COMPARING THE VARIABILITY OF SAMPLE CONSOLIDATION METHODS ON LOW WORKABILITY CONCRETE

By

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Bachelor of Science in Civil Engineering

Oklahoma State University

Stillwater, Oklahoma

2018

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2020

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CONSOLIDATION METHODS ON LOW

WORKABILITY CONCRETE

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ACKNOWLEDGMENTS

I want to thank WisDOT and the other contributors to this research. It was an honor to help them out and I hope it forwards their goals.

To the undergraduate and graduate students,

Thank you for making my graduate school career a memorable one. Without your help, I may not have produced the research that is being presented. You guys are like a second family to me, and I appreciate the help and support you gave me throughout my graduate school career. Keep up the excellent research and keep on changing the world!

To my family,

It seems like I was in school for a very long time, and now I am finally ready to go out into the world and make a difference. Without your love and support, I do not know if I could have done it. Thank you for being the most amazing family ever.

To my wife,

I don’t know where to begin. All of your love and support is one of the many reasons why I didn’t give up on my Masters. Even through the tears, the frustration and disappointment, you stood by my side and propped me up. You are my best friend and are one of the many reasons why this paper exists. You are as much of an author on this paper as me. Thank you!

Name: MARK WILLIAM FINNELL

Date of Degree: MAY, 2020

Title of Study: COMPARING THE VARIABILITY OF SAMPLE CONSOLIDATION METHODS ON LOW WORKABILITY CONCRETE

Major Field: CIVIL ENGINEERING

Abstract: Quality control and assurance testing for concrete provides quantitative information about the quality of the concrete being placed. Yet, improperly consolidating the fresh concrete sample can negatively affect the testing results and misrepresent the quality of the concrete being placed. This study investigates how different consolidation methods impact the variability of the Unit Weight, Air Volume, and SAM Number measurements. These performance testing of a workable concrete mixture and an undesirable workable mixture were compared with the consolidation methods of manual rodding, internal vibration, external vibration with a vibration table, and a novel portable external vibrator called the MinT. The results show external vibration methods provides a more consistent consolidation technique for Unit Weight, Air Volume, and SAM Number.

Keywords: Consolidation; Quality control testing; MinT; Sample preparation; Air content; Unit weight; SAM Number; air voids; concrete density; internal vibration; external vibration; vibration table

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CHAPTER I

INTRODUCTION

1.0 Consolidation of Concrete

One of the key tasks when placing and finishing concrete has been properly consolidating it. Consolidation is the purposeful act of removing large air voids from a fresh cementitious mixture by inputting mechanical energy [3]. The mechanical energy can come in the form of tamping or vibration. Removal of these large air voids increases the strength and durability and in turn will increase the service life [3].

1.1 Mechanisms Behind Consolidating Concrete

The mechanisms behind consolidation are well understood. Before vibration is introduced, the concrete matrix is held together via the friction forces between the aggregates and the paste and the surface tension and cohesive forces from the paste [19]. This balance of forces is disturbed by the vibrations coming from a vibration source in the form of compression waves (P-waves). These P-waves cause the water molecules to vibrate which collapses the matrix making the concrete behave like a fluid that allows gravity to consolidate the mixture [20].

The solids, aggregates and cementitious materials, are largely unaffected by vibration and do not aid in consolidation [20]. Once the vibrations cease, the concrete returns to a plastic state where the forces find a new equilibrium and concrete will maintain its shape.

1.2 Methods of Consolidating Concrete Test Samples

Consolidation methods have been incorporated into many ASTM standards. The method for consolidating concrete samples has been provided in the specific test method. General standards for both field and laboratory samples have also been developed and provide a standard procedure for consolidating both concrete cylinders and beams. ASTM C31/C31M [4] should be used for consolidating concrete samples in the field and ASTM C192/C192M [8] should be used for consolidating concrete samples in the laboratory. These standards have similar requirements for consolidation.

1.2.1 Rodding to Consolidate Samples for Unit Weight (Density) and Air Volume

Concrete with a slump of 1 in. or greater can be manually rodded according to ASTM C138/C138M [5]. This is completed by filling up the unit weight bowl in three lifts and rodding each lift 25 times. As shown in Figure 1.1(a) the rodding should be distributed as evenly as possible. For the second and third lift, the rod should penetrate 1 in. into the previous layer. Tap with a mallet or open hand around the sides of the mold 10 to 15 times to close any holes left by the rodding as shown in Figure 1.1(b) and (c).

(a) (b) (c)

Figure 1.1 demonstrates (a) rodding of sample, (b) holes from rodding, and (c) tapping with a hammer.

1.2.2 Internal Vibration to Consolidate Samples for Unit Weight (Density) and Air Volume

Internal vibration is required by ASTM C138/C138M [5] when the slump of the concrete is less than 1 in. The method requires the first lift to be half the volume of the unit weight bowl before consolidation takes place. Then a poker vibrator with a minimum vibration speed of 9000 vibrations per minute (vpm) is immersed in the concrete at 3 different locations. A second lift is placed to fill up the rest of the volume and the procedure for the first lift is repeated. The only difference is the vibrator needs to penetrate the previous layer by 1 in. on each immersion. ASTM is not clear on the locations of the immersions but it is recommended to evenly space them out. The amount of time the vibrator is immersed in the mixture is not controlled by ASTM either. The standard does warn against over-consolidating the sample because it can lead to segregation or loss of entrained air. Figure 1.2 shows a picture of internal vibration and how it is used.

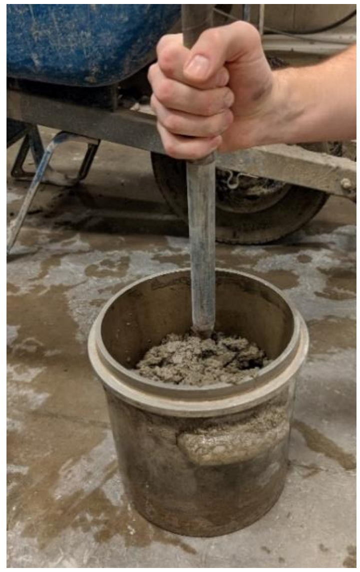


Figure 1.2 shows consolidation of unit weight bowl with internal vibration.

