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FIELD MEASUREMENT OF WATER-CEMENT RATIO FOR PORTLAND CEMENT CONCRETE PHASE I – EVALUATION OF EXISTING TECHNOLOGIES

FINAL REPORT

WISCONSIN DEPARTMENT OF TRANSPORTATION
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Field Measurement of Water-Cement Ratio for Portland Cement Concrete Phase I – Evaluation of Existing Technologies

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by

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16. Abstract

A rapid, portable, and accurate assessment of water-cement ratio of plastic concrete would provide the Wisconsin DOT and paving contractors with a quality assessment tool for strength and durability. Such a tool would provide a means to monitor quality and to invoke changes in concrete mixes in a timely manner before extensive quanitities of concrete are placed. The laboratory study described in this report identified existing technologies for field measurement of water-cement ratio and evaluated the most promising technologies in the laboratory. Two methods were examined, the Microwave Oven Method and the Troxler Nuclear Water-Cement Gauge. The laboratory evaluation consisted of a 27-mix test plan that included three mix types, three levels of temperature, and three levels of water-cement ratio. Under laboratory conditions, the Microwave Oven Method was capable of measuring water content with standard errors of 6.8 kg/m^3 to 13.5 kg/m^3 corresponding to a water-cement ratio error of 0.02 to 0.04. The water content errors for the Nuclear Gauge ranged from 6.4 kg/m^3 to 11.5 kg/m^3 and the cement content errors ranged from 3.8 kg/m^3 to 7.5 kg/m^3. These errors corresponded to water-cement ratio standard errors of 0.02 to 0.04. These errors can be tracked to a variety of sources that include concrete sampling issues as well as the operation of each method. Neither method is sufficiently developed to be used as a sole source for quality control in concrete paving, but each method shows considerable promise for further refinement. If the field use of these devices present no new challenges, then each method in its current form shows promise for use as supplementary quality control methods.

17. Key Words Portland Cement Concrete, Water Content, Cement Content, Water-cement Ratio, Field Measurement		18. Distribution Statement Unlimited	
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1. PROBLEM STATEMENT

During construction of Portland Cement Concrete (PCC) highway pavements, a target water-cement ratio is defined and the corresponding water and cement contents are proportioned at a batch plant. Batch weights are recorded at the plant as the trucks are loaded, are commonly used to ascertain the water-cement ratio of the in-place concrete. Discrepancies between the target water-cement ratio and the in-place concrete, however, can occur due to 1) errors during batching or 2) changes in water-cement ratio that occur between the batch plant and the time of placement. These changes can be caused by factors such as unexpected aggregate moisture content, extreme weather conditions, or on-site water addition to increase workability.

The Wisconsin DOT could benefit from a rapid field method that could verify, on-site, that concrete was properly prepared and quantify the extent the water-cement ratio matches that called for in specifications. Such a method can also assess uniformity between batches, which could ultimately reduce the amount of required compression tests and other means of on-site quality control. Moreover, a reliable field method that measures water-cement ratio of fresh concrete can provide quantitative information that can be directly correlated to hardened concrete performance. Accurate determination of water-cement ratio of concrete, while still in its plastic state, can significantly enhance the performance of the hardened concrete by providing quality control information at a time when changes to concrete being placed can still be made. *Is there a rapid and reliable test method that can be readily implemented in the field to determine water-cement ratio of fresh concrete?*

2. OBJECTIVES AND SCOPE OF STUDY

The results of this study are being offered to assist the Wisconsin Department of Transportation and the concrete pavement industry in achieving a higher level of quality control at the time of paving. In order for a method to function as a primary or sole means quality assessment of hardened concrete performance, the authors believe that determination of the water-cement ratio with a standard error of 0.01 or less is ideal. But even with higher errors, a reliable field method to measure water-cement ratio could enhance current quality control methods with quantitative information. Furthermore, the method must be practical and durable for field use. To determine the availability of a rapid and reliable test method that can determine water-cement ratio of fresh concrete in the field, three main tasks were undertaken:

A) Identify methods that measure water-cement ratio of fresh concrete and current practices.
B) Implement a laboratory test plan that determines the degree of accuracy achievable by potential field methods that measure water-cement ratio.
C) Implement a test plan that determines the effect of environmental conditions and potential construction factors on methods that measure water-cement ratio.

Laboratory assessment took place at the University of Wisconsin-Madison Structures and Materials Testing Laboratory. The 27-mix plan consisted of three mix types - labeled as types A, FA, and FA30 – which were based on proportions given in the *State of Wisconsin*

Department of Transportation Standard Specifications for Highway and Structure Construction-1996. The FA mix includes a 19% replacement of total cementitious content with fly ash, while the FA30 mixes included a 30% replacement. The mix plan also included three levels of water-cement ratio: w/c = 0.32, w/c = 0.40, and w/c = 0.48, as well as three levels of temperature of materials and environment during mixing: 10°C, 21°C, and 32°C. Tests were conducted at 15 and 45 minutes after addition of water to the batch. This study examined the effectiveness of methods only within laboratory conditions. Field tests will need to be conducted in future studies to accurately assess field reliability.

3. LITERATURE SEARCH SUMMARY

By conducting a comprehensive literature search of available technologies, as well as surveying various DOT agencies, the available methods for water-cement ratio determination in the field were identified and a preliminary assessment was completed. The Microwave Oven Method and the Troxler Water-Cement Gauge were chosen as the most promising techniques available, and were selected for evaluation under laboratory conditions.

Under laboratory conditions we investigated the effects of hold time, temperature, and changes in cementitious content on the nuclear gauge and the microwave oven method. None of the previous studies have conducted the number of tests, explored the sources of variability, and looked at calibration methods as we have. Appendix 3A includes survey results and Appendix 4A summarizes advantages and disadvantages for available methods.

3.1 PREVIOUS STUDIES: TROXLER WATER-CEMENT GAUGE

Few published studies have been performed on the Troxler Water-Cement Gauge. The Illinois Dept. of Transportation and the University of Illinois were recently conducting a study but a report from this study has not been available. Nagi and Whiting (1999), and the Highway Innovative Technology Evaluation Center (HITEC) investigated the gauge in 1996 (HITEC, 1996). HITEC estimated that readings can be obtained in approximately 10 minutes. According to the HITEC study, the gauge was capable of predicting cement content with a standard error of 5.3 to 11.9 kg/m^3 (9 to 20 lb/yd^3), while water content determination had a standard error of 1.2 to 5.3 kg/m^3 (2 to 9 lb/yd^3). HITEC determined that the gauge was sensitive to air content of the mix, and thus it must be carefully controlled to within ± 1% during calibration and ± 1.5% during field use. Tests with fly ash and slag resulted in the conclusion that the gauge could not be calibrated with mixes containing cement alone, and then be used to test mixes that include mineral additives. The calibration must be performed on actual materials used in the field. Furthermore, tests with varying aggregates indicated that recalibration is required for use of different types of aggregate, as well as for sizable shifts in the coarse to fine ratio. The evaluation recommended that the gauge needed to improve its ability to account for effects of temperature fluctuations. Since the HITEC report has been published, the gauge manufacturer has developed and implemented gauge-specific temperature correction factors. HITEC concluded that while the gauge method is rapid and practical, the use of the gauge is limited to those applications that deal with well-defined mixes that are used over a long period of time.

3.2 PREVIOUS STUDIES: MICROWAVE OVEN METHOD

The Minnesota DOT has implemented the Microwave Oven Method, based on AASHTO TP-23, as a verification tool for water-cement ratio. Under the Strategic Highway Research Program "Optimization of Highway Concrete Technology", Nagi and Whiting (Nagi and Whiting, 1994) evaluated a microwave oven method for measuring water content of fresh concrete using a 900W microwave, and a 1500g sample of fresh concrete. Tests were performed on conventional concrete mixes of varying aggregate types and admixtures. The authors found that 100% recovery can be achieved with the microwave within 14-16 minutes, both in the laboratory and field. Field worthiness was investigated under actual construction conditions; the technique was found to be sufficiently reproducible, and two tests by the same operator should not differ by more than 4.5 kg/m^3 (7.6 lb/yd^3). In general, the drying time is based on the total specified weight of the sample and the capabilities of the microwave oven. In another study (Halstead, 1993) investigating the same Microwave Method, Halstead identified several disadvantages of the microwave method, including decomposition of aggregate particles during heating and the popping of aggregate particles during heating, which results in a loss of material. Furthermore, Halstead writes that the effectiveness of the method depends greatly on obtaining a representative sample for testing.

4. METHODOLOGY AND TESTING REGIME

4.1 TEST PLAN

The laboratory evaluation conducted as part of this study included use of the following materials:

1) A Type I cement from LaFarge Corporation.
2) A Class C fly ash from Alliant Utilities, Portage, Wisconsin.
3) Natural river sand obtained from Wingra Corporation
4) 19-mm (¾-inch) coarse aggregate from Yahara Building Materials
5) Daracem 19, a high range water-reducer from Grace Products
6) Daravair 1400 Air Entrainment from Grace Products

The proportions and testing parameters are shown in Tables 1 and 2. A target air content of 6 ± 1% was specified for testing. If the air content was not achieved, a replacement mix was required. All data, however, was kept as an expanded database for evaluating the methods.

