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Automated Measurement and Control of Concrete Properties in a Ready Mix Truck with VERIFI

by

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16. Abstract

In this research, twenty batches of concrete with six different mixture proportions were tested with VERIFI to evaluate 1) accuracy and repeatability of VERIFI measurements, 2) ability of VERIFI to adjust slump automatically with water and admixture, and 3) effects on concrete properties when water and admixture are added continuously during transit instead of adding whole at the plant or jobsite. For each batch, concrete was sampled every 30 minutes up to 90 minutes and tested for slump, temperature, air content, unit weight, water content, bleeding (select batches), and rheology (select batches). Cylindrical concrete specimens were cast at 90 minutes and were tested for compressive strength at 3 and 28 d (or 3 and 14 d for IDOT mixes).

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Abstract

VERIFI is an automated system that enables a real time measurement and recording of the properties of fresh concrete in a truck mixer. VERIFI automatically adds water and/or water reducing admixtures within the allowable water-to-cementitious ratio (w/cm) limit to manage and maintain the slump at the target value at the plant, during transit, and at the jobsite. All water or admixture additions are recorded and can be monitored online during construction. This automated slump adjustment reduces the variation in fresh properties of concrete and improves uniformity of delivered concrete. The hardened properties are also expected to be improved since lower amount of water is added through automated VERIFI slump retention. No extra effort is required to adjust the slump of concrete when the truck arrives to the job site.

In this research, twenty batches of concrete with six different mixture proportions were tested with VERIFI to evaluate 1) accuracy and repeatability of VERIFI measurements, 2) ability of VERIFI to adjust slump automatically with water and admixture, and 3) effects on concrete properties when water and admixture are added continuously during transit instead of adding whole at the plant or jobsite. For each batch, concrete was sampled every 30 minutes up to 90 minutes and tested for slump, temperature, air content, unit weight, water content, bleeding (select batches), and rheology (select batches). Cylindrical concrete specimens were cast at 90 minutes and were tested for compressive strength at 3 and 28 d (or 3 and 14 d for IDOT mixes).

The statistical analysis of results shows that the accuracy of VERIFI system in measuring slump and temperature of concrete in a truck mixer is 0.5-in. and 1.5 °F, respectively. This is within the acceptable variation limit stated in ASTM C143 [1] and ASTM C1064 [2]. The confidence interval analysis of slump measurements reveals that the probability of having average slump deviation larger than 0.56 in. is less than 5%. The accuracy of VERIFI was not affected by load size or if concrete is mixed in different truck mixers.

VERIFI system was able to adjust and maintain the slump at the specified target slump until delivery by adding water or high-range water reducer (HRWR). The average and standard deviation of difference between the slump of concrete at delivery time and target slump are 0.66 in. and 0.42 in., respectively. When water was automatically added through VERIFI system during simulated transit to maintain slump, less water was used and the compressive strengths were equal or higher than when all water was added at once at job site. As expected, adding admixture during simulated transit to maintain slump resulted in higher compressive strength than when water was added. Nevertheless, all concrete strengths were higher than the design requirements. The air contents of both entrained and non-entrained mixes were not affected by VERIFI water or admixture additions in transit to maintain a target slump.

The results of this research indicate that 1) VERIFI is able to accurately measure concrete slump and temperature in the truck, 2) VERIFI is able to adjust slump automatically to target by adding water and admixture, and 3) adding water in transit instead of at the jobsite or plant does not negatively affect concrete performance. Compared to current industry practices, VERIFI provides more accurate and complete documentation of concrete properties, including all additions of water, so that engineers and inspectors can confirm whether concrete meets specification. Therefore, VERIFI can be allowed to add water during transit and data from VERIFI can be used for acceptance purposes.

1. Brief review of VERIFI system

VERIFI is an automated system that measures, manages and records properties of fresh concrete in truck mixers. As shown in Figure 1, sensors on the truck measure concrete slump, temperature, additions of water and admixture, drum speed, number of revolutions, and time of activity (loading, arrive site, begin pour, finish pour, etc.). The truck is also equipped with GPS.

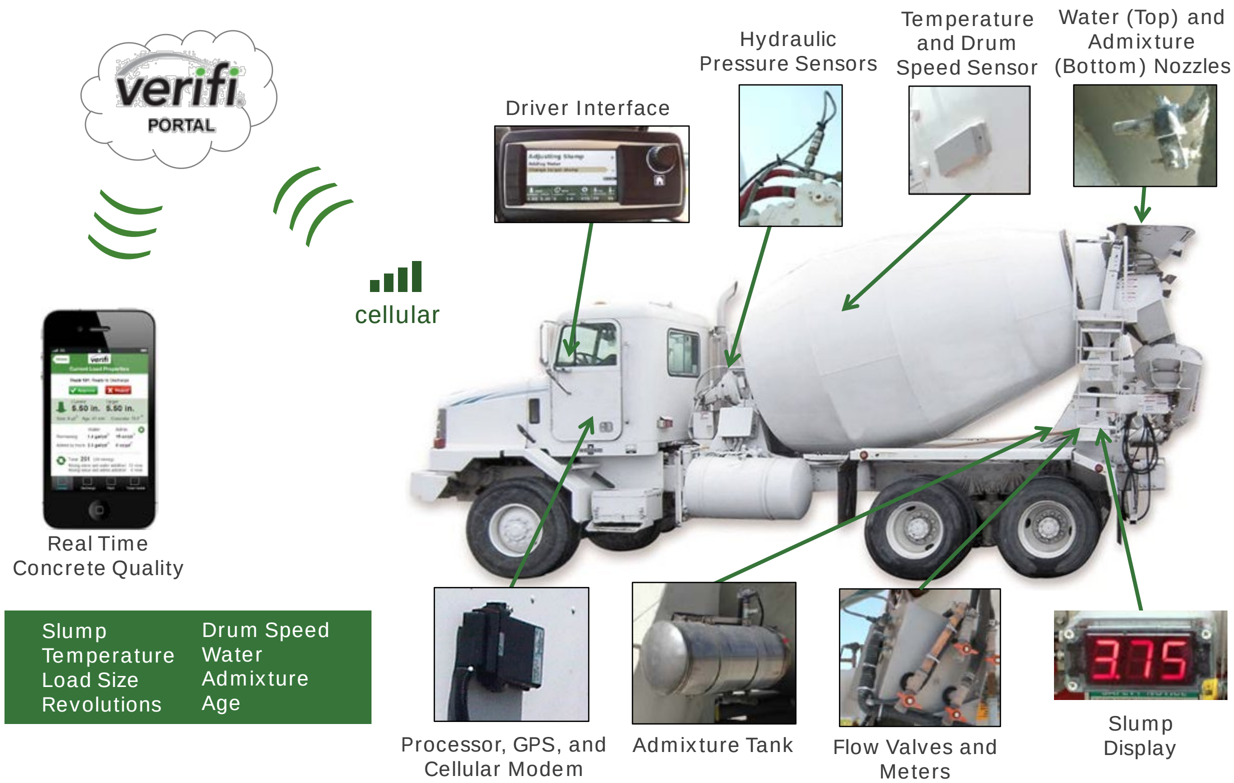
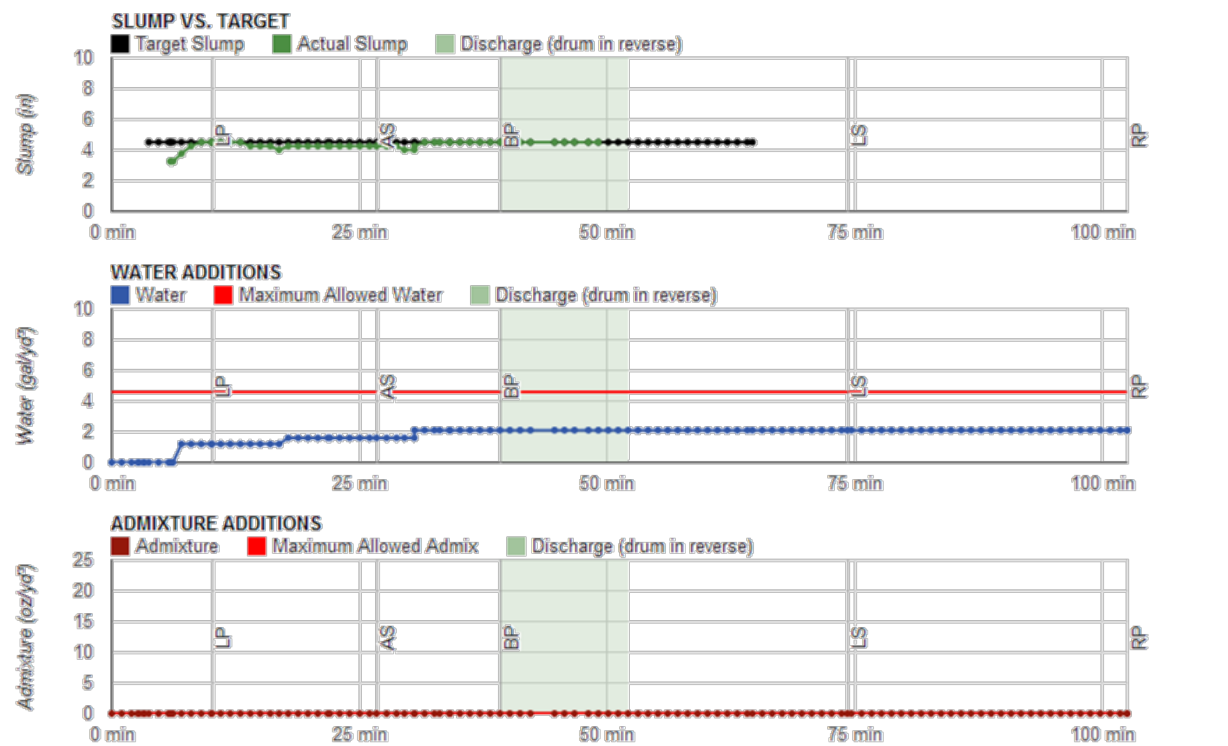


Figure 1- VERIFI Equipment

Each time the slump is more than 0.5 in below target, VERIFI can automatically add water or admixture to reach the slump target. This addition is automatic and without human involvement. VERIFI automatically calculates the amount needed to reach the target slump. VERIFI receives the maximum water for the load through a direct interface with the batch software and can stop water additions after reaching the maximum water content. The ready mix company sets up VERIFI Instructions for each mix design or group of mix designs. These Instructions set how the truck is to manage a load of concrete to comply with project specifications, including mixing requirements after batch and water additions, and when to add water or admixture.

All data is recorded in real time and transmitted via cellular connection to VERIFI servers, where all data can be viewed from any internet connected device. A sample load report is shown in Figure 2. In addition, VERIFI mounts displays in the cab and on the outside of the truck, where drivers, inspectors, and contractors can see current concrete properties, including the amount of water added to the load vs. the maximum water content.

Slump is calculated using a proprietary algorithm that considers the drum speed, hydraulic pressure to turn the drum (related to torque), load size, and mix design. Temperature is recorded from a small probe mounted through a hole drilled into the drum.



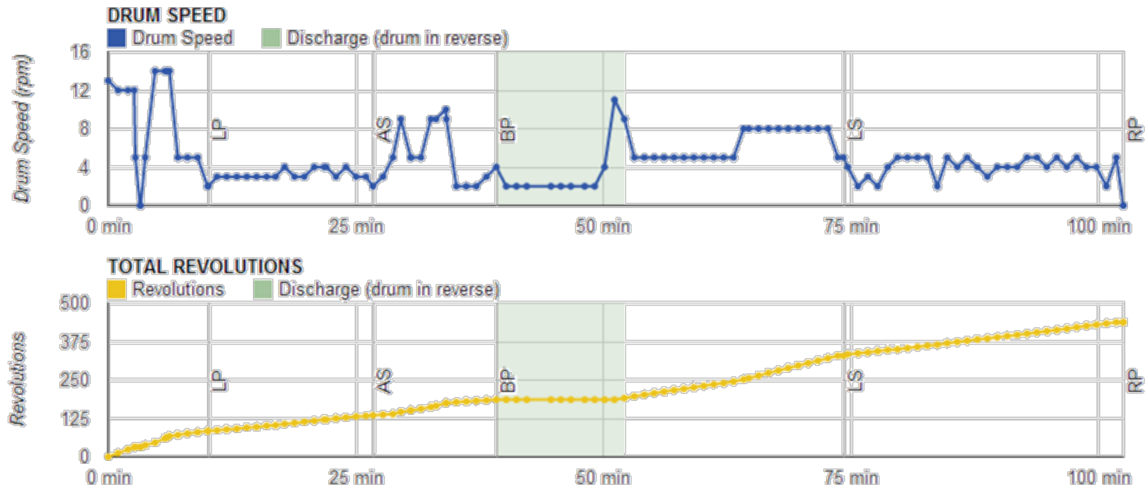


Figure 2- Typical Documentation of Concrete Delivery with VERIFI

2. Research objective

This study will evaluate the performance of VERIFI automated system for measuring, managing, and recording the fresh properties of concrete in truck mixer. The results of this study are expected to be used by Departments of Transportation (DOTs), concrete suppliers, engineers, and contractors as a guide to implementing automated slump management equipment into specifications and QC/QA programs.

The objective of this research is to evaluate 1) accuracy and repeatability of VERIFI measurements, 2) ability of VERIFI to adjust slump automatically with water and admixture, and 3) effects on concrete properties when water and admixture are added continuously during transit instead of at the plant or jobsite only. The tested parameters are briefly explained below:

- **Repeatability:** Repeatability or test-retest reliability is the variation in measurements reported by VERIFI on the same mix design. The purpose is to check the variations in slump and temperature measurements taken on the same mix design while all parameters, except one parameter are kept unchanged. The repeatability, which is related to the precision of the system, will be examined based on the variation observed in the results. The lower the variation observed, the more repeatable and precise is the system. To investigate repeatability, two series of tests are conducted. In the first series of tests, the variation of test results is investigated in different truck mixer loaded with the same mix having the same load size. In the second series of tests, the effect of volume of concrete on the repeatability of VERIFI measurements is investigated.

- **Measurement accuracy:** The accuracy of VERIFI measurements is investigated in different concrete mixtures by comparing the VERIFI reported results with the results obtained by the trained and ACI-certified technicians whom conducted the tests in accordance with the relevant ASTM standards. The mixtures are selected to represent the typical concrete mixture proportions commonly used in construction industry by Department of Transportation (DOT) and other construction agencies. The mixture proportions considered in this part of the study have different:
    - water-to-cementitious ratio (w/cm)
    - target slump
    - required compressive strength
    - Type and dosage of chemical admixtures e.g. air entraining agent (AEA), viscosity modifying admixture (VMA) and supplementary cementitious materials (SCM) e.g. fly ash

  The difference between measurement accuracy and repeatability is that the accuracy shows the closeness of the measured value to the true value while the repeatability reflects the precision of the repeated test (see Appendix A for details). Although the two words precision and accuracy can be synonymous in colloquial use, they are used differently in this report.

- **Slump retention:** VERIFI automatically manages slump at the specified target slump by adding controlled amount of water and/or chemical admixtures (in this study, high range water reducing admixture, HRWR, was used) within the allowable maximum limit. The results of this research will attempt to find the answers of the following questions:
    - Is VERIFI able to maintain slump close to the target value in-transit (either by adding water and/or HRWR)?
    - Is the VERIFI equipped truck mixer able to deliver the concrete at job site with the desired target slump?

- **Effects of additions of water and admixture in transit on concrete properties:** Automatic addition of water or HRWR, which is required for retaining slump of concrete close to the target value, would affect properties of hardened concrete. Such effects will be analyzed based on the comparison between mixes in which VERIFI method of in-transit water addition is applied and where water was added at jobsite to retemper the target slump. The results of this research will attempt to find the answers of the following questions:

- How much water is added in total when water is added gradually during transit compared to single addition at the jobsite to achieve the target slump at 90 minutes?
- How does the method of water addition affect the early and final compressive strength of concrete?
- Is there a significant effect on air content of concrete (both on entrained and non-entrained concrete)?