1.2.3 External Vibration to Consolidate Samples

Another method for consolidating samples has been through the use of external vibrators. This category of consolidation has been mainly used in the laboratory and may be preferred as an alternative to manually rodding or internal vibration for consolidating harsh mixtures or confined mold dimensions. For consolidating concrete samples in the laboratory ASTM C192/C192M [8] has only allowed two types of external vibrators, which can be either a table or plank. Figure 1.3 shows an external vibration table. The

Figure 1.3 displays a typical vibration table powered by a rotary motor.

sample mold being consolidated with external vibration must be clamped securely to the vibration apparatus.

1.3 Problem with Current Sample Consolidation Methods

The problem with the currently accepted consolidation methods is they are prone to variability in low slump concrete mixtures. It is common for operators in the field to use the rodding method to consolidate these mixtures, if it meets the greater than 1 in. slump requirement of ASTM C31/C31M [4]. Nevertheless, the low workability of mixtures like slip-form pavements are difficult to work with and require effort to consolidate. Figure 1.4(a) shows unit weight tests that are poorly consolidated while Figure 1.4(b) shows a compression strength test cylinder that is poorly consolidated with one of these mixtures. Using results from those samples will not provide accurate information about the concrete that was cast. New consolidation methods must be investigated to consolidate these low-slump mixtures so results from sample to sample are similar and comparable. However, the solution to the problem needs to be easy to use, portable and be consistent.

(a) **(b)**

Figure 1.4 shows (a) poorly consolidated unit weight samples and (b) poorly consolidated compression strength cylinder.

1.4 Overview of Thesis into Consolidation Issues of Concrete

The work here aims to compare the variability of different sample consolidation methods for quality-control tests (unit weight, air content and SAM Number) when using two different slip-form paving mixtures. The variability from each consolidation method will be compared to currently accepted literature to see if workability plays a role in variability. The reason why this is an issue is because current consolidation methods in the field may be prone to high variability when working with low workability mixtures. The results of inadequate consolidation on quality-control tests can lead to false presumptions of the mixture. It is necessary to know how variable a test result with a certain consolidation method is so the operator, engineer and owner understands how it can affect the final result.

CHAPTER II

IMPACT OF DIFFERENT CONSOLIDATION METHODS ON AIR QUALITY TEST METHODS FOR LOW WORKABILITY CONCRETE

2.0 Introduction

The concrete industry primarily uses two vibration methods: internal vibration and external vibration. Internal vibration is taking a portable, eccentric-weight vibrator known as a poker or spud vibrator and immersing the vibrating head into the mixture to consolidate it. Unlike its counterpart, external vibration consolidates the concrete by vibrating the forms [20]. ASTM C31[4] and C192 [8] provide guidelines on the properties of vibrators to be used for internal vibration and external vibration in field and laboratory settings, respectively. However, the methods on how to use these vibrators for sample consolidation is important and needs to be understood. The quality control and quality assurance testing can determine the acceptance of concrete and also determines contractor pay. The air content and air void distribution are important parameters to ensure the freeze-thaw performance of concrete.

Since the consolidation of concrete is known to impact the air content of concrete then this makes consolidation an important parameter in the quality control testing for air content. For example, if the concrete is not consolidated well enough then the test will measure additional air in the concrete. If the concrete is over-consolidated then this may remove air that will be retained in the concrete structure [16, 18]. This can lead to false readings that may cause concrete with poor freeze-thaw performance to be used. Because of this, ASTM C192/C192M [8] guides consolidating concrete by using a metal rod, internal vibration, or external vibration. Typically, the slump of the concrete is used to determine which method of vibration to use. Concrete with a slump < 1 in. must be vibrated, but mixtures with a slump > 1 in. can be manually rodded or vibrated according to the ASTM C31[4] and ASTM C192 [8] standards. The ASTM standards do not give specific time limits for the duration of vibration or how this should change with internal and external vibration. Both standards state that the sample should be consolidated with a vibrator until the surface is smooth. This means the duration of the vibration will depend on the mixture and the judgment of the operator.

This work aims to quantify the impact that different consolidation methods have on the measurement variability of air void systems in fresh concrete with low workability. This work also introduces a new portable consolidation method called the Miniature Vibration Table or MinT. The MinT is a portable vibration table that can reduce variability in field measurements. This work will give important insights into the reliability in making repeatable measurements of air void systems in low workability concrete mixtures. This information can be used to reduce the number of rejected concrete by understanding the impact of consolidation on the test variability and to help design for mixture variability in the design stage.

2.1 Experimental Methods

2.1.1 Materials

The materials used in the concrete mixture designs were a Type I Portland Cement ASTM C150 [7] where 20% of the cement content was replaced with a Class C ASTM C618 Fly-ash [12]. Table 2.1 provides the oxide content for the cement used and the fly-ash used in these experiments. Both mixtures used an ASTM C226 [9] wood rosin air-entrainer with a target air content of 5%. A mid-range water reducer (WR) Type A/ F ASTM C494 [11] was used in one mixture but not the other. This will be explained in the following sections. A #57 ASTM C33 crushed limestone, 3/8” intermediate crushed limestone, and an ASTM C33 natural sand was used as the aggregate source.

Table 2.1. Oxide contents for cementitious materials

Cement Oxide Content: Type I												
Element	SiO_2	Al2O3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO	BaO
Composition (%)	20.77	4.57	2.62	62.67	2.37	3.18	0.19	0.32	0.34	0.14	0.22	0.07
Fly-Ash Oxide Content: Class C												
Composition (%)	24.37	21.41	5.94	31.4	9.03	1.99	3.54	0.37	0.91	0.38	0.30	0

2.1.2 Mixture Designs

This testing used two concrete mixtures used in the field. One mixture required a high amount of external energy to consolidate the concrete and the other is a mixture that is modified to require significantly less. The mixture that required a high amount of external energy is known as the undesirable workability because of the challenges that were experienced in the field. Despite these challenges the mixture was used to produce and acceptable concrete pavement to the owner. The mixture that required less energy to consolidate will be known as a mixture with desirable workability. These two mixtures are investigate to determine the impact of the workability on the quality control tests used to measure the air void system. These mixtures were evaluated with the AASHTO TP 137 Box Test results and the Tarantula Curve. The Box Test measures how responsive a concrete mixture is to vibration. The Tarantula Curve is a technique using the combined gradation of aggregates to aid in the proportioning of mixtures to highlight workability issues [13]. The combined gradation of both mixtures using the Tarantula Curve can be shown in Figure 2.1. The proceeding subsections provide more details about each of these mixtures and were summarized in Table 2.2.