Table 1. Mix Proportions

	WISCONSIN Grade A		WISCONSIN A-FA		WISCONSIN FA-30	
Material	kg/m^3	lbs/ft^3	kg/m^3	lbs/ft^3	kg/m^3	lbs/ft^3
Type I Cement	**335**	20.9	**285**	17.8	**252**	15.7
Class C Fly ash	**0**	0.0	**65**	4.1	**108**	6.7
Fine Aggregate	**779**	48.6	**762**	47.6	**762**	47.6
Coarse Aggregate	**1075**	67.1	**1053**	65.7	**1053**	65.7

Table 2. Mix Plan

w/c ratio = 0.32			w/c ratio = 0.40			w/c ratio = 0.48		
Batch #	Mix Type	Temperature (°C)	Batch #	Mix Type	Temperature (°C)	Batch #	Mix Type	Temperature (°C)
1	A	10	**10**	A	10	**19**	A	10
2	FA	10	**11**	FA	10	**20**	FA	10
3	FA30	10	**12**	FA30	10	**21**	FA30	10
4	A	21	**13**	A	21	**22**	A	21
5	FA	21	**14**	FA	21	**23**	FA	21
6	FA30	21	**15**	FA30	21	**24**	FA30	21
7	A	32	**16**	A	32	**25**	A	32
8	FA	32	**17**	FA	32	**26**	FA	32
9	FA30	32	**18**	FA30	32	**27**	FA30	32

4.2 METHODOLOGY: TROXLER WATER-CEMENT GAUGE

The Troxler Model 4430 Water-Cement Gauge is shown in Figure 1 indicating the component parts, the water probe, the cement probe and the sample bucket. The gauge operates on two nuclear principles: neutron thermalization and photon interaction. Thermalization is the reduction in kinetic energy of a neutron through collisions with nuclei in the surrounding medium (Troxler, 1993). The probe that determines water content utilizes neutron thermalization of neutrons emitted from a californium-252 source. Hydrogen atoms present in the sample slow the neutrons that are emitted into the bucket of fresh concrete. A helium (^3He) detector, also located in the probe, counts the thermalized neutrons. Therefore, there is a direct relationship between water content and water counts. As water content increases, the water count also increases.

The cement probe operates on photon interaction principles and consists of an americium-241 source. Photon interaction involves the photoelectric absorption of photon radiation. Elements with high atomic numbers, such as calcium which has an atomic number of 20, are more likely to absorb low-energy photons (Troxler, 1993).

The photon detector detects emitted photons that are not absorbed. An inverse relationship, therefore, exists between cement counts and cement. As cementitious content decreases, the counts will increase.

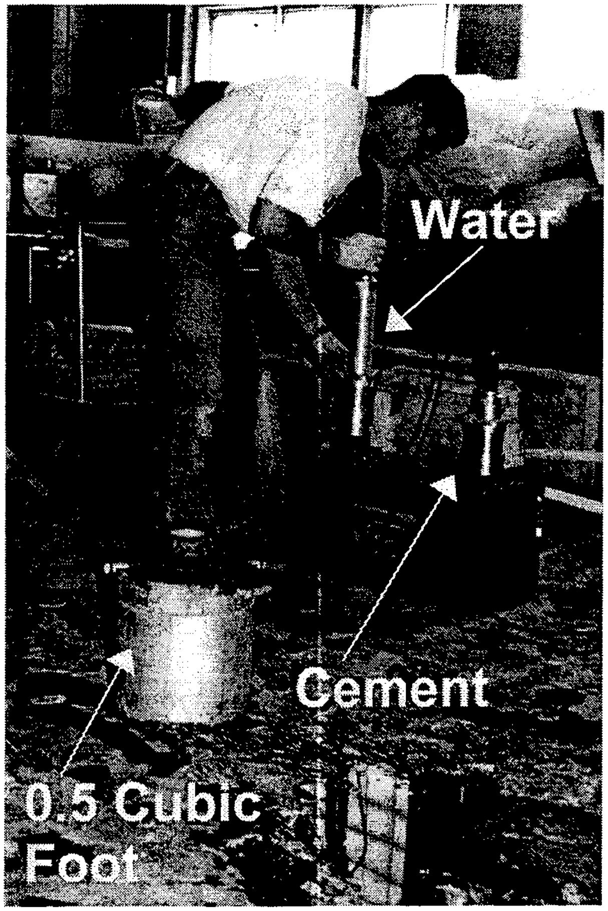

Figure 1. Troxler Water-Cement Gauge

The gauge determines cement and water counts and then provides content values based on a calibration of known contents and the corresponding counts. Troxler recommends that the calibration be performed for four separate mixes that bracket the target mix. The four mixes are:

- a mix with a water content 7% higher than the target mix,
- a mix with a water content 7% lower than the target mix,
- a mix with a cement content 7% higher than the target mix, and
- a mix with a cement content 7% lower than the target mix.

In addition, Troxler recommends the calibration include 4 mixes of the target mix. Troxler requires that the air content of all calibration mixes be within 1% of the target mix. "Excessive changes in air content will result in poor gauge calibration" (Troxler, 1993). Due to decay and environmental changes, standard counts of the radioactive sources are taken before the use of the gauge. The calibration count ratios, which are the measured counts divided by the standard counts, are stored in the Troxler electronics unit and used to create a calibration with a least squares linear fit routine. Constants, based on the regression are then used to determine the cement and water content. For this study, the Troxler gauge calibration method was not performed. Instead, all raw count ratios obtained from the core test plan were collected and we conducted our own data analysis and linear regressions outside the domain of the Troxler electronics.

When not in use, the entire gauge unit was stored at room temperature. For testing, as specified by the Troxler Gauge Manual, the gauge and sample container were placed on a solid, level surface which was at least two feet from any large object and at least four feet from the standard unit. Changes in conditions, particularly temperature, can distort the standard count. The gauge needed to acclimate to the testing conditions before use. The gauge, therefore, was placed in the testing area at least one hour before testing commenced.

Before each testing period, the gauge was allowed to enter a four-minute Self-Test and electronic stabilization mode. This procedure ensured that the gauge was operating correctly and that sufficient battery power was available. A 4-minute standard count of each probe was also measured and recorded before each test. The standard count process is required to account for radioactive decay in both the californium and americium sources. For testing, the gauge was programmed to take four 2-minute cement count readings, and one 2-minute water count reading. For calibration, Troxler recommended a 2-minute cement probe count time and a 2-minute water probe count time.

The 0.27 m^3 (0.46 ft^3) bucket provided by Troxler was filled in three lifts, with 25 rods and 10 strikes on the side of the bucket between each layer. The bucket was then weighed and the water probe was placed in the sample. After the 2-minute reading of the water probe, the cement probe was then placed in the sample. All counts were recorded and count ratios (cement or water counts normalized to the standard counts) were calculated. The count ratios were then plotted against measured values of cement and water contents to obtain the content values as determined by the gauge.

4.3 METHODOLOGY: MICROWAVE OVEN METHOD

The step-by-step procedure of the Microwave Oven Method for determining water content of a concrete mix is outlined in Table 3. This method is identical to that specified in AASHTO TP-23.

Table 3. Microwave Oven Method Procedure Summary

Materials and Equipment:	
900W Microwave Oven w/ turntable	
Metal Scraper	
Pestle	
229-mm by 229-mm (9-in by 9-in) Pyrex Glass Dish	
305-mm by 305-mm (12-in by 12-in) Fiber Glass Cloth	
Procedure:	
1. Record mass of glass dish and cloth	
2. Place 1500 ± 100g sample of fresh concrete on cloth. Wrap completely.	(WS)
3. Record mass of glass dish, cloth, and fresh concrete	
4. Microwave (Full Power) for 5 minutes.	(WF)
5. Remove sample from microwave, quickly unwrap.	
6. With metal scraper, separate coarse aggregate from mortar.	
7. With pestle, grind the mortar for no more than 60 seconds.	
8. Rewrap sample	
9. Microwave (Full Power) for 5 minutes.	
10. Remove sample from microwave	
11. Stir sample with scraper	
12. Record mass of dish, cloth, and concrete	
13. Rewrap sample	(WD_1)
14. Microwave (Full Power) for 2 minutes	
15. Remove sample from microwave	
16. Record mass of dish cloth, and concrete.	
17. If $WD_2 = WD_1 \pm 1$g, terminate testing; If not, return to Step 14.	(WD_2) (WD)

The predicted water content was expressed as a percentage of mass by the equation:

$$Water(\%) = \frac{100*(WF - WD)}{WF - WS} \qquad (4.1)$$

Where WF = Mass of Tray, Cloth, and Fresh Concrete
WD = Mass of Tray, Cloth, and Dry Concrete
WS = Mass of Tray and Cloth

From this value, the predicted water content based on the measured unit weight of the mix was obtained:

$$Water(\frac{mass}{volume}) = \frac{Water(\%)*(UW)}{100} \qquad (4.2)$$

5. TEST RESULTS

As indicated in the test plan (Table 2), mixes were prepared for three types of cementitious contents (A, FA, and FA30) and three water-cement ratios (0.32, 0.40 and 0.48). Several batches of each mix type were prepared and the measured properties of all batches are listed in Table 4. The prediction capabilities of the Troxler w/c gauge and the microwave oven method are compared with "actual w/c" as determined by batch weights used in the mixing process. In evaluating the test results, it must be understood that even the "actual w/c" value possesses some error. This "actual w/c" assumes that distribution of water, cement and aggregates are uniformly distributed throughout the concrete batch and that samples of the batch are completely consistent with the entire water and cement batch weights used for the entire batch. This potential source of variability is discussed more later.

