieved [10]. Since the vibrator that was used in the Box Test has a fixed size head and amplitude, the only change was the frequency of the vibrator. Consequently, when the high frequency was used in vibrating the concrete in the Box Test, the applied force to consolidate the concrete is larger. Therefore, a better consolidation result was obtained because higher frequencies primarily disturb fine particles. Since the majority of trapped air happens to be around these particles, higher frequencies allow more cement paste to cover the fine particles after the air removal and move the slurry and sand around the coarse aggregate [10] [21].

To conclude, in the Box Test, the need for an internal vibrator that would provide a consistent frequency while vibrating concrete is enormously important. It can be noticed that the reduction of the vibration frequency can majorly increase the critical voids identified for a side of a sample, which can indicate a poor response to vibration and lead to rejecting a mixture. However, when a sufficient and constant frequency is applied for the same sample, lower critical voids may appear and the same mixture can pass the Box Test.

3.4.2 Frequency effect on the radius of action:

The amplitude of a vibrator has a great impact on determining the radius of action, especially with a heavier mass of concrete because it causes the large coarse aggregate to move [21]. However, the frequency of a vibrator has an important effect on the radius of action as well. According to the images taken of the top surface of each concrete sample, the radius of action resulting from the vibration with the high frequency was larger than the radius of action that resulted from the medium frequency. It can be seen from the photos that the higher vibration frequency had a radius of action that can reach the edges of the sample. This means that the vibration force was sufficient and was able to travel through the concrete to remove entrapped air voids and obtain an acceptable consolidation. Low surface voids concentrations on the concrete sides of a sample were a major indication that an effective radius of action was developed by using the high frequency. Approximately, the radius of action was between 4” to 6”.

On the other hand, when the vibrator was used with the medium frequency, the radius of action was smaller, roughly below 4”. The liquefying of the concrete was limited to the surrounding area of the vibrator head as shown in figures 3.4 through 3.10. The dearation stage might not be as efficient as with the high frequency due to the high surface voids concentration on the sides of the samples vibrated with the medium frequency. Fig 3.11 shows a comparison between sides that were vibrated with a high frequency and other sides that were vibrated with a medium frequency.

In summary, the effect of changing the vibration frequency on the radius of action can be seen through the fluctuating of its size. When the frequency of the vibrator was reduced, the radius of action size became smaller.

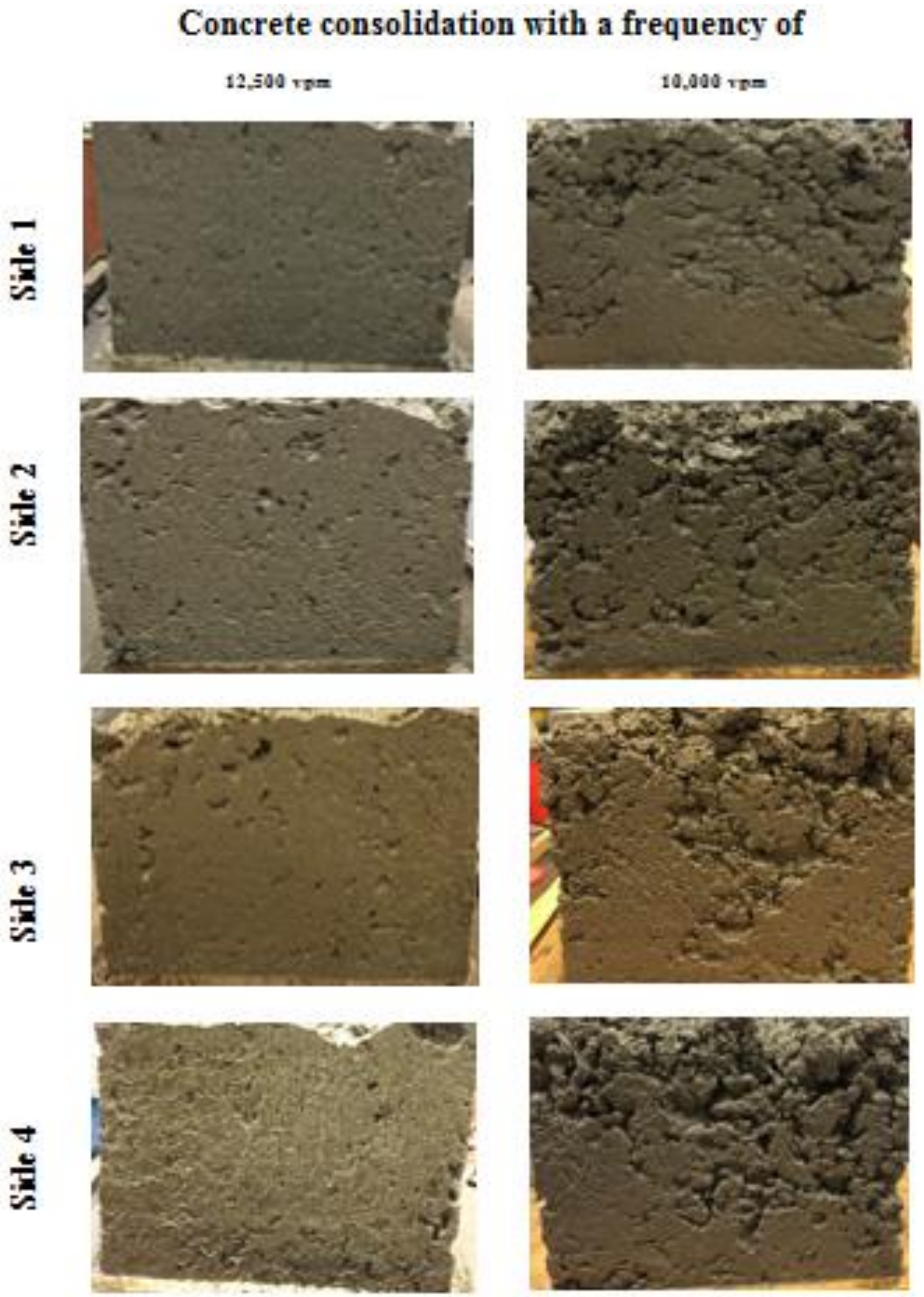


Figure 3. 11: an example of the variation in the surface voids concentrations between two Box Tests

3.5 Conclusion:

Vibrators are one of the effective methods in consolidating low slump concrete mixtures. To have an efficient consolidation, the vibrator characteristics should match the properties of fresh concrete. The key parameters that should be considered when utilizing vibrators are acceleration, frequency, amplitude, and concrete characteristics such as the nominal maximum aggregate size.

The consolidation effectiveness increases as the frequency of a vibrator increases. The surface voids concentrations can be increased extremely when the vibration frequency is reduced. The Box Test was used in evaluating the effect of different vibration frequencies of a vibrator on consolidating fresh concrete. The effect of the vibrating frequency change on the Box Test was in terms of the amount of critical voids identified on the sides of a sample. It was shown in this document that when vibrating two identical samples with different frequencies, 12,500 vpm and 10,000 vpm, the average absolute difference between the critical voids measured per each side of a sample could be 7.5 critical voids with an average SD of 2.64 critical voids.

Even though the amplitude has a great influence on the radius of action, the frequency is also a major factor in determining its size. The impact of the reduction in the vibration frequency on the radius of action was observed in this work. At a frequency of 12,500 vpm, the radius of action was sufficient to cover most of the top surface of the concrete in the Box Test while the radius of action that resulted from a frequency of 10,000 vpm was smaller.