2.1.2.1 Mixture Design with Undesirable Workability

The mixture with undesirable workability was designed with a 0.45 water-to-cementitious material ratio (w/cm), a target air content of 5% and the target slump range to be between 0.25 in. and 1 in. The combined aggregate gradation was plotted using the Tarantula Curve in Figure 1. The 0.5 in. sieve size for the combined gradation exceeded the Tarantula Curve limits, which was a major reason for the harsh workability of the mixture [13]. The only admixture in this mixture was a wood rosin air-entrainer that follows ASTM C260 guidelines. Table 2 gives the specific air-entrainer dosage for this mixture.

2.1.2.2 Desirable Workability Mixture Design

The second mixture investigated was designed by adjusting the aggregate gradation to see the effects on the workability without changing the other parameters in the mixture. This improved combined gradation with the Tarantula Curve can be seen in Figure 1. The addition of a mid-range water reducer was also added to improve the workability of the mixture. The water reducer dosage used in this mixture was used to meet the target slump range between 1 in. and 2 in. Table 2.2 provides a list of the proportions and material specifications used in the improved mixture design.

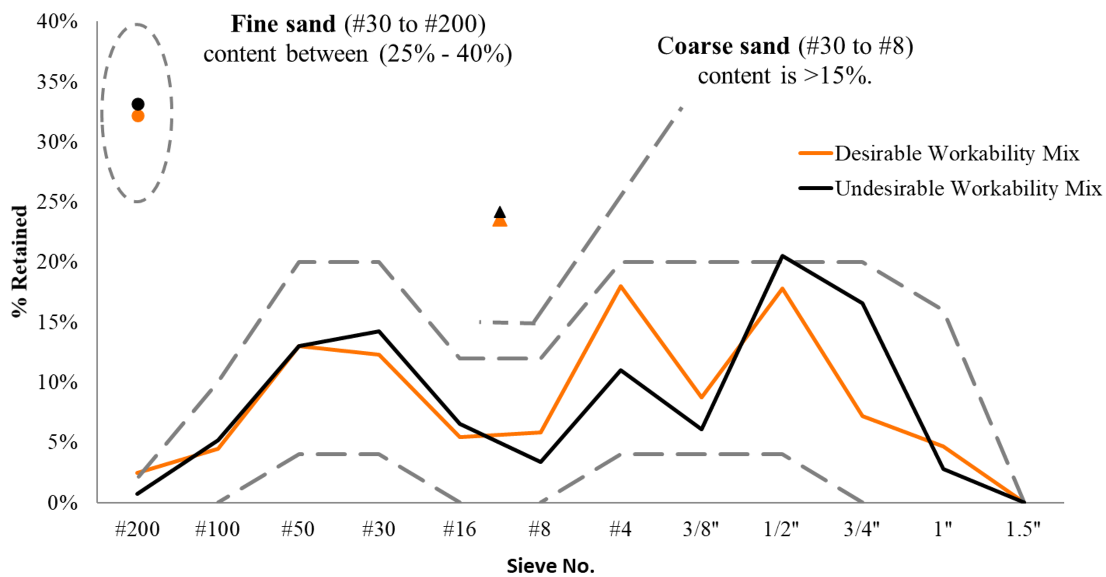


Figure 2.1. Mixtures in Tarantula Curve.

Table 2.2. Material amounts for each mixture

Material	Description	Undesirable Workability Mixture Weight (lbs./yd^3)	Desirable Workability Mixture Weight (lbs./yd^3)
Coarse Aggregate	57 crushed limestone	1752	1338
Intermediate Aggregate	3/8” crushed limestone	250	650
Fine Aggregate	ASTM C33 natural sand	1200	1240
Cement	ASTM C150 Type I	376	376
Fly Ash	ASTM C618 Class C fly ash	94	94
Water	Potable	211.5	211.5
Air Entrainer	ASTM C226 Wood rosin	1.62 oz/cwt	1.62 oz/cwt
Mid-Range Water Reducer	ASTM C494 Type A and F	0	5 oz/cwt

2.1.3 Mixing Procedure

Aggregates from outdoor storage piles were gathered and moved indoors to a controlled temperature of 73°F. Three samples for each aggregate type were collected from the mixer for moisture corrections. After moisture corrections were calculated, all of the aggregate and two-thirds of the water were placed in the mixer and spun for three minutes. This time allowed for evenly distributed aggregates and for the aggregates to be close to saturated surface dry (SSD). The residual water, cement, and fly ash were added next and mixed for three minutes. The mixing drum was then scraped and the concrete mixture rested for two minutes. Following the rest time, the mixer was spun for another 3 minutes and the admixtures were added.

2.1.4 Testing Procedure

For this testing each concrete mixture was evaluated with the following tests: Slump Test ASTM C143 [6], Box Test AASHTO TP 137-xx [2], Unit Weight ASTM C138 [5], and Sequential Air Meter (SAM) AASHTO TP 118 [1]. The slump test was used to help provide a general insight about the consistency of workability, and the Box Test was used to measure the workability of the mixture for slip formed paving. The results of the Box Test are determined by ranking the surface characteristics and edge slumping of the concrete block. Figure 2.2 provides the visual ranking system used for the Box Test. For unit weight and SAM testing, the samples were consolidated with either manual rodding, internal vibration, external vibration with a vibrating table, or the novel device based on external vibration. Each of these consolidation methods were described in the proceeding paragraphs. Also, the Unit Weight, air content, and SAM Number was measured using the testing equipment for the SAM.