3. Experimental program

The testing program is divided into five experimental tasks. The first two tasks were designed to examine the repeatability (or precision) of VERIFI while Task III examines the accuracy of the measurement system. The experiments of Task IV and Task V were performed to evaluate the ability of VERIFI in slump retention of concrete. The data collected from Task IV and Task V are used for investigating the effects of using the automatic slump retention on concrete properties. Details of these tasks are described in the following sections.

3.1. Task I: Repeatability of measurement in different truck mixers

Each truck has specific properties with respect to the hydraulic drive technology. The vehicle and the mixing drum properties may differ to some extent; therefore, it is required to compare the performance between different trucks equipped with VERIFI. The aim of this task is to investigate the precision of VERIFI measurements when different truck mixers are used. Therefore, two different trucks are loaded with each truck having 6 cubic yards of concrete with similar mixture proportions to investigate the presence of variability in VERIFI measurements. Two concrete mixtures, one with high slump and one with low slump, are used in this test. Table 1 summarizes the tests done under this task. Based on ASTM C94 [3], the maximum allowable discharge time is 90 minutes; therefore, the concrete is tested up to 90 minutes at 30 minute intervals provided that the concrete have sufficient fluidity.

Table 1- Controlling system calibration

Truck No.	**Truck Mixer I**	**Truck Mixer II**
Low Slump Concrete (Mix #1)	Batch #1	Batch #2
High Slump Concrete (Mix #5)	Batch #3	Batch #4

3.2. Task II: Repeatability of VERIFI measurement using different concrete volume

The effect of concrete volume on the precision of VERIFI measurements is also investigated. One truck is selected and is loaded with three different volume of concrete to determine the repeatability of the system measurements. Same concrete mixture proportion and truck mixer are used in three tests, shown in Table 2. The details of mixture proportions are given in Table 3.

Table 2- Controlling system calibration

Load amount	**60% of drum capacity**	**75% of drum capacity**	**Full drum capacity**
Control Mix Design (Mix #5)	Batch #3	Batch #5	Batch #6

3.3. Task III: Accuracy of VERIFI measurement in different mixture proportions

Depending on the project needs and specifications, mixes with different mixture proportions are used in ready mix industry. The ability of VERIFI in handling concrete with different mixture proportions is investigated in this task. The fresh properties obtained from VERIFI outputs are compared with the results of the conventional tests performed on samples taken from the ready mix trucks. Six representative concrete mixtures with different workability and/or strength requirements are selected to represent the typical mixture proportions used in DOT and other commercial construction projects. These six mixture proportions are shown below:

Mix No. 1 Typical DOT pavement mixture proportion - IDOT Class PV, SI (air-entrained)

Mix No. 2 Typical DOT mixture proportion for structural elements - similar to MoDOT Class B-2 (air-entrained)

Mix No. 3 A typical concrete used in municipal applications fly ash concrete, 4000 psi with HRWR, (air-entrained)

Mix No. 4 High volume fly ash concrete, 6000 psi (non air-entrained)

Mix No. 5 Typical high strength, highly workable mix for columns, grade beams, shear walls, etc. (non air-entrained)

Mix No. 6 Typical DOT concrete mix used for commercial applications, 71-PCC-065Z - IDOT 6.4 Bag Class BS (air-entrained)

In these mixes, the water-to-cementitious ratio (w/cm) varies in the range of 0.33 to 0.43 and the target slump of concrete varies between 2 and 10-in. The design compressive strength varies between 3500 and 8750 psi. Fly ash, set retarder, viscosity modifying agent (VMA), and air-entraining agent (AEA) were used in some mixes. The details of mixture proportions used in this research are summarized in Table 3.

Table 3- Mixture proportions

Mix Number			1	2	3	4	5	6
Material		**Specification & Description**	**One Cubic Yard Wts. (SSD)**					
Cement Type I/II	Lb	Continental Hannibal (2101-02)	435	490	655	470	446	658
Fly Ash Class C	Lb	LaFarge Pleasant Prairie (52403-02)	145	130	0	200	145	75
GGBF Slag	Lb		0	0	0	0	0	0
Fine Aggregate / ASTM C33 #2	Lb	Tricon Hennepin (51550-07)	1276	1138	1147	1147	1415	1290
Coarse Aggregate / ASTM C33 #57	Lb	LaFarge Joliet (51972-15)	1771	1830	1857	0	1790	1800
Coarse Aggregate / ASTM C33 #8	Lb	LaFarge Joliet (51972-15)	0	0	0	1762	0	0
Water (Allowable / Batch)	Lb	IDOT Sec. 1002	242/237	260/250	264/250	260/250	236/230	265/258
Water Reducing Agent	Oz/cwt	IDOT Sec. 1021.03 / ASTM C494, Type A	3.5	3.5	5.0	3.5	0.0	0.0
Air Entrain Agent	Oz/cwt	IDOT Sec. 1021.02 / ASTM C260	0.7-1.5	0.7-1.5	1.7-2.5	0.4-0.9	0.0	0.0
HRWR	Oz/cwt	IDOT Sec. 1021.03 / ASTM C494, Type F	0.0	0.0	5.0	4.0	4.0-7.0	4.0-7.0
Set Retarder	Oz/cwt	IDOT Sec. 1021.03 / ASTM C494, Type D	1.5	1.5	1.5	2.5	1.5	0.0-1.0
Viscosity Modifing Agent	Oz/cwt	ASTM C494, Type S	0.0	0.0	0.0	0.0	1.5	1.5
Strength Specification		psi @ 14 Days	3500	3500	3500*	4000	5000	8000
Slump Range		Inches	2-4"	2-4"	2-4"	6-8"	8-10"	7-9"
Air Content		%	5-8%	5-8%	5-8%	5-8%	0-3	0-3

1- *Admixture dosage rates listed are typical, but can vary - including air–entraining agent*
2- *Water listed as maximum allowable / typically batched - but amount may vary.*
**psi @ 14 Days per IDOT Specification.*

3.4. Task IV: Automatic slump adjustment (using water addition)

The fourth task of this experimental program is to investigate the ability of VERIFI in retaining slump at the desired value. VERIFI could use both water and/or chemical admixtures to retain the slump. In this task, only water was added to retain the slump at target value. Two different water addition methods were considered and the results are compared with each other. The batch numbers, the corresponding mixture numbers, and the water addition method are given in Table 4.

Table 4- Test experiments of Task IV

Method	Water addition method	Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	Mix #6
Method I: One-time addition	All water at the end	Batch #2	Batch #7	Batch #8	Batch #9	Batch #4	Batch #10
Method II: In-transit	Gradually during transportation	Batch #11	Batch #12	Batch #13	Batch #14	Batch #15	Batch #16

- **Method I, One-time water addition at final discharge:** In this method, the slumps of concrete were adjusted by adding all of the required water right before discharge at job site. The final discharge time was 90 minutes after batching. This procedure is a common industry practice in which visual observation is used for estimating the slump of concrete and evaluating the required water content to be added for increasing the slump to reach the desired value. The procedure used in this research was the same as described above except that instead of having visual observation for estimating the current slump of concrete, the slump reported by VERIFI was used to evaluate the required water content for slump retention. This approach was chosen to avoid human error associated with visual evaluation of slump. The results of these tests are considered as references which represent the conventional method at job site. ASTM C94 [3] accepts this procedure provided that the added water plus the batched water content do not exceed the maximum allowable water content specified in mixture proportioning. The typical slump loss during transportation and slump retention at job site are shown in Figure 3.

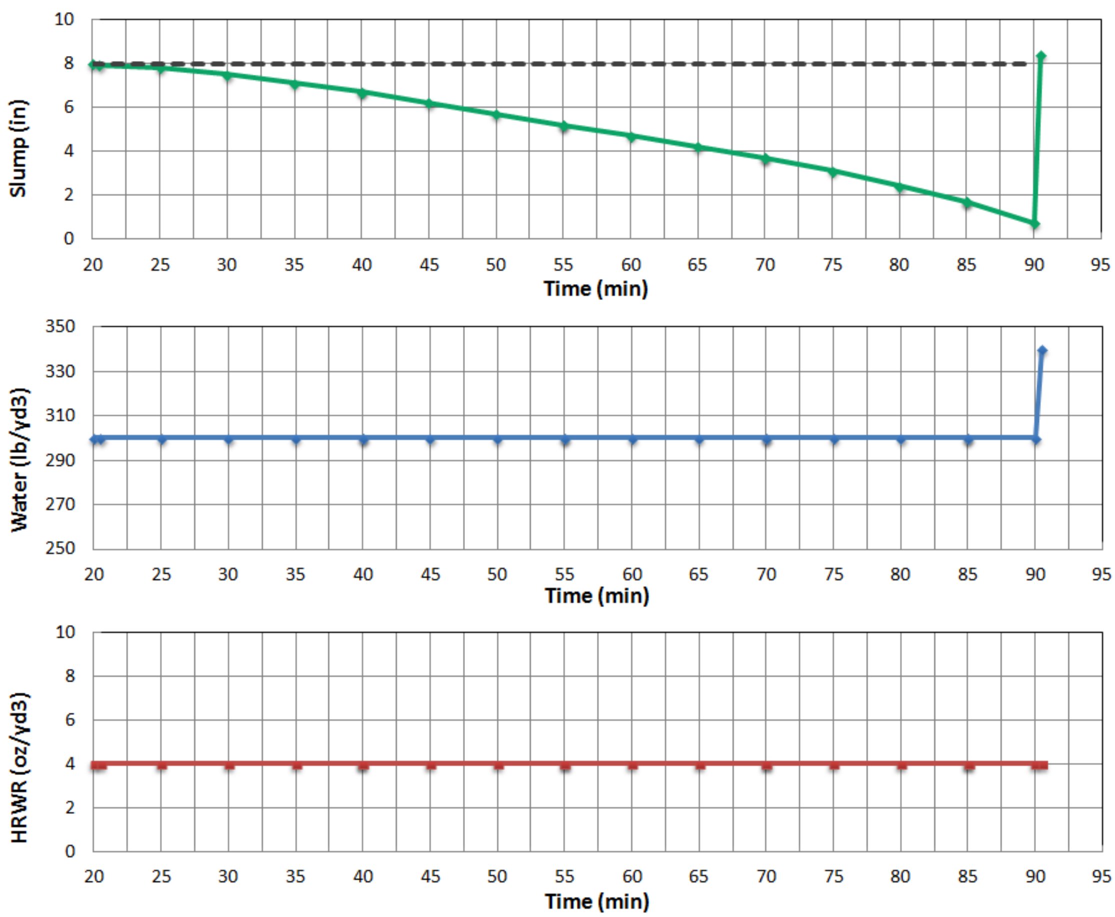


Figure 3- Schematic representation of slump retention using one-time water addition at jobsite

Method II, Automatic water addition in-transit: VERIFI was used here to maintain the slump at the target value after the truck mixer leaves the batch plant and in-transit. Based on the current slump, VERIFI automatically calculates the required water content to reach the target slump, and it automatically adds water within the allowable water content limit. Typical slump loss and water addition used in this method are shown in Figure 4.

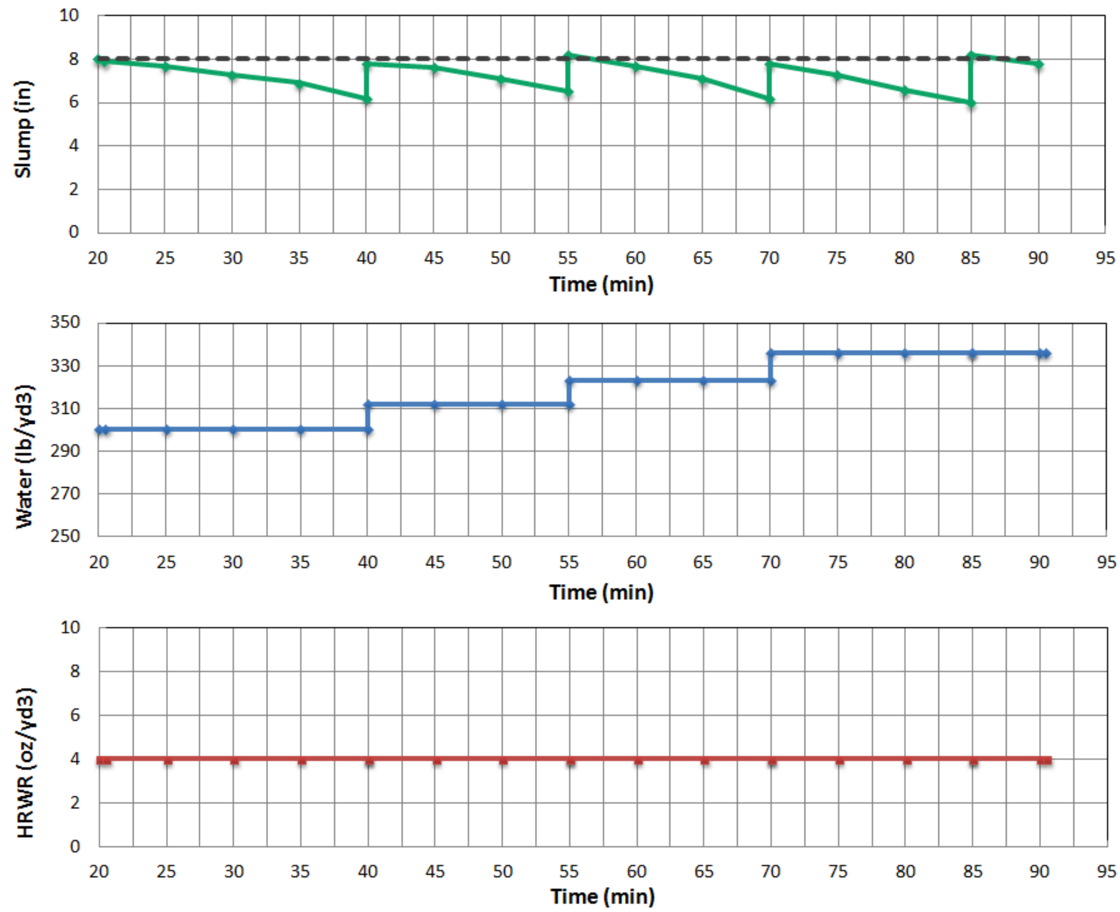


Figure 4- Schematic representation of slump retention using automatic in-transit water addition

3.5. Task V: Automatic slump adjustment (using HRWR addition)

This task is similar to Task IV except that instead of water addition, HRWR was used for retaining the slump at the desired value. Similar to the previous task, two different methods were used for adding HRWR to concrete mix. Mix #3 and Mix #5 were considered in this task. Details are shown in Table 5.

Table 5- Test experiments of Task V

Method	Admixture addition method	Slump retention with HRWR	
		Mix #3	Mix #5
Method I: One-time addition	**All added at the batch plant**	Test #17	Test #19
Method II: In-transit	**Gradually added in-transit**	Test #18	Test #20

- **Method I, HRWR addition at the batch plant:** In this method, the slump of concrete was adjusted by adding all of the required HRWR at the batch plant. Higher amount of HRWR was used in batching the concrete to increase the initial slump of concrete to compensate the slump loss during transportation. The amount of extra HRWR was equal to the total HRWR added in transit in Method II. The typical HRWR addition and corresponding slump are shown in Figure 5.