5.1 RESULTS: TROXLER WATER-CEMENT GAUGE

The gauge calculates linear regression constants based on cement or water contents and measured corresponding counts determined during calibration. For this study, the gauge results (in count ratios vs. *actual* contents based on specified batch proportions) were grouped according to mix type – A, FA, and FA30 - and linear regressions were determined for the data. The results of the regressions are shown in Figures 2 and 3.

The equations from the regression lines in Figures 2 and 3 were then used to calculate cement and water content similar to the manner in which the nuclear gauge with the Troxler calibration procedure. The resulting contents correspond to the readings that the gauge would output to the user based on a stored calibration. We chose standard error as the statistical parameter to quantify prediction capability and computed as shown in Eq. 5.1. This error is the average error about the line of perfect agreement between prediction and measurement.

$$SE = \sqrt{\frac{\Sigma(Actual - Experimental)^2}{n-2}} \qquad (5.1)$$

A summary of the corresponding computed standard errors is shown in Table 5.

Table 4. Measured Mix Properties

	Batch #	Mix Type	Corrected Air	UNIT WEIGHT kg/m³	lb/ft³	SLUMP cm	in	28-Day STRENGTH* MPa	psi
Water-Cement Ratio =0.32 (uncorrected)	7WC	A	6.3%	2245	139.5	6.4	2.5	37.7	5470
	4WCX	A	4.5%	2370	147.3	0.8	0.3	60.5	8770
	4WCR	A	6.3%	2264	140.7	7.6	3	56.6	8205
	5WC	FA	6.7%	2297	142.7	6.1	2.4	61.1	8865
	2WCX	FA	9.0%	2213	137.5	8.9	3.5	58.6	8495
	2WCRX	FA	7.3%	2284	141.9	5.8	2.3	59.5	8635
	8WC	FA	6.3%	2300	142.9	3.8	1.5	60.6	8795
	6WC	30	5.8%	2278	141.6	5.1	2	53.7	7790
	9WC	30	6.3%	2301	143	3.8	1.5	59.1	8570
Water-Cement Ratio =0.40 (uncorrected)	13WC	A	5.2%	2335	145.1	2.5	1	38.3	5550
	16WC	A	5.7%	2288	142.2	3.8	1.5	42.0	6085
	11WC	FA	6.2%	2302	143.1	5.9	2.3	33.2	4810
	14WCX	FA	4.7%	2312	143.7	3.8	1.5	42.7	6195
	14WCR	FA	5.1%	2284	141.9	2.5	1	43.5	6310
	17WC-R	FA	5.3%	2300	142.9	3.3	1.3	41.1	5960
	17WC-X	FA	4.9%	2291	142.4	0.8	0.3	47.0	6820
	15WC	30	6.5%	2221	138	4.6	1.8	32.4	4695
	18WCX	30	4.4%	2289	142.2	0.8	0.3	39.2	5680
	18WC-R	30	6.0%	2264	140.7	1.3	0.5	49.5	7175
Water-Cement Ratio =0.48 (uncorrected)	22WC	A	6.2%	2250	139.8	8.4	3.3	30.8	4460
	25WCR	A	6.9%	2277	141.5	4.6	1.8	37.6	5455
	23WC	FA	9.4%	2087	129.7	15.2	6	21.7	3145
	23WCR	FA	8.0%	2148	133.5	14	5.5	34.3	4970
	26WC	FA	6.4%	2206	137.1	8.9	3.5	30.5	4430
	24WC	30	7.0%	2159	134.2	7.6	3	26.5	3850
	27WCX	30	7.2%	2190	136.1	7.6	3	31.6	4590

* Corrected for Air Content (400 psi/% of air above 6%)
See Appendix 5A for uncorrected strength data

Table 5. Standard Errors for Nuclear Water-Cement Gauge

		Standard Error kg/m³ (lb/yd³)			
Mix Type	**w/c**	**Water Content**		**Cement Content**	
A	0.02	*6.4*	(10.8)	*3.8*	(6.4)
FA	0.04	*11.5*	(19.4)	*7.5*	(12.6)
FA-30	0.03	*8.7*	(14.7)	*4.3*	(7.2)

To minimize the impact of scatter in calibration data, Troxler recommends that the estimated error be less than 11.2 kg/m³ (20 lb/yd³) for the cement probe readings and 7 kg/m³ for the water probe when entering calibration data. In this study, while the cement probe determined contents within the recommended range of less than 11.2 kg/m^3 for all mix types, the water probe error was higher than 7 kg/m^3 for the FA mixes.

One potential source of variability for the water probe data is non-uniform water distribution in the measurement bucket, particularly for the higher slump mixes. The water probe only reads at one height in the measurement bucket, whereas the cement probe allows for four readings along the height of the bucket. We did not assess the occurrence of non-uniform water distribution in this study.

Another possible source of error was the length of time that the probe remained in the sample. Troxler recommends a one-minute water count during testing and a four-minute count for calibration. For this study, a two-minute water count was taken. This two-minute count time may have been inadequate to obtain consistent results. Troxler writes, "the accuracy of the gauge is directly dependent on the count time, calibration quality and mix variability; the longer the count time, the greater the gauge precision" (Troxler, 1993). The potential time effect was not investigated in this study.

Figure 2 reveals parallel regression lines for the FA and FA-30 Mixes, but a change in slope is shown for the A mixes. This indicates that the presence of fly ash significantly influenced the gauge water readings. Elemental analysis of the Class C fly ash used in this project revealed no significant content of hydrogen containing constituents, yet there may be an unexpected component of the fly ash that is contributing to the skew in slopes.

Previous studies with fly ash mixes by Nagi and Whiting (1999) have shown that the gauge predicted water contents ranging from 11.2 to 20.7 kg/m^3 (20 to 37 lb/yd^3) less than actual in the concrete. Nagi and Whiting also write that while "it is unclear as to how fly ash would influence the gage's response to water...there perhaps is some unexpected component of the fly ash contributing to low water content readings" (Nagi and Whiting, 1999). In this study, lower water content readings were predicted for fly ash mixes versus no-fly ash mixes for the higher water content mixes, as shown in Figure 2.

Troxler recommends applying *a slope offset* when any components of the concrete change such that the proportion of neutron thermalizing (hydrogen bearing) atoms changes (Troxler, 1993). The slope offset calculates the change in slope of a calibration based on counts and contents of a given mix and holding the intercept constant. For example, a slope offset could be used when the actual water content is higher than the gauge measured content, which can be caused by unexpected neutron absorbers such as chlorine or chloride admixtures in the water. Moreover, components such as water reducers and plasticizers can also affect the amount of hydrogen in the mix.