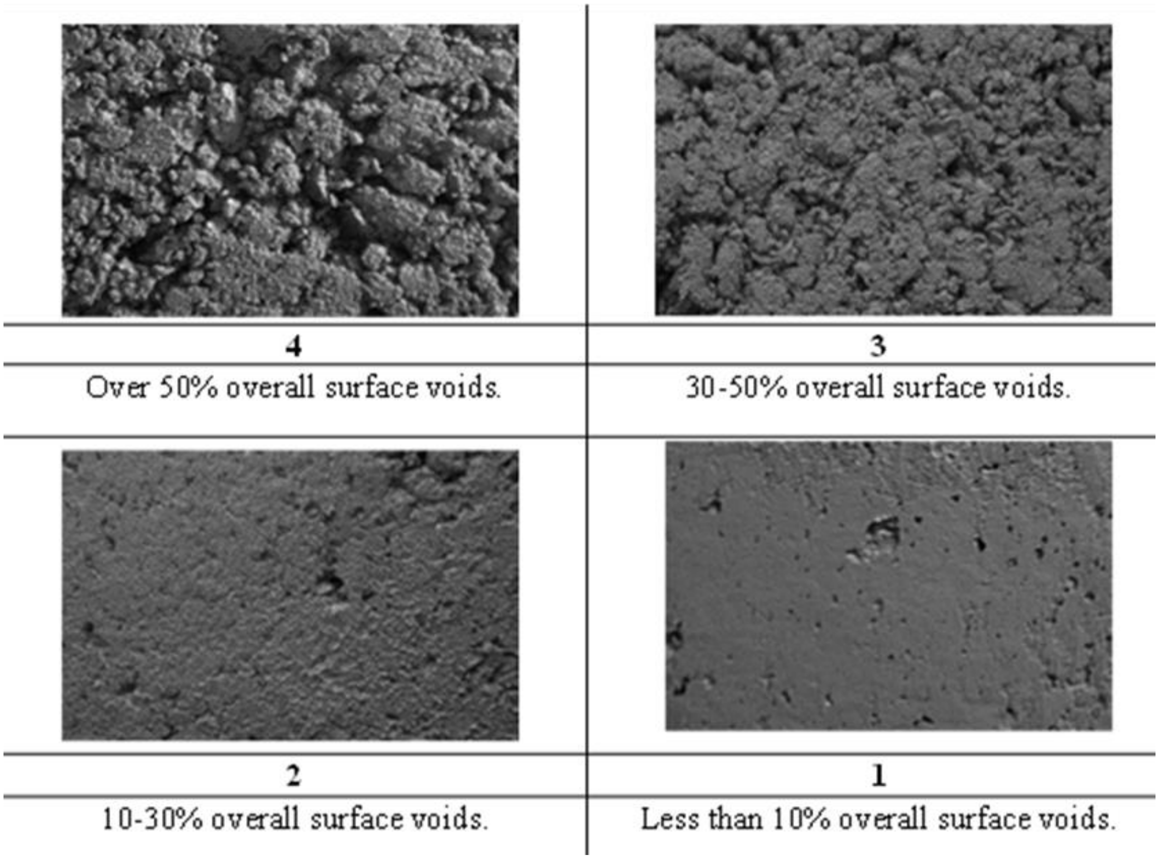


Figure 2.2 Visual ranking system for the Box Test

2.1.5 Consolidation Methods for Unit Weight and SAM

Table 2.3 details which consolidation methods were investigated for the undesirable workability mixture and desirable workability mixture. As shown in Figure 2.3 (a) through (d), the consolidation methods investigated were rodding, internal vibration with a 1” diameter portable concrete vibrator at 12,000 vpm, external vibration with a vibrating table, and external vibration with a novel device known as the MinT. These consolidation procedures followed ASTM C31[4] for field samples, ASTM C192 [8] for laboratory samples, and ASTM C138 [5] for unit weight based on the consolidation method.

Table 2.3. Consolidation methods investigated with each mixture

Mixture Design	Consolidation Method Investigated
Undesirable Workability	Rodding
	Internal Vibration
	Vibration Table
	MinT
Desirable Workability	Rodding
	Internal Vibration
	MinT

(a) **(b)** **(c)** **(d)**

Figure 2.3. (a) rodding, (b) internal vibration with poker vibrator, (c) vibrating table, and (d) MinT

2.1.5.1 Rodding

The rodding procedure was performed using the guidelines provided by ASTM C31[4] and ASTM C138 [5]. Concrete was placed in the damp unit weight bowl until one-third of its volume was full. A tamping rod with a diameter of 5/8 in. was inserted into the mixture 25 times. The holes created by the tamping rod were closed by using a standard mallet which smartly tapped the sides of the unit weight bowl between 10-15 times. Once the holes were closed, another third of the bowl's volume was filled and the process was repeated. Both the second layer and third layer were consolidated in the same manner.

2.1.5.2 Internal Vibration

Internal vibration of the unit weight bowl was performed following the guidelines given by ASTM C31[4] and ASTM C138 [5]. This requires an internal vibrator with vibration speeds greater than 9,000 vibrations per minute (vpm), the diameter of the vibrating head being less than one-quarter the diameter of the mold and the length of the vibration shaft must exceed the depth of the section being vibrated by 3 in. The first layer of concrete placed in the damp bowl filled halfway. A vibrator with a vibration speed of 12,000 vpm and 1 in. diameter head was inserted in three equally spaced locations into each layer of the concrete. The concrete was vibrated approximately 3 to 5 seconds until the surface of the layer being consolidated was smooth as stated in ASTM C138 [5]. This process was repeated for the final layer but the vibrator penetrated approximately 1 in. into the previous layer.

2.1.5.3 Vibration Table

One of the external vibration methods used a vibration table [3]. The vibration source is a rotary vibrator that oscillates at 3500 vpm. The consolidation procedure followed the general guidelines of ASTM C192 [8]. The concrete was placed in the damp unit weight bowl until it was half full. The bowl was then strapped down to the vibration table using a ratchet strap to hold it place during consolidation. Once it was firmly secured to the vibration table, the vibration table was turned on for 30 seconds to provide the minimum time to adequately remove large air voids within the mixture. After the vibration of the first layer, the second layer was placed in the bowl and the process was repeated. The vibration time was determined based on the average time it took for most of the large air voids to be removed from the mixture.