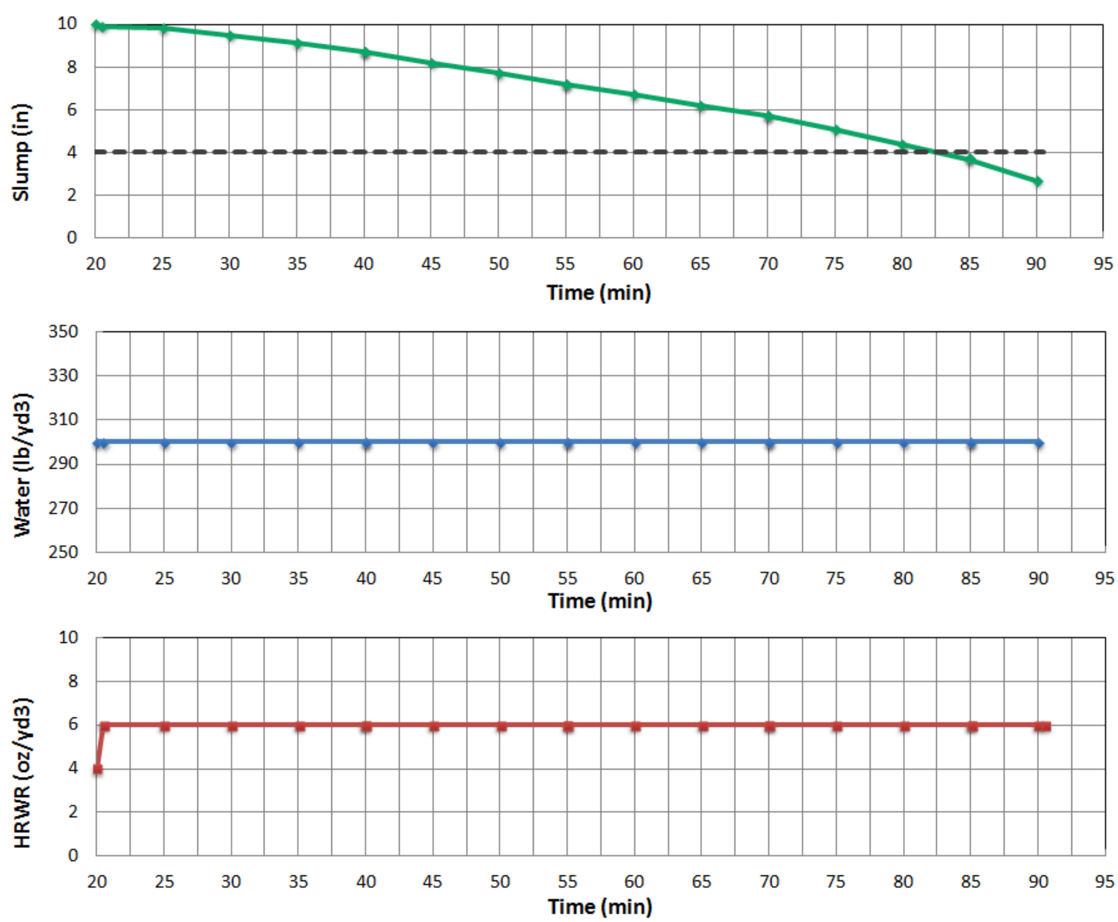


Figure 5- Schematic representation of slump retention using non-automatic HRWR addition

- **Method II, Automatic HRWR addition in-transit**: In this method, to maintain the specified target slump, HRWR was automatically added to concrete in-transit by VERIFI whenever slump was 0.5-in. below the target value. The gradual HRWR addition and corresponding slump are schematically shown in Figure 6.

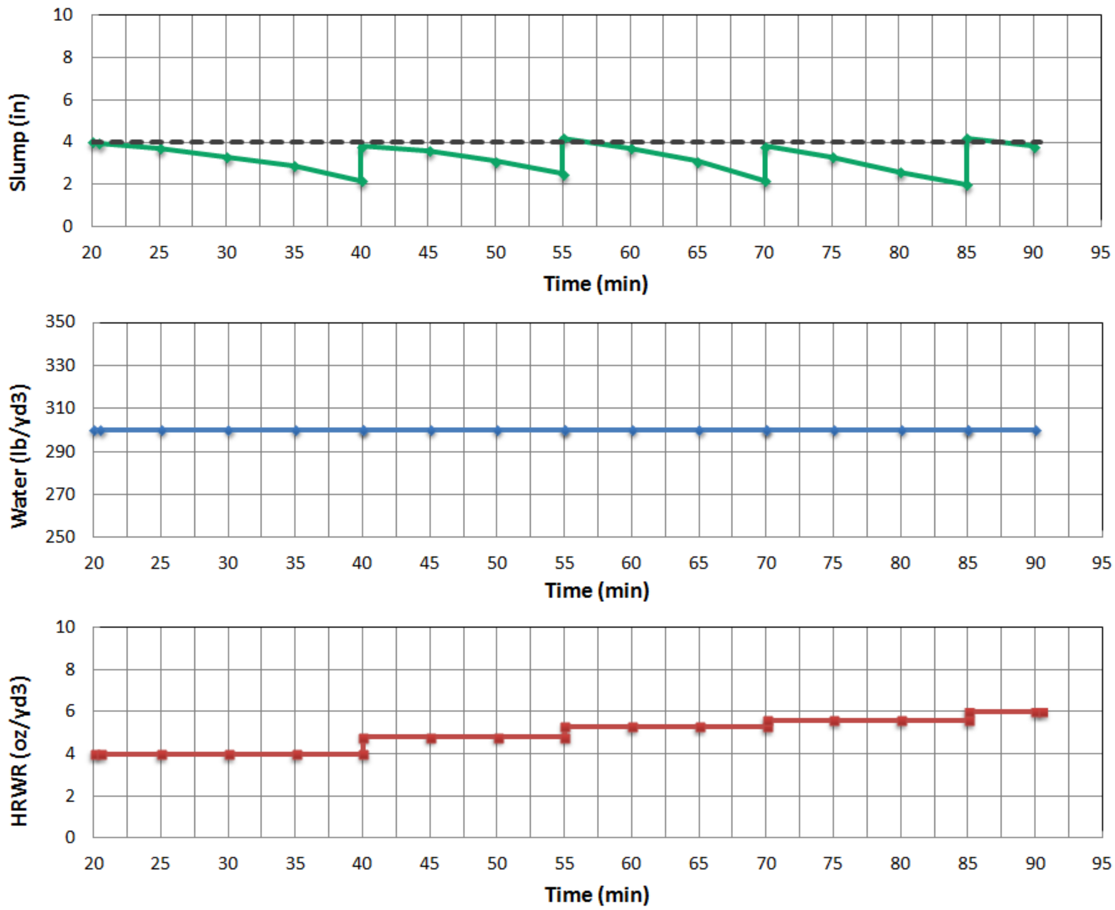


Figure 6- Schematic representation of slump retention using automatic in-transit HRWR addition

4. Batching, sampling, and testing protocol

Batching and testing were conducted at the *Ozinga Ready Mix Concrete* batching plant which is located near downtown Chicago. The truck mixers used in this research program were all equipped with the VERIFI system. Figure 7 shows one of these truck mixers. In all tests, excluding Test #5 and Test #6, 6 yd^3 of concrete were batched, which is an equivalent of 60% of the capacity of a truck mixer. Mixes were tested up to 90 minutes after batching with 30-minutes intervals. The volume of batched concrete in Test #5 and Test #6 was 7.5 yd^3 and 10 yd^3, respectively.

Figure 7- Truck mixer equipped with the VERIFI system

4.1. Batching and initial mixing protocol

The concrete constituents including cement, aggregate, supplementary cementitious materials, chemical admixtures and water were batched in the central batching plant and were mixed fully to achieve homogenous mixture. All concrete were from a central mixer, and were technically "shrink mixed". Wet batching was used in all mixes except Mix #2 in which dry batching was used for concrete production. Concrete mixtures were batched slightly below the target slump during batching, which required the water added during batching to be reduced ("trimmed") below the design water. The design water content typically takes into account any water needed to maintain slump until discharge at the jobsite. After loading the truck, VERIFI was used to increase the slump and adjust it to the target slump with water addition. The water added in the batching in addition to the water added during the initial slump adjustment is considered as the initial water of mixtures.

After loading the truck mixer, concrete was mixed at mixing speed (6-18 rpm) for about 40-60 revolutions. Thereafter, the rotation speed was reduced to agitation speed (2-6 rpm) until the first sampling. This mixing protocol was adopted to make sure that concrete is homogenous enough and ready for sampling. This can reduce random errors associated with concrete sampling. It is consistent with typical concrete specifications.

Loading concrete into truck mixer at batching plant ***initial mixing before leaving batching plant***

Figure 8- Concrete batching and initial mixing

4.2. Transportation mixing protocol

After batching and initial mixing, the truck mixers departed the batching plant en route to the laboratory. The final testing was done 90 minutes after batching, which is assumed as the final discharge time of the concrete. Truck mixers stayed at the lab until final testing. The rotation speed was kept constant at agitation speed of 2 rpm to simulate transport period. After each water addition (automatic gradual or single-time addition), the concrete was mixed for at least 15 revolutions at agitation speed before sampling. The minimum required revolutions after HRWR addition was 30 revolutions at agitating speed to make sure that the admixture is fully mixed with other premixed materials. This protocol was proposed by VERIFI and is followed by all VERIFI-equipped truck mixers. All concrete mixtures received 70-100 revolutions before the first sampling at 30 minutes. The total number of revolutions before final discharge was limited to 250-300 revolutions to avoid prolonged mixing. All concrete mixtures were mixed for 15 revolutions at high speed before sampling for the final test on 90 minutes.

Initial mixing at batching plant ***Staying in the lab (simulating transportation time)***

Figure 9- Truck mixer in batching and lab

The numbers of revolutions, rotation speed, shear stress, and shear rate to which the concrete is exposed will affect the rheological properties of cement-based materials. Hence, the mixing procedure was kept unchanged in all mixes to make sure that all concrete would have the same mixing history.

4.3. Sampling protocol

About 2 cubic feet of concrete was taken for testing. In some cases, 1-3 cubic feet of concrete were discarded into dumpster before pouring the concrete into the sampling cart. That was done to make sure the sampled concrete is homogenous enough and is representative of what is inside the drum of truck mixer. The sampling procedure is shown in Figure 10.

Throwing away top portion of concrete ***Pouring concrete into cart for sampling***

Figure 10- Sampling procedure

The sampling protocol of this research is summarized as follow:

- Sampling at 30, 60 and 90 minutes after batching
- Concrete poured into cart were fully mixed by scoop and shovel before testing to make sure that the concrete is sufficiently homogeneous
- Six 4”x8” cylinders were cast from the concrete sampled at 90 minutes
- For mixes of Task IV where water was added at 90 minutes to retain slump (Method I, non-Automatic slump retention), two series of samples were taken, one before and one after water addition. All fresh tests as well as the compressive strength sampling were done on both sampled concrete. The corresponding results were labeled as “*before water addition*” and *“after water addition”,* respectively.
- Concrete specimens were tested at 3 and 28 days for compressive strength, except for Mix #1 and Mix #6 which were tested at 3 and 14 days, as required by the Illinois Department of Transportation (IDOT) specifications.

4.4. Test protocol and standards

After sampling at 30, 60 and 90 minutes, the fresh concrete samples were tested. The list of performed tests and their corresponding standards are summarized in

Table ***6***. Some of these tests are shown in Figure 11.

Figure 11- Tests for determining fresh properties of concrete

Table 6- List of tests and standards

PROPERTY	STANDARD	TEST TITLE/DESCRIPTION	30 MIN	60 MIN	90 MIN
FRESH CONCRETE PROPERTY TESTS					
Unit Weight	ASTM C 138	Standard Test Method for Density (Unit Weight)	x		
Slump	ASTM C 143	Standard Test Method for Slump of Hydraulic-Cement Concrete	x x	x x	x x
Temperature	ASTM C1064	Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete	x x	x x	x x
Air Content	ASTM C 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method	x	x	x
Water Content	AASHTO TP23	Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying	x x	x x	x x
Rheological Properties	-	ICAR Rheometer	x	x	x
Bleeding	ASTM C232	Standard Test Methods for Bleeding of Concrete	x		
HARDENED MECHANICAL PROPERTY TESTS					
Compressive Strength	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens			x

In addition to the conventional tests, complementary tests were conducted. The rheological properties of concrete, e.g. yield stress and viscosity, were measured by the ICAR rheometer. There is no published standard for rheometer yet. However, all procedure was in accordance to the specs and the detailed description provided by the developer of this equipment. The "water content of freshly mixed concrete using microwave oven drying" was performed in accordance to AASHTO T318-02 (2011) [4]. The procedure is schematically shown in Figure 12. The water content test was performed twice at each sampling to reduce the testing error and increase reliability of the results. The temperature and slump were also measured twice by two different experimenters at the same time. The average of two results was reported for the slump, temperature and water content tests. The outline of tests conducted in this research is presented in Table 7. The task number, mix number and corresponding performed test are also given in this table.

Figure 12- Test of water content of freshly mixed concrete using microwave oven test

Table 7- Outline of research program and performed tests

Task #	Mix #	Batch #	time (min)	Unit weight	Temperature	Air Content	Water Content	ICAR Rheometer	Bleeding	Compressive strength
1	Mix #1	1	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x			x
		2	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x			x
	Mix #5	3	30	x	x	x	x x	x		
			60		x	x	x x			
			90		x	x	x x		x	x
		4	30	x	x	x	x x	x		
			60		x	x	x x			
			90		x	x	x x		x	x
2	Mix #5	5	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x
		6	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x
3	Mix #2	7	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x			x
	Mix #3	8	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x		x	X
	Mix #4	9	30	x	x	x	x x	x		
			60		x	x	x x			
			90		x	x	x x		x	x
	Mix #6	10	30	x	x	x	x x	x		
			60		x	x	x x			
			90		x	x	x x		x	x
4	Mix #1	11	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x			x
	Mix #2	12	30	x	x	x	x x			
			60		x	x	x x			
			90		x	x	x x			x
	Mix #3	13	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x		x
	Mix #4	14	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x		x
	Mix #5	15	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x
	Mix #6	16	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x
5	Mix #3	17	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x		x
		18	30	x	x	x	x x	x		
			60		X	x	x x	x		
			90		X	x	x x	x		x
	Mix #5	19	30	x	X	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x
		20	30	x	x	x	x x	x		
			60		x	x	x x	x		
			90		x	x	x x	x	x	x

5. Repeatability

The results of Task I and Task II were used for evaluating the repeatability of VERIFI. These results are presented and discussed in Sections 5.1 and 5.2.

5.1. Different truck mixers

The repeatability of the VERIFI measurement system is compared in two different truck mixers. Although both truck mixers were loaded with the same mixture proportion, there might be a slight variation while batching the materials. For instance, when the aggregates and cement are weighed, small errors may occur on each ingredient. Water content is based on the weights and moisture contents of the solid components being correct. Therefore, any error on the dry components will result in an error on the mix design and produce a variation in slump or the moisture of the product. The daily temperature variation will also affect the moisture content and temperature of the aggregate stockpiles and the rate of moisture evaporation of concrete. It will also affect the rate of hydration. All these parameters will in turn affect the temperature and slump of concrete. Therefore, the slump and temperature of two different truck mixers cannot be compared together even though they were assumed to be loaded with the same mixture proportions.