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CHAPTER IV

EVALUATION OF FIELD MIXTURES BY THE TARANTULA CURVE

4.0 Introduction:

A concrete mixture comprises of cementitious material, water, coarse aggregate, and fine aggregate. Admixtures are sometimes added to promote certain concrete properties. Each of these components has its significant function. For instance, the cementitious materials govern the material binding together; the water is responsible for starting the reaction and the hydration process by reacting with the cementitious materials. The coarse aggregate has a major influence on resisting shrinkage. The ability of a mixture to be handled, placed, and surface finished is influenced by the fine aggregate [5].

Aggregates contribute 60 to 80 percent of the total volume of a concrete mixture, which make the concrete more economical by limiting the cement quantity that is the most expensive ingredient of concrete and the greatest contributor to shrinkage [5] [15]. In addition, aggregate has an important impact on the workability of concrete [15]. Several concepts have been developed to determine the effects of aggregate on the workability, such as nominal maximum aggregate size, packing, aggregate characteristics, and gradation [6]. The gradation of aggregate is important in determining its ratio in a concrete batch.

4.1 Gradation Concepts:

Aggregate gradation describes the distribution of the particle size of the aggregate via sieve analysis measurements [5]. It has been considered as one of the common aggregate methods to determine the aggregate proportion to the cement paste in a concrete mixture [4]. Void space in a concrete matrix is also primarily influenced by the aggregate gradation. When varieties of aggregate sizes are available, the packing of aggregate can be better in which smaller particles can occupy and reduce the space between larger particles. Cement paste, which is the most expensive ingredient in concrete, is the binder that is used to fill the empty space between the aggregate particles and hold them together. By optimizing the aggregate gradation of a concrete mixture, the maximum amount of aggregate can be accommodated in a mixture's unit volume and lower paste content can be achieved [4] [6]. The resultant can be a more economical mixture with improved strength, durability, and sustainability.

Standards such as ASTM C 33 provide specification for coarse, intermediate, and fine aggregate gradations [3]. These limits were obtained practically by experience and the concrete performance may not be assured [5]. Therefore, a trial and error approach is normally used to achieve the desirable aggregate gradations in mixtures designs. It is common to express the gradation of all of the aggregates together as a single gradation. The combined gradation may be graphed and examined through numerous gradation techniques. Concrete producers typically utilize graphical gradation techniques for proportioning different local aggregates to achieve well concrete mixtures; examples of popular techniques are the Power 45 chart, the Individual Percent Retained chart, the Fineness Modulus, and the Coarseness Factor chart [6] [12]. In addition, a new graphical technique has been introduced, which is called the Tarantula Curve.

4.1.1 Power 45 chart:

Power 45 chart was proposed in 1907 by W.B. Fuller and S. E. Thompson. [16] [14]. In the chart, a plot is made between a combined gradation and the sieve size on the X-axis with logarithm spacing. The sieves are spaced to the power of 0.45 of the actual opening of the sieve. The power 45 chart has a diagonal line that is plotted from the origin to the nominal maximum size of aggregate [14]. In order to obtain the best aggregate blend, the aggregate gradation should be proportioned to the best-fit of the drawn straight line to obtain the maximum density, which means minimum volume of voids in a combined aggregate [5] [14]. Since the interaction between water and cement particles with the aggregate particles is dissimilar to the interaction between the aggregate particles that are packed alone, the curve might not give the desired density or strength. Therefore, an equation was developed to obtain the maximum density by Tolbot and Richart [16].

$$P = \left(\frac{d}{D}\right)^n$$

Where:

P = the amount that is finer than a d size;

d = the size of a particle;

D = the maximum size of particles.

n = an exponent, which is commonly equal to 0.45, but may ranges from 0.3 to 0.6 [6].

The exponent value was initially set as 0.5 but it led to stiff mixtures. Later in 1965, an adjustment was made by Good and Lufsey to adjust the value of the exponent to be 0.45. [7].

4.1.2 Individual Percent Retained Chart:

Another common combined gradation technique is the individual percent retained chart. It is also called the 8-18 chart because it is traditionally suggested that the retaining percent on each sieve should be between 8% and 18% from sieve No. 30 through a sieve that is less than the nominal maximum aggregate size. Based on experts, it was specified that the maximum gradational boundaries ranged between 18%-22% and minimum boundaries between 5%-12% retained on each sieve [11] [16]. The benefit of this chart stems from plotting the aggregate gradation and observing the excess and deficient amounts of materials retained on each sieve size. It shows a detailed aggregate gradation per each sieve and insures that the percent retained is within the specified limits to obtain the recommended [6].

4.1.3 Fineness Modulus (FM)

Fineness Modulus is an aggregate proportioning technique which was developed by Abram in 1918 [1]. A relationship was found between the water demand and the aggregate gradation in which a reduction in water content would result in stronger concrete by increasing the fineness modulus [1] [2]. Fineness modulus can be defined as an aggregate index that can be calculated as the summation of the percent retained on sieves No. 4, No. 8, No. 16, No. 30, No. 50, and No.100 divided by 100 [1] [5]. The boundaries of the fineness modulus can be within 2.3 through 3.1 [3]. In the mixture design, ACI 211 has adapted the fineness modulus method in determining the aggregate proportion per unit volume [16].

4.1.4 Coarseness Factor Chart:

Shilstone, J. M. invented the coarseness factor chart, or can be called the Shilstone method, when he noticed that the aggregate gradation could have an impact on the concrete workability [13]. A desired workability can be obtained by adjusting the gradation of aggregate rather than changing the water content of a mixture. The chart is traditionally classified into different zones depending on the mixture workability and construction applications [12].

Shilstone chart was developed through a combined gradation using two equations, which will plot a single point on that chart [13]. The main parameters in this method are the coarseness factor and the workability factor.

The coarseness factor can be calculated as the cumulative percent retained on the 3/8" (9.5 mm) sieve divided by the cumulative retained percent on the sieve No. 8 (2.36 mm). Higher coarseness factors indicate higher content of coarse aggregate in a mixture. The workability factor can be calculated by the following equation [12]:

$$\mathrm{WF}\,\% = \mathrm{W} \times 2.5(\mathrm{C} - 564)/94$$

Where:

WF % = workability factor;

C = the content of the cementitious material (lbs. /cy3);

W = percentage of aggregate passing sieve No. 8.

4.1.5 Tarantula Curve:

The Tarantula Curve is an improved version of the individual percent retained chart, which was developed in Oklahoma State University by Cook [6]. It was a result of a study on the effect of the aggregate distribution on the performance of concrete. A detailed investigation on the percentage retained on each sieve was made to determine the optimum gradation limits and suggest recommendations to concrete producers [5]. The resulted gradation curve was called "The Tarantula Curve" based on the curve's shape [9]. In this method, a new set of boundaries was assigned for each sieve size. In addition, there were suggested recommendations of amounts of the coarse and fine sand needed in a mixture to help improve cohesion and workability [9]. For coarse sand, the cumulative percentage of the retained amount of aggregate on sieves No.8, No.16, and No.30 should have a minimum value of 15%; to minimize surface finishing problems. Also, sieves No. 8 and No. 16 should be limited to 12% [6]. On the other hand, the fine sand percentage of cumulative aggregate retained on sieves No. 200, No.100, No. 50, and No. 30 should be in the range of 24% to 34% [6]. It was found that changing the aggregate gradation would change the mixture's workability, and the Tarantula Curve showed an improved performance when compared to other methods [8].

The Tarantula Curve is shown in Fig. 4.1 with the upper and lower limits as well as the coarse and fine sand criteria.