2.1.5.4 MinT

The Miniature Vibrating Table or MinT is a new consolidation technique that was developed to provide the benefits of the vibrating table in a portable field device. An overview of the MinT is shown in Figure 2.4. The MinT consists of a 1ft by 1ft metal table with clamps and a 1” diameter electric vibrator at 12,000 vpm. This work used a Makita XRV01Z battery-operated concrete vibrator. A 1-1/8” hollow steel tube at the bottom of MinT provides a pathway to insert the head of the vibrator and lock it into place with 4 adjustable screws. There are 3 screws in the steel tube and 1 screw going through the top of the table at one end of the tube. A custom steel O-clamp was welded to the top of the metal plate to keep the bowl from moving during vibration. The clamping system works by placing the unit weight bowl within the steel ring and engaging the latch

(a)

(b)

(c)

Figure 2.4. (a) An overview of the MinT being used, (b) side view of the MinT, and underside view of the MinT.

to hold it in place during operation. The vibrator head was inserted into the MinT and tightened with the 4 adjustable screws. Then the MinT was placed on a level surface. The unit weight bowl was placed in the clamping system and the latch was engaged. The unit weight bowl was filled in two even layers. Each layer was scooped into the unit weight bowl and consolidated for 50 seconds. While several different consolidation time intervals were investigated, 50 seconds was chosen because this time was the average amount of time to adequate consolidate the concrete. This time was determined by taking the average time it took for the removal of most large air bubbles [3, 5].

2.1.7 Comparing Measured and Reported Standard Deviations

The standard deviations recorded from the unit weights (density), air contents, and SAM Numbers from each mixture were compared with those reported in the test methods or relevant publications. The measured standard deviations were compared to ones reported in the Precision and Bias section in the ASTM test methods. The SAM Number standard deviation was found in published literature [17]. These are outlined in Table 2.4. The standard deviation of the results (σ_{exp}) was then compared to the standard deviations found in literature (σ_{lit}) and were taken as a ratio. The ratio taken was the result standard deviation over the literature standard deviation. So, if a ratio calculated was above 1 then the consolidation method is higher than the literature value. The opposite is true if the ratio calculated is below 1.

Table 2.4. List of standard deviations from test methods or publications

Referenced Test Method or Publication	Standard Deviation
ASTM C138/C138M: Unit Weight [5]	0.82 lbs./ft^3
ASTM C231/C231M: Type B Air Content [10]	0.29% for 5% Air
Determining the Air-Void Distribution in Fresh Concrete with the Sequential Air Method [17]	0.049

2.2 Results and Discussion

Table 2.5 shows the average slump and Box Test results from the mixtures. Figure 2.5 shows the performance of both mixtures in the Box Test. For the undesirable mixture, there are a lot of visible voids in the mixture which indicates the mixture needs high energy to consolidate. The Box Test results for the desirable workability mixture showed less void space. While the workability increased for this mixture, it was stiff to work with by hand and this made it a challenge to prepare samples without mechanical aid.

Figure 2.5 Box test results for undesirable mixture (left) and desirable mixture (right)

Table 2.5. Slump and Box Test results for mixtures

Mixture Design Measured	Number of Tests (n)	Average Slump (in.)	Std. Dev. (in.)	Average Box Test Result	Does it Pass Box Test?
Undesirable Workability	52	0.75	0.22	3.5	No
Desirable Workability	40	1.5	0.21	2	Yes

Note: A Box Test result less than or equal to 2 is acceptable [14]

The averages for most of the tests are similar to each other. There is overlap between all of the consolidation methods for the undesirable and desirable mixture results. Figures 2.6 through 2.8 show box and whisker plots of the data and how they overlap. It is important to remember an average is a measure of a typical value or what to expect [15]. The standard deviation is used to measure the variability of the measurement.

The results for each consolidation method for the undesirable mixture and desirable mixture can be found in Table 2.6. The table contains the averages, standard deviations and coefficient of variations for unit weight (density), air content and SAM Number for each consolidation method investigated. The table also provides the ratio of the experimental standard deviation over the literature standard deviation. It also provides the percent error between the experimental standard deviation and the literature standard deviation.