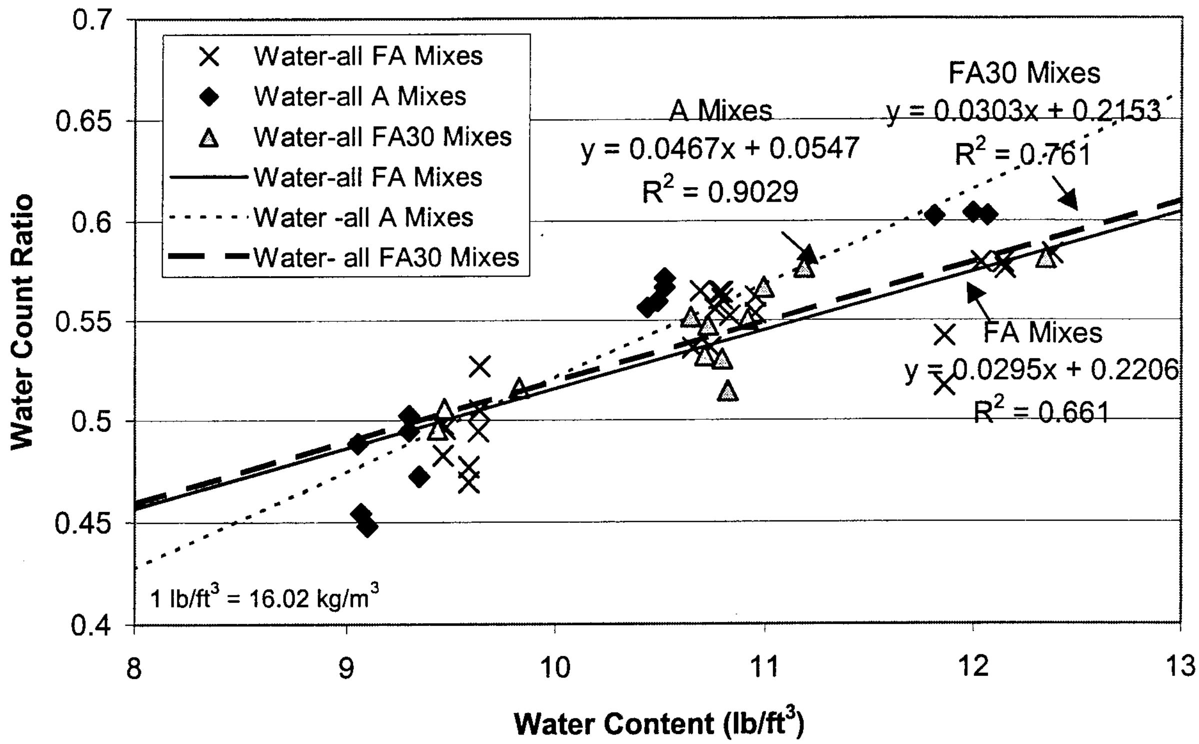

Figure 2. Nuclear Gauge: Actual Water Content vs. Water Count Ratio

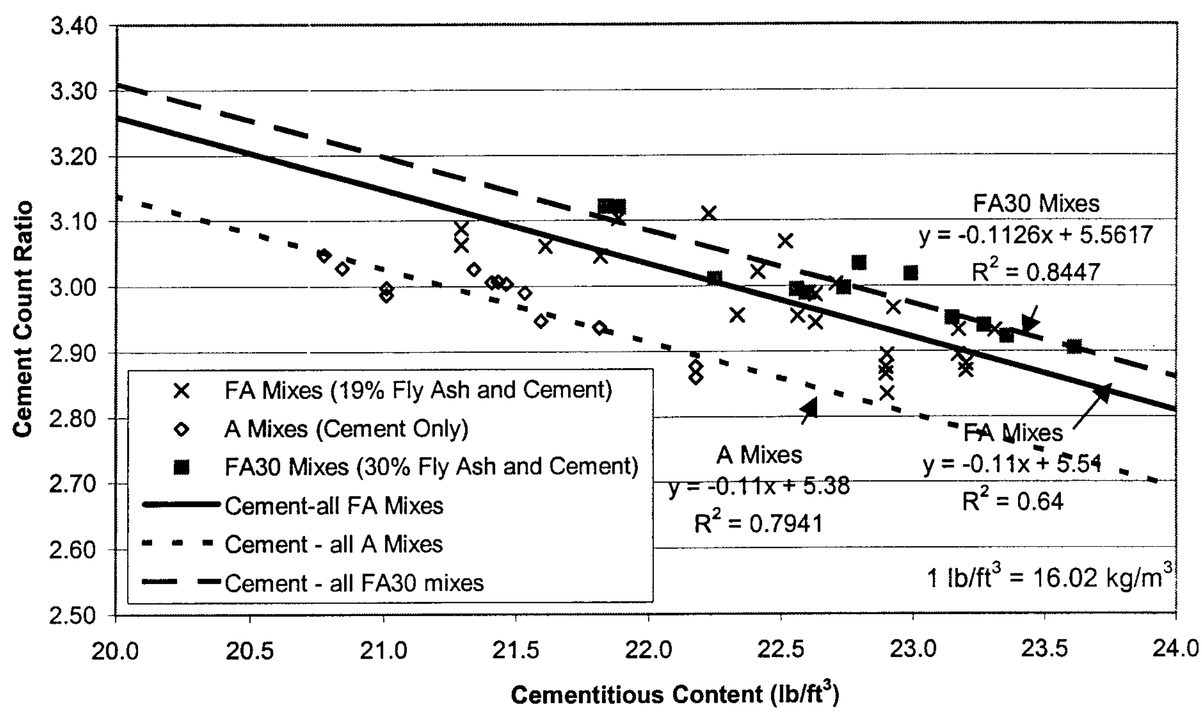

Figure 3. Nuclear Gauge: Actual Cement Content vs. Cement Count Ratio

The cement probe was sensitive to mix type. As shown in Figure 3, the mixes from the three mix series resulted in similarly sloped lines. The shift in intercept can be explained by the varying content of cementitious material between mix types. As previously discussed, the nuclear gauge determines cementitious content through photon interaction with calcium and *other high atomic-number* elements, such as iron. The reported calcium and iron contents, based on calcium oxide and iron oxide content, for the Portland Cement and fly ash used for this evaluation are shown in Table 6.

Table 6. Calcium and Iron Contents of Cementitious Materials

	Type I Cement	Class C Fly Ash
Calcium Oxide (CaO)	65.14%	23.05%
Iron Oxide (Feo)	2.88%	6.1%

Table 6 shows that the amount of calcium and iron present in the cement was significantly greater than that in the fly ash. The effect of the different calcium and iron contents is evident in Figure 3. The A mixes, which had the highest Type I cement content resulted in the line with the lowest y-intercept value, while the FA-30 mixes resulted in the highest y-intercept.

The nuclear gauge allows the user to adjust calibration data such that "the measured water and/or cement content is consistently read higher or lower by the value entered", known as a *shift offset* or an *intercept offset.* The shift offset allows the user to enter a value by which the intercept of the linear regression will be shifted. The intercept offset shifts the calibration intercept by a value calculated by the control unit based on stored contents and counts and holding the calibration slope constant. As shown in Figure 3, changes in cementitious type and content could benefit from intercept shifts, as long as the cause of the shift in data is accurately known.

Neither hold time nor temperature had significant effects on the measurement of cement and water content with the nuclear gauge as indicated in Tables 7 and 8 respectively. High humidity and temperature, however, did effect the handling of the gauge, because the electrical components required time to equilibrate to testing conditions. For several of the "warm" mixes, the gauge and materials were placed outdoors during times when the humidity was 30% or more than the conditions at which the gauge was stored. Because the gauge averages the last four standard count readings, four or five standard counts had to be taken until the gauge read "passing" standard counts. This resulted in an additional 16-20 minutes of testing for the procedure. This "environmental acclimation" issue is important because field use will most likely require the gauge to be stored in environmental conditions different from those in which it will be used to test.

Table 7. Nuclear Gauge Standard Errors for 15 and 45 Minute Tests

Standard Errors kg/m³ (lb/yd³)

Mix Type	WATER PROBE		CEMENT PROBE	
	15 Minute	45 Minute	15 Minute	45 Minute
A	7.8 (13.2)	6.8 (11.5)	4.9 (8.3)	5.0 (8.4)
FA	13.7 (23.1)	10.3 (17.3)	7.1 (12.0)	8.5 (14.3)
FA-30	8.5 (14.1)	9.2 (15.5)	3.3 (5.5)	5.5 (9.3)

Table 8 . Nuclear Gauge Standard Errors for 10°, 21°, and 32°C

Standard Errors kg/m³ (lb/yd³)												
Mix Type	WATER PROBE						CEMENT PROBE					
	10° C		21° C		32° C		10° C		21° C		32° C	
A	n/a		7.2	(12.1)	8.1	(13.7)	n/a		6.0	(10.1)	3.8	(6.4)
FA	13.7	(23.1)	14.3	(24.1)	9.4	(15.9)	9.7	(16.3)	7.0	(11.9)	8.6	(14.7)
FA-30	n/a		7.8	(13.1)	11.3	(19.1)	n/a		4.4	(7.4)	6.6	(11.1)

5.2 ALTERNATIVE CALIBRATION FOR THE TROXLER WATER-CEMENT GAUGE

The calibration procedure of the Nuclear Gauge currently calls for 8 batches of concrete composed of the same materials as the target mix, requiring significant time and effort, in addition to the time required for the actual testing. Tests were conducted with the gauge to determine the potential of measuring the individual components of fresh concrete to ultimately provide an alternative to the current calibration procedure.

The objective of this additional testing was to determine whether a relationship could be established between gauge readings of individual components and readings of the total mix. Figure 1B in Appendix B plots cement counts versus cementitious content for fly ash and cement. Similar relationships were determined for aggregates and water. Equations to determine counts given known contents were then developed for each concrete component. A mathematical relationship was then assumed for each probe to define total counts as a function of counts of individual components. The developed equations were able to predict water-cement ratio within 0.03. The error in the cement content increased with an increase in fly ash. The standard errors are shown in Table 9.

Table 9. Standard Errors of Predicted Values

		Standard Error kg/m³ (lb/yd³)	
Mix Type	w/c	Water Content	Cement Content
A	0.01	3.23 (5.45)	10.6 (17.88)
FA	0.02	7.44 (12.54)	12.5 (21.01)
FA-30	0.03	4.16 (7.01)	29.7 (50.01)

In general, developing an alternative to the current calibration method based on individual constituents, particularly for water content, seems promising. The water content was accurately predicted based on the given data. If aggregates are oven-dry and/or accurate moisture contents are known for all constituents, determining water content in this manner has potential as an alternative calibration. Cement content was more difficult to predict, especially in the presence of fly ash. As reflected in the errors from the core test plan, unexpected elements in the aggregates, cements, or other admixtures, could influence the ability to use definitive relationships to predict cement and water content.

5.3 RESULTS: MICROWAVE OVEN METHOD

The results obtained from the Microwave Oven Method tests were grouped according to water-cement ratio. Standard error increased with an increase in water-cement ratio. Figure 4 is a plot of the actual water content versus the water contents obtained from the Microwave Method. Table 10 summarizes the standard errors obtained by the Microwave Method. As before standard error is based on a comparison with the actual water cement ratio.

As shown in Figure 4, the majority of predicted w/c values fell below the line of perfect prediction, indicating lower predicted water contents. The values that are located above the line of true content were likely caused by the loss of material during testing. The data scatter may also be an effect of the small sample size relative to the entire batch.