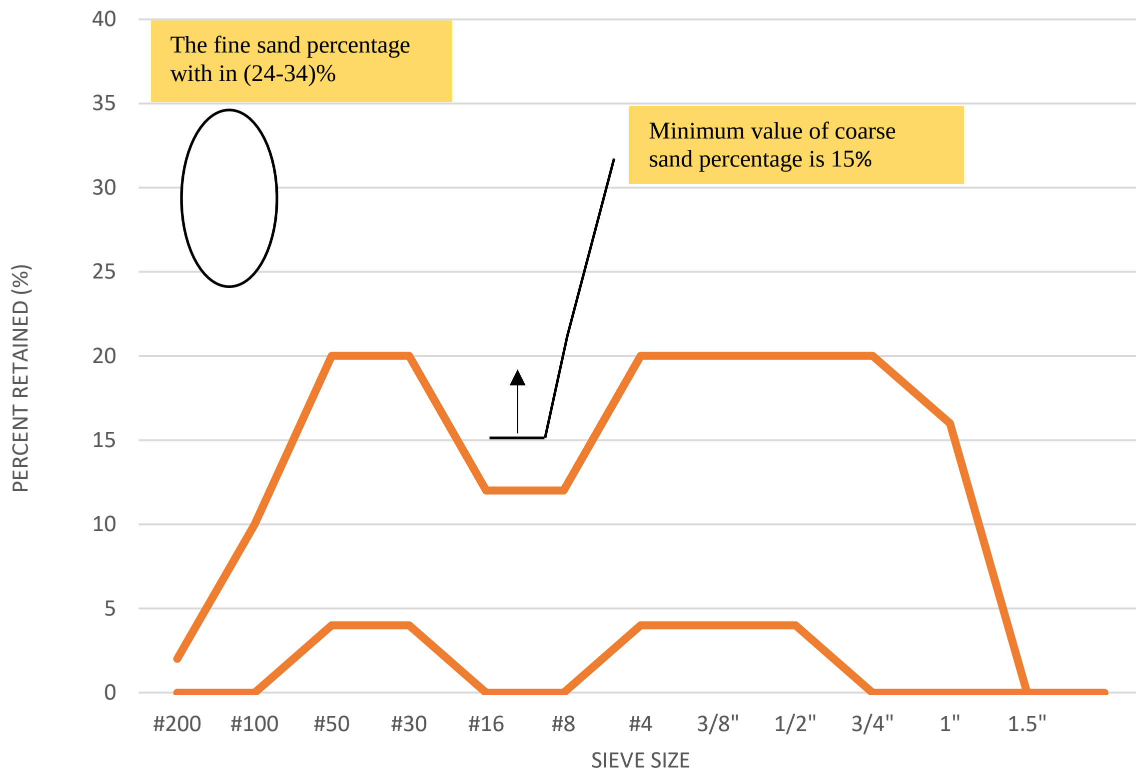

Figure 4. 1: Tarantula Curve criteria.

4.2 The International Roughness Index (IRI):

The roughness of a pavement can be expressed as the irregularities of its surface that can unfavourably impact the vehicle quality ride. It is considered as one of the important characteristics in pavements. The International Roughness Index (IRI) is a measurement of the pavement roughness that was developed in 1980s. The IRI values are based on the simulated response of a known suspension properties of a vehicle to the roughness in a wheel path of the road profile in which the roughness measurements of a road profile are processed by an algorithm. Then, the algorithm can simulate the response of a reference vehicle to the roughness inputs. The IRI values are expressed normally in inches/mile or meters/kilometres. The lower the IRI values, the smoother the pavement surfaces [10].

4.3 Object:

Mixture designs are commonly chosen based on experience and availability of aggregates from their local quarries [4]. The prime goal of the gradation process is to obtain the optimum aggregate gradation that can provide less cementitious material content in their concrete designs while maintaining workability and strength [8] [9]. Hundreds of successful and unsuccessful field mixtures from Iowa, Minnesota, and Michigan were organized and analyzed by the Tarantula Curve in this chapter.

4.4 Method:

Field mixture data from Iowa, Minnesota, and Michigan were provided along with the dates that they were used. The aggregate gradations of these mixtures were investigated to determine whether they were within the recommendation of the Tarantula Curve along with the fine and coarse sand limits. Charts and tables were used to illustrate the degree of agreement between these mixtures.

4.5 Results:

Each chart contains the Tarantula's upper and lower limits and the percentages of coarse and fine sand for every mixture. Following every chart, a column chart is provided to describe the percentages of agreement between the aggregate gradations of field mixtures with the Tarantula Curve's limits for every sieve as well as the coarse and fine sand criteria.

4.5.1 Evaluation of field mixtures from Iowa DOT agency:

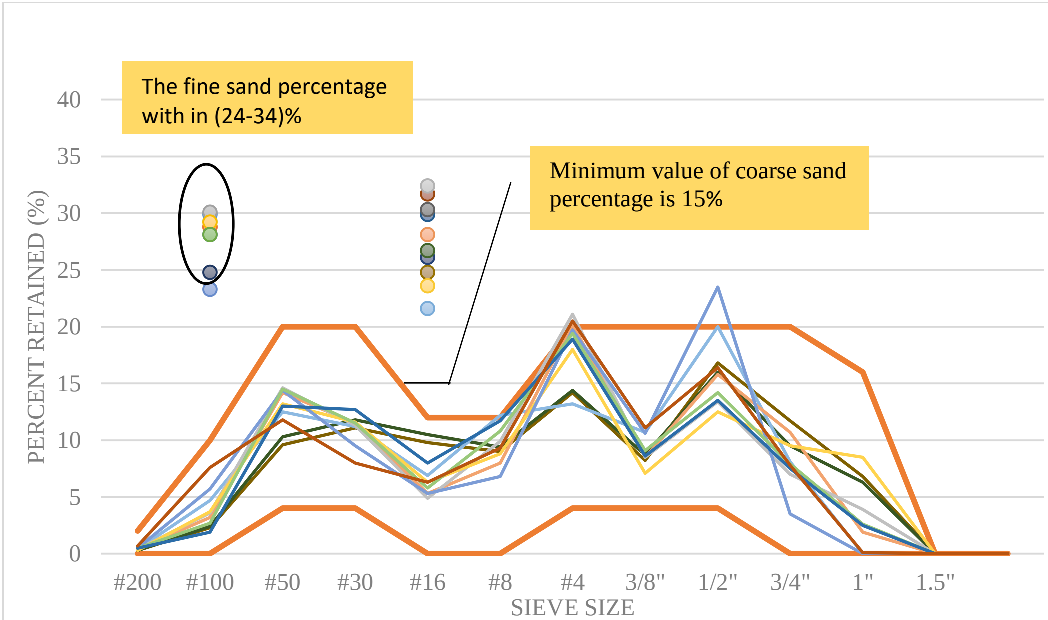

Figure 4. 2: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Iowa DOT 2004 to 2006.

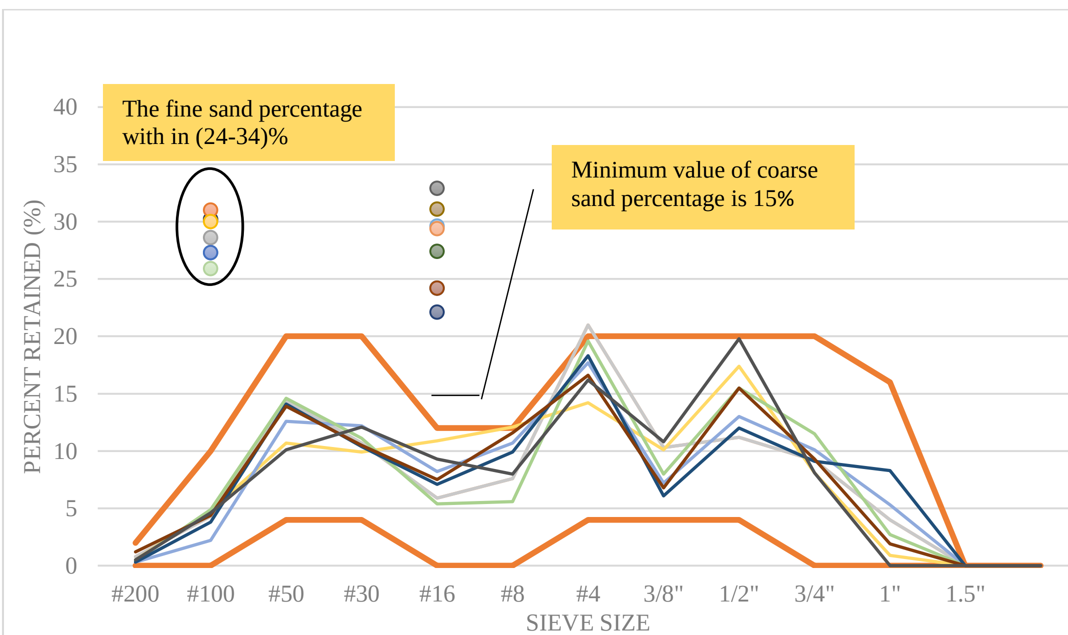

Figure 4. 3: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Iowa DOT 2007 to 2009.