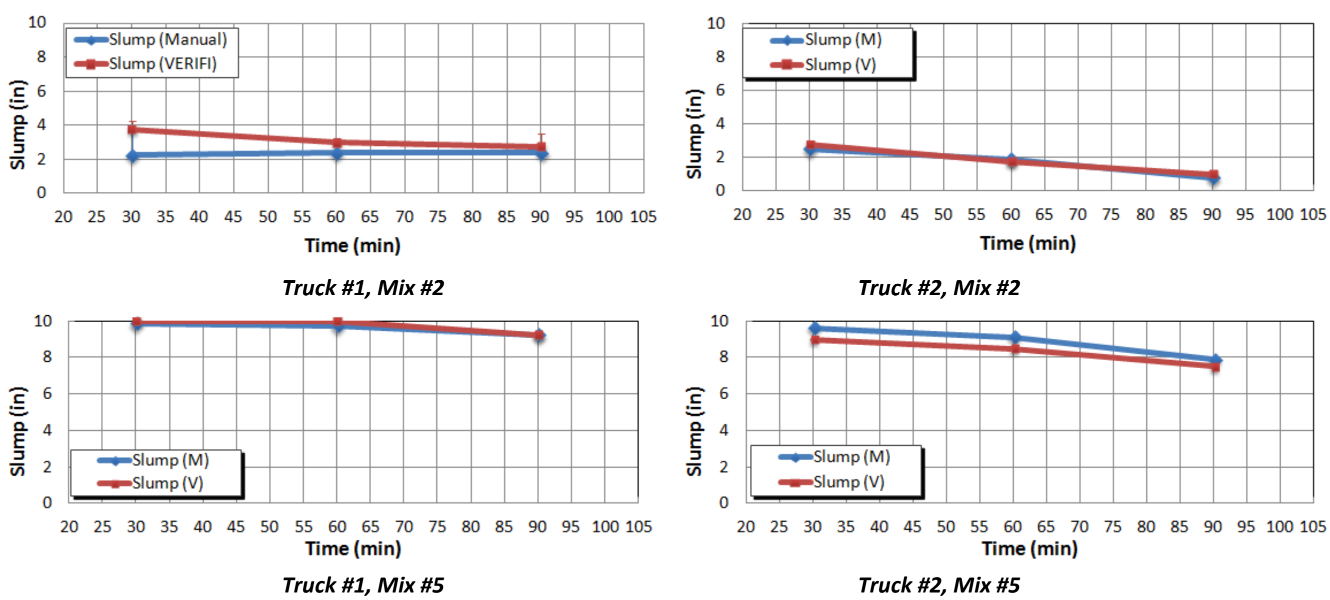
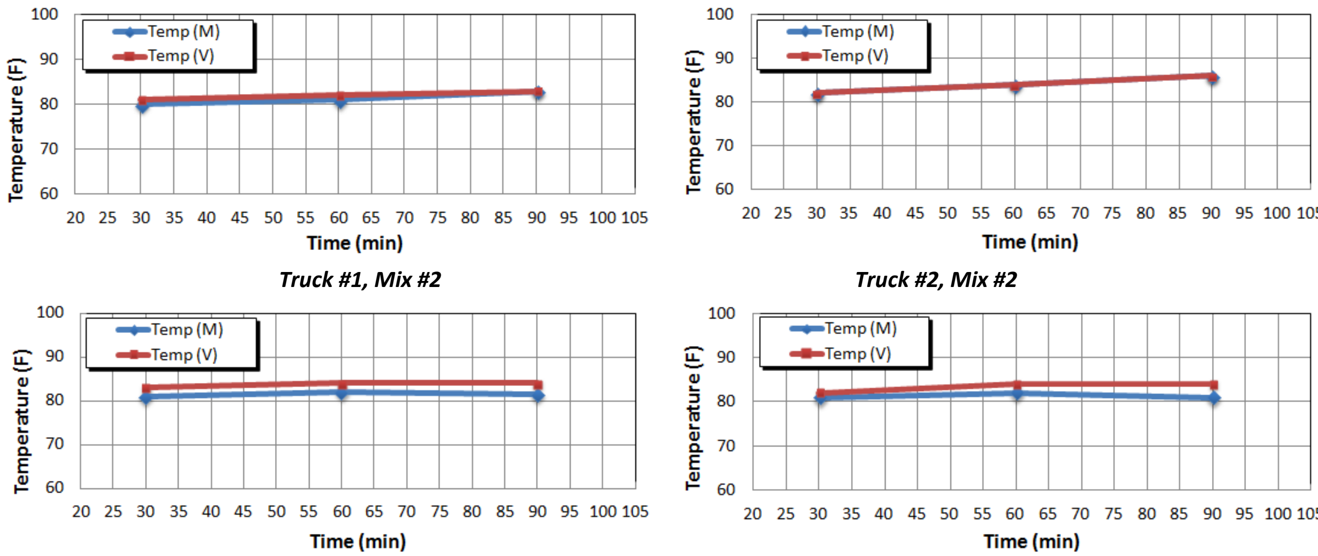


Figure 13- Slump measurement in two different trucks (M = manual, V= VERIFI)



Truck #1, Mix #2 ***Truck #2, Mix #2***

Truck #1, Mix #5 ***Truck #2, Mix #5***

Figure 14- Temperature measurement in two different trucks (M = manual, V= VERIFI)

The results of slump measurement of Task I are depicted in Figure 13. Slumps measured by the VERIFI are shown with red lines while blue lines are used for illustrating the results of slump measured manually in accordance with ASTM C143 [1]. The temperatures values measured both by VERIFI and thermometer in accordance with ASTM C1064 [2] are shown in Figure 14.

The results presented in the figures above show that in both investigated trucks, the automatically measured slump and temperature readings by VERIFI are very close to the measured readings in accordance with the relevant ASTM standards. The only exception is the 30 minute testing of Mix #2, Truck #1 in which the manually measured slump is 1.5-in. lower than the slump reported by VERIFI. However, this particular data is discarded in the analysis due to the obtained slump readings by the technicians presenting an unusual increasing behavior from 30 to 60 minutes when slump loss was expected.

5.2. Different volume of concrete

The results of manual slump and corresponding VERIFI reading in the truck loaded with 6, 7.5 and 10 yd^3 of concrete are shown in Figure 15. The manually measured temperature and the temperature measured by VERIFI are depicted in Figure 16. In both figures, the VERIFI measurements (red lines) are close to manual measurements (blue lines). The results show that VERIFI is not sensitive to the volume of concrete loaded into truck mixer, and is capable of measuring slump and temperature accurately. Based on the selected load size range, this conclusion is valid if a truck mixer is loaded with at least 60% of the nominal capacity. Nevertheless, VERIFI LLC states that the measurement system could be used of any load that is larger than 4 yd^3. In many practical applications, the truck mixer is usually loaded with 80% to 100% of its nominal capacity. Therefore, the investigated range is sufficient for system calibration.

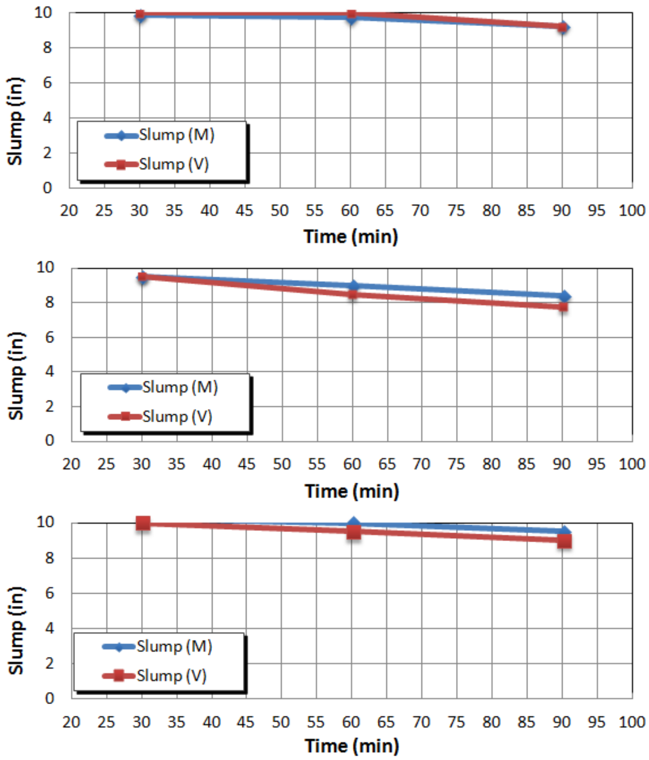


Figure 15- Slump measurement in trucks loaded with different volume of concrete (M = manual, V= VERIFI)

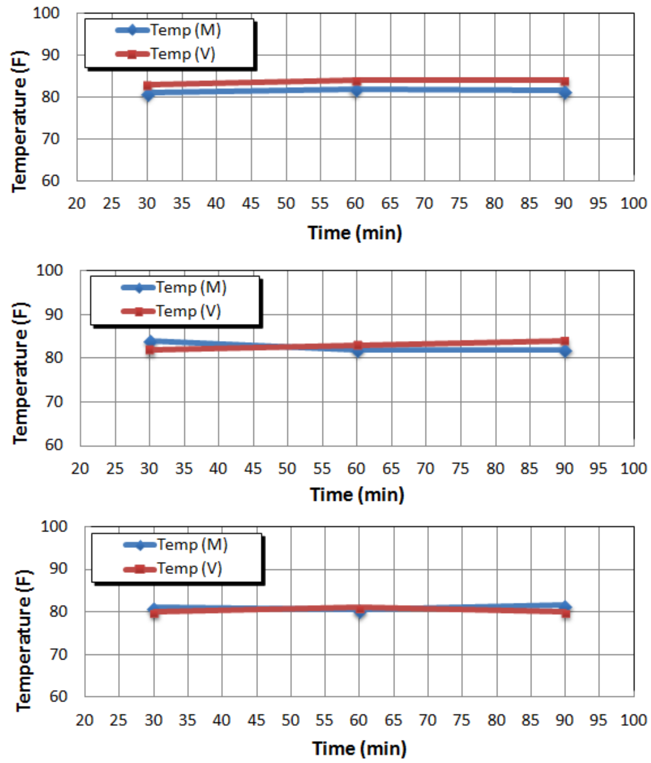


Figure 16- Temperature measurement in trucks loaded with different volume of concrete (M = manual, V= VERIFI)

Statistical analysis were also used to evaluate repeatability of results in different truck mixers or in one mixer loaded with different volume of concrete. The average spread in measuring the slump using truck #1 and truck #2 are 0.33-in. and 0.38-in., respectively, when comparing Verifi readings to manual slump test results. The standard deviations of spread of slump measured in these trucks are 0.21-in. and 0.23-in., respectively. The analyzed data are summarized in Table 8. Maximum, average, and standard deviation of spreads in two investigated trucks are almost the same. That means the accuracy of investigated truck mixers in measuring the slump is almost the same. The same conclusion could be reached regarding the data obtained in measuring temperature of concrete by different truck mixer and different load volumes. These data clearly show changing the truck mixer will not affect the VERIFI readings. In other words, the automatic slump measurement could be repeated in different truck mixers with acceptable precision.

Table 8- Comparing precision of measurement in Truck #1 with Truck #2

	Truck I		Truck II	
Absolute Spread	**Slump**	**Temperature**	**Slump**	**Temperature**
Max	0.63 in.	2.5 °F	0.63 in.	3.0 °F
Ave	0.33 in.	1.5 °F	0.38 in.	1.0 °F
Standard Deviation	0.21 in.	0.79 °F	0.23 in.	1.03 °F

The spread of measuring slump and temperature of concrete using the VERIFI is also compared with the precision of the tests done by technicians in accordance with the ASTM standards. Although, slump and temperature were performed by two technicians at the same time, the reported results varied. Therefore, the precision of manual measurements was determined and compared with the precision of the VERIFI measurements. Even though the VERIFI measurements have slightly higher average of spread compared to the manual measurements (0.35-in. vs. 0.22-in.), the standard deviations are almost identical (0.22-in. vs. 0.23-in.). Therefore, the precision of slump measured by VERIFI is very close to the precision of manual readings obtained by the technicians. The statistical analysis of VERIFI measurements and manual measurements are summarized in Table 9.

Table 9- Comparing precision of manual and VERIFI measurements

	VERIFI Measurement*		Manual Measurement**	
Absolute Error	**Slump**	**Temperature**	**Slump**	**Temperature**
Max	0.63 in.	3.0 °F	0.75 in.	2.0 °F
Ave	0.35 in.	1.26 °F	0.22 in.	0.5 °F
Standard Deviation	0.22 in.	0.95 °F	0.23 in.	0.63 °F

* *Comparison of VERIFI measurement to average of two manual measurements*

** *Comparison of two manual measurements*

Based on the above results, the repeatability of the VERIFI in different truck mixers can be judged reliable since the effect of using different truck mixer or load size did not affect the results. The spreads obtained from the VERIFI readings were similar to the spreads obtained by the technicians and were within the acceptable precision in accordance with the relevant ASTM standards.

6. Measurement accuracy

6.1. Different mixture proportions

The accuracy of VERIFI measurement in different concrete mixes is discussed in this chapter. Six concrete mixture with the water-to-cementitious (w/cm) ratio varying from 0.33 to 0.43, the design compressive strength varying from 3500 psi to 8750 psi and the specified slump requirements varying between 2-in. and 10-in. were tested in this research (Table 3). The slump and temperature of all the mixes were measured at 30, 60 and 90 minutes after batching. VERIFI was used only for measuring the slump and temperature and it was not used for retaining the slump at target value, thus there was no water nor HRWR addition; therefore, the slump decreased over 90 minutes. In Figure 17, the results of manual measurements are compared with those recorded by VERIFI. The blue and red lines show the manual and VERIFI measurements, respectively.

The accuracy of VERIFI is defined as the degree of proximity of the VERIFI reading to the values manually measured by the technicians. The maximum, average, and standard deviation of spread are shown in Table 12. The maximum spread in measuring slump and temperature are 1.5-in. and 4.5 °F, respectively. Although the maximum spread value seems to be high, the average and standard deviation are lower. The standard deviation in measuring slump and temperature of concrete are 0.40-in. and 1.27 °F, respectively.

To have better perspective, the accuracy of VERIFI in different mixes is compared with the precision of manual measurement. The results show that the accuracy of VERIFI slump measurement is close to the precision of manual slump testing. The standard deviation in VERIFI measurements is 0.53-in. while the standard deviation of slump measurement by technicians is 0.24-in. The standard deviation of temperature measurement by VERIFI is 1.27 °F while that value in manual measurement is 0.62 °F. It should be noted that the precision of manual measurement obtained in this research is not a fair representative of the usual precision at job site. Expert technicians in the controlled laboratory conditions conducted the tests while many of the parameters cannot be controlled at job site, which result in lower precision. In addition, the second technician knew the result from the first technician. Therefore, it is expected to see higher variation and lower precision in measuring slump and temperature manually in real conditions at job site.