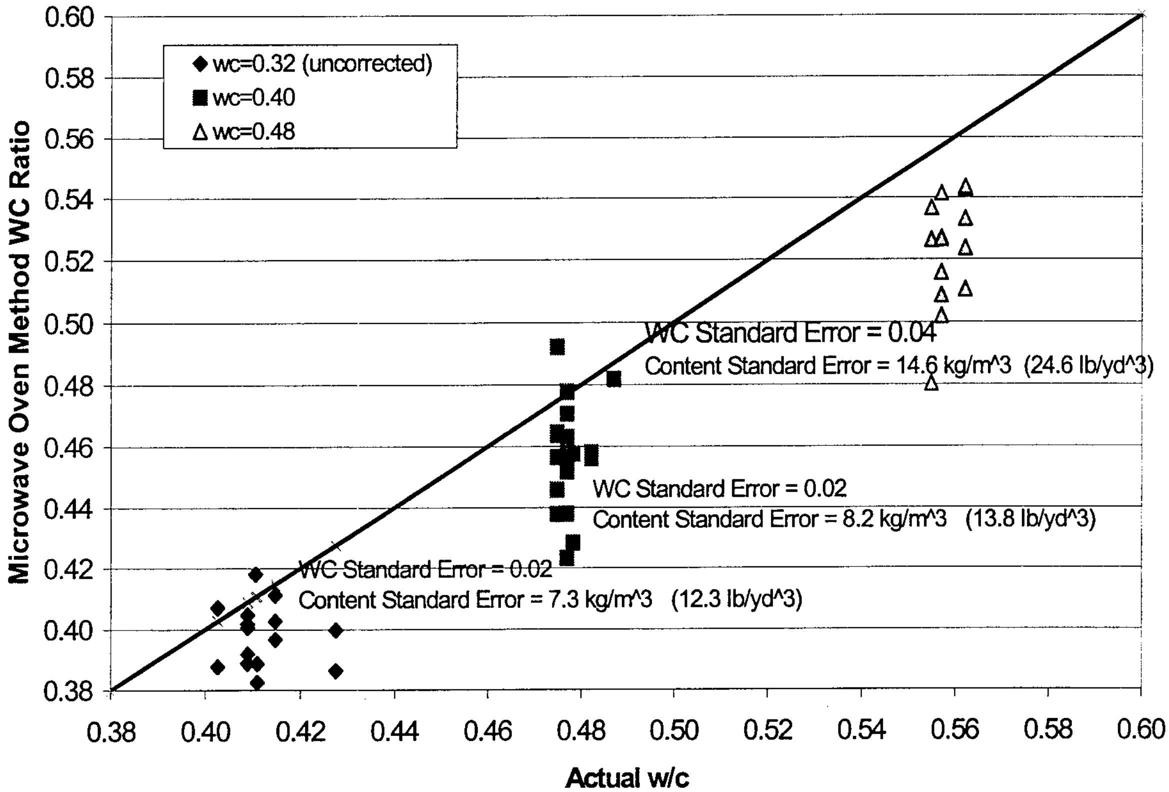

Figure 4. Microwave Oven Method:
Actual W-C Ratio vs. Microwave Oven W-C Ratio (Mixes grouped by w/c)

Table 10. Microwave Oven Method Standard Errors

	Water Content		WC
	Kg/m^3	(lb/yd^3)	Ratio
wc = 0.32	7.3	(12.3)	0.02
wc = 0.40	8.2	(13.8)	0.02
wc = 0.48	14.6	(24.6)	0.04

The AASHTO TP-23 Standard specifies that the sample be tested in the microwave until consecutive weight readings are within ± 1 gram. The amount of time required to meet this limit varied between mixes. Table 11 shows the length of "drying" time required to meet the 1 gram limit, as well as a 0.5 gram limit. The corresponding average standard errors are also given. Statistical analysis showed no significant difference in drying times or standard errors between mixes dried to the 1-gram versus 0.5-gram limit. This is an indication that an increase in drying time or requiring stricter weight limits will not affect the results.

Table 11. Drying time required for Microwave Oven Method and Standard Errors

	Drying Time (Min)		Standard Error Water Content kg/m³ (lb/yd³)		Standard Error wc ratio	
	for ± 1g	for ± 0.5g	W/ ± 1g limit	w/ ± 0.5g limit	w/ ± 1g limit	w/ ± 0.5g limit
w/c = 0.32	16.7	16.9	7.2 (12.1)	7.3 (12.3)	0.02	0.02
w/c = 0.40	17.2	17.3	12.6 (21.2)	8.2 (13.8)	0.04	0.02
w/c = 0.48	18	19.4	14.5 (24.4)	14.6 (24.6)	0.04	0.04

Hold time did have an effect on the Microwave Oven Method results. The standard errors for water content are shown below in Table 12 for the 15-minute results and the 45-minute results.

Table 12. Standard Errors for Microwave Oven Method: Effect of Hold Time

	Standard Errors – Water Content		
	15 min kg/m³ (lb/yd³)	45 min kg/m³ (lb/yd³)	P Value (ANOVA, $\alpha = 0.05$)
w/c = 0.32	6.4 (10.9)	8.7 (14.6)	0.15
w/c = 0.40	6.4 (10.8)	10.4 (17.5)	0.11
w/c = 0.48	8.1 (13.7)	13.8 (23.2)	0.05

The results in Table 12 show 1) an increase in standard error with increase in hold time and 2) an increase in the standard error difference between 15 minute and 45 minute tests as the wc ratio increased. The lower water recovery with the 45 minutes tests was likely due to a combination of:

1) *Evaporation of water from the fresh concrete during hold time.* During hold time, the batch of fresh concrete was covered and turned once. It was evident, however, that evaporation was occurring as condensation appeared on the plastic covering. Evaporation tests with a 9 x 12" pan of water at 21°C and 20% humidity were conducted. These tests concluded that approximately 0.5% of a covered 1500 gram sample of plain water will evaporate over a 30-45 minute period. This percentage corresponds to approximately a 3.4 kg/m³ (6 lb/yd³) decrease in water for fresh concrete. Due to a larger surface area of the fresh concrete versus a pan of water, moreover, a higher rate of evaporation can be expected.

2) *Absorption of water by aggregates.* During hold time, absorption of free water by the aggregates occurred. For this study, the batch water content was adjusted to account for aggregate absorption. While the majority of the water was recoverable, absorbed water that was not removed during the microwave process may have become "entrapped" in the coarse aggregate pores making it more difficult to recover.

3) *The decrease in workability resulted in increased difficulty to obtain representative samples.* The method requires only a 1500g (3.3 lb) sample, which raises the concern, particularly in the field, that the method will not always obtain an accurate representation of the actual mix. Particularly after 45 minutes, the stiffer consistency and segregation of water from the batch increased the likelihood that that an unrepresentative sample containing higher coarse aggregate content than the actual batch. No.4 sieve analysis of dried samples concluded that the amount of coarse aggregate in the sample is inversely proportional to predicted water. Figure 5 illustrates that an increase in coarse aggregate leads to a decrease in apparent water.

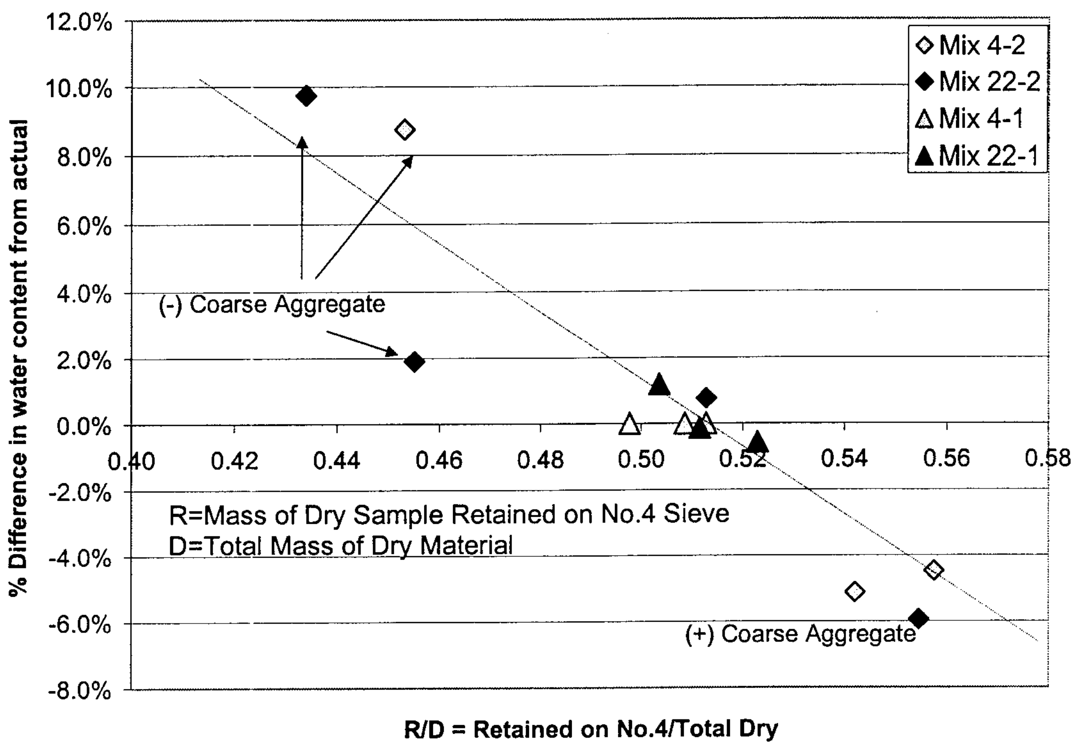

Figure 5. Effects of Changing Coarse Aggregate Content of Microwave Oven Method Samples.