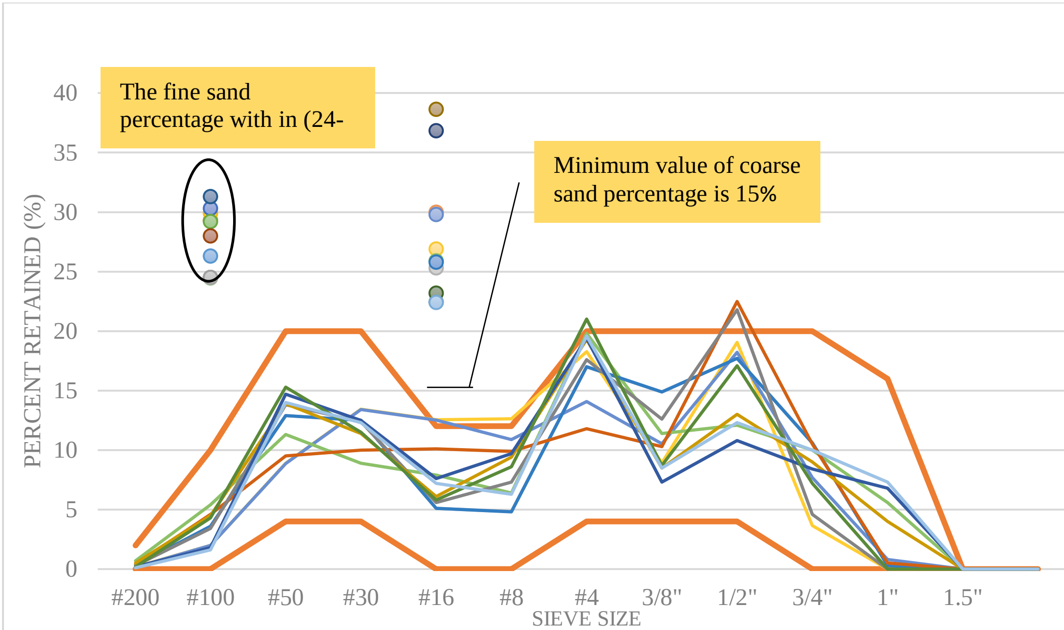

Figure 4. 4: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Iowa DOT from 2010 to 2012.

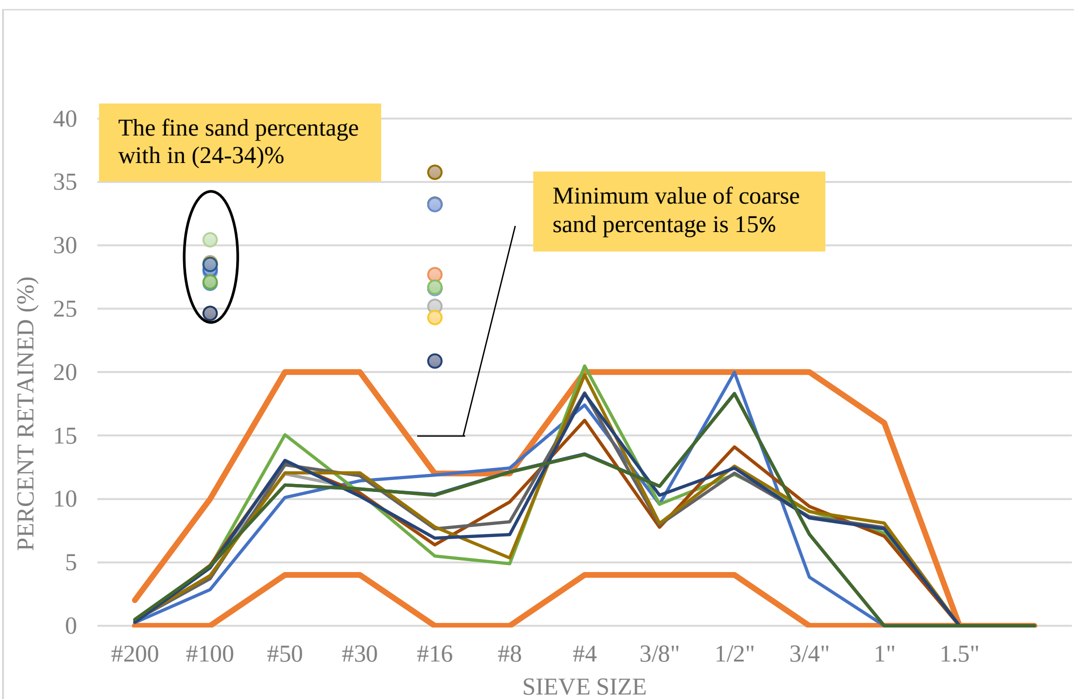

Figure 4. 5: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Iowa DOT 2013 to 2014.

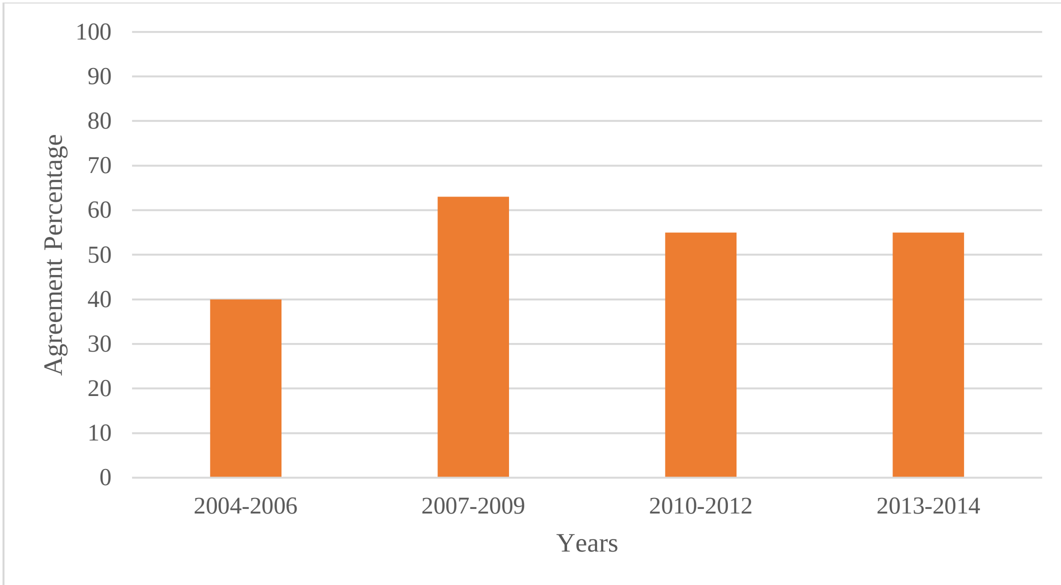

Figure 4. 6: Agreement percentages between the aggregate gradations from Field mixtures of Iowa with the Tarantula limits