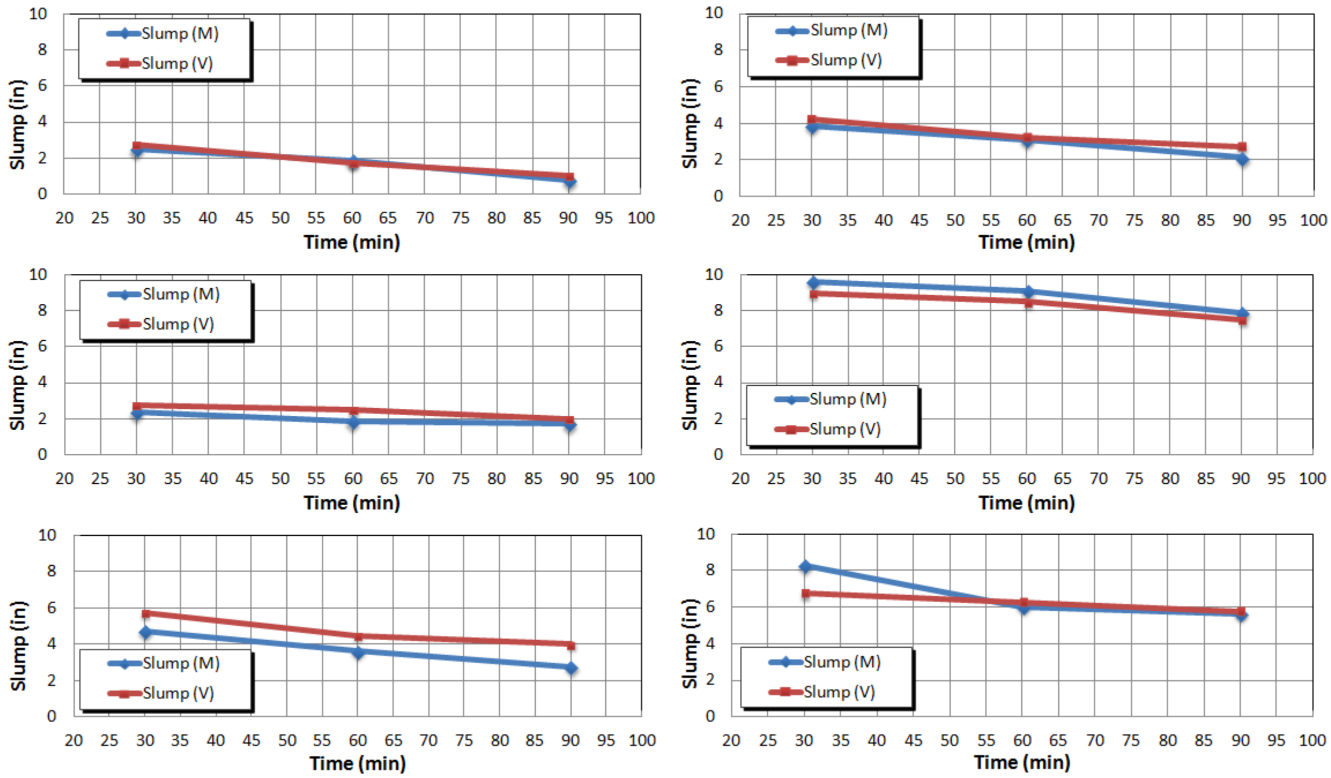


Figure 17- Comparing VERIFI and manual slump measurement in different mixes

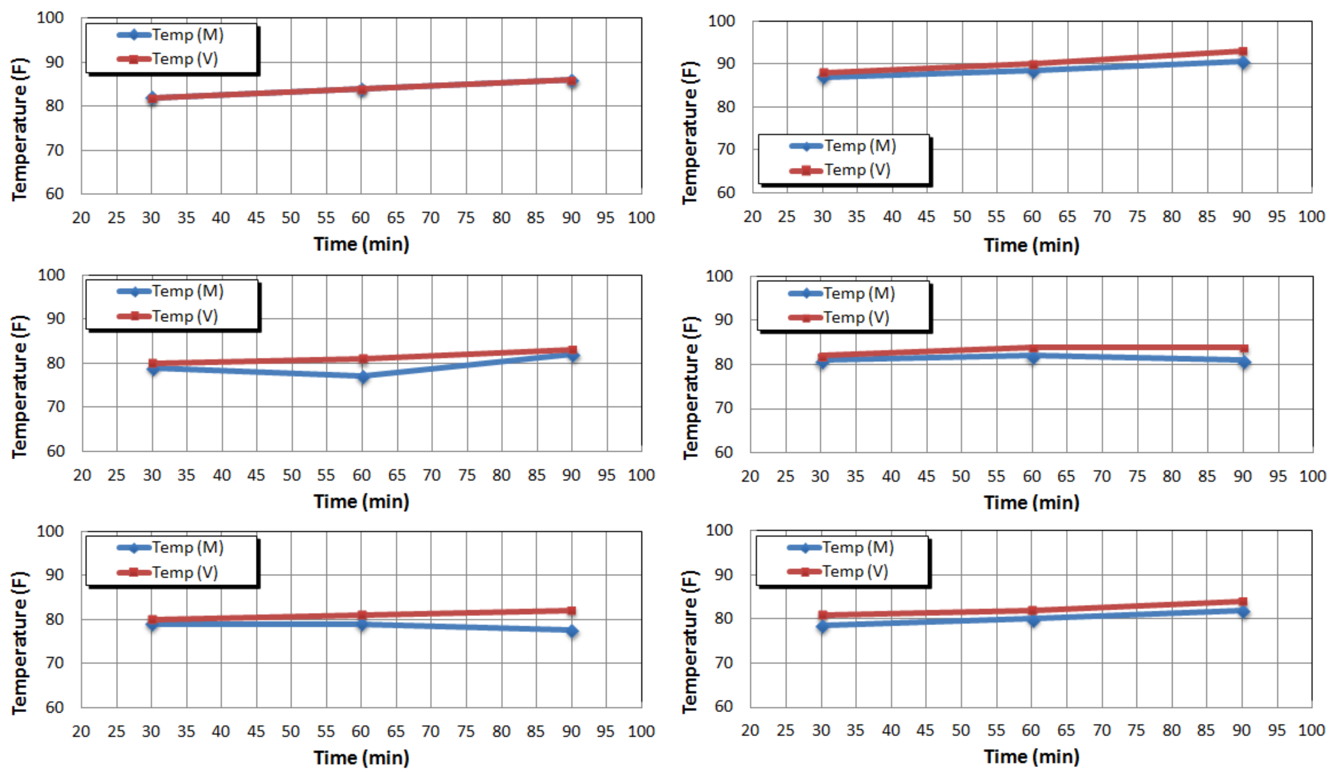


Figure 18- Comparing VERIFI and manually measured temperature in different mixes

Table 10- Comparing the accuracy of VERIFI measurements with manual measurements (Data of Task III)

	VERIFI Measurement*		Manual Measurement**	
Absolute Spread	**Slump**	**Temperature**	**Slump**	**Temperature**
Max	1.50 in.	4.50 °F	1.00 in.	2.00 °F
Ave	0.53 in.	1.72 °F	0.24 in.	0.44 °F
Standard Deviation	0.40 in.	1.27 °F	0.23 in.	0.62 °F

* *The difference between VERIFI and manual measurement*
** *The difference between two manual measurements*

6.2. Effect of the rheological properties on accuracy of slump measurement

The rheological properties of concrete are usually identified with Bingham model. A Bingham fluid has a linear relationship between shear stress and shear strain rate. This defines a plastic viscosity and a minimum stress, called yield stress, which is required to initiate flow. The slump of concrete is known to be related to the yield stress of concrete while the plastic viscosity governs the speed of concrete movement. The rheological properties of concrete or any other fluid can be measured by a rheometer.

VERIFI measures hydraulic pressure which is related to torque needed to rotate the drum of a truck mixer and use it for predicting slump. The mechanism used in VERIFI is very similar to the rheometer in which the force it exerts for rotating the vane is measured, which can be converted to a shear stress. Highly viscous mixes may affect the accuracy of measuring slump; therefore, the rheological properties of all concrete samples were determined by the ICAR rheometer to determine the effect of viscosity and yield stress on the accuracy of VERIFI.

The relation between yield stress of concrete that determined with the ICAR rheometer and the measured slump is depicted in Figure 19-a. The relation between plastic viscosity and slump is shown in Figure 19-b. As expected, slump is inversely related to yield stress, and no correlation was found between the plastic viscosity and slump.

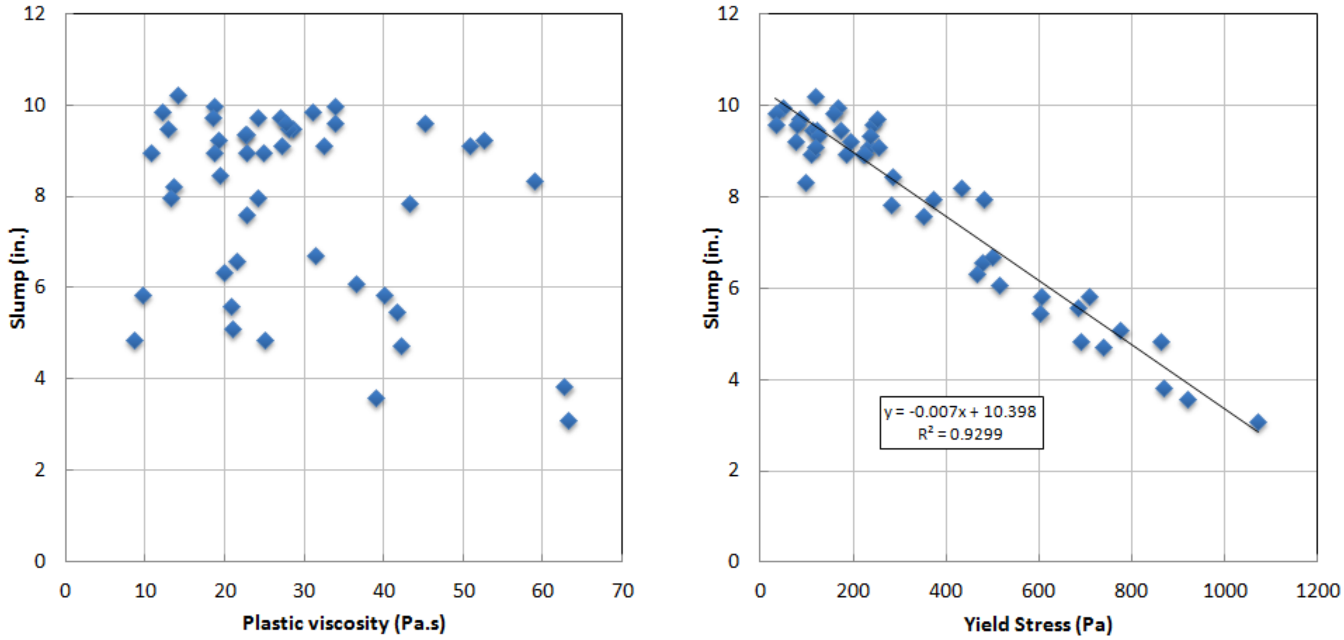


Figure 19- Relation between slump and rheological properties of concrete, a) plastic viscosity, b) yield stress

The spread of slump measurement versus the yield stress and plastic viscosity of concrete is shown in Figure 20. The plastic viscosity varied from 9 Pa.s to 63 Pa.s, and yield stress was from 33 Pa to 1072 Pa. VERIFI showed acceptable accuracy in slump measurement in this wide range of rheological properties.

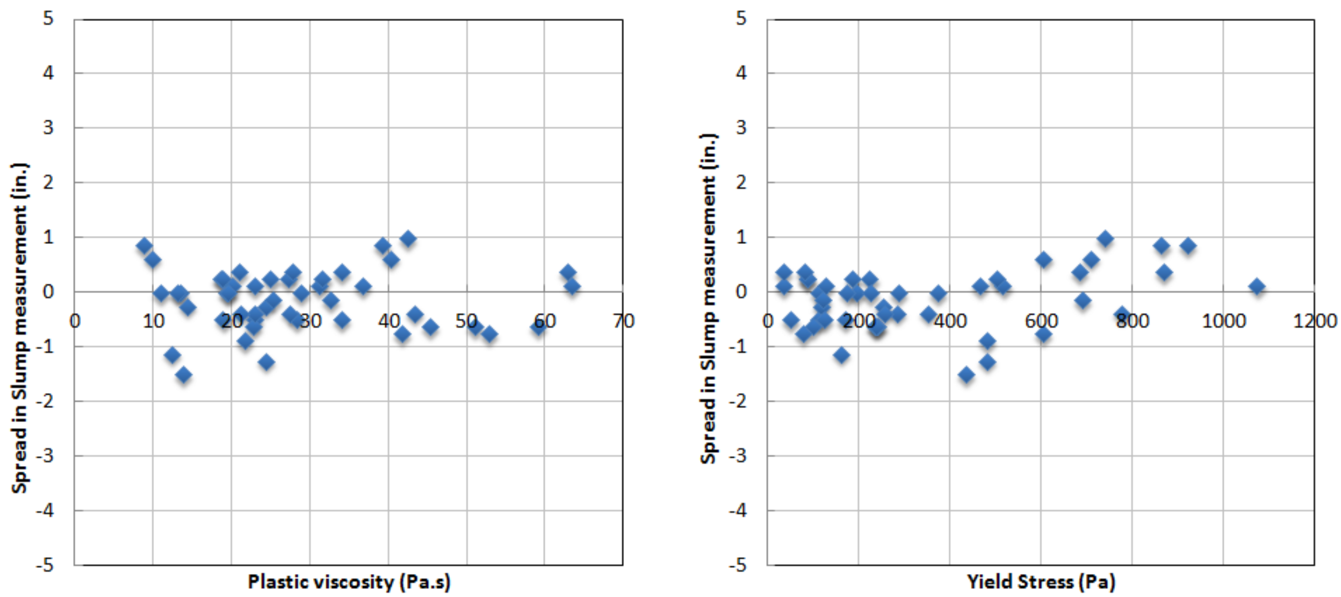


Figure 20- Relation between slump and rheological properties of concrete, a) plastic viscosity, b) yield stress

6.3. Analysis of temperature measurements

The temperature values of all the mixes measured in Task I to Task V are used here to evaluate the accuracy of VERIFI in recording the temperature of concrete in different conditions. In Figure 21, temperature readings recorded by VERIFI are plotted versus temperature measured by the technicians in accordance with ASTM C1064 (2012). The figure shows that the points are well scattered around the dashed line. The linear regression analysis of data reveals that the relation between VERIFI and manual temperature can be described as follows:

$T_v = 0.98\, T_m + 3.08$ Equation 1

where T_v is the temperature measured by the VERIFI system and T_m is the manually measured temperature. The coefficient of determination is R^2=0.91.

The slope of the regression line is very close to one (0.98). This shows that the multiplier error is negligible in measuring temperature of concrete. However, there is an offset error with magnitude of 3.08 ◦F. See Appendix B for details about multiplier and offset error. It should be noted that the constant term in regression analysis (3.08) shows the difference at origin (temperature = 0 ◦F), but when the temperature varies from 75 ◦F to 95 ◦F (that is the temperature range investigated in this study), the difference in regression line are reduced to 1.58 ◦F to 1.18 ◦F, respectively.

According to ASTM C1064 (2012), the multi-operator standard deviation of temperature readings on the same sample is 0.7 °F. Therefore, two tests conducted by different operators on the same material should not differ by more than 1.9 °F. Although most of the obtained readings were within this acceptable variation range, there was a few times in which the readings between manually measured temperature and the temperature recorded by VERIFI slightly varied. The possible reasons for this difference may be due to the fact that concrete was sampled from the top of the drum which was most likely cooler than the bottom part of the drum where the VERIFI sensor is located (Figure 22). Furthermore, at the time of discharge, concrete was in contact with the chute which was likely cooler than the drum. Moreover, concrete was poured and stored in a wheelbarrow which allows faster heat loss than the drum. Due to these factors, the some of the manual readings tested on the sampled concrete which was under different environmental condition might show slightly different readings compared to the VERIFI readings.