Temperature of mix materials and laboratory environment did not have an effect on the results of the Microwave Oven Method. The standard errors for water content of the mixes grouped by mixing temperature are shown below in Table 13. It is possible that in field conditions, however, extremely high temperatures over a period of time can cause accelerated hydration or evaporation of water in fresh concrete. Measures should be taken to ensure that the fresh concrete sample to be tested is not exposed to conditions different from those affecting the entire batch.

Table 13. Standard Error for the Microwave Oven Method based on temperature

	Standard Error		
Temperature	Water Content kg/m^3	(lb/yd^3)	wc ratio
10 C	12.3	(20.7)	0.03
21 C	11.3	(19.1)	0.03
32 C	8.9	(15.1)	0.03

5.4 STRENGTH PREDICTION RESULTS

A significant advantage of determining water-cement ratio at the time of paving is the ability to predict and control concrete strength when changes can still be made to the fresh concrete. Appendix 5A includes all strength data. Table 14 shows the standard errors of the predicted strengths. The predicted strengths were calculated based on linear regressions between the water-cement ratios determined by the nuclear gauge and microwave method and the actual strengths.

Table 14. Strength Results Standard Prediction Errors

	Standard Error MPa (psi)			
Mix Type	Nuclear Gauge		Microwave	
A	7.49	(1085)	8.31	(1204)
FA	8.58	(1244)	8.30	(1203)
FA30	8.50	(1232)	9.07	(1315)

The variability between batches of the same mix was quite high, while variability between samples from the same batch was quite low as shown in Table 15. ACI 217 reports that control of concrete strength could be rated as "very good" if the standard deviation is 1.4 to 1.7 MPa (200 to 250 psi) between samples from the same batch. Table 15 clearly shows that the limits for between sample variation are met. When apparent outlier data were removed from the results, the between batch standard deviation was significantly reduced. Further discussion concerning data variability and outlying data is in Section 5.4.

Table 15. Strength Results: Standard Deviations (MPa)

	Between Batch Standard Deviation			Between Sample Standard Deviation		
	wc= 0.32	wc=0.40	wc=0.48	wc= 0.32	wc=0.40	wc=0.48
A	12.2	2.6	4.8	0.8	2.1	0.8
FA	1.2	5.2	6.5	0.6	1.2	0.5
FA30	3.8	8.6	3.6	0.7	0.7	1.3

5.5 DATA VARIABILITY

Table 14 shows that high standard errors for the strength data were evident for all mix types and water-cement ratios. Outlier data significantly influenced the strength results. Batch 7WC, an A Mix, can be considered an outlier batch because it was noted during cylinder demolding that the concrete was unusually flaky and appeared to have not properly hydrated. As shown in Table 4, the strength of batch 7WC was significantly lower than the other batches of the same mix type and water-cement ratio. When this batch data, and other data that were believed to be outliers, were removed from the strength results, the strength standard errors greatly decreased, as shown in Table 16(a). The same outlier batches also contributed to data scatter in both the nuclear gauge and microwave method results.

Table 16. Comparing Error Results Without Outlier Data

(a) STRENGTH DATA

Standard Errors (MPa) With ALL Data	FA	A	FA30
Gauge	8.58	7.48	8.48
Microwave	8.31	8.31	9.07

Standard Errors (MPa) WITHOUT Outliers	FA	A	FA30
Gauge	4.10	3.72	5.58
Microwave	4.21	5.52	7.03

(b) GAUGE DATA

Standard Errors (kg/m^3) With ALL Data	FA	A	FA30
WATER	11.5	6.4	8.7
CEMENT	7.5	3.8	4.3
w/c	0.04	0.02	0.03

Standard Errors (kg/m^3) WITHOUT Outliers	FA	A	FA30
WATER	7.9	6.3	6.3
CEMENT	6.6	3.9	4.8
w/c	0.02	0.02	0.02

(c) MICROWAVE DATA

Standard Errors (kg/m^3) With ALL Data	wc=0.32	wc=0.40	wc=0.48
	7.3	8.2	14.6
w/c	0.02	0.02	0.04

Standard Errors (kg/m^3) WITHOUT Outliers	wc=0.32	wc=0.40	wc=0.48
	6.0	6.6	14.5
w/c	0.02	0.02	0.04

Removing the same outlier batch results from the gauge data resulted in a decrease in water-cement ratio error for the FA mixes, and a slight decrease for the FA 30 mixes. The nuclear gauge A mixes were not affected. The microwave data was not affected when the outliers were removed. These results indicate that a significant amount of data scatter in the strength results was largely due to unreliable strength data, and not a function of Microwave or Nuclear Gauge method related errors.

Without the outlier data, the remaining variability and error in the results for both methods result from a combination of factors, including air content measurement variability, unit weight measurement variability, and nuclear gauge method variability between tests on the same batch.

The contribution to data variability from the variations or error in unit weight and air content measurements in determining the "actual" water-cement ratio for a sample, was found to be minimal. The air meter was determined to vary by less than 0.5% air during repeated tests of concrete from the same batch, which would result in only a 0.002 change in actual water-cement ratio. Excluding Batch 7WC, which differed in unit weight by 112 kg/m^3 (7 lb/ft^3) between tests of the same batch, the unit weight measurements for the remaining mixes did not vary by more than 19.2 kg/m^3 (1.2 lb/ft^3) (average) between repeated tests. This difference corresponds to a change in water-cement ratio of 0.006.

Comparisons between the 15-minute and 45-minute nuclear gauge results were used to determine variability between tests on samples from the same batch for the nuclear gauge method. It was determined that hold time had no significant influence on the gauge results, and therefore the only measured difference between 15-minute and 45-minute samples was unit weight. This also provides an indication of the variability introduced by different samples of the same batch. The air content was assumed to be constant between tests and evaporation leading to the 45-minute test was assumed to be minimal as the concrete was kept covered during this time. Excluding Batch 7WC, the average difference in water-cement ratio between 15- and 45-minute tests with the nuclear gauge was 0.01.

To measure variability inherent in the gauge readings, three sets of readings were recorded for a single sample of fresh concrete. The gauge bucket was filled and count ratios were recorded three times within a period of 40 minutes. Standard counts were measured prior to each test. Tests revealed that the water and cement count ratios varied by an average of 2% and 1%, respectively, which correspond to an average water cement ratio change of 0.01. Further investigation is needed to determine whether an increase in count time could decrease this variability.

6. RECOMMENDATIONS and CONCLUSIONS

Based on the obtained errors of 0.02 to 0.04 water-cement ratio, and the apparent scatter in data, currently there is no field method that could be *solely* relied upon for accurate water-cement ratio measurement. As a primary means of quality control, an ideal field method should be able to determine water-cement ratio with a standard error of 0.01 or less in order to accurately predict hardened concrete performance. In order for either method to be used as a primary quality control tool, further development and evaluation is needed. At the same time, some variability is introduced by water-cement ratio variations in repeated samples from the same batch of concrete. We were not able to sort these variabilities out from the errors reported for each method. Repeated measures of identical concrete with the Nuclear Gauge indicated variations of about 0.01 in w/c.

As an *enhancement* to current means of quality control in the field, however, both the Nuclear Gauge and the Microwave Oven Method can currently be implemented in concrete acceptance procedures that are based on water content or water-cement ratio. Both methods are adequately reliable to provide quality control information that can supplement batch plant batch weight records.

In order to evaluate method feasibility under actual testing conditions, a field assessment of the Nuclear Water-Cement Gauge and the Microwave Oven Method is needed to complete the evaluation of existing technologies. A field assessment will provide a more comprehensive evaluation of field durability, ease of equipment handling, and water-cement ratio measurement reliability under actual testing conditions. In addition to the field assessment, the following recommendations are made:

The high standard errors with the water probe readings may have been affected by non-uniform water distribution in the measurement bucket. Two possibilities for improving this error would be to increase the length of time of measurement for the water probe and to take additional measurements at varying heights along the bucket. In general, the capabilities of the gauge were limited by the inherent variability of concrete batches and the individual components. This variability could be decreased with an increase in the amount of calibration mixes. An increase in number of calibration mixes, however, greatly decreases the field practicality of the Nuclear Gauge method.

A major disadvantage to this method is the extensive calibration required for operation. Future work should focus on determining a more accurate relationship between total counts and contents of individual mix components. By doing so, a potential alternative to the recommended 8 mixes for the current calibration could be developed. A promising alternative would require only the measurement of the individual components with the gauge at recommended contents. Even if mix proportions changed, the alternative method would be especially useful if the same materials are consistently used and could be conducted in a fraction of the time required for the Troxler calibration.

In order to maintain field practicality and yet achieve accurate results, a compromise must be made between increasing the sample size versus keeping the equipment manageable and the required testing time to a minimum. With the current 1500g sample, precautions must be taken, particularly for lower water-cement ratio mixes and less workable mixes, to ensure accurate representation of the target batch.