4.5.2 Evaluation of field mixtures from Minnesota DOT agency:

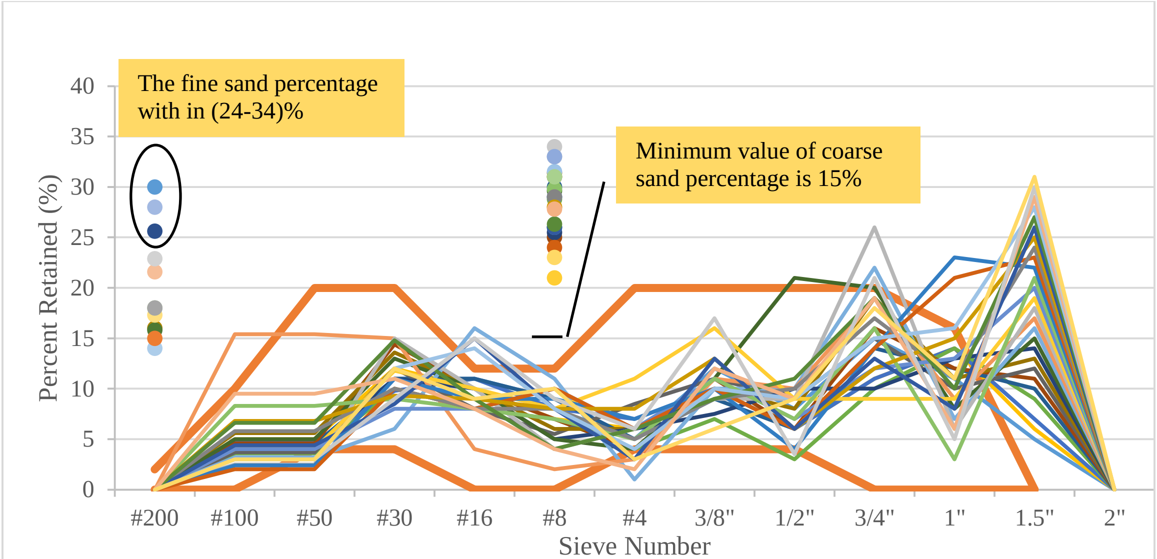

Figure 4. 7: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Minnesota DOT 1996 to1998.

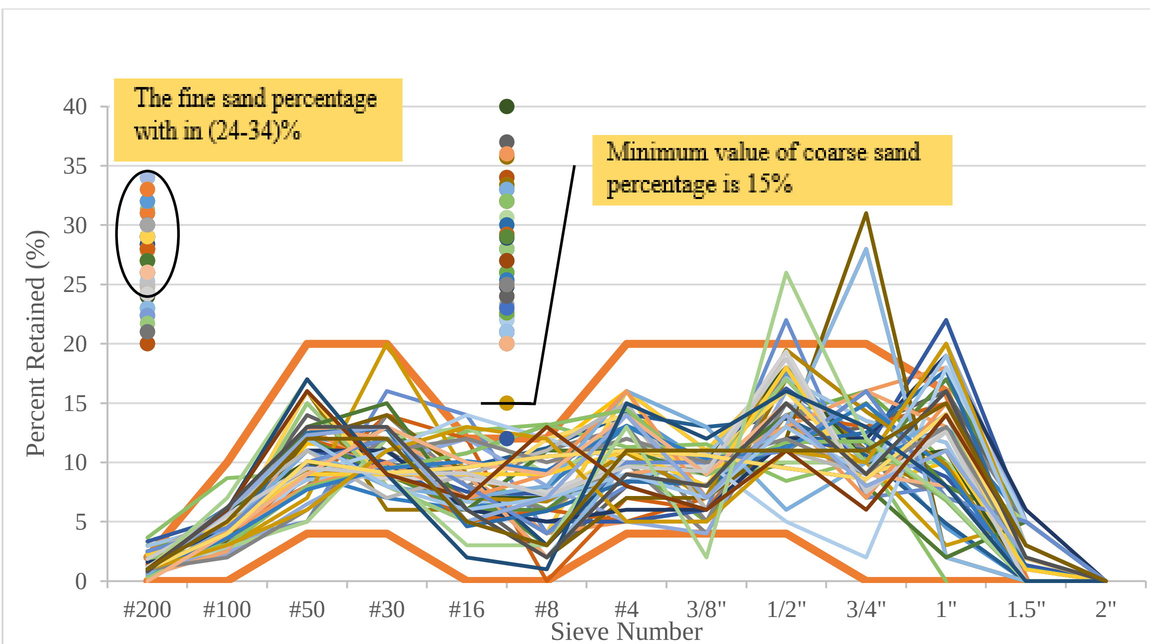

Figure 4. 8: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Minnesota DOT 2000 to 2002.

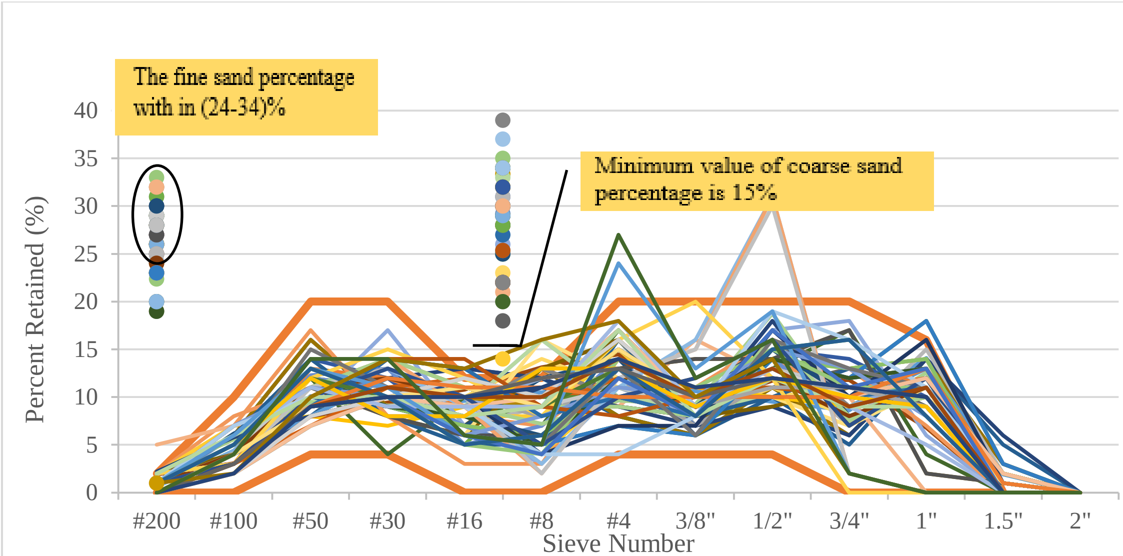

Figure 4. 9: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Minnesota DOT 2003 to 2005.