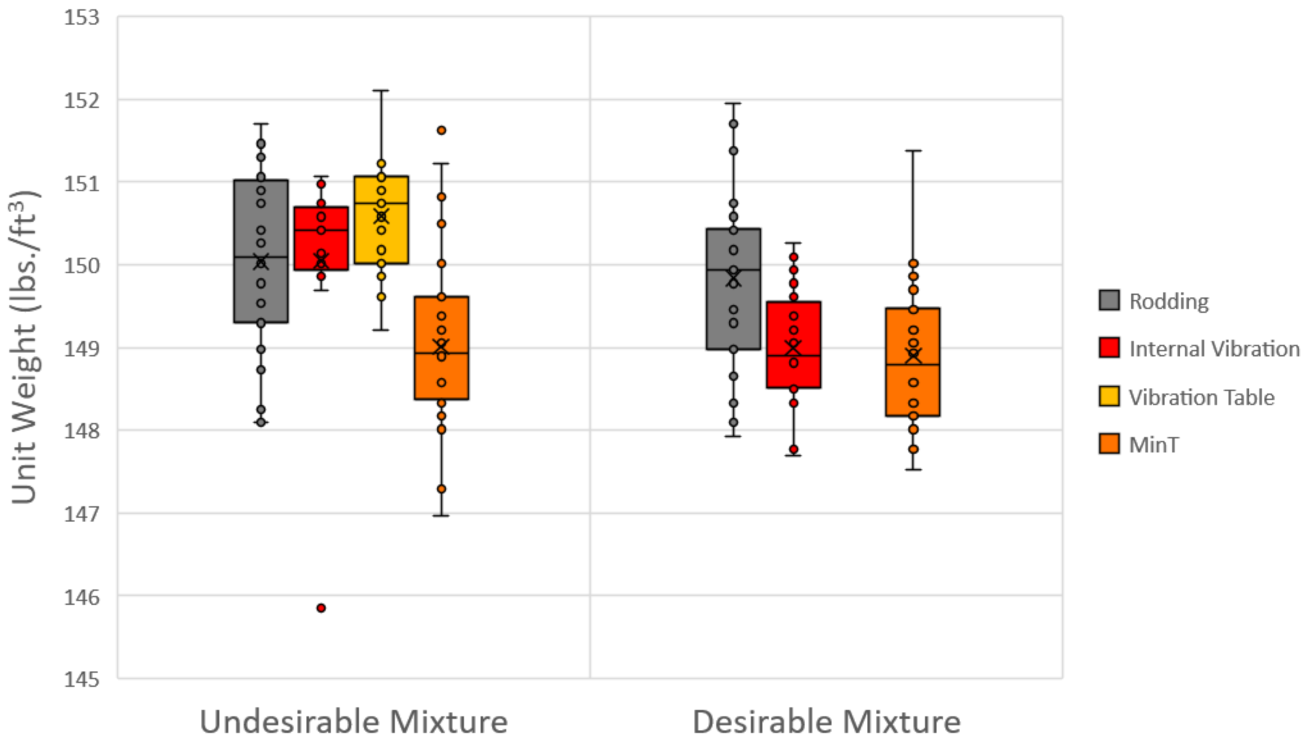


Figure 2.6. Box and whisker plot for unit weight.

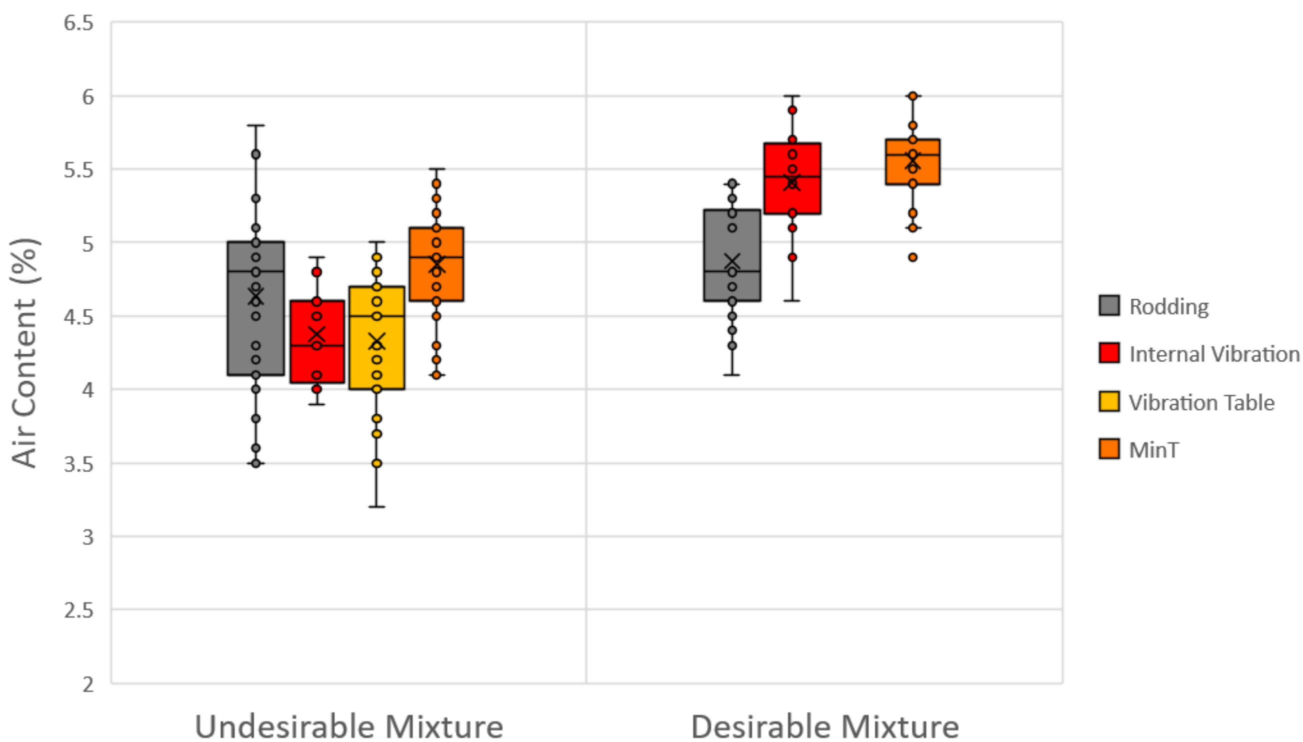


Figure 2.7. Box and whisker plot for air content.