For the field study, No.4 sieve analysis of the dry samples from the Microwave Method is recommended. In general, sieving the dry samples from the Microwave Oven Method can be beneficial to explain variations in results between samples. Furthermore, efforts must be made to limit the duration between time of water addition and time of testing with the Microwave Method.

Ultimately, the Troxler Water-Cement Gauge and the Microwave Oven Method have the potential to relieve contractors and WisDOT of gathering other on-site concrete quality control information during or after paving. With further development based on the recommendations from this study and the future field assessment, both methods could be implemented as primary means of water-cement ratio quality control for concrete pavements. The dominant benefit to be gained from using either method is the ability to have quantitative quality control information about fresh concrete at a time when changes can still be made.

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AASHTO TP23-93, *Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying*

ASTM C 127-93, *Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate*, Vol. 04.02.

ASTM C 128-93, *Standard Test Method for Specific Gravity and Absorption of Fine Aggregate*, Vol. 04.02.

ASTM C 231, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*, Vol. 04.02.

ASTM C 1078-92, *Standard Test Methods for Determining the Cement Content of Freshly Mixed Concrete*, Vol. 04.02.

ASTM C 1079-92, *Standard Test Methods for Determining the Water Content of Freshly Mixed Concrete*, Vol. 04.02.

Mix Quantities - Wisconsin A-FA (19%)				9 batches	
			Per batch	with Throwaway	
Materials	Weights – kg/m^3	Weights - lbs/ft^3	lbs	lbs	tons
Cement	285	17.79	32.54	586	0.29
Fly ash	65	4.06	7.42	134	0.07
Fine A (42%)	762.3	47.59	87.04	1567	0.78
Coarse A	1052.7	65.72	120.20	2164	1.08

Mix Quantities - Wisconsin Grade A (0%)				9 batches	
			Per batch	with Throwaway	
Materials	Weights – kg/m^3	Weights - lbs/ft^3	lbs	lbs	tons
Cement	335	20.91	38.25	689	0.34
Fly ash	0	0.00	0.00	0	0.00
Fine A	778.68	48.61	88.91	1600	0.80
Coarse A	1075.32	67.13	122.79	2210	1.11

Mix Quantities - Wisconsin FA 30%				9 batches	
			Per batch	with Throwaway	
Materials	Weights – kg/m^3	Weights - lbs/ft^3	lbs	lbs	tons
Cement	252	15.73	28.78	518	0.26
Fly ash	108	6.74	12.33	222	0.11
Fine A	762.3	47.59	87.04	1567	0.78
Coarse A	1052.7	65.72	120.20	2164	1.08

FOR 1 TEST:

Include:	Quantity	ft^3	Total Volume
Cylinders	4	0.058	0.232
Slump Test	1	0.2	0.2
Air Content Testing	1	0.25	0.25
Troxler Method	2	0.5	1
Microwave Method	2	0.022	0.044
10% Additional	1	0.103	0.103
		TOTAL	**1.83 ft^3**

Throw away factor 2	
Mix Type: WisDOT Mix A-FA	1
Coarse Aggregate: Crushed Limestone	1
Fine Aggregate: Natural River Sand	1
Target w/c Ratio: 0.32, 0.40, and 0.48	3
Temperature: 10, 21, and 32 (C)	3
Air Content: 6 ± 1 %	1
Fly Ash: 0, 15, and 30 % (of total F + C)	3
* Each Batch will be tested @ 15 minutes and then @ 45 minutes	27 BATCHES TOTAL

* Quantities in lbs

w/c ratio = 0.32

Batch #	Water	Cement	Fine	Coarse	Temp C	Air (±1%)	MIX TYPE	Fly Ash %	Total Cem	Corrected Water
1	12.24	38.25	88.91	122.79	10	6	A	0.00	38.25	15.38
2	12.79	32.54	87.04	120.20	10	6	FA	7.42	39.97	15.86
3	13.15	28.78	87.04	120.20	10	6	30	12.33	41.11	16.23
4	12.24	38.25	88.91	122.79	21	6	A	0.00	38.25	15.38
5	12.79	32.54	87.04	120.20	21	6	FA	7.42	39.97	15.86
6	13.15	28.78	87.04	120.20	21	6	30	12.33	41.11	16.23
7	12.24	38.25	88.91	122.79	32	6	A	0.00	38.25	15.38
8	12.79	32.54	87.04	120.20	32	6	FA	7.42	39.97	15.86
9	13.15	28.78	87.04	120.20	32	6	30	12.33	41.11	16.23

w/c ratio = 0.40

Batch #	Water	Cement	Fine	Coarse	Temperature	Air	Fly Ash %	Fly Ash	Total Cem	Corrected Water
10	15.30	38.25	88.91	122.79	10	6	A	0.00	38.25	18.44
11	15.99	32.54	87.04	120.20	10	6	FA	7.42	39.97	19.06
12	16.44	28.78	87.04	120.20	10	6	30	12.33	41.11	19.52
13	15.30	38.25	88.91	122.79	21	6	A	0.00	38.25	18.44
14	15.99	32.54	87.04	120.20	21	6	FA	7.42	39.97	19.06
15	16.44	28.78	87.04	120.20	21	6	30	12.33	41.11	19.52
16	15.30	38.25	88.91	122.79	32	6	A	0.00	38.25	18.44
17	15.99	32.54	87.04	120.20	32	6	FA	7.42	39.97	19.06
18	16.44	28.78	87.04	120.20	32	6	30	12.33	41.11	19.52

w/c ratio = 0.48

Batch #	Water	Cement	Fine	Coarse	Temperature	Air	Fly Ash %	Fly Ash	Total Cem	Corrected Water
19	18.36	38.25	88.91	122.79	10	6	A	0.0	38.25	21.50
20	19.18	32.54	87.04	120.20	10	6	FA	7.4	39.97	22.26
21	19.73	28.78	87.04	120.20	10	6	30	12.3	41.11	22.81
22	18.36	38.25	88.91	122.79	21	6	A	0.0	38.25	21.50
23	19.18	32.54	87.04	120.20	21	6	FA	7.4	39.97	22.26
24	19.73	28.78	87.04	120.20	21	6	30	12.3	41.11	22.81
25	18.36	38.25	88.91	122.79	32	6	A	0.0	38.25	21.50
26	19.18	32.54	87.04	120.20	32	6	FA	7.4	39.97	22.26
27	19.73	28.78	87.04	120.20	32	6	30	12.3	41.11	22.81

Department of Transportation Survey Results
Survey Conducted by Carina Santos, September 1997

State DOT	Contact	Reply Received	Current Method of W-C ratio Field Testing	Methods Investigated
Iowa DOT	Todd Hanson 515-239-1649	9/17/97	None	None
Illinois DOT	Matt Mueller (217) 785-1386	9/10/97	None	Nuclear Cement Gauge & Microwave Oven
Indiana DOT	Joseph Gunderson (317) 356-9351 fax	X	-	-
Kansas DOT	John Wojakowski (785) 296-3566	9/8/97	None	Kansas Water-Cement Ratio Meter
Minnesota DOT	Douglas Schwartz (612) 779-5576	9/2/97	Microwave Oven Method	Microwave Oven Method (data provided in MinnDOT specs)
Missouri DOT	Ray L. Purvis (573) 526-4308	9/12/97	None	None
Montana DOT	Mike Lynch (406) 444-6294	9/9/97	None	None
North Dakota DOT	Joel M. Wilt (701) 328-1269	9/11/97	None	Microwave Oven
South Dakota DOT	Ron McMahon (605) 773-3403	9/12/97	None	None
West Virginia DOT	Gary Robson GROBSON@mail.dot.state.wv.us	8/29/97	None	None

Field Measurement of Water Cement Ratio for Portland Cement Concrete

PHASE I – Evaluation of Existing Technologies
WisDOT HRS #97-03 SPR #0092-45-88
Literature Review Submitted by: Carina Santos
September 25, 1997