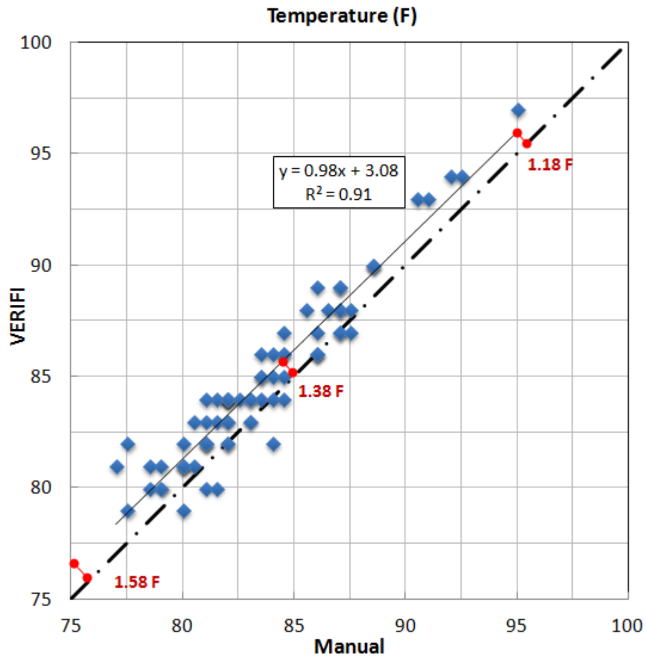


Figure 21- Relation between VERIFI and manually measured temperature

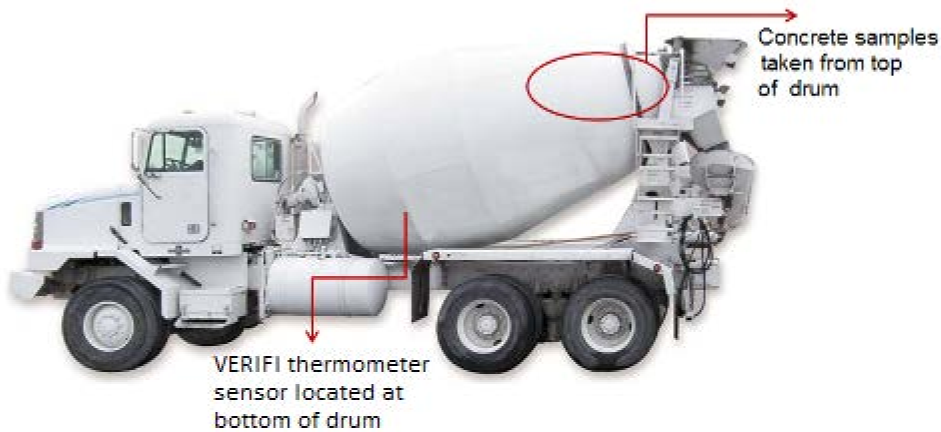


Figure 22- Concrete sampling and location of VERIFI thermometer sensor

6.4. Analysis of slump measurements

The relation between the slump values reported by VERIFI and manually measured slump is shown in Figure 23. The data points plotted in this figure were obtained by collecting the entire slump measurements conducted in Task I to Task V. Regression analysis of data gives the following linear relation between the VERIFI and manual slump readings:

$$S_v = 0.88\, S_m + 0.8 \qquad \textit{Equation 2}$$

Where S_v is the Slump measured by VERIFI system and S_m is the slump measured by technicians. The coefficient of determination for this data is R^2=0.97; therefore, linear regression well fits the current data. The regression analysis of data reveals that slump is overestimated in low slump concrete while it is underestimated in concrete with high slump values. In zero slump concrete, the spread is 0.80 in. that means VERIFI reported the slump 0.8-in. higher than the value measured by the technicians. On the other side, in flowable concrete with slump value of 10-in., VERIFI reported the slump 0.4-in. lower than the slump measured by the technicians. The difference between VERIFI readings and slump cone readings at the extreme slump values may be due to the fact that the slump cone test is not adequate to evaluate workability of concretes having slumps less than 0.50-in. and concretes with slumps greater than 9-in. The difference between VERIFI readings and the slump measured by the technicians was 0.44-in. for concrete with 3-in. of slump, and 0.44-in. for concrete with 7-in. of slump. The probability of having average spread larger than 0.56-in. is less than 5%.

The precision of slump and temperature measurements performed by two technicians on the same sample at the same time for the entire data set are given in Table 11. According to ASTM C143 (2013), the results of two properly conducted slump tests on the same material by two different operators should not differ from each other by more than 0.82, 1.10, and 1.50-in. for the obtained slumps of 1.2, 3.4, and 6.5-in., respectively. The obtained results of VERIFI and manual measurements are compared with the precision stated in ASTM C143 (2013). The comparison shows VERIFI accurately measures and records the slump, and the variations between slump cone and VERIFI readings are within the acceptable range stated in the ASTM standard. Therefore, it is concluded that VERIFI readings are reliable for measuring and recording the slump, thus it can be used for practical applications. It should also be noted that although the slump cone measurement may be affected by various factors during sampling and testing process, the VERIFI measurement would only encounter the testing error since no sampling is required in VERIFI measurements.

Table 11- Comparing accuracy of VERIFI and manual measurements (All collected data)

	VERIFI Measurement (Difference between VERIFI and Manual)		**Manual Measurement (Difference between two Manual Measurements)**	
Absolute Error	**Slump**	**Temperature**	**Slump**	**Temperature**
Max	1.50 in.	4.50 ◦F	1.00 in.	2.00 ◦F
Ave	0.47 in.	1.41 ◦F	0.24 in.	0.60 ◦F
Standard Deviation	0.37 in.	0.93 ◦F	0.22 in.	0.64 ◦F

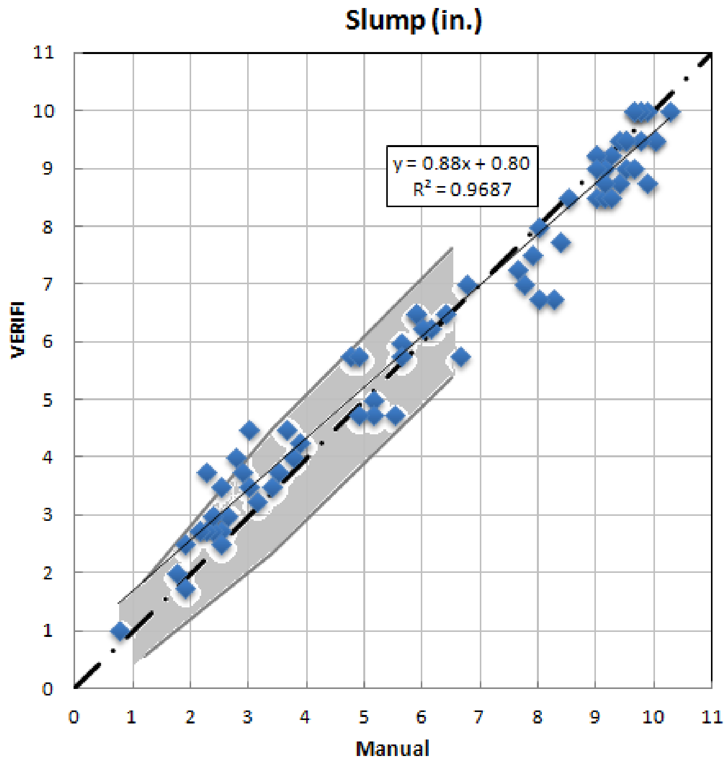


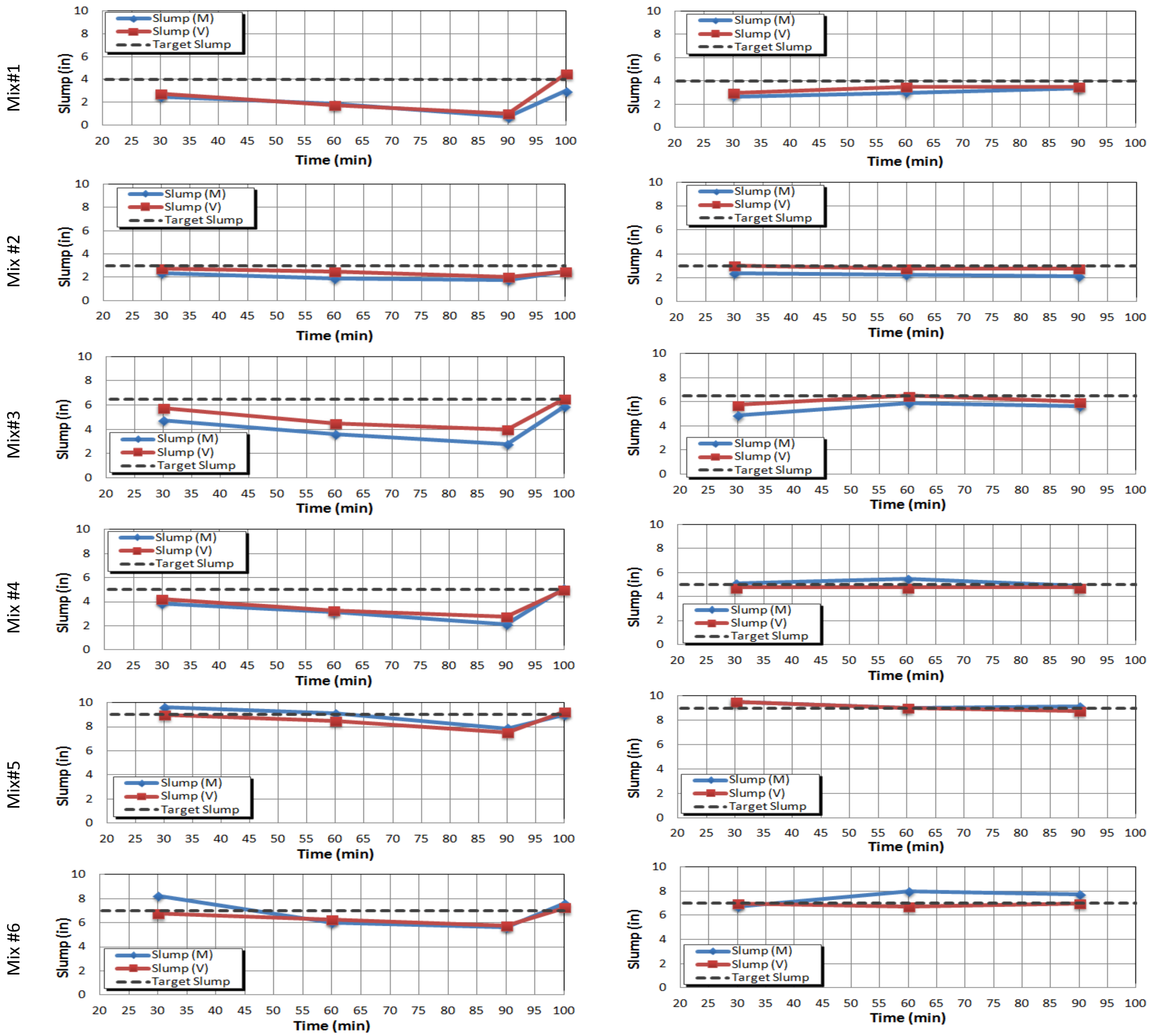
Figure **23**- Variation in slump measurement comparing to acceptable precision in ASTM C143 (shown by gray shaded area)

7. Slump adjustment in transit

One of the main features of VERIFI is its ability in retaining slump at target value at the plant, in transit, and at the jobsite, automatically and without the involvement of the driver. The results of Task IV and Task V will be used in this chapter to investigate the ability of VERIFI for automatic slump adjustment.

7.1. Slump adjustment in transit by water addition

In this section, the concrete properties of six mixes were compared between the case when water was automatically added by VERIFI in-transit and the case when water was added 90 minutes after batching to reach the target slump. For each mixture, two methods were analyzed. The first method was to simulate the conventional application where no slump adjustment is done in-transit until the arrival to the jobsite where slump is increased to the target value by adding water. In the second method for the same mix, VERIFI automatically calculated the required amount of water to maintain the slump at the desired value and added water through a truck-mounted nozzle directly to the center of the drum during transportation. Since concrete will have the target slump when the truck arrives to jobsite, no slump adjustment procedure is required upon arrival to the jobsite. The slump of concrete in both automatic VERIFI method and jobsite slump retention method (manual method) are illustrated in Figure 24. Red lines show VERIFI measurements and blue lines show manual slump measurements. Target slump is presented with dash line.



a) All water added at job site

b) Water addition in-transit (automatic VERIFI)

Figure 24- Slump adjustment in different mixes using one time addition method or automatic in-transit method

In Figure 29-a, the slump loss over time until the water addition at 90 minutes is observed. In this method, the required water for increasing the slump to the desired value was estimated based on the assumption that 1 gal/yd^3 of water is needed for 1-in. slump increment. The slump reported by VERIFI was used to estimate the required water content. After the addition of water, concrete was mixed for 15 revolutions at high speed to make sure that the added water is fully mixed and concrete is homogeneous. When the added water did not result in increasing the slump up to the target value, more water was added until reaching target slump. The non-automatic slump retention procedure, described above, took about 10 minutes to accomplish. Therefore, the final sample was taken about 90+10 minutes after batching.

In Figure 29-b, VERIFI maintained slump automatically by the addition of water in-transit, thus the slump of all the mixes were close to target slump during the testing period. Therefore, no extra effort was required to adjust slump at 90 minutes after batching which represents the arrival to jobsite.

The target slump of mixes varied from 3-in. up to 9-in. Maximum difference between manually measured and target slumps are 1.62-in. The average and standard deviation of difference between measured and target slumps are 0.66-in. and 0.42-in., respectively. Note that, concrete slump should be close to target value at discharge time when truck mixer arrives to site and the deviation during transportation is not so important. The results show that in all mixes the difference between slump of delivered concrete and the target slump is less than 1-inch.

The deviations from the target slump at discharge time are compared between two slump adjustment method in Figure 25 and Table 12. In all cases except Mix #5, the deviation from target slump in automatic in-transit slump retention method was lower than or equal to the deviation observed in non-automatic method. Maximum, average and standard deviation of difference between target and measured slump in automatic slump retention method are 0.88 in., 0.54 in. and 0.35 in., respectively. The corresponding values in non-automatic slump retention method are 1.00 in., 0. 84 in. and 0.37 in., respectively. The results show that the accuracy of VERIFI system in automatic slump retention is close to the accuracy of non-automatic slump retention. The benefit of VERIFI system is that no extra effort is needed to adjust the slump when concrete delivers to job site. It is worth also noting that, the non-automatic water addition was performed herein in controlled laboratory conditions. We could expect higher variation from target slump in non-automatic slump retention in ordinary job sites. The goal of this part of the research was to be able to compare concrete properties at the same final slump, not to evaluate typical variation of slump in the field.

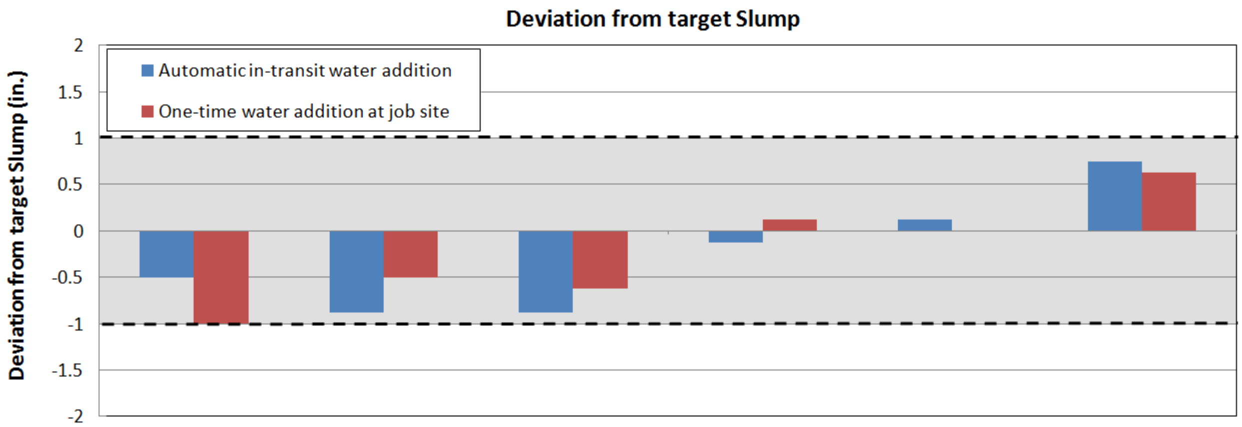


Figure 25- Deviation from target slump at delivery time

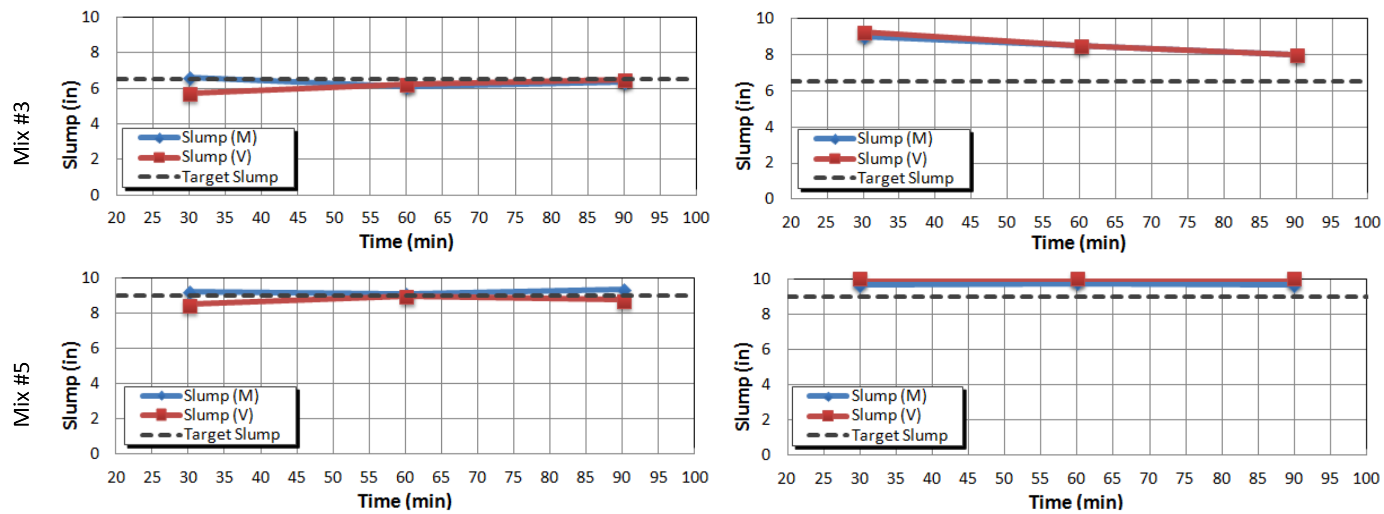
Table 12- Deviation from target slump in automatic or non-automatic water addition method