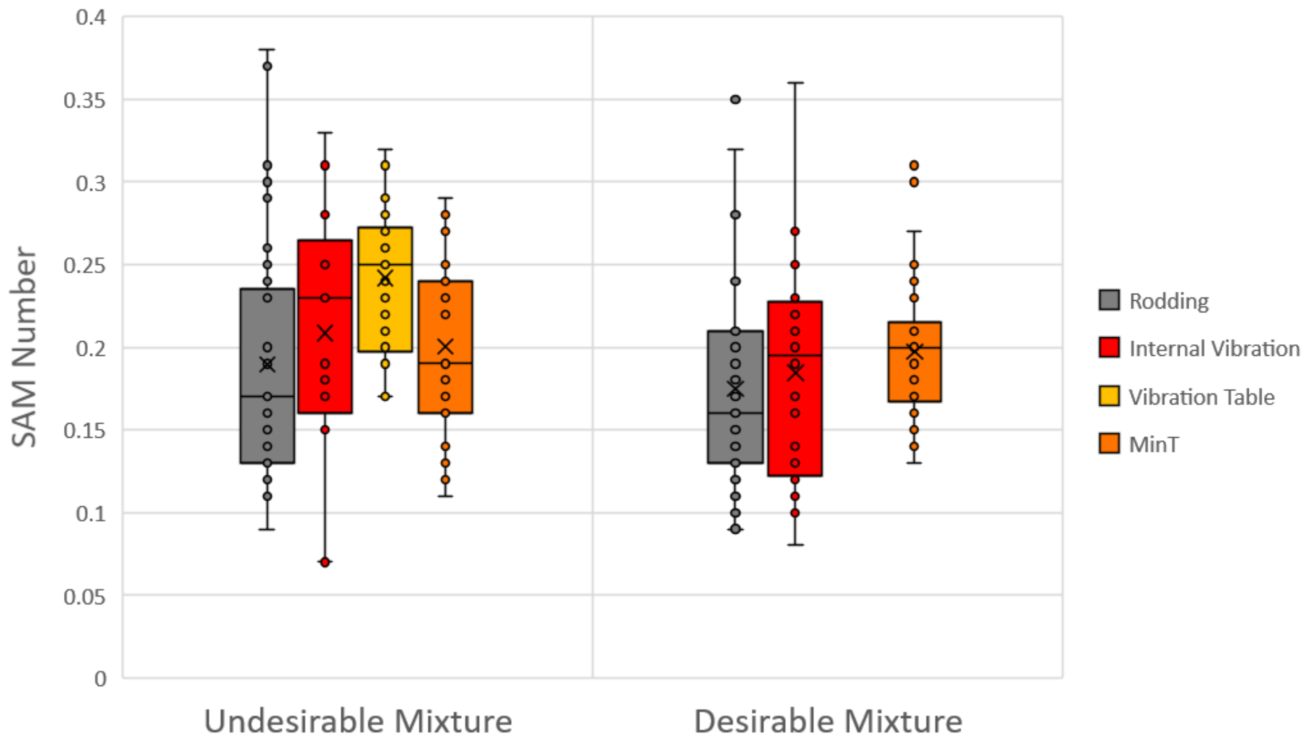


Figure 2.8. Box and whisker plot for SAM Number.

Table 2.6. Statistical Analysis of Air Quality Control Tests

Unit Weight (Density) Statistics					
Mixture Design Measured	**Consolid-ation Method**	**Number of Tests (n)**	**Average Unit Weight (lbs./ft^3)**	**Std. Dev. (lbs./ft^3)**	$\frac{Std.Dev.}{0.82}$
Undesirable Workability	Rodding	33	150.0	1.18	1.44
	Internal Vibration	13	150.1	1.33	1.62
	Vibration Table	26	150.7	0.68	0.83
	MinT	35	149.1	1.04	1.27
Desirable Workability	Rodding	30	149.8	1.04	1.27
	Internal Vibration	20	149.0	0.71	0.87
	MinT	30	148.9	0.88	1.07
Air Content Statistics					
Mixture Design Measured	**Consolid-ation Method**	**Number of Tests (n)**	**Average Air Volume (%)**	**Std. Dev. (%)**	$\frac{Std.Dev.}{0.29}$
Undesirable Workability	Rodding	33	4.6	0.62	2.14
	Internal Vibration	13	4.4	0.31	1.07
	Vibration Table	26	4.3	0.46	1.59
	MinT	35	5.3	0.43	1.48
Desirable Workability	Rodding	30	4.9	0.37	1.28
	Internal Vibration	20	5.4	0.35	1.21
	MinT	30	5.6	0.26	0.90
SAM Number Statistics					
Mixture Design Measured	**Consolid-ation Method**	**Number of Tests (n)**	**Average SAM #**	**Std. Dev.**	$\frac{Std.Dev.}{0.049}$
Undesirable Workability	Rodding	33	0.19	0.075	1.53
	Internal Vibration	13	0.21	0.078	1.59
	Vibration Table	26	0.24	0.046	0.94
	MinT	35	0.19	0.051	1.04
Desirable Workability	Rodding	30	0.18	0.065	1.33
	Internal Vibration	20	0.18	0.068	1.39
	MinT	30	0.20	0.045	0.92

Note: Internal vibration was performed with a 1 in. diameter vibration head.

2.2.1 Discussion of the Variability for Each Consolidation Method

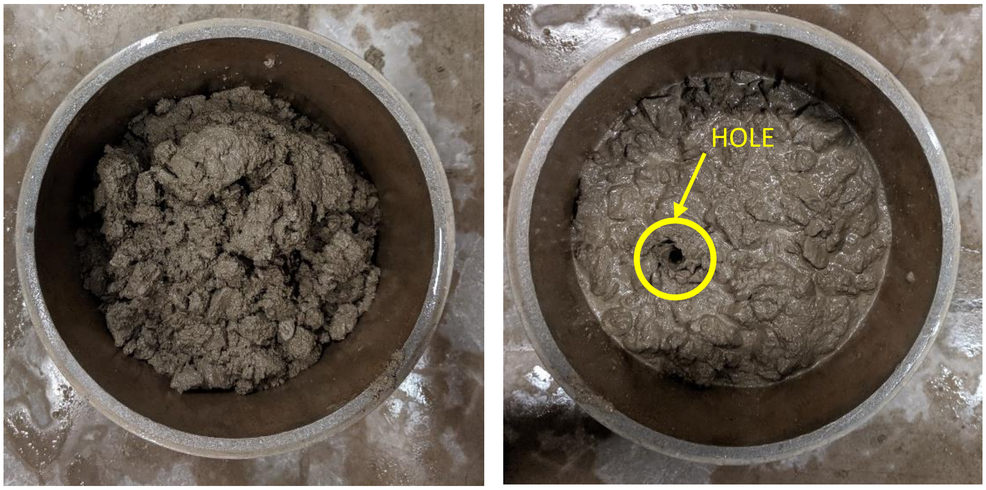
The harshness of these mixtures proved to be a challenge to consolidate using the rodding method. Mixtures that were rodded had standard deviations that were at least 25% greater than the published standard deviations for both mixtures with all of the consolidation methods. The source of the variability could be caused by the operator not being able to provide enough force with the mallet to adequately consolidate the concrete. Figure 2.9 shows a before and after result for rodding. After rodding these mixtures, it is common for voids to not be filled in. For this consolidation method, 10 to 15 mallet strikes are required to close the holes created by rodding. These unconsolidated voids could be responsible for the high variance of this method [16]. Another source for the variability is that there is not a standard way to strike the bowl with the mallet. Every operator using this method strikes the bowl at different locations and with varying force. Regardless of the reason, it is challenging to consolidate this concrete consistently to measure the unit weight, air volume or SAM Number.

(a) (b)

Figure 2.9. Rodding Method: before consolidation (a) and after consolidation (b).

Internal vibration had no measured standard deviation within any of the literature standard deviations. The standard deviations were at least 40% higher for all measurements except for the air volume of the undesirable workability that was only 7% higher. It is worth noting all but one of the standard deviations improved from the undesirable workability mixture to the desirable workability mixture.