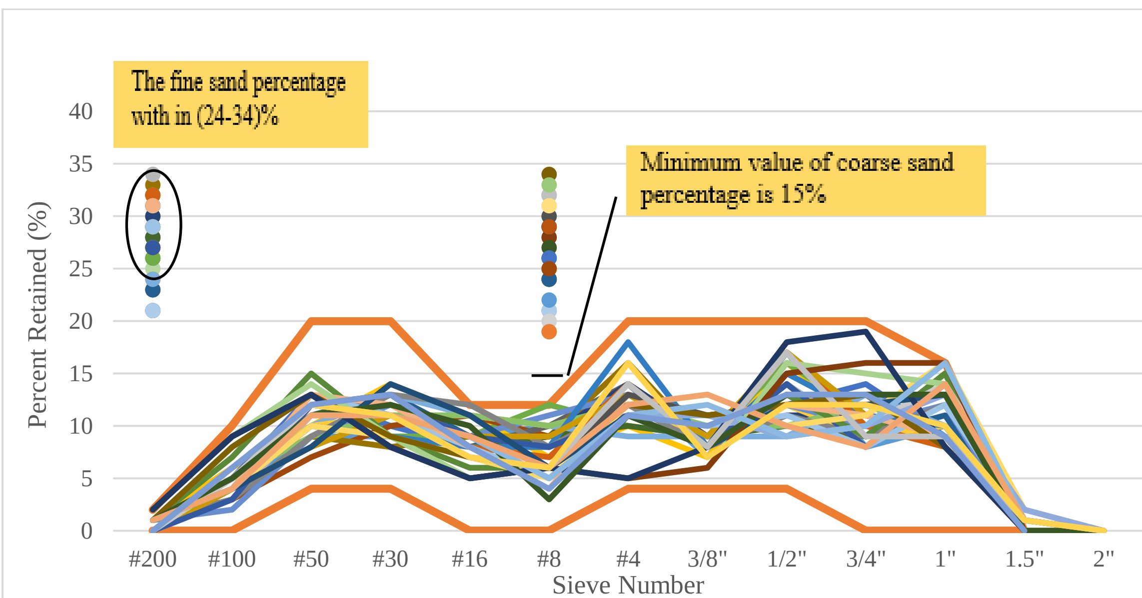

Figure 4. 10: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Minnesota DOT 2009.

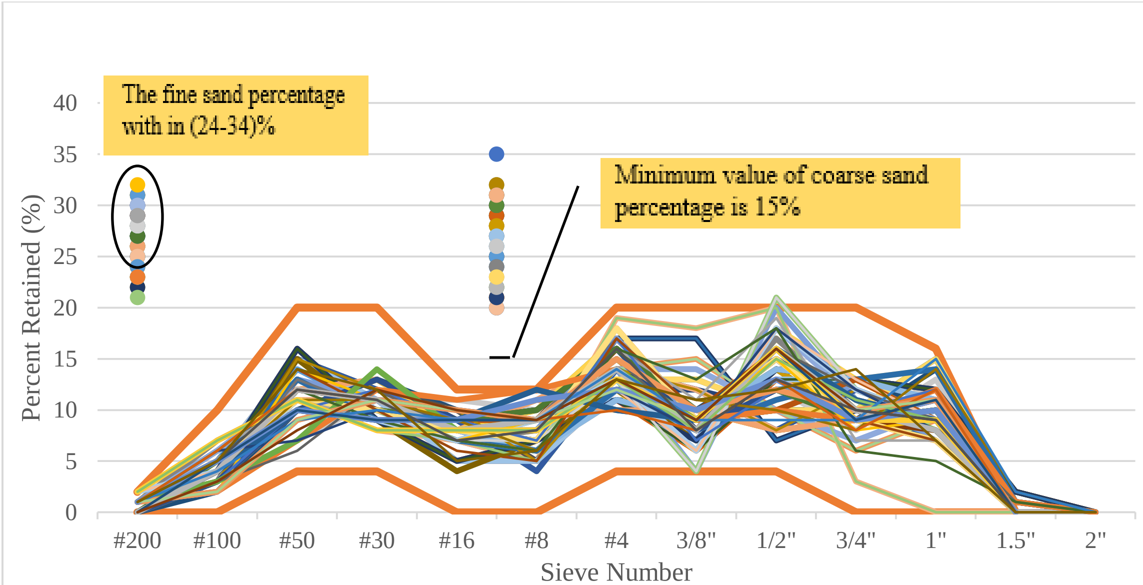

Figure 4. 11: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Minnesota DOT 2010 to 2011.

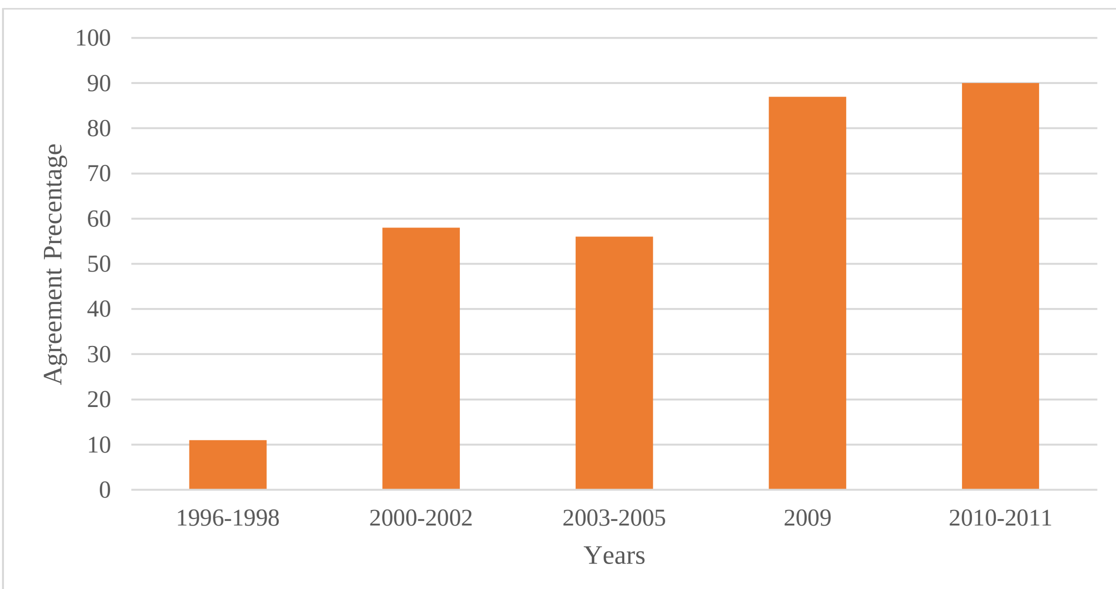

Figure 4. 12: Agreement percentages between the aggregate gradations from Field mixtures of Minnesota with the Tarantula limits

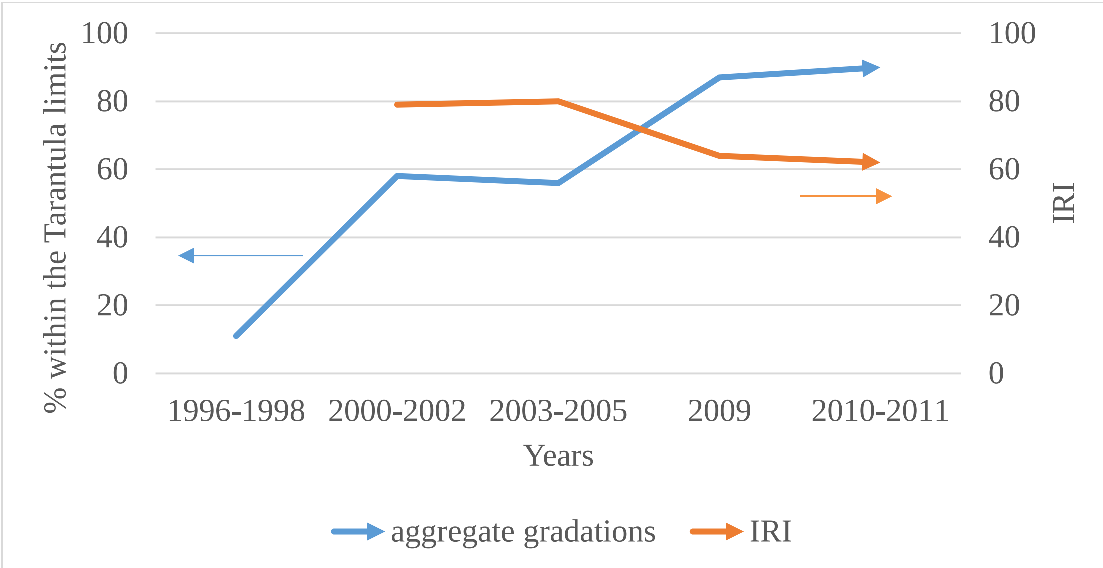

Figure 4. 13: A comparison between the IRI values of Minnesota mixtures and the agreement percentage of their aggregate gradations with the Tarantula recommendation