Mix #	Batch #	Slump retention Method	Slump		
			Target	Measured	Difference
1	2	Water Addition at the End	4	3	-1
	11	Automatic Water addition	4	3.5	-0.5
2	7	Water Addition at the End	3	2.5	-0.5
	12	Automatic Water addition	3	2.125	-0.875
3	8	Water Addition at the End	6.5	5.875	-0.625
	13	Automatic Water addition	6.5	5.625	-0.875
4	9	Water Addition at the End	5	5.125	0.125
	14	Automatic Water addition	5	4.875	-0.125
5	4	Water Addition at the End	9	9	0
	15	Automatic Water addition	9	9.125	0.125
6	10	Water Addition at the End	7	7.625	0.625
	16	Automatic Water addition	7	7.75	0.75

The results presented in this chapter confirm that VERIFI is able to automatically maintain the slump of concrete by the addition of water in-transit and deliver concrete at the specified target slump. The average of deviation from target slump is about 0.5 in., which is acceptable in many applications.

7.2. Slump adjustment by HRWR addition

In this chapter, the feasibility of automatic addition of HRWR for slump retention is presented and discussed. The results of automatic HRWR addition are compared with the non-automatic method in which all admixtures are added at the batch plant. Figure 26 compares VERIFI versus non-automatic slump retention in Mix #3 and Mix #5. The chart presented in Figure 26-b shows that HRWR could be used for slump retention both in-transit and at the time of delivery since both Mix #3 and Mix #5 had the slump values that were very close to the target slump. However, when HRWR was added at the batch plant, the slump values through the entire testing period were not close to the target value. It is a common application to batch concrete at high slump and let it lose slump over time. However, as it is presented in Figure 26-b, since the rate of slump loss depends on the environmental conditions including the temperature and humidity, it is challenging to batch concrete with the right amount of admixture dosage so that the target slump will be obtained at the time of delivery. Maximum, standard deviation, and average of deviation from target slump are given in Table 13.



a) All HRWR added at batching plant (non-automatic) b) HRWR addition during transportation (automatic)

Figure 26- Automatic and non-automatic slump retention using HRWR addition

Table 13- Statistical analysis of deviation from target slump in automatic HRWR addition

Slump Difference	Automatic HRWR addition
Max (Abs)	0.38 in.
Ave (Abs)	0.23 in.
Standard Deviation (Abs)	0.12 in.

8. Effects of in-transit water and admixture addition on concrete properties

The ready mixed concrete supplier designs the concrete mixture to ensure the specified performance criteria are met at final discharge, including the addition of water and admixture after batching. The addition of water and/or chemical admixture will affect the fresh and hardened concrete properties, such as reducing strength and durability (water only), altering air content and setting time, or increasing the risk of segregation. In this chapter, the total amount of water or HRWR added automatically by VERIFI during transportation will be compared with the water added at the jobsite or extra HRWR added at the plant for slump retention until the jobsite. The effect of water or HRWR addition on compressive strength will be discussed. Furthermore, the effect of automatic water/HRWR addition by VERIFI on air content will be discussed.

8.1. Water content measurement and calibration

The amount of water added for slump retention is of great importance because it will increase the w/c, which in turn deteriorate the mechanical properties. Therefore, the total amount of water added in-transit or at jobsite is restricted to a certain limit. This allowable limit is specified in the mixture proportions based on the project specifications. When the other parameters are kept constant, lower the amount of water added to concrete corresponds to a higher strength. All of the VERIFI equipped trucks have a tank of water and a connected flow-meter. The flow-meter is used for measuring and recording the water added to concrete (See Figure 27). The flow-meter calibration was checked to make sure that the amount of water added to concrete is equal to the actual water content reported by VERIFI.

The results presented in Table 14 show that the maximum difference between the water measured by VERIFI and the water measured manually is about 1.5% which is within the acceptable variation of ±3% of the added water (ASTM C94, 2013).

The microwave test, as described in Section 4.1, was also used to determine the water content of fresh concrete. Even though this test method is acceptable for measurement of total water content of concrete, it is not accurate enough for determining the water added to concrete for retaining the slump due to the low repeatability and high sensitivity of the sampling procedure. The total water content of concrete is about 30-40 gal/yd^3 while the water usually added for slump retention is in the range of 1-4 gal/yd^3. The high variation of water content measurement by microwave oven test were also reported previously in the literature [5-7]. Therefore, the amount of added water is measured by the flow meter installed on the trucks.

Figure 27- VERIFI water addition and flow meter system

Table 14- Accuracy of VERIFI water addition equipment

Measured by VERIFI Flow-meter	Measured Manually	Difference (M-V)	
(Gal)	(Gal)	(Gal)	%
9.54	9.50	-0.047	-0.49
2.53	2.49	-0.038	-1.52
17.55	17.39	-0.16	-0.91
2.52	2.54	0.016	0.63
6.55	6.52	-0.033	-0.50
9.53	9.46	-0.065	-0.69

8.2. Water added for slump adjustment

Figure 28 compares the water gradually added automatically by VERIFI in transit with the water added as a one-time addition at the end in non-VERIFI method. For all the mixes, the amount of water added automatically by VERIFI gradually in transit is lower or equal to the water added as a one-time addition at jobsite in non-VERIFI method. Since the properties of hardened concrete are greatly affected by the water-to-cementitious ratio, it is expected that when VERIFI is used for slump retention, the properties of concrete will be better or equal to the concrete in which all of the water is added as a one-time addition at the jobsite.

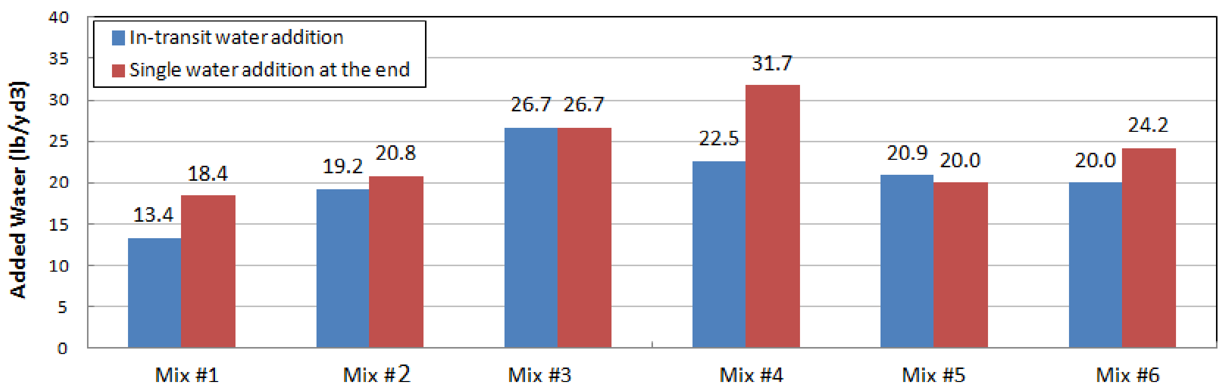


Figure 28- Comparing water required for slump retention

8.3. Effect on compressive strength

The compressive strength of all the mixes was tested at 3 and 28 days after casting excluding Mix #1 and Mix #6 which were tested at 3 and 14 days according to the IDOT specifications. For mixes with a one-time addition of water at the jobsite, samples were taken before and after the addition of water. The compressive strength results at 28 days (or 14 days in Mix #1 and #6) are compared with the design compressive strength in Figure 29. The required compressive strength values are shown with dashed line. The results show that the compressive strength of all the mixes is higher than the specified compressive strength. As expected, compressive strength is reduced after the addition of water. However, the reduction in compressive strength is lower when VERIFI is used to automatically retain slump at target value compared to the one-time addition of water at the end to achieve the same slump target. Therefore, from the compressive strength point of view, due to its lower water requirement for slump retention, VERIFI mode of adding water in transit is better than the conventional method for adding water as a one-time addition at the jobsite.

Table 15- Compressive strength of concrete

Mix #	Batch #	Slump retention Method	compressive strength (3 days, psi) Before Water Addition*	compressive strength (3 days, psi) After Water Addition	compressive strength (3 days, psi) reduction after slump retention	compressive strength (28 or 14 days, psi) Before Water Addition*	compressive strength (28 or 14 days, psi) After Water Addition	compressive strength (28 or 14 days, psi) reduction after slump retention	Required Compressive Strength (psi)
1	2	Water Addition at the End	4760	3050	-36%	6970	4590	-34%	3500 at 14 days
	11	Automatic Water addition		4130	-13%		6070	-13%	
2	7	Water Addition at the End	5870	4670	-20%	7,840	6,800	-13%	4000 at 28 days
	12	Automatic Water addition		6180	+5%		8,330	+6%	
3	8	Water Addition at the End	4,250	3,070	-28%	6,260	4,670	-25%	4000 at 28 days
	13	Automatic Water addition		4,550	+7%		7,030	+12%	
4	9	Water Addition at the End	5830	4880	-16%	9,760	8,640	-11%	6000 at 28 days
	14	Automatic Water addition		5150	-12%		8,600	-12%	
5	4	Water Addition at the End	7800	7250	-7%	11,140	10,520	-6%	8750 at 28 days
	15	Automatic Water addition		6690	-14%		10,770	-3%	
6	10	Water Addition at the End	5380	3820	-29%	6820	5780	-15%	4000 at 14 days
	16	Automatic Water addition		**4650**	**-14%**		**6060**	**-11%**	

**measured on mix with water added at end*

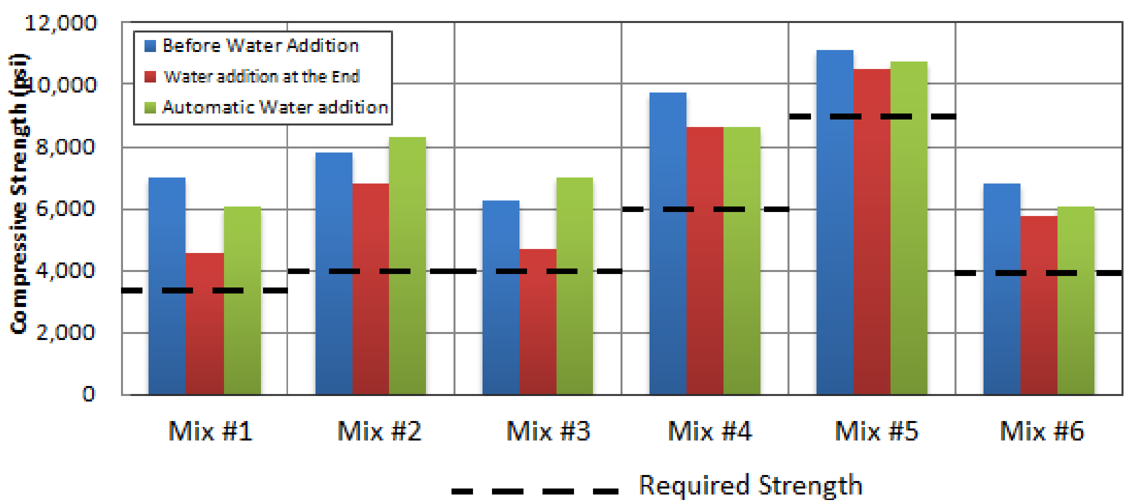


Figure 29- Comparing compressive strength of concrete samples with the required strength

8.4. Effect on air content

The results of the air content of fresh concrete and the specified air content requirement for each mix are provided in Table 16. To reach the target air content, a certain dosage of air-entraining admixture was used at the time of batching. Since air content affects the compressive strength and durability, it is desirable to deliver the concrete with the specified air content. Therefore, the slump retention method should not affect the air content of concrete.

Table 16- Air content of concrete with and without slump retention

Mix #	Comments	Air content (%) 30	60	90	Variation	Required Air Content (%)
1	without slump retention	7.1%	5.5%	4.5%	2.6%	5-8%
	Automatic Water addition	6.5%	6.4%	5.9%	0.6%	
2	without slump retention	6.3%	6.3%	5.1%	1.2%	5-8%
	Automatic Water addition	3.4%	4.0%	3.7%	0.6%	
3	without slump retention	6.3%	5.1%	5.0%	1.3%	4.5-7.5%
	Automatic Water addition	6.5%	7.3%	7.6%	1.1%	
	Automatic Admixture Addition	5.5%	5.1%	4.5%	1.0%	
4	without slump retention	1.5%	1.3%	1.6%	0.3%	0-3%
	Automatic Water addition	1.8%	1.6%	1.4%	0.4%	
5	without slump retention	1.2%	1.2%	1.4%	0.2%	0-3%
	Automatic Water addition	1.0%	1.0%	1.0%	0.0%	
	Automatic Admixture Addition	1.0%	0.8%	0.9%	0.2%	
6	without slump retention	5.6%	4.5%	4.1%	1.5%	5-8%
	Automatic Water addition	5.0%	4.1%	4.0%	1.0%	

The addition of water or HRWR during transportation may affect the air content of fresh concrete. The variation of air content in different mixes is presented in Figure 30. The specified range of air content is also shown with dashed line. The variation of air content in those mixes without any slump retention is also presented. According to the obtained results, the variations in air content of concrete are very similar to the variations of air content when no slump retention was applied on concrete. Therefore, the VERIFI slump retention has negligible effect on air content of concrete. Note that we are looking at the change in air over time, not the absolute value of air content. The initial air content could vary from batch to batch even in the same mix. Therefore, if air is outside the specified range, this should be corrected during batching.