The variability in these measurements could be due to the variable amount of time the vibrator is immersed in the mixture. ASTM C138 [5] requires the poker vibrator to be immersed in 3 different spots until the surface is smooth. There is no specific guidance on the spacing of these spots and so this can cause variability. Also, with each additional immersion spot less vibration time is required to make the local surface smooth and so this could cause the concrete to not receive a consistent amount of consolidation over the volume. Another source of variability can be during the removal of the vibrator from the mixture. When the vibrator is removed, it is possible to leave behind a hole which may leave a void that can trap air [16]. Figure 2.10 shows an example of this. Other sources of variability can come from how vertical the vibrator was during immersion[18]. Because of all these possible variations it is difficult to know how to reduce the variability of this consolidation method.



(a) **(b)**

Figure 2.10. Internal Vibration: (a) before consolidation and (b) after consolidation.

The vibration table was only used in three comparisons and all of these comparisons were done for mixtures with an undesirable workability. The air content standard deviation was within the published value for all tests except for the air content of the undesirable mixture. This standard deviation was 60% great than the published value. Since the vibration table applies uniform energy and the time is controlled then this may improve the consistency of the samples. Figure 2.11 shows a typical mixture before and after being consolidated with the vibration table. It is possible that with the low workability mixture the energy from the vibration table may not be high enough to consistently remove the air voids during the consolidation. This may explain the higher variability for the air volume and it is an area of future work.

(a) (b)

Figure 2.11. Vibration Table (a) before consolidation and (b) after consolidation.

The standard deviations for the MinT are within the range in two of the six comparisons made and two more comparisons are within 7% of the published values. Two of the standard deviations below the literature values and one that was within 7% were for the mixture with the desirable workability. This means that the MinT showed variability within or very close to the published standard deviation for the mixtures with the desirable workability. This is the only consolidation method that was able to do this. Also, the standard deviations decreased for the MinT as the workability increased. This matched the trend observed in the other consolidation methods and shows the impact of workability on the variability of measuring the air void systems in fresh concrete.

Figure 2.12 provides a visual reference of a before and after consolidation using the MinT. The consistency of MinT can be attributed to similar reasoning used for the vibration table. The vibrations were controlled and were set on a dedicated time limit which provides consistency from test to test. It is possible that for the mixture with an undesirable workability that a longer consolidation time or a larger vibrator may provide more consistent results. These are areas for future work.

(a) (b)

Figure 2.12. MinT: (a) before consolidation and (b) after consolidation.

2.3 Practical Implications

The work presented measured the variability of the unit weight, air content and air-void distribution each consolidation method had when the slump of the concrete is less than 2 in. The findings have revealed that the results from rodding and internal vibration slump less than 2 in can be consistently higher than the published values. This means those methods can provide misleading quality control information to contractors, engineers and owners for these mixtures.

It is important to note the resulting variations from these experiments are based on mixtures with low workability that may be used for slip form applications such as concrete pavements, curbs, or walls. This work shows that it may be necessary to update the published standard deviations in the respective test methods for unit weight, air content and SAM Number to accommodate for the workability and the consolidation method used in the test. This would allow people to quantify their variability and then decide which consolidation method is best for their testing.

The MinT was the only consolidation method that provided a standard deviation within an acceptable range for the unit weight, air volume, and SAM Number for the mixture with desirable workability. The MinT provides the consistency of a vibration table in a portable piece of testing equipment. The use of the MinT could be a useful way for builders to report values with less variability and for owners to feel more confident in the results.

2.4 Conclusion

Two similar concrete mixtures with a slump less 2 in. were compared in this study. One mixture required higher amounts of external energy for consolidate than the other. Consolidation methods of rodding, internal vibration, and two different external vibration methods were investigated based on using the standard deviation of the unit weight, air volume, and SAM Number. A new portable vibration table is presented called the MinT and compared to other methods of consolidation. The results show that the vibrating table and MinT provide lower variabilities and more variabilities within published values than rodding or internal vibration for mixtures with a slump less than 2".

The specific findings are:

- The mixture that required higher energy for consolidation had higher standard deviations for the unit weight, air volume, and SAM Number than the mixture that required lower energy for consolidation.

- Rodding and internal vibration had a standard deviation less than the published value in 1 out of the 12 comparisons.
- The MinT and vibration table had a standard deviation for standard deviations within 7% of the reported values for 6 of the 9 comparisons.
- The MinT is the only consolidation method that had a standard deviation within 7% of the published values for the mixture that was responsive to vibration.

The work suggests that the published standard deviations need to be adjusted for the workability and consolidation method used to perform the test. This work would benefit from a larger amount of testing with a wider range of materials. Further work needs to be done to understand why some methods are more consistent than others. Also, the MinT needs to be tested in field conditions to see if this reduces the variability of the measurements and to improve the robustness of the design.

CHAPTER III

CONCLUSION

3.0 Summary

The goal of this research was to compare various sample consolidation methods for low workability concrete. It is important to see how the harsh workability of these mixtures affects the variability of air quality control tests: unit weight, air content and SAM Test. These tests are important to know because they provide vital information about the freeze-thaw durability of concrete. The more knowledge about the variability each consolidation method produces, the more confident operators, engineers and owners are about the air void system of the concrete.

Two important concepts came out of this research. The first concept was the variability for certain consolidation methods that current literature suggests is not necessarily true across all mixtures. Operators, engineers and owners need to know the variability that is associated with the workability of the mixture and how it can differ from one consolidation method over another.

The second concept that came out of this research was a novel device based on external vibration. The MinT was able to reduce the variability of the unit weight, air content and SAM Number for mixtures with slumps less than 2 in. The ease of use, portability and repeatability of MinT make it a valuable tool to add to these quality control tests.

3.1 Future Work

Further work needs to be done with MinT and the vibration table to investigate why these external vibration methods are more consistent than currently accepted field test procedures needs to be a priority. Also, the MinT needs to be tested in field conditions to see if this reduces the variability of the SAM Numbers there. The MinT could have a wide variety of uses and can aid field operators who are working with harsh mixtures.

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