4.5.3 Evaluation of field mixtures from Michigan DOT agency:

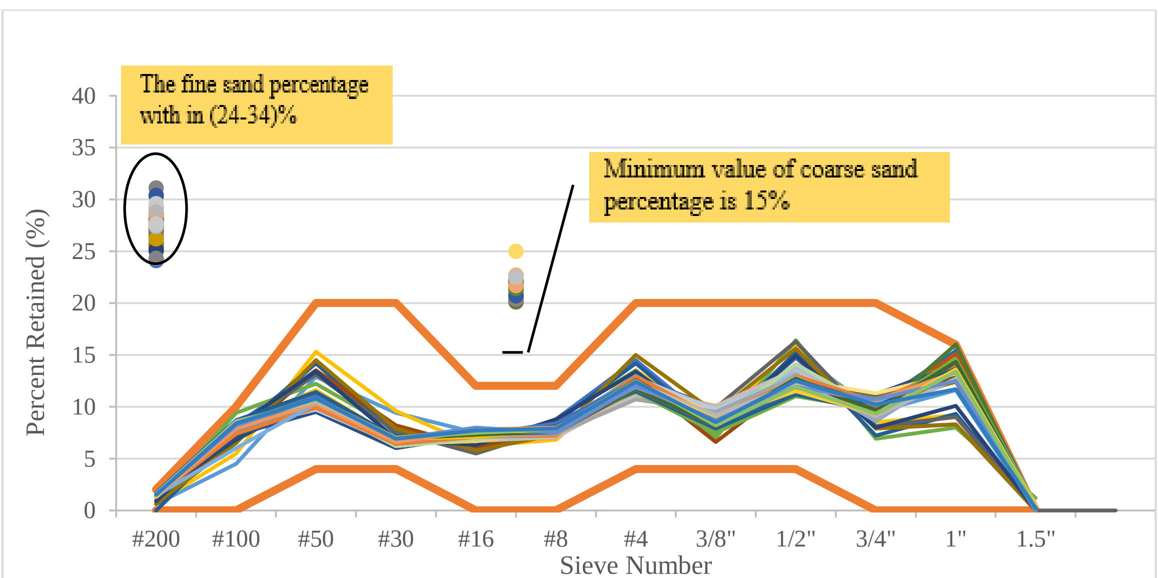

Figure 4. 14: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Michigan I-96-East projects.

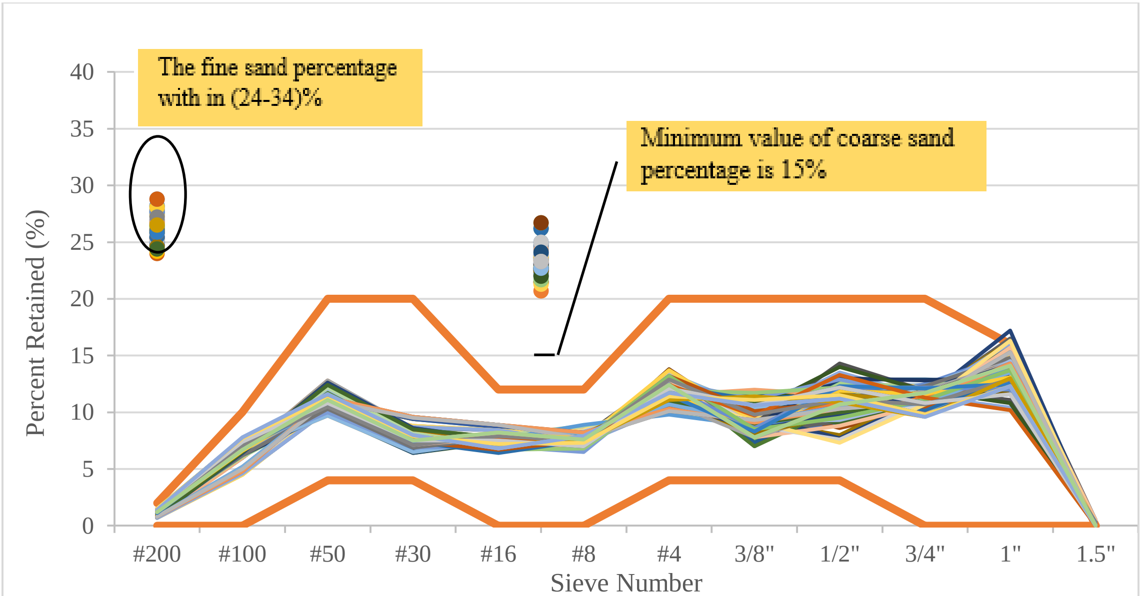

Figure 4. 15: Field mixtures' aggregate gradations compared to the limits of The Tarantula Curve from Michigan I-96-W8 to W12.

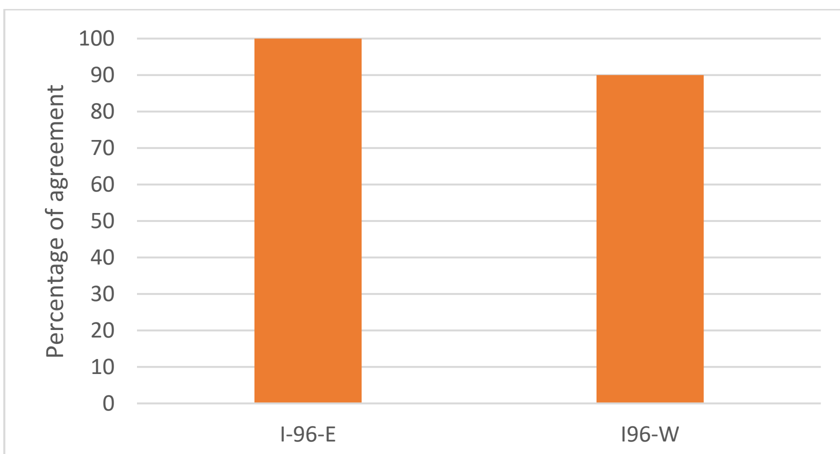

Figure 4. 16: Agreement percentages between the aggregate gradations from Field mixtures of Michigan with the Tarantula limits

4.6 Discussion:

The Tarantula Curve was developed to design an optimized concrete that can be handled and placed easily and have a high performance. Pavement mixtures that were placed and utilized for years were arranged in a spreadsheet to compare their aggregate gradations to the Tarantula's recommendations. By comparing existing concrete mixtures that gained satisfaction from concrete producers and DOT agencies, it can give an advantageous indication of how these mixtures' gradations can be accommodated within the suggested recommendations of the Tarantula Curve. Therefore, the gradations of hundreds of pavement mixtures were compared to the limits of the new aggregate proportioning technique. In the Tarantula Curve, each sieve size has upper and lower limits in which an aggregate gradation should be accommodated. According to the comparison results, it was shown that the aggregate gradations from the investigated field pavements were substantially accommodated within the Tarantula's recommendations. Each set of field mixtures will be evaluated as the following:

- Iowa's field mixtures:

The evaluated aggregate gradations of field mixtures from Iowa showed a reasonable accommodation within the Tarantula boundaries as shown in Fig. 4.2 through 4.5. It can be noticed that almost all the gradations were either inside the Tarantula boundaries or approximately at the limits. For instance, sieves No.8 and No.4 had values of aggregate percent retained that were around the limits or above the limit with a difference less than 1%. For the sieve size of 1/2 ", only three gradations that exceeded the suggested limits by a maximum of 3% of aggregate percent retained.