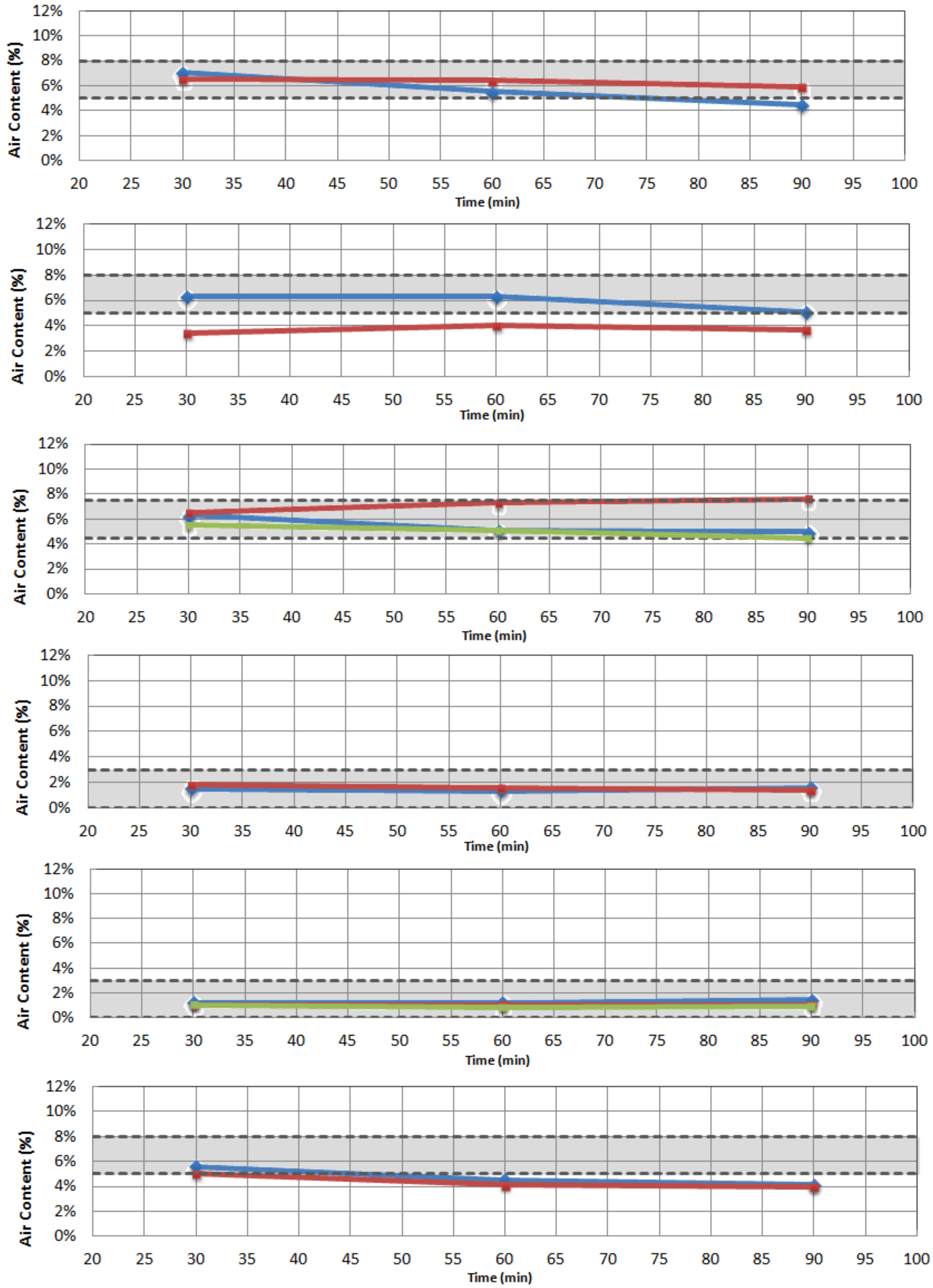


Figure 30- Variation of air content during transportation and at delivery time (Red = automated water addition, blue = water addition at end, green = automated admixture addition)

9. Conclusion

In this research, different aspects of the automated measurement of concrete properties by VERIFI have been investigated through extensive experimental program. Twenty concrete batches with a total volume of more than 120 cubic yard were examined to evaluate the repeatability, measurement accuracy, and slump retention ability of VERIFI. The obtained findings are summarized in the following sections.

9.1. Repeatability

The results obtained in this research showed that VERIFI measures the slump and temperature of concrete in different truck mixers or with different load size with an acceptable precision. The average spread in slump and temperature measurements are 0.35-in. and 1.26 °F, respectively.

9.2. Measurement accuracy

The accuracy of VERIFI in measuring slump and temperature of concrete were investigated in different mixes. The accuracy of measurement is defined as the degree of proximity of the VERIFI reading to the values manually measured by technicians.

- **Accuracy of temperature measurement:** The statistical analysis of the temperature measurement shows that the temperature measured by the VERIFI sensor is approximately 1.0°F to 1.5°F higher than the temperature measured by the technicians in accordance with the ASTM C1064, and is within the acceptable variation limit.
- **Accuracy of slump measurement:** The standard deviation of spreads in slump measurement, which shows how much variation from the true slump exists, is 0.37 inches. The average of errors was found to be 0.47 inches. Moreover, the confidence interval analysis reveals that the probability of having average error larger than 0.56 inches is less than 5%. These error bound are practically acceptable in many construction related applications. The regression analysis of all measured slump shows that the accuracy of VERIFI slump measurements is within the acceptable multi-laboratory precision of slump measurement given in ASTM C143. In other words, the accuracy of VERIFI slump measurement is approximately the same as precision of performing consecutive tests by expert experimenters on the same sample.

9.3. Slump adjustment

VERIFI maintains the slump automatically by adding water and/or HRWR within the specified limits. The average and standard deviation of difference between measured and target slumps at delivery time are 0.66 inches and 0.42 inches, respectively. The automated VERIFI method have also compared with non-automatic method in which the amount of extra HRWR or extra water were estimated by expert engineers and added entirely at batching plant or at job site. In almost all cases, the deviation from target slump in automatic slump retention method was lower than or equal to the deviation observed in non-automatic method. Both water and HRWR addition by VERIFI were able to retain the slump at the target value.

9.4. Effects of in-transit additions on concrete properties

The addition of water and/or chemical admixtures for increasing the slump and compensating the slump loss over time may affect the properties of fresh and hardened concrete. Therefore, the effect of automated water/HRWR additions by VERIFI in-transit on fresh and hardened concrete properties was investigated to ensure that the overall concrete performance is not sacrificed while meeting the workability requirements.

- **Water addition:** The comparison between the VERIFI method of in-transit additions with the non-VERIFI method of a one-time addition at the jobsite for slump retention shows that the amount of total water added in-transit by VERIFI is lower or equal to the water added at jobsite. In both methods, the total water content was kept lower than the specified maximum allowable water content.
- **Compressive strength:** The compressive strength results between the automated VERIFI in transit additions and the non-VERIFI mode of adding all water as a one-time addition at the jobsite were compared. As expected, the addition of water to retain the slump at target value reduced the compressive strength of concrete. The average reduction in compressive strength was 36% when water was added at jobsite whereas it was 14% when water added gradually by VERIFI. The reason of having higher compressive strength in the samples taken from the batch in which the VERIFI system was used comparing to the batch in which all water add once at jobsite is due to the lower amount of water requirement by VERIFI for slump retention. All compressive strengths were greater than the design requirement.

- **Air content:** The obtained results showed that the variations of air content in-transit when VERIFI method for slump retention was used to add water or admixture gradually in-transit were less than the variations of air content in concrete without retempering. The average of air content variation was less than 1% which is within the prescribed range specified in mixture proportioning. Therefore, it is concluded that VERIFI does not affect the air content of concrete in both air-entrained and non-air entrained concrete.

9.5. Concluding remarks

The following bullet points describe the essence of this research and highlight the main findings.

- **Is VERIFI able to measure slump and temperature accurately?**
    - VERIFI is able to measure the slump of concrete with an average error of 0.5-in. which is within the acceptable limit of the slump test.
    - VERIFI is able to accurately measure the temperature of concrete as the average error in measuring temperature was found to be about 1.5 °F, which is within the acceptable range of variation.

- **Is VERIFI able to retain the slump of concrete and deliver it at target slump?**
    - Both automated water and HRWR addition were found to work efficiently for maintaining slump within target.
    - The probability of having average deviation from target slump at delivery time higher than 0.56 inches is 5% (95% confidence interval).

- **What are the effects of using VERIFI in-transit addition of water or admixture for slump retention?**
    - The reduction in compressive strength is lower when VERIFI was used to automatically add water gradually in transit to maintain slump at target value compared to the non-VERIFI method of adding water to adjust slump only at the jobsite since VERIFI method requires lower water content to achieve the same slump.
    - In all cases, the compressive strength after water addition was higher than the specified strength because the total water content was kept below the maximum allowable limit.
    - VERIFI addition of water and admixture in transit did not affect the air content of both entrained and non-entrained concrete.

- **What are the benefits of using VERIFI in the ready mix industry?**
  - It is not uncommon in concrete industry for the contractor to add water at jobsite prior to discharging to increase the slump and improve the workability of the concrete. VERIFI retains concrete slump automatically by water and/or chemical admixture addition in-transit. Therefore, no extra effort is required to adjust the slump of concrete upon arrival of the truck to jobsite.
  - All water or HRWR added to concrete during transportation or at the jobsite is measured and recorded automatically and can be controlled through an online web-based application that makes the quality control (QC)/ quality assurance (QA) procedure easier to perform.
  - The amount of added water and the variation of the delivered slump are reduced when VERIFI slump management system is used. Therefore, the risk of delivering concrete having slump above the maximum allowable slump or exceeding the maximum allowable water-to-cementitious ratio is decreased.
  - The uniformity of concrete production and the control of concrete properties are improved when VERIFI is used. Moreover, the hardened properties are expected to be improved since lower amount of water is added in VERIFI slump retention method. The amount of water and/or admixture addition is also recorded and can be monitored in real-time online during the construction process.

- **What are the benefits to DOTs?**
  - Every load is recorded to ensure compliance with specifications. Measurements of slump, temperature, mixing, time of discharge, and water content are made.
  - The amount of water is controlled accurately on all loads to ensure hardened concrete performance. The amount of water added on the truck is recorded with a flow meter on the truck and water additions can be stopped upon reaching the maximum water content.
  - Testing costs can be reduced by using automated measurements since no manual slump measurement is required to determine the workability of fresh concrete after trucks arrive to job site.

- **Future work suggested for further research**
  - Weather condition may affect the rate of slump loss and water demand for slump compensation. Higher amount of water are usually required for slump retention in

hot environment which could affect efficiency of VERIFI system. The current research was conducted in Chicago, IL where ambient temperature during the testing period ranged between 70°F and 90°F. It is recommended to investigate the efficiency of VERIFI in extreme weather conditions in which concrete usually have higher rate of slump loss.

- This research was performed on various normal weight concrete mixes with the specified target slump of 2 to10-in. The unit weight of concrete will may affect the hydraulic forces required for rotating the drum of concrete mixers. The lightweight aggregate concrete (LWAC) and highly flowable concrete such as self-consolidating concrete (SCC) may require a different calibration curve, thus the efficiency of VERIFI measurements on these types of concrete should be investigated.
- The reduced impact of uncertainties make it possible to optimize the design procedure based on the reduced uncertainties in real structures. It is therefore recommended to setup a database of performance of VERIFI system in different job sites and use it for risk analysis of concrete production in ready mix industries. This database could be used for establishing a new acceptance/rejection criteria for delivered concrete also revising safety factor associated with concrete production.

9.6. Recommendations

The results of this research indicate that 1) VERIFI is able to accurately measure concrete slump and temperature in the truck, 2) VERIFI is able to adjust slump automatically to target by adding water and admixture, and 3) adding water in transit instead of at the jobsite or plant does not negatively affect concrete performance. Compared to current industry practices, VERIFI provides more accurate and complete documentation of concrete properties, including all additions of water, so that engineers and inspectors can confirm whether concrete meets specification. Therefore, VERIFI can be allowed to add water and admixture during transit instead of a one-time addition at the jobsite. In addition, data from VERIFI can be used for acceptance purposes.

10. Acknowledgment

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Appendix A

Precision and Accuracy of VERIFI Measurement

The repeatability or precision of the VERIFI measurement system is the degree to which repeated measurements under unchanged conditions show the same results. Therefore, what is important in repeatability is the proximity of a result of a test to the results of other consecutive repeated tests on the same mixture. On the other side, the accuracy of a system is the degree of closeness of measurements of slump and temperature to the actual or true value. Precision with respect to mean value and accuracy with respect to true value are schematically depicted in Figure 31.

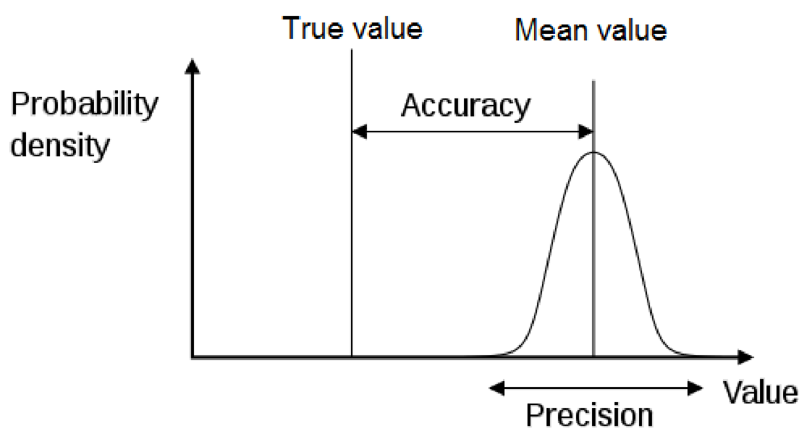

Figure 31- Schematic representation of precision and accuracy

The VERIFI measurement is precise if and only if the results of two or more consecutive measurements are close together. Regarding this definition, the deviation from the mean value of test results is important in evaluating the precision of VERIFI measurement. Therefore, the real or true value of slump and temperature measurement is not used in determining precision of VERIFI system. On the other hand, the accuracy is defined in respect to real or true value and without having the actual or true values, the accuracy is meaningless.

The true value of slump and temperature are assumed to be those values measured manually by experimenters according to related ASTM standards. It might be controversial because any test has an error in measurement that could be caused by sampling, performing, reading, calibration issue and etc that cannot be eliminated entirely. Therefore, the manually measured slump or temperature does not exactly reflect the true value and the error is included in the measured value. Nevertheless, the results of standard tests are generally accepted as an indicator of concrete properties and are usually used for evaluating and accepting/rejecting the delivered concrete at job site. Therefore, the accuracy of slump and temperature measured by VERIFI system is defined with respect to these values which are measured manually according to ASTM standards.

Systematic and random errors

Systematic errors in experimental observations usually come from the measuring instruments. They may occur because there is something wrong with the measuring instrument, or because the instrument is wrongly used by the experimenter. Systematic errors are contrasted with random errors. While the former usually caused by unknown and unpredictable changes in the experiment, the latter is generally, come from the instruments. The systematic error, therefore, could be reduced significantly by calibrating the measurement instrument.

Two types of systematic error can occur with instruments having a linear response:

- **Offset error** in which the instrument does not read zero when the quantity to be measured is zero
- **Multiplier error** in which the instrument consistently reads changes in the quantity to be measured greater or less than the actual changes.

The systematic errors are schematically shown in Figure 32. The dashed line shows the line with slop of one in which the system measurement is exactly equal to true value. Any deviation from this line shows an error in measurement system.

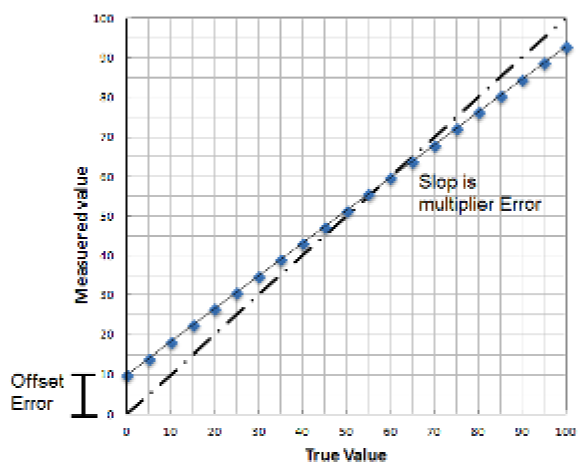

Figure 32- Systematic error in linear measurement system