METHOD	ADVANTAGES	DISADVANTAGES	TIME REQUIRED FOR ANALYSIS*
MICROWAVE OVEN METHOD	- This method is appropriate for field tests and does not require a skilled operator[1] - Currently used by Minnesota DOT[3] - Equipment (900W microwave with turntable) is commercially available and inexpensive - Method can be applied to conventional mixes, latex modified concrete, and silica fume concrete[4]	-Possible decomposition of aggregate and cementitious particles during heating , affecting liquid content of mix[2] -Because the method requires microwaves, no concrete containing metallic components can be tested[4] - Only determines the water content, therefore the cement content must be known in order to obtain w-c ratio[4] - Power required on the jobsite - Some experience suggests 30 minutes needed for analysis	16 minutes[4]
NUCLEAR WATER - CEMENT GAGE (Troxler Nuclear Water Cement Gage, Model 4430)	-Easy equipment handling *once trained* -The gauge has separate probes for water and cement	- Accurate calibration curves are required (test results are highly dependent on these curves)[5] -W-C ratio more difficult to determine with use of admixtures in concrete[5] -Accuracy of the readings is influenced by air content, aggregate type, and coarse to fine ratio[6] -Nuclear Regulatory Commission requires 1-day training session - High cost of equipment (approximately $15,000)	10 minutes[6]
ASTM C1078 (Cement content determination) **ASTM C1079** (Water content determination)	- These methods are the only w-c ratio determination methods currently standardized by ASTM[1] - Both methods permit either manual or instrumental analysis[2]	- May not be practical for field use since the methods require use of chemicals, calibration, and several pieces of laboratory equipment[2] - Basic chemistry skills are useful (although not necessary if sufficiently trained) - Can not be used for mixtures containing certain chemical admixtures or silica fume[1]	15 minutes[7]
TURBIDIMETRY (Kansas Water-Cement Ratio Meter)	- Aside from the equipment set-up and calibration, testing is completely automated[8] -Less expensive compared to Troxler's 4430 Water/Cement Gauge[9] - Tests can be performed up to 1 hour after batching[9]	- Calibration curves are required - Meter is unable to test Type III Cement, and sensitive to cement brand[9] - Device (1996) was not suitable for field testing[9] - Not capable of detecting 5% variations in cement content[9]	10 minutes[8]
RAPID ANALYSIS MACHINE (RAM)	-Fully automated device -Low skill requirement (once calibrated)	-Difficult calibration required [1] -High cost for maintenance, chemicals, and equipment[1] -Aggregate source and mix proportions should remain constant[10] -Operates most accurately on level ground[10] -110 volt AC supply required[10]	10 minutes[10]
BUOYANCY METHOD	-Relatively inexpensive because only standard laboratory equipment is required	-Highly dependent on accurate specific gravity and absorption data of the aggregate and cement[11] -Specific Gravity of aggregates assumed constant[10] -Aggregate source should remain constant[10]	15-20 minutes[10]

*Does not include time for calibration or setu

28 DAY COMPRESSION DATA				
		Uncorrected	Corrected*	
Batch #	Mix	**Strength, MPa (psi)**	**Strength, MPa (psi)**	Air Content +
2WCX-45	FA	50.28 (7293)	58.56 (8493)	9.0%
2WCRX-45	FA	55.95 (8115)	59.54 (8635)	7.3%
5-45	FA	59.19 (8585)	61.12 (8865)	6.7%
8-45	FA	59.80 (8673)	60.63 (8793)	6.3%
11-45	FA	32.61 (4729)	33.16 (4809)	6.2%
14-45	FA	46.00 (6672)	43.52 (6312)	5.1%
14WCX-45	FA	46.28 (6713)	42.70 (6193)	4.7%
17-45	FA	43.03 (6241)	41.10 (5961)	5.3%
17WCX-45	FA	50.08 (7263)	47.04 (6823)	4.9%
23-45	FA	18.93 (2746)	21.69 (3146)	7.0%
23-45R	FA	28.74 (4168)	34.25 (4968)	8.0%
26-45	FA	29.43 (4268)	30.53 (4428)	6.4%
4-90	A	55.74 (8085)	56.57 (8205)	6.3%
4WCX-A	A	64.61 (9371)	60.47 (8771)	4.5%
7-45	A	36.90 (5352)	37.73 (5472)	6.3%
7-45R	A			8.4%
13-45	A	40.46 (5868)	38.25 (5548)	5.2%
16-45	A	42.79 (6206)	41.96 (6086)	5.7%
22-45	A	30.20 (4380)	30.75 (4460)	6.2%
25-45	A	35.12 (5094)	37.60 (5454)	6.9%
6-45	30	54.28 (7872)	53.72 (7792)	5.8%
9-45	30	58.27 (8452)	59.10 (8572)	6.3%
15-45	30	31.00 (4497)	32.38 (4697)	6.5%
18WCX-45	30	43.58 (6321)	39.17 (5681)	4.4%
18-45	30	49.46 (7173)	49.46 (7173)	6.0%
24-45	30	23.77 (3448)	26.53 (3848)	7.0%
27WCX-45	30	27.80 (4032)	31.66 (4592)	7.4%

* Strength Correction = 400 psi/ % air away from 6%
+ Air Correction = 0.6

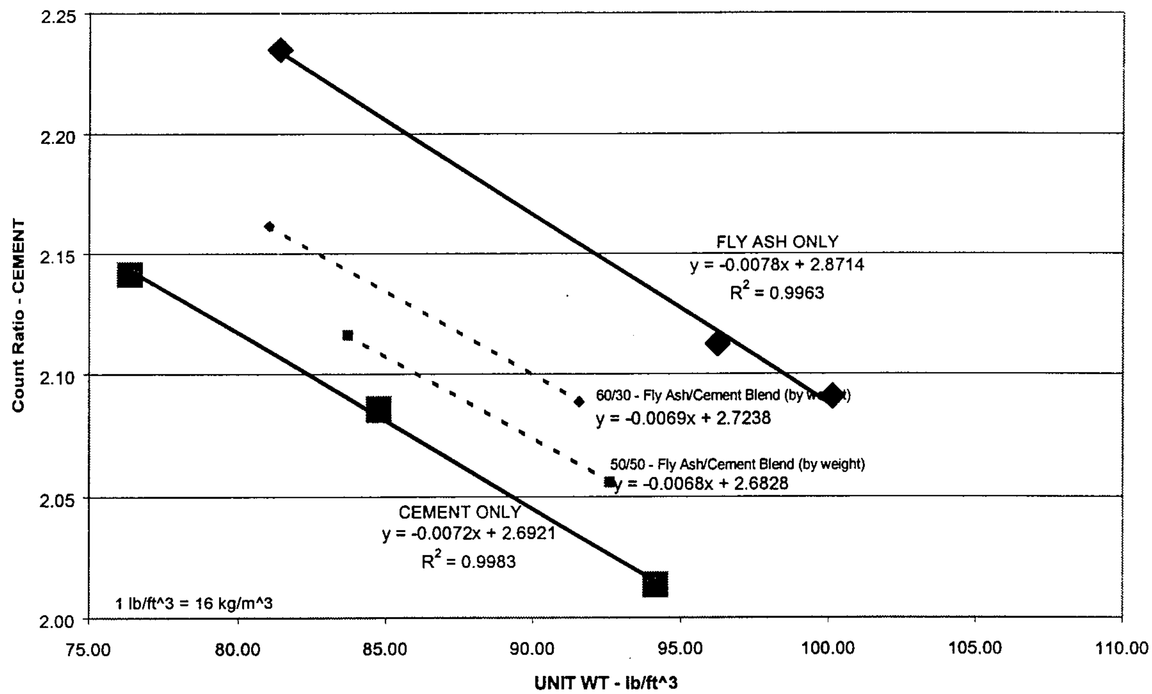

FIGURE 1B. Alternative Calibration Single Component Test Results: Cement or Fly Ash Content vs. Cement Count Ratio

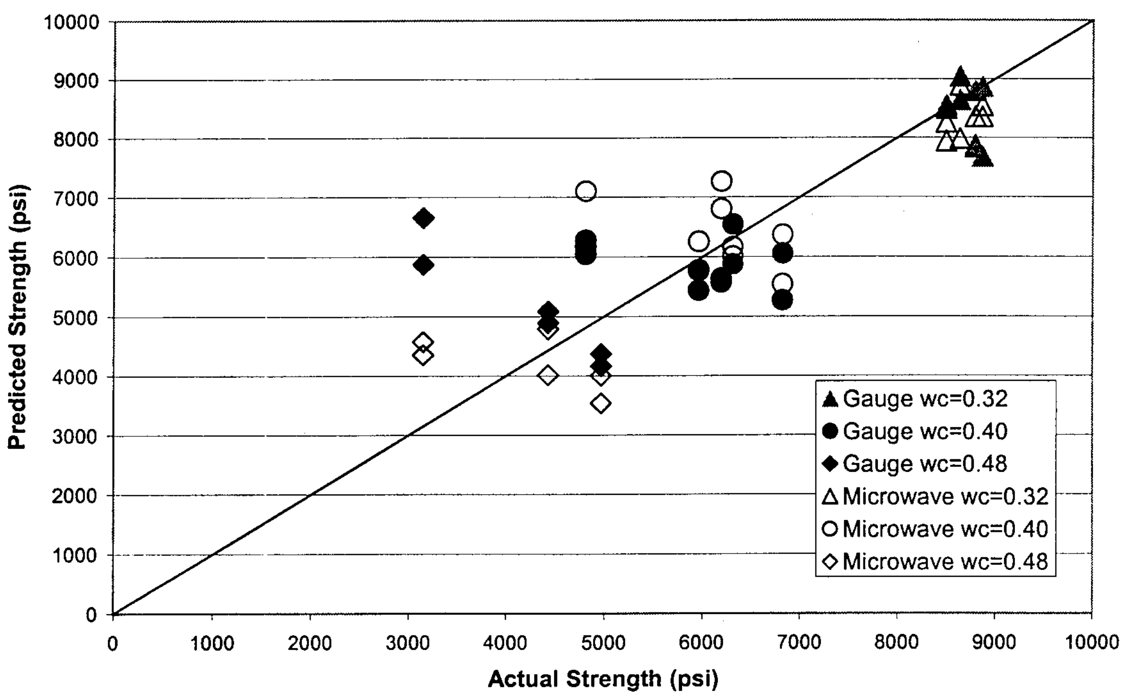

Figure 2B. 28-Day Strength Actual vs. Predicted: Nuclear Gauge and Microwave Oven Predictions for FA mixes