Figure 4.6 shows the percentages of agreement between the aggregate gradations of Iowa's field mixtures and the Tarantula recommendations. It was shown that the aggregate gradations utilized in field mixtures in Iowa had an average agreement percentage above 50% with the Tarantula recommendations. Nevertheless, all the investigated aggregate gradations were enormously near the limits.

- Minnesota's field mixtures:

Pavement mixtures of 1996 through 1998 had the lowest compatibility with the boundaries of the Tarantula Curve. Major sieves that had percent-retained aggregate outside the recommended limits were sieves No.50, No16, No.4, and ¾". According to Fig. 4.7, the aggregate percent retained on 1.5" sieve did not meet the specified value of the Tarantula Curve in all mixtures from 1996 to1998. These mixtures were the first in which Minnesota DOT tried to optimize their concrete mix designs.

From Figures 4.8 & 4.9, a better accommodation of mixtures that were made from 2000-2005 with the suggested recommendations was observed, especially for the 1.5" sieve size in comparison to the 1996-1998 field mixtures. Generally, mixtures that were made from 2000 to 2005 had aggregate gradations that were within the boundaries, or exceeded the boundaries by a maximum of 3% of aggregate percent retained on sieves such as No.16 & No.8.

From 2009 through 2011, the large majority of the gradations of field mixtures that were made during 2009-2011 were within the Tarantula boundaries. It was found that above 87% of these gradations satisfied the Tarantula limits.

According to Fig. 4.12, it can be seen that the aggregate gradations of these mixtures were better in accommodating with the Tarantula limits with time. Therefore, as the aggregate gradation designs were improved in Minnesota, they were more likely to meet the suggested limits. The improvement of the concrete mix designs was via the trial and error approach without knowing about the suggested limits by the Tarantula Curve. The percentage of agreement between the aggregate gradations and the Tarantula limits went from 11% in 1996-1998 to 90% in 2010-2011.

It can be observed from Fig.4.13 that as the aggregate gradations of Minnesota field mixtures met the Tarantula recommendations, the IRI values of these pavement mixtures decreased and the lower the IRI value the smoother the pavement surface.

- Michigan’s field mixtures:

Concrete mixtures from different pavement projects that were made and placed during 2010 in Michigan were investigated. The aggregate gradations of these mixtures were compared to the Tarantula limits for each sieve size. According to Fig 4.14 and 4.15, it can be observed that almost all the gradations were accommodated inside the Tarantula boundaries. These successfully placed pavements had an agreement percentage with the Tarantula Curve specifications above 90% as demonstrated in Fig. 4.16.

4.7 Conclusion:

Collections of pavement mixtures that were obtained from Iowa, Minnesota, and Michigan DOT agencies were analyzed by the Tarantula Curve. Comparisons between the aggregate gradations of pavement mixtures with the recommendations of the Tarantula Curve were made to investigate the relation between them.

From the comparison between the aggregate gradations of Iowa's field mixtures and the Tarantula Curve limits:

- Aggregate gradations utilized in Iowa's field mixtures showed a very good compatibility with the recommended limits by the Tarantula Curve. They were either inside or really close to the Tarantula boundaries.
- The average agreement percentage was above 50% with the limits.

From the comparison between the aggregate gradations of Minnesota field mixtures and the Tarantula Curve:

- Pavement mixtures that were made in 1996-1998 had the lowest agreement percentage with the Tarantula limits, which was 11%.
- With time, field mixtures were better in satisfying the recommendations in which the agreement percentage increased from 11% in 1996-1998 to 90% in 2011.
- It was observed that as the agreement percentage between the aggregate gradations of Minnesota pavements and the Tarantula Curve limits increased, the IRI values of these pavements decreased.

From the comparison between the aggregate gradations of Michigan field mixtures and the Tarantula Curve:

- Almost all aggregate gradations of field mixtures from Michigan were accommodated within the boundaries of the Tarantula Curve.
- The agreement percentage between the aggregate gradations and the Tarantula limits was above 90%.

To conclude, the Tarantula Curve limits of aggregate gradation were compatible with large numbers of mixtures that were made, placed, and utilized in different locations. The suggested recommendations were highly met by the investigated aggregate gradations.

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CHAPTER V

CONCLUSION

The Box Test was developed to measure the concrete responsiveness to vibration for low slump mixtures. In this document, a new evaluation system called “the point count method” was addressed. This method can provide a systematic approach to identify critical surface voids at the sides of a sample with the help of the “point count template”. The template’s characteristics and the suggested procedure were established and examined in Chapter II. The results illustrate that the point count evaluation technique in the Box Test is useful and repeatable to assess the surface voids of the sides of a sample.

- The repeatability of measurements on a single side of a sample had a maximum average difference of one critical void with an average SD less than one voids. It was demonstrated that 71% of the measurements had no variation in the numbers of critical voids counted in three rounds per each side.

- Multiple evaluators counting critical voids for each side of a sample had an average difference of one critical void with a SD of 0.6 voids and a COV below 5%.
- For a single operator repeating the Box Test three times in a single mixture, the SD of the results was 1.3 voids with a COV of 14.7%.
- For multiple operator repeating the Box Test three times in a single mixture, the SD of the results was 2.8 voids with a COV of 21%.
- A comparison was made between the visual inspection method and the point count method. Both techniques were used to evaluate the surface voids of the samples. The average difference in the percentages of surface voids concentrations obtained from both methods was 4.9% with a SD of 2.7%.

In Chapter III, An investigation was made to determine the effect of changing the vibration frequency of a vibrator on the concrete consolidation by the Box Test. In this research, two vibration frequencies were utilized to consolidate two identical samples in which the first sample would be consolidated with a vibrator with a frequency of 12,500 vpm (high frequency) and a frequency of 10,000 vpm (medium frequency) for the other sample. The results showed that there was a variation in the identified critical voids for each side of the samples. The maximum difference was 13 critical voids and an average absolute difference of 7.5 critical voids. When the high frequency was applied in the consolidation, it was observed from the top of the samples that the radius of action was reaching the edges. However, in cases where the medium frequency was utilized in the consolidation process, the radius of action was observed to be lower and cannot reach the edges of the samples.

Finally, The Tarantula Curve suggests advantageous recommendations that can help in reaching the optimum aggregate gradation in a concrete mixture design. In chapter IV, field mixtures from Iowa, Minnesota, and Michigan were analysed by the Tarantula Curve. Aggregate gradations of hundreds of field mixtures that had a satisfactory performance and made by contractors from different states were compared to the suggested recommendations. Results showed that the vast majority of the gradations of the investigated field mixtures met the Tarantula's suggested limits.

- From the Iowa data, the aggregate gradations met the Tarantula limits in an average agreement percentage above 50%. However, the aggregate gradations that did not satisfy the suggested limits were enormously close to the boundaries.
- From the Minnesota data, field mixtures of 1996-1998 had an average percentage agreement with the recommendations above 11%. The agreement percentage between the aggregate gradations of Minnesota mixtures and the Tarantula boundaries went from 11% in 1996-1998 to 90% in 2010-2011.
- Based on Michigan's data, the evaluated aggregate gradations of the field mixtures had the highest agreement percentage with the suggested recommendations, which was above 90%.

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